Effectiveness of purification processes in removing algae from Vaal Dam water at the Rand Water Zuikerbosch treatment plant in Vereeniging

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ABSTRACT

The aim of this study was to investigate the efficacy of purification processes at the Rand Water Zuikerbosch treatment plant near Vereeniging. Raw water is abstracted via a canal and gravity pipeline from the Vaal Dam (in the upper Vaal River) and purified to ensure it meets the stringent standards set for drinkable water. The first step was to determine the ecological status of the raw water and it was done by measuring chemical, physical and biological variables as well as to identify and enumerate the different algal groups that occur in the raw water. The turbidity of the raw water was low but the phosphorous and ortho-phosphate levels were high. The Cyanophyceae (blue-green bacteria) especially *Anabaena* species were dominant in the raw water for the duration of the study. Potential problems such as relatively high alkalinity, chemical oxygen demand (COD) and total dissolved solids (TDS) as well as potentially hazardous chemicals such as cadmium and lead were observed in the raw water.

The Zuikerbosch Water Treatment Plant (ZWTP) is a conventional water treatment plant which involves the following stages: coagulation, flocculation, sedimentation, sand filtration and chlorination. The use of pre-treatment chemicals ensures better water quality and effective removal of particles from the water. Only five of the variables (methylisoborneol (MIB); geosmin; chlorophyll-*a*; chlorophyll-665 and total organic carbon (TOC) were measured before filtration, after filtration and in the final water. Samples from the raw water, before and after filtration, as well as final water were collected weekly for a period of two years to measure the environmental variables as well as to do algal identification and enumeration.

The purification processes at ZWTP were not able to remove MIB, geosmin, chlorophyll-*a* and TOC from the final water. Algal concentration was reduced but not totally removed by the purification processes. Although some variables were not totally removed by the purification processes, ZWTP produce potable water that complies with the Rand Water guidelines.

Key words: water treatment, algal groups, geosmin and MIB.

OPSOMMING

Die doel van hierdie studie was om die effektiwiteit van suiweringsprosesse by Rand Water se Zuikerbosch suiweringsaanleg (ZWTP) naby Vereeniging te ondersoek. Rouwater word deur middel van ‘n kanaal en gravitasiepyplyn vanuit die Vaal Dam (in die boonste deel van die Vaalrivier) onttrek, waarna dit gesuiwer word om te verseker dat drinkwater aan die hoogste vereistes voldoen. Die eerste stap was om die ekologiese toestand van die rouwater te bepaal deur die meting van chemiese, fisiese en biologiese veranderlikes sowel as die alge wat in die kanaal voorkom. Die turbiditeit van die rouwater was laag, maar die fosfor- en ortofosfaatvlakke was hoog. Cyanophyceae (blou groenbakterieë), veral *Anabaena* spesies*,* was dominant in die rouwater gedurende die studietydperk. Potensiële probleme soos relatief hoë alkaliniteit, chemiese suurstofbehoefte (COD) en totale opgeloste soute (TDS) sowel as potensiële gevaarlike vlakke van kadmium en lood is waargeneem.

Die ZWTP is ‘n konvensionele watersuiweringsaanleg wat die volgende suiweringsprosesse insluit: koagulering, flokkulering, sedimentering, sandfiltrering en chlorinering. Rouwater word vooraf met chemikalieë behandel om sodoende beter water kwaliteit te verseker en om deeltjies in die water effektief uit te haal. Slegs vyf van die veranderlikes (metielisoborneol (MIB); geosmien; chlorofil-*a*; chlorofil-665 en TOC (totale organiese koolstof) is gemeet voor en na filtrering, asook in die finale water. Monsters wat weekliks van die rouwater, voor en na filtrasie asook van die finale water vir ‘n periode van twee jaar versamel is, is gebruik om die omgewingsveranderlikes te bepaal, asook vir die identifisering en tel van alge.

Die suiweringsprosesse by ZWTP was nie in staat om MIB, geosmien, chlorofil-*a* en TOC uit die finale water te verwyder nie. Die konsentrasie van alge het afgeneem, maar is nie ten volle verwyder deur die suiweringsprosesse nie. Hoewel sommige veranderlikes nie geheel en al deur die suiweringsprosesse verwyder is nie, produseer die ZWTP drinkwater wat voldoen aan Rand Water se riglyne.

Sleutelwoorde: watersuiwering, alggroepe, geosmien en MIB.

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LIST OF ABBREVIATIONS

C/F/S	Coagulation/Flotation/Sedimentation
CAPS	Chemical Assisted Primary Sedimentation
CEPT	Chemical Enhanced Primary Treatment
Chl-*a*	Chlorophyll-*a*
COD	Chemical Oxygen Demand
DAF	Dissolved Air Flotation
DOC	Dissolved Organic Carbon
DWA	Department of Water Affairs
FA	Factor Analysis
GAC	Granular Activated Carbon
H Chl 665	Total Chlorophyll
M-Alk	Methyl-orange Alkalinity
MIB	2-Methylisoborneol
PAC	Powered Activated Carbon
PCA	Principal Component Analysis
Phaeo	Phaeophytin-*a*
PMO	Phosphorus Management Objective
POC	Particular Organic Carbon

SANAS	South African National Accreditation System
SANS	South African National Standards
SS	Suspended Solids
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
TWQR	Target Water Quality Range
WMA	Water Management Area
Z	Zetafloc
ZWTP	Zuikerbosch Water Treatment Plant

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CHAPTER 1: INTRODUCTION

Earth is the “water planet”. It is hard to comprehend why a planet with 71% of its surface covered by water would be facing a water shortage. The demand for water is doubling every 21 years in some areas around the world and this suggests that we need to assure water quality and purity so that we do not face a dire water crisis in the near future (Ahuja, 2009). South Africa has long recognized that water is one of its prime limiting natural resources (DWA, 1986) and eutrophication is becoming increasingly serious due to its implications for water resource management and human health. Incidents of toxic algal occurrence and other eutrophication-related problems are forcing scientists to take a closer look at the trophic status of South Africa’s water resources (Van Ginkel *et al*, 2000).

The Department of Water Affairs promulgated the 1 mg/ℓ - phosphate effluent discharge standard in 1980 when a water resource prescribed in terms of Section 21(1) (a) of the Water Act, 1956, was announced in Government Notice No.1567 (Walmsley, 2000). This announcement declared a special standard for phosphate in industrial wastewater and read as follows:

“Waste water of effluent produced by or resulting from the use of water for industrial purposes and which drains to any portions of a river mentioned in Schedule 2 or any tributary of such a river within the catchment areas or portions thereof describe in the Schedule, shall not contain soluble orthophosphate in a higher concentration than 1.0 mg/ℓ” (Walmsley, 2000).

The target water quality control of eutrophication was set to maintain mean chlorophyll-*a* concentrations in the receiving water bodies at such levels that severe nuisance conditions would not occur for more than 20% of the time. This translated into a phosphorus management objective (PMO) to maintain mean total phosphorus concentrations in reservoirs at 130 µg/ℓ P (Van Ginkel *et al*, 2000).

Water rapidly absorbs both natural and man-made substances generally making the water unsuitable for drinking without some form of treatment (Gary, 2008). Water can be contaminated by a whole host of substances, including material from geological formations, soil, organic detritus, chemical constituents and radioactive substances (DWAF, 2000). DWAF (2002) provides information on the major inorganic chemical and water quality constituents of surface waters across South Africa to water resource managers, scientists, decision-makers, and the public in order to give an overview of the status of surface chemical water quality according to the water quality requirements of two user sectors, namely domestic water use and irrigated agriculture water use.

Rand Water has treated water from the Vaal River since 1923 when the impoundment of water in the Barrage Reservoir commenced. All Vaal River water was treated at Vereeniging Pumping Station until Zuikerbosch Pumping Station was brought into operation in 1954 (Pursell, 2010). At the Rand Water Zuikerbosch treatment plant, source (raw) water is extracted from the Vaal Dam via a canal and a gravity pipeline, which was constructed from the Vaal Dam in 1965 (Pursell, 2010).

The term “conventional water treatment” refers to the treatment of water from a surface source by a series of processes aimed at removing suspended solids and colloidal material from the water, disinfecting the water, and stabilizing the water chemically (Quality of Domestic Water Supplies (4), 2002). The raw water must undergo chemical dosing to ensure stabilization and coagulation. Ferric chloride, lime silica and/or polyelectrolytes are dosed in order to chemically destabilize the charge of colloidal particles which in turn results in colloids to form larger flocs in the flocculation process (Rand Water, 2010). During sedimentation the flocs are allowed to settle to the bottom of the sedimentation tanks. Filtration, as the penultimate step may take place as slow as sand filtration, rapid gravity filtration or high pressure filtration (An Illustrated Guide to Basic Water Purification Operation, 2006).

Disinfection is usually carried out with the addition of chlorine to remove pathogenic organisms and ensure a residual disinfectant during distribution. The term “phytoplankton” may be broadly defined as photosynthetic, free-floating organisms which are mostly microscopic (Swanepoel *et al*., 2008). The phytoplankton assemblage (composition) of a

water body can provide an indication of the prevailing water quality (Swanepoel *et al*., 2008). Removal of phytoplankton is often inhibited by various factors such as the specific phytoplankton species present, the total biomass of the phytoplankton in the source water, the effectiveness of the coagulation and flocculation unit processes as well as the effectiveness of the sand filtration process. Therefore it is important to monitor phytoplankton, not only in the source water, but also in the potable water (Swanepoel and Du Preez, 2007).

Each stage in the purification process is accompanied by changes in the physical and chemical conditions of the water. Certain phytoplankton (algal genera) can also penetrate the different processes causing extensive problems such as clogging of sand filters, the production of toxins and taste as well as odour problems in the final drinking water (Swanepoel and Du Preez, 2007). Certain species also penetrate through the whole water purification process and enter the final drinking water. The detection of phytoplankton in source water, as well as in potable water, is therefore very important in the drinking water industry (Swanepoel and Du Preez, 2007). One such alga is *Ceratium* sp. This dinoflagellate is recognized as a problem alga because it imparts taste and odour to potable water and clogs sand filters within the water treatment purification plant (Hart and Wragg, 2009).

Bloom forming species, such *Ceratium* sp., *Anabaena* sp., *Microcystis* sp., and *Oscillatoria* sp., pose a risk to water purification plants and its impact on purification processes needs to be investigated. *Ceratium* sp. was found for the first time in November 2000 in South African fresh waters and since has shown a significant increase in occurrence and concentration in the Rand Water source water. This study therefore investigate the physical, chemical as well as the biological changes that occur in the water after the following purification processes: (1) coagulation, flocculation and sedimentation; (2) filtration; and (3) chlorination, with emphasis on problem algae like *Ceratium*.

Water samples were taken weekly for a period of 2 years at four different sampling localities at the Rand Water Zuikerbosch treatment plant close to Vereeniging. The sampling localities are: the source (canal) water; before filtration (after sedimentation); after

filtration and in the final water. The chemical analysis of the water was done at the Rand Water's Analytical Services laboratories, by using SANAS accredited standard methods.

Algal identification was done with an inverted light microscope and enumeration by according to the Utermöhl method (Utermöhl, 1958). The concentration of algae detected after the purification processes gives an indication of the efficacy of algal removal by the different purification processes in the treatment plant. The algal abundance and percentage composition of populations at a given time, as well as the dominant genera will be determined. Special attention will be given to the removal of *Ceratium* sp., *Anabaena* sp., *Microcystis* sp., and *Oscillatoria* sp. during the investigation of purification processes, because of their potential to cause water related problems in treatment plants.

The aims of the study are as follows:

1. To determine the ecological status of the raw water from the Vaal River (Vaal Dam) in the Upper Vaal. It is important to have an ecological overview of the raw water quality of the Zuikerbosch Treatment Plant that is used to produce safe potable water for human consumption. An overview of the raw water quality can be used to determine the efficacy of each purification process, especially in removing algae from the Vaal Dam water.
2. To determine the efficacy of the purification processes before and after filtration in removing:
    - geosmin and MIB;
    - total chlorophyll, chlorophyll-*a*, TOC;
    - different phytoplankton groups, and
    - specific problem causing organisms such as *Microcystis* sp., *Anabaena* sp., *Oscillatoria* sp. and *Ceratium* sp.
3. To determine the biological variables that penetrates the final water.
4. To determine the correlation between algae and variables (chemical, physical and biological) in the raw water and final water.

CHAPTER 2: LITERATURE REVIEW

2.1 PURIFICATION PROCESSES

Many treatment processes (sometimes called unit processes and unit operations) are linked together to form a treatment plant that produces water of desired quality. Research on coagulation-flocculation, sedimentation and filtration (Figure 2.1) as basic water treatment processes during the early part of the previous century contributed to a better understanding of these processes and much improved performance (Schutte, 2006). The primary aim of coagulation and flocculation is to remove suspended particles from water and if possible any dissolved particles that may be undesirable in the final water or effluent (Leopold and Freese, 2009).

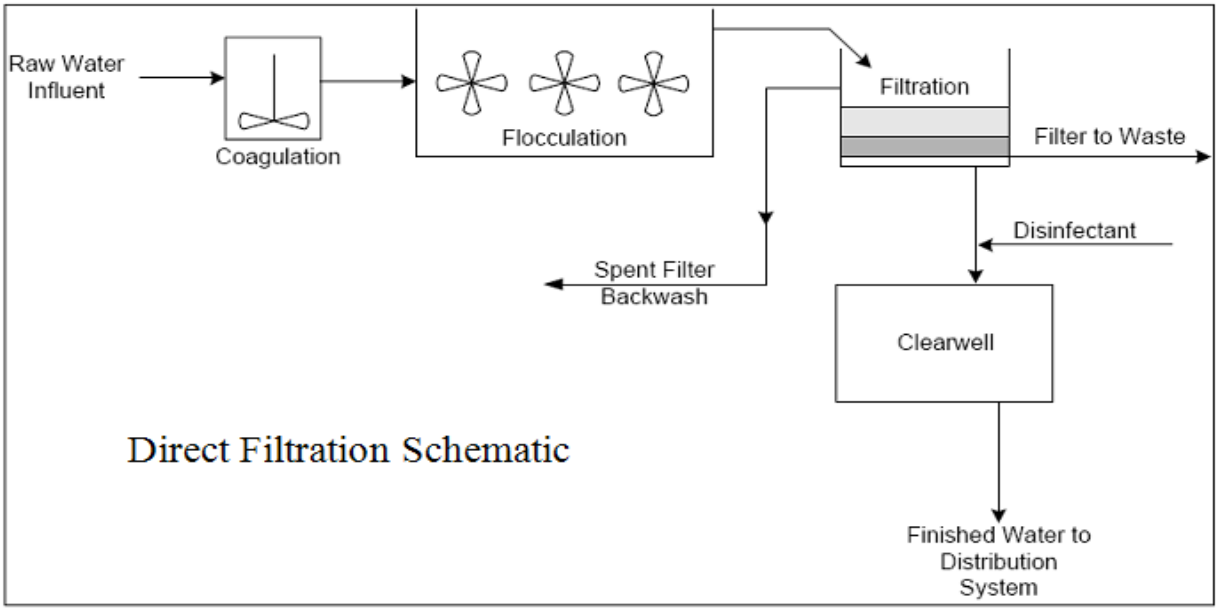


Figure 2.1: A schematic diagram of the different purification processes which includes coagulation, flocculation, filtration and disinfection (Oregon, 2010).

Dissolved air flotation (DAF) is generally considered more effective than sedimentation (S) in the treatment of algal-rich water, especially in removing gas vacuolated algal types. Diatoms e.g. are better removed by sedimentation. However, the type and dose of coagulant, as well as coagulation (C), flotation (F) and DAF operating conditions are key parameters for removing intact cyanobacterial cells

(Teixeira and Rosa, 2006). Ceronio *et al.*, (2002) evaluated three filtration facilities and found that certain problems were common to the three plants and that similar problems were likely to be encountered elsewhere. They also stated that these studies have been completed and provide an opportunity to reflect on the overall status of the filters at the three plants and possibly to use this information to focus the South African water treatment community's attention on the status of their filters. Ceronio *et al*. (2002) stated that filters require specific attention especially the hydraulic control system during filtration, the backwash system, and the filtration media. It would appear that as though most of the problems experienced in the filters can be related to a failure to properly clean the media and also in the failure of hydraulic control systems (Ceronio *et al.*, 2002).

Yeh *et al*. (2000) conducted a pilot-scale study in order to solve taste, odour and hardness problems that occur in the final water of a water works in south Taiwan. The conventional treatment processes with prechlorination, used by this water works, were not only unable to solve the taste and odour problems from the growth and decay of algae and other aquatic micro-organisms, but made it worse (Yeh *et al*., 2000). They compared three treatment processes, a conventional process without prechlorination, conventional process plus ozone, granular activated carbon (GAC) and pellet softening, and an integrated membrane process followed by a conventional process. Of the three methods the integrated membrane process was found to produce the highest quality finish water with an excellent biostability (Yeh *et al*., 2000).

Ericsson and Tragardh (1996) stated that conventional flocculation, sedimentation and rapid sand filtration have to be extended with an activated carbon treatment stage in order to safeguard the colour (humic matter) removal down to maximum of 5 mg Pt/ℓ and to control possible taste and odour problems.

Teixeira and Rosa (2006) did a comparative study of Coagulation (C)/Flotation (F)/Dissolved Air Flotation (DAF) and Coagulation (C)/Flotation (F)/Sedimentation (S) performances for removing, without causing damage, cultured cells of *Microcystis aeruginosa*, a surrogate for overall removal efficiency of cyanobacteria. This study found that both treatment processes, C/F/S and C/F/DAF, could efficiently remove *Microcystis aeruginosa* cells without releasing toxins into water; C/F/DAF performed

better than C/F/S as it yielded very high chlorophyll-*a* removal (93-98%), because *Microcystis aeruginosa* has vacuoles and tend to float rather than sink out. The best set of C/F/DAF operating conditions indicated that strong and small flocs and minimum recycle were needed for effective water treatment (Teixeira and Rosa, 2006), but not necessarily the best if other algae than Cyanobacteria are present.

2.2 CHEMICAL DOSING

Rand Water uses hydrated lime (1) for coagulation and flocculation, and activated sodium silica (2) and ferric chloride (3) as a flocculation aid (Figure 2.2). The average dose rates are as follows: Slaked lime (as calcium oxide) varies between 55 and 70 mg/ℓ, silica (as silicon dioxide) vary between 1 and 3 mg/ℓ as and ferric chloride ($FeCl_3$) varies between 1 and 5 mg/ℓ (Rand Water, 2010). Station 4 at Zuikerbosch pumping station uses any of three different combinations of chemical treatment namely, slaked lime and activated sodium silicate, slaked lime and Zetafloc (Z) 526 (50/50% polyamine/ polydadmac mix) or Zetafloc 526 only (Linde *et al*., 2000).

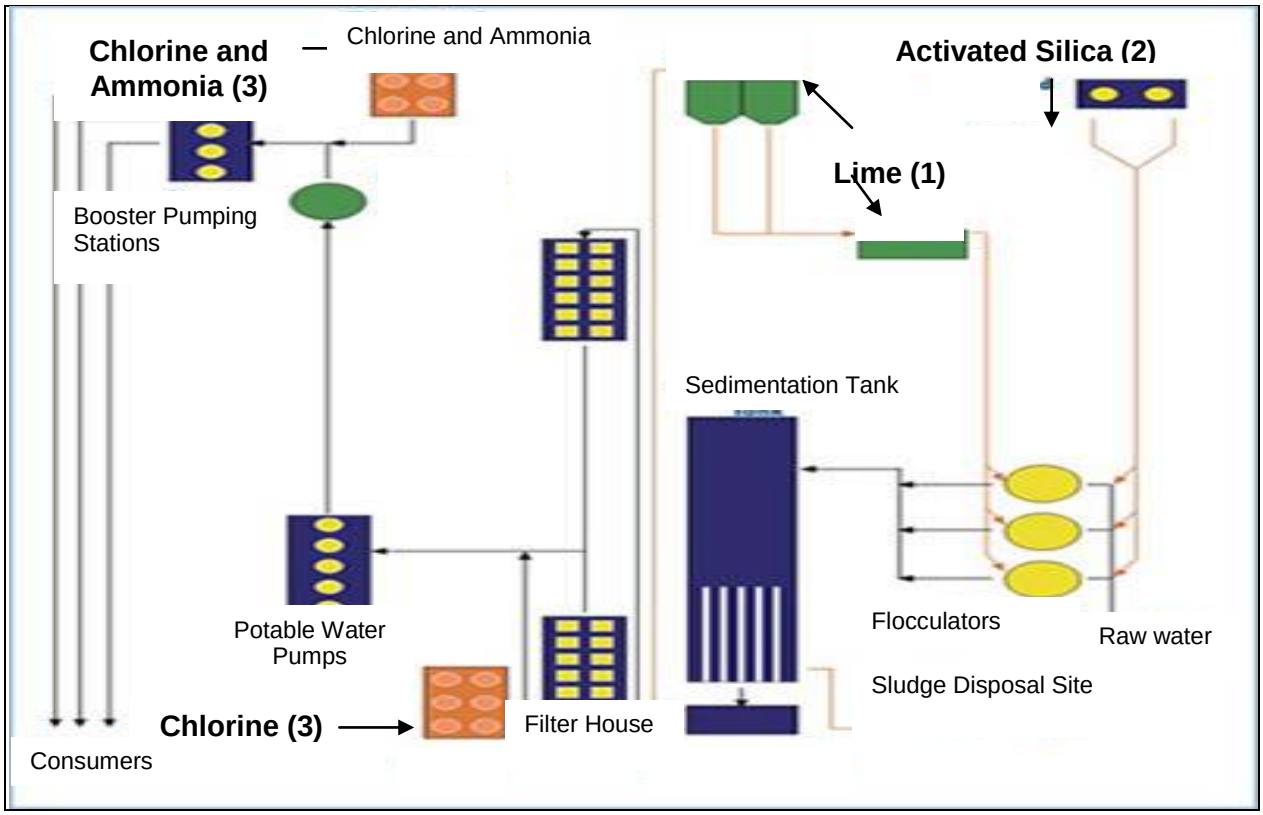


Figure 2.2: A schematic diagram of a treatment plant and the application of chemical dosing at each stage of water treatment (Rand Water, 2010).

Hydrated lime is generally purchased in powder form and then slurry is produced for dosing purposes. It may be fed directly into the water stream from some form of powder feeder placed directly above or near to the point of addition. Less desirable, addition can be into an intermediate solution tank but because of low solubility there is risk of settlement before it reaches the final dosing point (Schutte, 2006). Some of the advantages of lime dosing are lower costs and higher CaO content (Leopold and Freese, 2009).

Activated Silica is a floc aid that increases the weight and size of flocs formed after the addition of the coagulant. It is prepared by acidification of sodium silicate which has the formula $SiO_2.Na_2O$. The dosage of activated silica (as SiO_2) when used under normal practice as a coagulant aid on a plant is usually within the range of 0.5 to 4.0 mg/ℓ (Leopold and Freese, 2009).

Polyamines have become widely used in drinking water treatment for coagulation and flocculation of suspended solids. Depending on the circumstances, they might be used alone or in combination with aluminium salts, iron salts or additives such as bentonite. Polyamines are particularly useful in the treatment of high turbidity waters where they are generally more cost effective than high doses of aluminium sulphate of ferric chloride. In applications where colour removal is important, polyamines can also give good results. A further advantage of these products is that they have a pH close to neutral, therefore the use of lime for subsequent pH correction is either not necessary or can be reduced significantly, thereby reducing treatment costs (Leopold and Freese, 2009).

The application of ferric chloride in wastewater treatment is part of the process called ‘Chemical Enhanced Primary Treatment’ or CEPT. By adding iron to primary settling tanks, the flocculation process becomes much more efficient and significant proportions of phosphate can be removed in the sludge. Under these circumstances however, CEPT can provide a cost effective means of increasing the effective capacity of a treatment work without having to spend capital expenditure on plant extensions (Leopold and Freese, 2009).

It was reported that pre-treatment with oxidants may enhance the coagulation process and specifically enhance the removal of algae and other particulate matters

in subsequent treatment steps. Algal cell activity and chlorophyll concentration decreased, and the concentration of dissolved organic substances increase with increasing applied oxidant concentration. It was found that pre-treatment with chlorine dioxide (1, 3 or 5 mg/ℓ) or ozone enhanced algal coagulation (Ma and Liu, 2002).

Zuikerbosch pumping station at Vereeniging has a powered activated-carbon (PAC) mixing and dosing plant, a first for South Africa. Treating the raw water with activated carbon removes taste and odour causing compounds released into the water by algae in dams during the summer months (Pursell, 2010). Mamba *et al*. (2007) stated that treatment methods such as the use of PAC, biological degradation and conventional methods have been used for taste and odour control, but failed to remove geosmin and 2-MIB from water at ng/ℓ levels. Linde *et al*., (2000) gives the effect of different treatment chemicals on the PAC dosage required to achieve the desirable removal (Table 2.1) of geosmin.

Poon and Chu (1999) studied the effect of metal salt, ferric chloride ($FeCl_3$), and an anionic polymer on the removal of suspended solids (SS) of wastewater collected from two sewage treatment plants by using jar test experiments. The results showed that the optimum dosage for the removal of 60% SS was 30 ppm of $FeCl_3$ with 0.5 ppm polymer. A larger scale test further revealed that the addition of 30 ppm of $FeCl_3$ and 0.5 ppm polymer could provide a reduction of SS, total Nitrogen (N) and total phosphorus (P) higher than 80%, 70% and 40% respectively (Poon and Chu, 1999). According to Poon and Chu (1999) the Chemical Assisted Primary Sedimentation Process (CAPS) could be used as an alternative option to traditional biological treatment in the removal of total suspended solids, nutrients and heavy metals. Treatment chemicals can have a marked effect on the adsorption of taste and odour compounds by PAC (Linde *et al*., 2000), but was not investigated in this study.

Pieterse *et al*. (2000) found that lower $FeCl_3$ dosing concentrations were needed when calcium in the raw water increased, indicating that flocculation could be enhanced by calcium in the full-scale plant. Lower concentrations of polyelectrolyte in combination with $FeCl_3$ produced acceptable final water at lower cost than the high pH lime process. High pH lime treatment was shown to remove turbidity, dissolved organic carbon and iron more efficiently (Pieterse *et al.*, 2000).

Table 2.1: The effect of different treatment chemicals (Lime, Z526 and activated silica) on the PAC dosage required achieving the desirable removal (Linde *et al*., 2000).

PAC	**Treatment Chemical**	PAC dosage (mg/ℓ) required to achieve the respective geosmin removal rates (C_0 = 120 ng/ℓ)		
		60%	**70%**	**80%**
Sample 1	65 mg/ℓ lime and 2.5 mg/ℓ Z526	3.7	5.2	7.3
	5 mg/ℓ Z526	4.4	6.3	9.2
	65 mg/ℓ lime and 2.5 mg/ℓ activated silica	6.4	8.6	11.3
Sample 2	65 mg/ℓ lime and 2.5 mg/ℓ Z526	5.0	6.7	9.6
	5 mg/ℓ Z526	5.3	7.2	10.2
	65 mg/ℓ lime and 2.5 mg/ℓ activated silica	6.4	8.5	11.6

2.3 REMOVAL OF ALGAE

Elevated levels of phytoplankton (algae) can have negative consequences for the water purification industry. Potable purification costs are significantly increased when phytoplankton blooms occur, resulting in the need for algal cells and their by-products, to be removed from the water (Swanepoel *et al*., 2008). Visser and Pieterse (2000) investigated the occurrence of algal species in the Vaal River at Balkfontein, as well as the penetration of algal species into the different unit processes of treatment because different morphological features of the phytoplankton may affect coagulation and sedimentation. They found that

cyanobacteria, green algae and diatoms were almost always present in the sand filter effluent (Visser and Pieterse, 2000).

Venter *et al*. (2002) stated that blue-green bacteria represent only a small proportion of all phytoplankton groups in the Vaal River, but they are probably one of the most important, taking into consideration their potential to be problematic (whether toxin-producing, filter clogging, scum-forming or discouraging recreational activities). Cyanobacteria in source water can affect the drinking water treatment process (e.g. ineffective coagulation, flocculation and sedimentation, clogging sand filters), as well as the quality (e.g. the release of taste and odour compounds) of water produced by treatment plants (Du Preez *et al.*, 2007).

In this study the efficacy of purification processes in removing problem species such as *Anabaena* sp., *Microcystis* sp., *Oscillatoria s*p. and *Ceratium* sp., will be investigated. Cyanobacteria can release MIB and geosmin into water supplies. *Ceratium* spp. are also responsible for the secretion of odour compounds (Westerhoff *et al*., 2005 and Van Ginkel *et al*., 2001). The cyanobacterium *Anabaena cylindrica* (Ho *et al*., 2009) and *Microcystis aeruginosa* (Zhang *et al*., 2009) have the ability to co-produce geosmin and toxins, compounds which can compromise the quality of drinking water. Blooms of *O. simplicissima* result in the production of unpleasant odours and tastes in treated water and a general decline of the water quality (Venter *et al*., 2002).

CHAPTER 3: ECOLOGICAL OVERVIEW

3.1 INTRODUCTION

Rivers in South Africa are under constant pressure of pollution. Pollution leads to the presence of high concentrations of organic and inorganic compounds, which enhance algal blooms and concomitantly decrease water quality (Venter *et al*., 2003).

The Vaal River is one of South Africa's largest rivers, supplying water to highly populated and industrial areas. The Vaal River originates on the western slopes of the Drakensberg escarpment and flows about 900 km west-south-west across the interior plateau to join the Orange River near Douglas (Janse van Vuuren, 1996). Vaal River water is of high salinity and general poor quality as a result of large quantities of effluent and urban runoff which are discharged into the river in the Upper Vaal water management area (DWAF, 2002). Surface water quality is affected by sedimentation, erosion; diffuse discharges from irrigated farmland (both fertilizers and salinity through leaching), domestic and urban runoff, industrial waste, and sewage discharge (DWAF, 2002). The climatic conditions in the Upper Vaal Water Management Area (WMA) vary with the mean annual precipitation reducing from 800 mm in the headwaters to 500 mm at the Middle Vaal WMA (DWAF, 2002). The average monthly rainfall during the study period varied between 0 – 250 mm for Vereeniging in Gauteng, South Africa (South African Weather Service). The land use in the Upper Vaal WMA is characterized by the sprawling urban and industrial areas in the northern and western parts of the WMA. There are also extensive coal and gold mining activities located in the Upper Vaal WMA that generate substantial return flow volumes in the form of treated effluent from the urban areas and mine dewatering that are discharged into the river system. These discharges are having significant impacts on the water quality in the main stem in the Vaal River, throughout all three of the Vaal WMA's (DWAF, 2004).

The nutrient-rich and eutrophied Vaal River supplies water to the Zuikerbosch Water Treatment Plant (ZWTP). The ZWTP (Figure 3.1) is situated in Vereeniging, South

Africa south of Johannesburg (Mamba *et al*., 2007). Rand Water abstracts its raw water from the Vaal Dam (in the upper Vaal) via a canal (Figure 3.2) and a gravity pipeline, and by pumping from the Vaal River Barrage Reservoir at Lethabo, Zuikerbosch and Vereeniging, from where it undergoes the necessary purification process required to ensure that the water meets the stringent standards set for drinkable water (Rand Water, 2010).

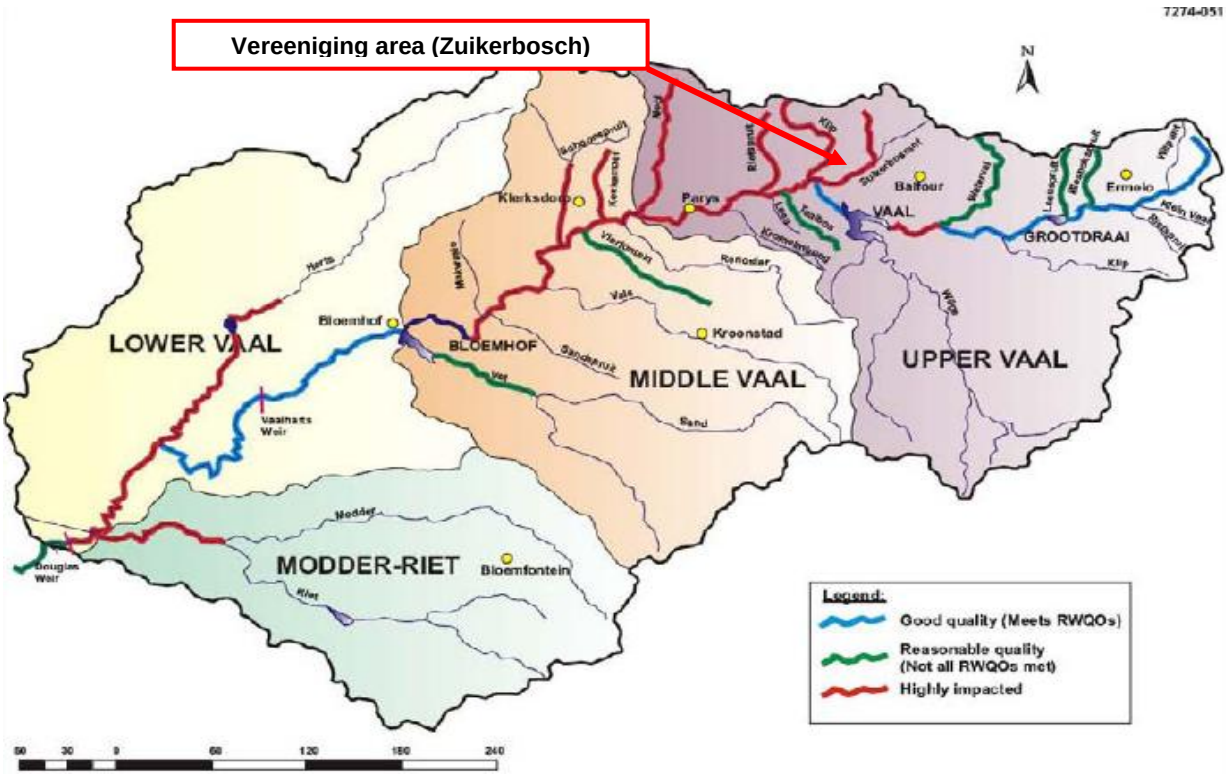


Figure 3.1: Map of the Vaal River (Vereeniging, ZWTP) showing the Upper Vaal, Middle Vaal and Lower Vaal (DWAF, 2007).

One of the aims of this study was to determine the ecological status of the source water of the ZWTP in order to have a baseline that can be used to determine the efficacy of the purification processes.

Figure 3.2: The open canal system transporting water from the Vaal Dam to the ZWTP where the water undergoes a series of purification processes.

3.2 MATERIAL AND METHODS

3.2.1 Environmental Variables

Water samples were collected weekly from February 2008 to March 2010 at the Zuikerbosch water treatment plant, by staff of Rand Water.

Chemical, physical and biological variables were measured by Rand Water Analytical Service according to standard laboratory (South African National Accreditation System (SANAS) accredited laboratory methods). The following environmental variables were measured in the raw water over a period of two years (February 2008 – March 2010):

- Ions: lead (in µg/ℓ), magnesium (in mg/ℓ), calcium (in mg/ℓ), cadmium (in µg/ℓ), potassium (in mg/ℓ), sodium (in mg/ℓ) and chloride (in mg/ℓ);
- total dissolved solids (in mg/ℓ);

- conductivity (in mS/m);
- suspended solids (in mg);
- turbidity (in NTU);
- temperature (in ^{o}C);
- chlorophyll-*a* (in µg/ℓ);
- pheaophytin (in µg/ℓ);
- chemical oxygen demand (in mg/ℓ);
- dissolved organic carbon (in mg/ℓ);
- geosmin and 2-methylisoborneol (in ng/ℓ);
- total silica (in mg/ℓ);
- sulphate (in mg/ℓ);
- nitrite (in mg/ℓ);
- nitrate (in mg/ℓ);
- ammonium (in mg/ℓ);
- Total Kjeldahl Nitrogen (in mg/ℓ);
- phosphate and phosphorus (in mg/ℓ);
- methyl-orange alkalinity (in mg/ℓ); and
- pH.

3.2.2 Identification and enumeration of phytoplankton

The correct identification and enumeration of phytoplankton in natural waters, together with the determination of the concentration of their by-products, is important, not only because of the different problems related to individual species, but also

because of their properties to be good indicators of different water qualities and/or environmental and ecological conditions (Swanepoel *et al*., 2008). Therefore, 150 ml samples of the raw water were collected and fixed with Lugol's solution or formaldehyde (final concentration = 2%). Sampling and fixing of water samples were done by the staff from Hydrobiology at Rand Water's Analytic services. These samples were used for the quantitative and qualitative phytoplankton analyses. All phytoplankton analyses were done in laboratories of the North-West University, Potchefstroom Campus.

Phytoplankton identification and enumeration analysis were done by using the sedimentation technique (gravity) (Lund *et al*., 1958) Samples were shaken in order to suspend the algae uniformly. Gas vacuoles of cyanobacteria were pressure-deflated using a specially-designed mechanical hammer that exerted a pressure of 49.5 kPa on the sample (Janse van Vuuren, 1996), which is approximately the pressure needed to collapse the gas vacuoles of cyanobacteria (Janse van Vuuren, 1996). Equal volumes of the collected samples, usually 6.0 mℓ, were transferred into sedimentation tubes with diameters of 16 mm. The sedimentation tubes were covered with circular glass cover slips and algae allowed to sediment by gravity for at least 48h. Containers were kept in a high humidity container to prevent evaporation of the sample. The algal concentrations were recorded as number of algal cells/mℓ.

These procedures were repeated for each water sample taken from (1) the raw water, (2) after coagulation, flocculation or sedimentation, (3) after rapid sand filtration and (4) in the final water.

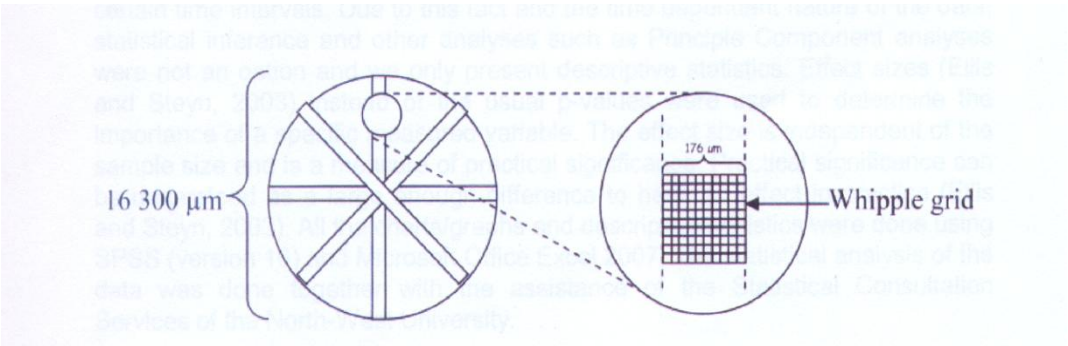


Figure 3.3: Line diagram showing the orientation of strips and the field of a Whipple grid (Swanepoel *et al*., 2008).

Algal cells were counted by means of the technique described by Utermöhl (1958), using an inverted light microscope. The Utermöhl method was applied to determine the concentration and composition of algal genera. One of the eyepieces of the inverted microscope contained a Whipple grid. The glass bottoms of the sedimentation tubes were examined in diametric transects. Algal cells lying counted within strips formed by the Whipple grid were counted (Figure 3.3) until about 300 cells were counted. Each algal cell within a colony, as well as in a filament was also counted individually. Lund *et al.* (1958) stated that, if the algal cells are randomly distributed on the base of the counting chamber, a single count will be sufficient to obtain an estimate of abundance within specific limits.

The cell counts, together with the original sub-sample volume transferred to the sedimentation tubes, as well as the number of strips counted in the sedimentation tubes, were used to calculate the concentration of the phytoplankton in cells/mℓ, with the aid of an Excel spreadsheet. The phytoplankton counts were used to determine genera abundance (indicated by the concentration of algal cells/mℓ), percentage composition of different genera at a given time and succession patterns of dominant algal species. Data on algal counts were entered into spreadsheets using Microsoft Excel. A spreadsheet was set up to calculate algal data such as species number and genera (indicated by the concentration of algal cells/mℓ) as well as for the estimation of missing values using linear interpolation between data.

Formulas for the calculation of algal biomass which are expressed as algal cells/mℓ (Swanepoel *et al*., 2008):

1) Calculating the final conversion factor:

Final conversion Factor = (Area of sedimentation chamber floor) / (Area of field) x (Number of fields counted) x (Volume sedimented)

Final conversion factor = Conversion factor/ Volume of sedimented

2) Calculating the area of the sedimentation floor:

$$\text{Area} = \pi r^2$$

3) Calculating the area of the Whipple grid:

Area of a field = Length x width

4) Calculate the area of one rectangular lane:

Lane area = diameter of sedimentation chamber x width of Whipple grid

5) Calculate the biomass as cells/mℓ

Biomass = Count x Final conversion factor.

3.3 DATA ANALYSIS

When a result was below the detection limit for a specific variable or determinant, the value was divided by two and subsequently included in the data analyses, e.g. <0.01 mg/ℓ Mg→ 0.005 mg/ℓ Mg.

Lead (Pb) and MIB were removed during the PCA because it remained constant throughout the study period.

Communalities must be higher > 0.3 /1.000 or 30% of all the variables that were measured. The communalities of the variables/determinants that were used in the PCA of the study are > 30% (see Table 3.1).

The total variance of 14 components that were used in the PCA is explained in Table 3.4. In Table 3.4, in example the percentage of the total variation explained by component 1 is:

- Initial eigenvalues: 3.664 (total) / 34 (the number of variables) x 100 = 10.776% variation
- The rotation sums of square loadings: 3.535 (total)/ 34 (number of variables) x 100 = 10.397% variation.

3.3.1 Principal component analysis

Principal component analysis (PCA) and factor analysis (FA) are statistical techniques applied to a single set of variables when the researcher is interested in discovering which variables in the set form coherent subsets that are relatively independent of one another (Tabachnick and Fidell, 2001). The basic idea of PCA is that data are collected from a matrix of n quadrants and m species or environmental variables. The original data matrix of, for example, 100 quadrants and 50 species/variables can be reduced to 100 quadrants and 5 or even fewer components. These components can be regarded as new 'super-species' or 'super-variables', made up of highly correlated combinations of the original 50 species or environmental variables (Kent and Coker, 1992).

The core of any PCA is eigenvectors and eigenvalues. The eigenvectors are a set of scores, each of which represents the weighting of each of the original species or variables on each component. The eigenvector scores are scaled like correlation coefficients and range from +1.0 throughout 0.0 to -1.0. For each component, every species or variable has a corresponding set of eigenvector scores and the nearer the score is to +1.0 or -1.0, that is the furthest away from zero, the more important is that species or variable in terms of weighting that component (Kent and Coker, 1992).

Eigenvalues (as opposed to eigenvectors) are values that represent the relative contribution of each component to the explanation of the total variation in the data. There is one eigenvalue for each component, and the size of the eigenvalue for a component is a direct indication of the importance of that component in explaining the total variation within the set data (Kent and Coker, 1992).

The specific goals of PCA or FA are to summarize patterns of correlations among observed variables, to reduce a large number of observed variables to smaller factors, to provide an operational definition (a regression equation) for an underlying process by using observed variables, or to test a theory about the nature of underlying processes (Tabachnick and Fidell, 2001).

Fourteen components (Table 3.4) were used to do the PCA (Table 3.5) for environmental variables and algal data (*Anabaena* sp.*, Microcystis* sp.*, Oscillatoria*

sp. and *Ceratium* sp.) of the raw water. Data was collected over a period of two years. Most of data was time dependent; hence the set of data was transformed to remove the autocorrelations and the time dependency. The principal components were rotated according to the Varimax method to complete the PCA.

Table 3.1: The communalities for 34 variables that were used in the PCA are given in this table. The communality of a variable is the variance accounted for by the factors. By using only communalities, the unique and error variance contained in each variable are excluded (Tabachnick and Fidell 2001).

Communalities		
	Initial	Extraction
Magnesium	1.000	.767
Calcium	1.000	.821
Cadmium	1.000	.702
Potassium	1.000	.715
Sodium	1.000	.751
Chloride	1.000	.699
Total Dissolved Solids	1.000	.842
Conductivity	1.000	.743
Hardness	1.000	.890
Suspended solids	1.000	.805
Turbidity	1.000	.800
Temperature	1.000	.794
Chlorophyll-*a*	1.000	.867
Total chlorophyll	1.000	.900
Pheaophytin	1.000	.744
Chemical Oxygen Demand	1.000	.733
Dissolved Organic Carbon	1.000	.611
Total Organic Carbon	1.000	.734
Geosmin	1.000	.554
Silica	1.000	.731

Sulphate (SO_4)	1.000	.743
Sulphur	1.000	.664
Phosphate (PO_4)	1.000	.643
Phosphorus	1.000	.721
Nitrate (NO_3)	1.000	.681
Ammonium (NH_4)	1.000	.715
Nitrite (NO_2)	1.000	.608
Total Kjeldahl Nitrogen	1.000	.747
M-alkalinity	1.000	.515
pH	1.000	.742
Anabaena sp.	1.000	.605
Microcystis sp.	1.000	.795
Oscillatoria sp.	1.000	.623
Ceratium sp.	1.000	.828
Extraction Method: Principal Component Analysis.		

3.4 RESULTS

Figures 3.4 to 3.24 show the monthly averages for the environmental variables as well as the algal concentration (counts) in the raw water from February 2008 to March 2010

3.4.1 Temperature

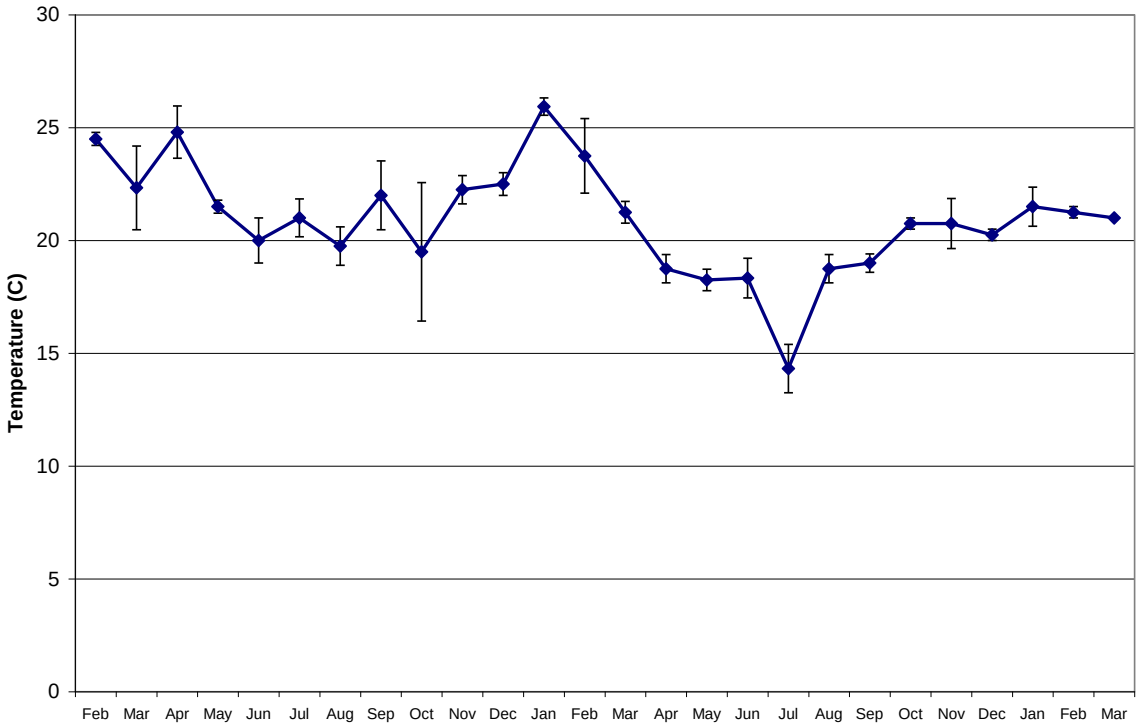


Figure 3.4: The monthly averages of temperature (^{o}C) measured in the raw water for the period February 2008 to March 2010.

The highest monthly average temperature of the raw water was 26 °C and was measured in January 2009, while the lowest monthly average temperature of 15 °C was measured in July 2009. The temperature measurements followed a typical seasonal pattern and were therefore higher in summer months and lower in the winter months. The 2009-2010 raining season had a high rainfall with a lot of cloudy days (South African Weather Service) explaining the lower average temperature from December 2009 to February 2010.

3.4.2 Rainfall data for Vereeniging area and the flow rate of the Vaal Dam

Figure 3.5 gives the rainfall trends for the Gauteng province from 2006 up until 2010. Rainfall influences the flow of the river and can influence certain variables such as temperature, conductivity, suspended solids and turbidity (Morrison, 2009).

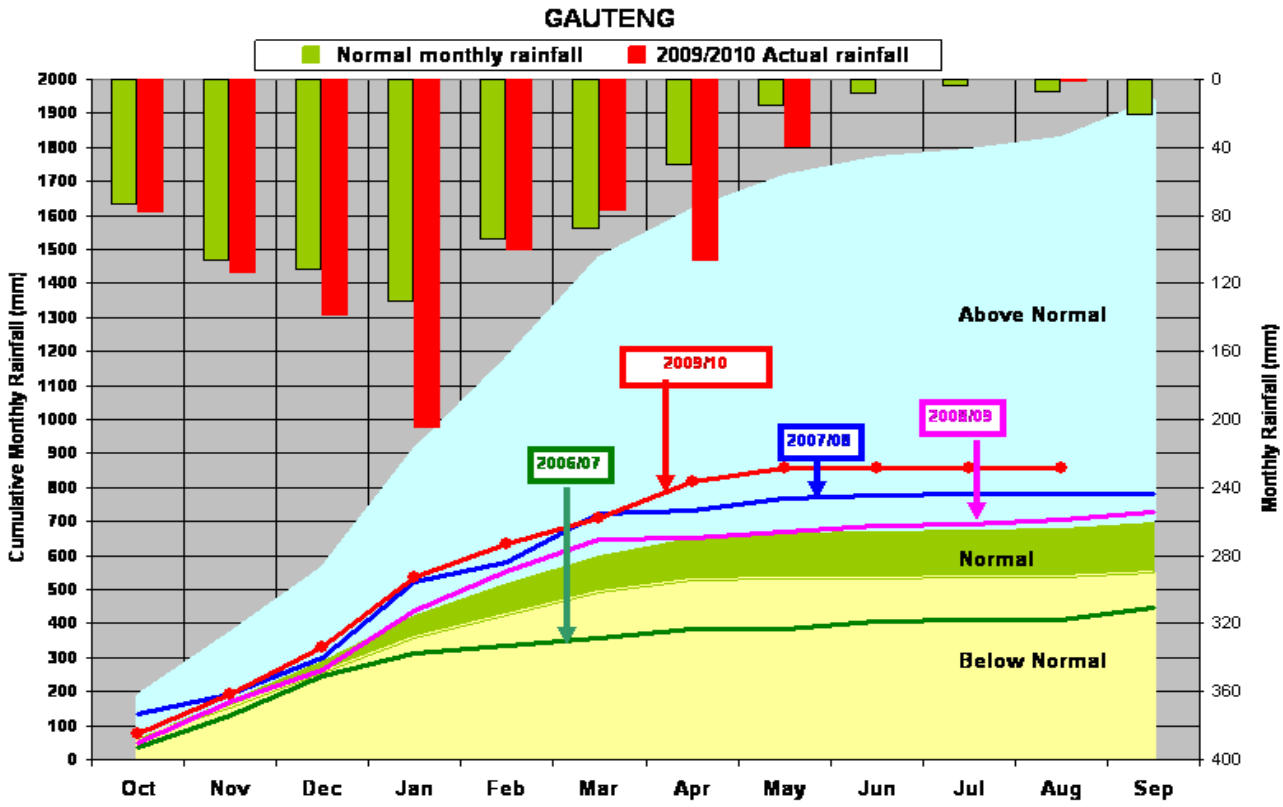


Figure 3.5: The normal monthly rainfall and actual rainfall for 2006 to 2010 in the Gauteng province. Both cumulative monthly and monthly rainfall in mm is given on the primary and secondary Y-axis (DWAF, 2010).

The rainfall data for Vereeniging was measured by the South African Weather Service. All flow data for the Vaal Dam (Vaal River) was measured by the Department of Water Affairs and Forestry (DWAF). The rainfall and flow data for the period February 2008 to February 2010 varies between 0 – 250 mm and 0 – 2500 cumec respectively. During 2008 to 2010 the rainfall trend for the Gauteng province was above normal as shown in the rainfall trend Figure 3.5.

Figure 3.6 shows the rainfall (mm) for Vereeniging and flow (cumec) data for the Vaal Dam (Station C2H122.A Vaal River at Annie's Rust).

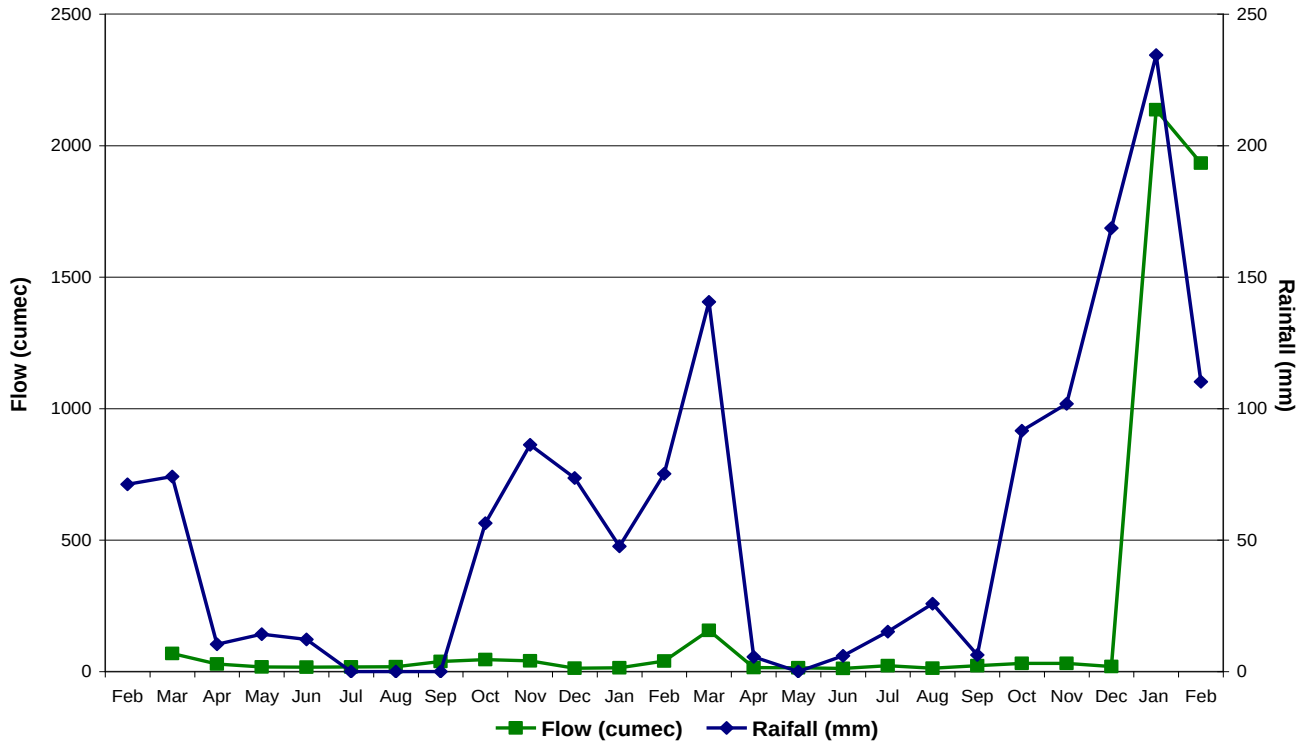


Figure 3.6: The flow (cumec) data for the Vaal Dam at station C2H122 and the rainfall (mm) for Vereeniging during the period February 2008 to February 2010.

The highest rainfall was measured in January 2010 (>200 mm), while the lowest rainfall occurred during June to September 2008 (<10 mm) and again in May 2009 (<10mm). The highest flow rate (± 2000 cumec) for the Vaal Dam (Station C2H122.A Vaal River at Annie's Rust) was measured during January to February 2010. Dyson (2009) stated that a significant rainfall event is defined when the average rainfall exceeds 10 mm, a heavy rainfall event when the average exceeds 15 mm and a very heavy rainfall event when the average rainfall exceeds 25 mm.

Both the rainfall of Vereeniging region and flow rate of the Vaal Dam was measured at the highest levels during January 2010. The level at peak (m) and flow rate (Table 3.2 and Figure 3.6) of the Vaal Dam were the highest during January 2010 as a result of high rainfall in the Vereeniging region during that time. The month of January usually has the highest monthly average rainfall as well as the highest

number of heavy and very heavy rainfall days in the Gauteng province (Dyson, 2009).

Table 3.2: The levels at peak (m) for the Vaal Dam (Station C2H122.A Vaal River at Annie's Rust) during the period February 2008 to February 2010.

2008	Level at peak (m)	2009	Level at peak (m)	2010	Level at peak (m)
				Jan	0.581
Feb	0.569	**Feb**	0.517	**Feb**	3.919
Mar	0.883	**Mar**	0.742		
Apr	0.666	**Apr**	1.186		
May	0.561	**May**	0.534		
Jun	0.546	**Jun**	0.519		
Jul	0.562	**Jul**	0.489		
Aug	0.571	**Aug**	0.611		
Sep	0.73	**Sep**	0.502		
Oct	0.772	**Oct**	0.613		
Nov	0.745	**Nov**	0.68		
Dec	0.503	**Dec**	0.68		

Dyson (2009) also found that within the Gauteng province, the month with the second-highest number of heavy and very heavy rainfall days is February followed by March and October. December has the second-highest monthly average rainfall and the most days with rain.

3.4.3 pH

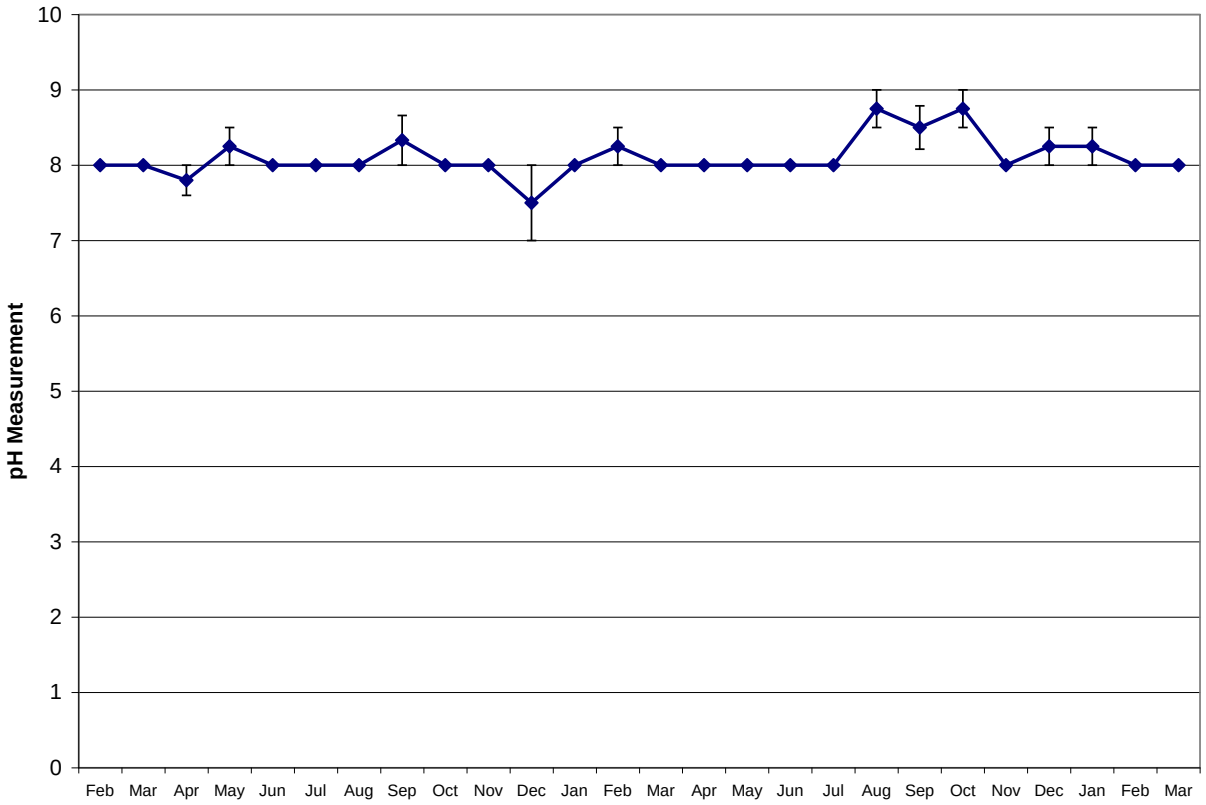


Figure 3.7: The monthly averages of pH measured in the raw water for the period February 2008 to March 2010.

The pH of the raw water did not vary much and the monthly averages for pH remained between pH ranges of 7 and 9 for the study period. The pH was relatively constant at 8 for the entire study period.

3.4.4 Methyl-orange Alkalinity

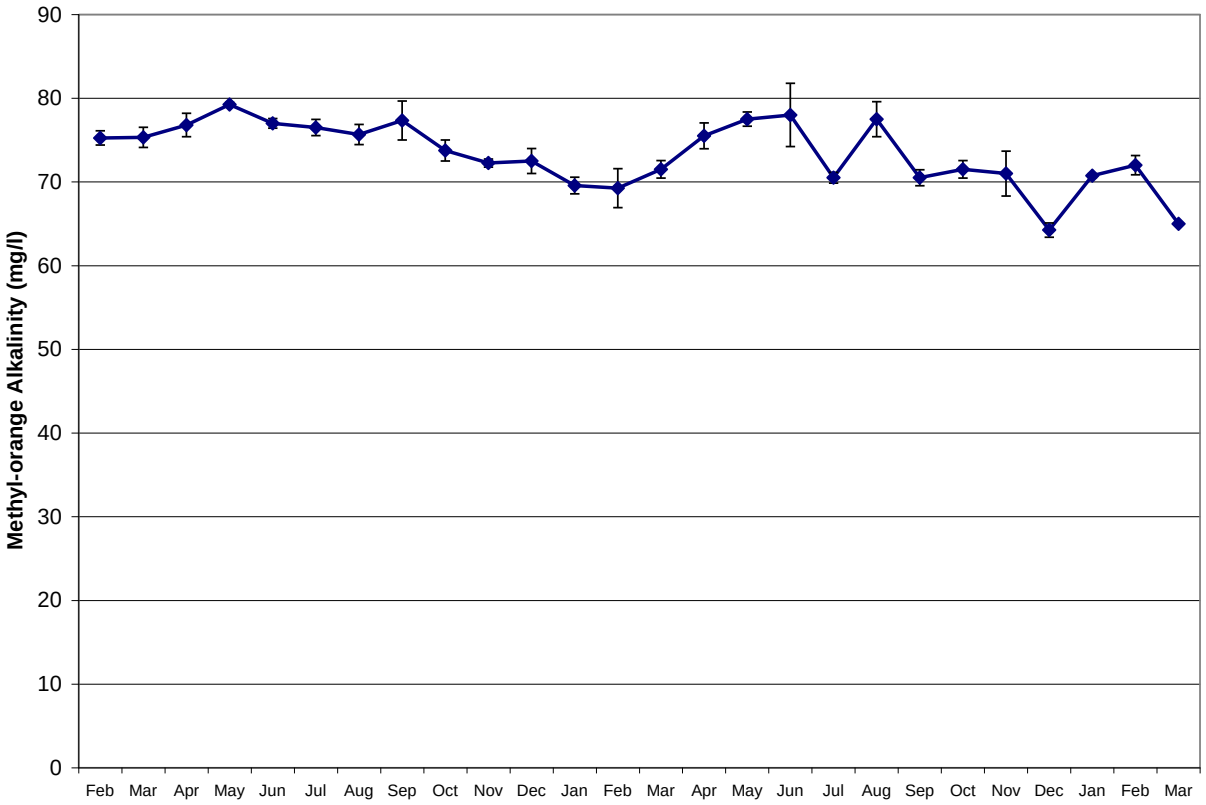


Figure 3.8: The monthly averages of methyl-orange alkalinity (mg/ℓ) measured in the raw water for the period February 2008 to March 2010.

Fig.3.8 indicates that the monthly averages of methyl-orange alkalinity ranged between 65 mg/ℓ and 80 mg/ℓ and have shown a slight decrease from the beginning towards the end of the study period. The highest measurement for methyl-orange alkalinity was done on the 09th of June 2009, with a measurement of 85 mg/ℓ.

3.4.5 Suspended Solids (SS) and Turbidity (Turb)

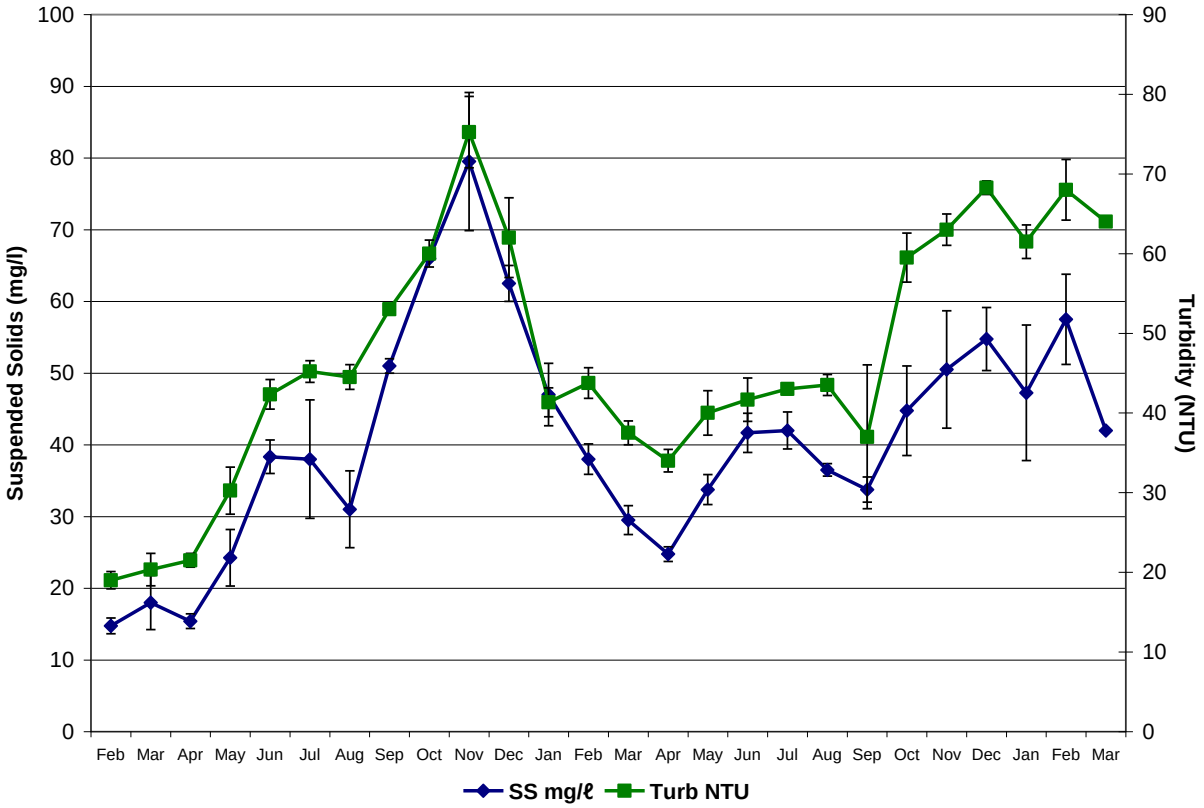


Figure 3.9: The monthly averages of suspended solids (mg/ℓ) and turbidity (NTU) measured in the raw water for the period February 2008 to March 2010.

In November 2008 the highest measurements for suspended solids (±80 mg/ℓ) and turbidity (>80 NTU) were made. The lowest monthly averages occurred in February 2008 for both of these variables, with measurements for suspended solids at 15 mg/ℓ and turbidity at 21 NTU. The two variables increased from February 2008 until November 2008, followed by a decrease until April 2009. Both variables increased during the 2009-2010 raining season. A good correlation can be seen between SS and turbidity, with same pattern throughout the study period (Fig. 3.9).

3.4.6 Total Dissolved Solids (TDS) and Conductivity

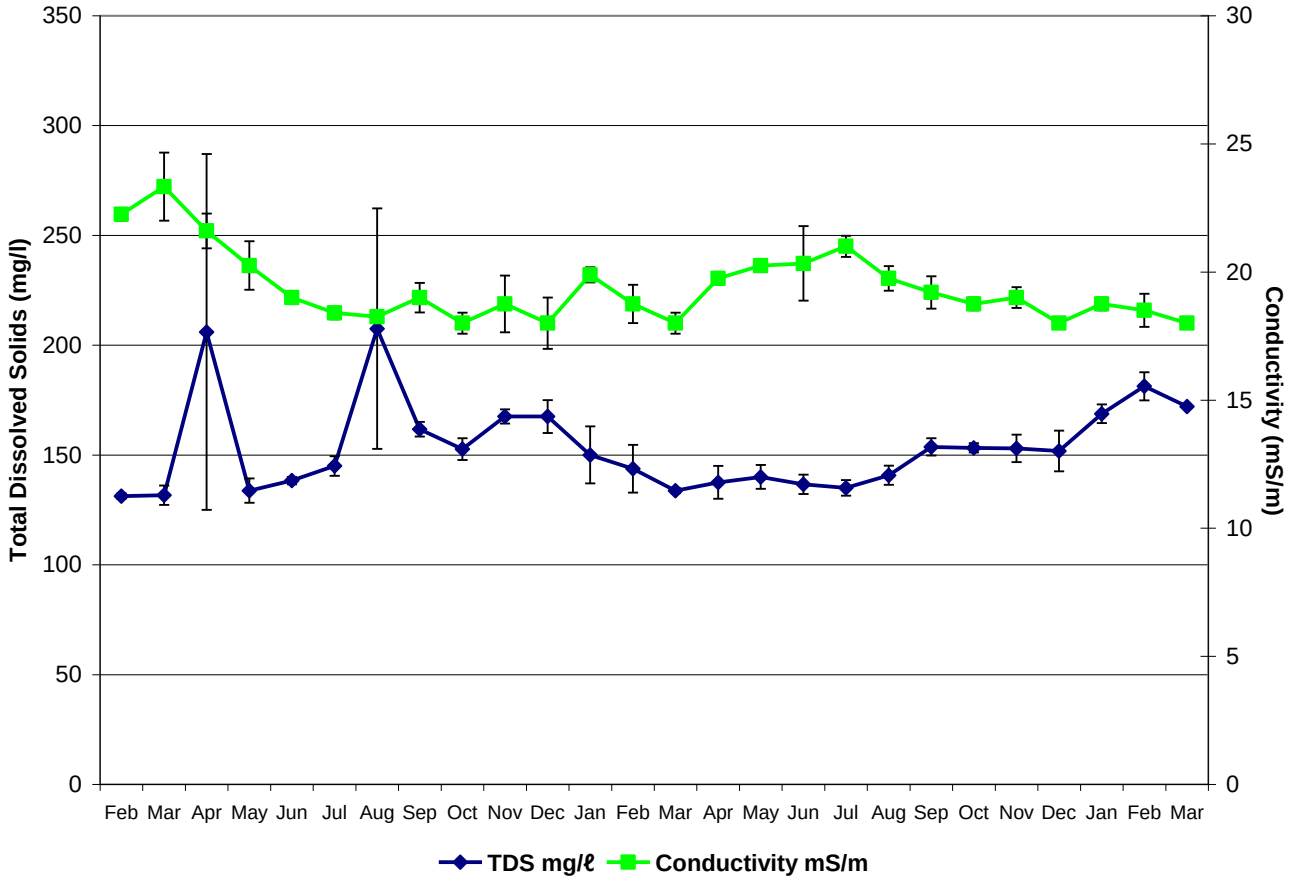


Figure 3.10: The monthly averages of total dissolved solids (mg/ℓ) and conductivity (mS/m) measured in the raw water for the period February 2008 to March 2010.

The monthly averages of TDS were measured between 130 mg/ℓ and 210 mg/ℓ for the entire study period, with the highest measurement made on the 1st of April 2008 (530 mg/ℓ), and another high measurement of 370 mg/ℓ was made on the 12th of August 2008. The lowest measurement for TDS was made on the 08th of April 2008 (115 mg/ℓ). TDS shows an increasing trend for the duration of the study period.

In March 2008, the highest monthly averages of conductivity were measured and the lowest monthly average was measured in October 2008. On the 04th of March 2008 the highest measurement for conductivity was made (26 mS/m). Conductivity shows a decreasing trend for the duration of the study period.

3.4.7 Lead (Pb) and Cadmium (Cd)

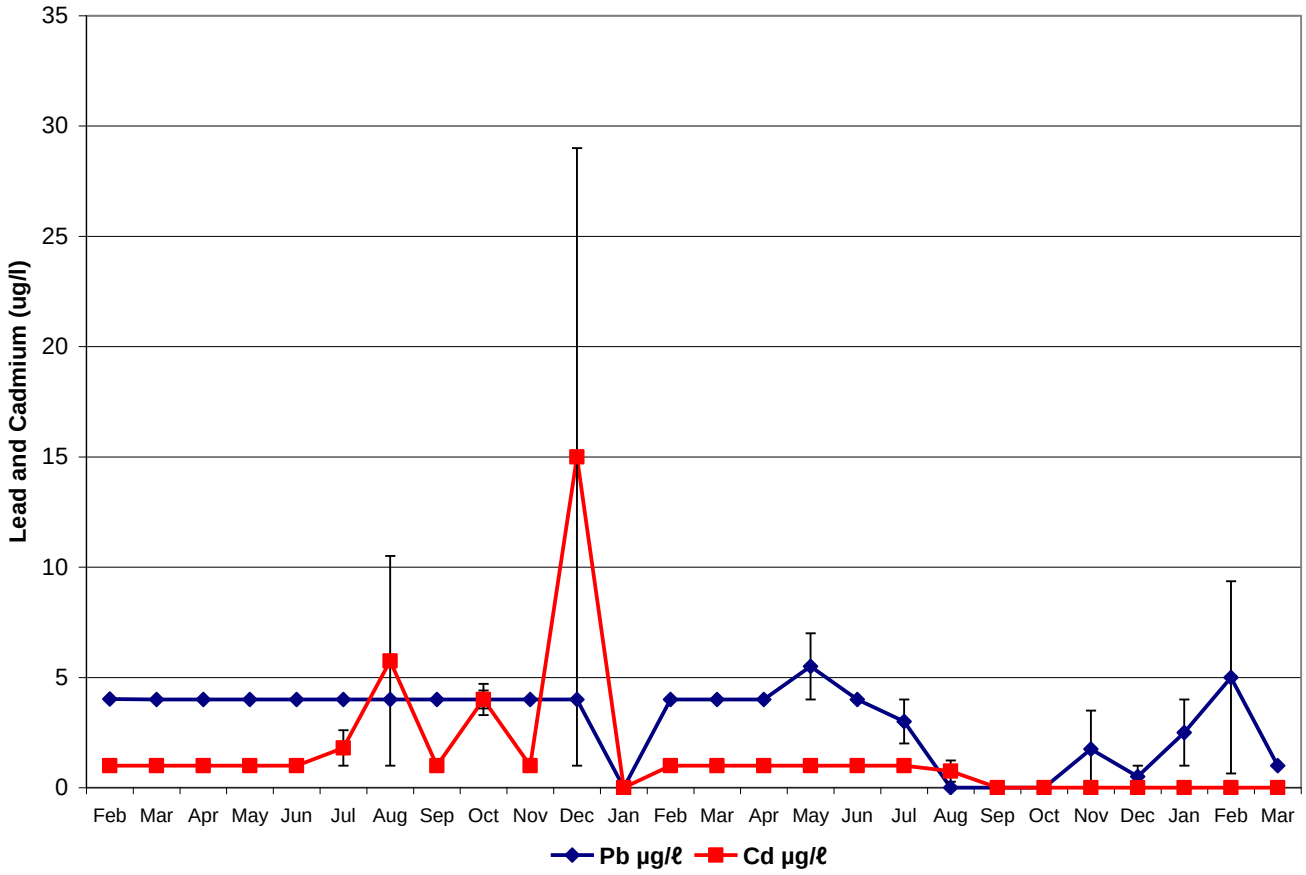


Figure 3.11: The monthly averages of lead (µg/ℓ) and cadmium (µg/ℓ) concentrations measured in the raw water for the period February 2008 to March 2010.

The average lead concentration of the raw water stayed constant for the first year (2008), but varies for the rest of the study period. It stayed below 5 µg/ℓ for most of the study period with peaks during May 2009 and February 2010. The highest measurement for lead was made on the 2nd of February 2010 (18 µg/ℓ).

Monthly averages of cadmium stayed below 5 µg/ℓ for most parts of the study period with peaks during August, October and December 2008. On the 26th of August 2008 a high of 11 µg/ℓ was measured and on the 2nd of December 2008 another peak of 29 µg/ℓ was measured.

3.4.8 Calcium (Ca), Magnesium (Mg), Potassium (K), Sodium (Na) and Chloride (Cl)

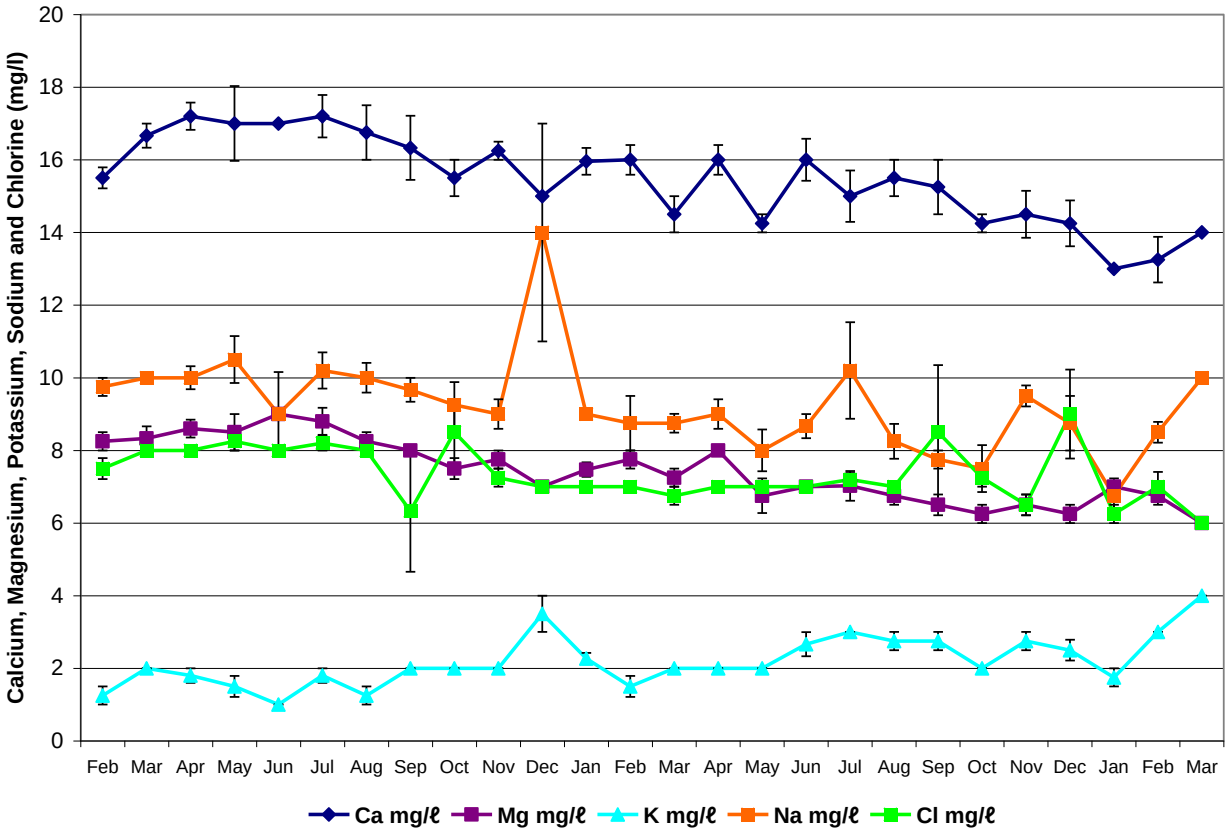


Figure 3.12: The monthly averages of calcium (mg/ℓ), magnesium (mg/ℓ) potassium (mg/ℓ), sodium (mg/ℓ) and chloride (mg/ℓ) measured in the raw water for the period February 2008 to March 2010.

During the study period K was present in the lowest concentration, followed by, Cl, Mg, Na, while Ca was measured in the highest concentration. The average concentration of Mg decreased during the two year period, with the highest measurements of 10 mg/ℓ on the 1st of June 2008.

The monthly averages measured for the Ca concentration were between 15 and 20 mg/ℓ for the first year (2008) of the study period, with the highest monthly averages in April, May, June and July 2008. In the second year (2009) the monthly averages of the calcium concentration decreased towards the end of the study period, measuring below 15 mg/ℓ. On the 13th of May 2008 the highest measurement for Ca was made (18 mg/ℓ).

K averages for the entire study period were measured below 5 mg/ℓ, but has shown a slight increase from about 1 mg/ℓ to 4 mg/ℓ. The highest measurement of 4 mg/ℓ for K was made on the 09th of December 2009 and the 2nd of March 2010.

During 2008 the monthly averages of Na stayed more or less constant at 10 mg/ℓ except for the spike in December (17 mg/ℓ measured on the 2nd of December 2008). For the rest of the study period the monthly averages were less than 10 mg/ℓ except for July 2009 and March 2010 when the averages were 10 mg/ℓ.

The monthly averages for Cl were between 5 mg/ℓ and 10 mg/ℓ at about 7.5 mg/ℓ for almost the entire study period, with the highest monthly average (9 mg/ℓ) in December 2009 and the lowest monthly average (6 mg/ℓ) during March 2010. On the 15th of September 2008, the highest measurement of 14 mg/ℓ was made. The concentration fluctuated towards the end of the study period.

3.4.9 Hardness

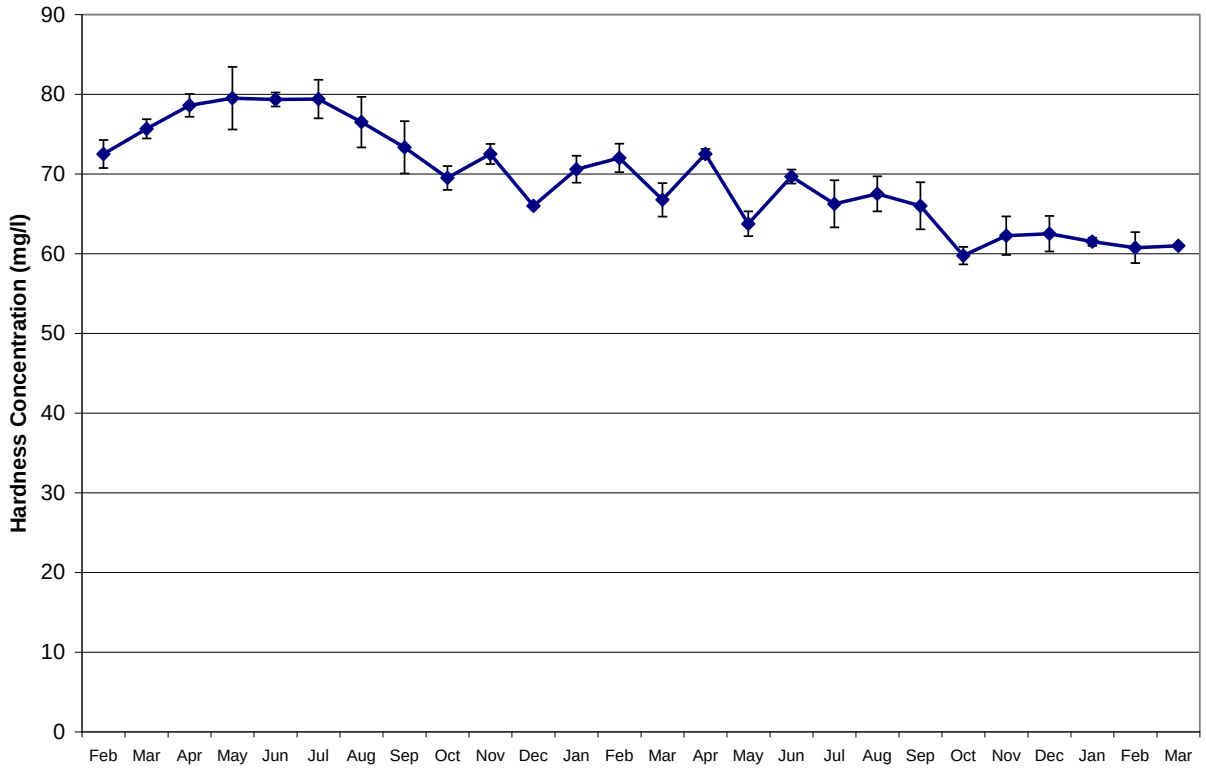


Figure 3.13: The monthly averages of hardness (mg/ℓ) measured in the raw water for the period February 2008 to March 2010.

The average hardness of the raw water ranged between 60 mg/ℓ and 80 mg/ℓ. The highest monthly averages were measured in May, June and July 2008. The lowest monthly average was measured in October 2009. The hardness of the raw water has shown a decreasing trend for the duration of the study period.

3.4.10 Total Silica

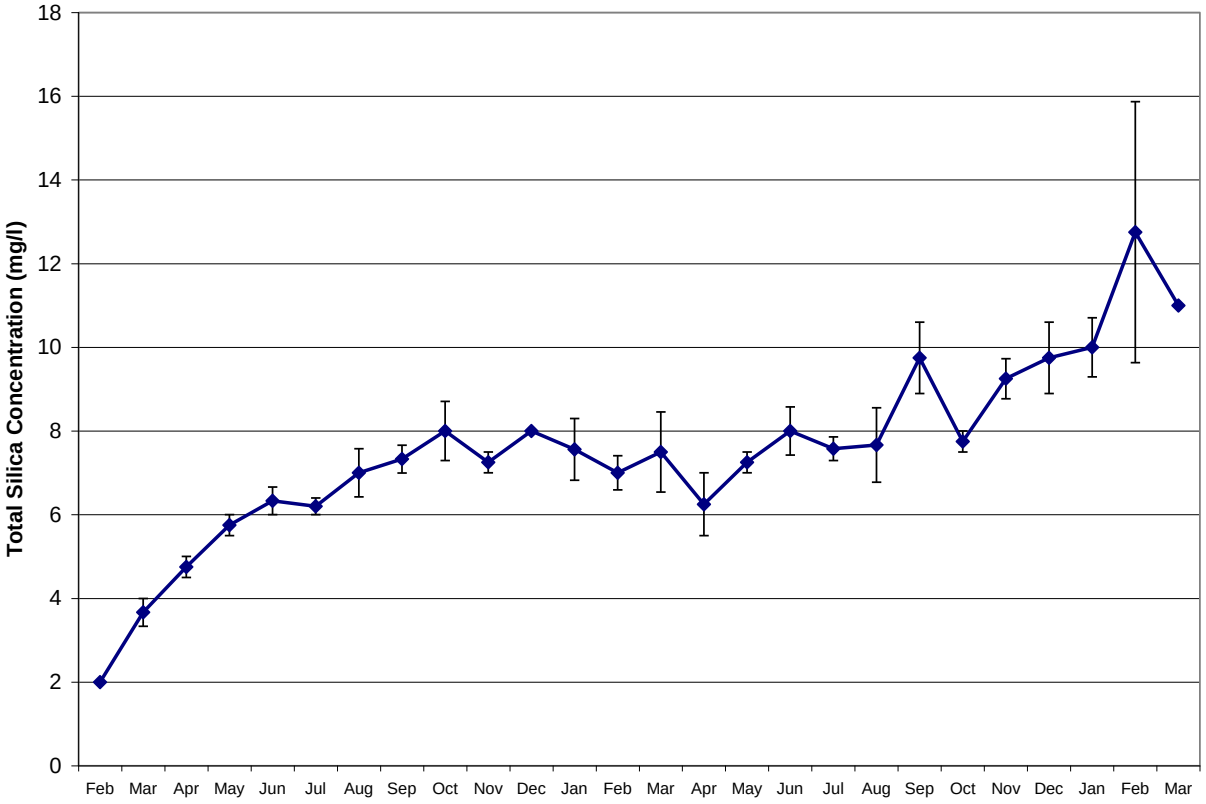


Figure 3.14: The monthly averages of total silica (mg/ ℓ) measured in the raw water for the period February 2008 to March 2010.

The monthly averages of total silica in the raw water show an increase during the study period, with the highest monthly average measured during the end of the end of the study period in February 2010 (> 12 mg/ℓ) and the lowest measurement during the beginning of the study period in February 2008 (2 mg/ℓ). The silica content of the raw water increased with more than 10 mg/ℓ during the study period. The highest measurement of 22 mg/ℓ for silica was made on the 16th of February 2010.

3.4.11 Sulphate (SO_4)

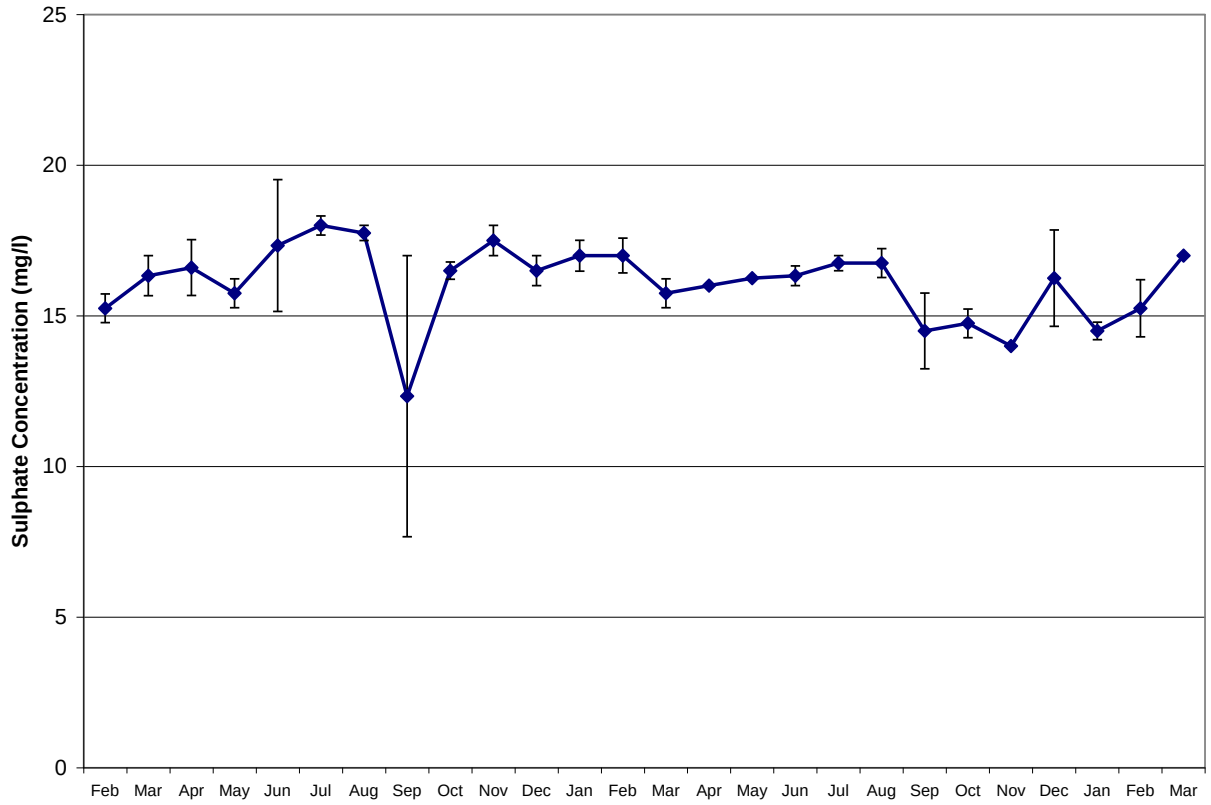


Figure 3.15: The monthly averages of sulphate (mg/ℓ) measured in the raw water for the period February 2008 to March 2010.

The monthly averages of sulphate measured in the raw water stayed between 10 mg/ℓ and 20 mg/ℓ for the study period. The highest measurement of 21 mg/ℓ for sulphate was made on the 08th of December 2009.

3.4.12 Phosphate (PO_4) and Phosphorus (P)

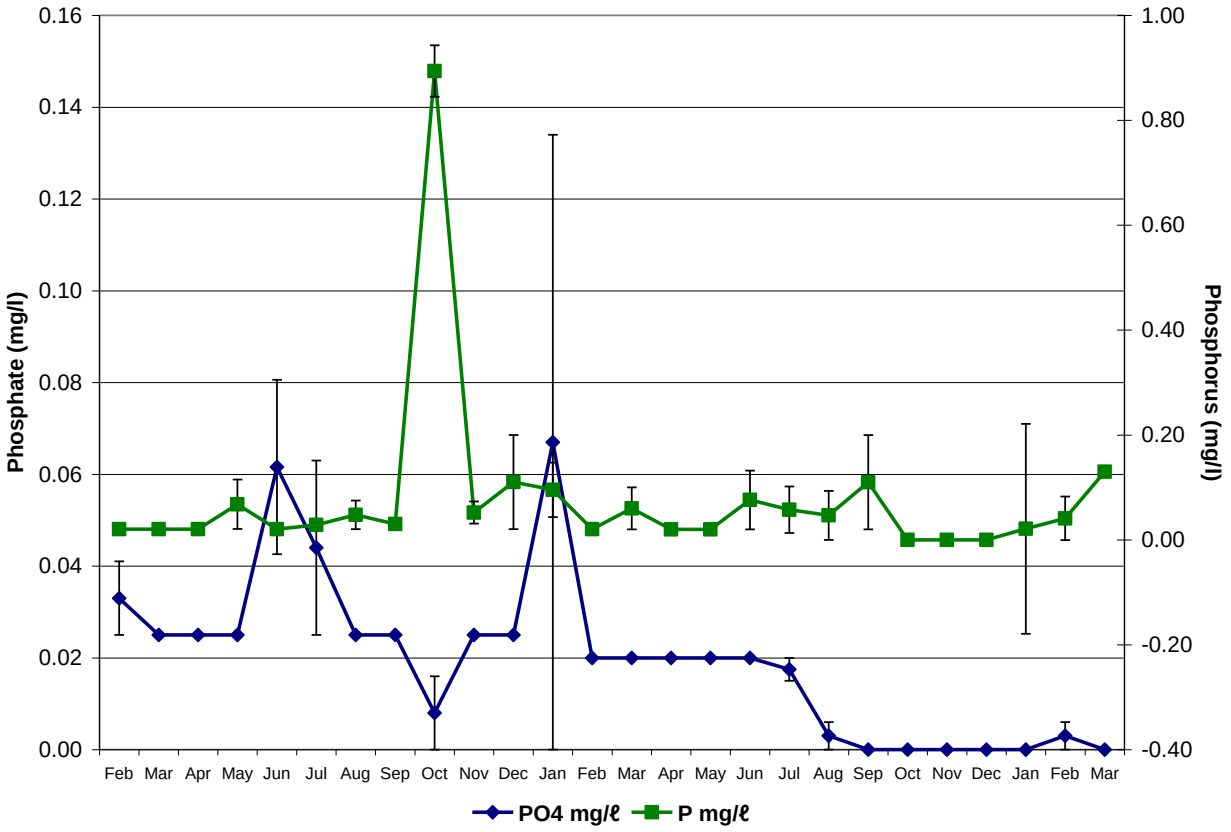


Figure 3.16: The monthly averages of phosphate (mg/ℓ) and phosphorus (mg/ℓ) measured in the raw water for the period February 2008 to March 2010.

The average phosphorus concentrations stayed relatively constant during the study period, while a decrease in average concentrations occurred for phosphate towards the end of the study period. The monthly averages for phosphate and phosphorus were measured <0.08 mg/ℓ for phosphates and <1 mg/ℓ for phosphorus respectively. The highest measurement of 0.2 mg/ℓ for phosphate was made on the 06th of January 2009, with the highest measurement of 0.24 mg/ℓ for phosphorus made on the 07th of October 2008.

3.4.13 Nitrogen: TKN, NH_4, NO_3 and NO_2

Figure 3.17 and 3.16 shows the average concentrations of nitrogen in the raw water for the study period February 2008 to March 2010. Figure 3.17 shows the average concentrations of Total Kjeldahl Nitrogen (TKN) and ammonium (NH_4) in the raw water for the study period February 2008 to March 2010.

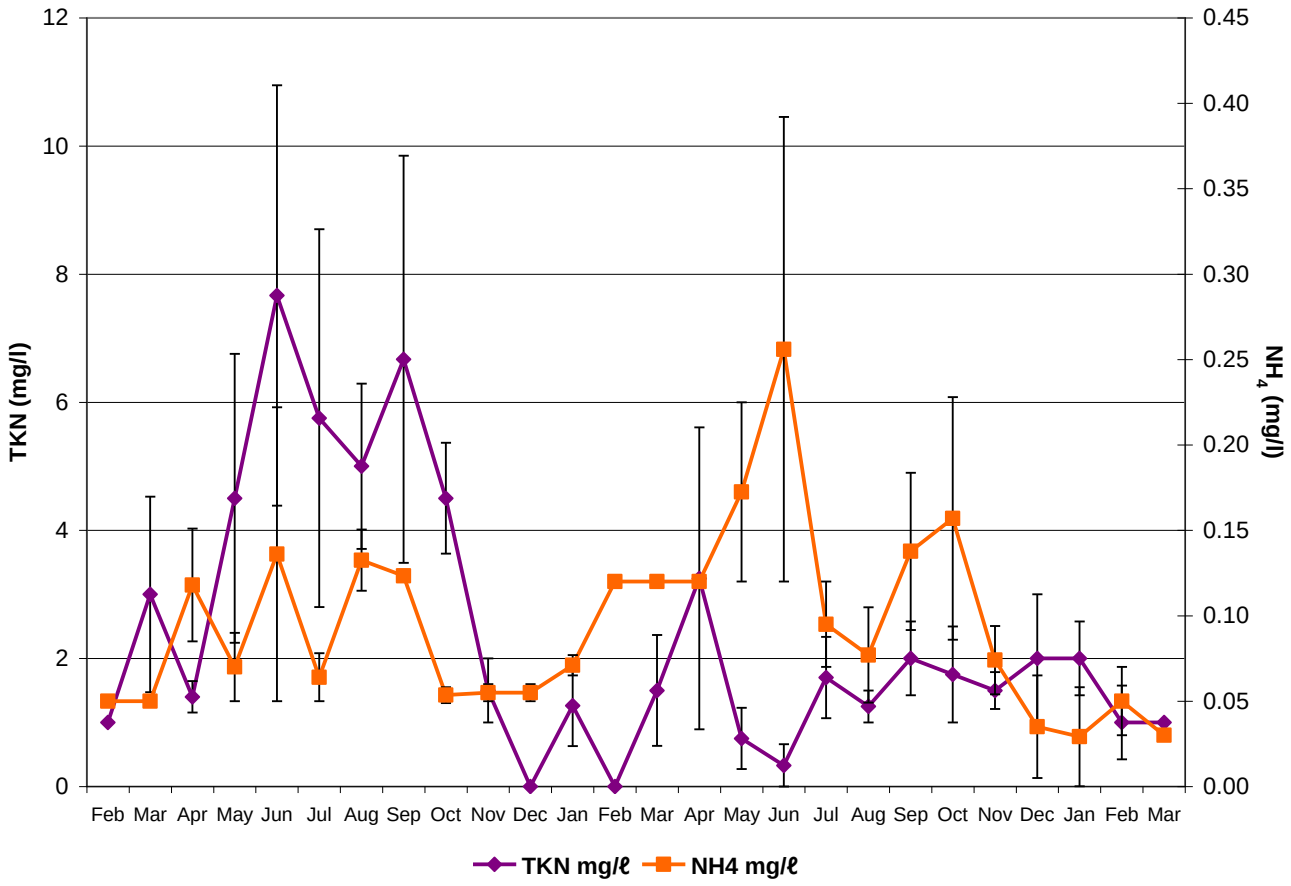


Figure 3.17: The monthly averages of Total Kjeldahl Nitrogen (TKN) and NH_4 (mg/ℓ) measured in the raw water for the period February 2008 to March 2010.

Total Kjeldahl Nitrogen includes organic nitrogen as well as NH_3 and NH_4. TKN was higher in 2008 than the rest of the study period, with the highest measurement of 14 mg/ℓ made on the 17th of June 2008 (Fig. 3.17). It is therefore expected that the TKN measurements should be higher than the NH_4 measurements but that was not the case for a large part of the study period. The average concentration of NH_4 was slightly higher in May and June 2009 with the highest measurement on the 23rd of June 2009 (0.53 mg/ℓ).

The Total Kjeldahl Nitrogen does not include nitrates and nitrites and therefore Figure 3.18 shows the concentrations of nitrate (NO_3) and nitrite (NO_2) in the raw water for the study period February 2008 to March 2010.

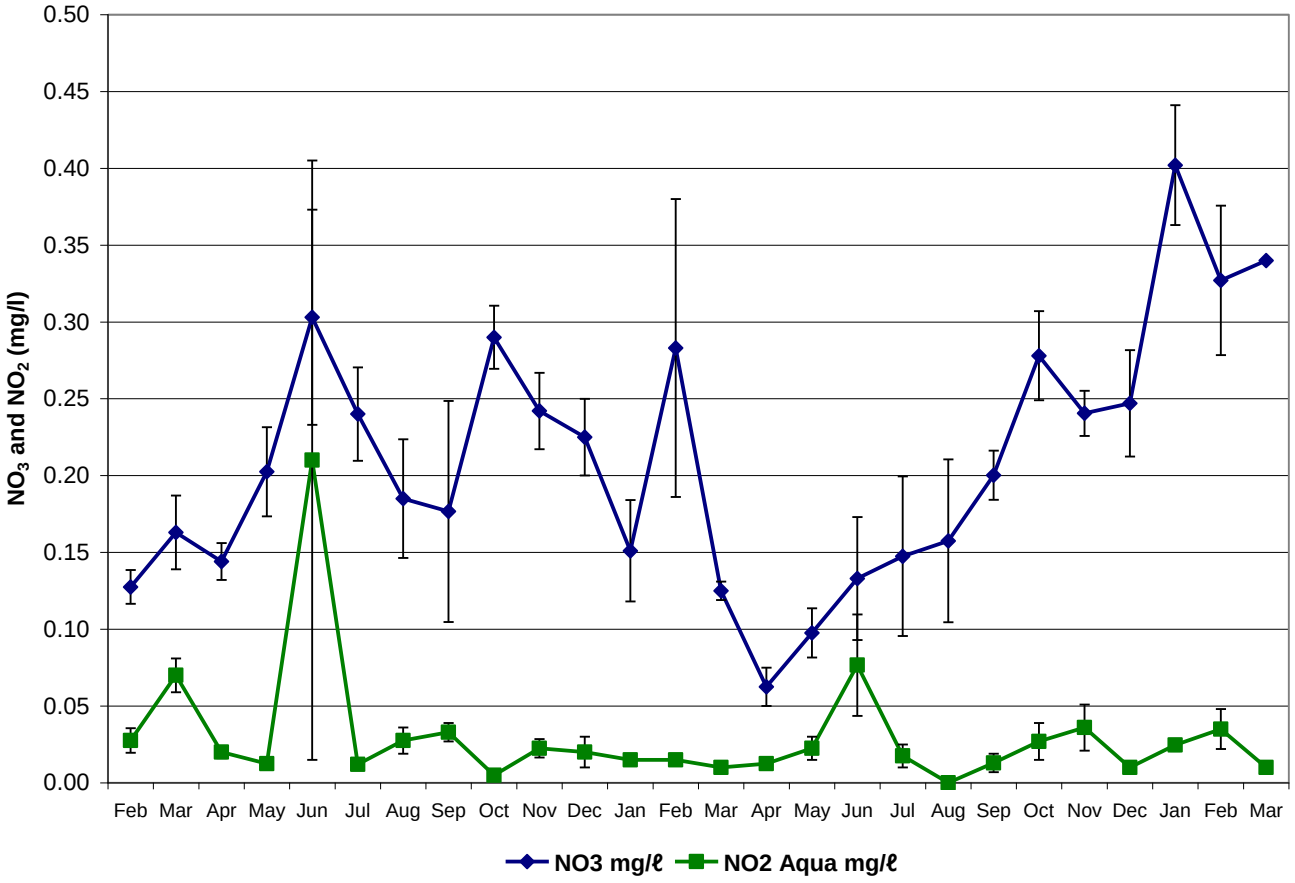


Figure 3.18: The monthly averages of nitrate (NO_3) and nitrite (NO_2) in mg/ℓ measured in the raw water for the period February 2008 to March 2010.

The average NO_3 concentration for the duration of the study period was higher than the NO_2 concentration and an increasing trend can be seem towards the end of the study period. On the 26th of January 2010, the highest measurement of 0.51 mg/ℓ for NO_3 was made, while the highest measurement of 0.6 mg/ℓ for NO_2 was made on the 10th of June 2008.

3.4.14 Chemical Oxygen Demand (COD)

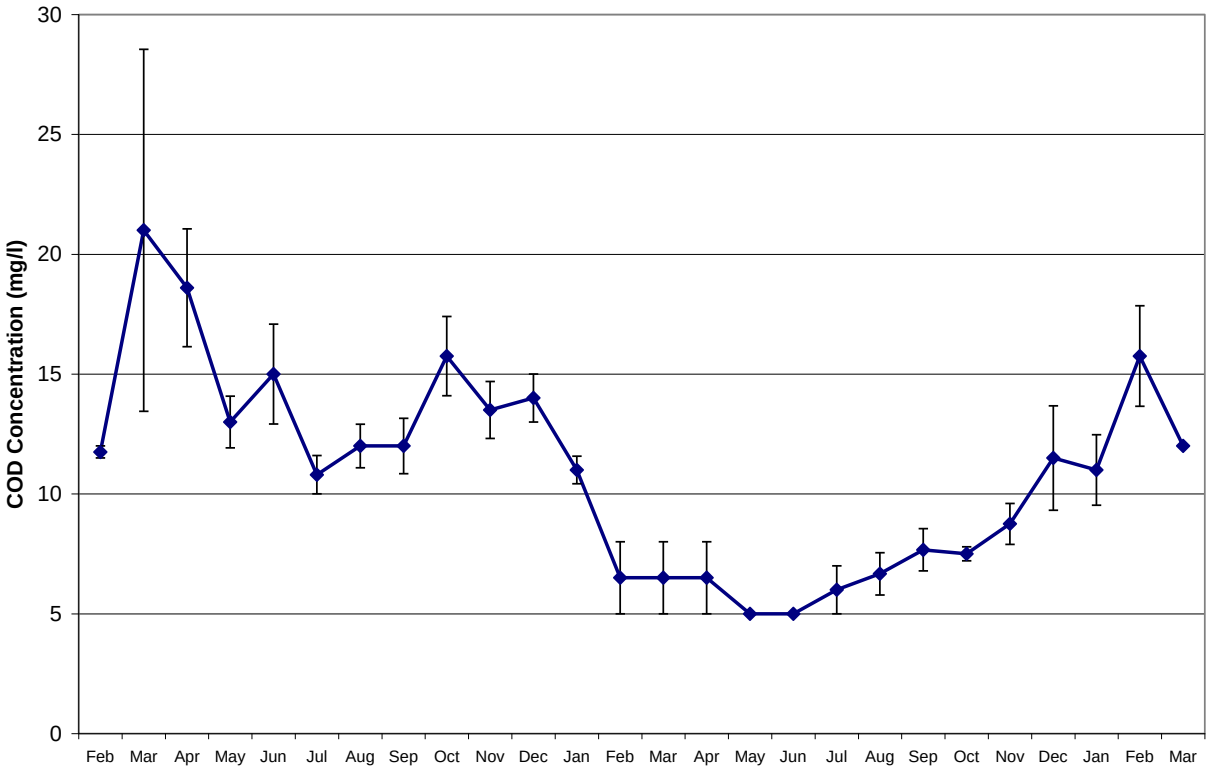


Figure 3.19: The monthly averages of chemical oxygen demand (mg/ℓ) measured in the raw water for the period February 2008 to March 2010.

Chemical oxygen demand was lower in 2009 than in 2008 but recovered in 2010. The highest measurement of 36 mg/ℓ for COD was made on the 18th of March 2008.

3.4.15 Dissolved Organic Carbon (DOC) and Total Organic Carbon (TOC)

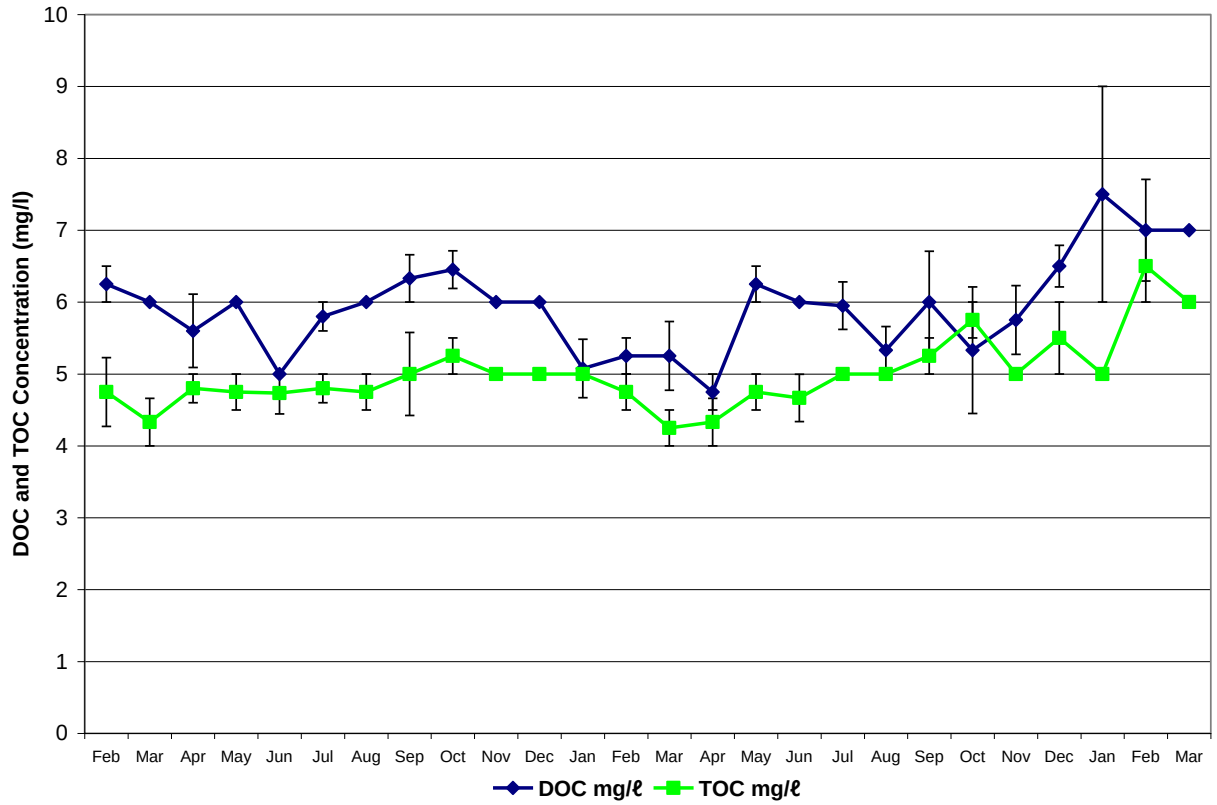


Figure 3.20: The monthly averages of dissolved organic carbon (DOC) and total organic carbon (TOC) measured in mg/ℓ in the raw water for the period February 2008 to March 2010.

The highest DOC concentration (12 mg/ℓ) was measured on the 26th of January and the highest TOC (8 mg/ℓ) was measured on the 09th of February 2010. DOC as well as TOC showed an increasing trend towards the end of study period.

3.4.16 Geosmin and Methylisoborneol (MIB)

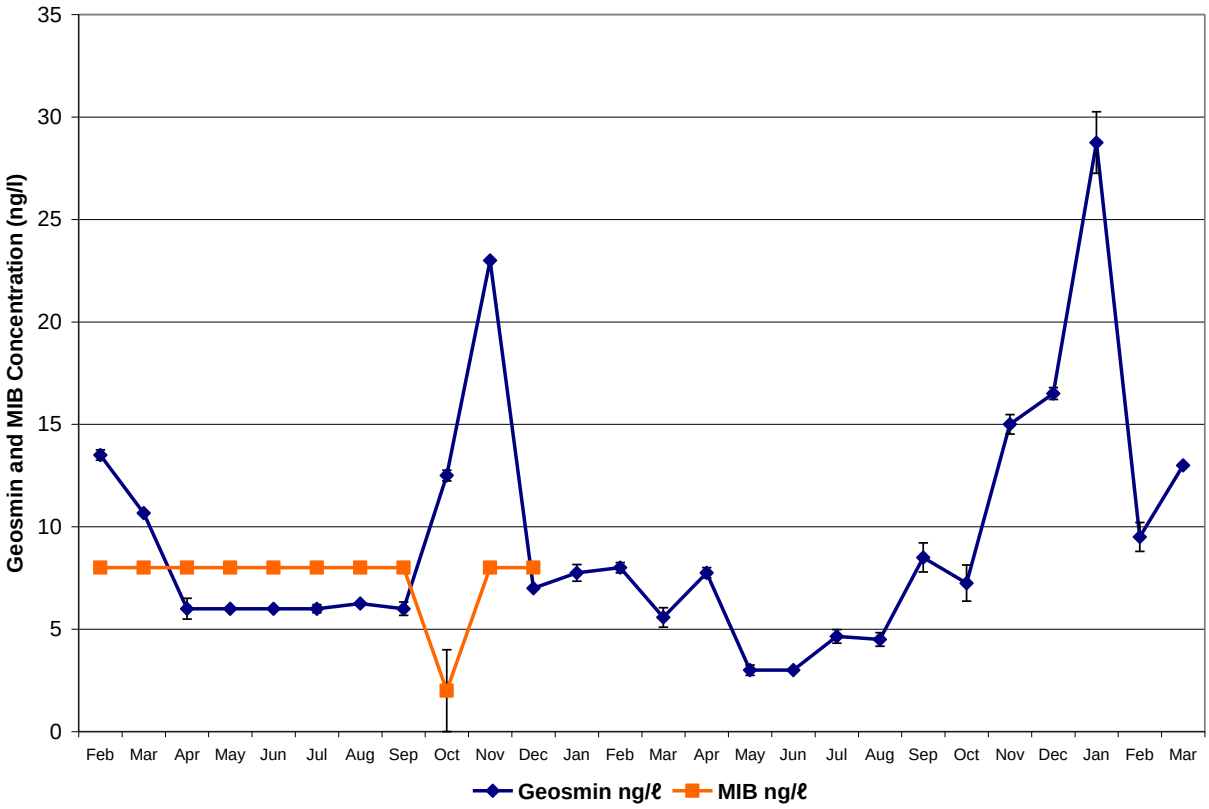


Figure 3.21: The monthly averages of geosmin (ng/ℓ) and methylisoborneol (MIB; ng/ℓ) measured in the raw water for the period February 2008 to March 2010.

Geosmin was high in February and March 2008, in October and November 2008 as well as in October 2009 to January 2010. The highest monthly average for geosmin was measured in January 2010 (>25ng/ ℓ), while the lowest monthly averages were measured in May and June 2009 (2.5 ng/ ℓ). The highest measurement of 93 ng/ℓ was made on the 05th of January 2010. MIB was only measured during 2008 and the monthly averages remained constant at 8 ng/ℓ with lower concentrations in October 2009.

3.4.17 Pigments

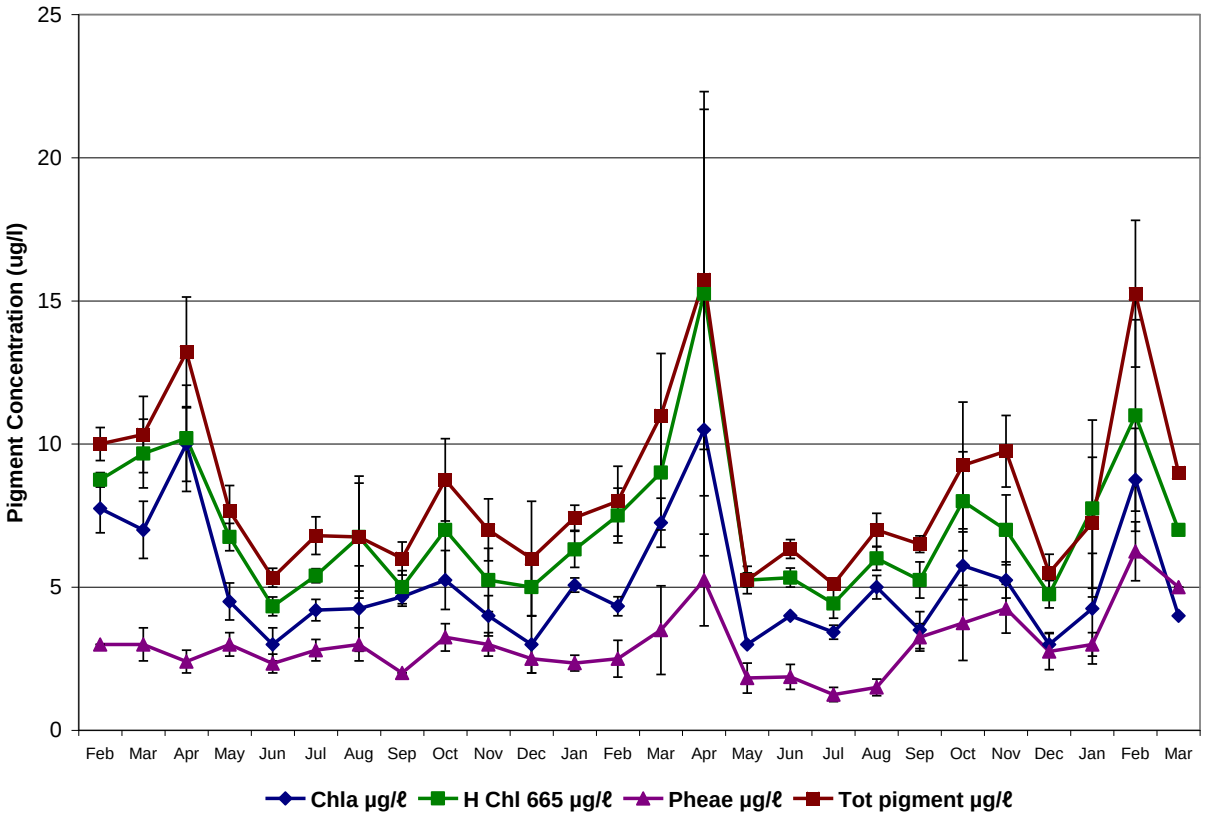


Figure 3.22: The monthly averages of chlorophyll-*a* (Chl-*a*; mg/ℓ), total chlorophyll (H Chl 665; mg/ℓ), phaeophytin (Phaeo; mg/ℓ) and total pigments (Tot pig; mg/ℓ) measured in the raw water for the period February 2008 to March 2010.

The monthly averages for all the pigments (chlorophyll-*a*, total chlorophyll, phaeophytin and total pigments) in the raw water followed more or less the same pattern for the study period. The highest monthly averages for chlorophyll-*a*, total chlorophyll and total pigments were measured in April 2008, April 2009 and February 2010. The highest monthly average for phaeophytin was measured in February 2010. Lower monthly averages for all the pigments were measured in the following months: June 2008, May 2009 until July 2009.

On the 07th of April 2009, the highest measurements of 23 mg/ℓ, 36 mg/ℓ and 33 mg/ℓ were made for chlorophyll-*a*, total chlorophyll and total pigments respectively. The highest measurement of 22 mg/ℓ for phaeophytin was made on the 23rd of February 2010.

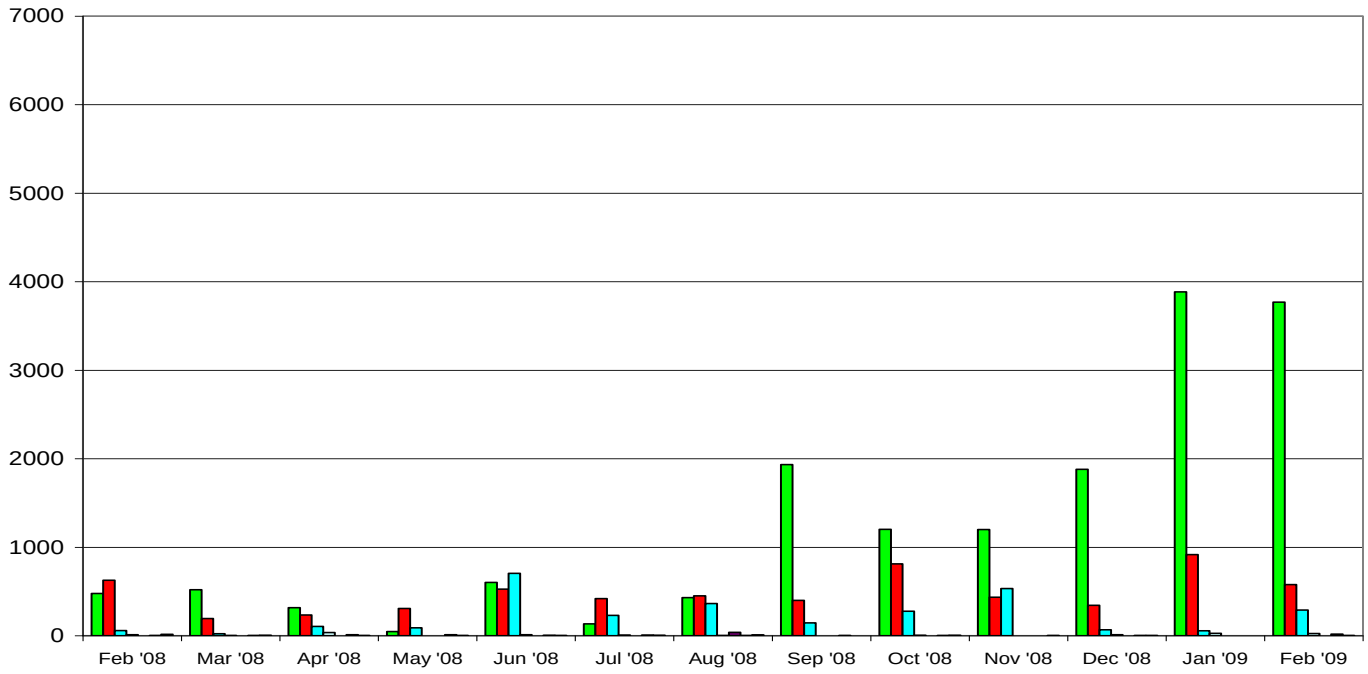
3.4.18 Phytoplankton assemblage

The blue-green bacteria (Cyanophyceae or cyanobacteria) may be in the form of single cells, colonies or filaments. Organisms are mostly blue-green or brown in colour, but very seldom bright green. (Janse van Vuuren *et al*., 2006). *Anabaena* sp., *Microcystis* sp. and *Oscillatoria* sp. were identified and counted in the raw water samples (see Table 3.3).

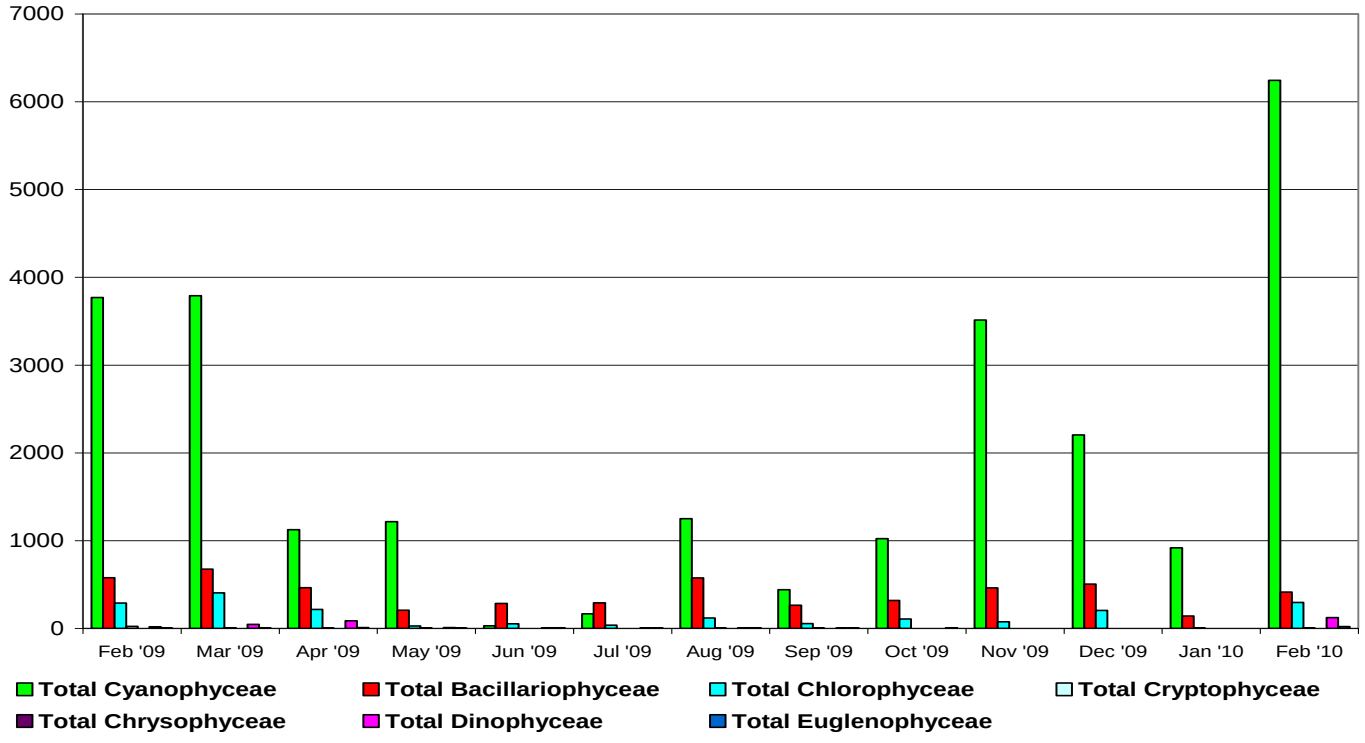
Figure 3.23 clearly shows that the Cyanophyceae was the dominant group during this study period. The occurrence of these organisms showed a seasonal variation with low counts during the colder months and an increasing concentration during the warmer months. The highest counts were made on the 17 November 2009 and 23 February 2010 (11321 and 9867 cells/ mℓ respectively) and the lowest counts on the 2 June 2009 (4 cells/ mℓ).

The Bacillariophyceae (diatoms) is mostly unicellular organisms but adjacent cells may be attached to each other to form chains or colonies (Janse van Vuuren *et al*., 2006). Eleven diatom genera were identified and counted in the raw water samples (see Table 3.3). The highest number of diatom cells per mℓ were counted during October 2008 to April 2009 with the highest counts made on 5 February 2008 (1490 cells/ mℓ) and the lowest on 23 February 2010 (25 cells/mℓ). This group was present for the duration of the study period (Figure 3.23), but no definite seasonal trend can be seen.

Chlorophyceae (green algae), cells may occur singly or in the form of colonies or filaments (Janse van Vuuren *et al*., 2006). Fifteen green algal genera were identified and counted in the raw water samples (see Table 3.3). The highest Chlorophyceae cells/ mℓ were counted during May 2008 to September 2008. The highest count was made on 25 November 2008, while the lowest count was made on 17 May 2009 (Figure 3.23).



(a)



(b)

Figure 3.23: The monthly average algal concentration in the raw water for the seven major algal groups during February 2008 to February 2009 (a) and February 2009 to February 2010 (b).

Organisms belonging to the Cryptophyceae (cryptomonads) are always unicellular. Cells may vary in colour from red, blue-green, olive-green to olive-brown (Janse van Vuuren *et al*., 2006). Only *Cryptomonas* sp. occurred in the raw water samples during this study period (see Table 3.3). The monthly averages for the Cryptophyceae were at ± 10 cells/ mℓ or < 10 cells/mℓ for the entire study period. In April 2008, January 2009 and February 2009 the monthly averages were > 20 cells/ mℓ. The highest number of cells/ mℓ were counted on 1 April 2008 (Figure 3.23).

In the Chrysophyceae (golden- brown algae) the organisms are mostly single cells or colonies that are yellow or golden-brown in colour (Janse van Vuuren *et al*., 2006). *Dinobryon* sp., *Mallomonas* and *Synura* sp. were identified and counted in the raw water samples (see Table 3.3). The cell counts for this group were very low during the entire study period (± 1 cell/ mℓ per month). However on 5 August 2008 155 *Synura* sp cells/mℓ were counted (Figure 3.23).

Euglenophyceae (euglenoids) cells are single and mostly bright green in colour, sometimes with a bright red eyespot (Janse van Vuuren *et al*., 2006). *Euglena* sp., *Phacus* sp., *Strombomonas* sp. and *Trachelomonas* sp. were identified and counted in the raw water samples (see Table 3.3). No seasonal trend can be seen in the graph (Figure 3.23).

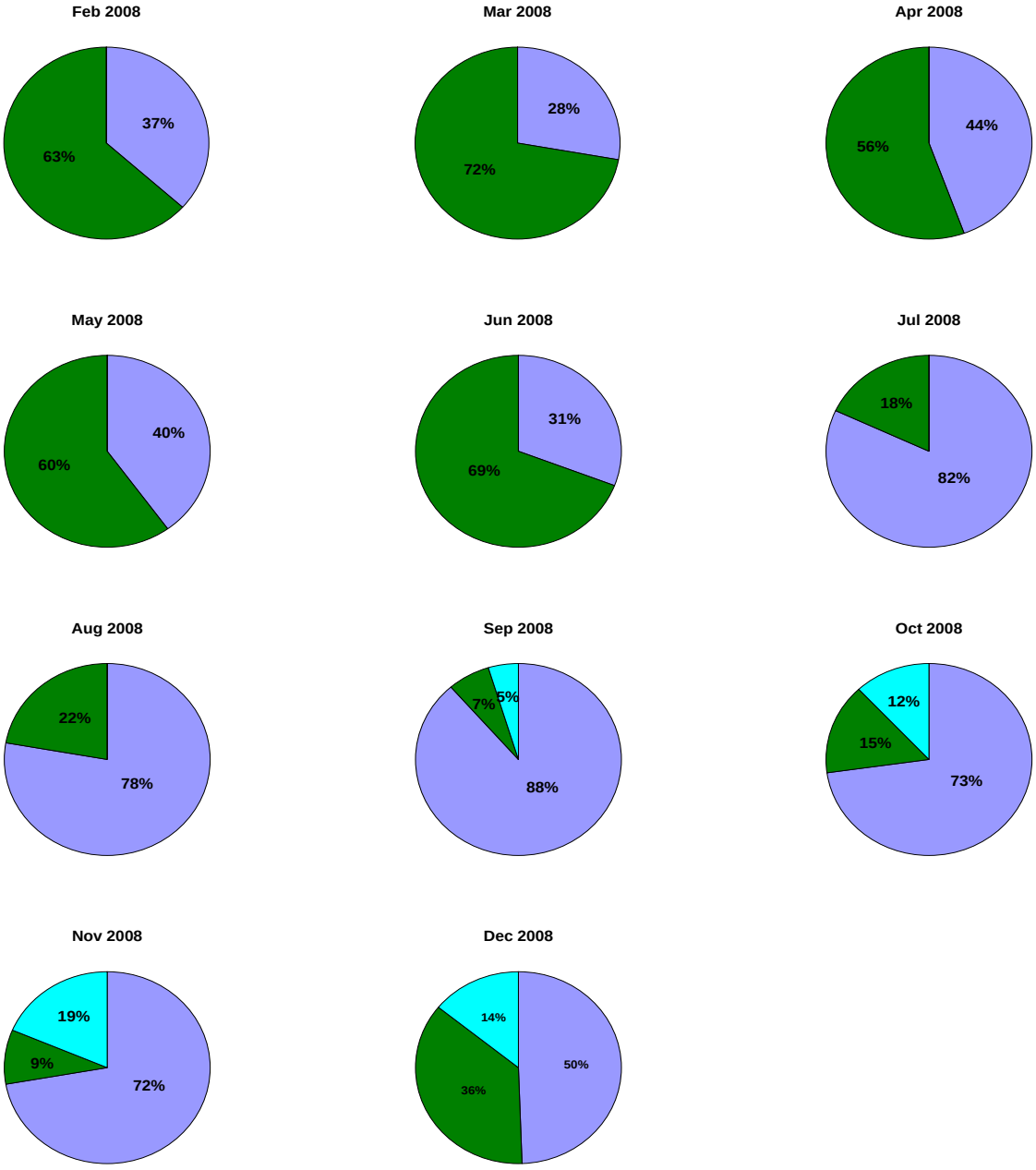
In the Dinophyceae (dinoflagellates) the organisms are usually brown to yellow-brown in colour (Janse van Vuuren *et al*., 2006). *Ceratium* sp. and *Peridinium* sp. were identified and counted in the raw water samples (see Table 3.3). The cell counts for this group was low for the most of the study period except from February until April 2009 and February 2010 when higher cell counts were made. *Ceratium* sp. was counted most of the time in this group with maxima of 286 cells/mℓ counted on 7 April 2009 and 203 cell/ mℓ on 23 February 2010 (Figure 3.23).

Table 3.3: Algal genera that were identified in the raw water during the study period (February 2008 – March 2010).

BACILLARIOPHYCEAE	*Staurastrum* sp.
Aulacoseira sp.	*Tetraedron* sp.
Asterionella sp.	*Tetrastrum* sp.
Cyclotella sp.	***CHRYSOPHYCEAE***
Cymbella sp.	*Dinobryon* sp.
Fragilaria sp.	*Mallomonas* sp.
Gomphonema sp.	*Synura* sp.
Gyrosigma sp.	***CRYPTOPHYCEAE***
Melosira sp.	*Cryptomonas* sp.
Navicula sp.	***CYANOPHYCEAE***
Nitzschia sp.	*Anabaena* sp.
Stephanodiscus sp.	*Microcystis* sp.
CHLOROPHYCEAE	*Oscillatoria* sp.
Actinastrum sp.	***DINOPHYCEAE***
Ankistrodesmus sp.	*Ceratium* sp.
Carteria sp.	*Peridinium* sp.
Chlamydomonas sp.	***EUGLENOPHYCEAE***
Closterium sp.	*Euglena* sp.
Cosmarium sp.	*Phacus* sp.
Coelastrum sp.	*Strombomonas* sp.
Dictyosphaerium sp.	*Trachelomonas* sp.
Monoraphidium sp.	
Oocystis sp.	
Pediastrum sp.	
Scenedesmus sp.	

3.4.19 Percentage composition of the Cyanophyceae genera

Figures 3.24 show the percentage occurrence of *Anabaena*, *Microcystis* and *Oscillatoria* species in the raw water for the study period February 2008 to March 2010.



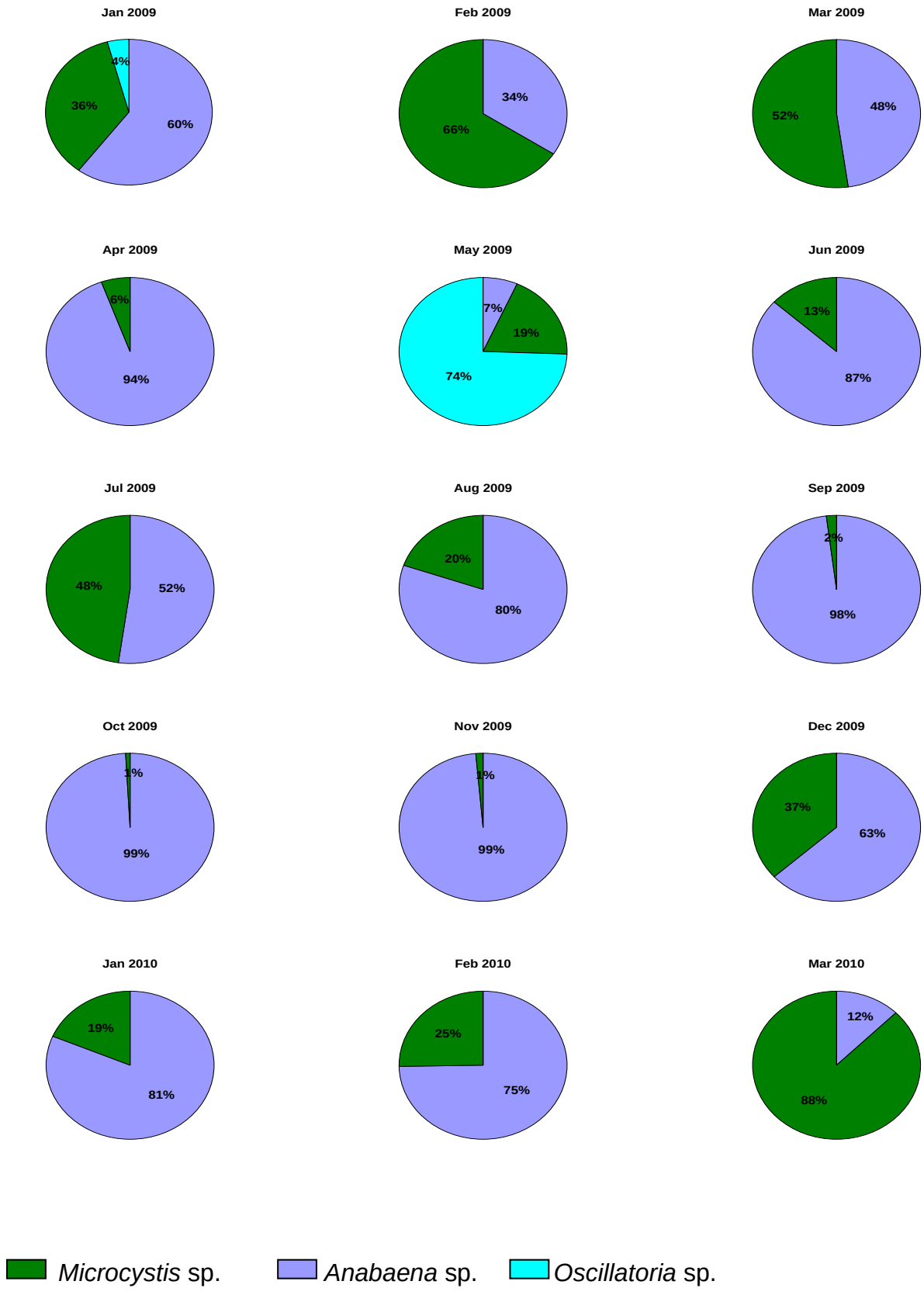


Figure 3.24: The monthly percentage composition of *Microcystis* sp., *Anabaena* sp. and *Oscillatoria* sp. in the raw water samples (February 2008 to March 2010).

It is clear that *Anabaena* sp. was the dominant Cyanophyceae species during the study period (Figure 3.24). *Microcystis* sp. dominated from February 2008 to June 2008 and from February 2009 to March 2009 as well as during March 2010. *Oscillatoria* sp. Only dominated during May 2009. *Anabaena* sp. and *Microcystis* sp. were present during the entire study period while *Oscillatoria* sp. were only present from September 2008 until January 2009 and in May 2009 (as the dominant genera).

Microcystis sp. was the dominant algal genera amongst the cyanobacteria during summer months while the *Anabaena* sp. shows dominance during winter months. *Oscillatoria* sp. only occurred from September 2008 until January 2009 (Figure 3.24).

3.4.20 Principle component analysis

The results of the principle component analysis are presented in Tables 3.4 and 3.5. The first component (component 1, Tables 3.4 and 3.5) was associated with algae, pigments and geosmin and explained 10.78% of the variance in data. Total chlorophyll, chlorophyll-*a*, phaeophytin, *Ceratium* sp., *Anabaena* sp. and geosmin correlated positively with component 1 (Table 3.5).

The second component (component 2, Tables 3.4 and 3.5) was associated with hardness, conductivity and major ions and explained 8.99% of the variance in data (Table 3.4). Hardness, calcium, magnesium, potassium and conductivity correlated positively with component 2 (Table 3.5).

The third component (component 3, Tables 3.4 and 3.5) was associated with nitrogen and geosmin and explained 6.48% of the variance in the data (Table 3.4). Ammonium and nitrite were negatively correlated while nitrate, DOC and geosmin were positively correlated with component 3 (Table 3.5).

The fourth component (component 4, Tables 3.4 and 3.5) was only associated with ions and explained 5.8% of the variance in the data (Table 3.4). Sodium, cadmium and phosphorus were positively correlated with component 4 (Table 3.5)

Table 3.4: PCA results of the raw water variables explained by 14 components. The initial eigenvalues, extraction and rotation sums of squared loadings and rotation sums of squared loadings give the total, percentage variance and cumulative percentage of the 14 extracted components. Eigenvalues are greater than 0.3 and thus considered to explain a large percent of the variance for that specific component (Kent and Coker, 1992).

Total Variance Explained									
	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.664	10.776	10.776	3.664	10.776	10.776	3.535	10.397	10.397
2	3.055	8.985	19.761	3.055	8.985	19.761	2.832	8.329	18.726
3	2.204	6.481	26.243	2.204	6.481	26.243	1.921	5.649	24.375
4	1.982	5.828	32.071	1.982	5.828	32.071	1.807	5.315	29.691
5	1.831	5.385	37.456	1.831	5.385	37.456	1.640	4.824	34.515
6	1.782	5.241	42.697	1.782	5.241	42.697	1.624	4.776	39.291
7	1.612	4.742	47.439	1.612	4.742	47.439	1.606	4.722	44.013
8	1.438	4.230	51.669	1.438	4.230	51.669	1.555	4.573	48.586
9	1.396	4.106	55.775	1.396	4.106	55.775	1.523	4.480	53.066
10	1.332	3.918	59.693	1.332	3.918	59.693	1.518	4.464	57.529
11	1.246	3.665	63.358	1.246	3.665	63.358	1.503	4.421	61.951
12	1.196	3.516	66.874	1.196	3.516	66.874	1.447	4.255	66.206
13	1.077	3.167	70.042	1.077	3.167	70.042	1.206	3.547	69.753
14	1.021	3.003	73.045	1.021	3.003	73.045	1.119	3.292	73.045

Table 3.5: PCA results are showing the 14 components and correlation between the algae and environmental variables. This table gives the results of fourteen PCA's performed on the set of 34 determinants (algae and environmental variables).

Rotated Component Matrix[a]														
	Component													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Total Chlorophyll	.929													
Chlorophyll-*a*	.901													
Ceratium sp.	.869													
Phaeo	.764													
Anabaena sp.	.466													
Hardness		.913												
Calcium		.859												
Magnesium		.798												
Ammonium (NH4)			-.787											
Nitrite (NO2)			-.629											
Nitrate (NO3)			.575				.313	.302						
Sodium				.817										
Cadmium				.772										
Phosphorus				.479							.467	.359		
TKN					.838									
Sulphur					.647									
M-alkalinity					.440									
Total Organic Carbon						.816								
Dissolved Organic Carbon			.423			.500								
Chloride							.806							
Suspended Solids								.862						
Microcystis sp.									.807					
Chemical Oxygen Demand						-.392		.346	.528					
Potassium		.304				.322			.490					
Temperature										.856				

Sulphate							.447			-.492				
Silica											.781			
Turbidity								.329		.319	-.493	.386		
Phosphate (PO4)											-.346	-.332		
pH												.816		
Oscillatoria sp.													.768	
Conductivity		.358						.379				.305	.453	
Geosmin	.306		.327										-.360	
Total Dissolved Solids														.903

Component five (component 5, Tables 3.4 and 3.5) was associated with total nitrogen, sulphur and alkalinity and explained 5.4% of the variance in the data.

Component six (component 6, Tables 3.4 and 3.5) was associated with carbon, potassium and COD and explained 5.2% of the variance in the data (Table 3.4). Total organic carbon, dissolved organic carbon, potassium were positively correlated with component 6, but COD was negatively correlated with component 6.

The seventh component (component 7, Tables 3.4 and 3.5) was associated with sulphate, chloride and nitrate and explained 4.7% of the variance in the data.

Component eight (component 8, Tables 3.4 and 3.5) was associated with nitrate, suspended solids, COD, turbidity and conductivity and explained 4.2% of the variance in the data.

Component nine (component 9, Tables 3.4 and 3.5) was associated with *Microcystis* sp., COD and potassium and explained 4.1% of the variance in the data.

The tenth component (component 10, Tables 3.4 and 3.5) was associated with temperature, sulphate and turbidity and explained 3.9% of the variance in the data (Table 3.4). Temperature and turbidity were positively correlated with component 10, while sulphate was negatively correlated with component 10.

Component eleven (component 11, Tables 3.4 and 3.5) was associated with silica, turbidity, phosphate and phosphorus and explained 3.7% of the variance in the data (Table 3.4). Silica and phosphorus were positively correlated with component 11, while phosphate and turbidity were negatively correlated with component 11.

The twelfth component (component 12, Tables 3.4 and 3.5) was associated with turbidity, phosphate, phosphorus, pH and conductivity and explained 3.2% of the variance in the data (Table 3.4). Turbidity, phosphorus and conductivity were positively correlated with component 12, but phosphate has shown a negative correlation with component 12.

The thirteenth component (component 13, Tables 3.4 and 3.5) was associated with *Oscillatoria* sp., conductivity and geosmin and explained 3.1% of the variance in the data (Table 3.4). *Oscillatoria* sp. and conductivity were positively correlated with component 13, but geosmin has shown a negative correlation with component 13.

TDS was the only variable that correlated with component 14 and explained 3% of the variance in the data (Tables 3.5).

3.5 DISCUSSION

3.5.1 Environmental variables

The Zuikerbosch Rand Water treatment plant abstracts water from the Vaal River and the quality of the water is of utmost importance to determine the purification methods necessary to obtain potable water of a high standard.

As expected, the temperature of the raw water showed seasonal variation with lower temperatures in the winter and higher temperatures in the summer (Figure 3.4). The highest rainfalls for Vereeniging area and flow rate of the Vaal Dam were measured during January 2010, when lower water temperature was measured (Figures 3.4 and 3.6). Temperature exerts a strong influence on many physical and chemical characteristics of water, including the solubility of silica oxygen and other gasses, chemical reaction rates and toxicity, and microbial activities (Dallas and Day, 2004).

Higher temperatures reduce the solubility of dissolved oxygen in water, decreasing its concentration and thus its availability to aquatic organisms (Dallas, 2008). All organisms have a range of temperatures at which optimal growth (adult size), reproduction and general fitness occur. This is often termed the 'optimum thermal regime' (Vannote and Sweeney, 1980). Temperature outside of the 'optimum thermal regime' of aquatic organisms may affect the metabolism, growth, behaviour, food and feeding habits, reproduction and life histories, geographical distribution and community structure, movements and migrations, and tolerance to parasites, disease and pollution (Dallas, 2008).

Alkalinity of water is a measure of its acid-neutralising capacity and plays an important role in buffering water to prevent changes in pH. Alkalinity is determined by the concentration of carbonate, bicarbonate and hydroxide by the pH (Schutte, 2006). The average alkalinity of the raw water for 2008 was 75.76 mg/ℓ and 72.17 mg/ℓ for 2009 (Figure 3.8). According to DWAF (1996a) alkalinity between 50-120 mg/ℓ can cause moderate damage to equipment and processes.

This study found that the monthly averages for both concentrations of suspended solid and turbidity of the raw water showed seasonal variation with lower monthly averages measured during autumn (March to May) and winter (June to August) periods of each year (2008 and 2009), with an increase in both variables from September (beginning of spring months) to February (end of summer months) of each year (Figure 3.9). The average turbidity of the raw water was 41.95 NTU for 2008 and 46.24 NTU for 2009 much lower than the 57-294 NTU Janse van Vuuren (2001) measured in the Vaal River.

The main water quality problems for domestic use throughout the country relate to widespread elevated salt levels. The elevated salt levels (expressed by TDS concentrations) also decrease the aesthetic value of water (DWAF, 2002). The total amount of substances dissolved in water is commonly measured in one of two ways: as total dissolved salts (TDS) or as conductivity. TDS refers to the summation of the concentration of individual ions. The most common dissolved substances are usually the cations Na^{+}, $K^{+,}$ Ca^{2+}, and Mg^{2+} and the anions HCO_3^{-} (bicarbonate), carbonates (CO_3^{2-}), Cl^{-} and SO_4^{2-} (Janse van Vuuren, 2001).

TDS measured in the raw water ranged between 100 and 250 mg/ℓ (Figure 3.10), while the conductivity ranged between 15 and 25 mS/m (Figure 3.10). During the autumn and winter months TDS of the raw water were low (below 150 mg/ℓ), but during spring and summer it was generally higher (above 150 mg/ℓ). TDS and conductivity usually correlate closely in most water (DWAF, 1996) but towards the end of the study period TDS show and increasing trend, whilst conductivity decreases. The increase in conductivity was unexpected because of the high rainfall measure during the 2009-2010 seasons (Figure 3.6). According to Morrison (2009) the conductivity of the raw water in the Vaal River decreased during the warmer summer months when the rainfall was high with diluted dissolved substances and an increase during the colder months when there was little or no rainfall which caused the dissolved substances to concentrate in the river. The conductivity measured for the raw water (Figure 3.10) did not show any seasonal variation but the high rainfall of the 2009-2010 seasons (Figure 3.6) might explain the observed decrease in conductivity.

According to DWAF (1996) the TDS concentration should not change by more than 15 % from the normal cycles of the water body under unimpacted conditions at any time of the year. The TDS of the raw water stayed fairly constant expect for a spike in April 2008 (530 mg/ℓ) and in August 2008 (370 mg/ℓ). However, it shows an increasing trend towards the end of the study period that might be of some concern as it occurred during a period of high rainfall.

Toxic metals in the raw water included cadmium and lead (Figure 3.11). The main source of metals in water bodies are geological weathering, the atmosphere, industrial effluents, agricultural runoff and acid mine drainage (Dallas and Day, 2004). Metals in the water can be potentially hazardous and usually exert their biological effect by forming stable co-ordinate bonds in proteins where they function as catalysts in redox reactions or where they form part of the active centre of enzymes (Dallas and Day, 2004). The uptake of lead is dependent on the action of calcium; therefore, hardness is an important factor determining the toxicity of lead in aquatic systems (DWAF, 1996a). The target water quality range (TWQR) criteria for lead in water with a hardness between 60 and 80 mg/ℓ (Figure 3.13) is 0.5 µg/ℓ that is

much lower than the average of 4 µg/ℓ measured for the raw water in 2008 or the average of 2.24 µg/ℓ measured for 2009.

The toxicity of cadmium in water is also dependent upon its hardness and chemical speciation, which is influenced by pH, water temperature and coexisting metal cations present in the water (DWAF, 1996a). Fortunately cadmium has a low solubility in alkaline water, such as the raw water (Figure 3.7). Bio-accumulation of cadmium generally increases with increasing water temperature and decreasing pH (DWAF, 1996a). The TWQR criteria for cadmium in water with a hardness between 60 and 80 mg/ℓ (Figure 3.13) is 0.25 µg/ℓ that is lower than the 0.5 µg/ℓ monthly average measured for the raw water. The average cadmium concentration for 2008 was 2.54 µg/ℓ and 0.57 µg/ℓ for 2009. Cadmium is easily absorbed by mammals and can influence metabolism.

The term “hardness” is frequently used as an assessment of the quality of water supplies. The hardness of water is governed by the content of calcium and magnesium salts, largely combined with bicarbonate and carbonate (temporary hardness) and with sulphates, chlorides and other anions of mineral acids (permanent hardness; Wetzel, 2001). The hardness of water is determined by the concentration of divalent cations in the water, mostly calcium and magnesium and is expressed in mg/ℓ CaCO3. Hardness affects the lather-forming ability of water with soap. Different forms of hardness can be distinguished all expressed as mg/ℓ $CaCO_3$ (Schutte, 2006). The hardness of the raw water of Vaal River, for the period February 2008 to March 2010, was measured between the range of 60 and 80 mg/ℓ $CaCO_3$. According to the hardness classification of Schutte (2006) the water of the Vaal River was reasonably soft during 2000-2001 (Kruskopf, 2002) as well as during the 2008-2010 periods (Figure 3.13; see Table 3.6).

Table 3.6: Hardness Classification (Schutte, 2006).

Hardness classification	**Total hardness as mg/ℓ $CaCO_3$**
Soft	Less than 50
Reasonably soft	50 to 100
Slightly hard	100 to 150
Reasonably hard	150 to 250
Hard	250 to 350
Very hard	More than 350

However, at a constant pH the solubility of lead decreases with increasing alkalinity. The pH of the raw water remained fairly constant (Figure 3.7) but the methyl-orange alkalinity showed a decrease towards the end of the study period (Figure 3.8). Therefore the lead concentration in the raw water can be a potential problem and should be addressed in the purification process. Lead tends to accumulate in living tissue and in vertebrates to become immobilized in bone (Dallas and Day, 2004).

Magnesium, potassium, calcium and sodium (Figure 3.12) are non-critical according to the classification of metals regarding toxicity and availability (Förstner and Whittmann, 1981). The relative proportion of the different major ions in water seems not to be of great significance since aquatic animals are likely to have evolved in situations requiring efficient ion regulation (Beadle, 1981).

The natural origins of chloride in inland water are attributable to leaching of salts from underlying rock strata. Other contributions come from irrigation return flow, sewage effluent discharges and various industrial processes (DWAF, 1996a). Chloride contributes to the concentration of TDS as well as salinity of the water, however chloride is not considered as a problem in inland waters (DWAF, 1996a). According to Janse van Vuuren (2001) the chloride concentration in the Barrage was

29.4 mg/ℓ compared to the average chloride concentration of the raw water for 2008 and 2009 of just above 7 mg/ℓ.

Availability of silica can have a strong influence on the overall pattern of algal succession and productivity in lakes and streams (Wetzel, 2001) and can be a problem in water used for industrial purposes as it can cause damage to equipment (DWAF, 1996a). According to DWAF (1996a) 5-10 mg/ℓ silica do not interfere with industrial processes. The average silica concentration (Figure 3.14) in the raw water for 2008 was 5.9 mg/ℓ with an increase in 2009 to 7.9 mg/ℓ.

Sulphate is a common constituent of water and results from the dissolution of mineral sulphates in soil and rock. The average concentration of sulphate for 2008 was 16.46 mg/ℓ and for 2009 15.89 mg/ℓ (Figure 3.15). At these concentrations sulphates do not damage equipment or interfere with processes (DWAF, 1996a).

Phosphorus (P) occurs as orthophosphate, polyphosphate and organic phosphate which can be dissolved or bound to particulate material. Orthophosphate is generally considered to be the most immediately available form of P (Walmsley, 2000). It is an essential macronutrient and is accumulated by a variety of living organisms (DWAF, 1996a). The flow regime is a major factor in the mobility, availability and spatial distribution of phosphorus within a river. Settlement of particulate matter and biotic uptake result in the removal of phosphorus from the water column to the sediments. During rainfall events phosphorus levels may be elevated by runoff from the land and by re-suspension of sediments (DWAF, 1996b). No real correlation could be seen between rainfall (Figure 3.6) and the phosphorus or phosphate content of the raw water (Figure 3.16), except for a slight increase in the phosphorus concentration at the end of the study period. Both the phosphate and ortho-phosphate concentrations in the raw water were high for the study period and eutrophication problems can be expected.

According to Wetzel (2001) nitrogen occurs in fresh water in numerous forms: dissolved molecular N_2; a large number of organic compounds from amino acids, amines, to proteins and recalcitrant humic compounds of low nitrogen content, ammonia (NH_4), nitrite (NO_2), and nitrate (NO_3). Combined nitrogen occurs as ammonia (NH_4), hydroxylamine (NH_2OH), nitrite (NO_2), nitrate (NO_3), and dissolved

and particulate organic nitrogen. NH_4-N can range from 0 to 5 mg/ℓ in unpolluted surface water, although concentrations are usually low, to well above 10 mg/ℓ in anaerobic hypolimnetic waters of eutrophic lakes (Wetzel, 2001). NO_2-N levels of natural waters are generally very low, in the range of 0-0.01 mg/ℓ. Concentrations of NO_3-N range from undetectable levels to nearly 10 mg/ℓ. According to Wetzel's classification the raw water during this study was unpolluted as NH_4 concentration varies from 0 – 0.3 mg/ℓ, NO_2 varies from 0 – 0. 25 mg/ℓ and NO_3 vary from 0.05 – 0.45 mg/ℓ. The TKN was a bit higher and varies from 0 – 8 mg/ℓ (Figures 3.15 and 3.16). High nitrate concentrations (>20 mg/ℓ) can cause problems in infants and adults (DWAF, 1996).

Chemical oxygen demand (COD) measures the oxygen equivalent of the oxidisable matter in a sample following oxidation with a strong chemical oxidant (DWAF, 1996a). The COD of the raw water was lower in 2009 (average of 7.28 mg) than in 2008 (average 14.22 mg/ℓ; Figure 3.19). According to the TWQR of DWAF (1996), a range of 0-10 mg/ℓ has no effect on industrial processes, but a range of 10-30 mg/ℓ can cause moderate damage to equipment and can interfere with industrial processes. As the COD of the raw water showed an increase in 2010, it can be a potential problem for the purification plant and processes.

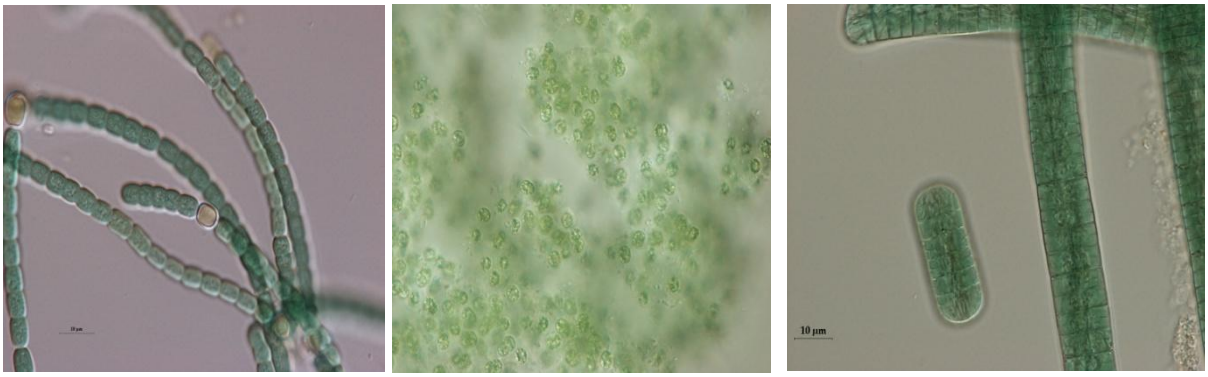
Nearly all of the organic carbon of natural waters consists of dissolved organic carbon (DOC) and dead particulate organic carbon (POC). The distribution of DOC within lakes and streams is relatively constant, with changes in season and in depth (Wetzel, 2001). Morrison (2009) found the following measurements for TOC and DOC in the Vaal River during the period October 2007 to September 2008: DOC and TOC minimum and maximum respectively 4.9 and 7.7 mg/ℓ; 4.8 and 13 mg/ℓ. In this study the minimum and maximum concentrations for DOC was 4 and 12 mg/ℓ and for TOC 4 and 8 mg/ℓ respectively (Figure 3.20).

The pigments have shown a definite seasonal variation in this study (Figure 3.22). The pigment concentrations were the highest during the autumn months of each year. And lower during the winter months (July to August) of each year. During the summer months (December to February) it increased. The increased monthly average measured in February 2010 could be due to an algal bloom in the raw water. The mean chlorophyll-*a* concentration of the raw water was 5.46 µg/ℓ for 2008

and 5.11 µg/ℓ for 2009, much lower than the averages of the Loch Vaal (139.3 µg/ℓ) and Barrage (33 µg/ℓ) measured during 2000 (Kruskopf, 2002).

3.5.2 Phytoplankton assemblages

Cyanobacteria are a natural part of the phytoplankton populations of many surface freshwater bodies. Cyanotoxins are produced by many cyanobacteria (Du Preez *et al*., 2007). The two major problems associated with cyanobacterial bloom events in South Africa are stock deaths due to toxins (Harding and Paxton, 2001) and taste and odour problems in purified drinking water (Van Ginkel and Conradie, 2001; Downing and Van Ginkel, 2004; Wnorowski, 1992 and Van Ginkel *et al*., 2006).



(a) **(b)** **(c)**

Figures 3.25: The filaments of *Anabaena* sp. (a), a colony of *Microcystis* sp. (b) and filaments of *Oscillatoria* sp. (c).

According to Swanepoel *et al*. (2008) the occurrence of cyanobacteria in raw water is important to water treatment facilities, because taste and odour substances, as well as toxins, may penetrate into the final drinking water.

In this study seven phytoplankton groups were identified and counted. Three of the groups, namely Cyanophyceae, Bacillariophyceae and Chlorophyceae, were present in high concentration for the entire study period (Figures 3.23 a and b). The Dinophyceae showed visible peaks during March, April and February 2009 and mainly composed of *Ceratium* species (Figure 3.23). The Cyanophyceae were prominent throughout the study period and consisted mainly of *Anabaena* sp., *Microcystis* sp. and *Oscillatoria* sp. (Figure 3.23). It seems that *Ceratium* sp. is a newcomer to the Vaal River as Pieterse and Janse van Vuuren (1997) did not list it in

their species list (1991 - 1993). Visser (1996) also did not find it in the Vaal River from 1994 to 1995. Kruskopf (2002) indicates that *Ceratium* sp. (Figure 3.26) was detected in the Vaal River during 1999 and 2000, specifically at the Loch Vaal. A comparison between Kruskopf (2002), Carrim (2006) and Morrison (2009) indicated that *Ceratium* sp. was found in the Vaal River from 1999 induces 2000 onwards (Morrison, 2009). Morrison (2009) counted *Ceratium* sp. during 2007 to 2008 and during this study *Ceratium* sp. was detected at high concentrations.

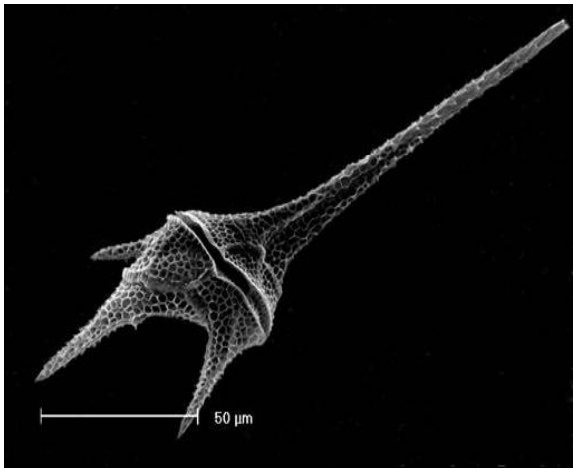


Figure 3.26: Electron micrograph of the dinoflagellate, *Ceratium hirundinella* (Swanepoel and Du Preez, 2010).

Kruskopf (2002) and studies by Morrison (2009) also found that the Cyanophyceae, Bacillariophyceae and Chlorophyceae are the most prominent algae in the Vaal River. During the colder autumn and winter months of 2008 lower algal concentrations (< 1000 cells/mℓ) were detected in the Vaal River water. The algal concentration of the different algal groups showed an increase during the spring and summer months of 2008 with the Cyanophyceae as the dominant algal group during the warmer spring and summer months (Figure 3.23a). During the autumn months of 2009 higher algal concentration were detected especially, the Cyanophyceae, with lower algal concentrations during the winter months (Figure 3.23b). During the spring and summer months of 2009 an increase occurred in the concentration of algal groups until highest algal concentration was reached in February 2010 (summer month) with a monthly average of above 6000 cells/mℓ (Figure 3.23).

The pigment measurements in the raw water showed peaks during April 2008 and 2009 as well as in February 2010. The high pigment measurements did not reflect in the cell counts during April 2008 and 2009. However, during February 2010 the cell count of the Cyanophyceae was on average 6000 cells/mℓ (Figures 3.23). There was also no correlation between the silica concentration in the raw water (Figure 3.14) and the Bacillariophyceae (Figure 3.23).

Geosmin and 2-MIB cause musty-earthy odours in drinking water and are mainly produced by cyanobacteria (such as *Anabaena* and *Oscillatoria* species) and actinomycetes (bacteria). Cyanobacteria. This is confirmed by the PCA analysis that grouped geosmin and *Anabaena* species as well as *Oscillatoria* species together (Table 3.5). Geosmin also grouped together with nitrogen and DOC (Table 3.5). According to Wetzel (2001), the nitrogen content of organic matter decreases progressively with increasing DOC concentration and similarly declines as the proportion of allochtonous to autochtonous organic matter increases. As a result, the organic C:N ratios increase – a reflection of an increased input of organic compounds low in nitrogen as well as decreased decomposition rates of more recalcitrant organic compounds.

The identification, qualification and removal of these compounds from water are essential because these compounds impact on aesthetic quality and consumer acceptability of drinking water. Geosmin and 2-MIB are detectable by the human nose at concentrations of as low as 10 ng/ℓ in water (Mamba *et al*., 2007). Therefore the removal of geosmin and 2-MIB from water is critical for water providers, both locally and internationally (Mamba *et al*., 2007). According to Mamba *et al* (2007), treatment methods such as the use of powered activated carbon, ozonation, biological degradation and conventional methods such coagulation, flocculation, sedimentation, filtration and disinfection have been used for taste and odour control. However, these methods fail to remove geosmin and 2-MIB from water at ng/ℓ levels.

Geosmin concentrations peaked (Figure 3.21) during periods when high cell counts for the Cyanophyceae (Figure 3.23) and especially *Anabaena* species (Figure 3.24) were made. The average concentration of geosmin was 9.44 ng/ℓ in 2008 and 7.70 ng/ℓ in 2009. The average concentration for MIB was 7 ng/ℓ for 2008 (Figure 3.21).

3.6 CONCLUSIONS

The status of the source water is of utmost importance to determine which purification processes are needed. Therefore the ecological status of the raw water was determined to serve as a benchmark to determine the efficacy of the different purification processes.

The following conclusions were made:

- The Cyanophyceae was the dominant algal group during the study period.
- The alkalinity of the water is relatively high and can cause potential damage to purification equipment.
- The turbidly was low when compared to the rest of the Vaal River.
- The increase in COD and TDS towards the end of the study period can cause potential damage to purification equipment.
- The cadmium and lead concentrations were higher than the TWQR criteria and therefore potentially hazardous.
- The silica or sulphate concentrations in the raw water were not a threat to equipment.
- Phosphate concentrations in the raw water were high in 2008 and 2009. The average ortho-phosphate concentration in 2008 was 0.026 mg/ℓ and 0.009 mg/ℓ in 2009. The raw water is eutrophied according to the Organisation for Economic Cooperation and Development (1982) criteria for assessing the trophic status of water bodies
- The average nitrate concentration in 2008 was 0.19998 mg/ℓ and in 2009 0.14722 mg/ℓ and would not have any adverse affect on human health according to DWAF (1996) criteria.

- However, according to the Organisation for Economic Cooperation and Development (1982) the raw water was mesotrophic because the average chlorophyll *a* concentration for 2008 was 5.46 µg/ℓ and for 2009, 5.11 µg/ℓ.

CHAPTER 4: THE EFFICACY OF PURIFICATION PROCESSES

4.1 INTRODUCTION

By the eighteenth century the removal of particles from water by filtration was an effective way of clarifying water and the first municipal water filtration plant started to operate in Scotland in 1832 (Schutte, 2006). Research on coagulation-flocculation, sedimentation and filtration as basic water treatment processes during the early part of the previous century contributed to a better understanding of these processes and improved performance. As water quality decreases, due to pollution, more advanced processes such as the use of ozone for disinfection, taste and colour enhancements were developed (Schutte, 2006).

According to Schutte (2006) the physical, chemical, biological and microbiological characteristics of water describe the quality of the water that is used for domestic purposes. The principle objective of water treatment is therefore to produce water, which is fit for domestic use from a raw water source at a cost that is reasonable to the consumers (Schutte, 2006).

Conventional treatment processes remove the suspended material and disinfect the water prior to pumping it to local authorities, the mining industry and other large industrial concerns. Each stage in the purification process is accompanied by changes in the physical and chemical composition of the water that is constantly monitored and corrective action is taken to prevent the water quality from deviating from the prescribed limits (Rand Water, 2010).

Rand Water has treated water from the Vaal River since 1923 but the Zuikerbosch pumping station was only brought in operation in 1954 due to problems with the water quality in the Barrage reservoir (Pursell, 2010). Zuikerbosch pumping station was sited upstream of the confluence of the Suikerboschrand and Klip Rivers in order to abstract water primarily from the Vaal Dam (Pursell, 2010). Figure 4.1 shows the series of purification processes in ZWTP which involve the following stages: coagulation, flocculation, sedimentation, sand filtration and chlorination.

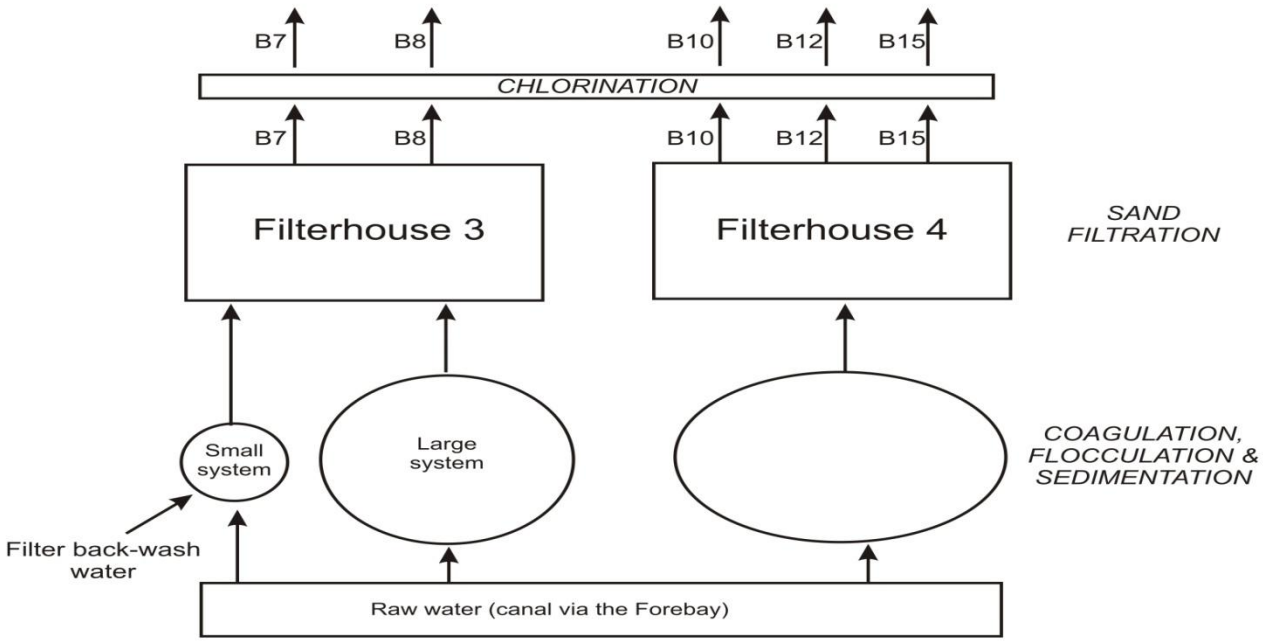


Figure 4.1: Schematic drawing of the ZWTP showing the series of purification processes that involve the following stages: coagulation, flocculation, sedimentation, sand filtration and chlorination.

The purification processes shown in Figure 4.1 involves the following:

- **Coagulation-flocculation** - effective coagulation and flocculation are critical to the successful operation of subsequent treatment processes. Problems associated with the coagulation-flocculation process result in high turbidity water in the overflow of the sedimentation tanks and /or the filtered water (Schutte, 2006).
- **Sedimentation** - sedimentation can typically remove 80 to 95% of suspended solids and will result in better filter performance and longer filter runs. However, performance of a sedimentation basin is dependent on effective coagulation-flocculation (Schutte, 2006).
- **Stabilisation** - operational problems associated with stabilisation systems are mainly associated with problems with liquid or dry chemical feeders (Schutte, 2006).
- **Filtration** - filtration is the only process that is capable of removing very small particles down to the level required (Schutte, 2006).

- **Disinfection** - the objective of water treatment is to produce a final product that is microbiologically and chemically safe for the consumer as well as aesthetically acceptable. In preparation of drinking water the term disinfection is used to describe the process of destroying or inactivating pathogenic organisms (Schutte, 2006).
- **Chloramination** - chloramination is used as either a primary or secondary disinfection process and is applied to produce a long lasting disinfectant residual in extended drinking water distribution systems (Schutte, 2006).

Processes that include coagulation, flocculation, sedimentation and stabilization take place before filtration. Disinfection and chloramination processes produce final drinking water.

Before filtration or after sedimentation

Sedimentation is the oldest known method of water purification. Rand Water uses horizontal flow tanks (Figure 4.2) with retention times of 4 hours and produces water with a turbidity of 5 NTU is considered acceptable for filtration. Depending on the turbidity of the incoming raw water, between 95% and 97% of the suspended particles are removed during sedimentation. Slaked lime is added to water as the main coagulant to destabilize the electrostatic charges of suspended particles in the water. A small quantity of activated sodium silicate is also added to the raw water to enable the suspended particles to clump together to form larger clusters or flock which can settle out by gravitation (Rand Water, 2010).

Filtration and final water

Following carbonation, the water passes into the filter houses where it flows through rapid gravity sand filter beds of finely graded silica sand and pebbles. The remaining suspended particles are removed at this stage. Filters are covered to exclude light to less than 25 lux to prevent algal growth on the sand filters. After filtration, the water has a residual turbidity of 0.5 NTU or less (Rand Water, 2010).

Figure 4.2: Sedimentation tanks of Rand Water's Zuikerbosch treatment plant close to Vereeniging (Google earth). Samples before filtration were collected at this locality in the treatment plant.

Figure 4.3: Rand Water's Zuikerbosch water treatment station 4 (Google earth). Samples after filtration were collected at this locality in the treatment plant.

Water leaving the purification works is disinfected with chlorine to kill micro-organisms. Secondary disinfection (chloramination) with chlorine protects the final water on the way to the consumers (Rand Water, 2010).

According to Swanepoel and Du Preez (2007) some phytoplankton species (mostly Cyanophyceae) causes extensive problems in water purification and can penetrate the water purification process into the final drinking water. Therefore, one of the major objectives during water purification is the removal of phytoplankton from the water that is often inhibited by a variety of factors such as the specific species present and the total biomass in the source water. Continuous monitoring of phytoplankton in source water as well as in potable water is therefore essential (Swanepoel and Du Preez, 2007).

Therefore the study in this chapter is to determine the efficacy of the different purification processes not only in removing algae and cyanobacteria, but also other variables such as geosmin and MIB. According to Swanepoel *et al*. (2008) sampling sites should be located at the intakes and where the source water (inlet water) enters the purification plant (namely, before purification) as well as where the purified drinking water leaves the purification plant, that is at a sampling point (tap connected directly to a pumping main) after chlorination or other final disinfection processes. Therefore sampling (Figures 4.1 and Figure 4.3) was done at the canal (raw) water, before filtration (Station 4), after filtration (Station 4) and final water (B7 or B8).

4.2 MATERIAL AND METHODS

A litre of water was collected from the ZWTP at the different sampling points: source water (raw water), before and after filtration as well as in the final water, from February 2008 until February 2010. Another litre of water was fixed with Lugol's or formaldehyde with a 2% final concentration (see Chapter 3, section 3.2.2) for the identification and enumeration of the phytoplankton.

The following variables were determined by Rand Water Analytical Services, a SANAS accredited laboratory for the different sampling points: MIB, geosmin, chlorophyll-*a*, chlorophyll-665 and TOC (see Chapter 3, section 3.2.1). Dosing information at sampling point B7 was provided by the staff at the ZWTP. Algal

identification and enumeration for all the sampling localities was done at the North-West University (see Chapter 3, section 3.2.2). The statistical analysis was done with STATISTICA version 9 and the help of the Statistical Services at the North-West University in Potchefstroom.

4.3 RESULTS

The results of the chemical dosing applied at sampling point B7 for the study period are shown in Figure 4.4 (Appendix, Table 1). The ZWTP of Rand Water simultaneously uses lime, poly-electrolytes (Poly) and chlorine dosing as pre-treatment. Pre-treatment with oxidants may enhance the coagulation process and specifically enhance the removal of algae and other particulate matters in subsequent treatment steps (Ma and Liu, 2002). The dosage used by Rand water usually consists of a high percentage lime and low percentage chlorine (Figure 4.4).

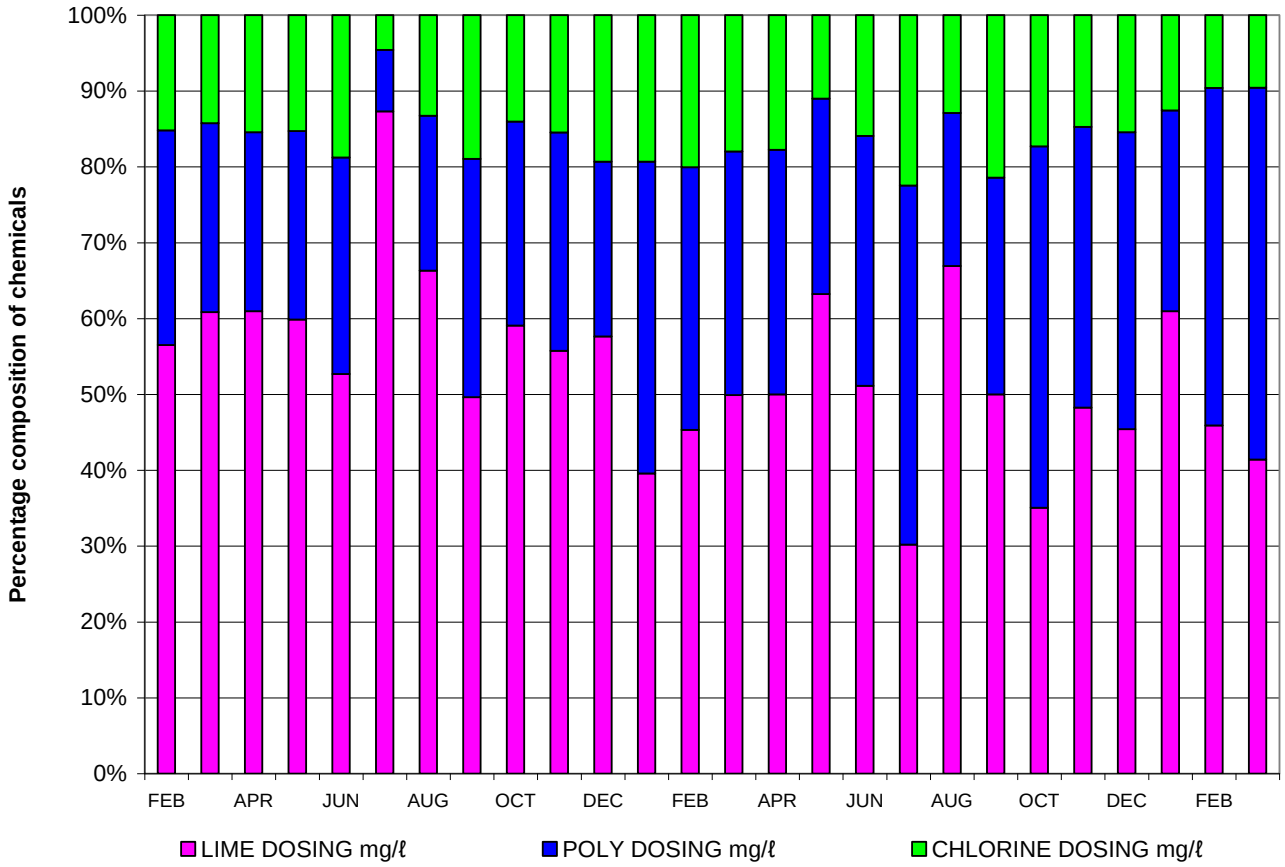


Figure 4.4: The percentage composition of pre-treatment chemicals used for chemical dosing during the study period (February 2008 – March 2010).

T-tests were used to determine if there was a statistical difference between the different variables in the:

- raw water and before filtration;
- water before and after filtration;
- water after filtration and the final water;
- raw and final water.

An assumption of a t-test is that the data should be independent. If the data in this study is time independent the slope of the regression line in the scatter plot is 0. Time dependency is indicated by a regression line with a positive or negative slope concluding that the t-test is not a valid test. The scatter plots of the variables over time are given in Figures 4.5 to 4.61. The level of significance is $p<0.05$.

Specific attention was given to the removal of the Cyanophyceae genera *Anabaena*, *Microcystis* and *Oscillatoria*, as well as the Dinophyceae genus *Ceratium*.

4.3.1: A comparison of the data of the raw water (canal water) and before filtration (after sedimentation).

In this section the concentration of 2-Methylisoborneol (MIB), geosmin, total chlorophyll, chlorophyll-*a*, total organic carbon (TOC), algal groups (Cyanophyceae, Bacillariophyceae, Chlorophyceae, Cryptophyceae, Dinophyceae and Euglenophyceae) and algal genera (*Anabaena* sp., *Microcystis* sp., *Oscillatoria* sp. and *Ceratium* sp.) are compared in the raw water and before filtration to determine the efficacy of the coagulation, flocculation and sedimentation processes in the purification plant

4.3.1.1: 2-Methylisoborneol (MIB)

Measurements for MIB were only done for a period of one year and have shown constant concentration levels for the entire year. From week 31 and 37 no MIB were detected in the raw water and no measurements were taken before filtration. Coagulation, flocculation and sedimentation did not remove MIB from the raw water,

because higher concentrations were measured before filtration. The concentrations of MIB were measured 8 µg/ℓ in the raw water and at 15 µg/ℓ before filtration. Cyanophyceae, especially *Anabaena* species, that are usually responsible for the production of MIB, were still present before filtration.

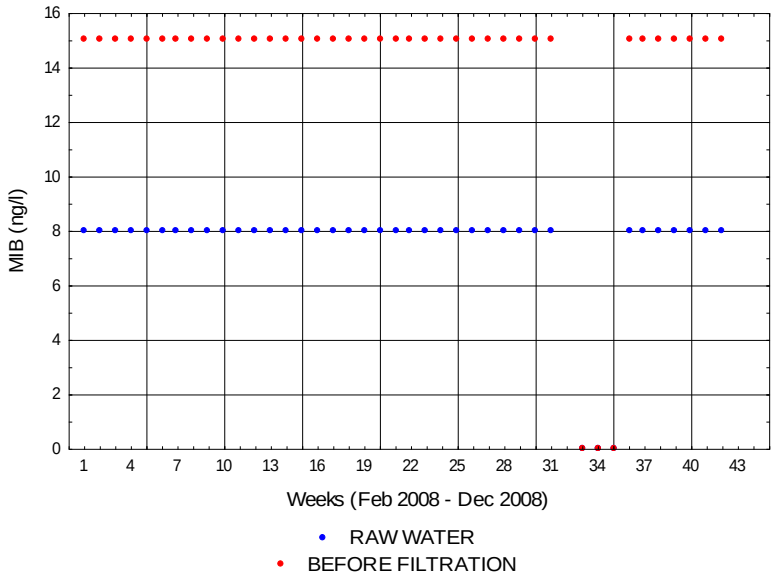


Figure 4.5: The measured concentrations of MIB (ng/ℓ) in the raw water and before filtration for the study period Feb 2008 to December 2008.

4.3.1.2: Geosmin

The concentration of geosmin in the raw water varied between 0 – 50 ng/ℓ during the period week 1 to 78, and 0 – 100 during week 85 to 92 ng/ℓ (Figure 4.6a). The purification processes coagulation, flocculation and sedimentation removed the geosmin before filtration to a range of 0 – 20 ng/ℓ between week 1 and 78. For week 85 to 92 where the geosmin concentrations were above 20 ng/ℓ after removal. The regression line is not visible because it lies on the X-axis. There is a statistically significant difference ($p = 0.01$) between the data measured for the raw water and before filtration and this step of water purification was successful in reducing geosmin in the water (Figure 4.6b).

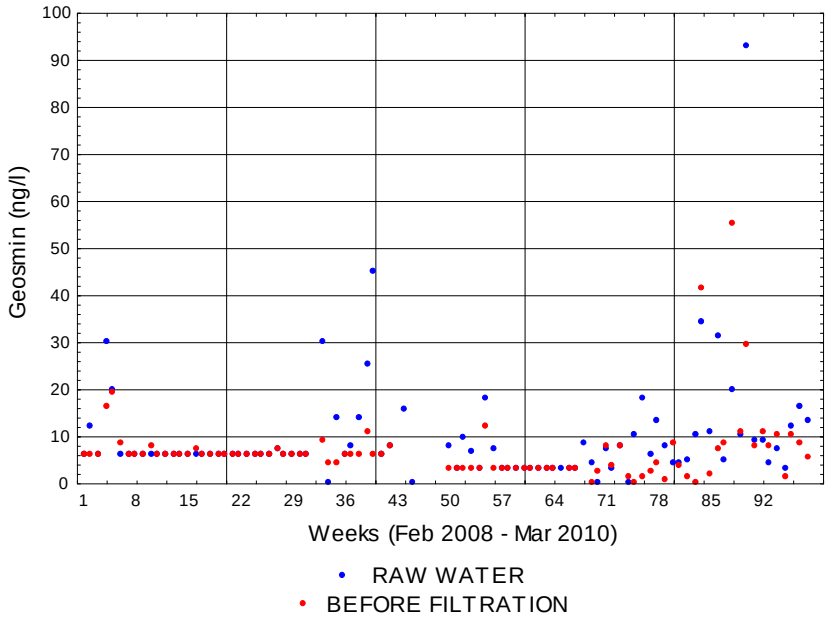


Figure 4.6a: The measured concentrations of geosmin (ng/ℓ) in the raw water and before filtration for the study period Feb 2008 to March 2010.

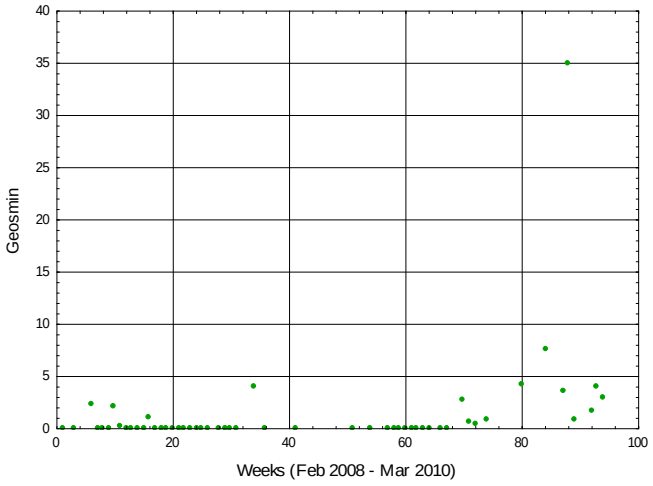


Figure 4.6b: The statistical differences in the concentrations of geosmin measured in the raw water and before filtration.

4.3.1.3: Total Chlorophyll

The concentrations of total chlorophyll in the raw water was usually measured between 5 and 15 µg/ℓ during the study period, with measurements above 15 µg/ℓ during certain weeks. The measurement for total chlorophyll varied between 0 – 5 µg/ℓ before filtration with only a few measurements above this range (Figure 4.7a). The purification processes reduced total chlorophyll from 10 µg/ℓ to below 5 µg/ℓ. There is statistically significant difference ($p < 0.001$) between the data measured for the raw water and before filtration and these steps of water purification were successful in reducing total chlorophyll in the water (Figure 4.7b).

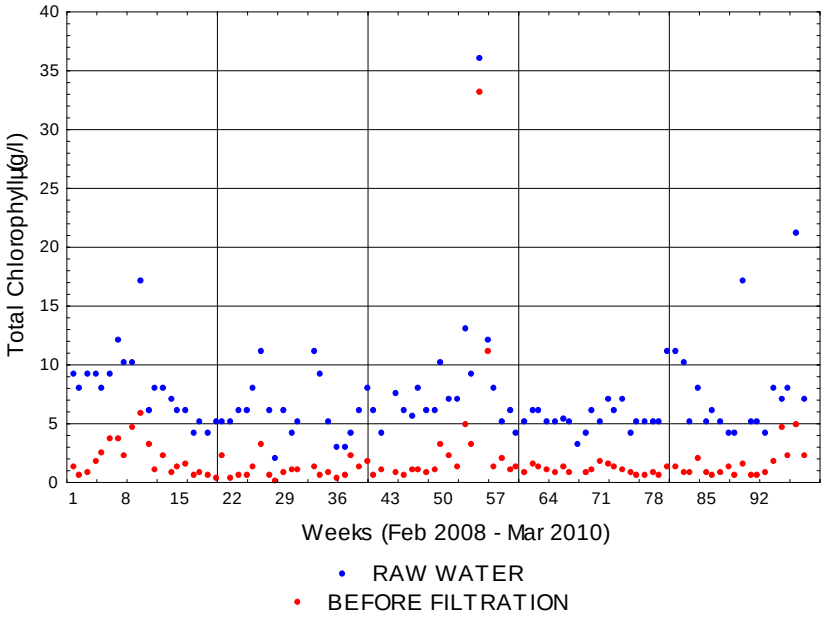


Figure 4.7a: The measured concentrations of total chlorophyll (µg/ℓ) in the raw water and before filtration for the study period Feb 2008 to March 2010.

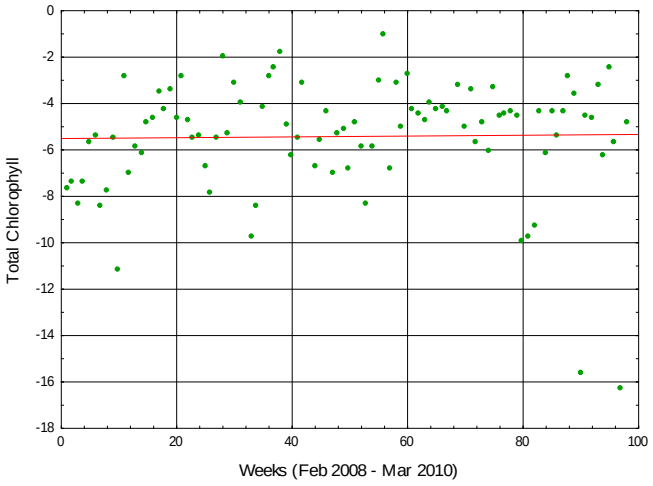


Figure 4.7b: The statistical differences in the concentrations of total chlorophyll measured in the raw water and before filtration.

4.3.1.4: Chlorophyll-*a*

The chlorophyll-*a* concentration in the raw water varied between 0 and 14 µg/ℓ for the entire study period, except for week 57 where measurements for both the raw water and before filtration were above 20 µg/ℓ. The chlorophyll-*a* concentrations before filtration varied between 0 and 10 µg/ℓ for most of the study period. There is statistically significant difference ($p < 0.001$) between the data measured for the raw water and before filtration and this step of water purification was successful in reducing chlorophyll-*a* in the water (Figure 4.8b).

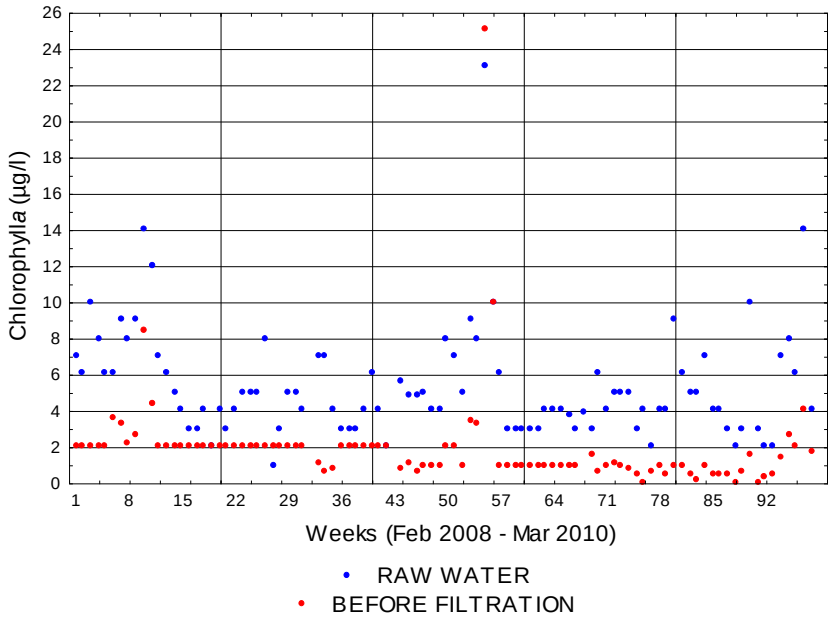


Figure 4.8a: The measured concentrations of chlorophyll-*a* (µg/ℓ) in the raw water and before filtration for the study period Feb 2008 to March 2010.

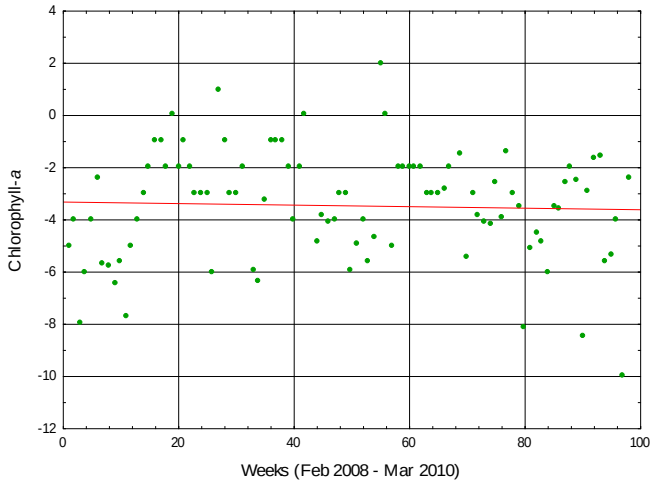


Figure 4.8b: The statistical differences in the concentrations of chlorophyll-*a* measured in the raw water and before filtration.

4.3.1.5: Total Organic Carbon (TOC)

The concentrations of total organic carbon in the raw water stayed more or less at 5 mg/ℓ, with some variation (Figure 4.9a). The purification processes reduced the TOC from a range of 4 – 8 mg/ℓ to a range of 3 – 6 mg/ℓ for most of the weeks during the study period. The slope of the regression line in Figure 4.9b indicates that the measurements of TOC were time dependent. This fact as well as the increased variation in the data points from week 80 until the end of the study period indicates that the t-test cannot be used to determine the statistical differences in the data.

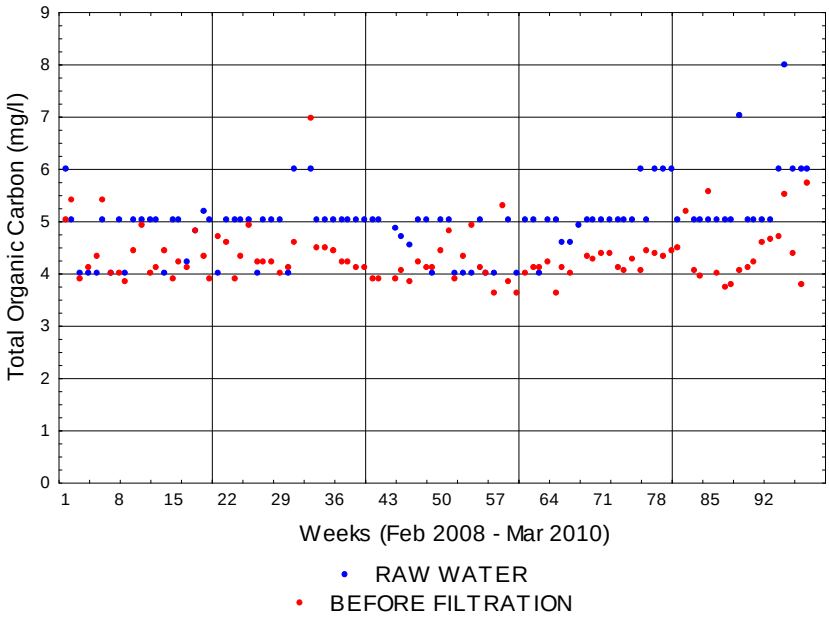


Figure 4.9a: The measured concentrations of total organic carbon (mg/ℓ) in the raw water and before filtration for the study period Feb 2008 to March 2010.

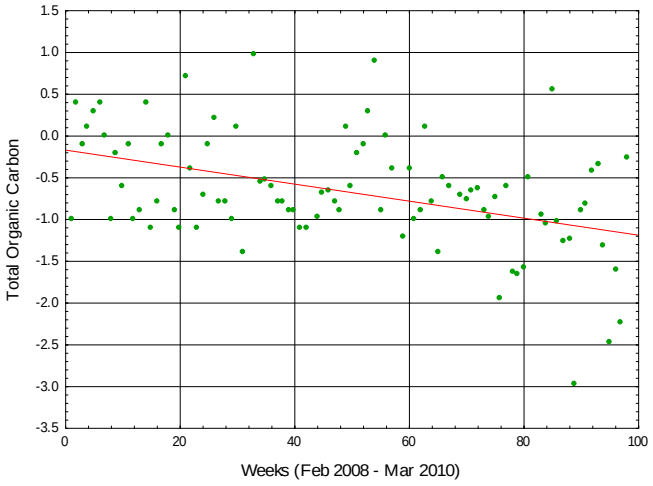


Figure 4.9b: The statistical differences in the concentrations of total organic carbon measured in the raw water and before filtration.

4.3.1.6: Cyanophyceae

The Cyanophyceae concentration varied between 0 - 12000 cells/mℓ in the raw water, while before filtration the Cyanophyceae was detected between the ranges of 0 - 6000 cells/mℓ (Figure 4.10a). From week 1 to 29 the concentrations of Cyanophyceae were less than 2000 cells/mℓ, above 2000 cells/mℓ from week 29 to 57, lower than 2000 cells/mℓ during weeks 57 to 78 and above 2000 cells/mℓ for the rest of the study period. It seems as if this step can only remove a certain concentration of Cyanophyceae cells and is less successful when the concentrations are too high. Figure 4.10b shows a regression line with a slope indicating that the t-test cannot be used because the data was time dependent. The scattered distribution of the data points from week 40 until the end of the study period also confirms the time dependency and that the t-test cannot be used to determine statistical differences in the data.

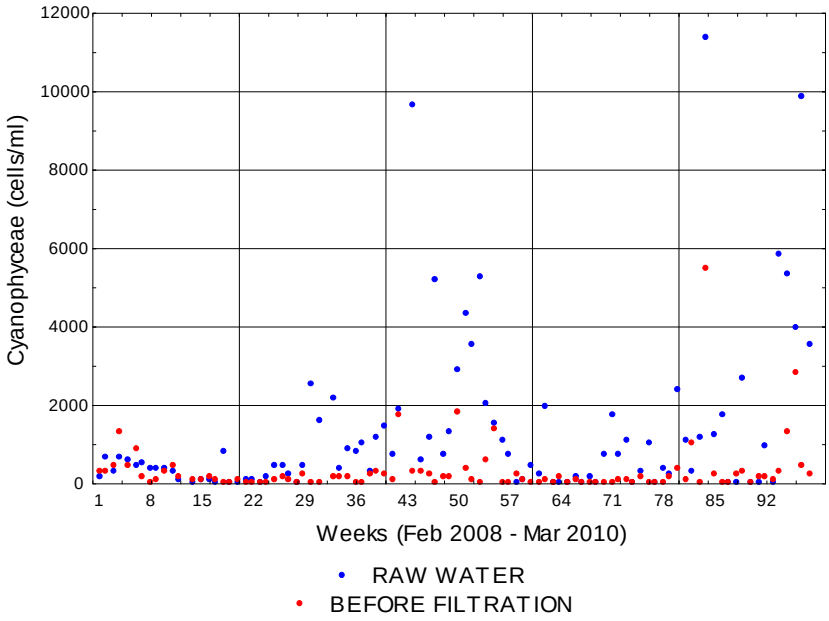


Figure 4.10a: The measured concentrations of Cyanophyceae (cells/mℓ) detected in the raw water and before filtration for the study period Feb 2008 to March 2010.

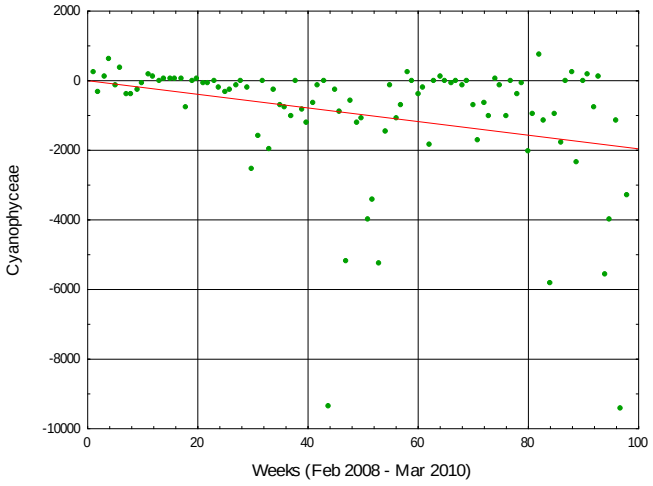


Figure 4.10b: The statistical differences in the concentrations of Cyanophyceae measured in the raw water and before filtration.

4.3.1.7: Bacillariophyceae

Bacillariophyceae concentration varied between 100 and 1600 cells/mℓ in the raw water, and between 0 and 200 cells/mℓ before filtration except for week 43 to 50 when more than 700 cells/mℓ were counted. The purification processes were successful in removing these algal cells from any concentration level in the raw water to less than 200 cells/mℓ, for the entire study period, except during week 43 – 50. That may be due to higher counts of Bacillariophyceae in the raw water during this period. There is a statistically significant difference ($p < 0.001$) between the data measured for the raw water and before filtration and this step of water purification was successful in reducing the Bacillariophyceae cells in the water (Figure 4.11b).

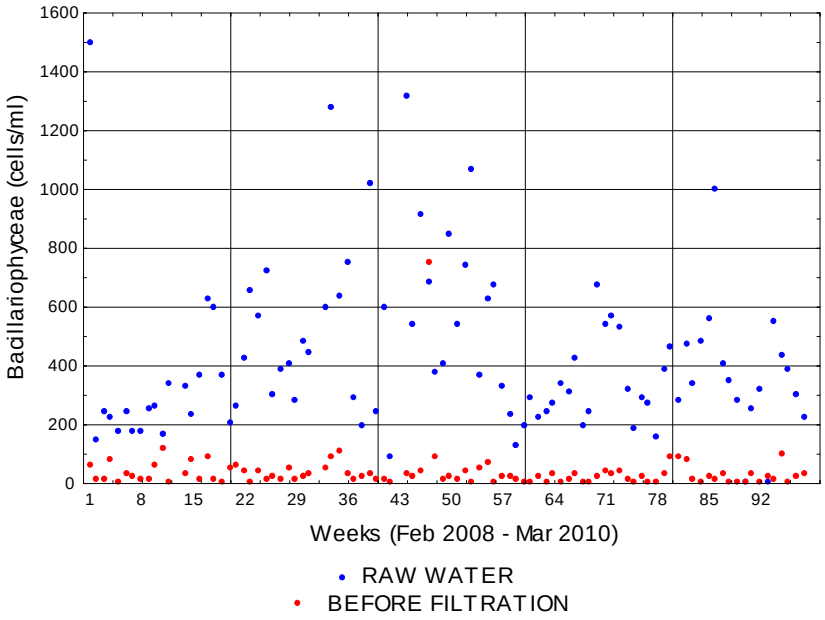


Figure 4.11a: The measured concentrations of Bacillariophyceae (cells/mℓ) detected in the raw water and before filtration for the study period Feb 2008 to March 2010.

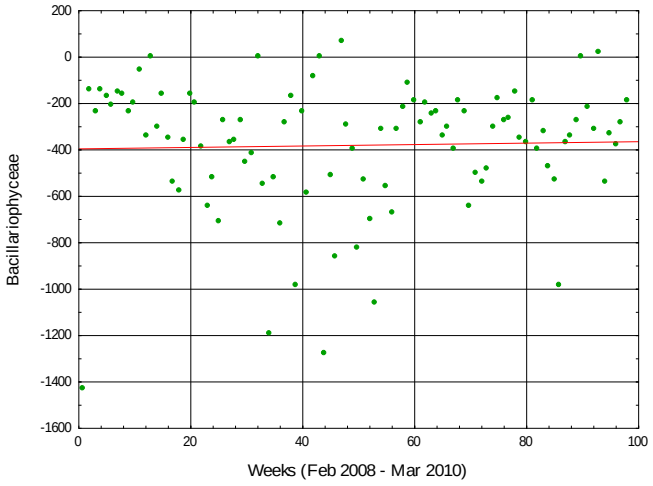


Figure 4.11b: The statistical differences in the concentrations of Bacillariophyceae detected in the raw water and before filtration.

4.3.1.8: Chlorophyceae

The Chlorophyceae concentrations varied between 0 and 2000 cells/mℓ in the raw water and were reduced to less than 600 cells/mℓ before filtration. The purification processes reduced the Chlorophyceae cells to below 200 cells/mℓ for most of the weeks. During week 1 to 8 the Chlorophyceae detected before filtration had a higher concentration level (>500 cells/mℓ) than the cells detected in the raw water, this could be due to a non representative sample during this period. There is statistically significant difference ($p < 0.001$) between the data measured for the raw water and before filtration and this step of water purification was successful in reducing the Chlorophyceae cells in the water (Figure 4.12b).

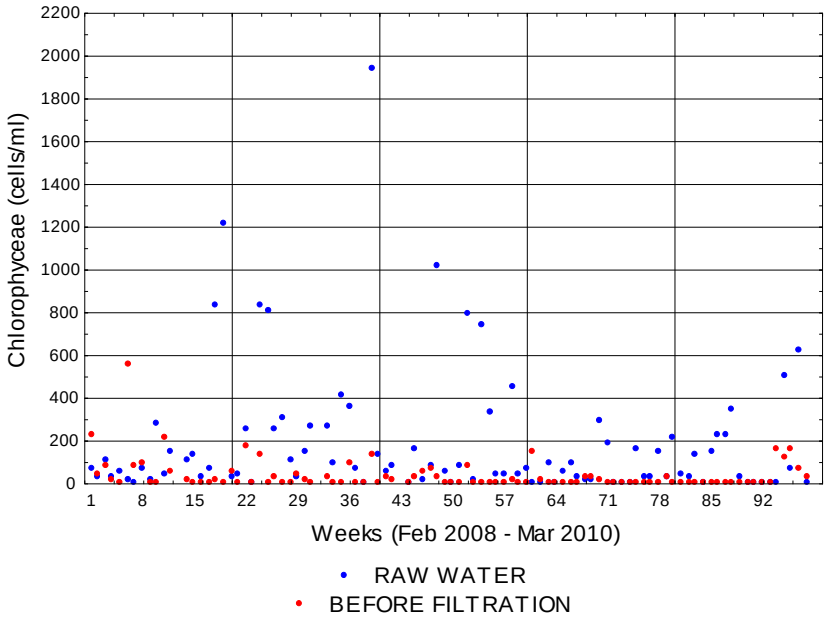


Figure 4.12a: The measured concentrations of Chlorophyceae (cells/mℓ) detected in the raw water and before filtration for the study period Feb 2008 to March 2010.

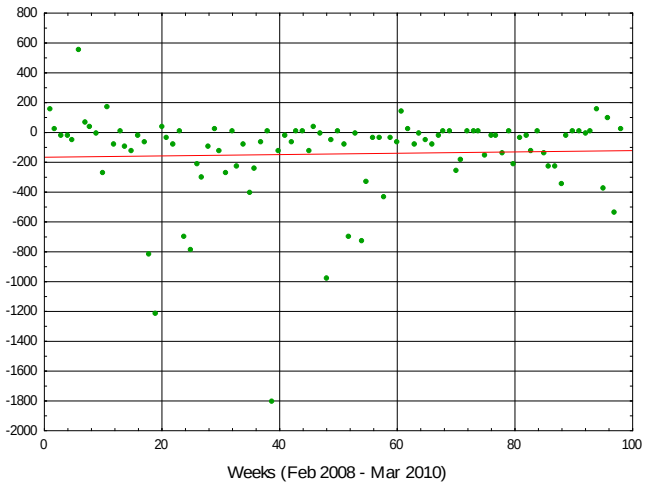


Figure 4.12b: The statistical differences in the concentrations of Chlorophyceae detected in the raw water and before filtration.

4.3.1.9: Cryptophyceae

During the study period, less than a 100 Cryptophyceae cells/mℓ was counted in the raw water and less than 20 cells/mℓ was counted before filtration (Figure 4.13a). Figure 4.13b shows a regression line with a slope indicating that the t-test cannot be used, because the data was time dependent. The scattered distribution of the data points for the first part of the study period also confirms the time dependency and that the t-test cannot be used to determine statistical differences in the data.

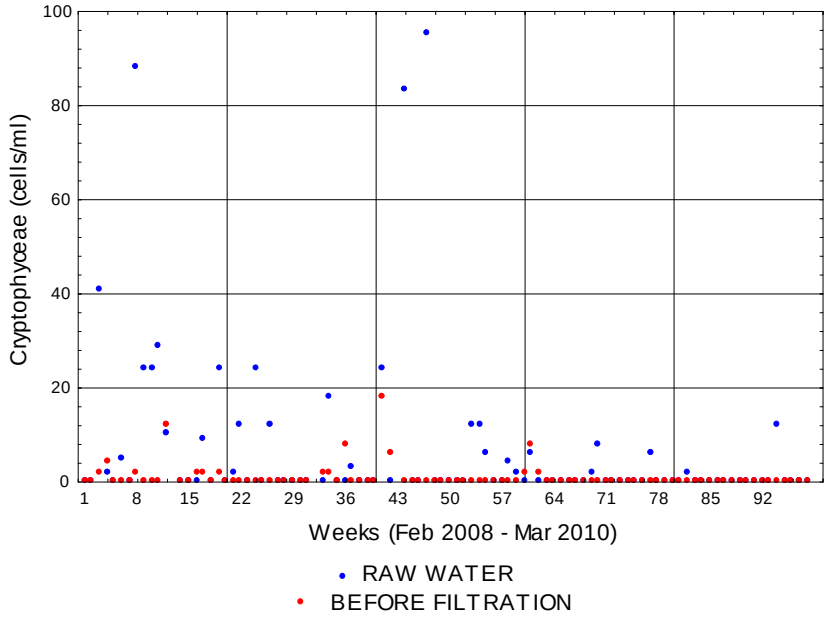


Figure 4.13a: The measured concentrations of Cryptophyceae (cells/mℓ) detected in the raw water and before filtration for the study period Feb 2008 to March 2010.

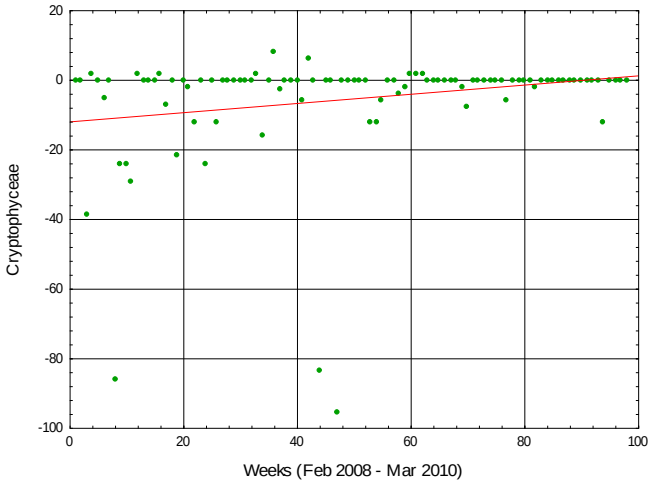


Figure 4.13b: The statistical differences in the concentrations of Cryptophyceae detected in the raw water and before filtration.

4.3.1.10: Dinophyceae

Figure 4.14a shows that the concentrations of Dinophyceae varied between 0 and 300 cells/mℓ in the raw water and were reduced to less than 100 cells/mℓ before filtration. Only *Ceratium* sp. was detected during the study period. Although the processes before filtration reduced the numbers of *Ceratium* cells, Figure 4.14b shows a regression line with a slope indicating that the t-test cannot be used to determine if the data differ statistically because the data was time dependent.

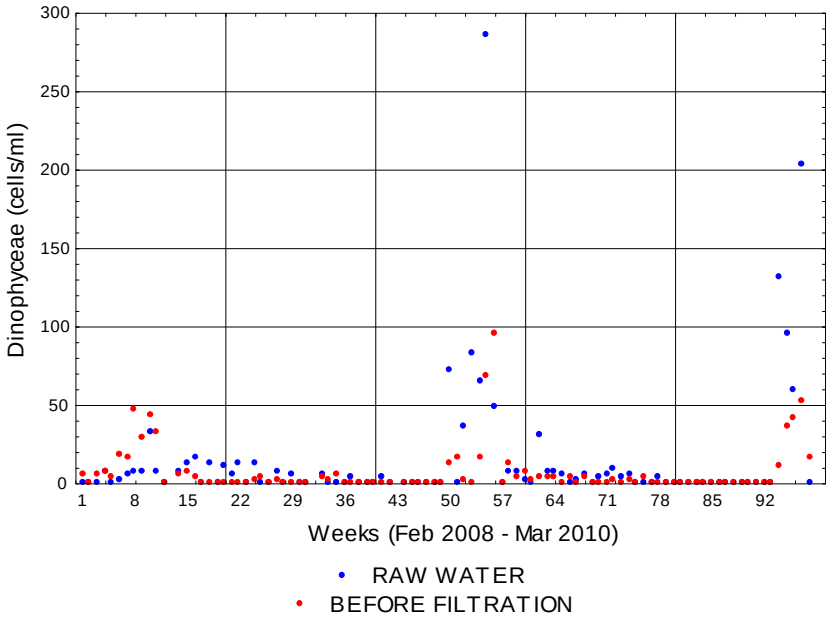


Figure 4.14a: The measured concentrations of Dinophyceae (cells/mℓ) detected in the raw water and before filtration for the study period Feb 2008 to March 2010.

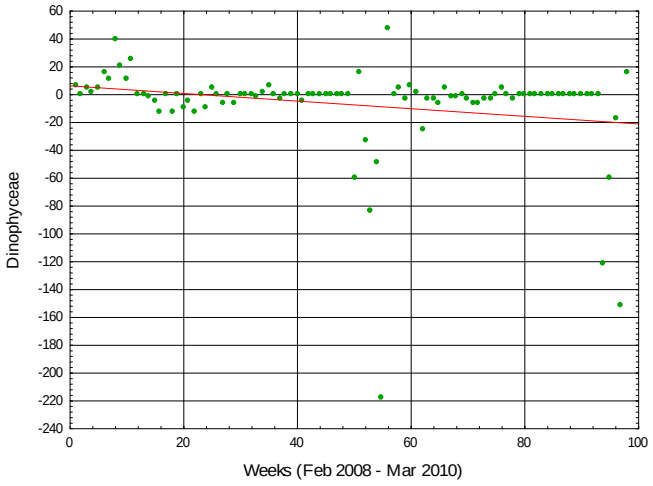


Figure 4.14b: The statistical differences in the concentrations of Dinophyceae detected in the raw water and before filtration.

4.3.1.11: Euglenophyceae

The concentration of the Euglenophyceae varied between 0 and 50 cells/mℓ in the raw water and was reduced to less than 20 cells/mℓ before filtration in most cases. There is a statistically significant difference ($p < 0.001$) between the data measured for the raw water and before filtration. This step of water purification was successful in reducing the Euglenophyceae cells in the water (Figure 4.15b).

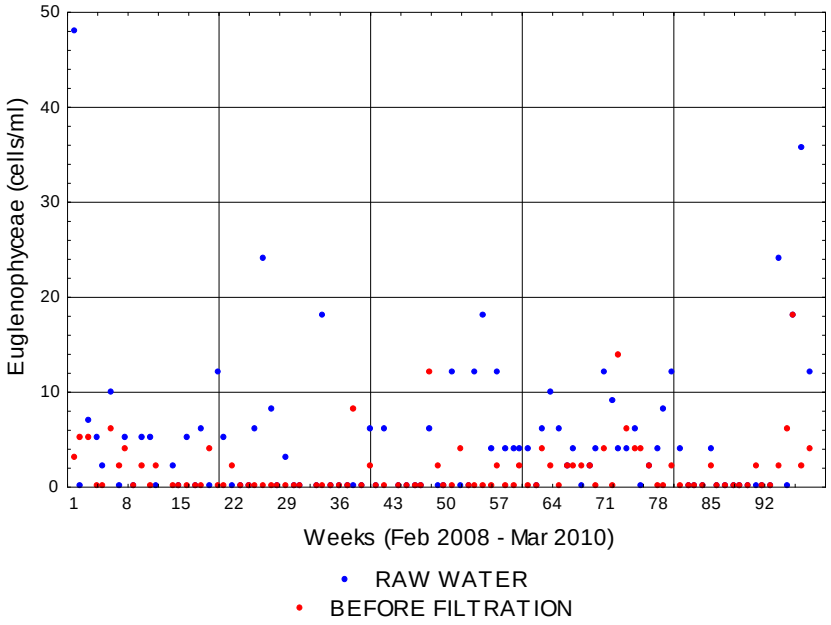


Figure 4.15a: The measured concentrations of Euglenophyceae (cells/mℓ) detected in the raw water and before filtration for the study period Feb 2008 to March 2010.

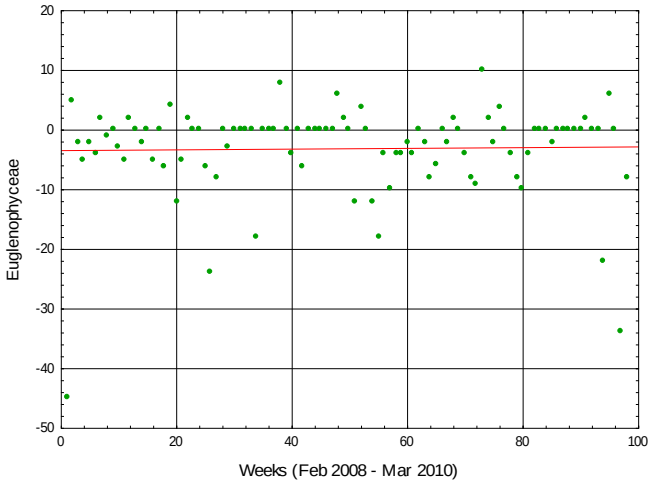


Figure 4.15b: The statistical differences in the concentrations of Euglenophyceae detected in the raw water and before filtration.

4.3.1.12: *Anabaena* species

The concentration of *Anabaena* species varied between 0 and 12000 cells/mℓ in the raw water and was reduced to less than 6000 cells/mℓ before filtration. During periods when concentrations were higher than 4000 cells/mℓ in the raw water, higher concentrations were also detected before filtration. Figure 4.16b shows a regression line with a slope, indicating that the t-test cannot be used because the data was time dependent.

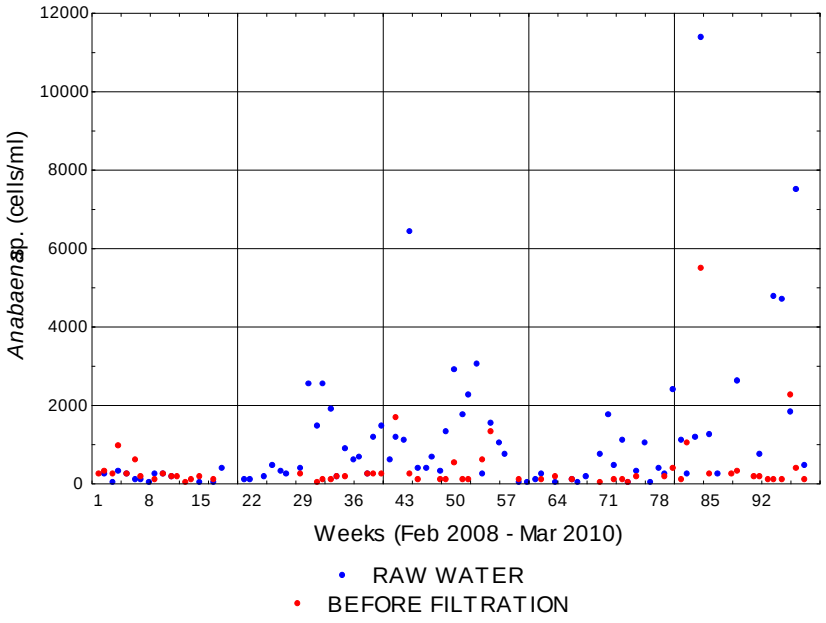


Figure 4.16a: The measured concentrations of *Anabaena* sp. (cells/mℓ) detected in the raw water and before filtration for the study period Feb 2008 to March 2010.

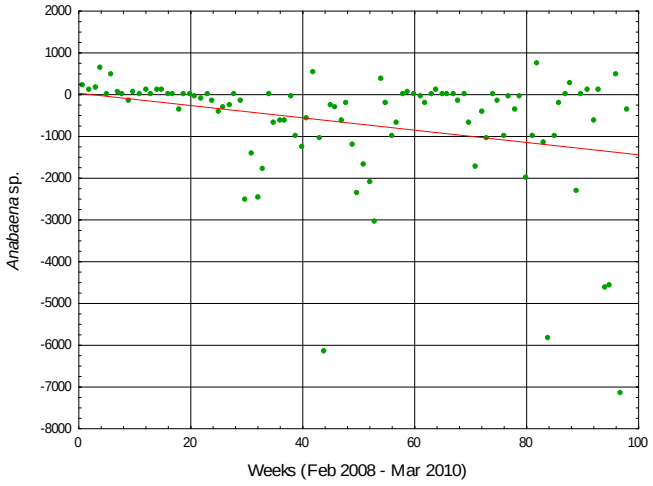


Figure 4.16b: The statistical differences in the concentrations of *Anabaena* sp. detected in the raw water and before filtration.

4.3.1.13: *Microcystis* species

The highest concentrations (> 1000 cells/mℓ) for *Microcystis* species were detected between weeks 43 to 57 and from week 92 towards the end of the study period, while the rest of the concentrations were lower than 500 cells/mℓ in the raw water (Figure 4.17a). Periods with higher *Microcystis* concentration in the raw water was also characterised by high concentrations in water before filtration. Figure 4.17b shows a regression line with a slope, indicating that the t-test cannot be used because the data was time dependent. The scattered distribution of the data points between weeks 40 to 60, and week 80 until the end of the study period also indicates that the t-test cannot be used to determine statistical differences in the data.

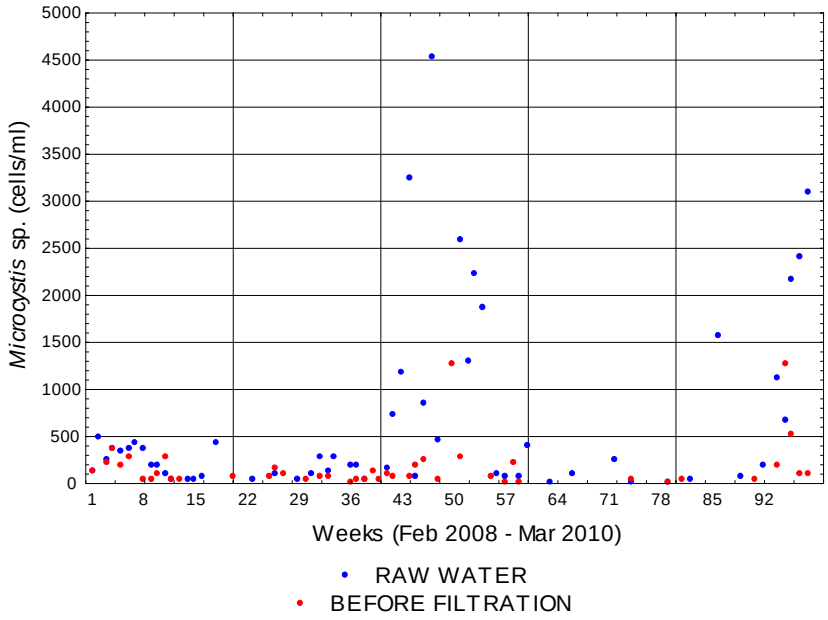


Figure 4.17a: The measured concentrations of *Microcystis* sp. (cells/mℓ) detected in the raw water and before filtration for the study period Feb 2008 to March 2010.

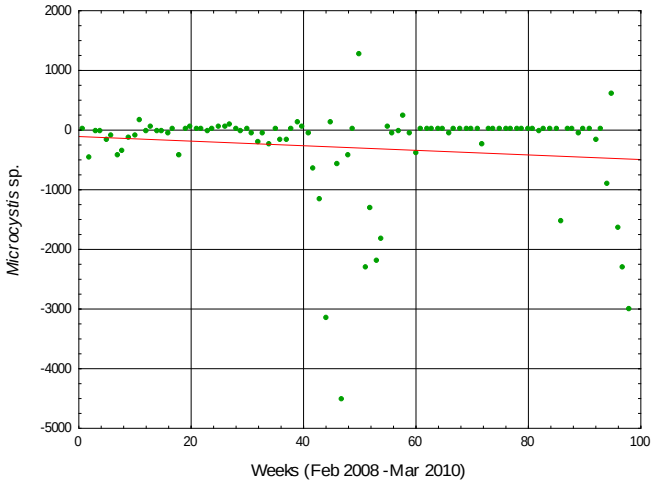


Figure 4.17b: The statistical differences in the concentrations of *Microcystis* sp. detected in the raw water and before filtration.

4.3.1.14: *Oscillatoria* species

Oscillatoria was only present during weeks 29 to 64 in the raw water. During certain periods this organism was found in the water before filtration even though it was not detected in the raw water. Because concentrations of *Oscillatoria* sp. did not occur during the same periods in the raw water and before filtration, the efficacy of this step to remove the cells could not be determined.

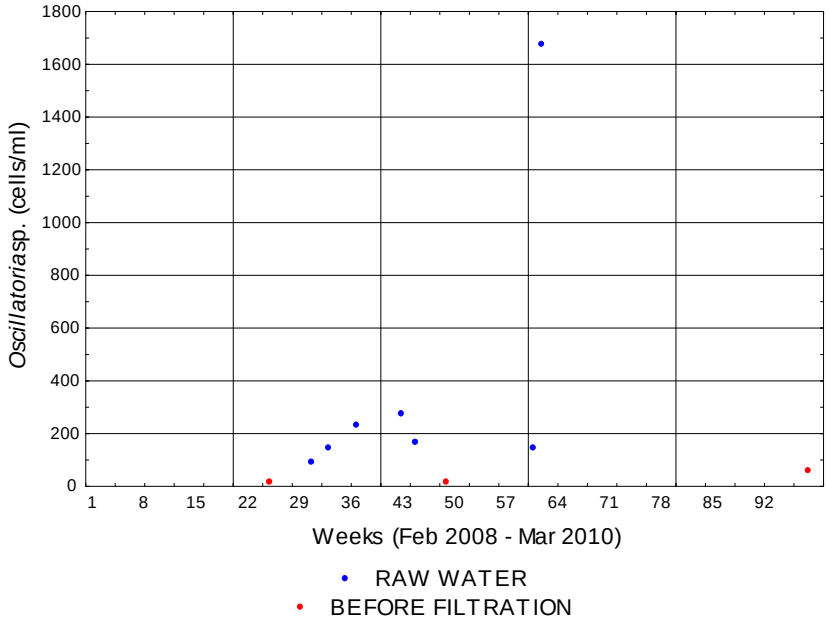


Figure 4.18: The measured concentrations of *Oscillatoria* sp. (cells/mℓ) detected in the raw water and before filtration for the study period Feb 2008 to March 2010.

4.3.2: A comparison of the data measured before and after filtration.

In this section the concentrations of 2-Methylisoborneol (MIB), geosmin, total chlorophyll, chlorophyll-*a*, total organic carbon (TOC), algal groups (Cyanophyceae, Bacillariophyceae, Chlorophyceae, Cryptophyceae, Dinophyceae and Euglenophyceae) and algal genera (*Anabaena* sp., *Microcystis* sp., *Oscillatoria* sp. and *Ceratium* sp.) are compared before and after filtration to determine the efficacy of filtration in the purification process.

4.3.2.1: 2-Methylisoborneol (MIB)

The concentrations of MIB varied between 14 and 16 ng/ℓ before filtration and between 7 and 8 ng/ℓ after filtration (Figure 4.19a). Although MIB concentrations were reduced during the filtration process Figure 4.19b shows a regression line with a slope indicating that the t-test cannot be used to determine if the data before and after filtration differ statistically, because the data was time dependent.

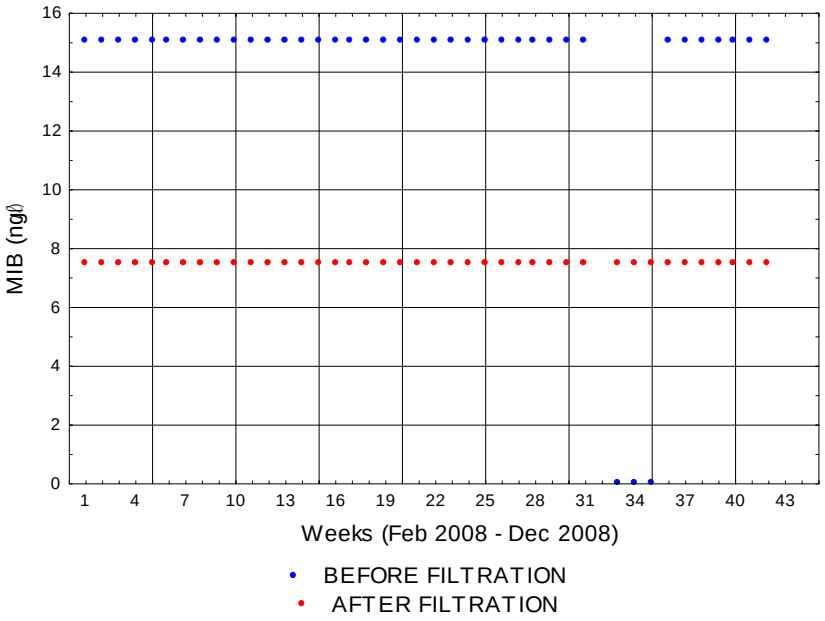


Figure 4.19a: The measured concentrations of MIB (ng/ℓ) before and after filtration for the study period February 2008 to December 2008.

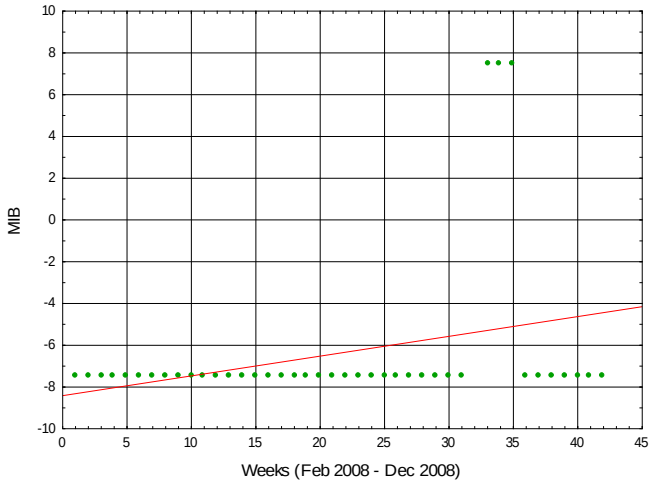


Figure 4.19b: The statistical differences in the concentrations of MIB measured before and after filtration.

4.3.2.2: Geosmin

Geosmin concentrations before and after filtration varied between 0 and 20 ng/ℓ from week 1 to week 78 and between 0 and 60 ng/ℓ during week 85 to 92 (Figure 4.20a). However, there were times when the geosmin concentrations were higher after filtration and that might be due to filter backwash activities. There is statistically significant difference ($p = 0.003$) between the data measured before and after filtration and therefore filtration was successful in reducing the geosmin in the water (Figure 4.20b).

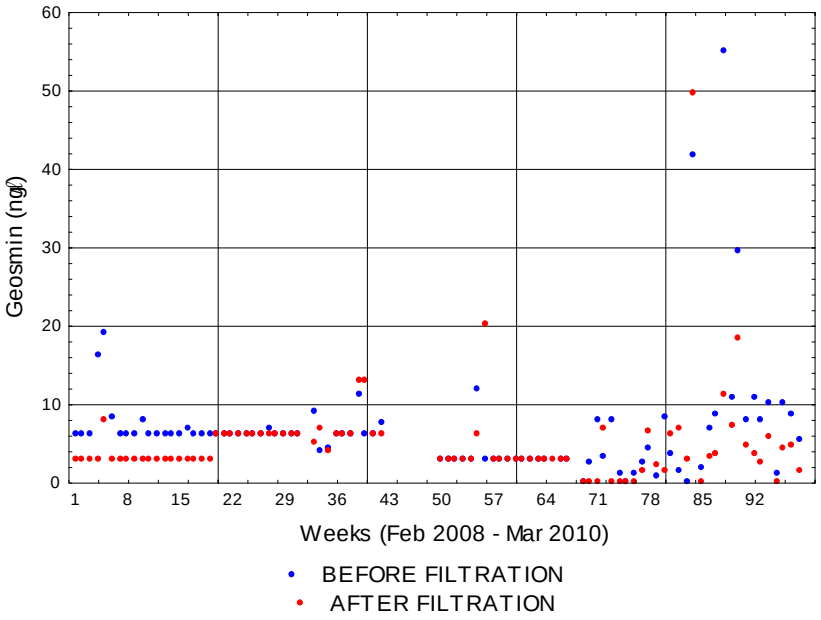


Figure 4.20a: The measured concentrations of geosmin (ng/ℓ) before and after filtration for the study period February 2008 to March 2010.

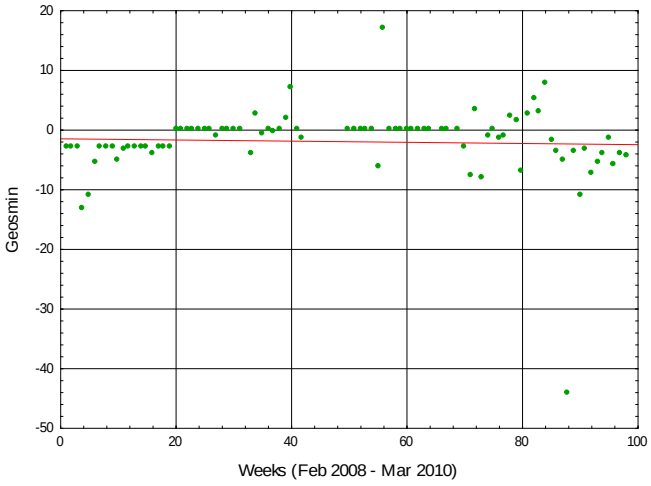


Figure 4.20b: The statistical differences in the concentrations of geosmin measured before and after filtration.

4.4.2.3: Total Chlorophyll

The total chlorophyll concentrations before filtration varied between 0 and 10 µg/ℓ for most of the weeks except for the period, weeks 50 to 57 when they were higher than 30 µg/ℓ. After filtration, the concentrations of total chlorophyll varied between 0 and 5 µg/ℓ for the entire study period (Figure 4.21a). There is statistically significant difference ($p < 0.001$) between the data measured before and after filtration and therefore filtration was successful in reducing the total chlorophyll in the water (Figure 4.21b).

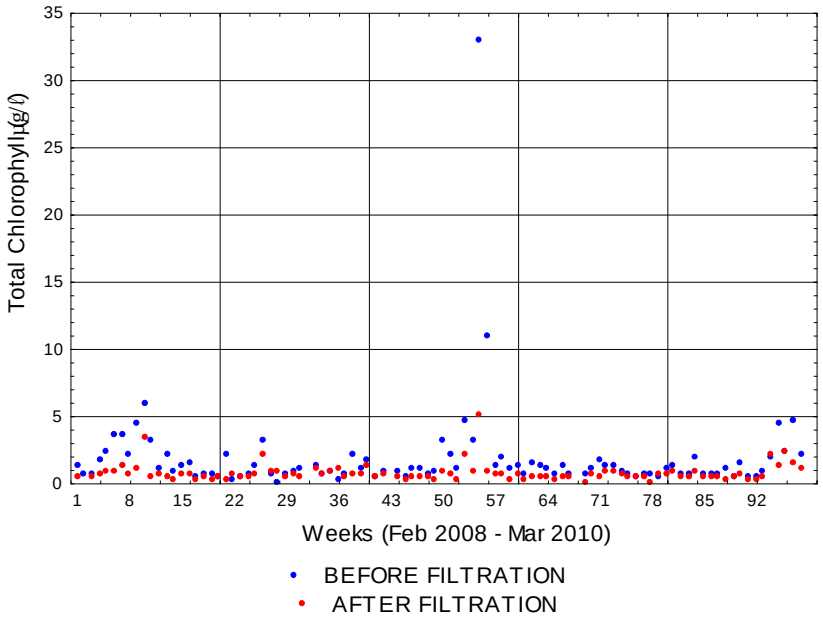


Figure 4.21a: The measured concentrations of total chlorophyll-*a* (µg/ℓ) before and after filtration for the study period February 2008 to March 2010.

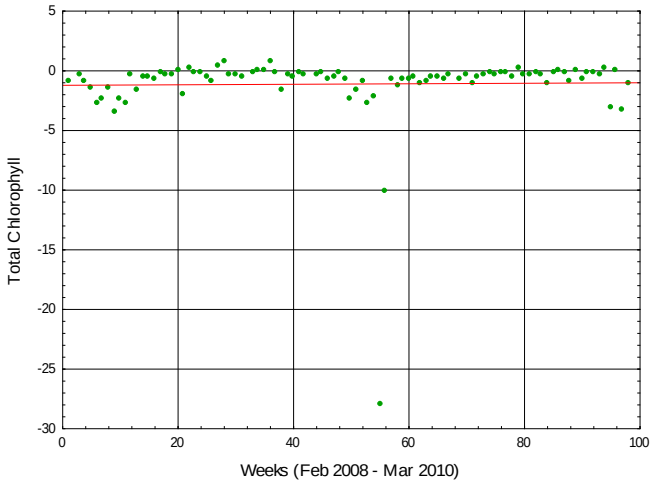


Figure 4.21b: The statistical differences in the concentrations of total chlorophyll measured before and after filtration.

4.3.2.4: Chlorophyll-*a*

The chlorophyll-*a* concentrations before filtration usually varied between 0 and 4 µg/ℓ for most of the weeks, but were higher during weeks 8 to 15 and 50 to 57. After filtration the concentrations of chlorophyll-*a* varied between 0 and 10 µg/ℓ with a higher concentration observed after week 50. There is statistically significant difference (p = 0.001) between the data measured before and after filtration and therefore filtration was successful in reducing the chlorophyll-*a* in the water (Figure 4.22b).

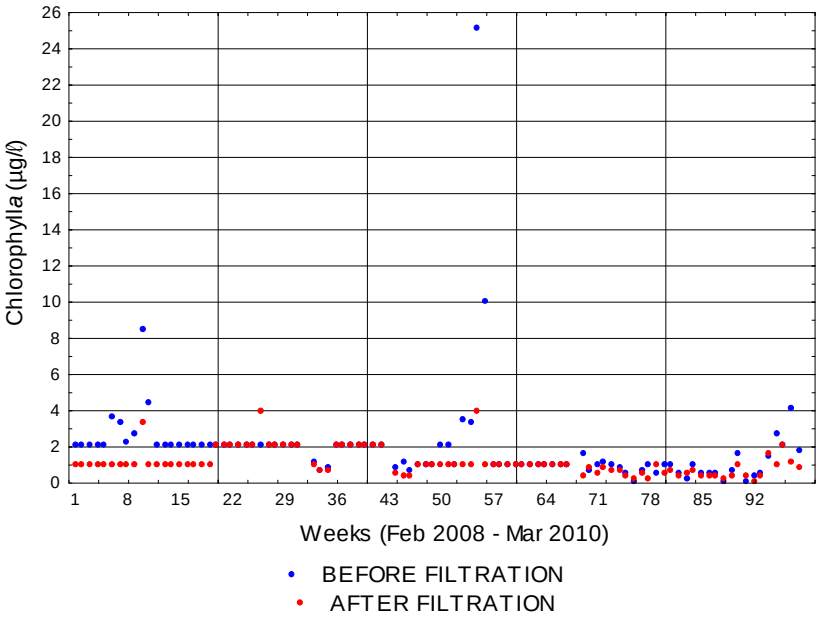


Figure 4.22a: The measured concentrations of chlorophyll-*a* (µg/ℓ) before and after filtration for the study period February 2008 to March 2010.

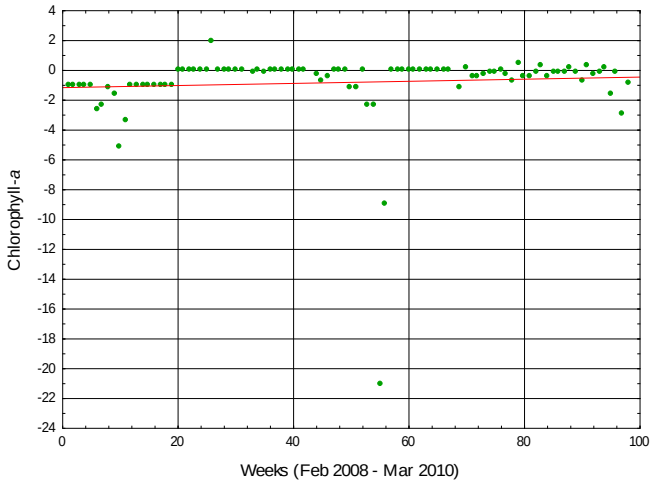


Figure 4.22b: The statistical differences in the concentrations of chlorophyll-*a* measured before and after filtration.

4.4.2.5: Total Organic Carbon (TOC)

The concentrations of TOC before and after filtration usually varied between 3 and 5 mg/ℓ (Figure 4.23a). Although the concentration before and after filtration varied between 3 and 5 mg/ℓ, the concentrations of TOC after filtration were always lower. There is statistically significant difference ($p < 0.001$) between the data measured before and after filtration and therefore filtration was successful in reducing the TOC in the water (Figure 4.23b).

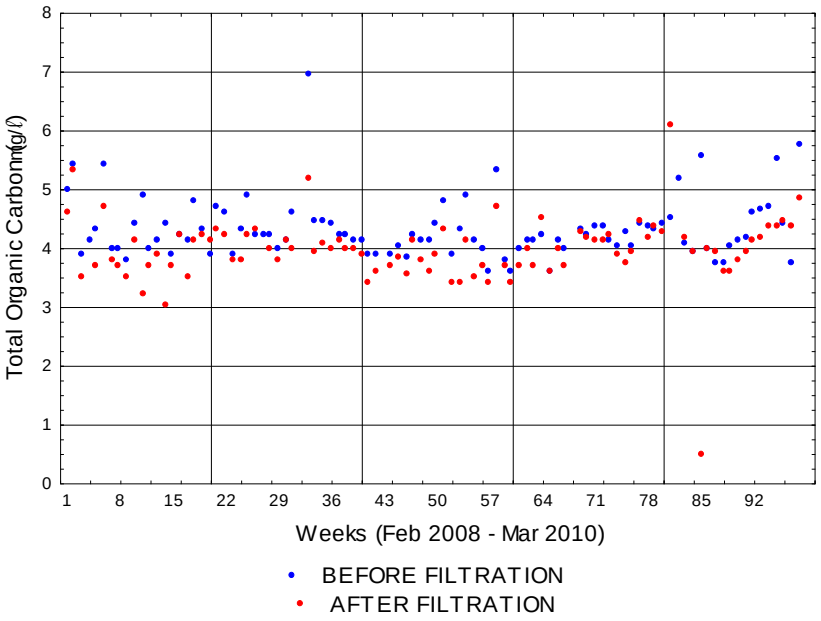


Figure 4.23a: The measured concentrations of total organic carbon (mg/ℓ) before and after filtration for the study period February 2008 to March 2010.

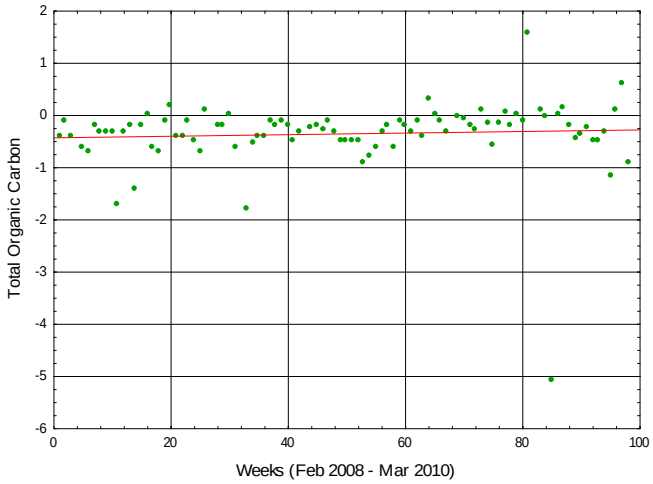


Figure 4.23b: The statistical differences in the concentrations of total organic carbon measured before and after filtration.

4.3.2.6: Cyanophyceae

During weeks 1 to 78 the concentrations of Cyanophyceae before filtration varied between 0 and 2000 cells/mℓ and from week 78 towards the end of study period between 0 and 6000 cells/mℓ. The concentrations of Cyanophyceae after filtration declined and varied between of 0 and 500 cells/mℓ for the entire study period (Figure 4.24a). Although filtration reduced the concentration of the Cyanophyceae cells Figure 4.24b shows a regression line with a slope indicating that the t-test cannot be used to determine if the data before and after filtration differed statistically, because the data was time dependent.

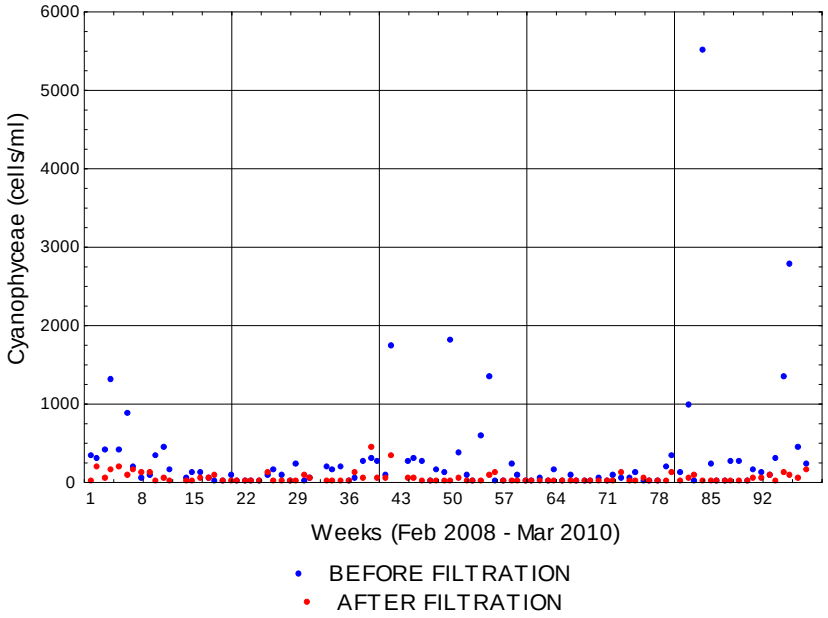


Figure 4.24a: The measured concentrations of Cyanophyceae (cells/mℓ) before and after filtration for the study period February 2008 to March 2010.

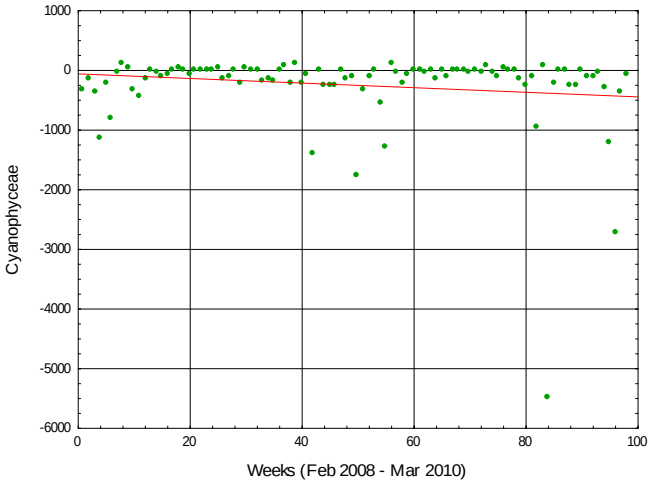


Figure 4.24b: The statistical differences in the concentrations of Cyanophyceae detected before and after filtration.

4.3.2.7: Bacillariophyceae

Before filtration the Bacillariophyceae concentrations varied between 0 and 100 cells/mℓ for most of the study period, with higher concentrations during week 8 to 15; week 36 and week 43 to 50 (Figure 4.25a). After filtration the concentrations of Bacillariophyceae varied between 0 and 100 cells/mℓ. Although filtration reduced the numbers of Bacillariophyceae cells in the water, Figure 4.25b shows a regression line with a slope indicating that the t-test cannot be used because the data was time dependent. The distribution of data points between weeks 40 and 60 also indicates the time dependency and that the t-test cannot be used to determine the statistical differences in the data before and after filtration.

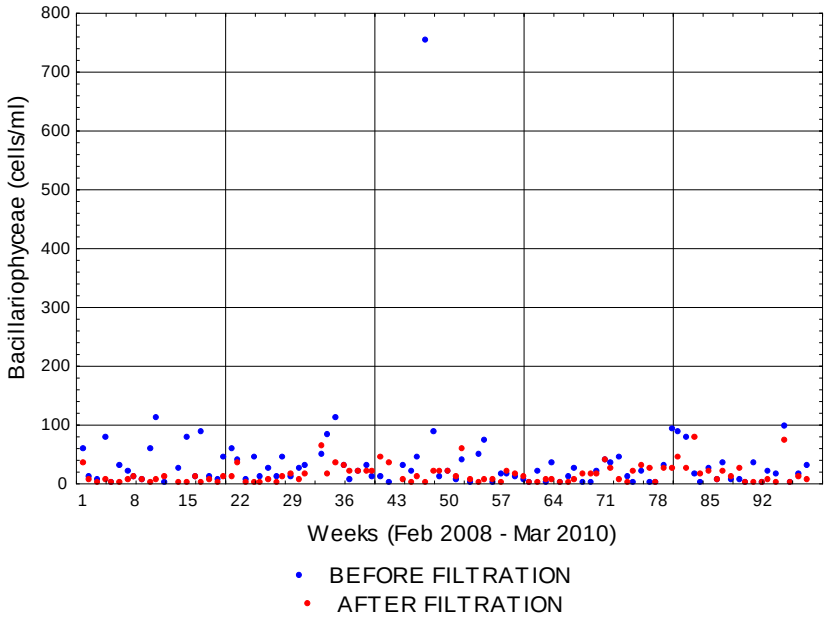


Figure 4.25a: The measured concentrations of Bacillariophyceae (cells/mℓ) before and after filtration for the study period February 2008 to March 2010.

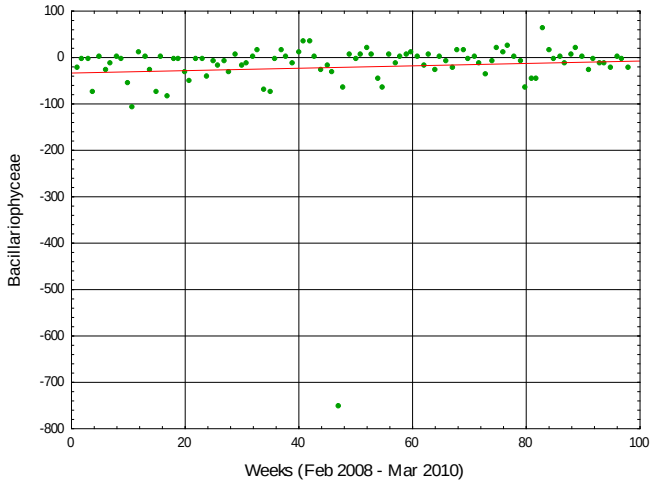


Figure 4.25b: The statistical differences in the concentrations of Bacillariophyceae detected before and after filtration.

4.3.2.8: Chlorophyceae

The Chlorophyceae concentrations before filtration for weeks 1 - 6 varied between 0 and 600 cells/mℓ but for most of the study period it varied between 0 and 200 cells/mℓ. The concentrations of Chlorophyceae after filtration varied between 0 and 100 cells/mℓ, except for weeks 36 to 43 (Figure 4.26a). Although filtration reduced the Chlorophyceae cells in the water Figure 4.26b shows a regression line with a slope indicating that the t-test cannot be used because the data was time dependent. This fact as well as the scattered distribution of data points between weeks 1 and 60 also indicates the time dependency and that the t-test cannot be used to determine the statistical differences in the data before and after filtration.

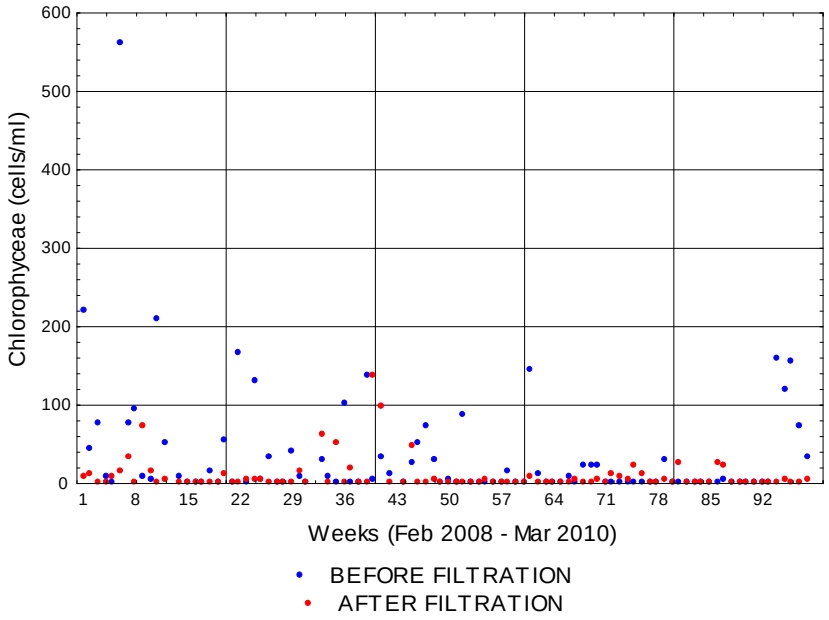


Figure 4.26a: The measured concentrations of Chlorophyceae (cells/mℓ) before and after filtration for the study period February 2008 to March 2010.

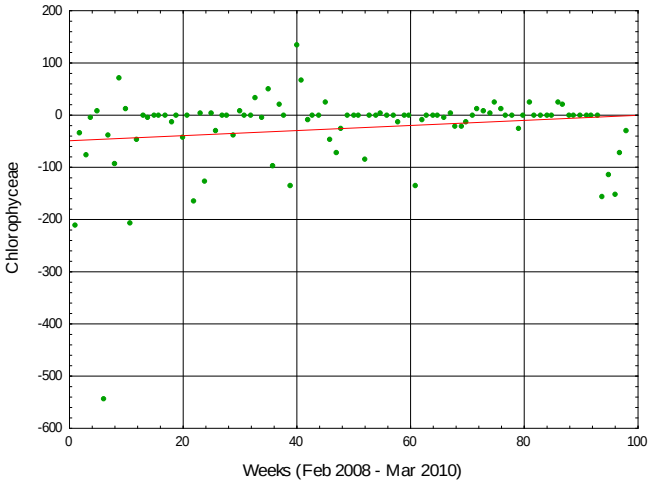


Figure 4.26b: The statistical differences in the concentrations of Chlorophyceae detected before and after filtration.

4.3.2.9: Cryptophyceae

The Cryptophyceae concentrations varied between 0 and 20 cells/mℓ before filtration, while the concentrations varied between 0 and 6 cells/mℓ after filtration, for the entire study period (Figure 4.27a). Although filtration reduced the Cryptophyceae cells, Figure 4.27b shows a regression line with a slope indicating that the t-test cannot be used because the data was time dependent. This fact as well as the scattered distribution of data points throughout the study period also indicates the time dependency and that the t-test cannot be used to determine the statistical difference in the data before and after filtration.

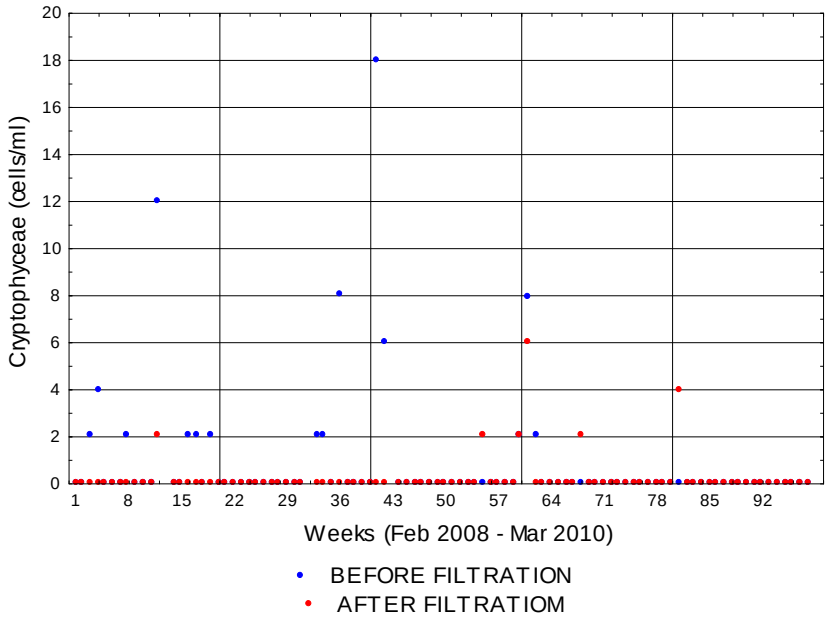


Figure 4.27a: The concentrations of Cryptophyceae (cells/mℓ) before and after filtration for the study period February 2008 to March 2010.

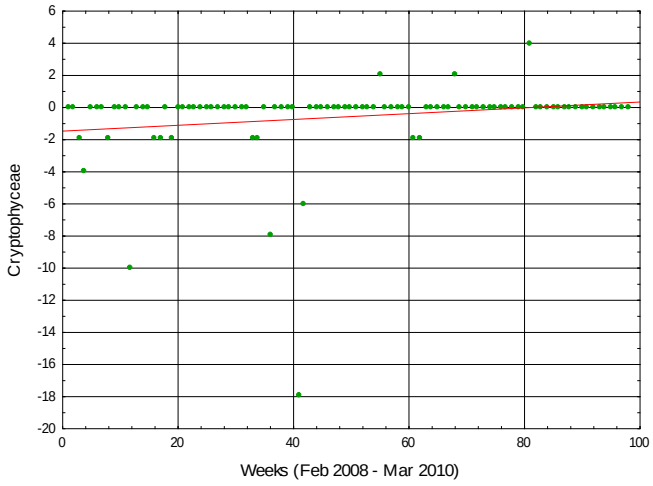


Figure 4.27b: The statistical differences in the concentrations of Cryptophyceae detected before and after filtration.

4.3.2.10: Dinophyceae

The concentration of Dinophyceae, in this case *Ceratium* cells, before filtration varied between 0 and 60 cells/mℓ, except for weeks 50 to 64 (Figure 4.28a). After filtration the concentration of the cells varied between 0 and 20 cells/mℓ except for weeks 50 to 64. It seems that filtration is less effective during higher concentrations of *Ceratium* cells. There is a statistically significant difference ($p < 0.001$) between the data measured before and after filtration and therefore filtration was successful in reducing the *Ceratium* cells in the water (Figure 4.28b).

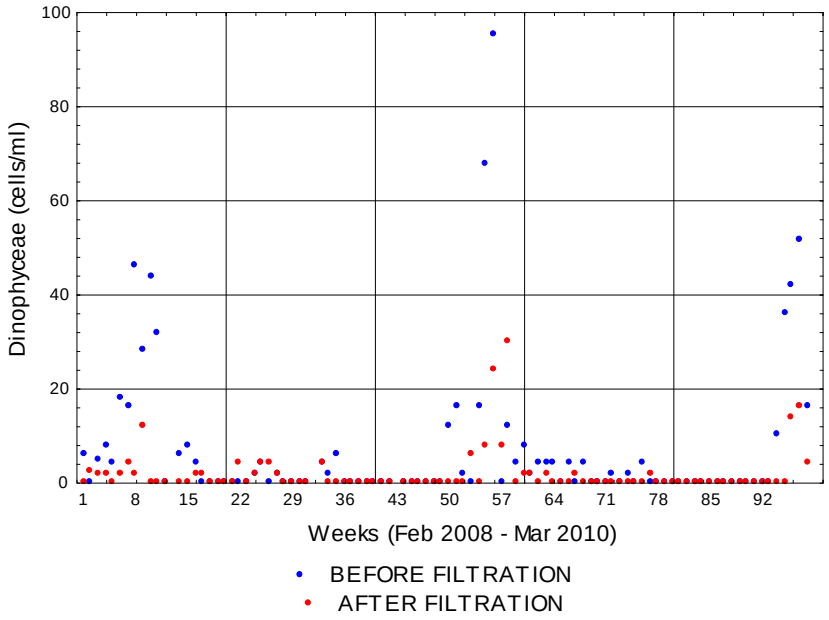


Figure 4.28a: The measured concentrations of Dinophyceae (cells/mℓ) before and after filtration for the study period February 2008 to March 2010.

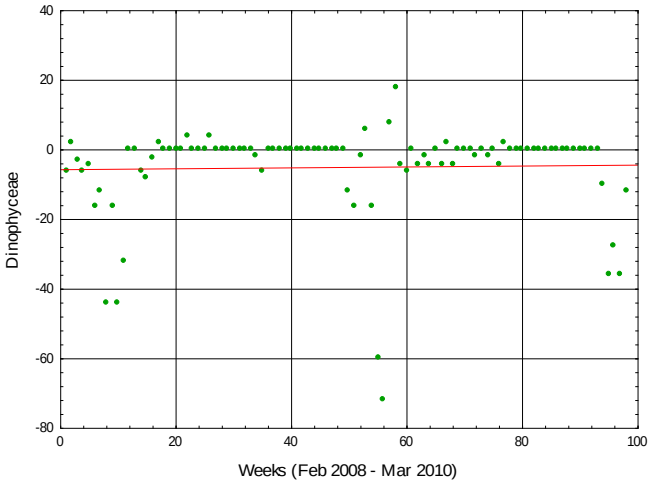


Figure 4.28b: The statistical differences in the concentrations of Dinophyceae detected before and after filtration.

4.3.2.11: Euglenophyceae

The concentration of Euglenophyceae before and after filtration varied between 0 and 18 cells/mℓ. In some instances higher counts were observed after filtration (Figure 4.29a). Figure 4.29b shows a regression line with a slope indicating that the t-test cannot be used because the data was time dependent. This fact as well as the scattered distribution of data points throughout the study period also indicates the time dependency and that the t-test cannot be used to determine the statistical differences in the data before and after filtration.

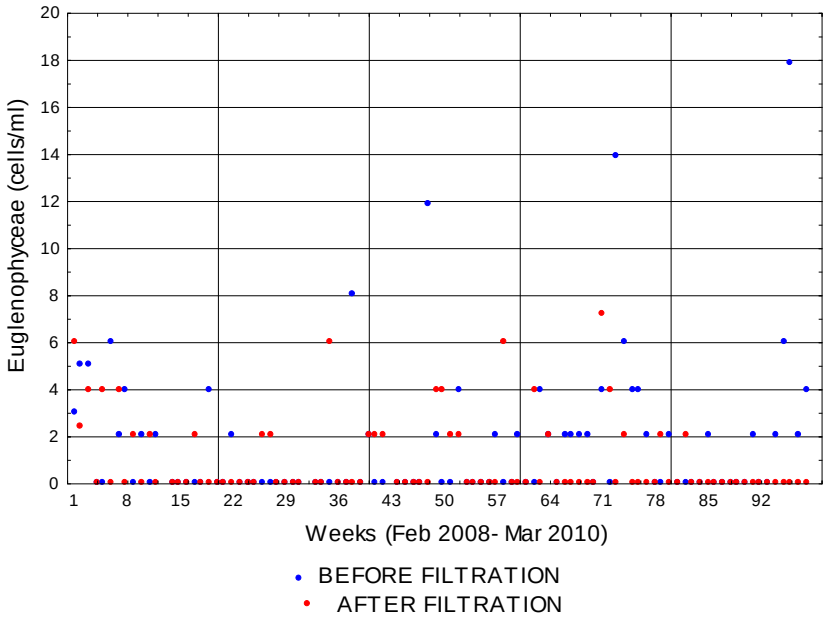


Figure 4.29a: The measured concentrations of Euglenophyceae (cells/mℓ) before and after filtration for the study period February 2008 to March 2010.

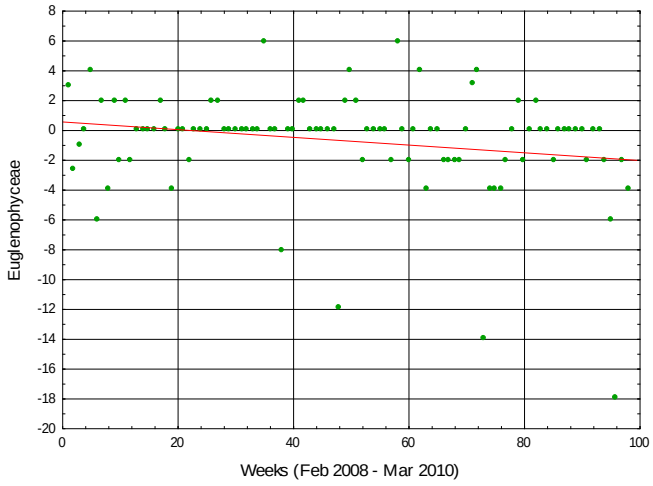


Figure 4.29b: The statistical differences in the concentrations of Euglenophyceae detected before and after filtration.

4.3.2.12: *Anabaena* species

The concentrations of *Anabaena* sp. before filtration varied between 0 and 2000 cells/mℓ during weeks 1 to 78 and between 0 and 6000 cells/mℓ from week 78 towards the end of the study period. After filtration the cell count varied between 0 and 500 cells/mℓ (Figure 4.30a). Although filtration reduced the *Anabaena* cells in the water Figure 4.30b shows a regression line with a slope, indicating that the t-test cannot be used because the data was time dependent. This fact as well as the distribution of data points from week 80 until the end of the study period also indicates the time dependency and that the t-test cannot be used to determine the statistical differences in the data before and after filtration.

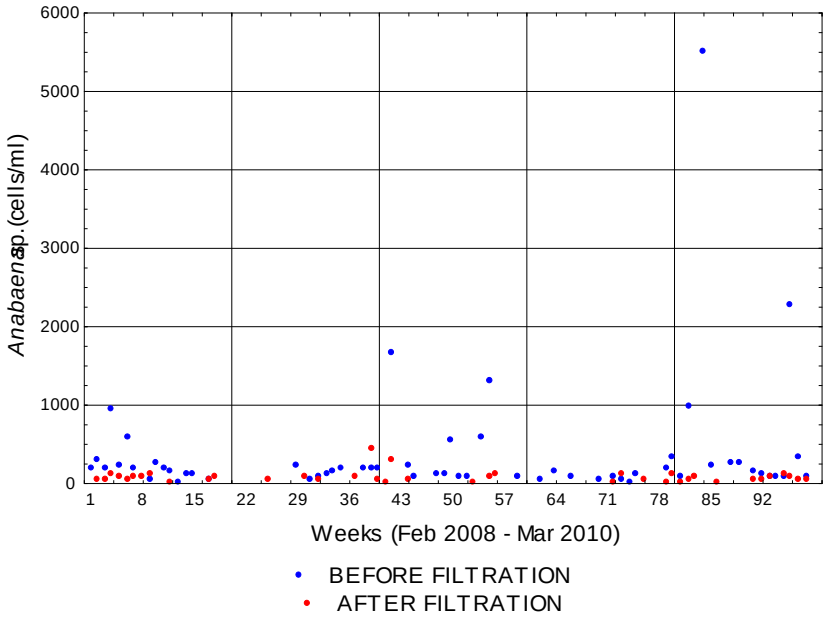


Figure 4.30a: The measured concentrations of *Anabaena* sp. (cells/mℓ) before and after filtration for the study period February 2008 to March 2010.

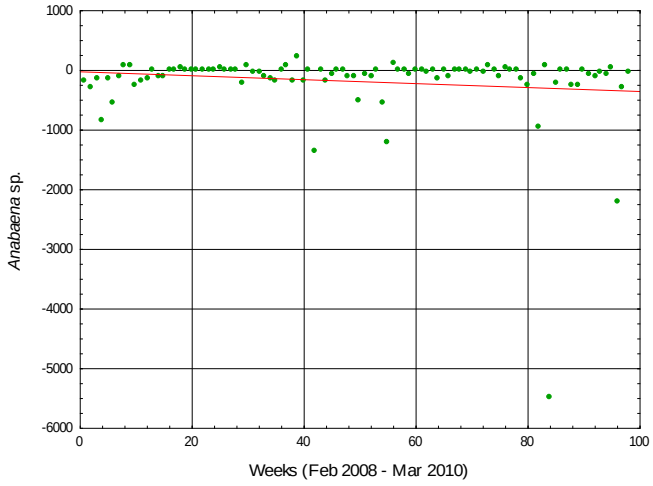


Figure 4.30b: The statistical differences in the concentrations of *Anabaena* sp. before and after filtration.

4.3.2.13: *Microcystis* species

The concentrations of *Microcystis* sp. varied between 0 and 1400 cells/mℓ before filtration and between 0 and 200 cells/mℓ after filtration (Figure 4.32a). Although filtration reduced *Microcystis* cells in the water, Figure 4.31b shows a regression line with a slope indicating that the t-test cannot be used because the data was time dependent. This fact as well as the distribution of data points between weeks 40 to 60, and 80 until the end of the study period also indicates the time dependency and that the t-test cannot be used to determine the statistical differences in the data before and after filtration.

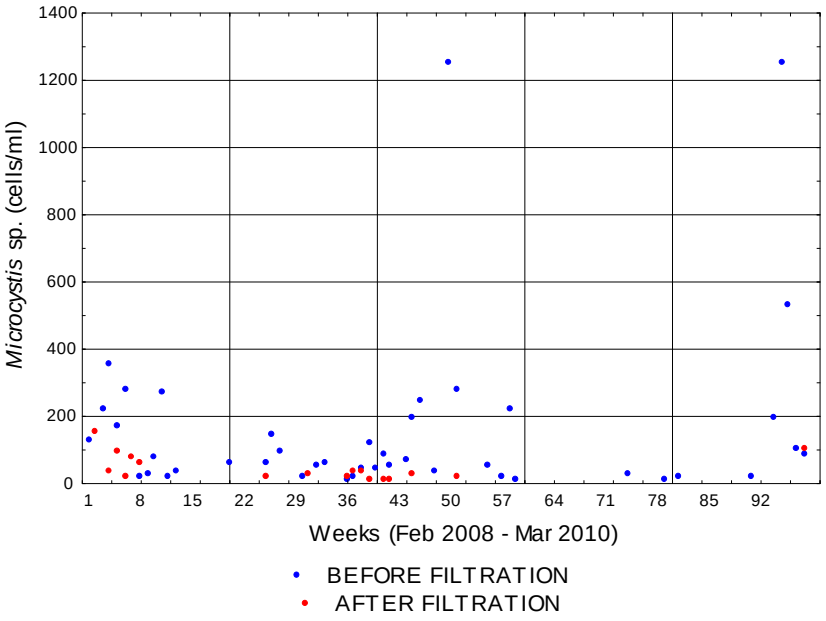


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Figure 4.31a: The measured concentrations of *Microcystis* sp. (cells/mℓ) before and after filtration for the study period February 2008 to March 2010.

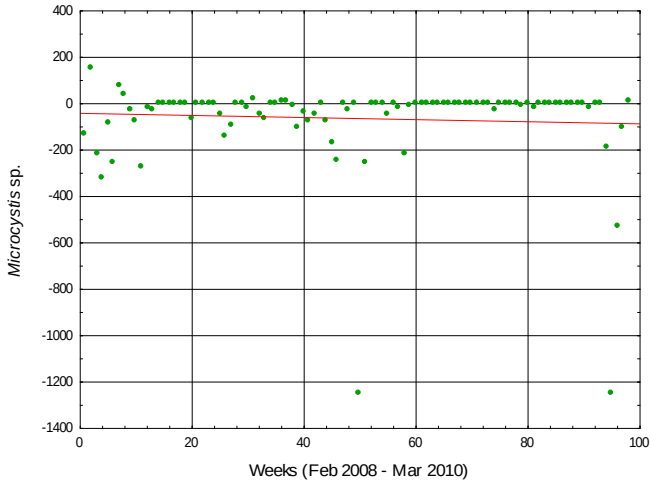

Figure 4.31b: The statistical differences in the concentrations of *Microcystis* sp. before and after filtration.

4.3.2.14: *Oscillatoria* species

Oscillatoria cells were sometimes found in water after filtration but not before filtration. It may be due to low concentrations of this organism in the water and that *Oscillatoria* filaments were not sampled. Therefore, the efficacy of this step in the purification plant to reduce *Oscillatoria* cells cannot be determined.

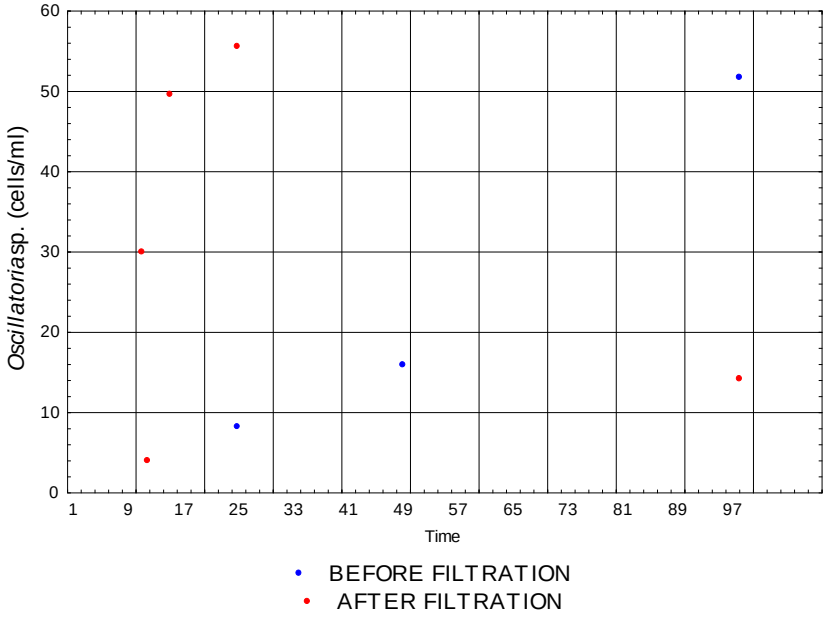

Figure 4.32: The measured concentrations of *Oscillatoria* sp. (cells/mℓ) before and after filtration for the study period February 2008 to March 2010.

4.3.3: A comparison of the data measured after filtration and the final water.

In this section the concentration of 2-Methylisoborneol (MIB), geosmin, total chlorophyll, chlorophyll-*a*, total organic carbon (TOC), algal groups (Cyanophyceae, Bacillariophyceae, Chlorophyceae, Cryptophyceae, Dinophyceae and Euglenophyceae) and algal genera (*Anabaena* sp., *Microcystis* sp., *Oscillatoria* sp. and *Ceratium* sp.) are compared after filtration and in the final water to determine the efficacy of chlorination in purification processes.

4.3.3.1: 2-Methylisoborneol (MIB)

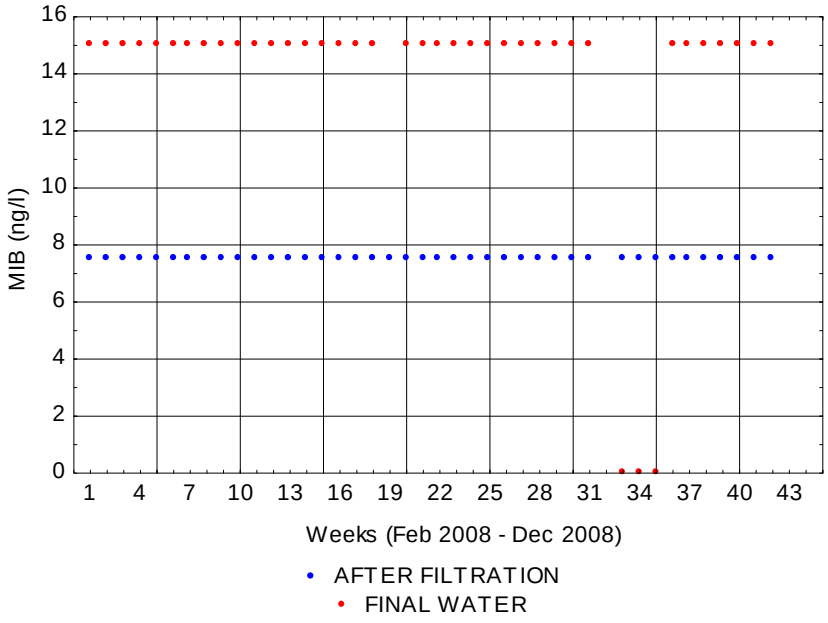

Figure 4.33: The measured concentrations of MIB (ng/ℓ) after filtration and in the final water for the study period Feb 2008 to December 2008.

The concentrations of MIB were always higher in the final water (15 ng/ℓ) than after filtration (8 ng/ℓ) and it seems that chlorination does not remove MIB from the water.

4.3.3.2: Geosmin

The concentrations of geosmin were measured between 0 and 50 ng/ℓ after filtration and between 0 and 20 ng/ℓ in the final water (Figure 4.34a). The slope of the regression line in Figure 4.34b indicates that the measurements of geosmin were time dependent. This fact as well as the scattered distribution in the data points between weeks 25 until the end of the study period indicates that the t-test cannot be used to determine statistical differences in the data.

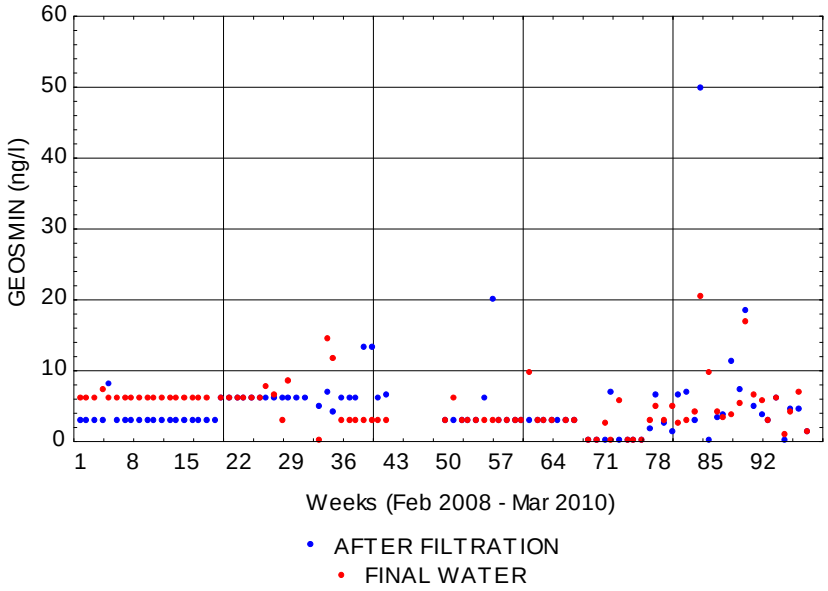

Figure 4.34a: The measured concentrations of geosmin (ng/ℓ) after filtration and in the final water for the study period February 2008 to March 2010.

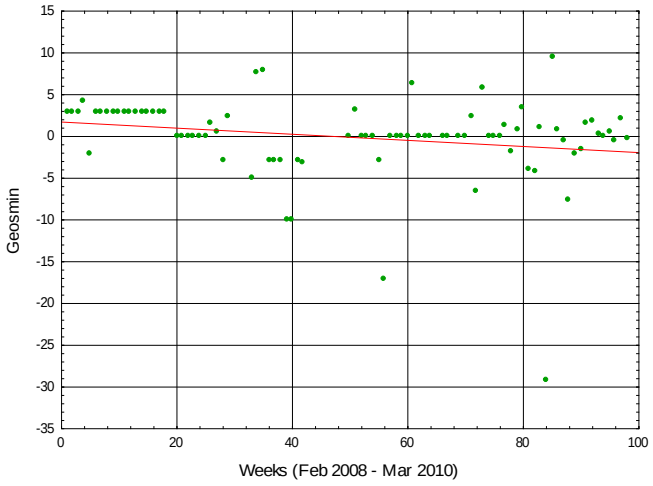

Figure 4.34b: The statistical differences in the concentrations of geosmin measured after filtration and in the final water.

4.3.3.3: Total Chlorophyll

The total chlorophyll concentration varied between 0 and 5 µg/ℓ after filtration and was lower than 1 µg/ℓ in the final water (Figure 4.35a). It seem as if chlorination played a huge role in removing total chlorophyll pigments from the water. The slope of the regression line in Figure 4.35b indicates that the measurements of total chlorophyll were time dependent. This fact as well as the scattered distribution in the data points throughout the study period indicates that the t-test cannot be used to determine statistical differences in the data.

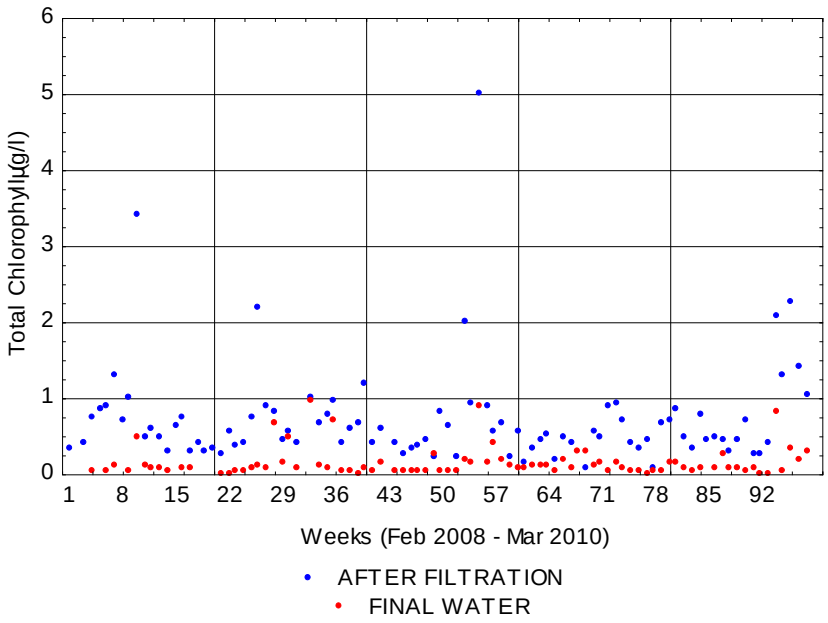

Figure 4.35a: The measured concentrations of total chlorophyll (µg/ℓ) after filtration and in the final water for the study period Feb 2008 to March 2010.

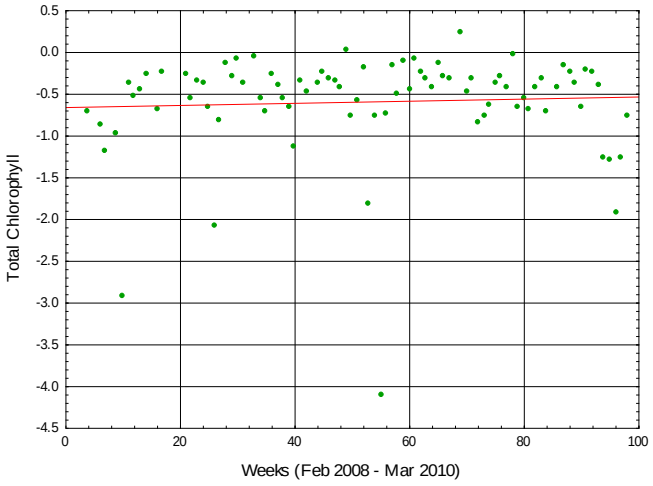

Figure 4.35b: The statistical differences in the concentrations of total chlorophyll measured after filtration and in the final water.

4.3.3.4: Chlorophyll-*a*

The chlorophyll-*a* concentration after filtration was less than 1 µg/ℓ for most of the time except for a few spikes (Figure 4.36a). The chlorophyll-*a* concentrations in the final water were sometimes higher than after filtration (especially during weeks 1 to 29). The slope of the regression line in Figure 4.36b indicates that the measurements of chlorophyll-*a* were time dependent. This fact as well as the scattered distribution in the data points throughout the study period indicates that the t-test cannot be used to determine statistical differences in the data.

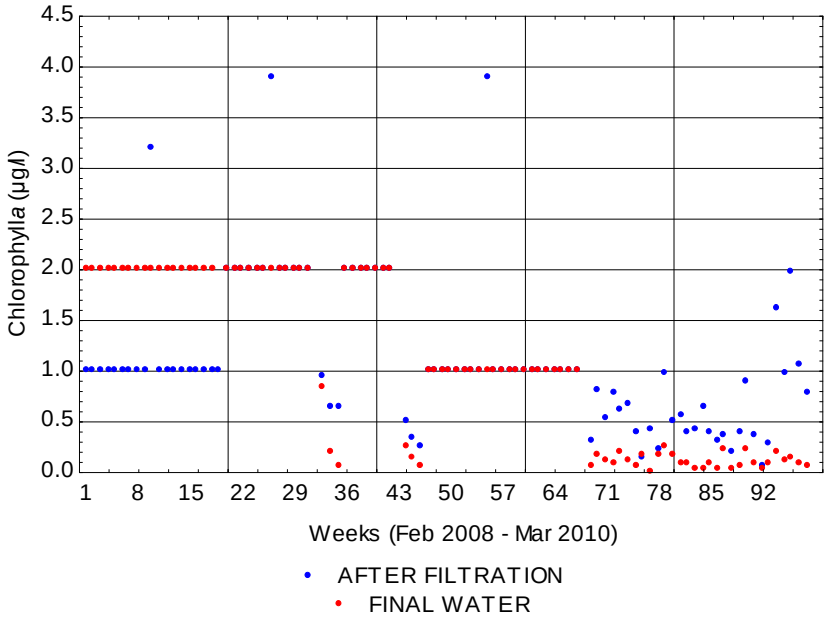

Figure 4.36a: The measured concentrations of chlorophyll-*a* (µg/ℓ) after filtration and in the final water for the study period Feb 2008 to March 2010.

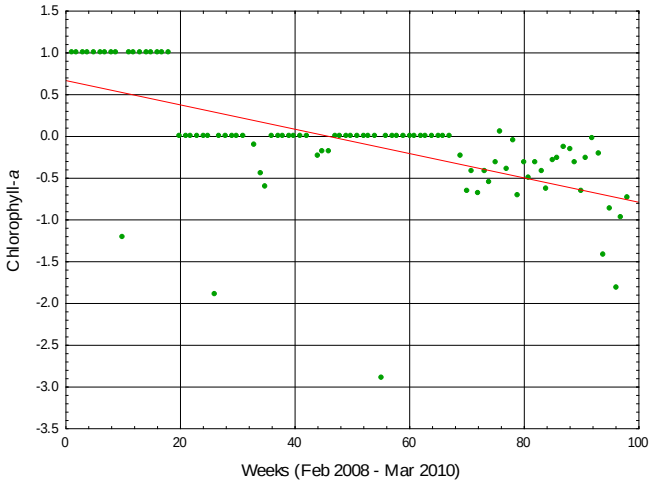

Figure 4.36b: The statistical differences in the concentrations of chlorophyll-*a* measured after filtration and in the final water.

4.3.3.5: Total Organic Carbon (TOC)

The concentration of TOC both after filtration and the final water were measured between the ranges of 3 and 5 mg/ℓ during the study period, There is not a statistically significant difference (p=0.100) between the data after filtration and the final water and therefore this step in the purification process was not successful in reducing TOC in the water.

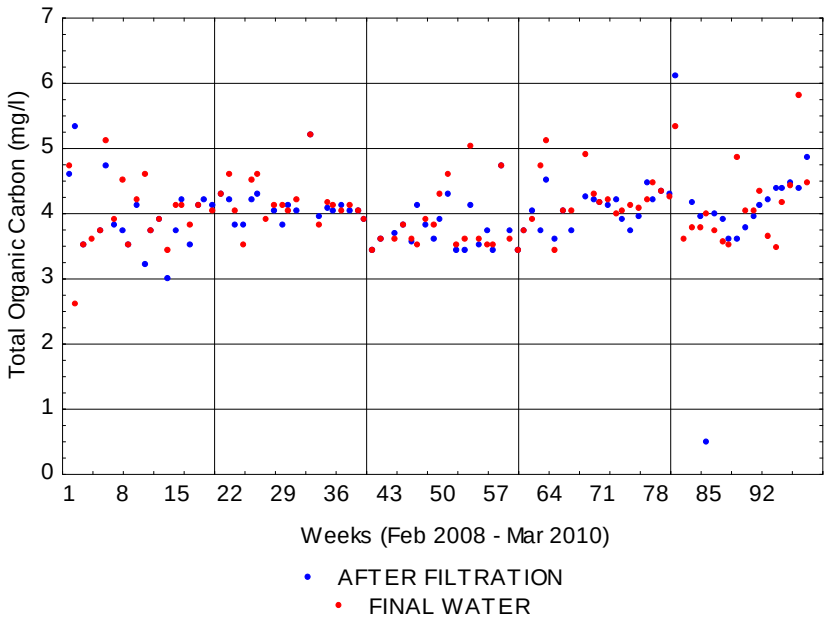

Figure 4.37a: The measured concentrations of TOC (mg/ℓ) after filtration and in the final water for the study period Feb 2008 to March 2010.

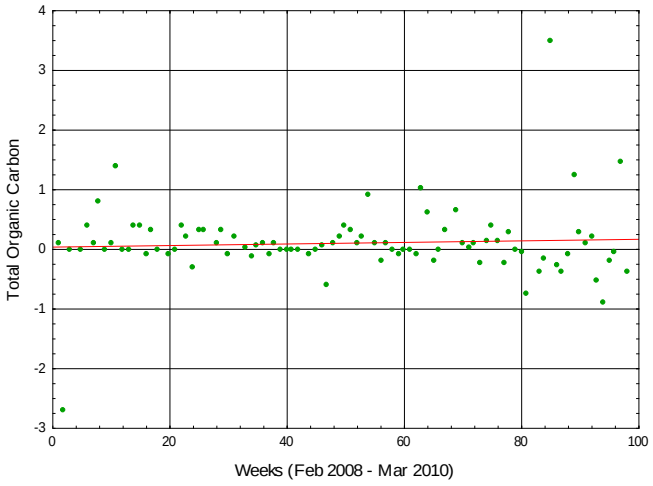

Figure 4.37b: The statistical differences in the concentrations of TOC measured after filtration and in the final water.

4.3.3.6: Cyanophyceae

The concentrations of Cyanophyceae cells varied between 0 and 450 cells/mℓ before filtration and between 0 and 150 cells/mℓ in the final water (Figure 4.38a). Figure 4.38b shows a regression line with a slope indicating that the t-test cannot be used because the data was time dependent. The scattered distribution in the data points throughout the study period also confirms the time dependency and that the t-test cannot be used to determine statistical differences in the data.

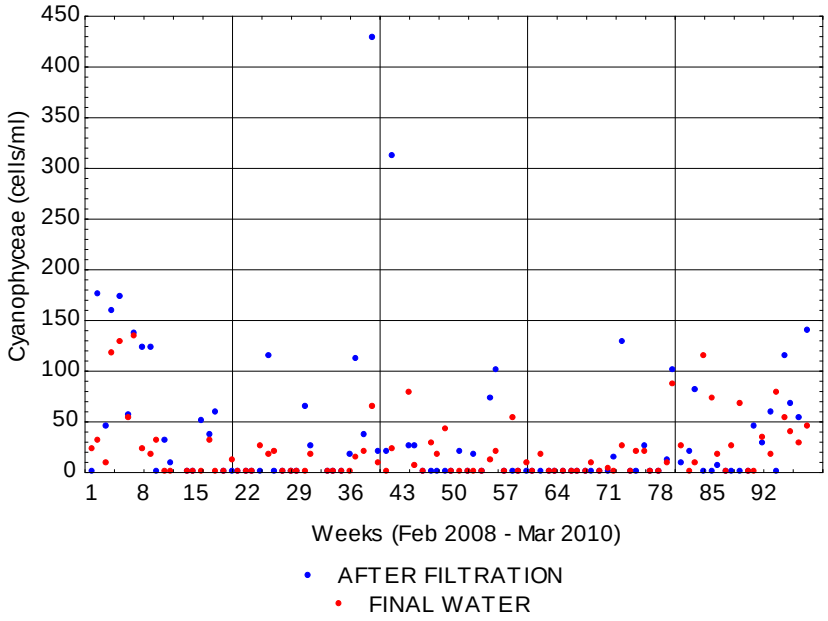

Figure 4.38a: The measured concentrations of Cyanophyceae (cells/mℓ) after filtration and in the final water for the study period Feb 2008 to March 2010.

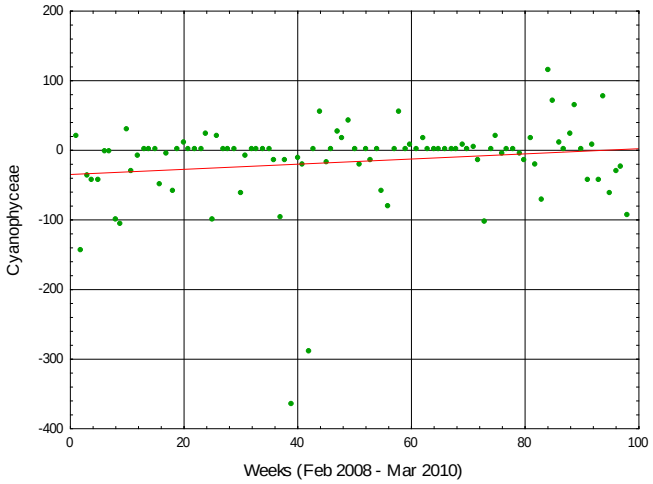

Figure 4.38b: The statistical differences in the concentrations of Cyanophyceae detected after filtration and in the final water.

4.3.3.7: Bacillariophyceae

The concentrations of Bacillariophyceae cells varied between 0 and 80 cells/mℓ after filtration and between 0 and 60 cells/mℓ in the final water. There is statistically a significant difference ($p < 0.001$) between the data measured after filtration and the final water, therefore this step of water purification was successful in reducing the Bacillariophyceae cells in the water (Figure 4.39b).

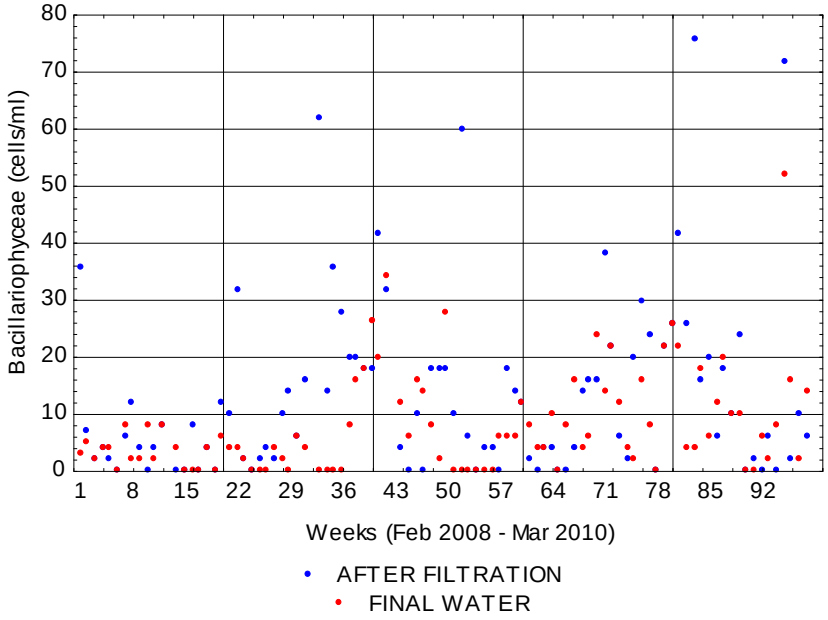

Figure 4.39a: The measured concentrations of Bacillariophyceae (cells/mℓ) after filtration and in the final water for the study period Feb 2008 to March 2010.

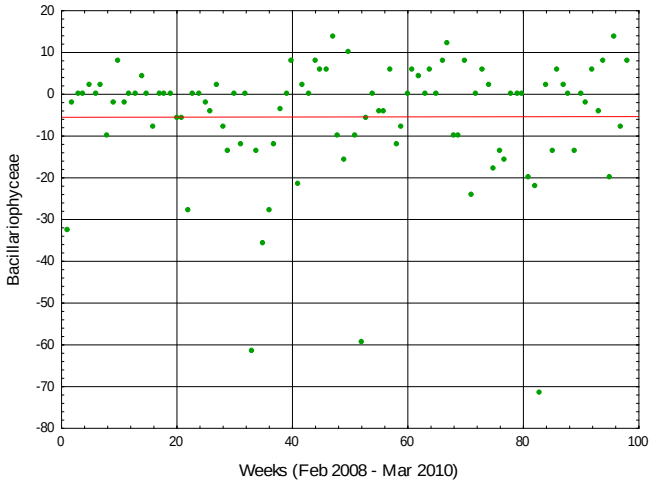

Figure 4.39b: The statistical differences in the concentrations of Bacillariophyceae detected after filtration and in the final water.

4.3.3.8: Chlorophyceae

The concentrations of the Chlorophyceae cells varied between 0 and 140 cells/mℓ after filtration and between 0 and 120 cells/mℓ in the final water (Figure 4.40a). Figure 4.40b shows a regression line with a slope indicating that the t-test cannot be used because the data was time dependent. The scattered distribution in the data points throughout the study period also confirms the time dependency and that the t-test cannot be used to determine statistical differences in the data.

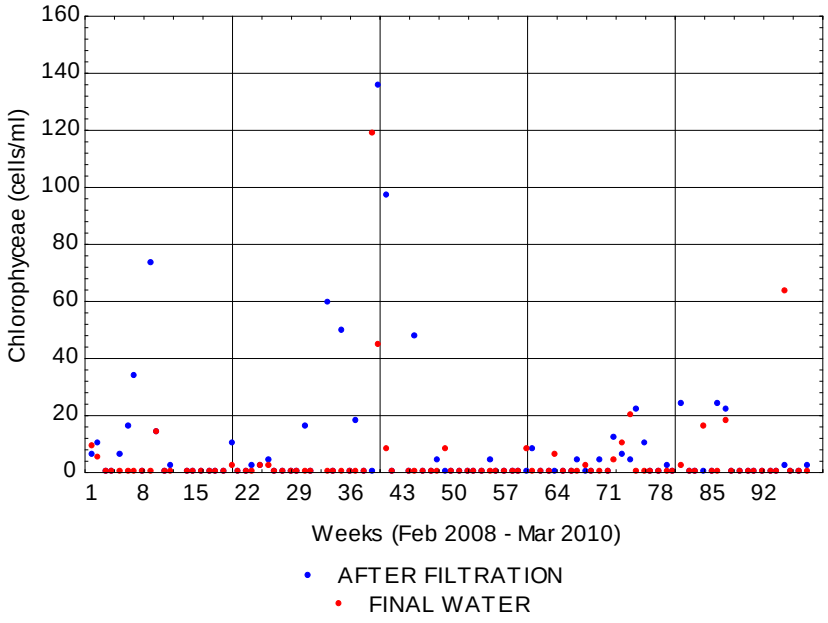

Figure 4.40a: The measured concentrations of Chlorophyceae (cells/mℓ) after filtration and in the final water for the study period Feb 2008 to March 2010.

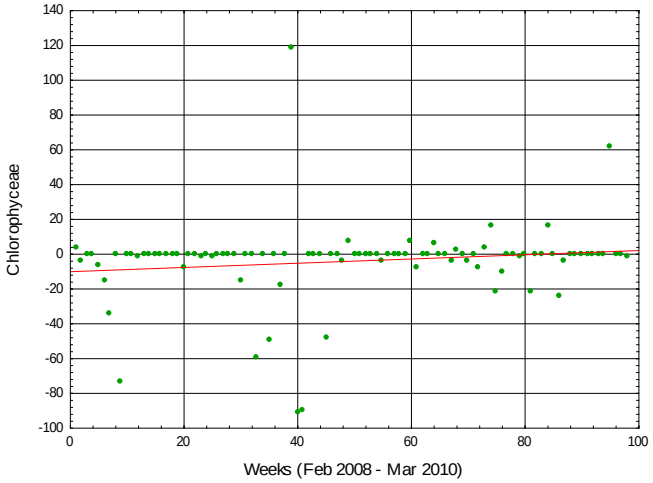

Figure 4.40b: The statistical differences in the concentrations of Chlorophyceae detected after filtration and in the final water.

4.3.3.9: Cryptophyceae

Samples from weeks 1 to 15 contained Cryptophyceae cells in the final water but not in any of other samples. Figure 4.41b shows a regression line with a slope indicating that the t-test cannot be used because the data was time dependent. The scattered distribution in the data points throughout the study period also confirms the time dependency and that the t-test cannot be used to determine statistical differences in the data.

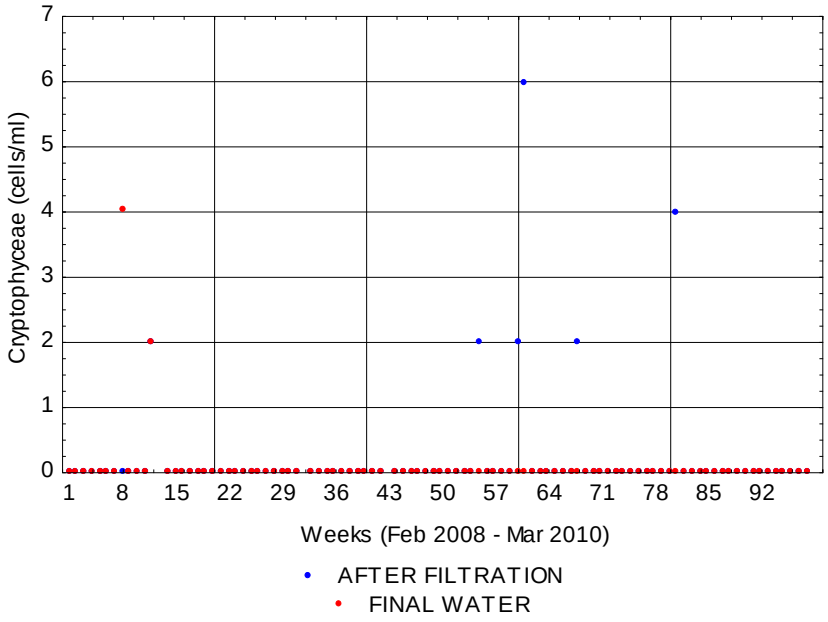

Figure 4.41a: The measured concentrations of Cryptophyceae (cells/mℓ) after filtration and in the final water for the study period Feb 2008 to March 2010.

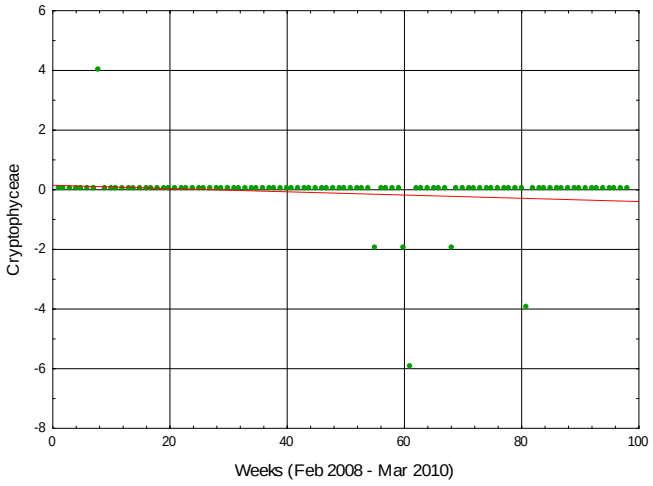

Figure 4.41b: The statistical differences in the concentrations of Cryptophyceae detected after filtration and in the final water.

4.3.3.10: Dinophyceae

Dinophyceae concentration was higher in the final water and lower after filtration for the same weeks during the study period (Figure 4.42a). Higher concentration of Dinophyceae could be due to backwashing of the filters, or other clogging material that trapped the algal cells in the filters (Figure 4.42a). Figure 4.42b shows a regression line with a slope indicating that the t-test cannot be used because the data was time dependent. The scattered distribution in the data points throughout the study period also confirms the time dependency and that the t-test cannot be used to determine statistical differences in the data.

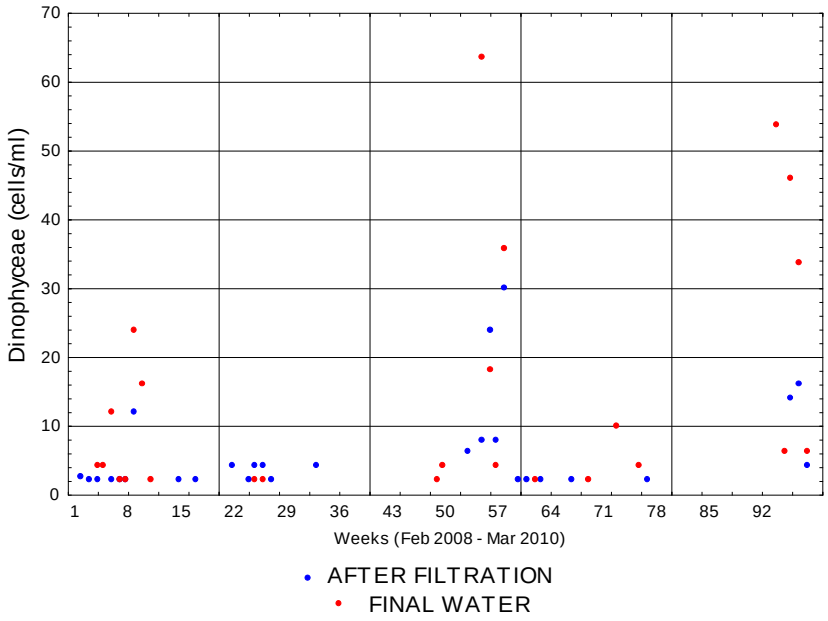

Figure 4.42a: The measured concentrations of the Dinophyceae species *Ceratium* (cells/mℓ) after filtration and in the final water for the study period Feb 2008 to March 2010.

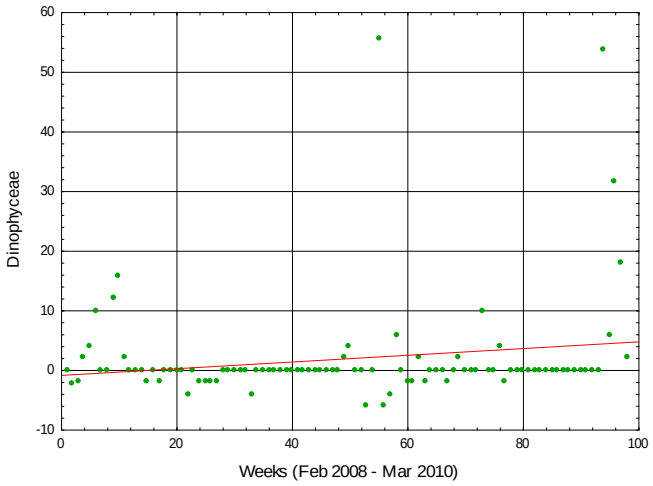

Figure 4.42b: The statistical differences in the concentrations of Dinophyceae species *Ceratium* detected after filtration and in the final water.

4.3.3.11: Euglenophyceae

Lower concentrations were observed in the final water, than after filtrations. It seems as if the filtration and chlorination did reduce the concentration of Euglenophyceae (Figure 4.43a). There is not a statistically significant difference (p=0.723) between the data measured and therefore this step in the purification process did not reduce the Euglenophyceae cells in the water significantly.

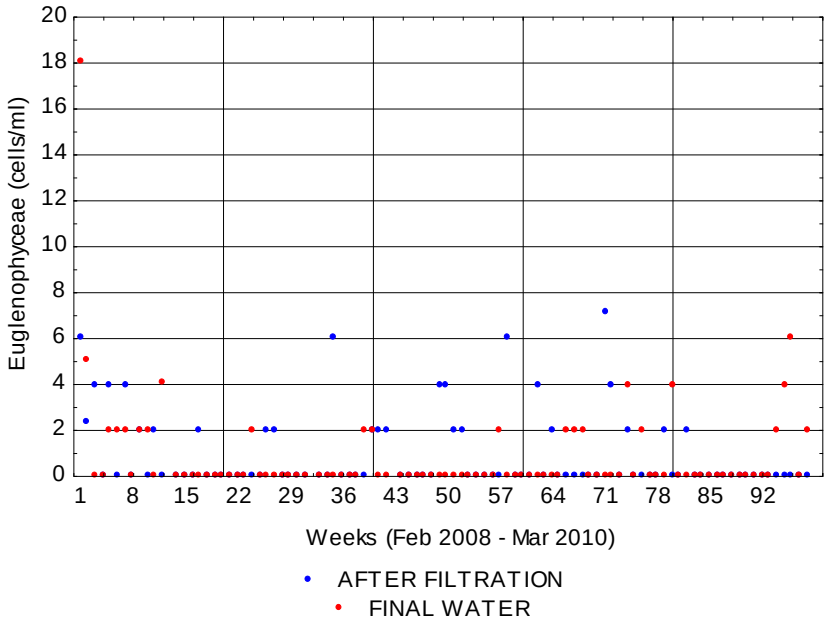

Figure 4.43a: The measured concentrations of Euglenophyceae (cells/mℓ) after filtration and in the final water for the study period Feb 2008 to March 2010.

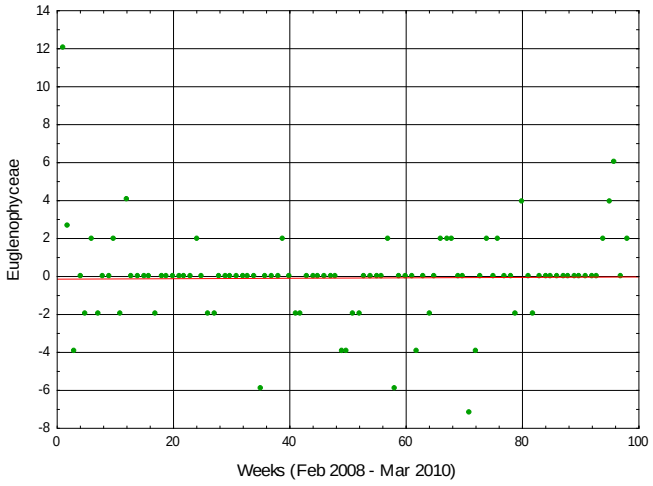

Figure 4.43b: The statistical differences in the concentrations of Euglenophyceae detected after filtration and in the final water.

4.3.3.12: *Anabaena* species

During weeks 36 to 43 high concentrations of *Anabaena* cells were present after filtration, but during the rest of the study period were present in more of less the same concentration after filtration and in the final water. The concentration of the algal cells were not always present at the same time (weeks) after filtration and in the final water (Figure 4.44a). Figure 4.44b shows a regression line with a slope indicating that the t-test cannot be used because the data was time dependent. The scattered distribution in the data points during the study period also confirms the time dependency and that the t-test cannot be used to determine statistical differences in the data.

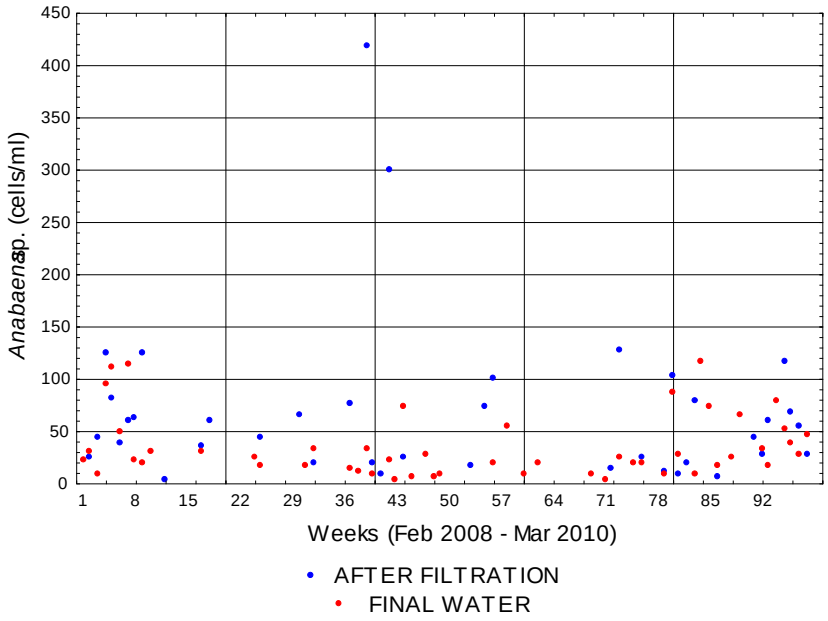

Figure 4.44a: The measured concentrations of *Anabaena* sp. (cells/mℓ) after filtration and in the final water for the study period Feb 2008 to March 2010.

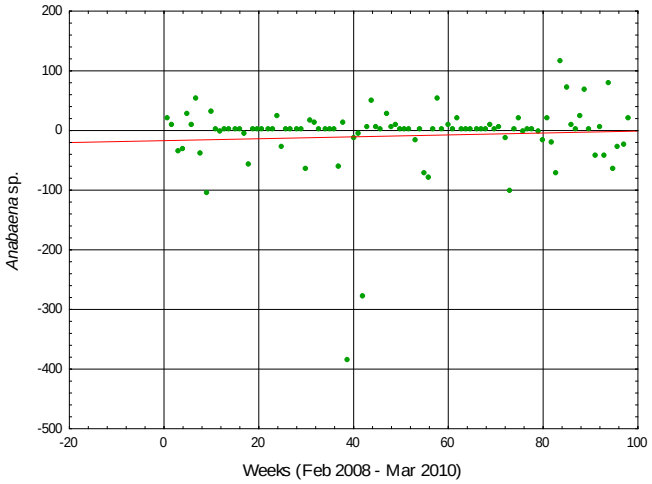

Figure 4.44b: The statistical differences in the concentrations of *Anabaena* sp. detected after filtration and in the final water.

4.3.3.13: *Microcystis* species

Chlorination usually removed *Microcystis* cells were, except for certain periods when concentrations were higher in the final water than after filtration. From Figure 4.45a it is clear that the *Microcystis* cells were not always present at the same time after filtration and in the final water. Figure 4.45b shows a regression line with a slope indicating that the t-test cannot be used because the data was time dependent. The scattered distribution in the data points at the beginning of the study period also confirms the time dependency and that the t-test cannot be used to determine statistical differences in the data.

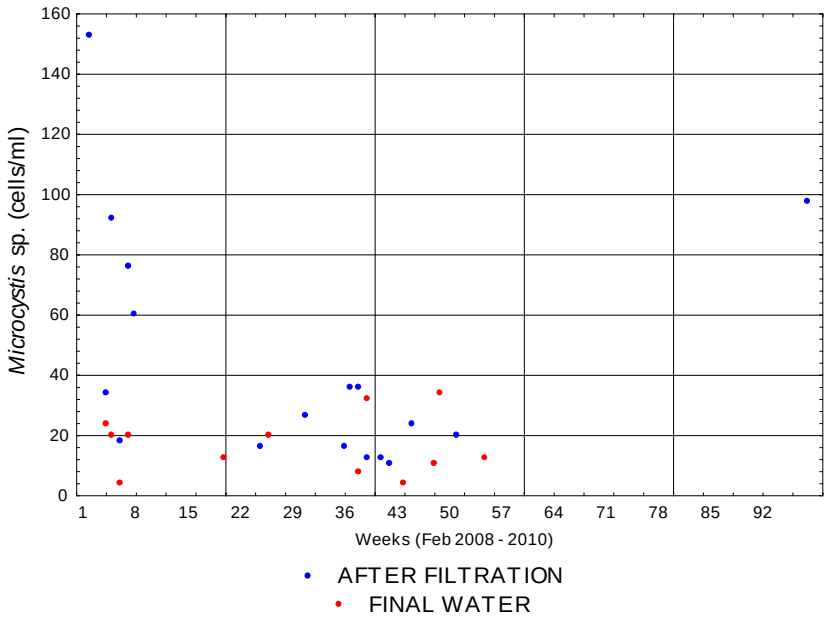

Figure 4.45a: The measured concentrations of *Microcystis* sp. (cells/mℓ) after filtration and in the final water for the study period Feb 2008 to March 2010.

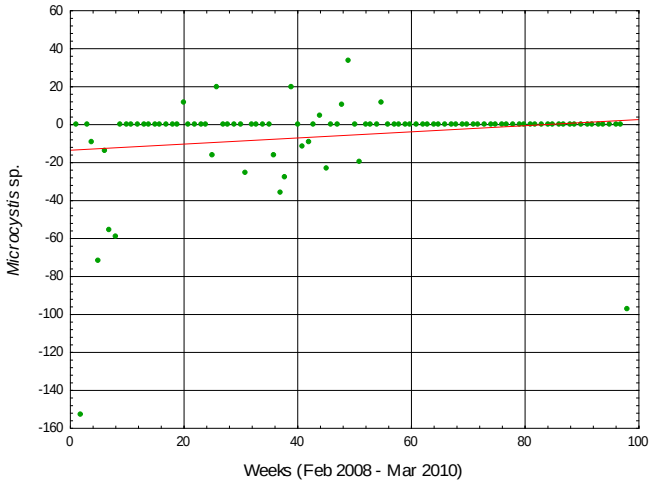

Figure 4.45b: The statistical differences in the concentrations of *Microcystis* sp. detected after filtration and in the final water.

4.3.3.14: *Oscillatoria* species

The concentration of *Oscillatoria* sp. ranged between of 0 and 60 cells/mℓ after filtration with no cells counted in the final water. This step in the purification process removed all the *Oscillatoria* filaments or no *Oscillatoria* filaments were sampled.

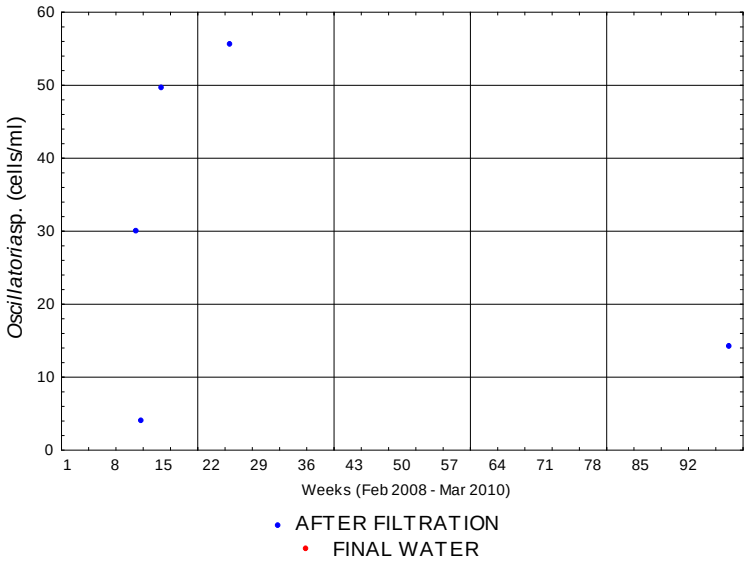

Figure 4.46: The measured concentrations of *Oscillatoria* sp. (cells/mℓ) after filtration and in the final water for the study period Feb 2008 to March 2010.

4.4.4: A comparison of the data of the raw water (canal water) and the final water.

In this section the concentration of 2-Methylisoborneol (MIB), geosmin, total chlorophyll, chlorophyll-*a*, total organic carbon (TOC), algal groups (Cyanophyceae, Bacillariophyceae, Chlorophyceae, Chrysophyceae, Dinophyceae and Euglenophyceae) and algal genera (*Anabaena* sp., *Microcystis* sp., *Oscillatoria* sp. and *Ceratium* sp.) are compared in the raw water and final water to determine the overall efficacy of the purification processes to produce potable drinking water from raw water.

4.3.4.1: 2-Methylisoborneol (MIB)

MIB concentrations in the raw water were measured at 8 ng/ℓ, while in the final water the concentrations were measured at 15 ng/ℓ (Figure 4.47). The purification processes used in the treatment plant did not remove MIB at all, but rather show an increase through the purification process.

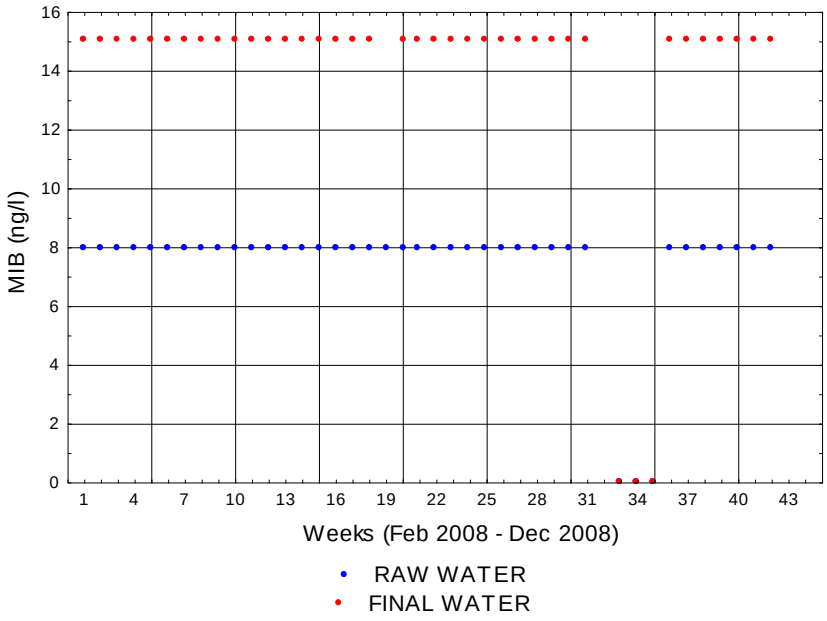

Figure 4.47: The measured concentrations of MIB (ng/ℓ) in the raw and final water for the study period February 2008 to December 2008.

4.3.4.2: Geosmin

Geosmin in the raw water (0 and 100 ng/ℓ) was removed by the purification processes to 0 and 20 ng/ℓ in the final water (Figure 4.48a). Although the purification processes reduced the geosmin in the water, the slope of the regression line in Figure 4.48b indicates that the measurements of geosmin were time dependent. This fact as well as the scattered distribution of the data points during the study period indicates that the t-test cannot be used to determine statistical differences in the data.

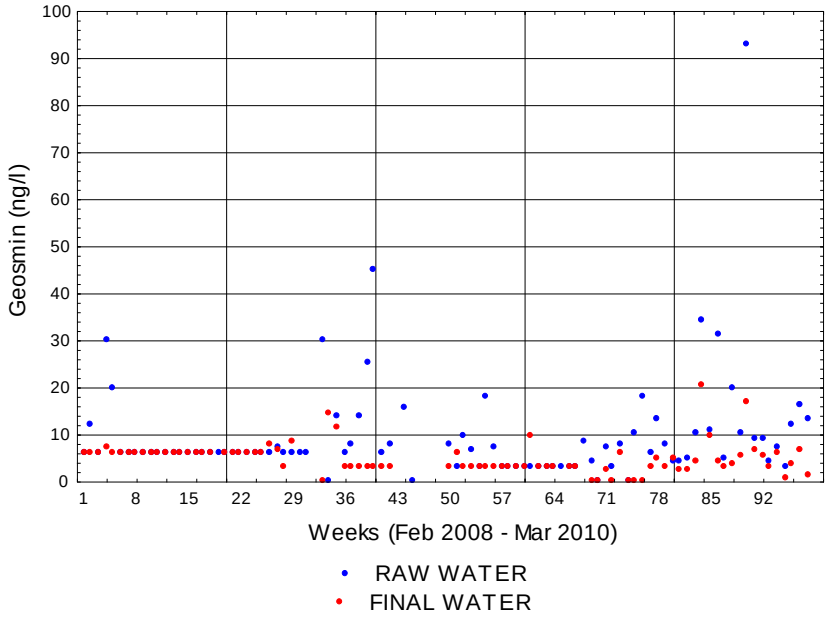

Figure 4.48a: The measured concentrations of geosmin (ng/ℓ) measured in the raw and final water for the study period February 2008 to March 2010.

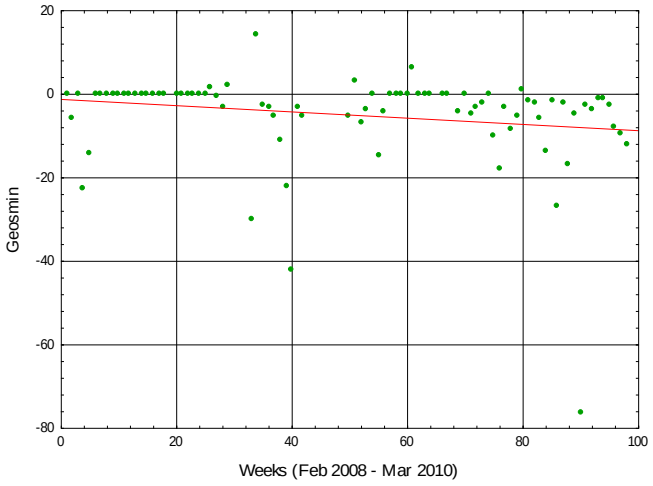

Figure 4.48b: The statistical differences in the concentrations of geosmin measured in the raw and final water.

4.3.4.3: Total Chlorophyll

The total chlorophyll concentration varied between 0 and 40 µg/ℓ in the raw water and was reduced by the purification processes to less than 5 µg/ℓ in the final water (Figure 4.49a). There is statistically significant difference ($p < 0.001$) between the data measured for the raw and final water, therefore the purification process was successful in reducing the total chlorophyll in the water (Figure 4.49b).

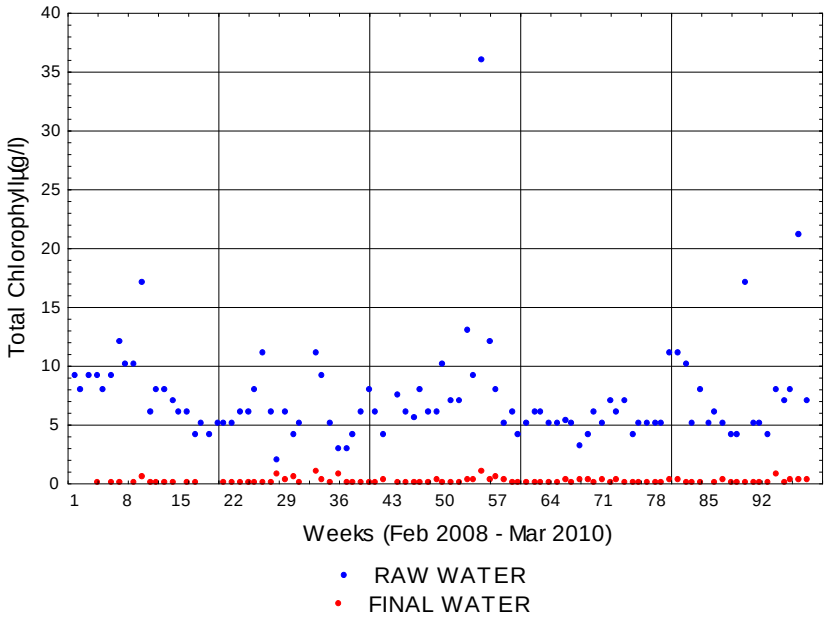

Figure 4.49a: The measured concentrations of total chlorophyll (µg/ℓ) in the raw and final water for the study period February 2008 to March 2010.

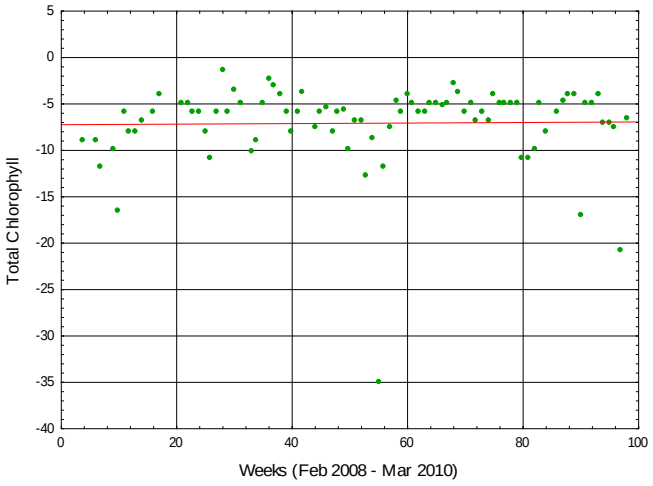

Figure 4.49b: The statistical differences in the concentrations of total chlorophyll measured in the raw and final water.

4.3.4.4: Chlorophyll-*a*

Chlorophyll-*a* concentration (between 1 and 24 µg/ℓ) in the raw water was reduced to 2 µg/ℓ or less in the final water (Figure 4.50a). However, the slope of the regression line in Figure 4.50b indicates that the measurements of chlorophyll-*a* were time dependent. This fact as well as the scattered distribution of the data points during the study period indicates that the t-test cannot be used to determine statistical differences in the data.

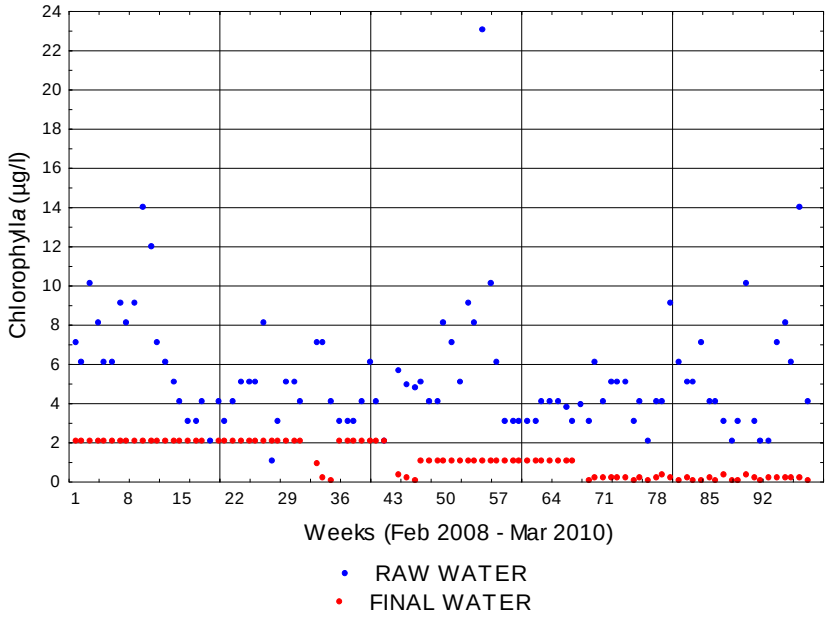

Figure 4.50a: The measured concentrations of chlorophyll-*a* (µg/ℓ) in the raw and final water for the study period February 2008 to March 2010.

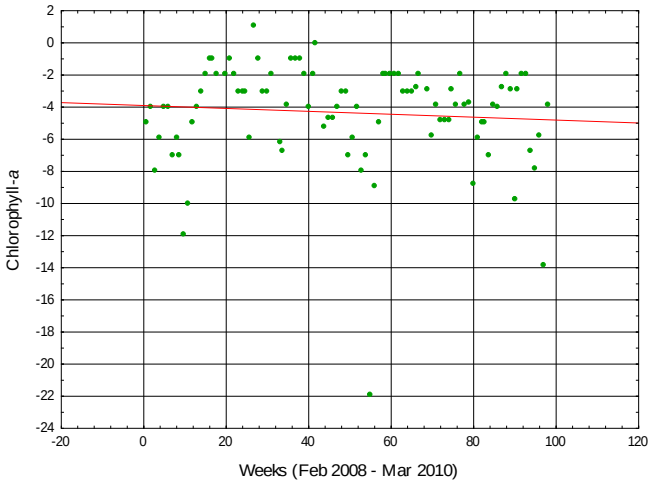

Figure 4.50b: The statistical differences in the concentrations of chlorophyll-*a* measured in the raw and final water.

4.3.4.5: Total Organic Carbon (TOC)

TOC concentration in the raw water varied between 4 and 8 mg/ℓ and between 2 and 6 mg/ℓ in the final water (Figure 4.51a). However, the slope of the regression line in Figure 4.51b indicates that the measurements of TOC were time dependent. This fact as well as the scattered distribution of the data points during the study period indicates that the t-test cannot be used to determine statistical differences in the data.

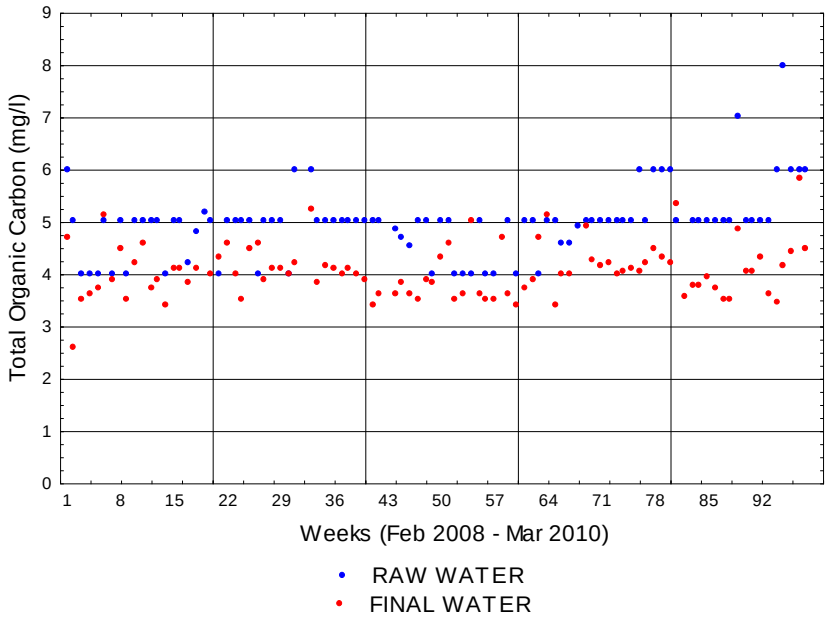

Figure 4.51a: The measured concentrations of total organic carbon (mg/ℓ) in the raw - and final water for the study period February 2008 to March 2010.

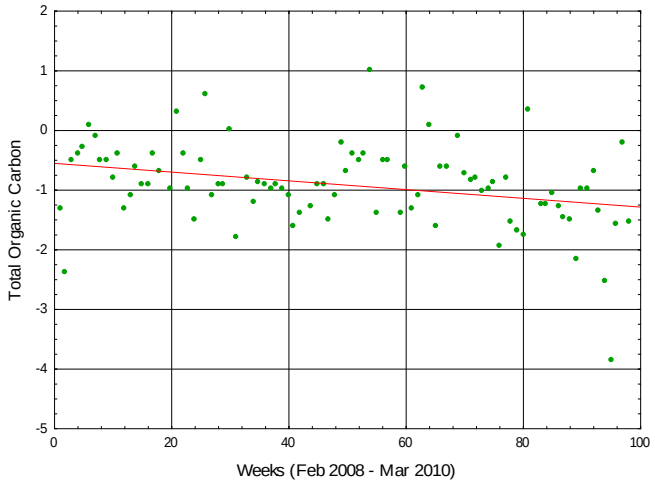

Figure 4.51b: The statistical differences in the concentrations of total organic carbon measured in the raw and final water.

4.3.4.6: Cyanophyceae

Cyanophyceae cells varied between 0 and 12000 cells/mℓ in the raw water and were reduced to less than 100 cells/mℓ in the final water (Figure 4.52a). However, the slope of the regression line in Figure 4.52b indicates that the counts of Cyanophyceae were time dependent. This fact as well as the scattered distribution of the data points during the study period indicates that the t-test cannot be used to determine statistical differences in the data.

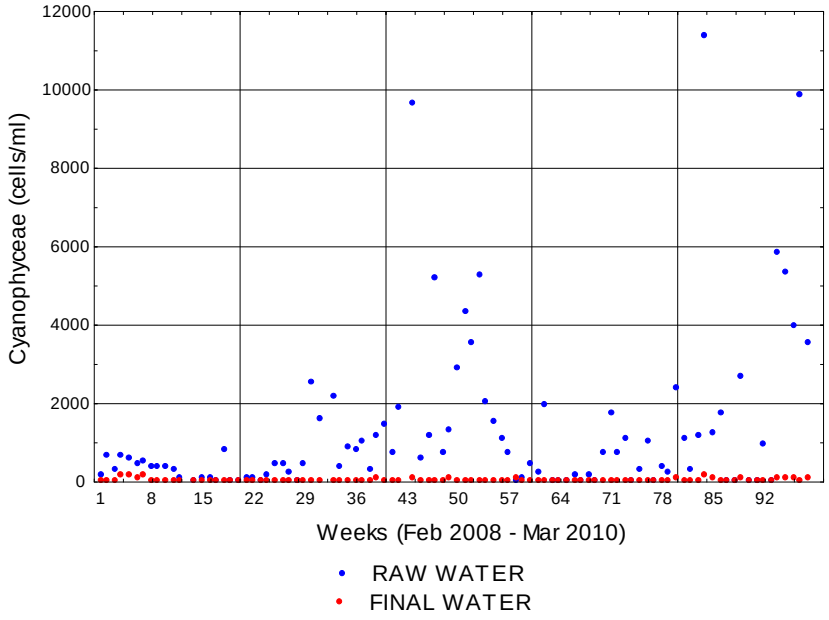

Figure 4.52a: The measured concentrations of Cyanophyceae (cells/mℓ) in the raw and final water for the study period February 2008 to March 2010.

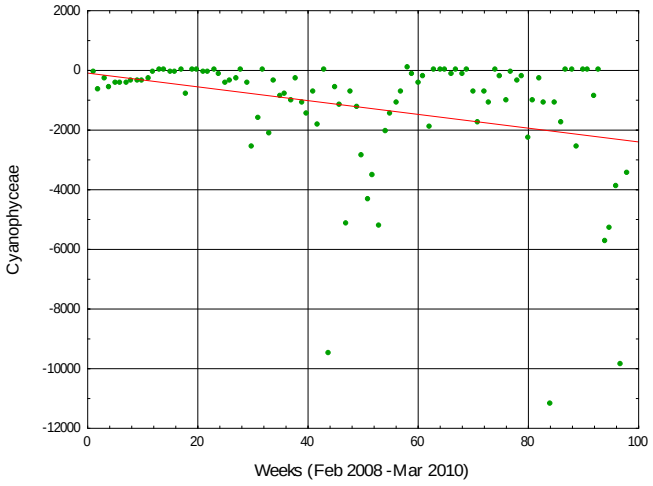

Figure 4.52b: The statistical differences in the concentrations of Cyanophyceae measured in the raw and final water.

4.3.4.7: Bacillariophyceae

The Bacillariophyceae cells varied between 0 and 1600 cells/mℓ in the raw water and were reduced to less than 100 cells/mℓ in the final water (Figure 4.53a). There is statistically significant difference ($p < 0.001$) between the data measured in the raw and final water, therefore the purification process was successful in reducing the Bacillariophyceae cells in the water (Figure 4.53b).

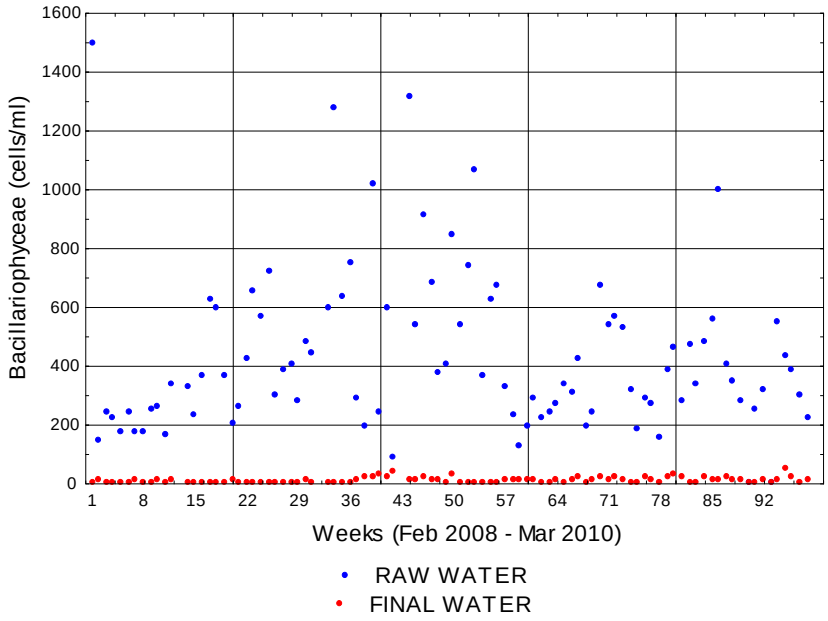

Figure 4.53a: The measured concentrations of Bacillariophyceae (cells/mℓ) in the raw and final water for the study period February 2008 to March 2010.

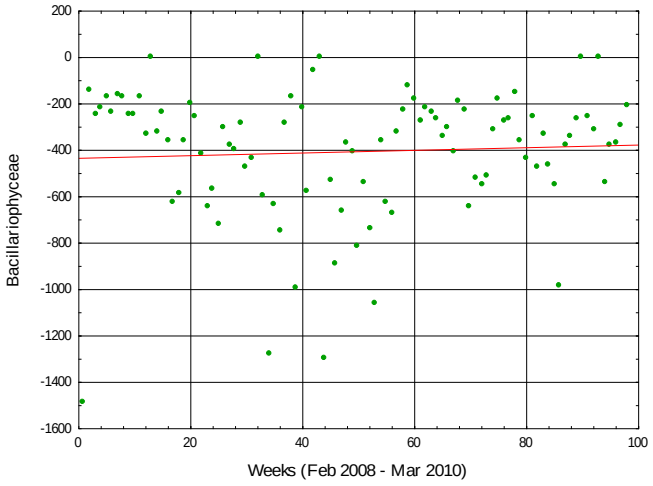

Figure 4.53b: The statistical differences in concentrations of Bacillariophyceae in the raw and final water.

4.3.4.8: Chlorophyceae

The Chlorophyceae cells varied between 0 and 2200 cells/mℓ in the raw water and were reduced to 100 cells/mℓ or less in the final water (Figure 4.54a). However, the slope of the regression line in Figure 4.54b indicates that the counts of Chlorophyceae were time dependent. This fact as well as the scattered distribution of the data points during the study period indicates that the t-test cannot be used to determine statistical differences in the data.

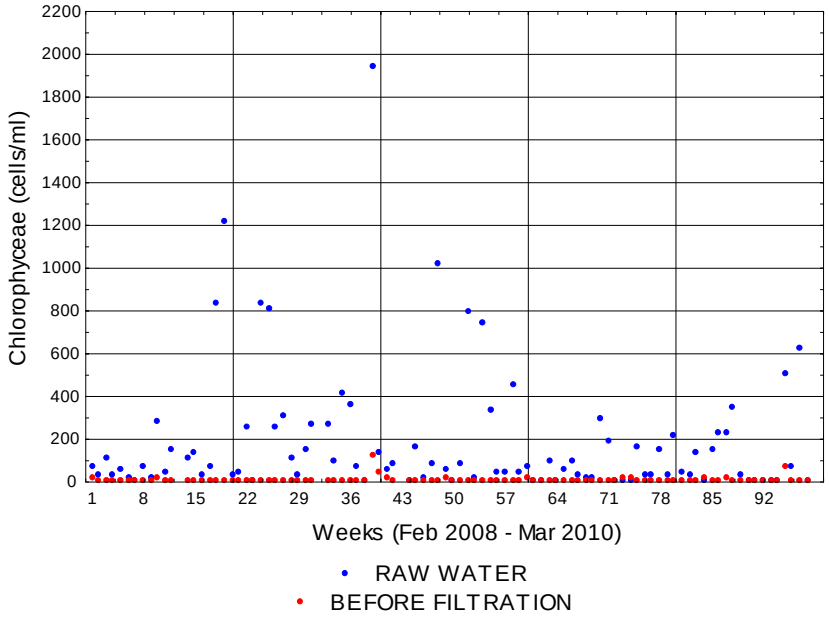

Figure 4.54a: The measured concentrations of Chlorophyceae (cells/mℓ) in the raw and final water for the study period February 2008 to March 2010.

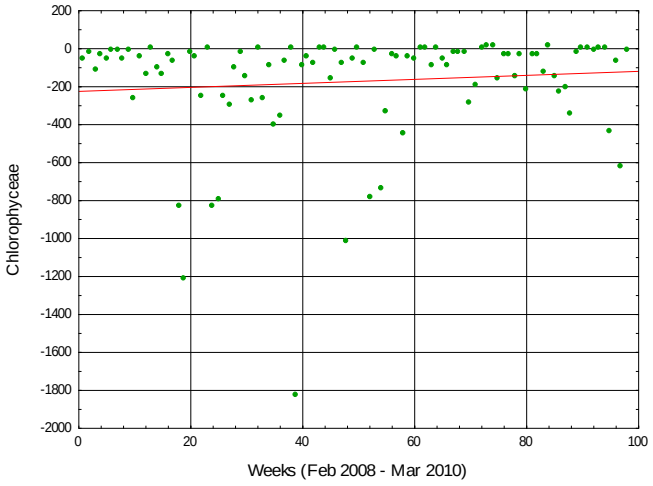

Figure 4.54b: The statistical differences in the concentrations of Chlorophyceae in the raw and final water.

4.3.4.9: Cryptophyceae

The Cryptophyceae cells varied between 0 and 100 cells/mℓ in the raw water and were reduced to less than 10 cells/mℓ in the final water. However, the slope of the regression line in Figure 4.55b indicates that the counts of Cryptophyceae were time dependent. This fact as well as the scattered distribution of the data points during the study period indicates that the t-test cannot be used to determine statistical differences in the data.

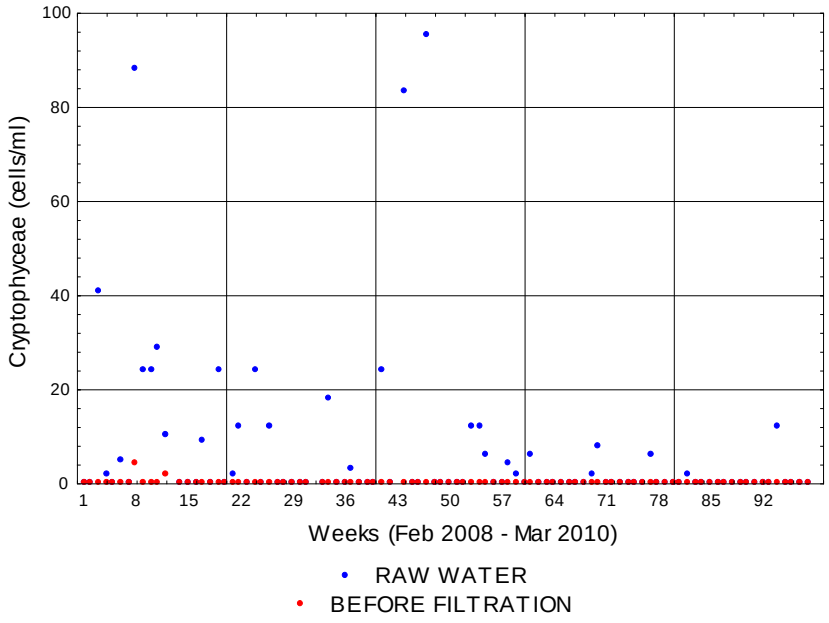

Figure 4.55a: The measured concentrations of Cryptophyceae (cells/mℓ) in the raw and final water for the study period February 2008 to March 2010.

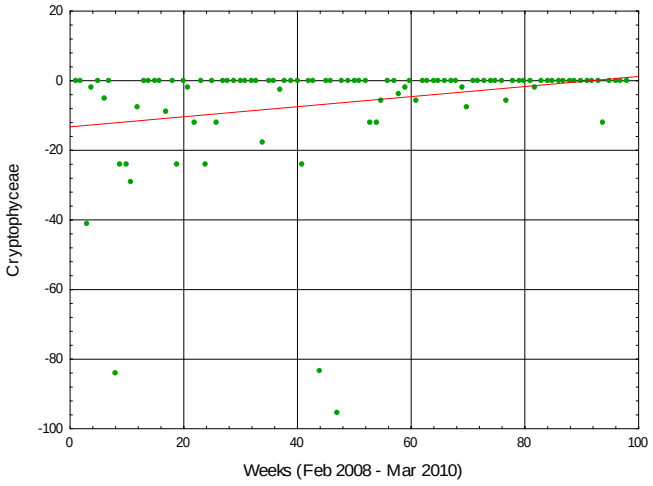

Figure 4.55b: The statistical differences in the concentrations of Cryptophyceae in the raw and final water.

4.3.4.10: Chrysophyceae

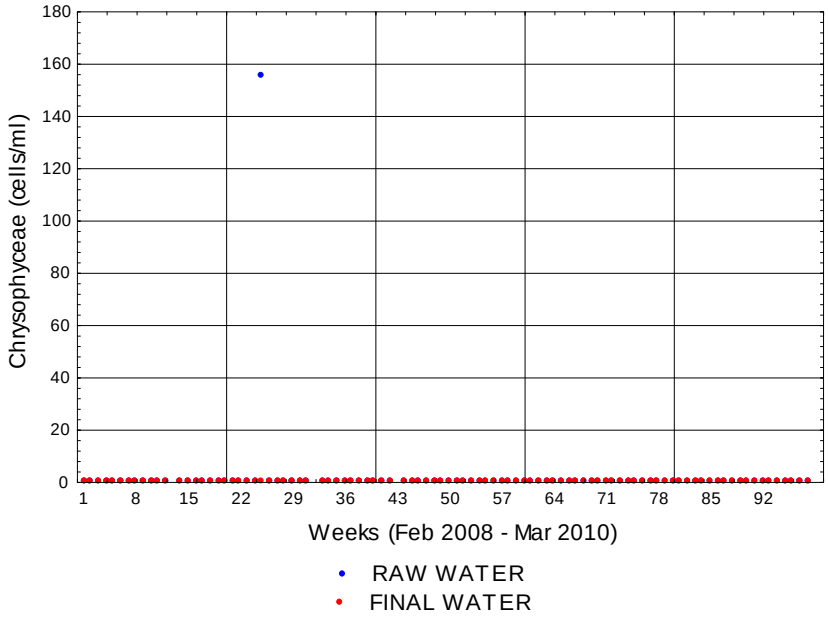

Figure 4.56: The measured concentrations of Chrysophyceae (cells/mℓ) before in the raw and final water for the study period February 2008 to March 2010.

The Chrysophyceae cells were counted at only one time during the study period and it seems as if the cells were successfully removed by the purification processes.

4.3.4.11: Dinophyceae

The Dinophyceae cells (*Ceratium* sp.) varied between 0 and 300 cells/mℓ in the raw water and were reduced to 100 cells/mℓ in the final water (Figure 4.57a). However, the slope of the regression line in Figure 4.57b indicates that the counts of Cyanophyceae were time dependent. This fact as well as the scattered distribution of the data points between weeks 40 to 60, and 80 until the end of study period indicates that the t-test cannot be used to determine statistical differences in the data.

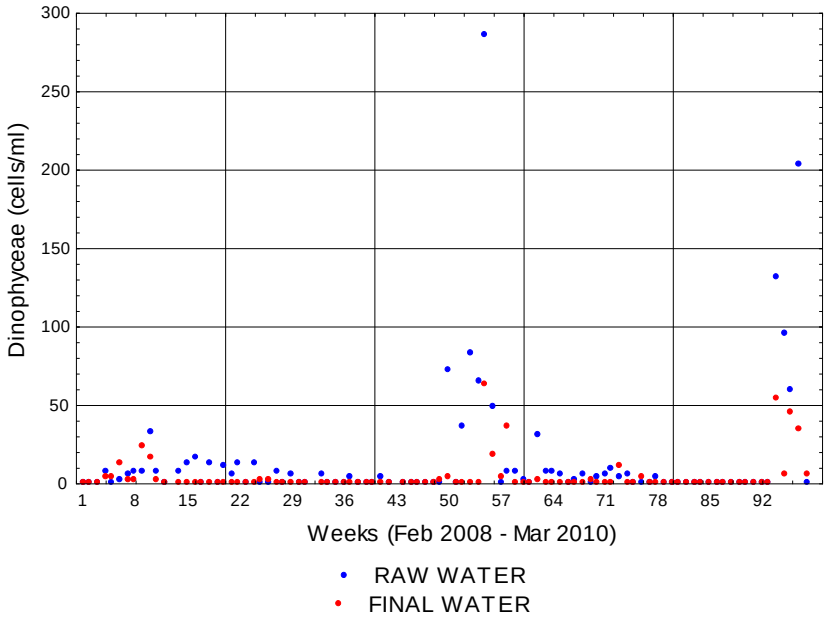

Figure 4.57a: The measured concentrations of the Dinophyceae genus *Ceratium* (cells/mℓ) in the raw and final water for the study period February 2008 to March 2010.

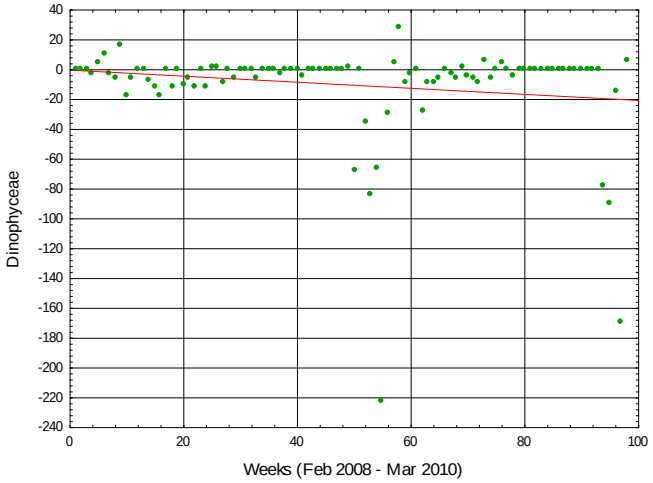

Figure 4.57b: The statistical differences in the concentrations of the Dinophyceae genus *Ceratium* in the raw and final water.

4.3.4.12: Euglenophyceae

The Euglenophyceae cells varied from 0 to 50 cells/mℓ in the raw water and were reduced to less than 20 cells/mℓ in the final water. However, the slope of the regression line in Figure 4.58b indicates that the counts of Euglenophyceae were time dependent. This fact as well as the scattered distribution of the data points during the study period indicates that the t-test cannot be used to determine statistical differences in the data.

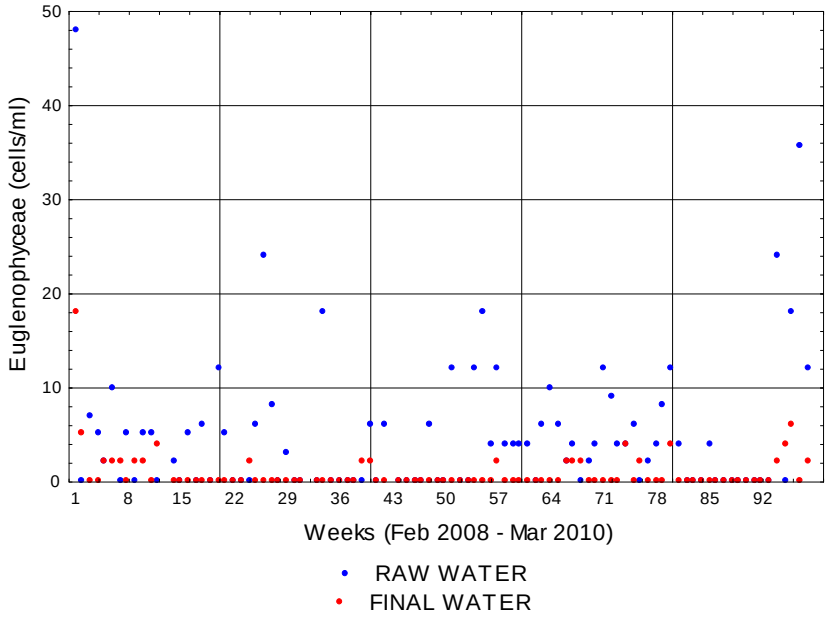

Figure 4.58a: The measured concentrations of Euglenophyceae (cells/mℓ) in the raw and final water for the study period February 2008 to March 2010.

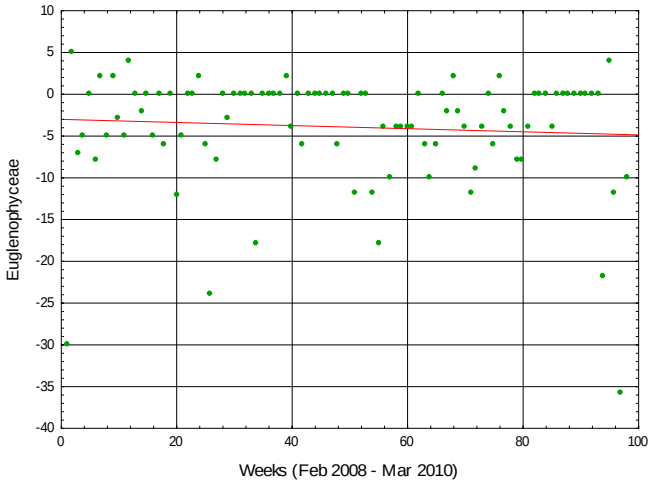

Figure 4.58b: The statistical differences in the concentrations of Euglenophyceae in the raw and final water.

4.3.4.13: *Anabaena* species

The *Anabaena* species varied between 0 and 12000 cells/mℓ in the raw water and were reduced to less than 50 cells/mℓ in the final water (Figure 4.59a). However, the slope of the regression line in Figure 4.59b indicates that the counts of *Anabaena* species were time dependent. This fact as well as the scattered distribution of the data points during the study period, specifically toward the end indicates that the t-test cannot be used to determine statistical differences in the data.

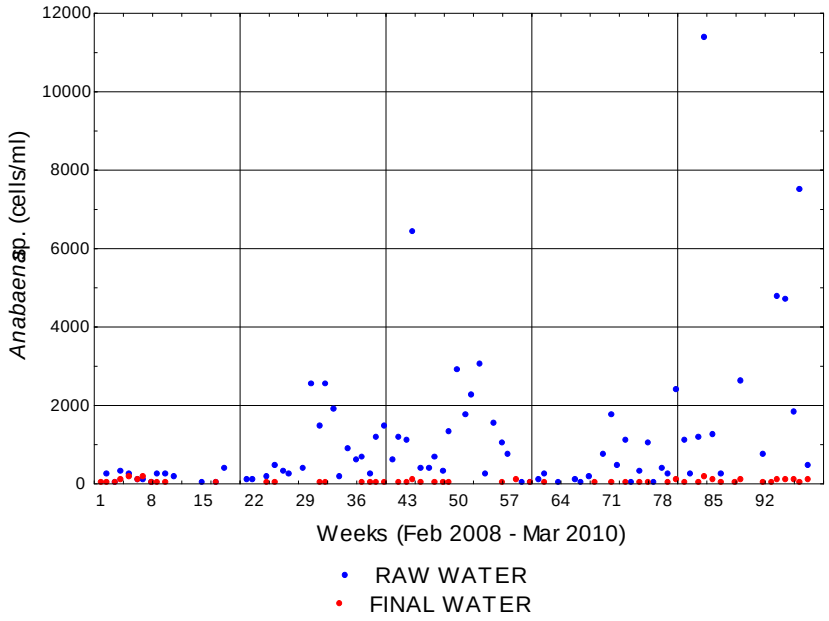

Figure 4.59a: The measured concentrations of *Anabaena* sp. (cells/mℓ) in the raw and final water for the study period February 2008 to March 2010.

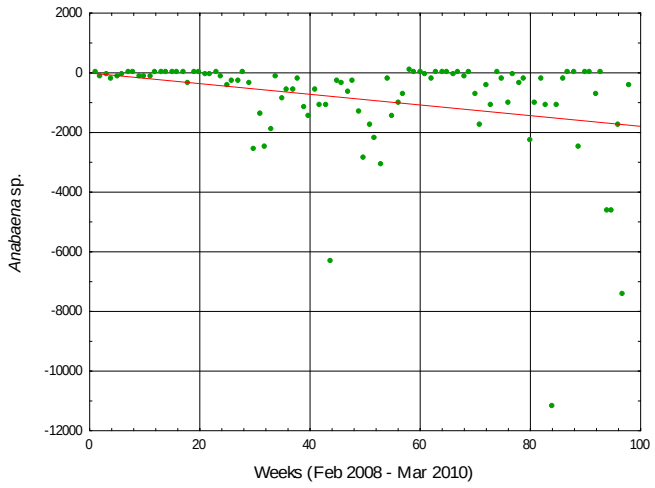

Figure 4.59b: The statistical differences in the concentrations of *Anabaena* sp. in the raw and final water.

4.3.4.14: *Microcystis* species

Microcystis varied between 0 and 4500 cells/mℓ in the raw water and were reduced to less than 100 cells/mℓ in the final water. However, the slope of the regression line in Figure 4.60b indicates that the counts of *Microcystis* species were time dependent. This fact as well as the scattered distribution of the data points during the study period (weeks 40 to 60, and 80 until the end) indicates that the t-test cannot be used to determine statistical differences in the data.

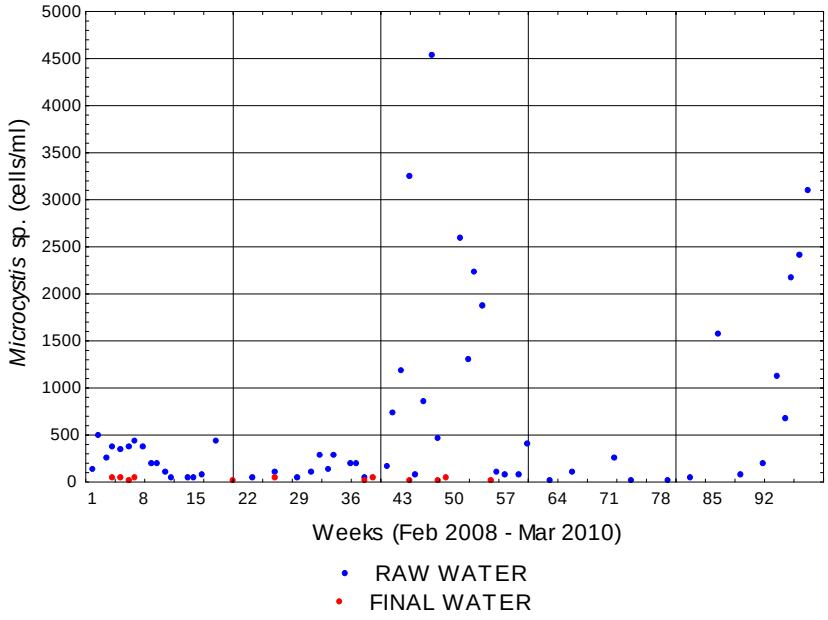

Figure 4.60a: The measured concentrations of *Microcystis* sp. (cells/mℓ) in the raw and final water for the study period February 2008 to March 2010.

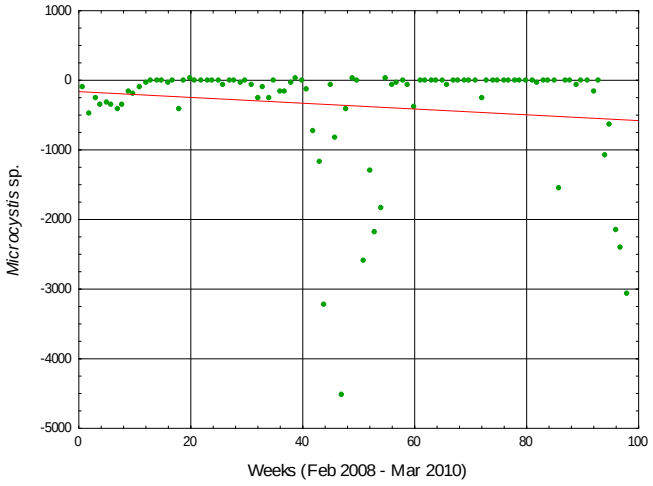

Figure 4.60b: The statistical differences in concentrations of *Microcystis* sp. in the raw and final water.

4.3.4.15: *Oscillatoria* species

Oscillatoria varied between 0 and 1800 cells/mℓ in the raw water and no cells were detected in the final water. Therefore the purification processes were effective in removing the *Oscillatoria* filaments in the final water.

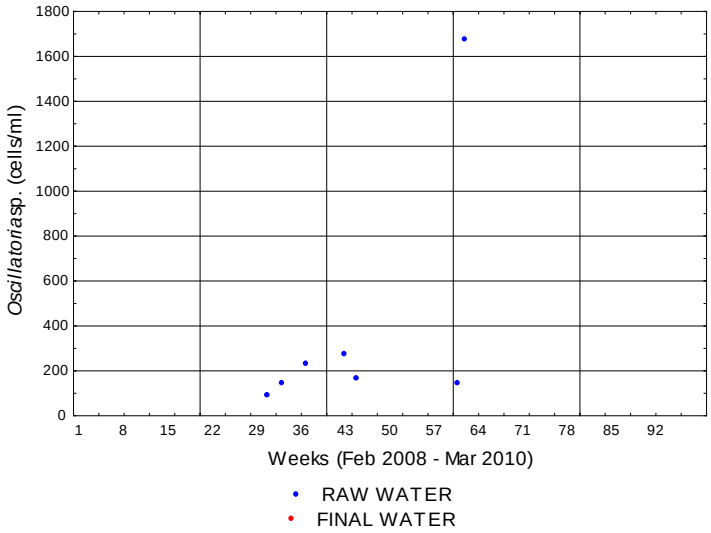

Figure 4.61: The measured concentrations of *Oscillatoria* sp. (cells/mℓ) in the raw and final water for the study period February 2008 to March 2010.

4.4 DISCUSSIONS

According to Ho and Newcombe (2010) optimised coagulation processes can remove cells and therefore a large proportion of metabolites such as MIB and geosmin, but our results showed that MIB was not removed during any stage of water treatment. Other water treatment options include powered activated carbon, granular activated carbon, oxidation as well as biological filtration (Ho and Newcombe, 2010), however, the use of oxidants can break down algal cells and release toxin or taste and odour compounds (Hall, 2010).

Tables 4.1 and 4.2 summarize the results of purification processes in removing or reducing variables between the different sampling localities. Processes before filtration include coagulation, flocculation, sedimentation and stabilization and after filtration, disinfection and chlorination. MIB was not reduced or removed during any stage of water treatment; in fact the concentration of MIB increased from 8 ng/ℓ in the raw water to 15 ng/ℓ in the final water. The geosmin concentration was reduced by coagulation, flocculation and sedimentation, but not effectively removed after filtration (by disinfection chlorination). MIB and geosmin are produced by actinomycetes and cyanobacteria (Suffet, 1995) as well as *Dinobryon*, *Synura*, *Ceratium* and *Peridinium* (Detlef *et al*., 2004). Cyanobacteria such as *Anabaena*, *Microcystis* and *Oscillatoria* as well as *Ceratium* and *Dinobryon* were present in the raw water as well as during different stages in the purification process. *Synura* (Chrysophyceae) was only detected in the raw water and not in the treatment plant. It is therefore possible that the increase in MIB can be ascribed to taste and odour producing organisms that enters the purification system with the raw water as well as with the backwash water. This study showed that the purification processes did reduce the cyanobacterial cells in the water but did not remove it. The only cyanobacteria that were successfully removed were *Oscillatoria* and this organism was present in low concentrations in the raw water.

The concentrations of both total chlorophyll and chlorophyll-*a* were effectively reduced by coagulation, flocculation and sedimentation, but the purification processes after filtration did not reduce it effectively. Chlorination did reduce total chlorophyll but not chlorophyll-*a* effectively. ZWTP experienced a chlorophyll breakthrough in the potable water during February 2010. On the 16th of February 2010 the measurements for

chlorophyll-*a* and total chlorophyll in raw water were 6 and 8 µg/ℓ respectively, but increased to 14 and 21 µg/ℓ on the 23rd of February 2010. Swanepoel and Du Preez (2010) speculated that the presence of *Ceratium hirundinella* in the source water may be one of the factors that caused the breakthrough. The presence of *Ceratium* in the raw and final water during February 2010 was confirmed by this study (see Table 4.2 and Figure 3.23b). However, there was also *Anabaena* species as well as diatom species present in the final water at that time. Therefore, according to the cell counts not only *Ceratium* species, but also *Anabaena* and to a lesser extent diatoms caused the chlorophyll breakthrough.

Table 4.1: Different sampling localities (raw water, before filtration, after filtration and final water) in the treatment plant and an indication whether MIB, geosmin, total chlorophyll, chlorophyll-*a*, and TOC (biological variables) were **statistically effectively** removed by the different purification processes. (√) = reduced or removed the variable. (x) = did not reduce or remove the variable.

Environmental variables	**RAW WATER/ BEFORE FILTRATION**	**BEFORE FILTRATION/ AFTER FILTRATION**	**AFTER FILTRATION/ FINAL WATER**	**RAW WATER/ FINAL WATER**
MIB	x	x	x	x
Geosmin	√	√	x	x
Total Chlorophyll	√	√	x	√
Chlorophyll-*a*	√	√	x	x
TOC	x	√	x	x

Coagulation, flocculation and sedimentation did not effectively reduce the TOC but filtration and chlorination reduced the TOC content in the water.

The genus *Ceratium* belongs to the algal group Dinophyceae and was not removed by coagulation, flocculation and sedimentation (Table 4.2). This might be due to the ability of *Ceratium* to destroy the flocs formed during coagulation and flocculation (Pieterse *et al.*, 2000). Although *Ceratium* cells were effectively reduced by the

filtration stage of water treatment, disinfection and chlorination failed to remove these algal cells from water.

Removal of algae from water treatment processes is difficult because of their small size and the low specific gravity (Ma and Liu, 2002). Although coagulation is the main treatment process for algal removal in conventional drinking water treatment (Ma and Liu, 2002), only a few algal groups and genera were removed effectively by the purification process in this study. Chrysophyceae cells were only detected in the raw water during week 22 to 29 (*Synura* sp. in August 2008) and were successfully removed before filtration.

Table 4.2: Different sampling localities (raw water, before filtration, after filtration and final water) in the treatment plant and an indication whether the algal groups and algal genera (phytoplankton) were **statistically effectively** removed by the different purification processes. (√) = reduced or removed the variable. (x) = did not reduce or remove the variable. (-) = was not determined/or did not occur.

Phytoplankton	**RAW WATER/ BEFORE FILTRATION**	**BEFORE FILTRATION/ AFTER FILTRATION**	**AFTER FILTRATION/ FINAL WATER**	**RAW WATER/ FINAL WATER**
Cyanophyceae	x	x	x	x
Bacillariophyceae	√	x	√	√
Chlorophyceae	√	x	x	x
Cryptophyceae	x	x	x	x
Chrysophyceae	-	-	-	√
Euglenophyceae	√	x	x	x
Ceratium sp.	x	√	x	x
Anabaena sp.	x	x	x	x
Microcystis sp.	x	x	x	x
Oscillatoria sp.	-	-	-	√

The Bacillariophyceae cells were reduced by coagulation, flocculation and sedimentation but the filtration process did not effectively reduce the cells in the

water. However, the purification processes disinfection and chlorination were effective in reducing the diatom cells in the final water. The only processes that reduced the Chlorophyceae effectively were coagulation, flocculation and sedimentation. Although the t-test did not show a statistical difference, the Cryptophyceae cells were reduced especially by the first stage of the purification process.

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

Quality variable	**Measuring units**	**Source water**		**Potable water**		
		Recommended Maximum limit	Maximum allowable limit	Recommended limit	Maximum allowable limit	Crisis limit
Chlorophyll-665	µg/ℓ	0 - 15	> 30	1	5	7

According to Table 4.3 the maximum recommended limit for total chlorophyll is between 0 and 15 µg/ℓ for the source water. During 2008 the annual average of the total chlorophyll for the source water was 6.90 µg/ℓ and in 2009 7.06 µg/ℓ. The recommended limit for the final water is 1 µg/ℓ. During 2008 the annual average of the total chlorophyll for the final water was 0.15 µg/ℓ and in 2009 0.12 µg/ℓ. Therefore it can be concluded that the processes in the ZWTP produce potable water that comply with the guidelines presented in Table 4.3.

In some cases the t-test could not be used to determine the efficacy of the purification processes due to the time dependency of the data. This may be rectified by increasing the amount of samples taken.

4.5 CONCLUSIONS

The efficacy of a conventional water treatment plant is determined by the effectiveness of the different purification processes to remove physical, chemical and biological variables from the water. This study measured different variables at different sampling localities in the ZWTP and the following conclusions were made:

- Conventional water purification processes did not remove the MIB content from drinking water supplies.
- Geosmin and chlorophyll concentrations were effectively reduced by coagulation, flocculation, sedimentation and stabilization as well as filtration.
- The algal groups found in the raw water have the potential to penetrate the purification process and some of the algal groups were present in the final water (Table 4.2).
- The Bacillariophyceae, Chlorophyceae and Euglenophyceae were effectively reduced by coagulation, flocculation, sedimentation and stabilization.
- The Bacillariophyceae cells were effectively removed by coagulation, flocculation, sedimentation as well as chlorination, but not filtration.
- Cyanophyceae species such as *Anabaena* and *Microcystis* were not effectively removed by conventional water treatment processes.
- *Ceratium* was effectively reduced by the filters, but penetrated coagulation, flocculation and sedimentation as well as disinfection and chlorination.
- *Oscillatoria* sp. did not occur at the same time in the raw water and different stages of the water treatment plant, while *Synura* sp. (Chrysophyceae) was detected only in the raw water. However, both these algal species were effectively removed by the purification processes.

CHAPTER 5: CONCLUSIONS

Eutrophication (nutrient enrichment of surface water) constitutes the greatest single threat to the impoundment of raw, potable and irrigation water (Harding, 2008). In countries such as South Africa, where treated effluents and other wastewaters comprise a significant proportion of return flows to reservoirs (dams), the problems associated with eutrophication are exacerbated (Harding, 2008). Such waters are typically associated with an increased incidence and frequency of algal development, often noxious, resulting in increasing water treatment costs (Harding, 2008). This problem is especially apparent in the urban areas such as the Johannesburg-Pretoria complex (Harding, 2008). The removal of organic compounds and pollutants has become a serious challenge for municipalities and industries in South Africa as some of these pollutants are toxic and pose serious health risks to humans and animals (Sithole *et al*., 2007).

Source water of a water treatment plant is categorized by turbidity, colour, ammonia, hardness, trophic status and dissolved metal content and the water quality abstracted from a river can be expected to vary more than water abstracted from a dam or reservoir (Van der Walt *et al*., 2009). The status of the source water is of utmost importance to determine purification processes needed in a treatment plant. Water from the Vaal Dam that enters the water works at the Zuikerbosch purification facilities and primary pumping stations (Brent and Landu, 2007) contains highly dispersed particles, which, because they are colloidal, tend to remain suspended for a long period (Brent and Landu, 2007). It was therefore necessary to determine the ecological status of the source water to serve as a benchmark to determine the efficacy of the different purification processes.

The investigation into the source water of the ZWTP revealed that the Cyanophyceae was the dominant algal group during the study period. The most dominant species was the taste and odour producing species, *Anabaena*. *Anabaena* generally gives rise to grassy odours intensifying to almost septic odours as the cells disintegrate (Gary, 2008). Diatoms such as *Asterionella*, *Fragilaria* and *Melosira* that were found in

the raw water also have the potential to produce a fishy odour (Gary, 2008). *Microcystis* species that has the potential to produce toxins occurred in high numbers during cooler periods. According to Botha-Oberholster and Oberholster (2008) toxic cyanobacteria found in eutrophic, municipal and residential water supplies are an increasing hazard in South Africa. The presence of algae in raw water can cause problems in the removal processes employed to separate algae from water during treatment (Schutte and Focke, 2007).

The alkalinity of the raw water was relatively high and can cause potential damage to purification equipment. Alkalinity serves as a pH buffer and a reservoir for inorganic carbon and this can help to determine the ability of water to support algal growth and other aquatic life (Owuor *et al*., 2007).

The turbidity of the raw water was low when compared to the rest of the Vaal River. However, turbid water should always be treated with concern as soluble iron and manganese that enter the mains can form insoluble particles if the water is aerated and the pH increases (Gary, 2008).

Chemical oxygen demand is a measurement of the substances in the effluent that can be oxidised (Van der Walt *et al*., 2009). Most wastewater treatment plants employ some form of biological treatment process to reduce COD levels (Van der Walt *et al*., 2009). The increase in COD and TDS towards the end of the study period is of concern as high COD in raw water source is normally associated with high coliform counts, high levels of ammonia, DOC, phosphates (Van der Walt *et al*., 2009) and have the potential to damage purification equipment. High COD levels in a potable water treatment plant can be an indication of poorly treated sewage effluent or pollution from an untreated effluent source (Van der Walt *et al*., 2009). However, the COD levels in the ZWTP were not determined.

The cadmium and lead concentrations in the raw water were higher than the TWQR criteria and therefore potentially hazardous (Wetzel, 2001). Cadmium is a known carcinogen (Gary, 2008) and lead can cause health problems. Inputs of many trace

elements and heavy metals to fresh water are increasing as a result of pollution from industrial and combustion emissions to the atmosphere and subsequent deposition via precipitation (Wetzel, 2001).

The ortho-phosphate concentrations of the raw water were high for the duration of the study period. Phosphates are not toxic to people and animals unless they are present in very high levels. Digestive problems could occur from extremely high levels of phosphate (www.water-research.net).

Water treatment plants must be able to produce a finished product of consistently high quality regardless of the demand (Gary, 2008) and the quality of the source water. The cleaner the source water, the smaller number of steps or unit processes is required and hence the overall cost of the water is less (Gary, 2008). South African National Standard (SANS) 241: 2006 features a two-tier water quality standard. Class 1 and Class 2 are distinguished by their allowable long- and short-term exposure. A revision of SANS 241 was released in 2009 and the 2009 version contained significant changes (e.g. the removal of the class 1 and 2 system, the inclusion of the blue drop or green drop certification and the compulsory of Water Safety Plans). The ZWTP of Rand Water is a water treatment plant that supplies Class 1 (blue drop certified according to the 2009 version) drinking water according to SANS 241: 2006. A variety of water quality standards are used throughout the world. The standards are continuously reviewed, updated and refined as new pollutants are identified and new toxicological evidence requires the revision of exposure levels of known substances (Van der Walt *et al*., 2009).

The efficacy of a conventional water treatment plant is determined by the effectiveness of the different purification processes to remove physical, chemical and biological variables from the water. The purification processes at the ZWPT was not successful in reducing the MIB levels in the final water and although the geosmin levels were reduced, it was not completely eliminated. According to Westerhoff *et al*. (2005) conventional water treatment achieves minimal removal of MIB and geosmin and rarely removes these compounds to a commonly accepted organoleptic detection

level by the human nose of 5 – 10 ng/ℓ. These compounds are usually removed with powered activated carbon, ozone or granular activated carbon. Activated carbon absorption is very effective but other compounds such as natural organic matter compete for absorption sites with MIB and geosmin (Westerhoff *et al*., 2005). Sithole *et al*. (2007) observed a high percentage removal of geosmin and 2-MIB during a study on the ZWTP by using β-cyclodextrin polymers. The difference in absorption of geosmin and MIB by polymers was also observed and could be attributed to the difference in the structure of the compounds (Sithole *et al*., 2007). Westerhoff *et al*. (2005) also stated that the MIB concentrations varied from year to year with no strong correlation to water quality parameters, but were generally higher in the summer months.

The high MIB and geosmin concentration in the water could have been due to the presence of Cyanophyceae species especially *Anabaena.* Echenique *et al*. (2006) found that a strong off-odour event detected in domestic water supply was due to geosmin, produced by *Anabaena circinalis*. However, MIB and geosmin are also produced by actinomycetes (Suffet, 1995) as well as *Dinobryon*, *Synura*, *Ceratium* and *Peridinium* (Detlef *et al*., 2004) that were present in the ZWTP. This study found that *Anabaena* and *Microcystis* species were not effectively remove by the purification processes. Visser and Pieterse (2000) found that small unicellular blue-green algae, which include *Anabaena* and *Microcystis* species, are difficult to remove from water during purification processes as the cells do not flocculate efficiently and therefore penetrate the purification processes. According to Pieterse *et al*. (2000) the algal biomass in the final water will be high if the algal biomass in the raw water is high. Visser and Pieterse (2000) also found that filamentous algae such as *Oscillatoria simplicissima* were usually removed effectively during filtration because the algae were not present in the filtration effluent of the different modules. This study could not determine the efficacy of the purification processes in removing *Oscillatoria* filaments because it was present in the treatment plant without being detected in the raw water. No cells were detected in the final water.

The purification processes did reduce cell numbers in the final water. Different groups did however penetrate the purification processes and were sometimes found in the

final water. The Bacillariophyceae, Chlorophyceae and Euglenophyceae were effectively reduced by coagulation, flocculation, sedimentation and stabilization. This was confirmed by the chlorophyll concentrations, which were effectively reduced by the same processes. The Bacillariophyceae were the only algal group that were effectively removed by coagulation, flocculation, sedimentation as well as chlorination, but not filtration. The Dinophyceae (*Ceratium* sp.) was effectively reduced by the filters, but penetrated coagulation, flocculation and sedimentation as well as disinfection and chlorination. Algal groups such as Cyanophyceae, Bacillariophyceae, Chlorophyceae, Cryptophyceae, Dinophyceae and Euglenophyceae may be present in the final water because of their morphology (shape and structures). Algal species with flagella can move and may be able to avoid processes such as flocculation-coagulation and sand filtration (Pieterse *et al*., 2000).

Recommendations: The fact that the MIB measurements stayed constant for the first part of the study period is suspicious. Rand Water should investigate the protocol of the MIB measurements. If the protocol is above board the purification process should be looked at. The data clearly shows an increase in the MIB-concentrations in the plant and this can be a serious problem and can lead to consumer complaints about taste and odours. It should be determined if the backwash or recycling of waste water is the cause of the elevated levels or maybe it is the result of odour producing organisms growing on canal walls. If algae such as *Ceratium* and *Anabaena* species penetrate the entire purification process they can cause taste and odours problems in the final water. Organisms such as *Microcystis* also penetrate the process and have the potential to produce toxins. These organisms penetrate the sand filters and were not effectively removed by disinfection and chlorination. Sand filtration, disinfection and chlorination processes need to be improved to ensure effective removal of algae in the final water.

Most of the variables were effectively reduced or removed by coagulation, flocculation, sedimentation and filtration, but once the variables passed the filtration process it was not effectively removed by disinfection and chlorination. After evaluation of three filtration facilities, Ceronio *et al*. (2002) stated the problems

experience in the filters can be related to a failure to properly clean the media and also in the failure of hydraulic control systems. It should be investigated.

The filtration process reduced the TOC concentration effectively but the TOC levels in the final water was higher than the US Environmental Protection agency specifies namely a maximum of 2mg/l in treated water and 4 mg/l in the source water. Higher values can lead to the production of haloforms in the drinking water (www.env.gov.bc.ca accessed 6/12/2010). The reduction of TOC levels in both raw and final water should be investigated.

High alkalinity in the raw water can cause problems in the purification process. It should be determined if the addition of lime lowers the alkalinity in the purification plant to an acceptable level.

The high phosphorus and ortho-phosphate concentrations in the raw water can lead to eutrophication symptoms and should addressed.

The concentrations of lead and cadmium were high in the raw water. As these compounds can cause serious health problems, it is necessary to investigate if the purification processes in ZWTP remove them.

Processes at the Zuikerbosch water treatment plant did not totally removed some variables but did produce potable water that complies with national and Rand Water's production standards or guidelines for drinking water.

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APPENDIX

Table 1: The monthly averages of chemical dosing that was used in the treatment plant during the study period. Three chemicals were used at the same time in the treatment plant.

	LIME DOSING	POLY DOSING	CHLORINE DOSING
	mg/ℓ	mg/ℓ	mg/ℓ
FEB	9	4	2
MAR	10	4	2
APR	9	3	2
MAY	9	4	2
JUN	6	3	2
JUL	40	4	2
AUG	12	4	2
SEP	7	4	3
OCT	9	4	2
NOV	7	4	2
DEC	10	4	3
JAN	4	4	2
FEB	5	4	2
MAR	6	4	2
APR	5	3	2
MAY	10	4	2
JUN	6	4	2
JUL	2	4	2
AUG	12	4	2
SEP	7	4	3
OCT	4	5	2
NOV	7	5	2
DEC	6	5	2
JAN	13	6	3
FEB	12	12	3
MAR	13	15	3