EFFICACY OF A RECOVERED WASH WATER PLANT IN REMOVING CYANOBACTERIA CELLS AND ASSOCIATED ORGANIC COMPOUNDS

Silvestina Mkhonto

389833

A Research Report submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science.

CANDIDATE'S DECLARATION

I Mkhonto Silvestina, student number 389833, declare that this research report is being submitted to the Faculty of Science for Master of Science: Research and Coursework in Environmental Science at the University of Witwatersrand, Johannesburg. It is my own work and it has not been submitted before for examination, or any degree at any university

2018/10/07

Signature of candidate and date

ABSTRACT

Cyanobacteria cells enter water treatment plants from the raw water abstracted from surface water destined to supply the water treatment plants. The presence of cells might interfere with purification processes such as coagulation and flocculation and may subsequently result in the release of taste and odourous compounds. This study is aimed at determining the efficiency of a Recovered Wash Water Plant (RWWP), in removing cyanobacteria cells and associated organic compounds at three stages of treatment, namely raw water, after sedimentation and after filtration. Concentration outcomes were statistically analysed to determine removal ability of the RWWP. The cyanobacteria genera *Microcystis*, *Anabaena* and *Oscillatoria* were detected in the three sampling points (raw water, after sedimentation and after filtration) selected. The organic compounds detected included geosmin, 2-methylisoborneol (2-MIB), and a cyanotoxin, microcystin. It is recommended that the effectiveness of the RWWP should be investigated seasonally during further research.

Keywords: Cyanobacteria; Organic Compounds; Recovered wash water plant; Coagulation; Sand filtration; Water quality

DEDICATION

To my daughter and mother

Neo and Catherine Mkhonto

ACKNOWLEDGEMENTS

I would sincerely like to acknowledge the following individuals and institutions:

My supervisor, Dr G C Snow, for your support and valuable advice.

My co-supervisor, Dr H Ewerts, for your valuable advice and guidance, your support and encouragement, for your assistance and for always being a call or an email away - you inspired me a lot. This project would not have been possible if it was not for you.

To Dr A Swanepoel for your advice and making sure the paperwork is in order for data analysis.

Prof H H du Preez for supporting the project.

Mrs A Schoeman for making sure that the project is scheduled, and bottles are prepared.

Scientific Service LIMS (Laboratory Information Management System) for data capturing (to P Legodi for making sure I collect bottles, even after hours, THANK YOU).

Rand Water Scientific Services for sample analysis.

Rand Water Zuikerbosch management for support and for the use of your facility and resources.

Rand Water for funding the study.

Rand Water Training development for your support.

To my family, friends and colleagues thank you so much for your support.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

2-MIB	2-Methylisoborneol
DAF	Dissolved Air Flotation
DOC	Dissolved Organic Carbon
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWTP	Drinking Water Treatment Plant
EC	Electrical Conductivity
$FeCl_3$	Ferric Chloride
FRS	Filtered Recovered Sump
HDMI	High Definition Multimedia Interface
LIMS	Laboratory Information Management System
NOM	Natural Organic Matter
NTU	Nephelometric
pH	Potential of Hydrogen
RWW	Recovered Wash Water
RWWP	Recovered Wash Water Plant
SANAS	South African National Accreditation Standard
SANS	South African National Standard
THMs	Trihalomethanes
TOC	Total Organic Carbon
WHO	World Health Organisation

WRC	Water Research Council
WTP	Water Treatment Plant

UNITS

cells/mL	cells per millilitre
µg/L	microgram per litre
ML/d	Megalitres per day
mS/m	milli-siemens per meter
mg/L	Milligrams per litre
ng/L	nanogram per litre
<	Less than
>	Greater than
≤	Less-Than or Equal to

CHAPTER 1: INTRODUCTION

1.1 Background

Life on earth is dependent on water for survival. Water is the most essential substance on earth and it is an essential natural resource used to retain a healthy lifestyle and to make natural and industrial products (Masato *et al*., 1999). Adequate supply of potable water is recognised as a basic human need and right (Oyem *et al*., 2014) Although water is essential to life, water quality is degrading at an alarming rate, adding to water scarcity (Govender, 2016) and putting more pressure on government in meeting increasing demand of potable water supply (Oyem et al., 2014).

Population growth, and associated development, is placing more pressure on the quality of water resources. In South Africa the quantity and quality of water are affected by factors such as rainfall patterns (climate), anthropogenic pollution, domestic use, mining, agriculture, industry and government policies that are used to protect, control, manage and determine the access to the water use (Oberholster, 2010). Water contamination and pollution can be ascribed to wastes or pollutants produced by mining and industrial activities, the runoff of agricultural fertilisers into the surface water and the erosion of sediments (Claassen, 2010). Mining waste typically contains metals and often increases the acidity of water, while urban development typically increases water salinity and microbiological content, and industrial waste increases salinity and contains chemicals that pollute surface water and leach into the groundwater (Naroth, 2016). The effluents discharged from mining and industries change the quality of the watercourse (Oberholster, 2010).

South Africa started to experience environmental pollution problems in the early 19th century due to an accumulation of waste from industrialisation and urbanisation. This contributes to increased water contamination and reduces the availability of water (Lowies, 2014). The deterioration in water quality and quantity is generally connected with an increase in population growth. According to census 2011 South Africa’s population is at 51.8 million and according to projections it is estimated that it will grow to 67.3 million people in 2035. Simultaneously the domestic water demand will also increase with the growing population (Cilliers, 2015).

Water quality is affected by organic and inorganic water source pollution, that contribute to eutrophication (Ewerts, 2013). Eutrophication is the enrichment of water resources with nutrients, predominately nitrogen and phosphorus, which accelerates primary production and leads to a build-up of organic matter that has high biological oxygen demand (Chislock *et al.*, 2013). The process of eutrophication is exacerbated by anthropogenic activities, in many cases from the discharge of human waste due to poorly maintained sewerage systems. Eutrophication can lead to the proliferation of cyanobacterial blooms, which become a problem when the cells die and decay, utilising dissolved oxygen and stressing other aquatic life that require oxygen for their survival. Cyanobacterial blooms can also generate bio-toxins that might be harmful to other terrestrial animals such as birds and humans (Oberholster, 2010), as well as secrete odourous organic compounds such as geosmin and MIB (Srinivasan and Sorial, 2011).

Cyanobacterial blooms are causing poor aesthetic conditions, such as colour and odours, in water and it is also associated with public health risks such as vomiting, skin rash and possible motor neuron diseases (Banack *et al*., 2010; Chislock *et al.*, 2013). The problem tends to be particularly bad during the rainy season and warmer summer months when sufficient nutrients and light become available. The drinking water treatment costs may increase significantly due to the presence of cyanobacteria in raw water resources which requires treatment before consumption (Gary, 2008).

The presence of cyanobacteria in moderate or abundant quantities in the source water supplied to conventional drinking water treatment plants (DWTP) may interfere with conventional water treatment operations. The following problems may occur during water treatment if cyanobacteria are present:

(i) Inadequate coagulation, flocculation and sedimentation (Oberholster *et al*., 2004; Bezuidenhout, 2013; Hudson, 2015).

(ii) Clogging of inlet screens and filters, thereby affecting water flow, disturbing filtration rates, increasing filter backwash cycles, and destroying filter media (Ewerts, 2013).

(iii) The possibility of organic compound releases into the water, causing unpleasant taste and odour issues (Oberholster *et al.*, 2004; Bezuidenhout, 2013; Ewerts, 2013).

(iv) Regrowth in the distribution system, giving the water a greenish colour (DWAF, 1996).

(v) Formation of trihalomethanes when organic material reacts with chlorine during pre-oxidation (McDonald and Komulainen, 2005).

Water suitable for consumption should not cause health-related diseases or corrosion of household equipment, such as kettles and geysers (WHO, 2004). Basically, the water available in surface waters, such as dams and rivers, is not safe for drinking and it should be treated to meet safe drinking standards requirements as specified in the South African National Standard (SANS 241) and South African drinking water framework. The following parameters are used to monitor drinking water:

- It should not contain pathogens (harmful microorganisms that can cause health-related problems such as cholera).
- It should not cause damage to household equipment and distribution systems.
- It should be aesthetically acceptable, not having any odours, colours, or tastes (Hudson, 2015).

The main goal of water treatment plants (WTP) is to treat water to provide communities with safe drinking water. The treatment type used by a specific WTP depends on several aspects, such as the size of water treatment plant, the water source (such as surface, spring or ground water) and the quality of the source water. Surface water is exposed to non-point and point sources of pollution and can be contaminated by runoff. Raw water quality affects the effectiveness of drinking water treatment plants (DWTP), the cost of treatment and the distribution of the treated water (Piontek and Czyewska, 2012).

In this study the term “raw water” refers to filter backwash water destined for recycling.

1.2 Recovered wash water plant (unit processes)

In South Africa conventional water treatment is performed, by applying unit processes such as coagulation, flocculation, sedimentation, filtration and disinfection (Schutte, 2006; Ewerts, 2010; Bezuidenhout, 2013; Hudson, 2015). These processes are designed to remove suspended particles making the water unsuitable for human consumption (DWAF, 1996).

The 35 ML/d Zuikerbosch Recovered Wash Water Plant (RWWP) at Vereeniging is a conventional water treatment plant that uses coagulation, flocculation, sedimentation and sand filtration to treat backwash water. Details of the treatment process are illustrated in Figure 1.1.

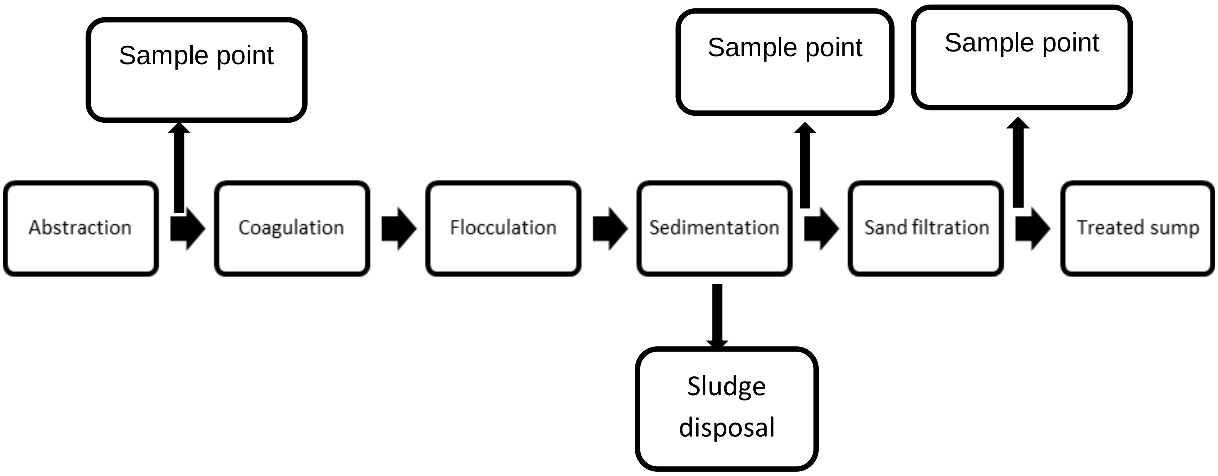


Figure 1.1: Schematic illustration of the RWWP showing the sequence of purification processes, including coagulation, flocculation, sedimentation and sand filtration. The sampling points are indicated with arrows facing upwards.

1.2.1 Abstraction

The water from filter washing is collected and stored in a sump (man-made reservoir) that is used as a raw water source for the RWWP. Screens are installed to remove algae and other solids, preventing them from progressing to the plant balancing tank. The water is pumped to the RWWP.

1.2.2 Coagulation and flocculation

Coagulation is a process where the water is rapidly mixed with chemicals, called coagulants, which destabilise the source water particles. The purpose of rapid mixing is to distribute the coagulant evenly and enable particles to become attached to form floccules during the process of flocculation (Delphos and Wesner, 2005). Particles carry a negative charge, repelling each other through anionic repulsion, the positive charge of the coagulant neutralises the charge and the suspended particles form floccules (Van Der Walt, 2010). The coagulants, which consist of polyelectrolytes and 23% $FeCl_3$ solution, are dosed directly into the raw water (Figure 1.2) using diaphragm pumps. The dosing rate is calculated from the recommended dosing concentration determined using jar tests experiments. The dosing rate is adjusted by changing the pump speed manually on the HDMI (High Definition Multimedia Interface). The dosing rate at the time of study was set at 5 mg/L polyelectrolytes and 4 mg/L $FeCl_3$.

The plant uses blades to initiate and mix the coagulant with water during coagulation. Effective coagulation and flocculation are critical to the successful performance of treatment processes. Problems associated with the coagulation and flocculation process result in high turbidity water in the overflow of the sedimentation tanks or the filtered water (Schutte, 2006). The coagulation process may result in the cyanobacteria cells lysing. thereby releasing cyanotoxins into the water (Hoger, 2003). The process of coagulation might be effective in removing cyanobacteria from water, but ineffective in removing soluble cyanotoxins.

Figure 1.2: Coagulation unit where $FeCl_3$ and polyelectrolyte are dosed

After coagulation water enters the flocculator tank equipped with paddles, which produce slow mixing conditions for the floccules to form (Schutte, 2006). In the flocculation process, the suspended particles collide with one another, and clean water separates from the particles as they form floccules. From here the water enters the next unit, namely the sedimentation tank.

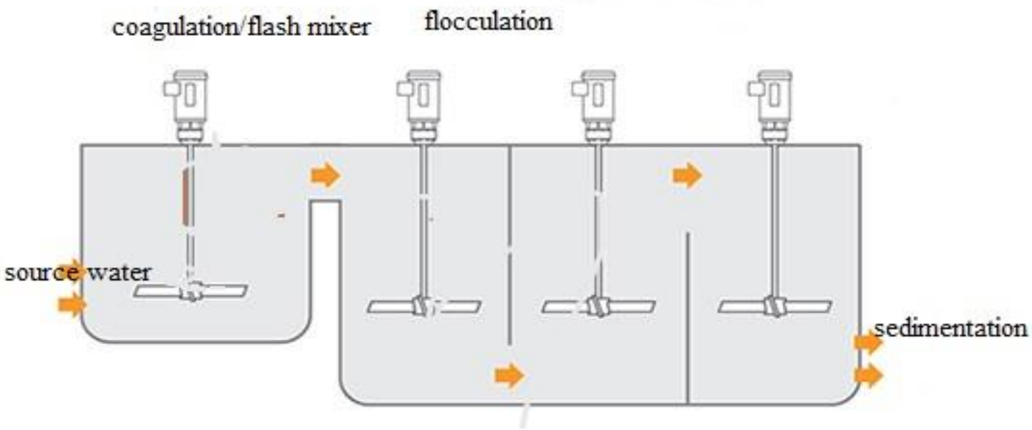


Figure 1.3: Diagrammatic illustration of the coagulation and flocculation processes (James, 2015)

1.2.3 Sedimentation

During the process of sedimentation, the floccules can settle out of suspension in the standing water. Sedimentation typically removes 80-95% of suspended solids, resulting in better filter performance and longer filter runs. However, the performance of a sedimentation basin is dependent on effective coagulation and flocculation (Schutte, 2006).

Some algal floccules, such as cyanobacteria with gas vacuoles, are buoyant and do not settle and may require the use of an advanced method such as dissolved air flotation (DAF) to be removed. In DAF process air is dissolved in water under pressure and released to the atmosphere and it will create air bubbles that will be attached to suspended particles with buoyance and form float. The float is a mixture of bubbles and particles attached to bubbles. Overtime the float concentration become sludge and is collected at the top of the tank and the subnatant (clear water) is collected at the bottom of the tank (Edzwald, 2010).

The sedimentation occurs in a tank called the densilator, installed with lamella plates to increase the settling process. The lamella plates improve the hydraulic distribution of the water and reduce turbulence, enhancing the settlement of the floccules. The sludge is collected from the bottom of the densilator tank by means of pumps. According to the operating procedure of the RWWP the turbidity of the clarified water is set at <5 NTU, to prevent overload and blocking of the sand filters with sediment.

Figure 1.4: Photograph of the sedimentation tank with lamella plates

1.2.4 Filtration

Filtration usually follows sedimentation and is regarded as the heart of water treatment. It is the only process that can remove very small particles (Schutte, 2006). Sand filters are used for the filtration process. The remaining floccules are trapped by the sand media as the water passes through by gravity. The resulting clear water after filtration blends with the final treated water of the Zuikerbosch water treatment plant for distribution. Filters are cleaned by the process of backwashing.

1.3 Problem statement

The filter wash process typically results in the loss of a large amount of contaminated water. In an arid country (such as South Africa) with low annual rainfall in certain regions, recycled water can play a significant role to ensure that the consumers' demands for drinking water are met. However, contaminants such as cyanobacteria and other substances trapped by the filter media during the filtration process, might be relatively high. Recycled water from filters exposed to abundant cyanobacteria should be treated before being discharged or pumped back into the inlet of the treatment plant. The costs related to treatment of filter backwash water might be significantly higher to ensure that the final product produced complies with the South African National Standards (SANS 241:2015) for drinking water. Cyanobacteria produce taste and odour compounds as well as cyanotoxins and their presence increase the risk of producing unsafe drinking water with an unacceptable level of taste and odour. The cyanotoxins released by cyanobacteria have the ability to cause diarrhoea and can affect the human liver or nervous system (Rose, 2014). Therefore, this study investigates the efficacy of a RWWP facility in removing cyanobacteria and their associated organic compounds from recovered wash water.

1.4 Aim

The objective of water treatment works is to treat water to a level where it is free of harmful organisms that can cause health related problems or unpleasant tastes and odours. Therefore, the aim of the study is to determine the effectiveness of RWWP in removing the cyanobacteria cells and associated organic compounds from recovered wash water. The following water quality variables were measured to determine the cyanobacterial removal efficiencies of the RWWP:

- Cyanobacteria cells concentrations
- Organic compounds concentrations (geosmin, methylisoborneol (2-MIB) and microcystin)
- Physical water quality variables (turbidity, electrical conductivity and pH)
- Chemical water quality variables (Total Organic Carbon (TOC) and Dissolved Organic Carbon (DOC)

CHAPTER 2: LITERATURE REVIEW

2.1 Characteristics of cyanobacteria

Cyanobacteria (Phylum Cyanophyta) are also known as cyanobacteria or often incorrectly referred to as blue-green algae. These organisms are not algae since they are prokaryotic gram-negative bacteria without any double membrane bounded organelles. Globally the presence of cyanobacteria cells is a concern in water treatment facilities (AWWA, 2010), especially where raw water destined for drinking water purification contains high nutrient (e.g. phosphate and nitrate) content. Aquatic cyanobacteria contain chlorophyll *a* (Hitzfeld *et al.*, 2000) and other accessory pigments, such as phycocyanin and phycoerythrin, for photosynthesis (Schubert *et al*., 1989). The gas vacuoles in the cells are used for buoyancy control. Cells are much more common and problematic in freshwater environments (Hitzfeld *et al.*, 2000).

Cyanobacteria can also be a nuisance, particularly in water treatment. Abundant cyanobacteria growth can create problems in the water treatment process where toxic or unpleasant taste and odour producing substances can be released (Mur *et al.*, 1999). The presence of cyanotoxins, such as microcystins released by cyanobacteria following cell lysis, can induce health related problems in humans such as skin irritations and liver damage. Other problems related to toxic cyanotoxin exposure are damage to the nervous system and body cells (Jung, 2009). Aquatic cyanobacteria are largely known for highly visible blooms that occur in fresh water environments, e.g. the Vaal Dam (Figure 2.1). The blooms can be toxic and affect recreation in the water source (Jung, 2009).

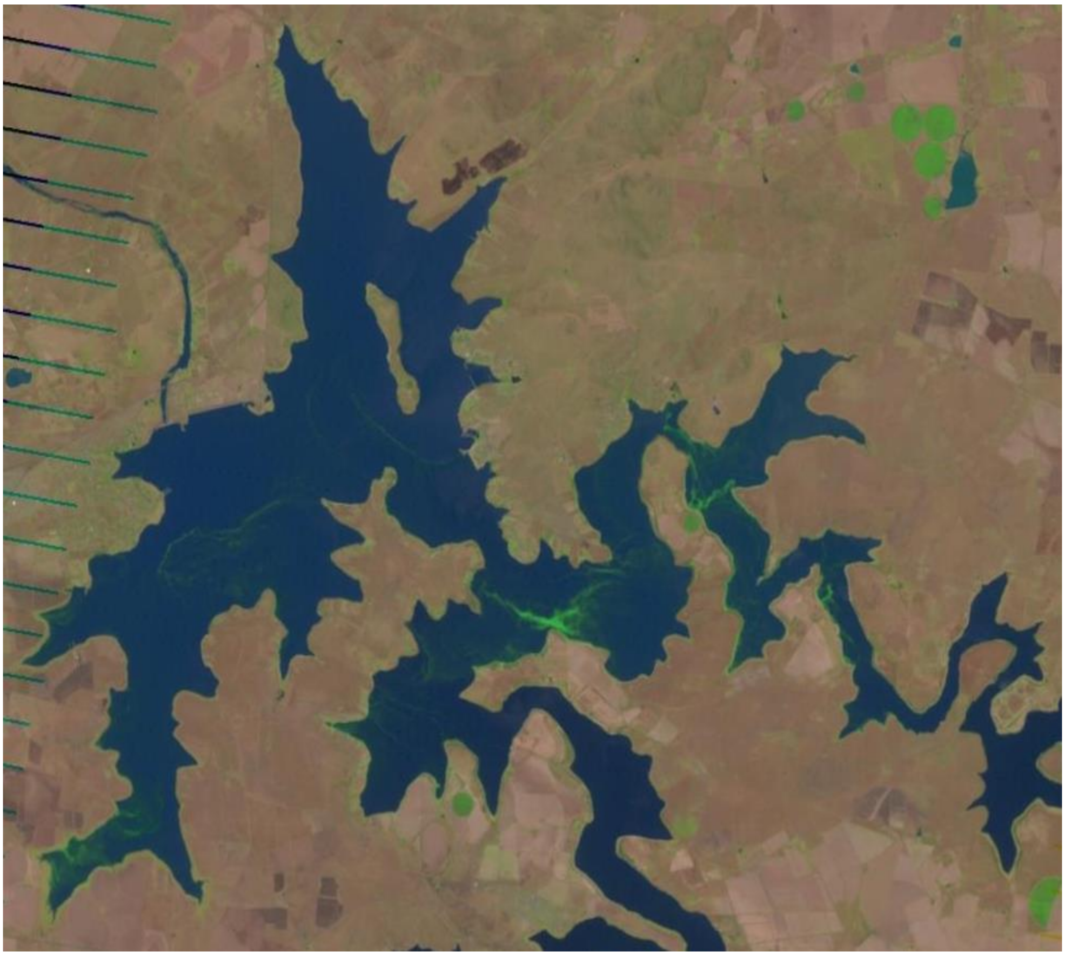


Figure 2.1: Landsat image of the Vaal Dam taken in November 2017 - the greenish colour represents the presence of cyanobacteria

2.2 Eutrophication of freshwater bodies in South African

The first major study regarding eutrophication in South Africa was published by Allanson and Gieskes (1961) and several later studies drawn attention to eutrophication problems in the 1970s and 1980s. The Department of Water Affairs and Forestry (DWAF), now the Department of Water and Sanitation (DWS), initiated a monitoring program in 1985. Data from this monitoring program indicated that water bodies in the vicinity of big cities in South Africa are experiencing eutrophication-related problems (DWAF, 2002). The presence of cyanobacterial blooms in South African water bodies threatens the supply of reliable and sufficient drinking water to consumers (Van Ginkel, 2011). According to Chinyama *et al*. (2016) the following cyanobacteria genera have been found in South African impoundments in previous studies: *Anabaena*, *Cylindrospermopsis*, *Lyngbya*, *Microcystis* and *Oscillatoria*.

Nutrient enrichment has become a critical problem in many freshwater systems across South Africa. Due to nutrient-rich effluents from wastewater treatment plants, agriculture and industries, the Vaal River has a high load of nutrients (Oberholster, 2010). The Vaal Dam is a freshwater source that supplies water treatment facilities with raw water that is treated and distributed to Gauteng, Free-State and the North-West provinces (Van Der Walt, 2010). The Vaal Dam (found on the Vaal River system) is one of the reservoirs in South Africa with eutrophication problems resulting in the occurrence of cyanobacteria. Studies by Downing and Van Ginkel (2004) and Mamba *et al*. (2007) have indicated the presence of cyanobacteria in the reservoir.

The trophic status of a water source is defined by the degree of nutrient enrichment. Oligotrophic status is characterised by low production because of low concentrations of nutrients, such as nitrogen and phosphorus, mesotrophic water body is characterised by medium-levels of nutrients, hypereutrophic are water bodies characterised by excessive algal growth and high presence of nutrients (Carlson and Simpson, 1996). Eutrophic water body is characterised by high nutrient content that can cause water quality problems, for example nuisance growth of algae and macrophytes. The nutrients (phosphorus and nitrogen) support algal growth and subsequent decomposition that occurs at the bottom of the water bodies uses up available oxygen (Van Ginkel *et al.*, 2001). Harding (2008) classified the Vaal Dam reservoir as eutrophic based on the total in-lake phosphorus and chlorophyll-a (chl-*a*) content.

According to Harding (2015) between 41% and 71% of water sources located in the center of South Africa are either eutrophic or hypereutrophic. In general South Africa is an area experiencing water related problems such as water shortages and poor water quality. A satellite remote sensing study was conducted by Matthews and Bernard (2014) to assess the condition of the 50 largest water sources in South Africa and the study found that most of the water sources were eutrophic or worse.

It is challenging for water boards to treat water from the Vaal River due to high concentrations of cyanobacteria and algae (Van Rensburg *et al*, 2016). The middle Vaal River (located downstream of the Vaal and Rietspruit confluence and upstream of the Bloemhof Dam) to Bloemhof Dam, is considered to be hypereutrophic. The Vaal River system is dominated seasonally by cyanobacteria and algal (e.g. diatom) blooms

(DWAF, 2004). The presence of algae and cyanobacteria has increased treatment costs over the years (Sibande, 2013).

2.3 Effects of cyanobacteria on water treatment

2.3.1 Aesthetic impacts of cyanobacteria on potable water treatment

In the 19th century professionals used taste and odour to assess water quality. Even today, consumers often complain about the appearance and smell of water despite of the fact that the water quality is monitored before distributed to consumers (Dietrich, 2006). Potable water should however be safe and aesthetically pleasing to the consumers. The impacts caused by cyanobacterial blooms on the water quality and water treatment plants depend on the extent and frequency of blooms (Srinivasan and Sorial, 2011).

Through cell lysis, cyanobacteria release toxins during the water treatment process potentially causing health related problems following ingestion of water contaminated with the toxins (Oberholster *et al.*, 2006). Microcystins are the largest group of toxins that result in acute or sub-acute liver toxicity (Harding and Paxton, 2001).

Taste and odour problems in drinking water are common and they are usually caused by geosmin and 2-MIB (Srinivasan and Sorial, 2011) and they are associated with customer complaints (Bezuidenhout, 2013). Geosmin and 2-MIB are the most common naturally occurring organic compounds released by cyanobacteria creating an earthy-musty odour in the water (Yoo *et al*, 1995). Geosmin is known to be produced by *Microcystis, Aphanizomenon, and Oscillatoria, while Oscillatoria, Pseudoanabaena, and Synechococcus* are known to produce 2-MIB (Swanepoel *et al*., 2008).

Elevated geosmin and 2-MIB concentrations are commonly caused by cyanobacteria and Actinomycetes (gram positive bacteria) that are found in soil and its runoff into water bodies during rainy seasons. It is important to identify and remove the compounds in drinking water due to its ability to impact the aesthetic quality of water (Mamba *et al.*, 2007). The most common toxic cyanobacteria genera found in South African impoundments *Microcystis, Oscillatoria, Anabaena, Cylindrospermopsis, Aphanizomenon, Nodularia and Nostoc* (Harding and Paxton, 2001).

Figure 2.2: Common toxic freshwater cyanobacteria; (A) colony of *Mycrocystis* sp., (B) filament of *Anabaena* sp. and (C) filament of *Oscillatoria* sp. (Van Vuuren *et al*., 2006)

Srinivasan and Sorial (2011) reviewed relevant treatment alternatives and found that conventional treatment processes were not 100% effective in removing 2-MIB and geosmin. Advanced technologies with powdered activated carbon (PAC), ozonation and bio-filtration appeared to be more effective, even though much work should be performed on optimising the plants.

Table 2.1: Common compounds causing taste and odour issues in water (Bezuidenhout, 2013)

Compound	Source	Taste and Odour
Geosmin	Cyanobacteria and Actinomycetes	Earthy
2-MIB	Cyanobacteria and Actinomycetes	Musty
B-cycloidal	Green algae	Grassy
Metals	Iron and manganese	Metallic
Mercaptans	Sulphate-reducing bacteria	Sulphur
Metals	Sodium and potassium	Salty

2.3.2 Effects on the treatment process

Surface water is contaminated with dissolved and suspended solids. It is a requirement for water utilities to treat water for potable use before distributing it to the consumers as it has the potential to carry pathogens. The occurrence of cyanobacteria has cost implications. To remove organic compounds associated with cyanobacteria, additional chemicals such as PAC (powered activated carbon) are added to the water being treated (Sibande, 2013).

Blooms of cyanobacteria can cause clogging of filter systems, leading to high maintenance costs. The presence of cyanobacteria affects the flocculation process as they may destabilise floccule formation (Ewerts, 2010). Cyanobacterial cells have gas vacuoles and tend to float on the water or are suspended within the water column destabilising floccule formation and settling, thereby increasing the load on the sand filters often resulting in blockages. The clogging of filters reduces filter run time and increases the need for filter backwashing. Cyanobacteria have the potential to penetrate into the final treated water causing problems such as taste, odour and potentially toxic chemical loads (Van Der Walt, 2010). In addition, the algal cells can potentially regrow in the distribution system if Chlorine dosage is not sufficient and give the water a greenish colour. The presence of algal cells in the treated water can result in the formation of trihalomethanes (THMs) when chlorine is dosed (DWAF, 1996).

The use of free chlorine to treat water for microbiological contamination may result in the formation of THMs. The four Types of THMs having the highest risk to human health are $CHCl_3$ (chloroform), $CHCl_2Br$ (dichlorobromomethane), $CHClBr_2$ (dibromochloromethane) and $CHBr_3$ (bromoform) (DWAF, 1996). The formation of THMs in treated water is a function of DOC concentration, pH, chlorine dosage and the length of exposure time. Trihalomethanes have the potential of being carcinogenic, posing a severe health risk to consumers (McDonald and Komulainen, 2005). Although the evidence for the formation of cancer in people who have been consuming chlorinated water over their lifetimes is weak, high doses of THMs have been found to be carcinogenic in rodent bioassays. Currently, a maximum THMs concentration of 100 µg/L has been stipulated in South African regulations (DWAF, 1996). According to WHO (2005) THMs might act as an indicator of other by-products present in the drinking water.

According to a study by Ewerts (2010) conventional water treatment processes did not remove 2-MIB from the Zuikerbosch water treatment plant but instead increased the concentration, while the geosmin concentration was lowered but not effectively removed.

Piontek and Czyzewska (2012) concluded that conventional water treatment plant processes improved water quality by removing phytoplankton, odour and total suspended solids but advanced technologies are needed to strengthen the effects of the water treatment. Hudson (2015) determined that advanced technologies are efficient in removing cyanobacteria from source water and that the ozonation process usually increased biodegradable dissolved organic carbon (DOC), which resulted in the promotion of bacterial development.

2.4 Water quality variables

2.4.1 Physical and chemical water variables

The physico-chemical water quality of water is determined by intrinsic characteristics as well as dissolved and colloidal substances in the water. The intrinsic properties include odour, taste, colour, temperature and electrical conductivity. The general attributes of water that play a role in the treatment process are discussed below.

2.4.1.1 Potential of Hydrogen (pH)

Water with a pH of less than 7 reflects acidity and if greater than 7, alkalinity. The pH is a logarithmic expression of the hydrogen ion concentrations in water and has an indirect effect of causing corrosion or scaling in steel pipelines. It can also have direct health effects on mucous membranes when exposed to extreme pH levels resulting from dissolution of metals such as copper, zinc and cadmium that can be toxic and influence the taste of the water (Antoniou, 1999).

2.4.1.2 Turbidity

Turbidity is an indicator of the number of suspended particles in water that affects water clarity - it is a universal indicator of suspended sediment. Elevated turbidity levels in water will result in lower dissolved oxygen and affects the aesthetic quality of water (DWAF, 1996). Bacteria, viruses and parasites attach themselves on the dirt of the water. When organic matter decay, bacteria in water can consume oxygen, reducing the oxygen in water. High levels of turbidity result in low levels of dissolved oxygen (Kale, 2016).

Turbidity is a measure of the cloudiness of the water, it may affect the colour of the water and result in a muddy taste, particularly in the southern hemisphere. The water in the Southern hemisphere turbidity is usually caused by inorganic suspensoids such as clay, silt and mud particles-thus the “orange”, “grey” and “brown” coloured rivers. Northern hemisphere rivers are mostly turbid as a result of organic particles such al algae- therefore the “turquois blue” colour of their rivers. Turbidity is measured using Nephelometric Turbidity Units (NTUs) (Davies and Walmsley, 2012).

2.4.1.3 Electrical conductivity (EC)

Electrical conductivity is a measurement used to determine the ability of water to conduct an electric current. It is directly proportional to the Total Dissolved Solids (TDS) and concentration of ions present in the water source (Antoniou, 1999; Schutte, 2006).

2.4.1.4 Total organic carbon and dissolved organic carbon

Total Organic Carbon (TOC) is the sum of the organic carbon found in solution and in suspended matter. It originates from decaying Natural Organic Matter (NOM) and it can be used to estimate the presence of NOM in water (DWAF, 1996).

Dissolved Organic Carbon (DOC) is the sum of the organic carbon found in solution and in suspended matter and its presence in drinking water can affect water quality by affecting the water taste, colour and odour (DWAF, 1996).

2.5 Microbiological water quality parameters

Microbiological quality is determined by the type and density of micro-organisms present in the water. Due to water pollution from non-point and point sources, algal blooms frequently occur in the source water used by water treatment plants. The presence of algal blooms in the water treatment process is a problem (Du Plessis, 2006). There are analyses that are performed by water utilities to ensure the potable water produced for consumers is free of micro-organisms.

2.6 Removal of harmful cyanobacteria

Algae and cyanobacteria are gaining attention in the drinking water industry because of associated problems such as clogging intake screens and increasing coagulant demand. As a result, cyanobacteria should be removed from water used for human consumption (Oberholster *et al.*, 2004).

Swanepoel *et al.* (2017) investigated the occurrence and removal of cyanobacteria from the Vaalkop Dam using conventional and advanced water treatment methods. They found that the removal of cells from the water treatment plant was not 100% effective and that some cyanobacteria species penetrated the treated water.

Removal of cyanobacterial cells during water treatment can reduce the intensity of tastes and odours as well as the concentration of toxic metabolites present in the treated water. In a jar test study by Chow *et al*. (1999), it was found that *Microcystis aeruginosa* could be removed from solution when using Alum as a coagulant. This finding has been supported by De Almeida *et al*. (2016) who found that conventional water treatment, which includes the use of Alum, was effective removing *Microcystis* cells from water and that disinfection was effective removing 50% of microcystin. Alum has the potential to increase the aluminium concentrations in treated water more than it was in the raw water. High concentrations (3.6 to 6 mg/l) of alum in treated water have negative impacts, such as an increase in turbidity and reduction in disinfection efficiency. It might cause the treated water to not comply with SANS 241 (Srinivasan *et al*., 1999).

Ando *et al*. (1992) found that the conventional treatment processes of coagulation, flocculation, sedimentation and filtration were not effective in removing taste and odour below the threshold numbers.

The study focused on the following water quality variables;

- Phytoplankton identification and enumeration are important parameters for water treatment personnel that are monitoring water quality and treatment efficiency at water treatment works, as they improve knowledge of algal abundance, genus diversity and growth potential (Yentsch and Menzel, 1963).

- Chlorophyll-*665* is a measurement of absorbance after acidification. The use of chlorophyll-665 method in drinking water is to determine total pigment concentration (TPC), which is a sensitive method that detects low concentrations of chlorophyll. Chlorophyll analysis in drinking water is important to determine raw and drinking water problems related to phytoplankton (Swanepoel *et al*., 2008).

CHAPTER 3: METHODOLOGY

3.1 Study area

The study was performed at Three Rivers East, located 20 km from the town of Vereeniging. The Recovered Wash Water Plant (RWWP) of the Zuikerbosch Water Treatment Plant is used to recycle backwash water, treating drinking water from the Vaal Dam. The water for the backwash process is stored in a Filtered Recovered Sump (FRS) and pumped to the 35 ML/d RWWP for treatment.

3.2 Data collection methods

The water stored at the FRS is used as raw water to supply the RWWP. Three sampling points were selected: raw water (P-R-FBWW), after sedimentation (P-A-Sed-FBWW), and after filtration (P-T-FBWW). Samples were collected twice monthly from April to June 2017 and transported to Vereeniging Rand Water Scientific Service for analyses.

Figure 3.2: Raw water sampling point (P-R-FBWW) at the RWWP

Figure 3.3: After sedimentation sampling point (P-A_Sed-FBWW) at the RWWP

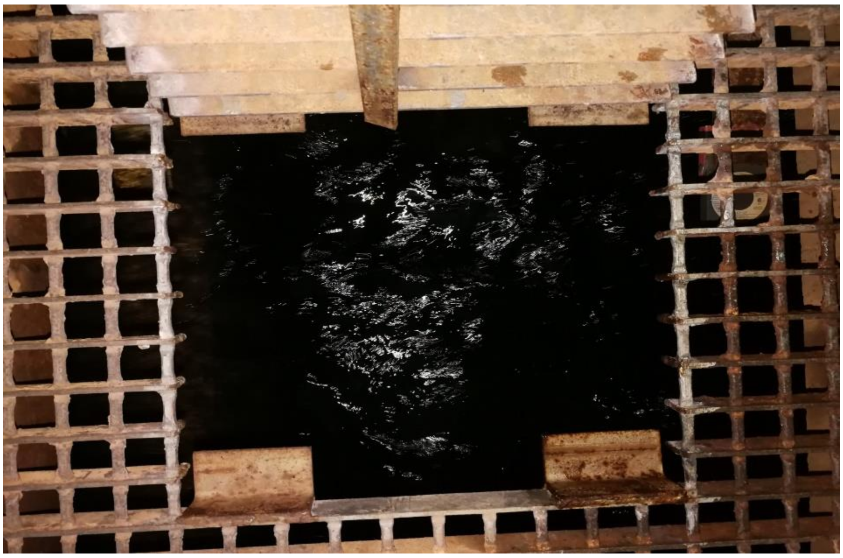


Figure 3.4: After filtration sampling point (P-T-FBWW) at the RWWP

The following water quality variables were measured on-site during sample collection:

i. Water pH (in pH units) was measured using a 691 pH Metrohm meter
ii. Electrical conductivity (µS/cm) using a LF 538 conductivity meter
iii. Turbidity (NTUs) using a Hach 2100N turbidity meter

The following parameters were analysed in scientific service laboratory of Rand Water, Vereeniging:

i. Dissolved Organic Carbon (DOC)
ii. Total Organic Carbon (TOC)
iii. Microcystin
iv. Geosmin
v. 2-MIB
vi. Phytoplankton identification and enumeration

The "after sedimentation'' samples in the 2nd week of June was not collected due to maintenance at the plant. Water sample and physical analyses and measurement were done onsite by the student and phytoplankton identification and enumeration, organic compounds and chemical analysis were analysed by the Rand Water Scientific Service laboratory, according to Rand Water board analysis methods. The method used for analysing the data was adopted from Swanepoel *et al.* (2008).

Table 3.1: Methods used by Rand Water Scientific Services to analyse water samples (Swanepoel *et al.*, 2008)

Method number	Quality variable	unit
1.1.2.02.1	Chlorophyll-665	µg/L
1.1.2.09.1	Microcystin	µg/L
1.1.2.03.1	Phytoplankton identification and enumeration	cells/mL
1.1.2.03.1	*Anabaena* sp. *Microcystis* sp. *Oscilatoria* sp.	cells/mL
2.2.1.01.2	Dissolved Organic Carbon	mg/L as C
2.2.2.02.10*	2-Methyl Isoborneol (2-MIB) Geosmin	ng/L
2.2.3.02.1	Total Organic Carbon	mg/L as C

3.3 Wash water treatment plant chemicals

The polyelectrolyte 3835 is dosed as the primary coagulant and 45% $FeCl_3$ as a secondary coagulant at the RWWP. The optimum dosages, as was shown by jar test experiments, were 5 mg/L polyelectrolyte and 4mg/L $FeCl_3$.

3.4 Statistical analysis

Three sets of data were used for the analysis, namely raw water, after sedimentation and after filtration. The data were used to determine the efficiency of the conventional water treatment plant in removing cyanobacteria and associated organic compounds. Different variables were examined such as cyanobacteria types and concentration present, organic compounds such as geosmin, 2-MIB and microcystin, and physical variables such as turbidity and electrical conductivity.

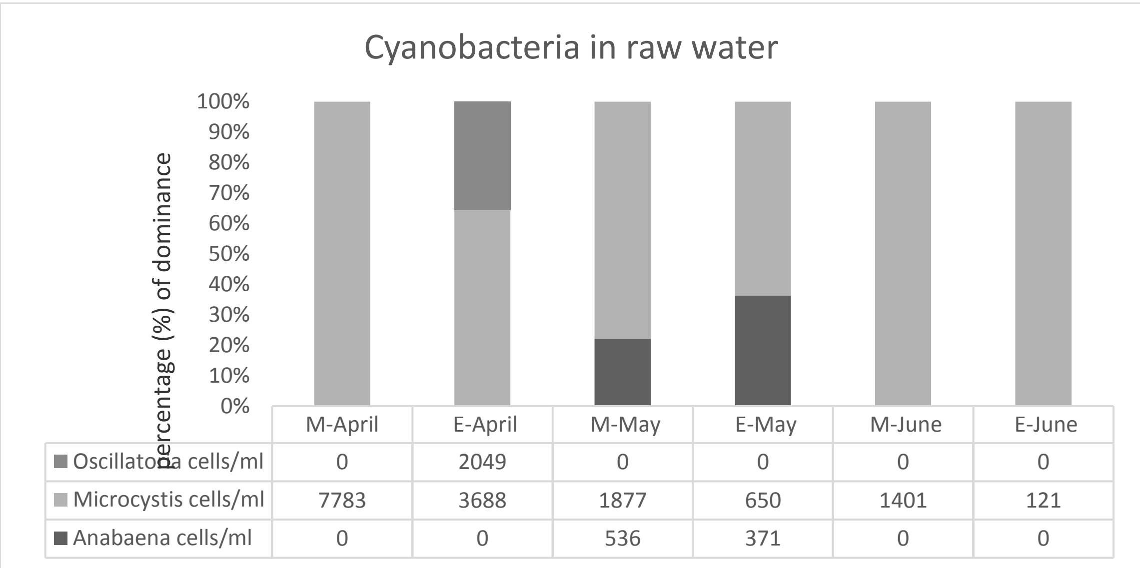
A single factor analysis, variance ANOVA, and t-test were carried out to determine removal efficiencies by different stages of water treatment (statistically significant differences). The level of significance for all statistical analysis was set at p value ≤ 0.05 and the hypothesis difference equal to zero.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Assessment of the raw water from the RWWP

The total phytoplankton composition in raw water was dominated by cyanobacteria, consisting of the following genera: *Anabaena, Microcystis* and *Oscillatoria* (Figure 4.1). The highest cyanobacteria concentration in the raw water (7783 cells/mL) was recorded on 11 April 2017. *Microcystis* was dominant in the raw water for the duration of the study and was present in all water samples collected. There was a general decrease in cyanobacteria cell concentration over the study period from a maximum of 7783 cell/mL in mid-April to 121 cells/mL at the end of June in the raw water samples. This decrease could be due to a decrease in cell concentrations entering the main treatment works. *Anabaena* was detected mid-May (536 cells/mL) and end-May (371 cells/mL). *Oscillatoria* was only detected in the last week of April (Figure 4.1) at a 35.7% relative abundance of the total cyanobacteria.

High cell concentrations are likely to affect the drinking water process when cyanobacteria enter the water treatment plant (Swanepoel *et al*., 2008). As a result, coagulant optimisation strategies should form an integral part of the water treatment when raw water is characterised by relatively high (> 2000 cells/mL) cyanobacteria concentrations.



	M-April	E-April	M-May	E-May	M-June	E-June
Oscillatoria cells/ml	0	2049	0	0	0	0
Microcystis cells/ml	7783	3688	1877	650	1401	121
Anabaena cells/ml	0	0	536	371	0	0

Figure 4.1: Relative abundances (%) of the three Cyanophyceae genera (*Anabaena*, *Microcystis* and *Oscillatoria*) in the raw water detected during the

study period (April-June 2017). M-A = Mid-April, E-A =end-April, M-May= Mid-May, E-M = End-May, M-J =Mid-June, E-J= End-June.

Descriptive statistics, namely the average, minimum, maximum and standard deviations (SD) for the phytoplankton identified in the raw water are presented in (Table 4.1) for the study period (April-June 2017).

Table 4.1: Descriptive statistics of phytoplankton cell densities identified in raw water samples for April-June 2017 Mean ± standard deviation (SD), minimum (Min) and maximum (Max) values are presented.

Phytoplankton classes	Units	Mean ± SD	Min	Max
Bacillariophyceae	cells/mL	885 ± 566	181	1479
Chlorophyceae	cells/mL	240 ± 419	0	1086
Cryptophyceae	cells/mL	335 ± 265	0	724
Cyanophyceae	cells/mL	3079 ± 3015	121	7783
Euglenophyceae	cells/mL	13 ± 32	0	78
Dinophyceae	cells/mL	22 ± 55	0	134

It is important for water treatment facilities to determine the types of phytoplankton present in raw water because the cells may have an impact on the water treatment process. Some genera produce organic compounds that affect water quality and can cause taste and odour, while some produce toxins that might be harmful to consumers' health. For example, several cyanobacteria, such as *Microcystis, Anabaena, Nodularia* and *Oscillatoria*, produce the hepatoxin and microcystin (USEPA, 2018). Knowledge of the phytoplankton community structure and density assists in optimising the chemicals that should be utilised in the treatment plant. It is important to remove potentially harmful phytoplankton, including cyanobacteria, from the water treatment plant, preferably before they undergo cell lysis and release toxins and taste and odour producing substances in the water.

The organic compounds associated with cyanobacteria (geosmin and 2-MIB) may affect the quality of the drinking water, because of their potential to produce odour and taste compounds. Though not toxic, taste and odour compounds result in water that may not be aesthetically pleasing. The toxic substances produced by cyanobacteria (e.g., microcystin) may be harmful to consumers (Oberholster *et al*., 2006).

The three cyanobacteria genera found during the study, and listed in Table A1, also possess the potential to produce by-products, such as trihalomethanes, during chlorination (AWWA, 2004; Ewerts *et al*., 2013). Cyanobacterial blooms occur mostly in warm eutrophic waters. *Anabaena, Oscillatoria* and *Microcystis* are toxic genera that have the potential to form massive blooms near the surface of the water in summer months (Hoger, 2003; He *et al*., 2016), clogging of filters, produce toxins and taste and odour problems (Swanepoel *et al*., 2017). Cyanobacteria penetrate the final treated water (Swanepoel, 2015). However, *Oscillatoria* can also effectively grow in oligotrophic waters at lower temperatures (AWWA, 2004).

4.2 Assessment of the after sedimentation water from the RWWP

The number of algal cells in the RWWP was reduced from an average of 3079 cells/mL in the raw water to an average of 44 cells/mL after sedimentation. The total phytoplankton composition in after sedimentation water was dominated by Bacillariophyceae, with a total concentration of 231 cells/mL for the period of the study (April-May 2017). Cyanobacteria cells were also detected, consisting of *Anabaena, Microcystis* and *Oscillatoria* genera. The highest cyanobacteria density in the after sedimentation water (148 cells/mL) was recorded on 11 April 2017. There was a general decrease in cyanobacteria cell density over the study period from a maximum of 148 cell/mL in mid-April to 18 cells/mL mid-May and the densities went up slightly mid-June to 35 cells/mL in the post-sedimentation water samples. *Microcystis* was detected mid-April (67 cells/mL), end-April (20 cells/mL) and mid-June (13 cells/mL); the lowest concentration detected for the study period (April-June 2017). *Anabaena* was detected mid-April 81 cells/mL the highest density detected for the study period (April-June 2017) and mid-May 18 cells/mL. *Oscillatoria* was only detected in the mid-June at 20 cells/mL.

The chemical water quality variables of TOC and DOC decreased from an average of 4 mg/L as C and 3 mg/L as C in raw water to an average of 3 mg/L and 2 mg/L as C post-sedimentation respectively, and the concentration increased to an average as the same as the raw water for after filtration.

When DOC reacts with chlorine during disinfection process, the DOC could cause harmful by-products and increase the potential for algal growth in the distribution system (Ozdermir, 2014).

4.3 Assessment of the after filtration water from the RWWP

The number of algal cells in the RWWP was reduced from an average of 3079 cells/mL in the raw water to an average of 25 cells/mL after filtration.

The presence of organic carbon can affect drinking water quality and has the potential to enhance growth of algae. The study found that TOC and DOC were lower than the SANS 241 threshold in the raw water. The average of DOC and TOC in the raw water and after filtration remained the same (DOC 3 mg/L as C and TOC 4 mg/L as C respectively). A study by Volk *et al.* (2000) indicated removal of between 0% and 74% organic matter by a treatment facility and it also indicated that the quantity and quality of the NOM influences treatment efficiency. The RWWP has 0% removal of DOC and TOC.

The geosmin concentration detected in the after filtration was an average of 2 ng/L (Table 4.2) and the raw water geosmin concentration average was 6 ng/L. The geosmin concentration did not comply with SANS 241: 2015, saying that geosmin concentrations should be ≤ 1 ng/L. The RWWP was, however, able to remove geosmin to an acceptable organoleptic detection level of the human nose 5-10 ng/L; (Westerhoff *et al.*, 2005). 2-MIB in the raw water was the same as after filtration at an average of 1ng/L. 2-MIB is an organic chemical responsible for the musty odour in drinking water.

Table 4.2: Descriptive statistics for chemical water quality variables measured after filtration. Treated water within SANS241/RW guideline limits (✔), treated water not within the guideline limits (X), AF%= percentage removal after filtration

Variables	Units	Min	SANS/RW	Max	SD	Average	AF %
Geosmin	ng/L	1	X	4	1	2	66.7
2-MIB	ng/L	1	✔	1	0	1	0
Microcystin	µg/L	0	✔	0	0	0	100

4.4 A comparison of the data collected from raw water, after sedimentation, and after filtration

4.4.1 Percentage removal of cyanobacteria by RWWP

Source water supplied to the RWWP contained relatively low concentrations of cyanobacteria cells (121–7783 cells/mL) compared to 3 000 000 *Microcystis* cells/mL in source water supplied to a similar water treatment plant in California (Szlag *et al.*, 2015). The density of cyanobacteria cells in the FRS reduced from an average of 3079 cells/mL in the raw water to an average of 25 cells/mL after filtration.

Figure 4.2 displays the percentage removal of cyanobacteria from raw water by the RWWP to After filtration. The cyanobacteria detected in the raw water were *Microcystis, Anabaena* and *Oscillatoria*. The percentage removal of cyanobacteria through coagulation and flocculation and sedimentation, was 99.2%. According to (Figure 4.2) *Microcystis* average increased from an average 20 cells/mL post-sedimentation to an average 25 cells/mL post-filtration. The RWWP resulted in no removal of *Microcystis* cells by the filtration process. An average of 44 cells/mL cyanobacteria penetrated the sedimentation process and 25 cells/L cyanobacteria were detected in the post-filtration water samples. According to Swanepoel *et al.* (2017), a high initial algal density in the raw water (> 100 000 cells/mL) is likely to result in cells penetrating the potable water. The average percentage removal (above 90% during the entire period of the study) indicates effectivity. The results show that the presence of cyanobacteria did not have a major impact on the water treatment unit process due to low initial concentration of 3079 cells/mL (average); this do, however, still exceed the concentration of 2000 cells/mL recommended by the World Health Organisation (WHO) source guidelines (WHO, 1998). Mohamed (2016) studied seven Drinking Water Treatment Plants (DWTPs) in Egypt and the dominant cyanobacterium was *Oscillatoria* with cell density ranging from 660-1877 cells/mL in the source water. The *Oscillatoria* cells were not completely removed by the unit processes of the conventional water treatment plant. In this study, *Oscillatoria* cells were only detected during mid-April 2017 and it was 100% removed after the filtration process.

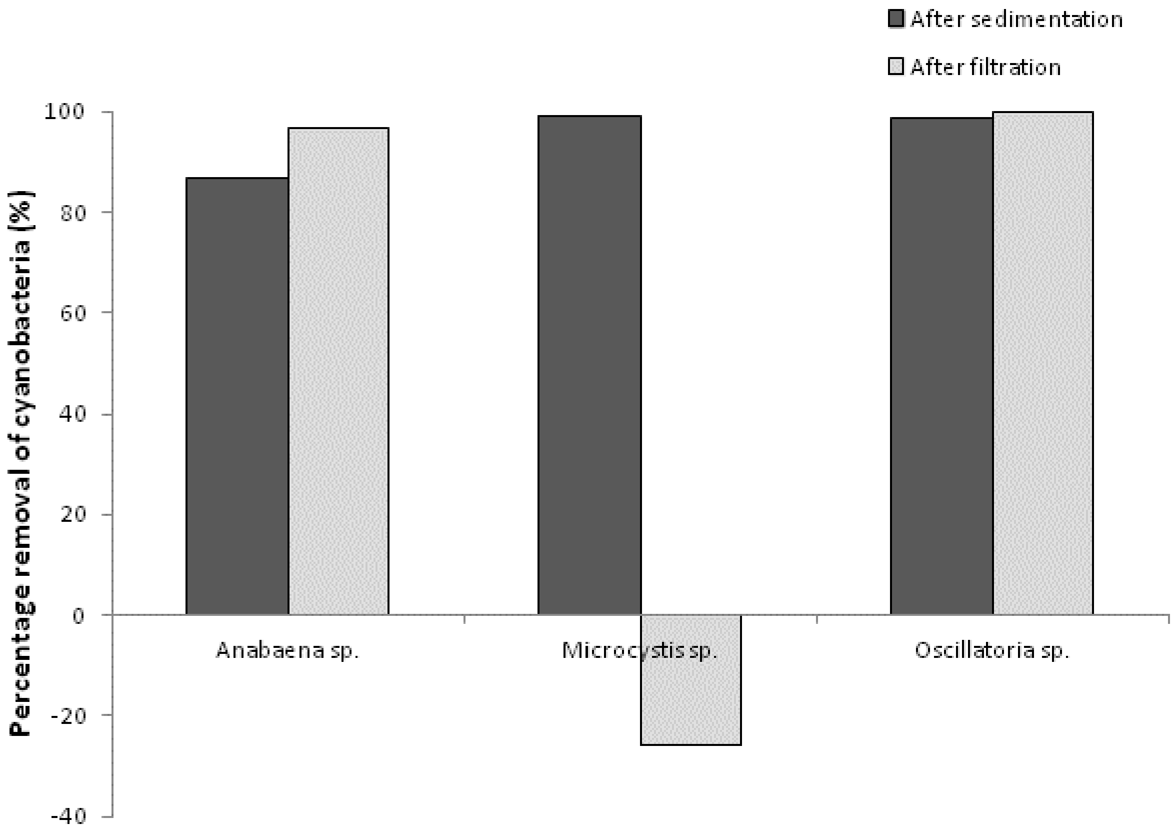


Figure 4.2: Percentage (%) cyanobacteria cells remaining following treatment.

4.4.2 Percentage removal of cyanotoxins and organic compound by the RWWP. AS = After sedimentation and AF = After filtration

Figure 4.3 indicates that microcystin concentration average in the raw water was 0.452 µg/L and it decreased to 0.360 µg/L and 0.360 µg/L following sedimentation and filtration respectively. The average microcystin concentration was less than the 0.8 µg/L chronic effects threshold for domestic use in South Africa (DWAF, 1996) but on one occasion (2nd week of April) the concentration was 0.910 µg/L, highlighting a potential concern. According to WHO guideline for drinking water microcystins are set at 1 µg/L. Microcystins are the most common cyanotoxins in freshwater and produced by cyanobacteria such as *Microcystis, Anabaena* and *Oscillatoria*. It is important for water treatment to remove cyanobacteria toxins (Mohamed, 2016). The cyanotoxins produced by *Microcystis* might be harmful to humans if consumed. The microcystin concentration detected in raw water samples collected was <1 µg/L. The percentage removal of microcystin by the RWWP plant exceeded 20%. According to Szlag *et al*. (2015) and Swanepoel *et al.* (2017), similar observations were made where the microcystin detected in raw water samples was <1 µg/L and nothing was detection in the treated water. The concentrations of microcystins are considered low, probably because of low concentrations of cyanobacteria detected in the raw water samples. Mohamed (2016) detected 14.1 µg/L in the raw water of DWTP 7 and the lowest concentration was 0.66 µg/L at DWTP 4. Lowest concentrations were detected in the final water (0.37-3.8 µg/L) after disinfection with chlorine.

The results showed that the taste and odour compounds, geosmin and 2-MIB, were not effectively removed by the coagulation and flocculation and sedimentation processes (Figure 4.3). Geosmin and 2-MIB are detectable by humans at concentrations between 5-10ng/l. Therefore, these compounds may be noticeable before the potential cyanobacterial producers become noticeable (Graham *et al*., 2008). According to Ho and Newcombe (2010), optimised coagulation processes can remove entire cells and therefore a large proportion of metabolites such as 2-MIB and geosmin. Geosmin concentration was 5.917 ng/L and decreased to 3.280ng/L and 2.043 ng/L after sedimentation and filtration respectively. The removal percentage following filtration was 66.7% for geosmin concentrations. 2-MIB concentratin was 0.650 ng/L in the raw water and increased to 0.680 ng/L and 0.783 ng/L after sedimentation and filtration respectively. The mean geosmin concentrations after filtration were over the SANS 241 limit of 1 ug/L (Table 4.2). According to Chow *et al.* (1999) conventional water treatment, using B-cyclodextrin polymers, was effective in removing 2-MIB and geosmin, indicating that the type of coagulant plays a role in removing organic compounds from raw water. In the mid-April samples, after filtration, the concentration of 2-MIB was 2 ng/L while the raw water concentration was 1 ng/L. The 2-MIB may have been produced by *Anabaena* that was detected after sedimentation and *Microcystis* which was detected throughout the study (Ewerts *et al*., 2013).

Taste and odour substances penetrating treated water are problematic and mostly caused by cyanobacteria and actinomycetes (Mamba *et al*., 2007). When geosmin and 2-MIB are released in water it is difficult to remove by conventional treatment processes, requiring advanced technologies (Swanepoel *et al*., 2008). The presence of tastes and odours in drinking water reduces the consumers’ confidence in the water treatment authorities.

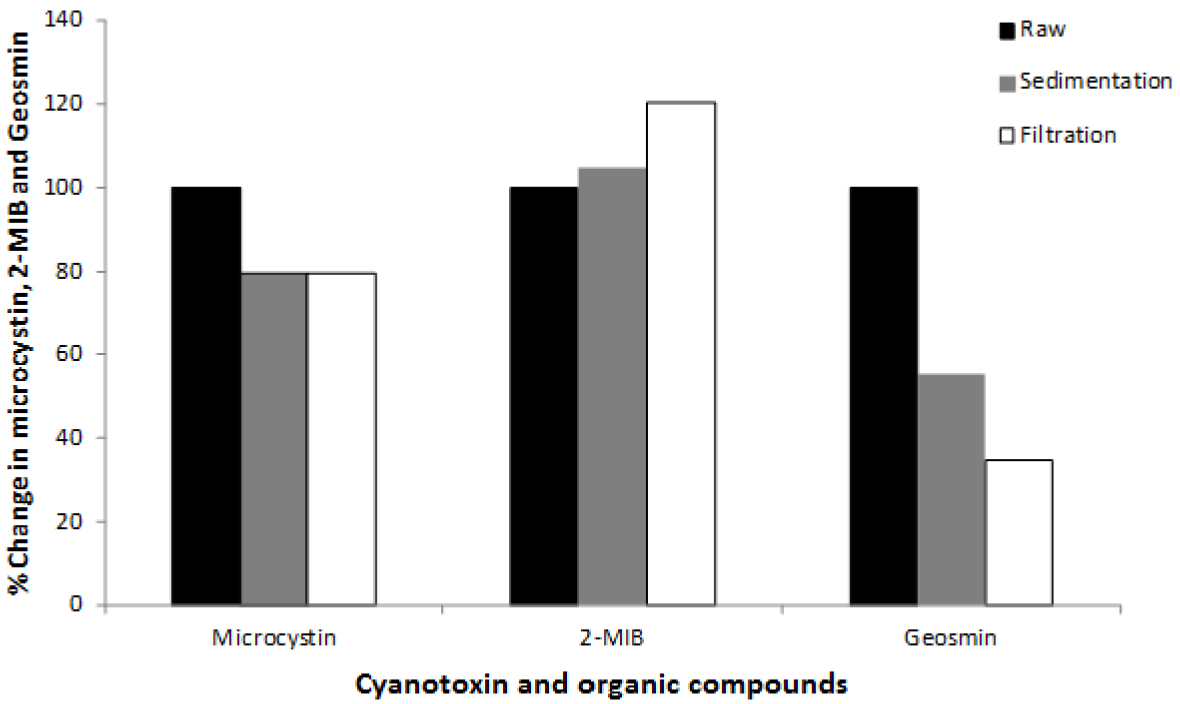


Figure 4.3: Percentage (%) change of the cyanotoxin (microcystin) and organic compounds (2-MIB and geosmin) following sedimentation and filtration.

4.5 Assessment of chlorophyll-*a* (Chl-*a*) measured at RWWP

Chlorophyll-665 is based on the spectrophotometric measurement of absorbance at a wavelength of 665 nm before and after acidification. The use of the chlorophyll-665 protocol in drinking water is to determine total pigment concentration (TPC), which is a sensitive method that detects even low concentrations of chlorophyll. Chlorophyll analysis in drinking water is relatively easy and important to determine raw and drinking water problems related to phytoplankton (Swanepoel *et al*., 2008). The concentration of chlorophyll-665, referred to as chlorophyll-a (Chl-*a*) from here, is used as an index of phytoplankton biomass, which can also be used to estimate the trophic status of water bodies and to monitor algal growth (Mohale, 2011).

When chlorophyll-*a* reaches 10 µg/L, taste and odour problems are likely to be experienced (Department of Health and Environment, 2011). Surface waters with high levels of Chl-*a* are typically high in nutrients such as phosphorus and nitrogen, where the nutrients accelerate the growth of algae. The raw water of the RWWP had an average of 14 µg/L of Chl-*a* and the highest Chl-*a* was measured mid-June 2017 at 26 µg/L. An average of 2 µg/L was detected after sedimentation and after filtration there was no Chl-*a* detected (Figure 4.4). Table 4.4 indicates that water collected from the RWWP after filtration complied with Rand Water and SANS 241 guidelines for Chl-*a*; the RWWP had a 100% removal of Chl-*a*.

Chl-*a* measured can be estimated *in situ* and has shown to be positively associated with microcystin (Hollister and Kreakie, 2016). The study found out that high concentrations of microcystin LR co-occur with high concentrations of Chl-*a*. Elevated Chl-*a* concentrations does not necessarily predict high microcystin LR concentrations but Chl-*a* may be predictive of the probability of exceeding a certain threshold.

Figure 4.4 indicates the Chl-*a* detected in each unit process though the study period (April-June 2017).

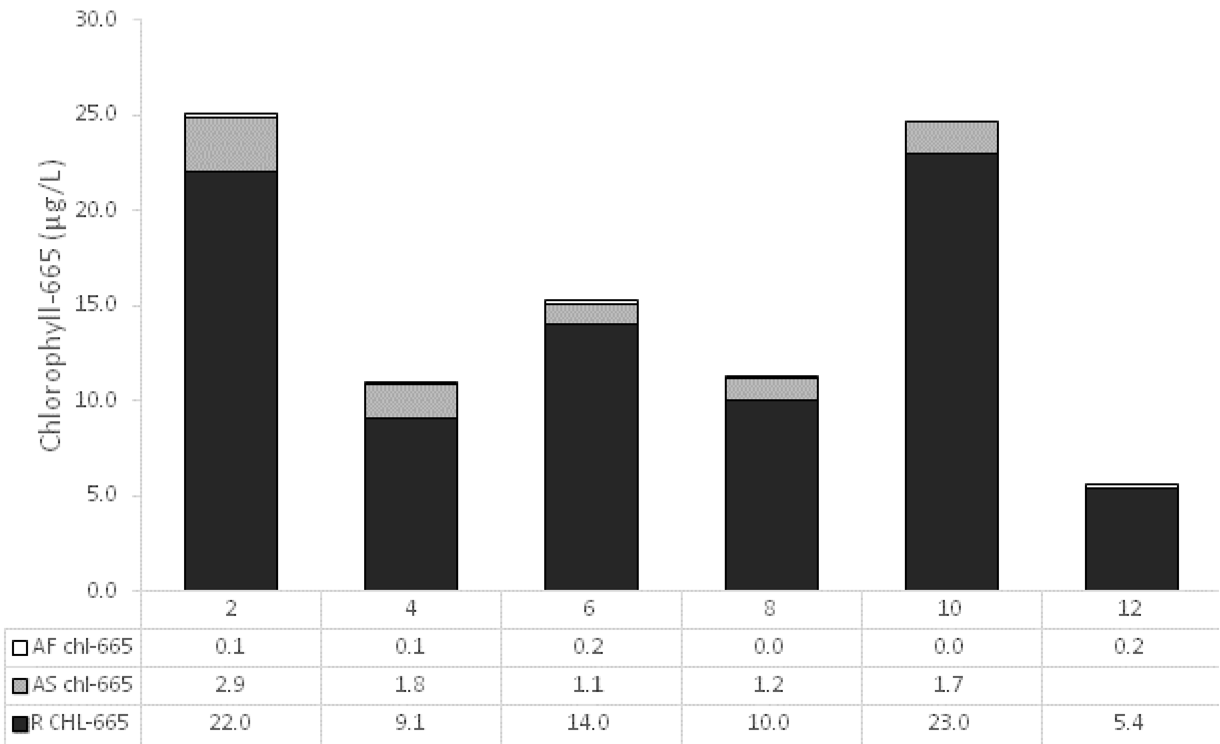


Figure 4.4: measured chlorophyll-665 in the unit process: AF (After filtration), AS (After sedimentation) and R (Raw water)

Table 4.3 shows the recommended limit according to Rand Water guidelines for chlorophyll-665.

Table 4.3: A water quality guideline for chlorophyll-665 in raw water and treated water (Rand Water guidelines).

Quality variable	units	Raw water		Treated water		
		Recommended maximum limit	Maximum allowable limit	Recommended limit	Maximum allowable limit	Crisis limit
Chl-665	µg/L	0-15	> 30	1	5	7

Table 4.4 describes the Minimum (min), Maximum (Max) and Standard Deviation (SD) of chlorophyll-665 measured in after or post-filtration water. The post-filtration water sample results indicate 100% removal of chlorophyll-665 and the water complied with SANS 241 and Rand Water drinking water quality guidelines.

Table 4.4: Descriptive statistics of Chlorophyll-665 measured after filtration (AF). Treated water within SANS241/RW guidelines

Variable	Units	SANS/RW	Min	Max	SD	AF %
Chl-665	µg/L	✔	0	0	0	100

4.6 Statistical results

The removal of phytoplankton by conventional water treatment processes is difficult due to the small size of the cells and their low specific gravity. Cyanobacteria cells have difficulty in settling and may remain at the surface due to the presence of gas vacuoles (Hitzfeld *et al.,* 2000). To determine which unit process of conventional water treatment was most effective in removing cyanobacteria cells and associated organic compounds the performance of each unit process was evaluated (Tables 4.5a and 4.5b). The evaluation includes coagulation, flocculation and sedimentation represented by the sampling points between raw water, after sedimentation and sand filtration. The ANOVA results comparing water treatment processes (sedimentation and filtration) and the organic compounds (geosmin, 2-MIB and microcystin) are displayed in Table 4.5a. The results indicate that there was enough evidence to suggest a statistical significance difference of cyanobacteria (*Anabaena, Oscillatoria and Microcystis*) and the three sampling points were not all equal ($F > F_{crit}$). There was not enough evidence to suggest any statistical significance of organic compounds (microcystin, geosmin and 2-MIB).

Table 4.5a: ANOVA results indicating statistically significance differences (✔) or absence thereof (X) between three data groups obtained from raw water (RW), after sedimentation (AS) and after filtration (AF); level of significance was set at $p \leq 0.05$

Cyanobacteria and organic compounds	Units	Sampling points			Statistically significant				
		RW	AS	AF	F	F_{Crit}	Total	P-value	
Cyanobacteria									
Cyanobacteria	cells/mL	3079	44	25	5.545	3.739	17	0.02	✔
Organic compounds									
Microcystin	µg/L	0.47	0.36	0.36	0.906	3.739	17	0.43	X
Geosmin	ng/L	5.8	3.2	2.2	3.091	3.739	17	0.07	X
2-MIB	ng/L	1	1	1.2	0.906	3.739	17	0.43	X

The removal of intact cyanobacteria cells by the water treatment plant will potentially reduce the concentration of the taste, odour and the toxic metabolites present in treated water (Chow *et al.,* 1999). To evaluate the individual processes and their ability to remove cyanobacteria and associated organic compounds, a t-test was performed between data from each consecutive process to determine if a statistical significant difference exists between the water quality before and after each unit process (Table 4.5b).

The results showed that the processes of sedimentation and filtration had no statistically significance difference on the density of cyanobacteria cells or organic compounds. The chemical dosage may not have been appropriate for the removal of cyanobacteria. According to Chow *et al.* (1999) *Microcystis* was effectively removed by a conventional water treatment using alum as a coagulant. It is important to perform plant optimisation with a coagulant that is significant to the removal of cyanobacteria cells and associated organic compounds (Ho and Newcombe, 2010).

Table 4.5b: T-test results performed to indicate the efficiency of each unit process, not enough evidence (X)

Cyanobacteria and organic compounds		**Sampling points**	
		Raw water vs after sedimentation	**After sedimentation vs after filtration**
Cyanophyceae			
Cyanobacteria	cells/mL	X	X
Organic compounds			
Microcystin	µg/L	X	X
2-MIB	ng/L	X	X
Geosmin	ng/L	X	X

4.7 Assessment of physical parameters after filtration

4.7.1 Turbidity

The RWWP (Rand water standard) operating limit for turbidity is set at <0.5 NTU for the plant after filtration and the purification processes were effective in removing turbidity, in the form of suspended solids, from the raw water. The after filtration water quality complied with SANS 241 and the operation guidelines of the RWWP. Particulate matter in water can create aesthetic and health issues because it can be made up of soil particles, organic matter, and pathogens. It is important for treatment plants to remove the particles in water because they can cause an objectionable appearance, tastes, and odours and they can interfere with disinfection (Ramavandi, 2014). Rosinska and Dabrowska (2016), used polyaluminium chlorides, and obtained an 89% turbidity removal from the DWTP. The turbidity of potable water from the Vaalkop water treatment plant reached a maximum of 9.8 NTU during summer months (Swanepoel *et al.*, 2017). The value was higher than the SANS 241 allowable limit for a limited period ≤ 5 NTU and ideally recommended operation limit is 1 ≤ NTU.

4.7.2 pH

The pH measured was within the Rand Water operating guidelines, which is between 7.6 and 8.8. pH influences the taste and odour and indicates possible corrosion problems (Mashele, 2016). Water with low pH might corrode household water systems made of copper and galvanised pipes (DWAF, 1998) and might give the water a sour taste (Mashele, 2016). High pH values might cause scale build up in the household water system (Ander *et al*., 2016).

4.7.3 Electrical conductivity

Electrical Conductivity (EC) in drinking water is used as an indicator of Total Dissolved Solids (TDS) and it is used to determine if the water is fit to be consumed and the water will also quench thirst. They are no health, aesthetic or treatments risks associated with ECs ranging from 0 to 70 mS/m in drinking water (Mohale, 2011). Conductivities exceeding 150 mS/m impart a salty taste to the water and water with conductivity above 300 mS/m does not slake thirst (DWAF, 1998). These are well within the target range proposed by DWAF (1996) for waters with no risks. The RWWP conductivity average was 18 mS/m, low conductivity indicates less chemicals dissolved in water.

Table 4.6: Descriptive statistics of physical water quality variables measured after filtration (AF). Treated water within (✔) and not within (X) the SANS 241/RW guidelines. (South African National Standard/ Rand Water; SANS/RW)

Variable	Units	SANS/RW	Min	Max	SD	AF %
Turbidity	NTU	✔	0	0	0	100
pH	pH units	✔	8	8	0	11
Conductivity	mS/m	X	170	200	10	-6

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The RWWP plant is based on conventional water treatment principles with unit processes that include coagulation, flocculation, sedimentation and filtration. The water treatment plant makes use of organic polymer and 43% ferric chloride ($FeCl_3$) as coagulants. The efficacy of the water treatment plant was determined by the effectiveness of the different purification processes to remove physical, chemical and biological variables from the water. Different water quality variables were measured during the study, including phytoplankton (particularly cyanobacteria) identification and enumeration. The organic compounds measured were chlorophyll-665, microcystin, TOC, DOC, 2-MIB and geosmin, while the physical variables included turbidity, pH, and electrical conductivity. The compliance of the water treated against the SANS 241 guidelines is vital in determining the efficacy of the treatment plant and indicates whether the water is of acceptable drinking quality.

The raw water supplied to the water treatment plant contained the following algal classes: Bacillariophyceae, Cyanophyceae, Cryptophyceae, Chlorophyceae, Dinophyceae and Euglenophyceae. The Cyanophyceae was the dominant class and consisted of *Anabaena, Microcystis* and *Oscillatoria. Microcystis* was identified as a problem-causing genus during the investigation due to it (i) being the most dominant genus in the raw water, (ii) the ability to produce cyanotoxins and taste and odour compounds, and (iii) the potential to clog filters.

Although cyanobacteria cells were removed effectively 99% removal (Figure 4.2) from the water, the removal percentage of geosmin, associated with *Microcystis,* was only 67% (Table 4.2). 2-MIB averaged 1 ng/L and the sample analysis detected 1 ng/L on the days of sampling and the concentration increased to 2 ng/L mid-April. There was an increase in *Microcystis* cell density where an average of 25 cells/mL was measured in the after-filtration water and an average of 20 cells/mL was measured in the after-sedimentation water. An average density of 25 cells/mL was obtained after filtration for *Microcystis* cells, the RWWP was able to remove *Anabaena* and *Oscillatoria*.

Chlorophyll-665 was removed effectively by the different processes, due to the effective removal of cyanobacteria cells and other phytoplankton present in the raw water. The raw water is classified as mesotrophic because of the average chl-*a* detected at 14 µg/L according to Van Ginkel (2001). According to Rand water guidelines chl-*a* allowable limit in raw water is between 0-15 µg/L, treated water is 1 µg/L and crisis limit is an average of 7 µg/L. The RWWP raw water average was 14 µg/L, it was under the allowable limit and after filtration complied with the guidelines. It can be concluded that the RWWP removed chl-*a* 100%.

It was evident that conventional water treatment was effective in removing the physical water quality variables (turbidity and pH). Conductivity remained the same through the process of treatment at an average of 18 mS/m.

TOC and DOC was not effectively removed by sedimentation and filtration processes of the RWWP.

Recommendations and suggestions

The ecological status of the raw water from the RWWP should be investigated during further research to obtain information that can be used as the baseline of the treatment processes and the effectiveness thereof. The information attained can also be used in monitoring the presence of organic and inorganic compounds in the raw water as they enhance algal blooms and potentially decrease water quality.

It is recommended that the routine sampling schedule include phytoplankton sampling for analyses to ensure that proper corrective measures are followed by the plant and laboratory personnel in optimising the plant process.

If cyanobacteria cells penetrate the water treatment process, re-sampling should occur for further investigation to determine which phase of treatment was not performing effectively.

Training should be provided to the process controller regarding the development and implementation of the cyanobacteria incident management framework and an awareness about the impact of cyanobacteria to the treatment processes should be established.

The efficiency of the RWWP to remove cyanobacteria cells and associated organic compounds, must be determined seasonally.

Optimizing the coagulation and flocculation unit process by performing jar test regularly.

The fact that the 2-MIB measurements stayed constant through the treatment process for the study period is suspicious. An investigation about the protocol of the 2-MIB measurements should be initiated. It should be determined if it is the result of odour producing organisms growing in the FRS.

If organisms such as *Anabaena* and *Microcystis* species can penetrate the entire purification process they can cause taste and odour problems in the after-filtration water. *Microcystis* species penetrated the process and was detected in the after-filtration water, which has the potential to cause toxins such as microcystin to be released into the drinking water. Sedimentation and sand filtration processes need to be improved to ensure effective removal of algae. The efficiency of the filter media and the backwash process should be investigated further as they may not be working effectively; the *Microcystis* penetrated the filtration process.

The removal of sludge in the sedimentation tank should be investigated, with some organisms such as *Anabaena* and *Microcystis* penetrating the sedimentation process.

TOC and DOC levels should be investigated as these were not effectively removed by the RWWP.

REFERENCES

(AWWA) American Water Works Association. (2004) Detection and removal strategies for drinking water treatment plants*:* Report number 90971. American Water Works Association Research Foundation, Denver, USA: pp.466.

(AWWA) American Water Works Association. (2010) *Algae source to treatment: Report M57*. Denver, USA. ISBN 978-1-58321-787-0.

Allanson, B.R., Gieskes, J.M.T.M. (1961) Part II: An introduction to the Limnology of Harbeespoort Dam with special reference to the effect of industrial and domestic pollution. *Hydrobiologia*, 18(1-2): 25-33.

Ander, E.L., Watts, M.J., Smedly, P.L., Hamilton, H.M, Close, R., Grabber, H., Fletcher, T., Rimell, A., Studden, M., Leonardi, G. (2016) Variability in the chemistry of private drinking water supplies and the impact of domestic treatment systems on water quality. *Environ Geochem Health*, 38: 1313-1332.

Ando, A.M., Miwa, M.K., Tatsumi, S. (1992) Removal of musty-odourous compounds in water and retained in algal cells through water purification processes. *Water Science and Technology*, 25(2): 299-306.

Antoniou, A.V. (1999) The water quality of the rivers in the vicinity of the Sasol Secunda industrial complex. Master of Science dissertation, Rand Afrikaans University, Johannesburg, South Africa.

Banack, S.A., Caller, T.A., Stommel, E.W. (2010) The Cyanobacteria Derived Toxin Beta-N-Methylamino-LAlanine and Amyotrophic Lateral Sclerosis. *Toxins,* 2, pp. 2837-2850. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3153186/pdf/toxins-02-02837.pdf. [Accessed: 28 January 2018].

Bezuidenhout, N. (2013) An investigation into the cyanobacteria and related cyanotoxins in the Vaalkop Dam and Vaalkop Treatment Plant Rustenburg, North West Province. Master of Science Dissertation, University of Johannesburg, Johannesburg, South Africa.

Carlson, R.E., Simpson, J. (1996) *A coordinator's guide to volunteer lake monitoring methods*. North America Lake Management Society, 96. Retrieved from www.secchidipin.org. [Accessed: 05 December 2017]: pp. 96.

Chinyama, A., Ochleng, G.M., Snyman, J., Nhapi, I. (2016) Occurrence of cyanobacteria genera in the Vaal Dam: implications for potable water production. *Water SA,* 42 (3): 415-420

Chislock, M.F., Doster, E., Zitomer, R.A., Wilson, A.E. (2013) Eutrophication: causes, consequences, and controls in aquatic ecosystems. *Nature Education Knowledge,* 4(4): 1-8.

Chow, C.W.K., Drikas, M., House, J., Burch, M.D., Velzeboer, R.M.A. (1999) The impact of conventional water treatment processes on cells of cyanobacterium *Microcystis aeruginosa. Water Research,* 35(15): 3253-3262.

Cilliers, J. (2015) South Africa futures 203: Institute for security studies. Paper 282, Retrieved from https://repository.up.ac.za/bitstream/handle/2263/51774/Cilliers_South_2015.pdf?sequence=1 [Accessed: 17 September 2017].

Claassen, M. (2010) A CSIR perspective on water in SA: how much water do we have? Retrieved from: www.csir.ac.za [Accessed: 16 May 2015].

Davies, B.R., Walmsley, R.D. (2012) Perspectives in Southern Hemisphere Limnology: proceedings of symposium, held in Wilderness, South Africa, July 3-13, 1985, Dr W Junk publishers 1st edition, Netherlands.

De Almeida, C.R., Spiandorello, F.B., Giroldo, D., Yunes, J.S. (2016) The effectiveness of conventional water treatment in removing *Ceratium furcoides* (Levander) Langhans, *Microcystis*. sp and microcystins, *Water SA*, 42 (4): 606-611.

Delphos, P.J., Wesner, G.M. (2005) Mixing, coagulation and flocculation. pp.6.1- 6.25. In Baruth, E.E. Water treatment plant design, 4th Ed, McGraw Hill.

Department of Health and Environment. (2011) Water quality standards white paper: chlorophyll-a criteria for public water supply lakes or reservoirs, Retrieved from www.kdheks.gov [Accessed: 26 Septermber 2018].

Dietrich, A.M. (2006) Aesthetic issues for drinking water. *Journal of Water and Health*, 4(1): 11-6.

Downing, T.G., Van Ginkel, C. (2004) Cyanobacterial monitoring 1990–2000: Evaluation of SA data. WRC Report No. 1288/1/04. Water Research Commission, Pretoria, South Africa.

Du Plessis, J. (2006) The assessment of the water quality of the Hex river catchment - North West Province. Master of Science Dissertation, University of Johannesburg, Johannesburg, South Africa.

DWAF (Department of Water Affairs and Forestry) (1996) S*outh African water quality guidelines, volume 1: domestic water use, 2nd edition.* Department of Water Affairs and Forestry, Pretoria, South Africa.

DWAF (Department of Water Affairs and Forestry) (2002) National Eutrophication Monitoring Program: Implementation 1st edition. Department of Water Affairs and Forestry (DWAF), South Africa.

DWAF (Department of Water Affairs and Forestry). (1998) Quality of domestic water supplies volume 1: assessment guide. Department of water affairs and forestry (DWAF) report number: TT 101/98, South Africa.

DWAF (Department of Water Affairs and Forestry). (2004) South Africa, Middle Vaal Water Management Area: Internal Strategic perspective, DWAF. Report no P WMA 09/000/00/0304, Pretoria, South Africa.

Edzwald, J.K. (2010) Dissolved air flotation and me. *Water research*, 44: 2077-2106

Ewerts, H. (2010) The effectiveness of purification process in removing algae from Vaal Dam water at the Rand Water Zuikerbosch Treatment Plant in Vereeniging. Master of Science Dissertation, North-West University, Potchefstroom, South Africa.

Ewerts, H., Swanepoel, A., Du Preez, H.H. (2013) Efficacy of conventional drinking water treatment processes in removing problem-causing phytoplankton and associated organic compounds. *Water SA,* 39(5): 739-749.

Gary, N.F. (2008) Drinking water quality: Problems and solutions. *Water and Environmental Journal,* 9(2): 217.

Govender, J. (2016) An assessment of the water quality of the Baynespruit River and its linkages to the health of the Sobantu community. Master of Science dissertation, University of Kwazulu-Natal, Pietermaritzburg, South Africa

Graham, J.L., Loftin, K.A., Ziegler, A.C., Meyer, M.T. (2008) Guidelines for design and sampling for cyanobacterial toxin and taste-and odour studies in lakes and reservoirs. U.S. *Geological Survey Scientific Investigations*, 5038: 39.

Harding, W.R. (2015) Living with eutrophication in South Africa: A review of realities and challenges. *Transactions of the Royal Society of South Africa*, 70(2): 155-171.

Harding, W.R., Paxton, B.R. (2001) *Cyanobacteria in South Africa: A review.* WRC Report no. TT 153/01, Water Research Commission, Pretoria, South Africa.

He, X., Liu, Y.L., Conklin, A., Westrick, L.K., Dionysiou, D.D., Lenhart, J.J., Mouser, P.J., Szlag, D., Walker, H.W. 2016. Toxic cyanobacteria and drinking water: impacts, detection and treatment. *Harmful algae*, 54: 174-193.

Hitzfeld, B.C., Hogers, S.J., Dietrich, D.R. (2000) Cyanobacterial toxins: removal during drinking water treatment, and human risk assessment. *Environmental Health Perspective,* 108(1): 113-122.

Ho, L., Newcombe G. (2010) Optimising water treatment processes for the removal of cyanobacteria and their metabolites. 2nd National Cyanobacterial Workshop, Melbourne Australia.

Hoger, S.J. (2003) Problems during drinking water treatment of Cyanobacteria-loaded surface waters: consequences from human health. Doctor of Philosophy, Universität Konstanz Gefördert durch die Deutsche Bundesstiftung Umwelt (DBU).

Hollister, J.W., Kreakie, B.J. (2016) Associations between chlorophyll a and various Microcystin health advisory concentrations, *F1000 Research*, 5: 151.

Hudson, Z. (2015) The applicability of advanced treatment processes in the management of deteriorating water quality in the mid-Vaal River system. Master of Science Dissertation, North-West University, Potchefstroom, South Africa.

James, B. (2015) Flash mixing with a rapid mixer: flash mixing in water treatment. Retrieved from www.dynamixinc.com [Accessed: 10 June 2017].

Jung, J. (2009) Removal of microcystin-LR from drinking water using adsorption and membrane processes. Doctor of Philosophy Thesis, Ohio State University, Columbus, Ohio, U.S.

Kale, V.J. (2016) Consequences of Temperature, pH, Turbidity and Dissolved Oxygen Water Quality Parameters. International Advanced Research Journal in Science, Engineering and technology, 3 (8): 186-190

Lowies, M. (2014) A comparative study of chemical and physical water quality along the Crocodile River in the Gauteng and North West provinces, South Africa. Master of Science Dissertation, University of Johannesburg, Johannesburg, South Africa.

Mamba, B.B., Krause, R.W., Malefetse, T.J., Mhlana, S.D., Sithole, S.P., Salipira, K.L., Nxumalo, E.N. (2007) Removal of geosmin and 2-methylisorboneol (2-MIB) in water from the Zuikerbosch treatment plant using B-cyclodextrin polyurethanes. *Water SA,* 33(1): 223-228.

Masato, I., Norimasa, K.,Takumi, M. (1999) Kurita handbook of water treatment. 2nd edition, Kurita, Japan, pp. 1-4.

Mashele, A.R. (2016) The impact of the Blue Drop certification programme on drinking water quality management in three South African municipalities, Master of Science dissertation, University of Pretoria, Pretoria, South Africa.

Matthews, M.W., Bernard, S. (2014) Eutrophication and cyanobacteria in South Africa standing water bodies: A view from space. *South African Journal of Science*, 111(5/6):1-8.

McDonald, T.A., Komulainen, H. (2005) Carcinogenicity of the chlorination disinfection by-product. *Journal of Environmental Science and Health, part C,* 23(2): 163-214.

Mohamed, Z. (2016) Breakthrough of *Oscillatoria limnetica* and microcystin toxins into drinking water treatment plants-examples from the Nile River, Egypt. *Water SA,* 42(1): 161-165.

Mur, L.R., Skulberg, O.M., Utkilen, H. (1999) Toxic cyanobacteria in water: A guide to their public health consequences, monitoring and management, ISBN 0-419-23930-8, E and FN Spon, London

Naroth, N. (2016) Assessing the sustainability of direct potable water reuse: the Beaufort west reclamation plant. Master of Science Dissertation, University of Witwatersrand, Johannesburg, South Africa.

Oberholster, P.J. (2010) *A CSIR perspective on water in SA:* the current status of water quality in SA. Retrieved from www.csir.ac.za [Accessed: 16 May 2015].

Oberholster, P.J., Botha, A.M., Cloete, T.E. 2006. Toxic cyanobacterial blooms in a shallow, artificially mixed urban lake in Colorado, USA. *Lake and reservoirs: Research and Management*, 11: 111-123.

Oberholster, P.J., Botha, A.M., Grobbelaar, J.U. (2004) *Microcystis aeruginosa*: Source of toxic microcystins in drinking water. *African Journal of Biotechnology,* 3(3): 159-168.

Oyem, H.H., Oyem, I.M., Ezeweali, D. (2014) Temperature, pH, electrical conductivity, Total Dissolved Solids and chemical Oxygen Demand of Groundwater in Boji-Boj, Agbor/Owa area and immediate suburbs. *Research Journal of Enivornmental Science*, 8(8): 444-450.

Ozdermir, K. (2014) Characterization of Natural Organic Matter in conventional water treatment process and evaluation of THM formation with chlorine. *The Scientific World Journal*, 2014: 1-7

Piontek, M., Czyzewska, W. (2012) The efficiency of the drinking water treatment process: Removal for phytoplankton with special consideration for cyanobacteria and improving physical and chemical parameters. *Polish Journal of Environmental Studies,* 21(6): 1797-1805.

Ramavandi, B. (2014) Treatment of water turbidity and bacteria by using a coagulant extracted from *Plantago ovata. Water Resources and Industries,* 6: 36-50.

Rose, J.B. (2014) *What happened to Toledo's drinking water: understanding microcystins*. Retrieved from: (http://www.waterandhealth.org/happened-toledos-drinking-water-understanding-microcystins/) [Accessed 30 January 2018].

Rosinska, A., Dabrowska, L. (2016) Enhancement of coagulation process with powdered activated carbon in PCB and heavy metal ions removal from drinking water. *Desalination and Water Treatment*, 57(54): 26336-26344.

Schubert, H., Schiewer, U., Tschirner, E. (1989) Fluorescence characteristics of Cyanobacteria (blue-green algae). *Journal of Plankton Research*, 11(2): 353-359.

Schutte, F. (2006) *Handbook for the operation of water treatment works*. Report TT 265/06, Water Research Commission, Pretoria, South Africa.

Sibande, R.X. (2013) Cost of eutrophication at the Vaal River System: An integrated economic model. Master of Commerce Dissertation University of Pretoria, Pretoria, South Africa.

Srinivasan, P.T., Viraraghavan, T., Subramanian, K.S (1999). Aluminium in drinking water: an overview. *Water SA*, 25 (1): 47-56

Srinivasan, R., Sorial, G.A. (2011) Treatment of taste and odour causing compounds 2-methyl isoborneol and geosmin in drinking water: A critical review. *Journal of Environmental Science,* 23(1): 1-13.

Swanepoel, A. (2015) Early warning system for the prediction of algal-related impacts on drinking water purification. PhD thesis, North West University, Potchefstroom, South Africa

Swanepoel, A., Du Preez, H.H., Cloete, N. (2017) The occurrence and removal of algae (including cyanobacteria) and their related organic compounds from source water in Vaalkop Dam with conventional and advanced drinking water processes. *Water SA*, 43(1): 67-80.

Swanepoel, A., Du Preez, H.H., Schoeman, C., Janse Van Vuuren, S. and Sundram, A. (2008) Condensed laboratory methods for monitoring phytoplankton, including cyanobacteria, in South African freshwaters. WRC Report TT 323/08, Water Research Commission, Pretoria, South Africa.

Szlag, D.C., Sinclair, J.L., Southwell, B., Westrick, J.A. 2015. Cyanobacteria and cyanotoxins occurrence and removal from five high-risk conventional treatment drinking water plants, *Toxins*, 7: 2198-2220.

USEPA (United States Environmental Protection Agency) (2018) Microcystin. USEPA report. Retrieved from: https://iaspub.epa.gov/tdb/pages/contaminant/contaminantOverview.do?contaminantId=-1336577584, [Accessed 25 January 2018].

Van Der Walt, N. (2011) Investigation into the occurrence of the dinoflagellate, *Ceratium hirundinella*, in source water and the impact thereof on drinking water purification. Report number: CER.07.2010.2. Scientific Services, Rand Water, Johannesburg. pp. 177.

Van Ginkel, C.E. (2011) Eutrophication: present reality and future challenges for South Africa. *Water SA*, 37(5): 693-701.

Van Ginkel, C.E., Hohls, B.C., Belcher, A., Vermaak, E., Gerber, A. (2001) Assessment of the trophic status project. Internal report no. N/0000/00/DEQ/1799. Department of Water and Forestry, Pretoria, South Africa.

Van Rensburg, S.J., Barnard, S., Kruger, M. (2016) Challenges in the potable water industry due to changes in source water quality: case study of Midvaal Water Company, South Africa. Water SA, 42(4): 633-640.

Van Vuuren, S.J., Taylor, J., Van Ginkel, C., Gerber, A. (2006) *Easy identification of the most common freshwater algae: A guide for the identification of microscopic algae in South African freshwaters*. Department of Water Affairs and Forestry and North-West University. ISBN:0-621-35471-6.

Volk, C., Bell, K., Ibrahim, E., Verges, D., Amy, G., Lechevallier, M. (2000) Impact of enhanced and optimized coagulation on the removal of organic matter and its biodegradable fraction in drinking water. *Water Research*, 34(12): 3247-3257.

Westerhoff, P., Summers, R.S., Chowdhury, Z., Kommineni, S. (2005) Ozone-enhanced biofiltration for geosmin and MIB removal. AWWA Research Foundation, Denver. pp. 1–220.

World Health Organisation (WHO). (1998) Guidelines for drinking water quality Addendum volume 2, cyanobacterial toxins: *microcystin L.R.* World Health Organisaion, Geneva, Switzerland.

World Health Organisation (WHO). (2004) *Guidelines for drinking water quality.* 3rd, 1: pp 1-540. ISBN: 92-4-1546387.

World Health Organisation (WHO). (2005) Trihalomethanes in drinking water: background document for development of WHO guidelines for drinking water quality. WHO Report no. WHO/SDE/WSH/05.08/64, World Health Organisation.

Yentsch, S. and Menzel, D.W. (1963) 'A method for the determination of phytoplankton chlorophyll and phaeophytin by fluorescence', *Deep Sea Research and Oceanographic Abstracts*, 10(3), pp. 221-234.

Yoo, R.S., Carmichael, W.W., Hoehn, R.C., Hrudey, S.E. (1995) Cyanobacterial (blue green algal) toxins: A resource guide. AWWA (American Water Works Association) Research Foundation and American Water Works Association, USA (United State of America), pp. 1-11. ISBN: 0-89867-824-2.

APPENDIX A

A1 Assessment of raw water from the RWWP

The raw water sample analyses resulted in six algal classes; Bacillariophyceae (diatoms), Chlorophyceae (green algae), Cyanophyceae (cyanobacteria), Dinophyceae (dinoflagellates), Chrysophyceae (golden-brown algae) and Euglenophyceae (Euglenoids) (Table A1). The focus of the study was based on the removal of cyanobacteria cells by the RWWP. Based on the results attained from the laboratory, the dominant phytoplankton class during the study period was the Cyanophyceae.

Table A1: Complete list of phytoplankton genera identified in raw water samples

Phytoplankton Class	Genus
Bacillariophyceae	*Cymbella* *Navicula* *Nitzschia* *Gomphonema* *Diatoma*
Cyanophyceae	*Anabaena* *Microcystis* *Oscillatoria*
Chlorophyceae	*Carteria* *Chlamydomonas* *Chlorella* *Monoraphidium* *Scenedesmus* *Coelastrum* *Ankistrodesmus*
Dinophyceae	*Peridinium*
Cryptophyceae	*Cryptomonas*
Euglenophyceae	*Euglena*

APPENDIX B

Table B1: RWWP performance determined by t-test output for cyanobacteria data obtained from different sampling points (raw water, after sedimentation and after filtration); significance level of $p \geq 0.05$

	Raw water	**After sedimentation**
Means (cells/mL)	3079.3	44.2
Number of samples (n)	6	5
Variance	9087390	352.1
P(T<=t) two-tail	0.06	
t-critical two-tail	2.57	
	After sedimentation	**After filtration**
Means (cells/mL)	44.2	25.17
n	5	6
Variance	3521.1	1283.4
P(T<=t) two-tail	0.55	
t-critical two-tail	2.45	

Table B2a: RWWP performance determined by t-test for microcystin data obtained from different sampling points (raw water, after sedimentation and after filtration); significance level of p ≥ 0.05.

	Raw water	**After sedimentation**
Means (cells/mL)	0.47	0.36
n	6	5
Variance	0.07	0
P(T<=t) two-tail	0.36	
t-critical two-tail	2.57	
	After sedimentation	**After filtration**
Means (cells/mL)	0.36	0.36
n	5	6
Variance	0	3.70
P(T<=t) two-tail	0.08	
t-critical two-tail	2.57	

Table B2b: RWWP performance determined by t-test output for 2-MIB data obtained from different sampling points (raw water, after sedimentation and after filtration) to determine performance of RWWP; significance level of p > 0.05.

	Raw water	**After sedimentation**
Means (cells/mL)	0.65	0.68
n	6	5
Variance	0.135	0.16
P(T<=t) two-tail	0.90	
t-critical two-tail	2.31	
	After sedimentation	**After filtration**
Means (cells/mL)	0.68	0.78
N	5	6
Variance	0.16	0.48
P(T<=t) two-tail	0.77	
t-critical two-tail	2.31	

Table B2c: RWWP performance determined by t-test output for geosmin data obtained from different sampling points (raw water, after sedimentation and after filtration); significance level of $p \geq 0.05$.

	Raw water	**After sedimentation**
Means (cells/mL)	5.92	3.28
n	6	5
Variance	16.76	2.03
P(T<=t) two-tail	0.19	
t-critical two-tail	2.45	
	After sedimentation	**After filtration**
Means (cells/mL)	3.28	2.04
n	5	6
Variance	2.03	1.02
P(T<=t) two-tail	0.15	
t-critical two-tail	2.36	