THE OCCURRENCE, DISTRIBUTION AND REMOVAL OF ALGAL SPECIES AND RELATED SUBSTANCES IN A FULL-SCALE WATER PURIFICATION PLANT

AJH Pieterse and co-workers

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PART 1 : SUMMARY REPORT

WRC Report

submitted to the Water Research Commission

by

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EXECUTIVE SUMMARY

The Vaal River is eutrophied, polluted and mineralised because of the extensive utilisation of the water through household, mining and industrial activities and because of the release of effluents as well as because of specific agricultural practices. These effects have resulted, and will result, in large-scale algal blooms and, consequently, in serious ecological, aesthetic and water purification problems.

Almost no information was available on the connection between morphological and physiological characteristics of phytoplankton species on the one hand, and aspects of water purification processes such as coagulation, flocculation, sedimentation, flotation and filtration on the other hand. Therefore, a complete and integrated investigation of the connections between environmental variables and algae in the river as well as algae and purification problems experienced, was necessary in the South African context in general and in the Vaal River context in particular. An integrated approach was followed because the interrelated nature of the different aspects strongly suggests that conditions unique to the environment in which the algae grow, select for specific algae with characteristics that cause specific problems in the different phases of the purification process. Aspects of different interrelationships between the various subjects referred to have, therefore, been studied, using the Balkfontein purification works of Goudveld Water on the Vaal River near Bothaville as case study.

The emphasis of the planned investigation was on those algal species that are affected, or that are not affected, by the purification processes. The role of dissolved material, non-living suspensoids as well as physical-chemical and physical-morphological aspects of algal cells, algal colonies and algal filaments in the purification processes were investigated.

The aim of the investigation into algal species in water purification plant was to determine the nature and extent of algal-related problems and the types of algae involved. In addition, the contribution of algal cells to extracellular organic substances and substances posing health implications, such as chlorinated hydrocarbons, were also investigated.

The aim of the study into aspects of the oxidation, flocculation, sedimentation, filtration and flotation characteristics of algal cells, colonies, filaments and associated material was to investigate different characteristics of the algae in connection with coagulation and flocculation before sedimentation, as well as coagulation and flocculation before flotation.

Results from this integrated study include the following:

High pH lime treatment was shown to remove turbidity, dissolved organic carbon and iron more efficiently than which aluminium and chlorophyll (i.e. algal cells) were removed. When using the poly-electrolyte U5000 as secondary coagulant in

addition to the high lime process, humic- and fulvic acids, protein and carbohydrates were removed better than in the high lime process alone. Results also showed that $FeCl_3$ and poly-electrolyte were efficient removal agents when centric diatoms were present in the raw water. Jar tests conducted in the laboratory indicated that better dissolved organic carbon (DOC) removal is obtained when no pre-chlorination was performed.

The dissolved air flotation / filtration (DAFF) process performed better than the control line (sedimentation) in removing Al, Fe and chlorophyll-a. DOC removal in the control line was better. Results indicated that temperature affected the removal of organic substances and determined whether it was necessary to dose $FeCl_3$ or poly-electrolyte. Temperature was, however, apparently not affecting the removal of chlorophyll-a (algal cells).

In general, diatoms were reduced to a larger extent than green algae in the treatment process. Diatoms were removed more efficiently under the prevailing conditions of flow, coagulation, flocculation and filtration. The efficient removal of diatom cells is most probably partly explained by the cells being more dense because of silica-containing frustules. Surface characteristics apparently play an important role in the removal of algal cells, because green algae (cellulose cell walls) were better removed by $FeCl_3$ while diatoms (silica frustules) were better removed by lime.

The following algal species were removed less efficiently by sedimentation and filtration and should be considered problem species: *Carteria globosa, C. simplicissima, Chlamydomonas incerta, Crucigenia tetrapedia, Monoraphidium arcuatum, M. circinale, Oocystis lacustris* (all unicellular green algae) as well as *Chroococcus dispersus* and *Synechococcus cedrorum* (small semi-colonial blue-green algae). The *Carteria* and *Chlamydomonas* species may have partially avoided flocculation because they are able to move with flagella. The other green algal all deviate in shape from the sphere (being elongated or triangular). The blue-green cells are much smaller than the other algae, and proved difficult to remove, even under high dosage concentrations.

These results clearly indicate that the efficiency of coagulation, flocculation, sedimentation, flotation and sand filtration at the Balkfontein plant are affected by a complex array of conditions, processes, substances and organisms. However, all the interrelating aspects between algae, water chemistry and treatment processes which play a role in the treatment of water need to be further investigated in detail in order to better understand the underlying principles in water purification so that new processes, or new combinations of processes, can be developed in order to be able to continue producing potable water under conditions of dynamic change in the source waters.

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Goudveld Water made all the facilities at the Balkfontein Plant available for research, and members of staff were responsible for the taking of samples and the analyses of various environmental variables.

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INTRODUCTION

The eutrophied, polluted, salinised and mineralised state of the Vaal River have resulted, and will more extensively in future, result in large-scale algal blooms, and consequently, in serious ecological, aesthetic, health and water purification problems.

The Balkfontein plant of Goudveld Water treats water for potable purposes from the middle Vaal River. The water in the river consists of a large fraction of recycled water from household, mining and industrial activities as well as a fraction arising from specific agricultural practices (Pieterse, 1986; Heynike & McCulloch, 1982; Basson & Pieterse, 1993).

The eutrophic nature of the raw water in the middle Vaal River (Pieterse, 1986) results in a constantly changing raw water quality which, together with the chemical characteristics of the raw water, high algal biomass or particular algal species at lower biomass concentrations as well as other unknown factors, are sometimes causing the impairment of flocculation and other processes in the different treatment phases in operation at the Balkfontein plant (Pieterse, 1989; Pieterse *et al.*, 1993; Bernhardt & Schell, 1989). Different algal species penetrate the entire purification process (Pieterse *et al.*, 1993).

The diversity of chemical substances in the water and rapid changes in the quality of the raw water, require that coagulant dosages sometimes have to be adjusted at short time intervals. Oftentimes high dosages of metallic salts, which traditionally are used with great success, are not able to efficiently purify the water. Under such conditions other treatment options must be adopted at high financial costs.

The purpose of the investigation was therefore to monitor chemical and biological water quality parameters and relate these to effective treatment measures, such as different dosages of oxidants and coagulants.

Algae are common inhabitants of surface waters exposed to sunlight, where they often give rise to large quantities of organic material which cause various problems in rivers and lakes (Palmer, 1980). In water purification systems, algae may clog sand filters and

distribution pipes, shorten filter runs, cause unpleasant tastes and odours, resist sedimentation and interfere with industrial uses (Pieterse, 1989).

The production of drinking water from eutrophic waters requires the elimination of phytoplankton and zooplankton as well as the removal of high concentrations of algal-derived organic matter. Suitable removal methods include, for example, biological treatment processes and others such as sand filtration (Bernhardt & Clasen, 1991). In order to be a useful fluid for human consumption, water must be free from organisms that are capable of causing disease as well as free from minerals and organic substances that could produce adverse physiological effects (Tate & Arnold, 1990).

Very little information is available on the penetration of algal species in the different phases of water purification. In addition, almost no information is available on the connections between morphological and physiological characteristics of phytoplankton species on the one hand, and aspects of water purification processes such as oxidation, flocculation, sedimentation, filtration and flotation on the other hand. The wax and wane of algal assemblages and biomass in the river, the result of environmental conditions, most probably directly affect treatment processes and removal efficiency in the treatment plant. A complete, inclusive, integrated investigation of the connections between environmental variables and algal assemblages in the river as well as algal components and the purification potential and purification problems in the treatment plant, was therefore necessary in the South African context in general and in the Vaal River context in particular.

Additional aims of the investigation were therefore to determine the nature of algal-related problems and the types of algae involved, as well as the relationships between algae in the raw water and in different phases of the purification process. In addition, the contribution of algal cells to extracellular organic substances were also investigated. The importance in, and effect of, internal and external morphological characteristics of algal cells were considered in relation to the different unit processes. The theoretical importance of various differences between algal cells and colloidal particles during coagulation and flocculation of these particles, were considered in an attempt to explain why algal cells, colonies and filaments could penetrate unit processes.

STUDY SITE, MATERIAL AND METHODS

The water purification plant of Goudveld Water consists of three modules or lines that treat water in parallel fashion (Fig. 1).

The localities of pumping stations (Old PS, New PS), chemical dosing and rapid mixing, the three Modules (Modules I, II, III), sedimentation tanks of the three modules, filter blocks with the filters of the three modules and the reservoirs where the water is stored before it is pumped to the different areas, are shown in Fig. 1. For the purpose of this study, nine sampling localities were selected in the purification plant at Balkfontein (Fig. 1), namely at the Intake (1), after Secondary sedimentation for Modules I, II & III (1.3, 2.4 & 3.4 respectively) after Flotation for Module I (1.4a), after Sand filtration for Modules I, II & III (1.6, 2.5 & 3.5 respectively) and the Final water (4).

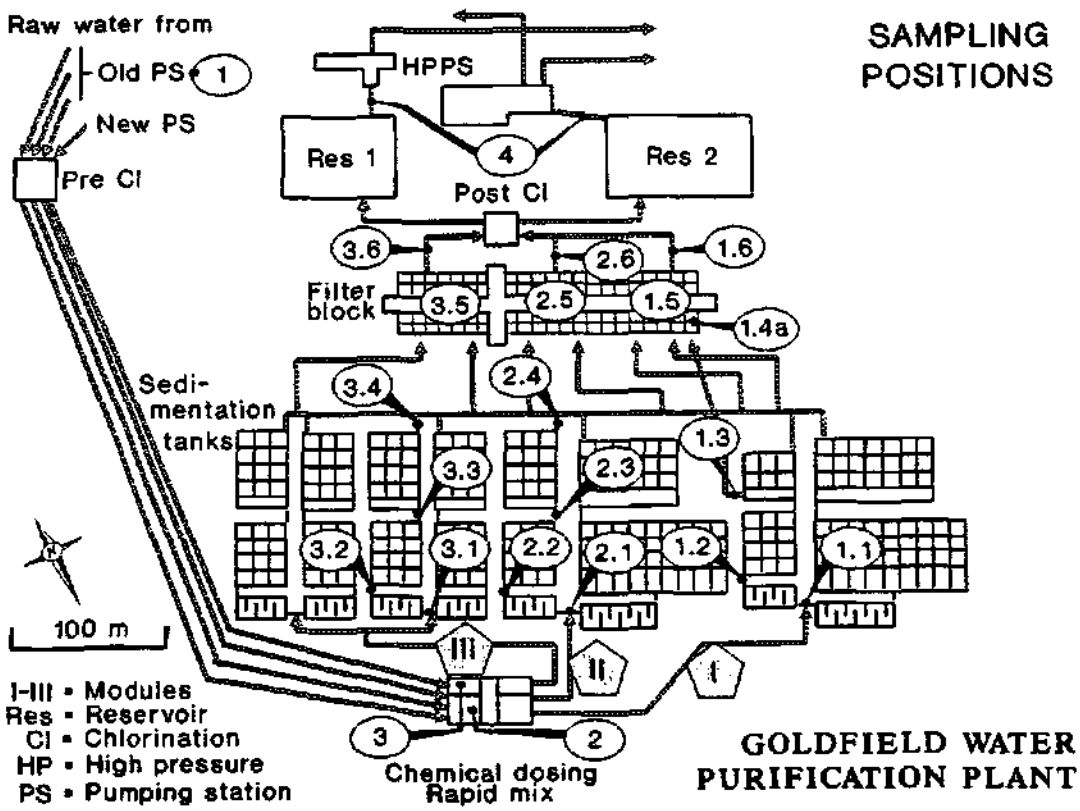

Figure 1: Goudveld Water Purification Plant at Balkfontein, Bothaville.

In Module I an air flotation unit is combined with the sand filter (DAFF unit; i.e. dissolved air flotation-filtration unit). A water sample was taken 200 mm above the sand filter in the DAFF unit. This sample represents water that has been flotated prior to sand filtration.

Maximum G values (mean velocity gradient) of 2 100 s^{-1} can be obtained at the primary dosing points (Fig. 1) when operating at full capacity. Energy is obtained via a hydraulic jump. These dosing points are mainly used for lime dosing. Contact time is approximately 2,8 seconds. Poly-electrolytes are dosed at a second hydraulic jump. Rapid mixing is done by means of an in-line mixing system and the primary coagulant, which is usually a metallic salt, is dosed here. G values of 4 800 s^{-1} can be reached at contact times of 0.33 seconds. Tables 1 and 2 summarise the operating characteristics of the Balkfontein plant.

The serpentine channels consist of 30 and 90 Ml/d units. The G values in the 30 Ml/d units are 155 s^{-1} and in the 90 Ml/d units 48 s^{-1} maximum, at contact times of approximately 820 and 970 seconds respectively.

When the plant is being operated at full capacity the primary sedimentation time in Module II and Module III is 6 hours. In Module III secondary sedimentation time is also 6 hours, whereas for Module II it is only 4 hours. For the purpose of this study, Module I was changed to treat only 12 Ml/d, allowing for a primary sedimentation time of almost 15 hours.

The plant has 30 sandfilters with an open area of 100,8 m^2 each, and a total depth of 1m. Filtration speed is 5 m/h when operating at full capacity. The design capacity of the plant is 360 Ml/d; 120 Ml/d per module. The facility exists to use different chemical dosing points with different Camp numbers.

Different chemicals were added to facilitate the purification of the water from the Vaal River. Table 2 summarise dosages of the different chemicals.

Table 1: Operating characteristics of the Balkfontein purification plant.

	Module 1 (Filter 2) (Operation Volume - 12 Ml/d)			Module 2 (Design Capacity - 120 Ml/d)			Module 3 (Design Capacity - 120 Ml/d)		
	G-value s^{-1}	**Retention time**	**Volume m^3**	**G-value s^{-1}**	**Retention time**	**Volume m^3**	**G-value s^{-1}**	**Retention time**	**Volume m^3**
Primary dosing	2469	1.41 s		2469	1.41 s		2105	2.86 s	
Lime mixing channels	468	37.05 s		468	37.05 s		250	67.41 s	
Rapid Mixing units	4817	0.33 s		4817	0.33 s		4816	0.33 s	
Secondary dosing units	1452	2.86 s		1452	2.86 s		1721	2.86 s	
Split channels									
Channel	45	253 s		38	80.40 s		74	118.60 s	
Flume	917	2.87 s		1260	4.10 s		981	3.65 s	
Channel (2nd)							22	99.30 s	
Flume (2nd)							1584	2.97 s	
Serpentine channels									
30 Ml/d units	45	966.8 s		45	966.80 s		45	966.80 s	
90 Ml/d units				32	821.50 s				
Primary sedimentation tanks	-	15.2 h	7596	-	6.08 h	30386	-	6.08 h	30386
Secondary sedimentation tanks		-	-	-	3.8 h	18991	-	6.08 h	30386
Sand filters			1 x 100.8 (x 1 filter)			1 x 100.8 (x9 filters)			1 x 100.8 (x20 filters)

Table 2: Flow and filtration rates, retention time and chemical dosages in the three modules of the Balkfontein purification plant.

	UNITS	MODULE 1			MODULE 2			MODULE 3		
		MIN	MAX	MEAN	MIN	MAX	MEAN	MIN	MAX	MEAN
Flow	Ml/d	0	130.00	65.37	55.10	143.00	98.49	0	115.70	76.03
Retention time	h	0	15.19	6.43	8.26	21.504	12.62	0	165.70	17.57
Filtration rate	m/h	0	34.40	5.97	0	6.00	2.73	0	6.50	3.62
Dosage										
Pre-chlorination	mg/l	0	7.00	5.40	0	7.00	2.81	0	7.40	3.93
Post-chlorination	mg/l	0	5.40	2.86	1.03	7.00	3.94	1.30	5.50	3.64
Pre-Lime [$Ca(OH_2)$]	mg/l	0	62.40	22.35	0	264.00	55.71	0	66.60	23.63
Post-Lime [$Ca(OH_2)$]	mg/l	0	6.10	2.32	0	18.80	3.81	0	18.60	3.59
Carbon dioxide	mg/l	0	33.30	14.15	0	66.60	23.20	0	60.50	15.35
$FeCl_3$ (as Fe)	mg/l	0	5.80	2.80	0	5.80	2.07	0	5.80	2.99
$Fe_2(SO_4)_3$ (as Fe)	mg/l	0	0	0	0	2.40	0.06	0	2.50	0.04
Polymer	mg/l	0	0.70	0.25	0	17.00	1.50	0	14.00	1.25
Dosage cost										
Pre-chlorination	c/kl	0	2.59	1.42	0	2.59	1.06	0	2.74	1.46
Pre-Lime	c/kl	0	1.12	0.41	0	4.75	1.04	0	1.40	0.45
$FeCl_3$	c/kl	0	2.23	1.06	0	1.95	0.70	0	2.22	1.09
Polymer	c/kl	0	0.24	0.09	0	8.35	0.74	0	6.85	0.57
$Fe_2(SO_4)_3$	c/kl	0	0	0	0	0.70	0.03	0	0.71	0.01
Post-chlorination	c/kl	0	2.00	1.06	0.48	2.59	1.48	0.48	2.02	1.37
Post-lime	c/kl	0	0.11	0.04	0	0.34	0.07	0	0.34	0.07
CO_2	c/kl	0	1.63	0.68	0	3.26	1.07	0	11.18	0.84

Standard methods were used to analyse water from the river as well as from different sampling positions in the plant (Basson & Pieterse, 1999; Visser & Pieterse, 1999). Jar tests were used to investigate the effect of different coagulants, algal cells and extracellular products from algal cells on coagulation and sedimentation of particles from Vaal River water (Traut & Pieterse, 1999). The components and concentration of the extracellular products from the algal cells were determined after extraction from water from which the algal cells were removed (Pieterse *et al.*, 1999). Approximation theory was used in comparison with classical theory of flocculation with colloidal particles to investigate and quantify differences between colloidal particles and algal cells (Cloot & Pieterse, 1999).

RESULTS AND RECOMMENDATIONS

CHARACTERISTICS OF VAAL RIVER WATER AT BALKFONTEIN

Vaal River water at the Balkfontein Plant of Goudveld Water consists of a large fraction of recycled water from household, mining and industrial activities as well as a fraction arising from specific agricultural practices. The diversity of chemical substances in the water and rapid changes in the quality of the raw water, required that coagulant dosages sometimes have to be adjusted at short time intervals. Often high dosages of metallic salts, which traditionally are used with success, are not able to efficiently purify the water. Under such conditions other treatment options, such as high pH lime treatment or poly-electrolyte dosing, had been adopted at high financial costs.

The characteristics of Vaal River water at Balkfontein in relation to conditions for efficient treatment, have been investigated by Basson & Pieterse (1999).

Chemical costs on the plant had increased since 1993 from approximately 4 c kl^{-1} to 7 c kl^{-1} (Fig. 2).

Increased concentrations of iron, manganese (Fig. 3) organic substances (Fig. 4) and possibly chlorophyll-a (Fig. 5) were most likely the cause of the escalating costs.

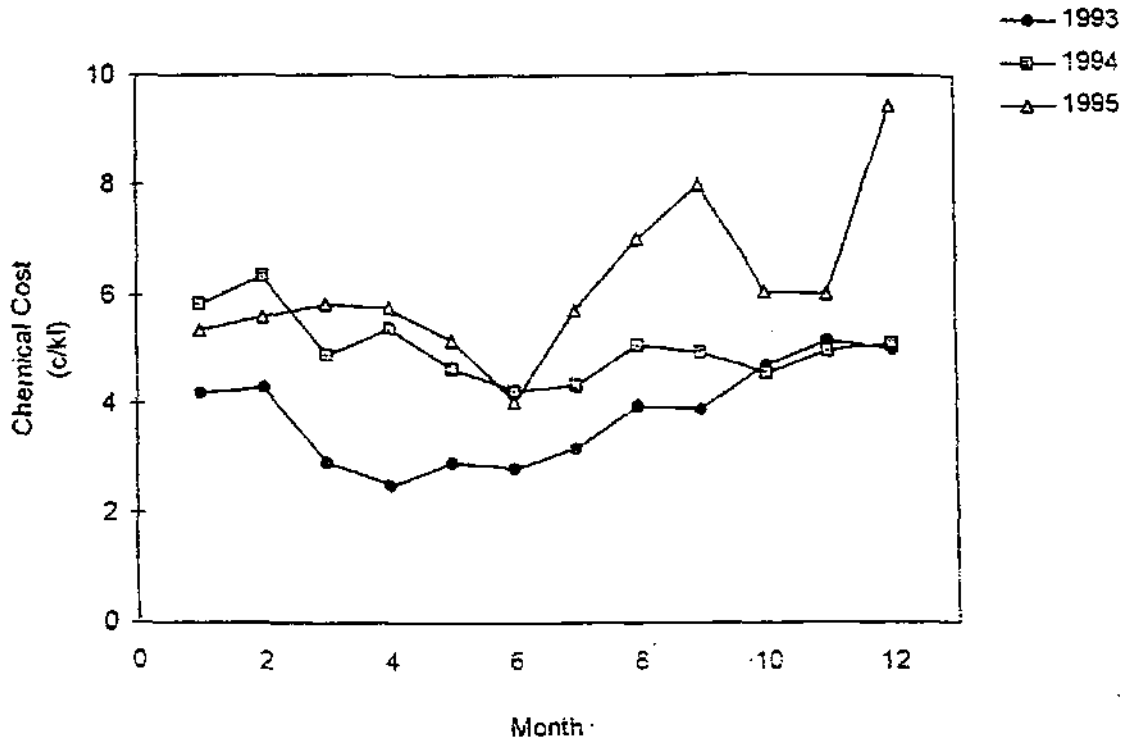

Figure 2: Monthly average chemical cost - 1993 tot 1995 (Basson & Pieterse, 1999).

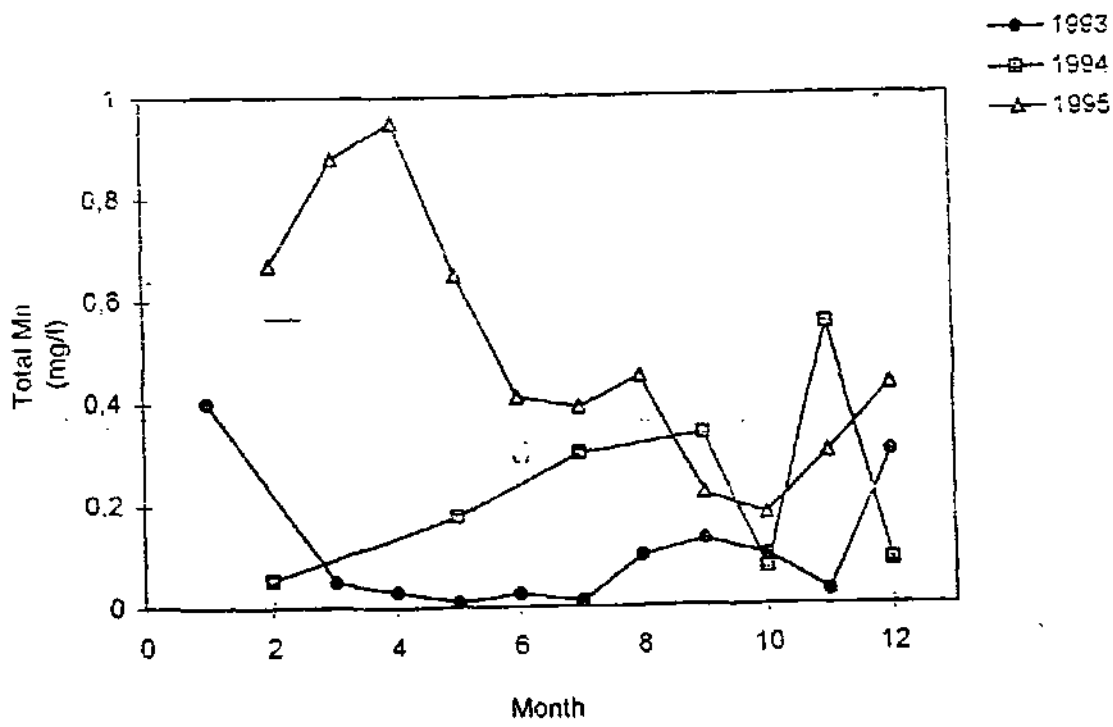

Figure 3: Monthly average manganese concentrations in the river water - 1993 to 1995 (Basson & Pieterse, 1999).

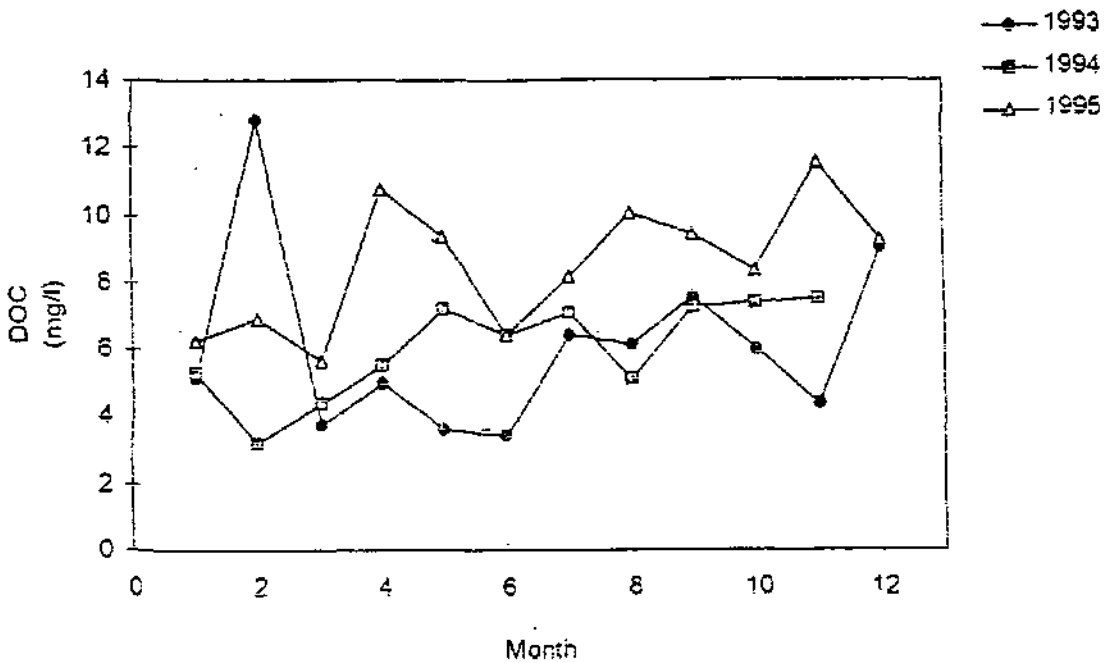

Figure 4: Monthly average DOC concentrations in the river water - 1993 tot 1995 (Basson & Pieterse, 1999).

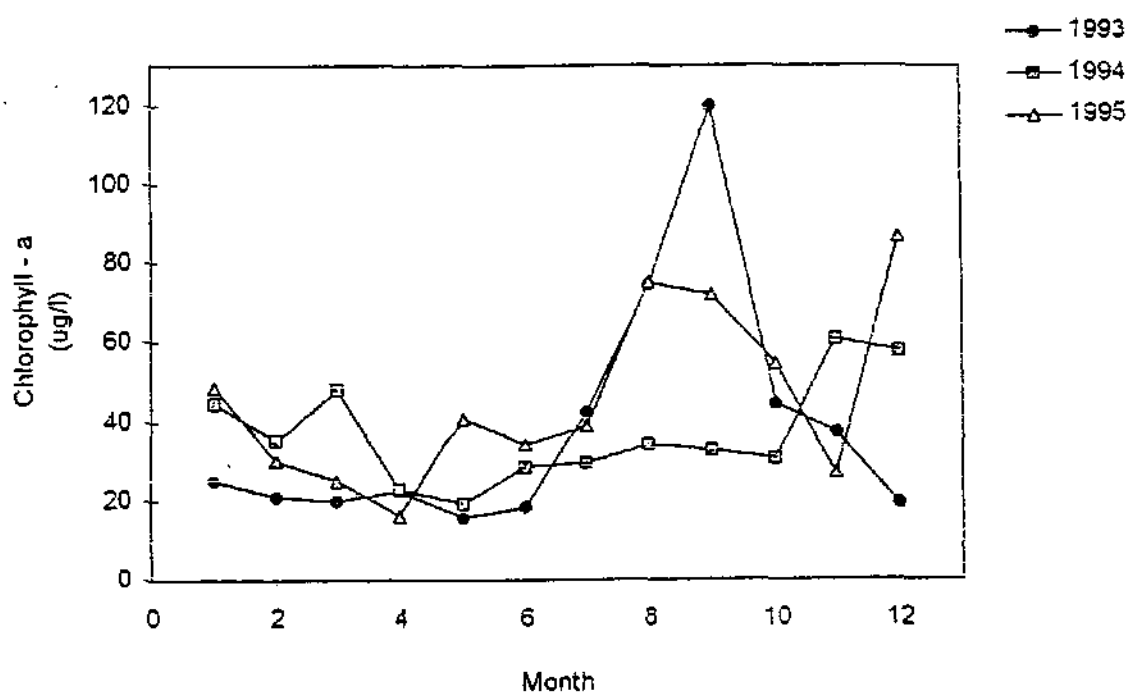

Figure 5: Monthly average chlorophyll a concentrations in the river water - 1993 to 1995 (Basson & Pieterse, 1999).

Vaal River water was much more susceptible to conventional treatment processes during winter months. Rainfall during summer months most probably contributed to increasing levels of contaminants such as iron, manganese and dissolved organic carbon. The high pH lime process was shown to be approximately 2 c kl^{-1} more expensive than the other processes employed at Balkfontein plant. Low concentrations (1 mg l^{-1}) of poly-electrolyte in combination with $FeCl_3$ produced acceptable final water at lower costs than the high pH lime process.

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. This observation confirms that of Bernhardt *et al.* (1986) who showed that flocculation was enhanced by calcium.

High pH lime treatment was shown to remove turbidity, dissolved organic carbon and iron more efficiently than aluminium and chlorophyll (i.e. algal cells). The low turbidity of the water after sedimentation caused filamentous algal growth in the secondary sedimentation tanks in Module II, which could have contributed to higher chlorophyll-a levels obtained in the high lime process. The positive effect of pre-chlorination on the removal of chlorophyll-*a*, as illustrated in Table 3, could possibly also have contributed to the poorer removal of chlorophyll-*a* in the high lime process where no pre-chlorination was performed. Although protein was removed better in the high lime process when compared with ferric chloride plus poly-electrolyte U5000, slightly better reduction of chlorophyll-*a* was obtained with poly-electrolyte U5000. This is in contradiction to the findings of Al-Layla and Middlebrooks (1974) who stated that algal organic matter is composed mainly of protein. Chlorophyll-a reductions were >96% in the modules and an explanation can probably be that the protein originating from algal organic matter was removed efficiently in the modules. The fraction of protein which was removed better in the high lime process could thus have been from a different source.

Results in Table 4 show that when $FeCl_2$ was used in jar tests, the removal of organic substances varies within certain pH-ranges. This could be the result of the effect of Ca^{++} (Bernhardt *et al.*, 1986), or it could be the result of the relationship between the effectiveness of chlorine and pH. The increase in reduction at pH > 10.3 can be explained in terms of the adsorption theory according to Leentvaar and Rebhun (1992).

Table 3: Results from jar tests to demonstrate the effect of pH, chlorine and coagulant concentration on the removal of iron, chlorophyll-a and SAC (Basson & Pieterse, 1999).

pH	Fe (mg/l)	U5000 (mg/l)	Chlorine (mg/l)	Turbidity removal (%)	Chlorophyll -a removal (%)	Fe (Total) removal (%)	SAC removal (%)
7.70	7.00	0	4.26	41.00	89.90	71.1	6.00
7.80	1.18	12	4.2	80.40	89.90	87.3	20.16
8.85	7.00	0	4.2	50.00		69.0	21.10
8.70	1.18	12	4.2	89.00		81.4	24.30
9.78	7.00	0	4.2	83.90	91.19	76.5	14.30
9.76	1.18	12	4.2	90.61	94.90	90.0	25.20
7.78	7.00	0	0.0	40.65	25.35	53.1	6.00
7.80	1.18	12	0.0	91.23	59.23	99.0	54.80
8.85	7.00	0	0.0	41.10		54.3	18.00
8.70	1.18	12	0.0	90.94		99.1	52.80
9.78	7.00	0	0.0	42.06	57.04	68.1	34.80
9.76	1.18	12	0.0	92.00	68.90	99.6	55.50

Table 4: Results from jar tests to demonstrate the effect of pH, chlorine and coagulant concentration on the removal of iron, manganese and organic matter (Basson & Pieterse, 1999).

pH	Fe (mg/l)	U5000 (mg/l)	Chloroine (mg/l)	Turbidity (%)	DOC (%)	Fe (Total) (%)	Fe (Diss.) (%)	Mn (Total) (%)	Mn (Diss.) (%)	SAC (%)
7.51	2.22	0.50	3.70	42.86	2.08	93.66	ND	3.33	0.80	11.01
7.49	0.59	10.00	3.70	91.71	15.64	97.73	ND	36.67	26.09	37.42
8.74	2.22	0.50	3.70	92.86	7.39	64.99	ND	6.67	39.13	10.69
8.68	0.59	10.00	3.70	91.71	12.03	81.52	ND	51.67	47.83	34.28
9.87	2.22	0.50	3.70	94.86	3.952	87.84	ND	7.50	60.87	24.21
9.85	0.59	10.00	3.70	91.43	12.20	93.35	ND	65.00	69.57	33.65
7.78	2.22	0.50	0.00	66.57	9.52	88.04	ND	2.30	1.00	17.59
7.91	0.59	10.00	0.00	89.71	22.75	97.68	ND	9.09	14.29	43.04
8.59	2.22	0.50	0.00	92.57	6.70	68.93	ND	3.45	7.14	17.06
8.63	0.59	10.00	0.00	89.43	17.8	90.71	ND	6.20	57.14	36.75
9.82	2.22	0.50	0.00	90.86	6.66	79.64	ND	22.73	7.14	28.08
9.79	0.59	10.00	0.00	92.57	12.70	85.36	ND	22.73	57.14	42.26

When using the poly-electrolyte U5000 as secondary coagulant in Module III, and compared with the high lime process, humic- and fulvic acids, protein and carbohydrates were removed better in Module III than in the high lime process during the period when increasing DOC concentrations were observed in the raw water.

The increasing DOC concentrations also coincided with the poorer removal of iron in the high lime process.

Results showed that $FeCl_3$ and poly-electrolyte were efficient removal agents when centric diatoms were present in the raw water. One possible explanation for this observation may be that centric diatoms possibly excrete smaller amounts and fewer organic acids than green algal representatives (see Table 6). However, poly-electrolyte dosing was always needed when centric diatoms were present in the raw water. Diatoms reduced the removal of Fe, which had to be removed by higher dosages of poly-electrolyte.

During 1993 high poly-electrolyte concentrations were applied to deal with problems experienced with the removal of iron and turbidity. Jar tests performed with $FeCl_3$ during the presence of DOC levels exceeding 10 mg/l, sometimes produced a gelatine-like slimy floc. Bernhardt *et al.* (1986) referred to the disturbance of flocculation by EOM as result of a mechanism whereby the particle is enclosed in a gel due to molecular interlacing and co-precipitation together with the metal hydrolyses used as flocculant. In periods during 1994 and 1995 iron could not be removed below 100 µg/l by using $FeCl_3$ as the only coagulant even at pH values of approximately 9,6. Lapin and Yedigarova (1990) emphasised the fact that EOM (also from blue-green algae) effectively binds and retains Fe(III) when pH $\geq$ 8. The problems experienced with iron removal could be the result of these bindings at pH values of this order measured in the raw water source.

The use of poly-electrolytes for the removal of organic substances is described in the literature and was correlated with findings in the laboratory and in the plant, where the addition of poly-electrolyte U5000 presented better results than only $FeCl_3$ in the removal of fulvic- and humic acids, carbohydrates and chlorophyll-*a*. Protein was removed better with $FeCl_3$ at temperatures between 24.5 °C and 16.5 °C. Between 16 °C and 12 °C better results were obtained with the addition of U5000. At temperatures below 12 °C $FeCl_3$, without U5000, performed better. The removal of humic acids was better at temperatures

below 16 °C when only $FeCl_3$ was used. The addition of U5000 contributed to the better removal of humic acids at temperatures above 16 °C.

Pre-chlorination was performed in the plant almost throughout the experimental period in order to enhance the removal of Mn and chlorophyll-*a*. It was therefore not possible to properly evaluate the role of pre-chlorination in the removal of DOC and Fe. It is not possible to conclude from jar tests and a short evaluation period on the plant that pre-chlorination is in fact detrimental to the removal of DOC and Fe.

Jar tests conducted in the laboratory (Tables 3 and 4) indicated that better DOC removal is obtained when no pre-chlorination was performed. This could be one of the reasons for the better reduction obtained by the high lime process, because no pre-chlorination was done during this process. The effect of pre-chlorination on DOC removal was also tested in the plant by running two Modules (II and III) on $FeCl_3$ and U5000, the only difference being that no chlorine was added to Module II. Better DOC reduction was obtained in Module II. DOC values exceeding 12 mg/l were measured in the plant. Jar tests showed most of the time that pre-chlorination had some adverse effect on DOC removal. Yeh & Huang (1993) indicated that the removal of hydrophilic fractions are limited and that pre-chlorination probably transforms some organics from other fractions into hydrophilic-neutral fractions.

By analysing the results in Table 4 it is clear that in order to obtain low final manganese concentrations, the coagulation pH had to be raised to at least 9,6 and an oxidant had to be used.

The DAFF process performed better than the control line in removing Al, Fe and chlorophyll-*a*. DOC removal in the control line was better. When using poly-electrolyte U5000 as a secondary coagulant in the DAFF process, DOC removal was better than in the control line where only $FeCl_3$ was used. The removal of chlorophyll-*a* in the control line compared well with the removal in the DAFF process on two occasions when poly-electrolyte had to be used on both modules. It seems that the poly-electrolyte as secondary coagulant, for these specific periods, enhanced the removal of DOC and chlorophyll-*a*. Al-Layla & Middlebrooks (1974) stated that algal organic matter is

composed mainly of protein, which possibly explains the better reduction of both chlorophyll-*a* and protein by the DAFF process with U5000 as secondary coagulant.

Results indicated that temperature affected the removal of organic substances. Threshold temperatures determined whether it was necessary to dose $FeCl_3$ or poly-electrolyte. Temperature was, however, apparantly not affecting the removal of chlorophyll-*a*, and therefore, algal cells.

The results clearly showed the necessity to qualify and quantify different fractions of dissolved organic substances in solution. Dissolved organic substances affected the removal of material in suspension, and different components were apparently requiring different conditions for removal. The concentration of dissolved organic carbon and dissolved iron should be used in addition to turbidity as indicators of treatment efficiency.

ALGAL SPECIES AND ASSOCIATED MATERIAL

Visser & Pieterse (1999) 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. The penetration of species were related to specific treatment conditions.

Different algal groups were present in Vaal River water, namely blue-green algae (Cyanophyceae), diatoms (Bacillariophyceae), green algae (Chlorophyceae), euglenophytes (Euglenophyceae), dinoflagellates (Dinophyceae) and cryptophytes (Cryptophyceae). Blue-green algae, green algae and diatoms were almost always present in the treated water, that is, they were almost always present in the sand filter effluent.

The green algae was present in relative small quantities in the river water (Figs 6 & 7), but increased proportionate to the other groups through the purification processes to the final water (Figs 8 & 9) where they reached dominant proportions.

Blue-green algae, similar to green algae, also increased proportionate to the other groups from the river to the final water (Figs 6, 7, 8 & 9). These results indicated that green and

blue-green algae in general are less efficiently removed by the unit processes employed at Balkfontein.

In general, diatoms were reduced to a larger extend than green algae. Diatoms were removed more efficiently under the prevailing conditions of flow, coagulation, flocculation and filtration. The efficient removal of diatom cells is most probably partly explained by the cells being more dense because of silica-containing frustules. Surface characteristics apparently played an important role in the removal of algal cells, because green algae (cellulose cell walls) were better removed by $FeCl_3$ while diatoms (silica-frustules) were better removed by lime.

High phytoplankton biomass in the raw water increased the biomass and species diversity in the final water. *Synechococcus* sp., a blue-green alga, grew within the treatment plant because its concentration frequently increased from the river to the sand-filtered water. Sedimentation was shown to be primarily responsible for algal biomass removal, but not for reduction in species diversity.

The following algal species were removed less efficiently by sedimentation and filtration and should be considered problem species: *Carteria globosa, C. simplicissima, Chlamydomonas incerta, Crucigenia tetrapedia, Monoraphidium arcuatum, M. circinale, Oocystis lacustris* (all unicellular green algae) as well as *Chroococcus dispersus* and *Synechococcus cedrorum* (small semi-colonial blue-green algae). The *Carteria* and *Chlamydomonas* species may have partially avoided flocculation because they are able to move with flagella. The other green algae all deviate in shape from the sphere (being elongated or triangular). The blue-green cells are much smaller than the other algae, and proved difficult to remove, even under high dosage concentrations.

The algal species present in the river and in different phases of the treatment process were divided into the following morphological groups: unicellular algae (Un) with flagellated cells (Unfl), spherical cells (Unsp), elongated cells (Unel) and discoidal cells (Undi); colonial algae (Co) with spines (Cospi), with spherical cells (Cosp), and with discoidal cells (Codi); as well as filamentous algae (Fila).

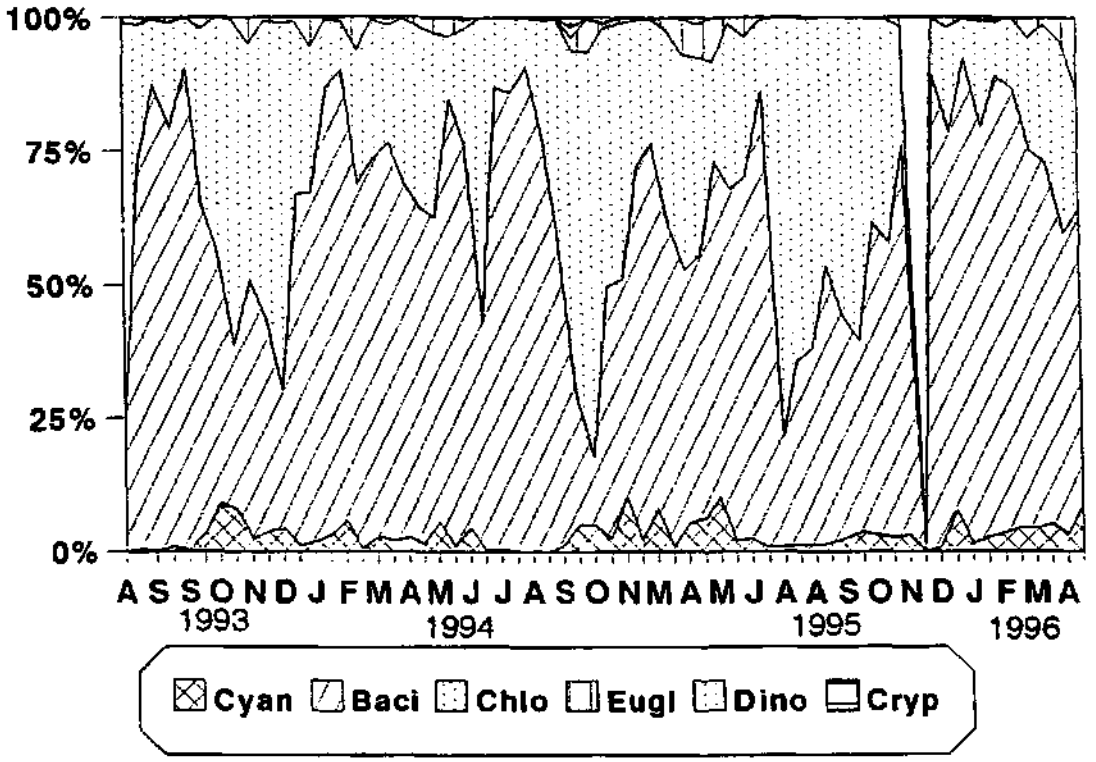

Figure 6: Composition of major phytoplankton groups in the river water from August 1993 to April 1996 (Visser & Pieterse, 1999). Cyan = *Cynophyceae* (blue-green algae), Baci = *Bacillariophyceae* (diatoms), Chlo = *Chlorophyceae* (green algae), Eugl = *Euglenophyceae* (euglenophytes), Dino = *Dinophyceae* (dinoflagellates) and Cryp = *Cryptophyceae* (cryptophytes).

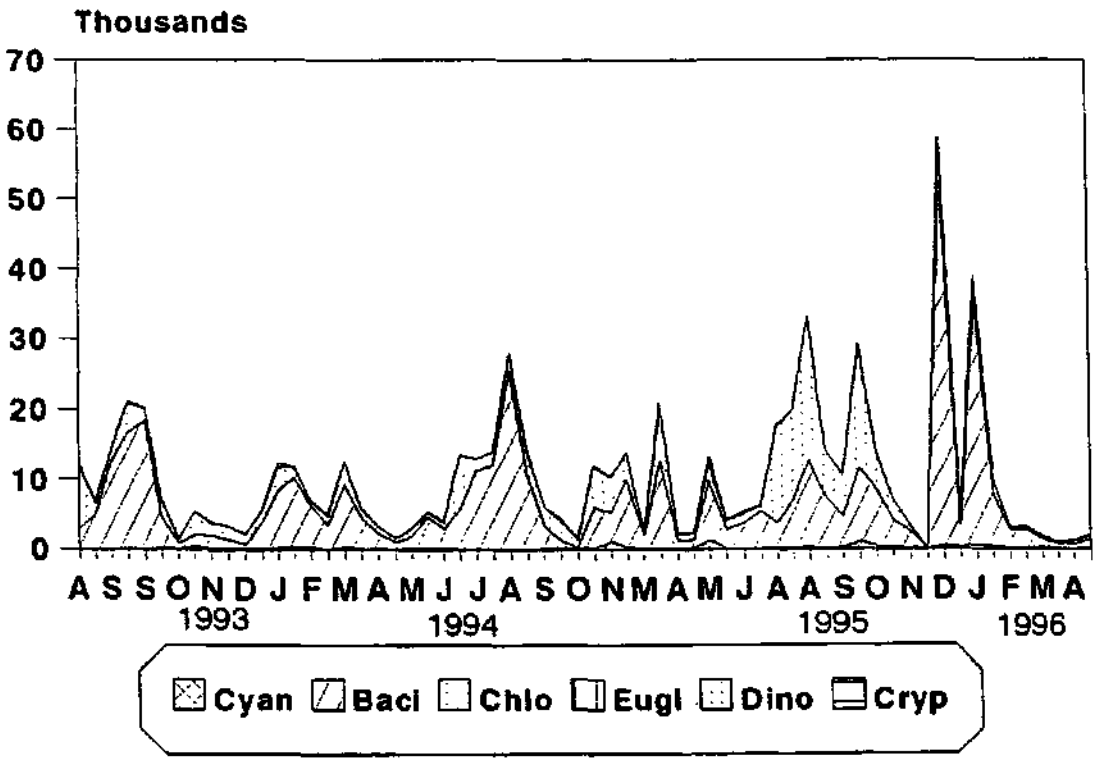

Figure 7: Concentration of major phytoplankton groups in the river water from August 1993 to April 1996 (Visser & Pieterse, 1999). Abbreviations are explained in Fig. 6.

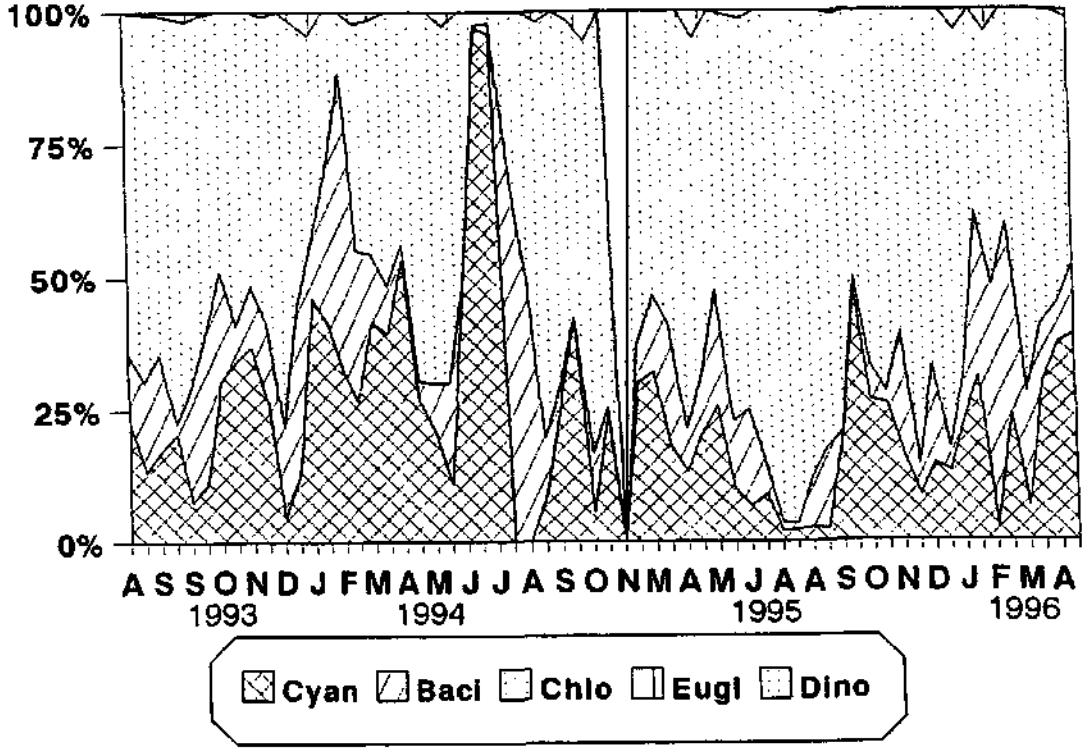

Figure 8: Composition of major phytoplankton groups of the final (sand-filtered) water from August 1993 to April 1996 (Visser & Pieterse, 1999). Abbreviations are explained in Fig. 6.

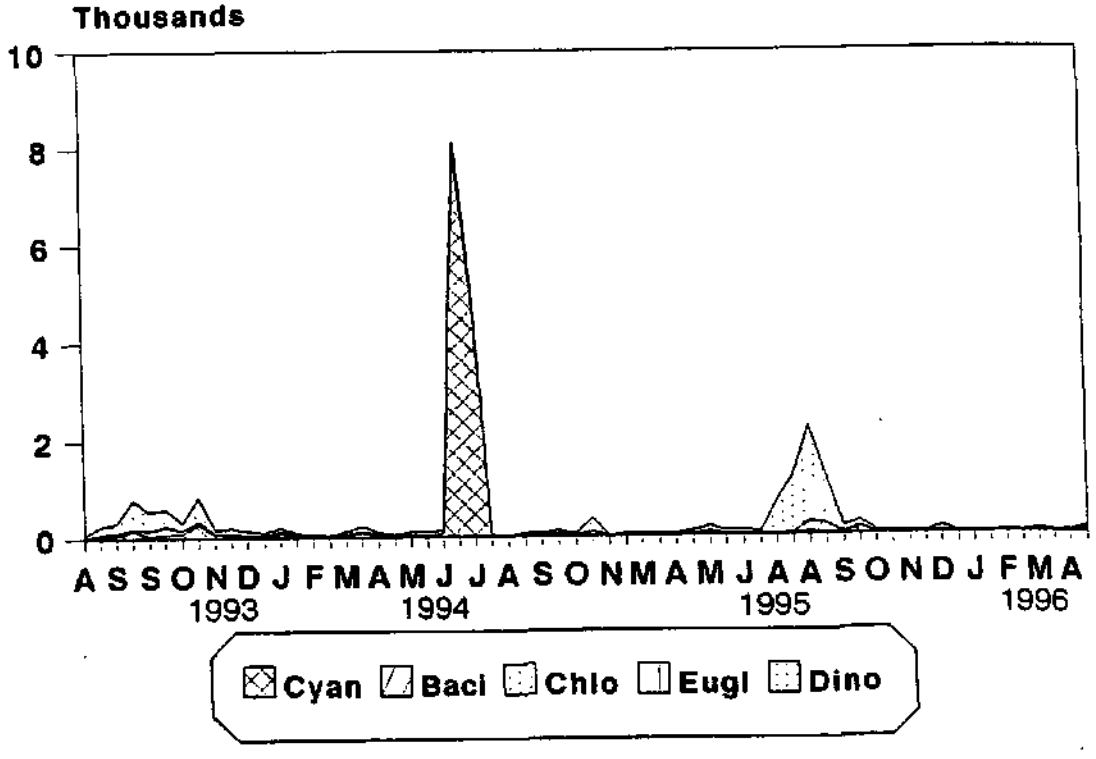

Figure 9: Concentration of major phytoplankton groups in the final (sand-filtered) water from August 1993 to April 1996 (Visser & Pieterse, 1999). Abbreviations are explained in Fig. 6.

Unicellular discoidal cells (centric diatoms) were generally dominant in the river water, followed by colonial algae with spines (*Scenedesmus* spp.) and filaments (*Oscillatoria simplicissima*; Figs 10 & 11). In the final (sand-filtered) water (Figs 12 & 13), unicellular algae with flagella (*Chlamydomonas* and *Carteria* spp), unicellular algae with elongated cells (*Monoraphidium* and *Ankistrodesmus* spp. and unicellular spherical cells (*Synechocystis* and *Synechococus* spp.). *Synechococus cedrorum*, a blue-green alga, was shown to have increased in numbers in the treatment plant.

Unicellular algae with flagella with elongated and with spherical cells were, therefore, shown to be difficult to remove.

In the previous paragraphs results were presented indicating that the size and shape of algal cells, as well as the organic material excreted by the cells, have an effect on the coagulation, sedimentation and filtration of the algal entities (single cells, colonies and filaments). In order to provide more information on these aspects, Traut & Pieterse (1999) investigated the effect of organic substances excreted by algal species on coagulation and sedimentation. Pieterse *et al.* (1999) investigated the types and amounts of certain organic compounds excreted by the individual algal species. In addition, Cloot & Pieterse (1999) investigated the possible effect of size and metabolic characteristics of algal cells on coagulation and sedimentation in comparison with colloidal particles.

Traut & Pieterse (1999) showed with jar tests on Vaal River water that it is not necessary to dose $FeCl_3$ in higher concentrations than 18 mg l^{-1}. Low Fe^{3+} concentration (lower than approximately 4 mg l^{-1}) dosages gave lower flocculation and removal efficiencies. These results apparently show the effect of too little Fe^{3+} available to form positive charged Fe-hydroxo complexes for charge neutralisation. With higher Fe^{3+} concentrations, flocculation and removal occurred more efficiently.

The occurrence of flocs on the surface of water in jar tests and in treatment plants is often observed. The main factor responsible for the formation of flocs on the surface could be flocculant overdose. The optimum flocculant concentration, based on the results of the experiments, was between 8 and 10 mg l^{-1} Fe^{3+} for a pH range between 5 and 11. Under these conditions, flocs rarely concentrated on the water surface.

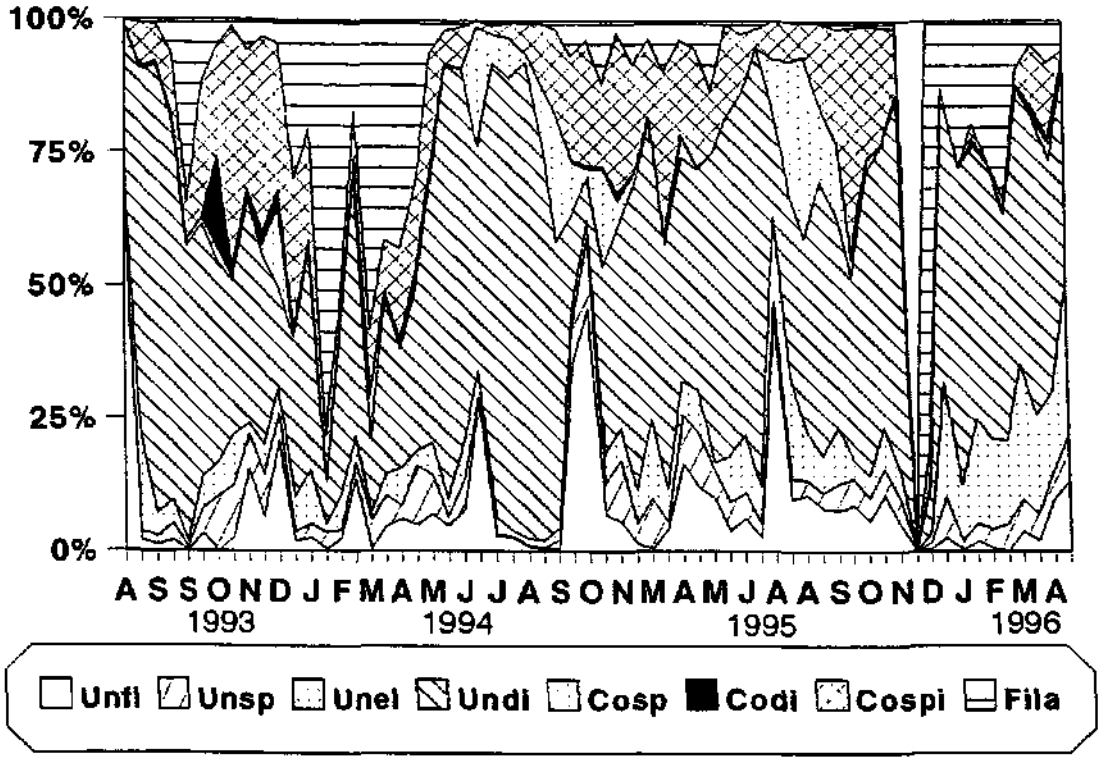

Figure 10: Morphological composition of phytoplankton in the river water from August 1993 to April 1996 (Visser & Pieterse, 1999). Unfl = unicellular flagellated, Unsp = unicellular spherical, Unel = unicellular elongated, Undi = unicellular discoidal, Cosp = colonial spherical, Codi = colonial discoidal, Cospi = colonial with spines, Fila = filamentous.

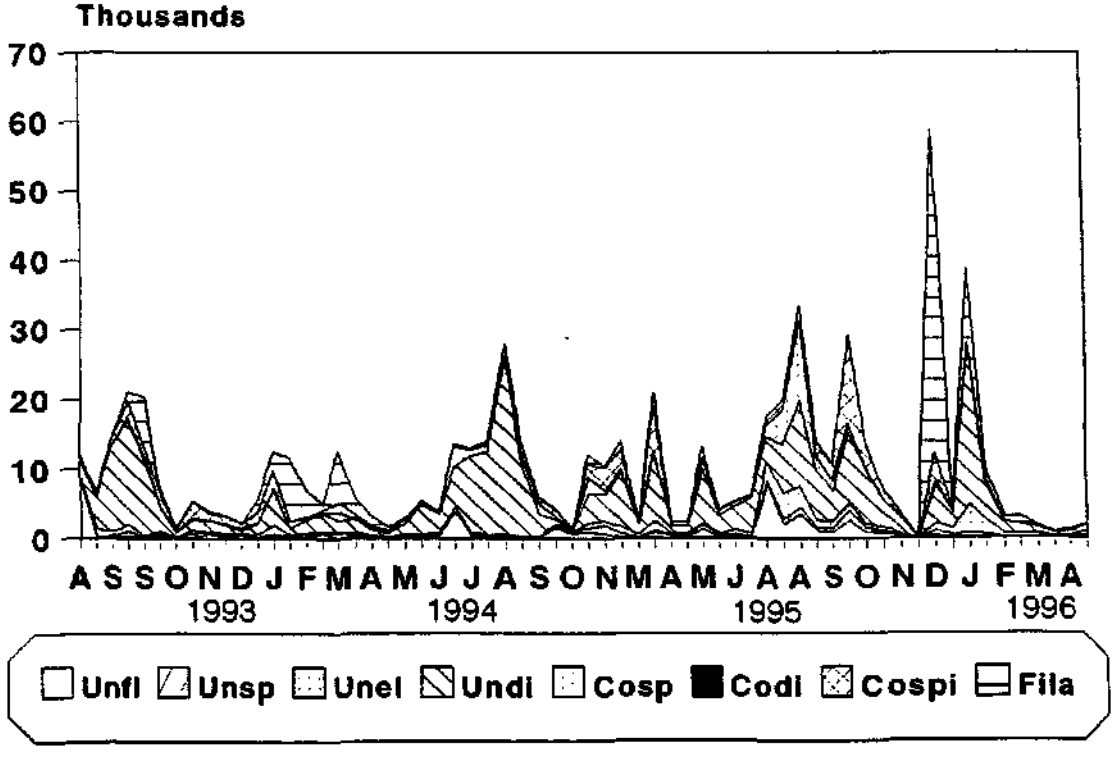

Figure 11: Concentration of different morphological groups in the river water from August 1993 to April 1996 (Visser & Pieterse, 1999). Abbreviations are explained in Fig. 10.

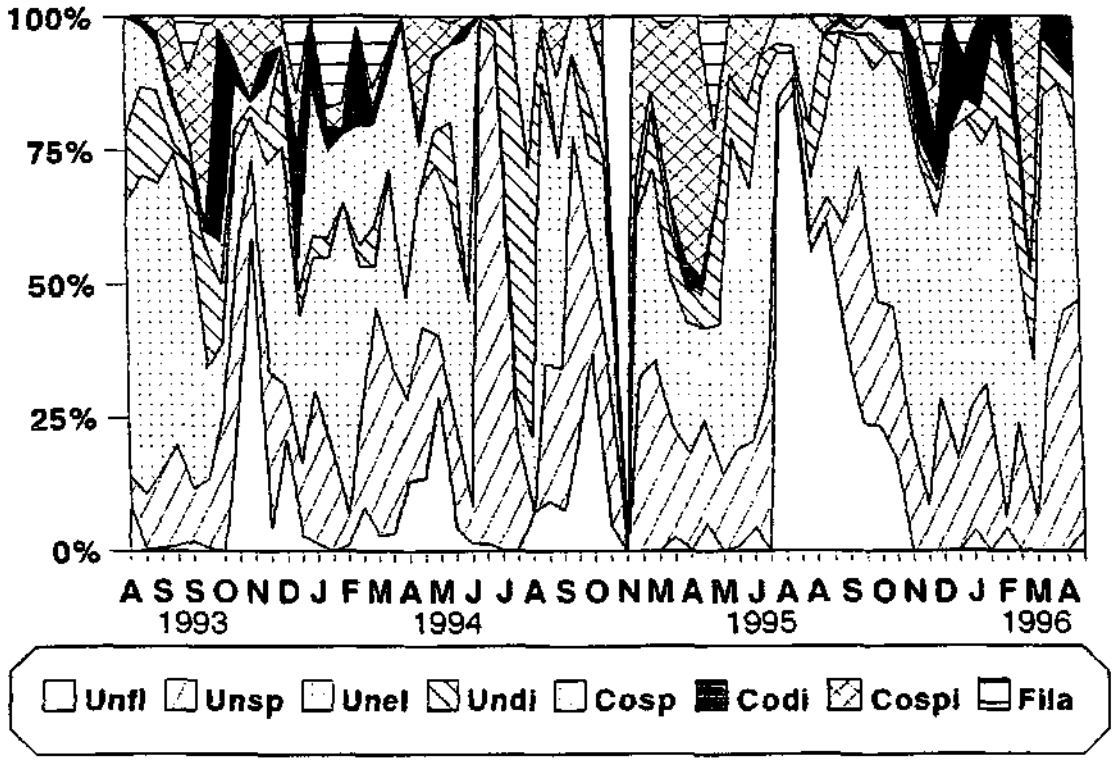

Figure 12: Morphological composition of phytoplankton in the final (sand-filtered) water from August 1993 to April 1996 (Visser & Pieterse, 1999). Abbreviations are explained in Fig. 10.

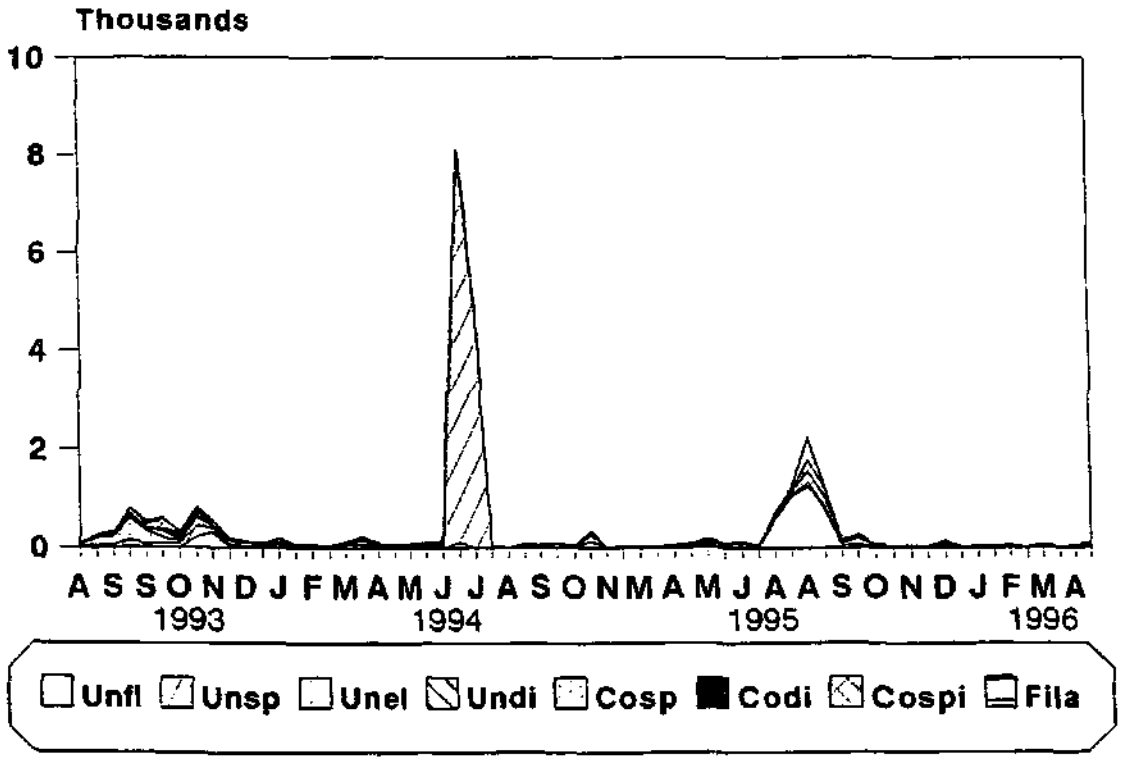

Figure 13: Concentration of different morphological groups in the final (sand-filtered) water from August 1993 to April 1996 (Visser & Pieterse, 1999). Abbreviations are explained in Fig. 10.

The formation and concentration of flocs or aggregates on the surface of the treated water could also be an indication that the phytoplankton in the water produce gas vacuoles which enable the cells in the flocs to float. In addition, the concentration at the surface could be due to mucilage material present around some algal cells which entraps gasses such as O_2 and CO_2 released by the cells. Differences in densities between the mucilage material and the water may also have resulted in the concentration of material at the surface of the water.

The results showed that the flocculation and removal of Dissolved Organic Carbon (DOC) decreased with an increase in pH. The most efficient removal of DOC occurred at pH 5, which is an indication that $FeCl_3$ as sole flocculant was inefficient in the removal of DOC at pH conditions between 7 and 11. However, when the pH was raised to 11.5, the removal of DOC increased. The increase in removal of DOC was enhanced with the addition of iron.

Ca^{2+} ions apparently did not participate directly in flocculation processes when the pH was unchanged. When the pH was adjusted to 11.5, algal cells and suspended particles were effectively removed even when no Ca^{2+} was added. The removal was, therefore, the result of the high pH conditions. It is, however, possible that a pH of 11.5, in conjunction with the added Ca^{2+}, resulted in the formation of precipitates of calcium carbonate and magnesium hydroxide which can possibly assist in flocculation. It was shown in other studies that suspended particles can be adsorbed onto these precipitates (Parker *et al.*, 1975; Dziubek and Kowal, 1984).

The use of high Fe^{3+} concentrations (> 6 mg l^{-1}) under low pH conditions (<7) for the water used in this study may have contributed to the relatively efficient removal of DOC. Investigations by Black and Christman (1963), Hall and Packham (1965), Dempsey *et al.* (1984), Edwards and Amirtharajah (1985) and Sinsabaugh *et al.* (1986) showed that coagulation of DOC was dependent primarily on pH conditions, the coagulant dose, and the concentration of DOC. Effective removal of DOC occurred at lower pH conditions than did turbidity. The optimum pH conditions for coagulation of organic matter was around pH 4 for Fe(III) salts. Gray (1988) reported that below pH 6, removal occurs by coprecipitation of ferric-organic matter/ferric hydroxide precipitates and concluded that effective removal of DOC with Fe(III) occurs primarily by the formation of an iron-organic

precipitate rather than the formation of ferric hydroxide. This investigation showed that DOC was also effectively removed at pH 11.5 in conjunction with increased Fe^{3+} concentrations (> 8 mg l^{-1}).

The experiments demonstrated that low Fe^{3+} concentrations (< 6 mg l^{-1}) gave lower flocculation and removal efficiencies. With an increase in Fe^{3+} concentration (i.e. 8 to 18 mg l^{-1}), an increase in the efficiency of flocculation and removal were observed. It was possible to determine the optimum Fe^{3+} concentration (approximately 8 mg l^{-1}) necessary for efficient flocculation and removal of algal biomass (indicated by chlorophyll-*a*), DOC and total suspended solids for the water and conditions experienced in the present study.

The experiments enable the determination of the optimum pH for flocculation with $FeCl_3$ as flocculant. Except for the removal of DOC, the removal of total suspended solids in the water was optimal at pH 11. Therefore, it is possible to conclude that optimal conditions for flocculation with $FeCl_3$ as flocculant is at pH 11 at a Fe^{3+} concentration of 8 mg l^{-1}. Ferric chloride was more efficient in affecting the coagulation process than ferric sulphate.

The results obtained from the comparison between lime and sodium hydroxide showed that lime was more efficient in affecting flocculation. This can be due to the increase in suspended particles and possibly calcium concentration which apparently assisted in flocculation as a result of calcium carbonate precipitates which forms at pH conditions higher than 10.5 (Ronen, 1981).

Addition of *Monoraphidium minutum* cells increased the chlorophyll-*a* concentration in experiments with approximately 60 µg l^{-1}. The high concentration of chlorophyll-*a* was removed less efficiently at pH 6.4 (see Figs 14 and 15). When algal cells were added which were suspended in culture medium in which the cells grew (excreted organic substances present), the removal of the cells at pH 11.5 was more effective than when the cells were suspended in distilled water (compare Figs 14 and 15). Therefore, culture medium in which the cells grew apparently assist in flocculation. The assistance could be due to the dissolved inorganic components of the nutrient medium, or the excreted organic substances. The algal cells themselves, however, apparently obstructed the flocculation process when high chlorophyll-*a* concentration occurred in the water.

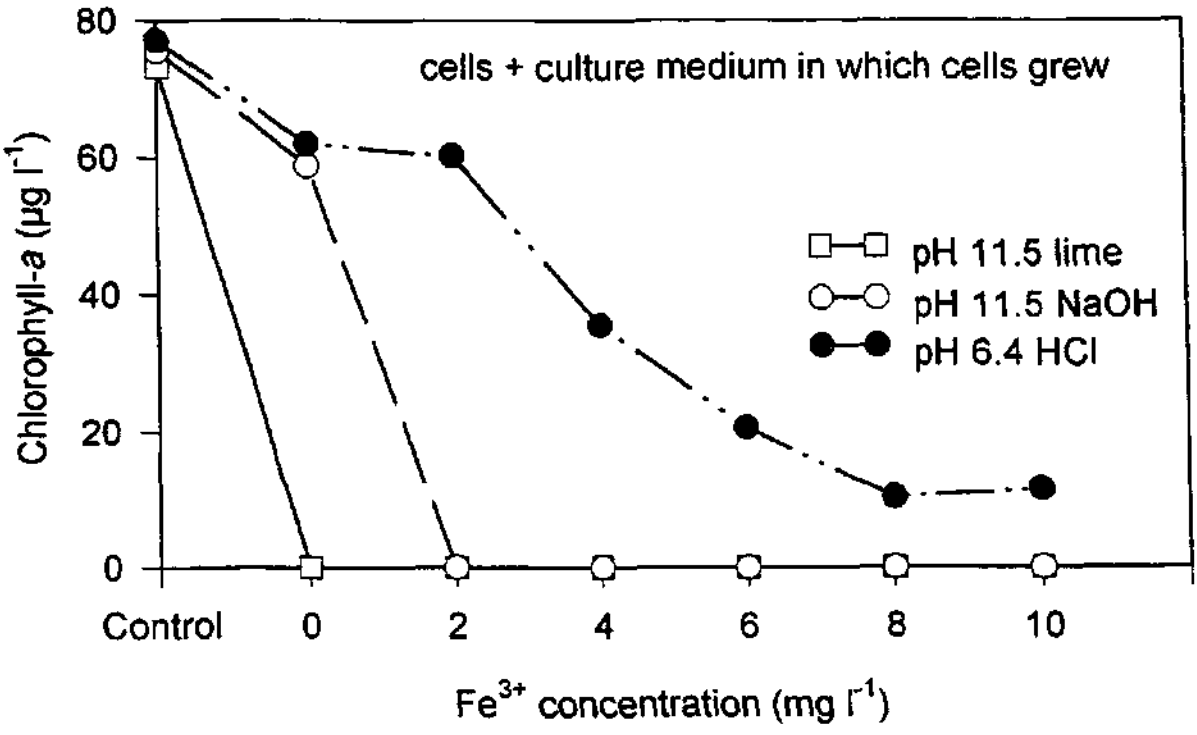

Figure 14: Variation in chlorophyll-a concentration (µg l^{-1}) with increased Fe^{3+} concentration. *Monoraphidium minutum* cells, suspended in culture medium in which the cells grew, were added to Vaal River water (Traut & Pieterse, 1999).

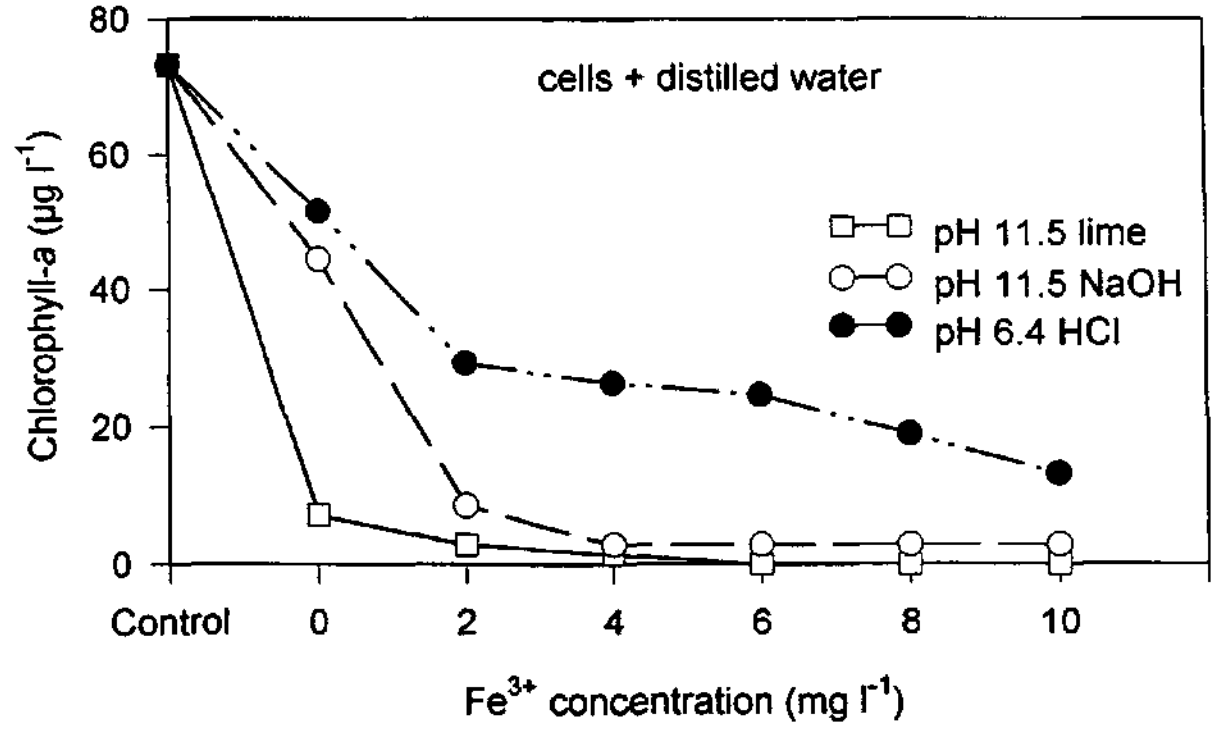

Figure 15: Variation in chlorophyll-a concentration (µg l^{-1}) with increased Fe^{3+} concentration. *Monoraphidium minutum* cells, suspended in distilled water, were added to Vaal River water (Traut & Pieterse, 1999).

Other results showed that organic substances excreted by the cells apparently caused poorer removal of the cells. Better removal of organic substances was observed at pH 11.5. Other results also showed that excreted organic compounds assisted in the flocculation and removal of suspended solids. *M. minutum* cells themselves enhanced the removal of DOC.

The addition of *Cyclotella meneghiniana* cells in experiments increased the chlorphyll-*a* concentration with approximately 30 $\mu g\ l^{-1}$. The increased chlorophyll-a was less efficiently removed at pH 6.4 when lower iron concentrations (< 6 mg l^{-1}) was added (Figs 16 and 17). Efficient removal occured at pH 11.5. Other results showed that organic substances excreted by *C. meneghiniana* did not affect the flocculation of algal cells at pH 11.5. At a pH of 6.5, however, the excreted organic substances apparently inhibited the removal of algal cells. Effective removal of suspended solids in the presence of *C. meneghiniana* was also observed at pH 11.5, while better removal of suspended material at pH 6.5 was only observed at higher $FeCl_3$ concentrations (> 6 mg l^{-1}). *C. meneghiniana* cells apparently assist in the removal of suspended solids pH 6.4. Excreted organic substances did not affect the removal of inorganic suspend particles. However, *C. meneghiniana* cells apparently assisted in the removal of DOC at pH 11.5, and inhibited the removal at pH 6.4.

The addition of *Pandorina morum* colonies increased the chlorophyll-a concentration in experiments with approximately 60 $\mu g\ l^{-1}$. This increase in chlorophyll-*a* was less efficiently removed at pH 6.4 when lower iron concentrations (< 4 mg l^{-1}) were added (Figs 18 and 19). Other results showed that *P. morum* colonies inhibited the removal of algal biomass, apparently because of their ability to move by way of flagella. Organic compounds excreted by the colonies apparently also inhibited the removal of algal biomass. pH 6.4 was ineffective in the removal of suspended particles in the presence of *P. morum* colonies except when high Fe^{3+} (> 6 mg l^{-1}) concentrations were added. Effective removal occurred at pH 11.5 with increased Fe^{3+} concentrations. The removal of suspended particles was apparently not affected by excreted organic substances or by *P. morum* colonies. However, indications were that *P. morum* colonies improved the removal of DOC, but excreted organic substances apparently did not affect the removal of DOC.

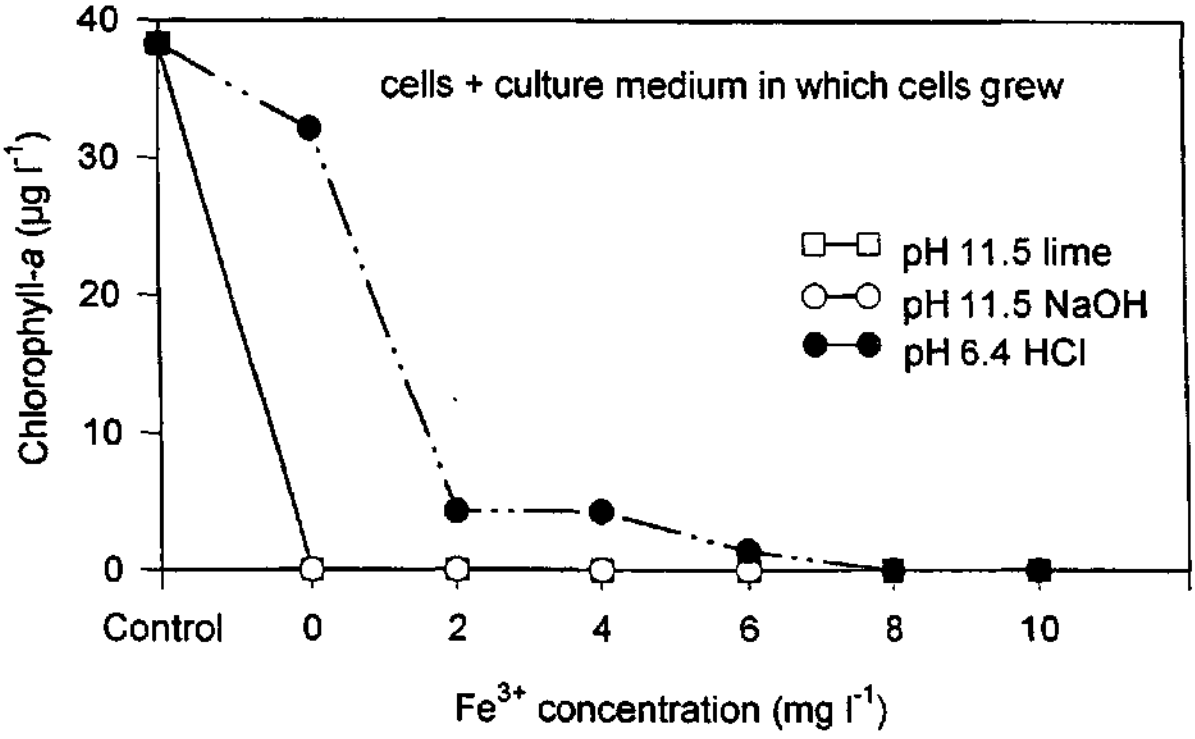

Figure 16: Variation in chlorophyll-*a* concentration (µg l^{-1}) with increased Fe^{3+} concentration. *Cyclotella meneghiniana* cells, suspended in culture medium in which cells grew, were added to Vaal River water (Traut & Pieterse, 1999).

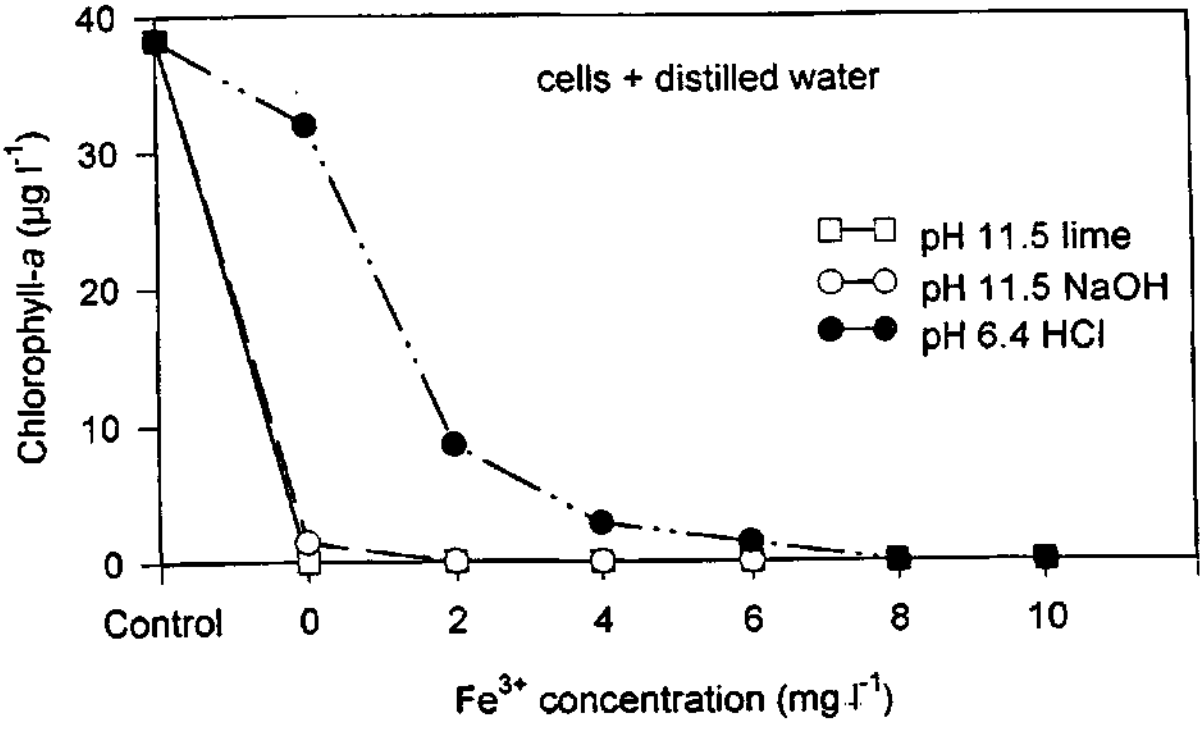

Figure 17: Variation in chlorophyll-*a* concentration (µg l^{-1}) with increased Fe^{3+} concentration. *Cyclotella meneghiniana* cells, suspended in distilled water, were added to Vaal River water (Traut & Pieterse, 1999).

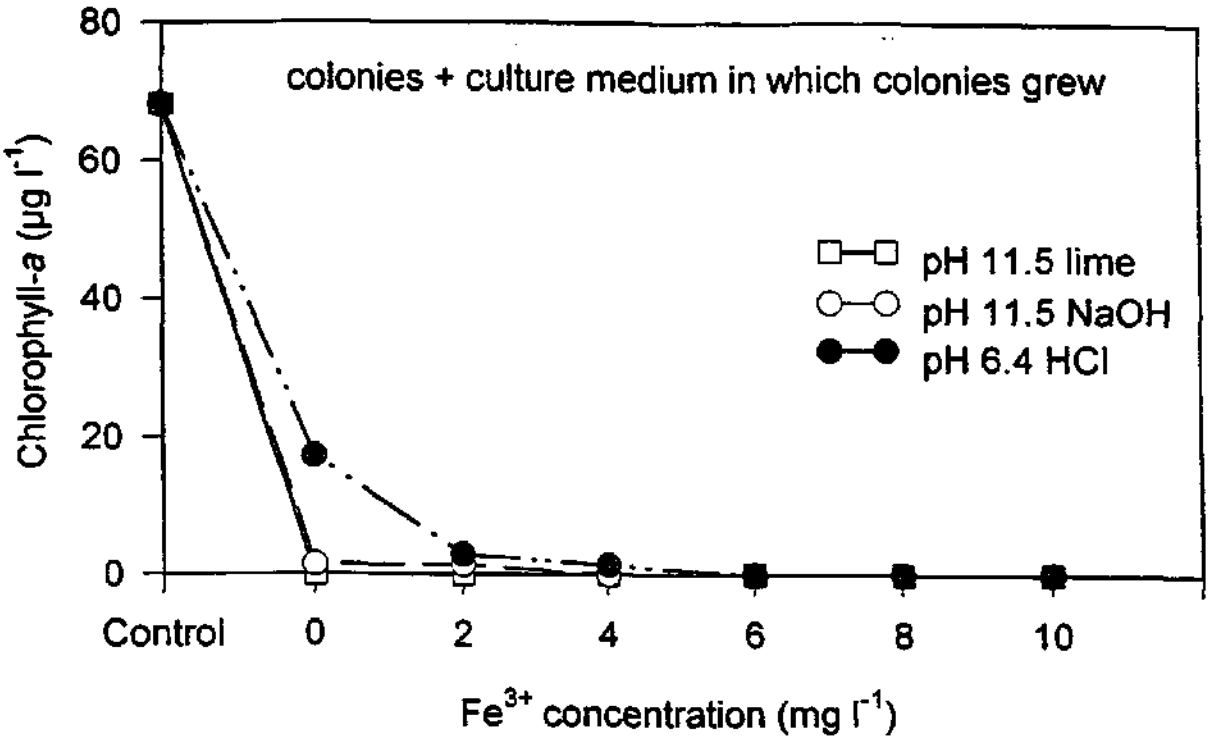

Figure 18: Variation in chlorophyll-*a* concentration (µg l^{-1}) with increased Fe^{3+} concentration. *Pandorina morum* colonies, suspended in culture medium in which colonies grew, were added to Vaal River water (Traut & Pieterse, 1999).

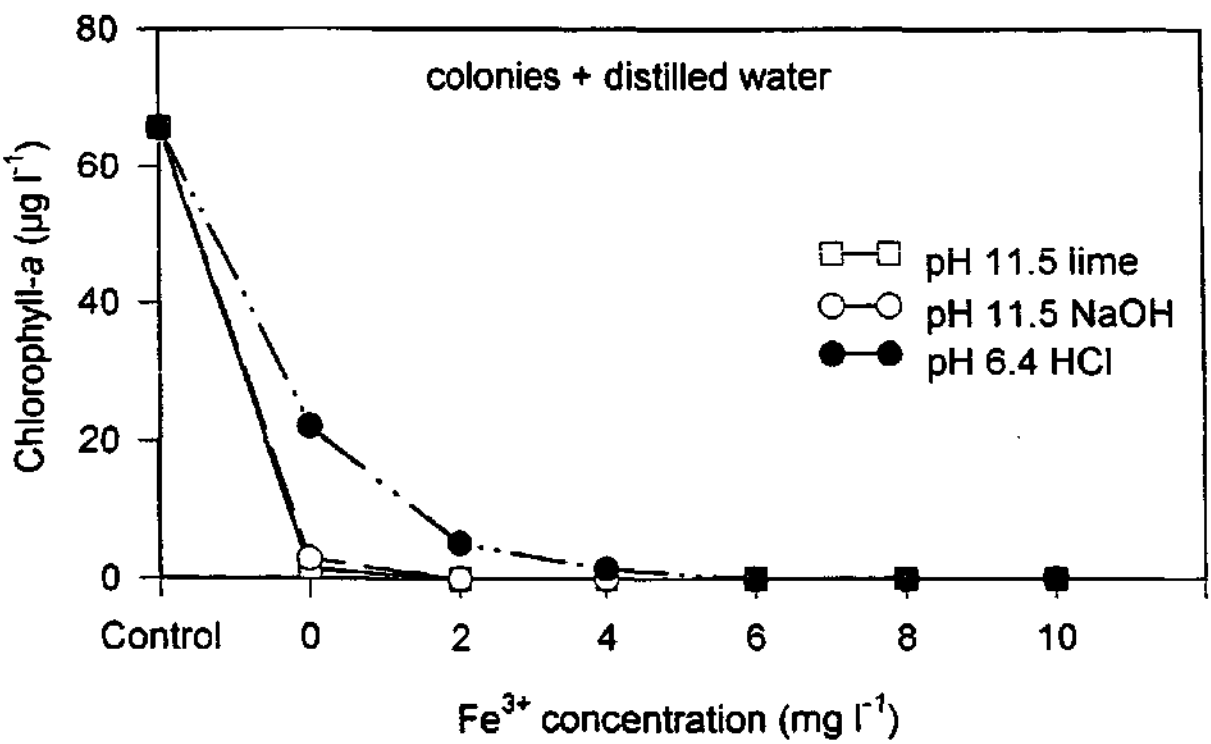

Figure 19: Variation in chlorophyll-*a* concentration (µg l^{-1}) with increased Fe^{3+} concentration. *Pandorina morum* colonies, suspended in distilled water, were added to Vaal River water (Traut & Pieterse, 1999).

When all the findings presented by Traut & Pieterse (1999) on the effect of *Monoraphidium minutum*, *Cyclotella meneghiniana* and *Pandorina morum* are taken into account, the following conclusions can be drawn to summarise the results.

Monoraphidium minutum cells (green alga) were ineffectively removed at pH 6.4, but effective removal occurred at pH 11.5. *M. minutum* cells are elongated and cresent shaped which can be responsible for the possibility that the compactness of the flocs in which they were included, was low and that sedimentation would be affected.

M. minutum addition reduced the removal of chlorophyll-*a* (algal cells). The organic matter excreted by the cells possibly improved the removal of chlorophyll-*a* at pH 11.5, but inhibited removal at pH 6.4. Organic matter excreted by *M. minutum* apparently assisted in the removal of suspended matter present in Vaal River water. The organic substances excreted by *M. minutum* cells reduced the removal of DOC, or had no effect. The culture medium in which *M. minutum* grew contained higher concentrations of monocarboxylic, fatty and aromatic acids in addition to glycerol than the culture media of the other algae (Table 5).

Cyclotella meneghiniana cells (diatom) were more effectively removed than *Monoraphidium minutum* cells. Organic substances excreted by *Cyclotella meneghiniana* reduced the removal of chlorophyll-a (algal cells) at pH 6.4. The culture medium in which *C. meneghiniana* grew had higher concentrations of dicarboxylic acids than the culture media of the other algae (Table 5). *C. meneghiniana* cells apparently enhanced the removal of suspended particles at pH 6.4. When the pH was adjusted to 11.5, *C. meneghiniana* apparently enhanced the removal of DOC.

C. meneghiniana cells were effectively removed when added to Vaal River water, except when pH was adjusted to 6.4 and low iron concentrations (< 4 mg l^{-1}) was added. The areolae in the frustules, which can capture oxygen during photosinthesis, could possibly be responsible for the ineffective removal at pH 6.4 when low Fe^{3+} concentrations (< 4 mg l^{-1}) was added. *C. meneghiniana* cells apparently enhanced the removal of suspended matter at pH 6.4.

Pandorina morum colonies (green alga with flagella) were effectively removed when the pH was adjusted to 11.5 and Fe^{3+} concentrations higher than 4 mg l^{-1} were added. Ineffective removal occurred at pH 6.4 when low Fe^{3+} concentrations (< 2 mg l^{-1}) were added. The ineffective removal at pH 6.4 can possibly be due to the presence of the mucilage sheath around the colonies. The density of the mucilage is lower than the density of water (Reynolds, 1975) and, therefore, sedimentation would be slower. The ineffective removal can also be due to the movement of the colonies by means of flagella.

Table 5: Extracellular organic substances from uni-algal cultures of *Monoraphidium minutum* (Monmin; 10 days old), *Cyclotella meneghiniana* (Cycmen; 18 days old), and *Pandorina morum* (Panmor; 10 days old) isolated from the Vaal River (Traut & Pieterse, 1999).

Compound	Concentration µg l^{-1}			ng/µg chlorophyll-a^{-1}		
	Monmin	Cycmen	Panmor	Monmin	Cycmen	Panmor
Monocarboxylic acids	354.8	188.9	34.4	99.8	219.1	10.8
Dicarboxylic acids	266.0	348.0	266.1	74.8	403.6	83.9
Fatty acids	331.4	39.9	-	93.3	46.3	-
Aromatic acids	231.8	-	109.6	65.2	-	34.6
Glycerol	34.3	-	-	9.7	-	-
Phosphoric acid	-	-	6.7	-	-	2.1

Although *P. morum* colonies are motile by means of flagellar movements, the colonies were more effectively removed when compared with the removal of *Monoraphidium minutum* cells. Organic substances excreted by *Pandorina morum* colonies apparently reduced the removal of chlorophyll-*a* (algal colonies). *P. morum* colonies, and the organic substances excreted by them, did not affect the removal of suspended particles in Vaal River water. *P. morum* colonies apparently enhanced the removal of DOC slightly. The organic substances excreted by *P. morum* did not affect the removal of DOC. The culture medium of *P. morum* had less monocarboxylic and aromatic acids in solution than the media of the other algae (Table 5).

The results showed that algal cells, especially of *Monoraphidium minutum*, *Cyclotella meneghiniana* (at pH 11.5) and *Pandorina morum* colonies themselves, possibly assist in the removal of DOC.

Although the extracellular substances of the different algae differed markedly, and while it is tempting to suggest that the differences in effect might have been attributable to the

differences in concentration and relative ratios of the extracellular organic substances, the present investigation do not provide conclusive answers.

It can in general be concluded that increases in biomass, together with the excreted organic matter from the algal cells, affect the removal of biomass, suspended matter and dissolved organic carbon. However, more detailed studies are needed to determine the exact effect of the algal cells and colonies as well as their excreted organic substances on coagulation and sedimentation.

Table 5 illustrates major groups of organic compounds excreted by the three algal species used in the experiments where the effect of the species added to Vaal River water was investigated. Table 6, based on results given by Pieterse *et al.* (1999), shows the diversity of organic substances excreted by the algae, as well as the relative amounts excreted.

A diverse amount of organic, fatty and aromatic acids, as well as dimers, glycerol, and phosphoric acids were found in the media. *Monoraphidium minutum* excreted the largest number of substances (Table 6), followed by *Cosmarium laeve*, *Chlamydomonas* sp., *Pandorina morum* and *Cyclotella meneghiniana*.

High, concentrations of hydroxy-Acetic/Glycolic acid, 3-4-dihydroxy-Butyric acid, Oxalic acid, Lauric acid and Hydroxy-propylenediphenol were excreted by *Monoraphidium minutum*. *Chlamydomonas* sp. excreted high concentrations of Decanoic and Octanoic acids, while *Pandorina morum* excreted high concentrations of Oxalic and Benzoic acids. *Cosmarium laeve* excreted several carboxylic and fatty acids in high concentrations; a high concentration of 1 236 $\mu g\ l^{-1}$ of Octanoic acid was demonstrated. *Cyclotella meneghiniana* excreted high concentrations of Lactic and Oxalic acids. Apart from affecting chlorination and the removal of suspended and dissolved substances, the excreted substances most probably contribute negatively to the aesthetic quality of the water, such as producing tastes and odours.

Although it was demonstrated that the exctracellular organic substances most probably affected coagulation and sedimentation of algal cells and colonies as well as colloidal

particles, the effect of the individual substances were not investigated. This aspect needs to be studied in detail in future investigations.

Table 6: Components of extracellular organic substances (in ng/µg chlorophyll-*a*) from uni-algal cultures of species isolated from the Vaal River (Pieterse *et al.*, 1999). Monmin = *Monoraphidium minutum*, Cycmen = *Cyclotella meneghiniana*, Panmor = *Pandorina morum*, Chlamy = *Chlamydomonas* sp., Coslae = *Cosmarium laeve*.

Compound	Monmin	Cycmen	Panmor	Chlamy	Coslae
1. Monocarboxylic acids					
Lactic acid	9.7	219.1	10.8	9.9	91.7
hydroxy-Acetic/ Glycolic acid	38.2	-	-	7.2	81.1
3-hydroxy-Propanoic acid	13.4	-	-	-	114.6
3,4-dihydroxy-Butyric acid	38.5	-	-	-	-
2. Dicarboxylic acids					
Cytric acid	53.0	-	-	-	-
Oxalic acid	70.9	274.2	79.4	26.3	109.7
Succinic acid	4.0	76.4	4.5	21.2	31.9
3. Fatty acids					
Decanoic acid	-	-	-	81.2	177.2
Lauric acid	37.0	-	-	-	-
Myristic acid	22.3	-	-	-	-
Palmitic acid	16.5	46.3	-	-	-
Stearic acid	17.4	-	-	-	-
Octanoic acid	-	-	-	197.0	598.8
4. Dimers					
Diglycolic acid	-	-	-	23.7	-
5. Aromatic acids					
Benzoic acid	-	-	34.6	-	-
Methylenediphenol	14.5	-	-	-	-
Hydroxyethylene-diphenol	21.6	-	-	-	-
Hydroxy-propylenediphenol	29.1	-	-	-	-
6. Other					
Glycerol	9.7	-	-	-	16.6
Phosphoric acid	-	-	2.1	-	14.4

It is also necessary to identify and quantify organic compounds in Vaal River water and in the various phases of the treatment process, as well as whether these compounds are oxidised preferentially to algal cells. Other aspects that need to be investigated are to determine how changes in charge characteristics affect the characteristics of the flocs formed during coagulation, the possible change in algal-extracellular products when the

cells are exposed to stress conditions, e.g. by oxidation reagents (chlorine) and other chemicals, e.g. $FeCl_3$, and what effect different purification chemicals in different concentrations and combinations has on the formation of flocs containing algal cells.

Investigations are also necessary to determine whether extracellular products, consisting of proteins and polysaccharides, are excreted in appreciable numbers and concentrations.

Since the pioneering work of Von Smoluchowski (1917), who described the kinetics of flocculation of monodispersed, spherical colloidal particles by means of Brownian movement, much research has been done towards the understanding and modelling of colloid stability (Batchelor, 1972; Overbeek, 1977; Van de Ven & Mason, 1977; Adler, 1981; Melik & Fogler, 1981).

Mathematical models based on mechanisms to simulate the performance of settling tanks in a water purification plant are available from the literature (Lawler *et al.*, 1983; Lawler & Wilkes, 1984; Valioulis & List, 1984). The models usually provide computational results that are in agreement with small-scale experiments as long as the sedimentation of colloidal particles is involved. However, because of the increasing levels of eutrophication of many rivers such as the Vaal River, coupled with the occurrence of algal blooms, the problems of water purification are not only restricted to the removal of inorganic elements from the water, but also has to deal with the sedimentation of organic material, such as algal cells, present in the water.

Superficially the flocculation of algal cells in a sedimentation tank can be considered to be identical to the flocculation of colloidal particles (see Ives, 1954). It is true that the different interactions mentioned above are not valid only for colloidal particles; they should also play a role in the removal of algae. However, algae show specific properties that are not shared by colloidal particles. These specific properties might be important in the understanding of the flocculation process involving algal cells. Algal cells may be elongated in shape or may be arranged in filaments or colonies, or the cells may have long spines that could affect the efficiency of flocculation. Others have flagella with which the cells could avoid flocculation or with which they could swim out of flocs, or break up the flocs.

Usually colloids are sized in the nanometer range, while algal cells are generally characterised by diameters in multiples of 10 micrometers, resulting in a typical size ration of 10^3 to 10^4. One of the main implications of the difference in size may be the presence of a significant mutual attraction force (universal gravitation), as an additional short-range interaction force between the larger algal cells. Within the framework of the flocculation of algal cells, it appears that the mathematical modelling of the flocculation process should not, as in the case of colloidal particles, be based on the Van der Waals interactions alone. Modelling of the flocculation of algal cells should also take the effect of gravitational forces into account.

Another fundamental difference between colloidal and algal particles is the physiological ability of the cells to respond to conditions in their immediate environment. This physiological activity can affect the overall efficiency of the flocculation process in different ways. For example, when assimilating CO_2 and other nutrients, when producing O_2, or when substances like organic molecules are excreted, an algal entity (cell, filament or colony) affects its immediate environment by acting as a sink (during uptake) or a source (during excretion) of material.

As shown in Table 7, the photosynthetic activity of the algae results in a net mass uptake which most probably perturbs the dynamics of the approach of two particles when they are close to each other, by creating an additional hydrodynamical force or interaction, namely a photosynthetic pulling force, which could be favourable to the efficiency of the flocculation process.

Table 7: Comparison between the photosynthetic pulling forces and Van der Waals forces (Cloot & Pieterse, 1999).

Cell	**Net photosynthetic pulling force x 10^{-15}g cm sec^{-2}**	**Distance where F_{vdw}/F_{ph}~ 1 *ø algae**
Microcystis aeruginosa	0.002	4.75
Chlamydomonas species	0.16	2.00
Cyclotella meneghiniana	0.14	1.75

It can therefore be concluded that, as in the case of the gravitational force, the hydrodynamical interactions resulting from the photosynthetic activity developed by the algae, should be taken into account when attempts are being made to model the flocculation of algal cells. Another consequence of the uptake and/or excretion process, is the possible modification of the fluid viscosity in the immediate vicinity of the colliding algal entities which, one again, can affect the efficiency of collisions.

GENERAL CONCLUSION

Results presented in the present study clearly indicated that flocculation, filtration and flotation at the Balkfontein plant are affected by a complex array of conditions, processes, substances and organisms. These include the nature and origin of inorganic and organic substances as well as suspended particles, i.e. colloidal and algal entities. It is highly likely that these particles and substances mutually affect each other, as well as the processes involved in the purification of the water. All these aspects need to be investigated in detail in order to better understand the underlying principles in water purification so that new processes, or new combinations of processes, can be developed in order to be able to continue producing potable water under conditions of dynamic change in the source waters.

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THE OCCURRENCE, DISTRIBUTION AND REMOVAL OF ALGAL SPECIES AND RELATED SUBSTANCES IN A FULL-SCALE WATER PURIFICATION PLANT

(Project 567)

PART 2: DETAILED REPORT

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EXECUTIVE SUMMARY

THE OCCURRENCE, DISTRIBUTION AND REMOVAL OF ALGAL SPECIES AND RELATED SUBSTANCES IN A FULL-SCALE WATER PURIFICATION PLANT

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Introduction

The eutrophied, polluted, salinised and mineralised state of the Vaal River have resulted, and will more extensively in future, result in large-scale algal blooms, and consequently, in serious ecological, aesthetic, health and water purification problems.

Almost no information has been available on the connections between morphological and physiological characteristics of phytoplankton species on the one hand, and aspects of water purification processes such as oxidation, flocculation, sedimentation, filtration and flotation on the other hand. The wax and wane of algal assemblages and biomass in the river, the result of environmental conditions, affect treatment processes and removal efficiency in the treatment plant. A complete, inclusive, integrated investigation of the connections between environmental variables and algal assemblages in the river, as well as algal components and the purification potential and purification problems in the treatment plant, was therefore necessary in the South African context in general and in the Vaal River context in particular.

The aim of the investigation was to determine the nature and extent of algal-related problems and the types of algae involved, as well as the relationships between algae in the raw water and in different phases of the purification process. In addition, the

contribution of algal cells to extracellular organic substances were also investigated. The *importance in, and effect of,* internal and external morphological characteristics of algal cells were considered in relation to different unit processes. The theoretical importance of various differences between algal cells and colloidal particles during coagulation and flocculation of these particles, were considered in an attempt to explain why algal cells, colonies and filaments could penetrate unit processes.

Characteristics of Vaal River water at Balkfontein

On-going water quality problems, and changes in the quality, resulted in the need to employ different purification processes during the study period.

Vaal River water at the Balkfontein Plant of Goudveld Water consists of a large fraction of recycled water from household, mining and industrial activities, as well as a fraction arising from specific agricultural practices. The diversity of chemical substances in the water and rapid changes in the quality of the raw water, required that coagulant dosages sometimes have to be adjusted at short time intervals. Often high dosages of metallic salts, which traditionally are used with success, are not able to efficiently purify the water. Under such conditions other treatment options, such as high-pH lime treatment or poly-electrolyte dosing, had been adopted at high financial costs.

Chemical costs on the plant increased since 1993 from approximately 4 c kl^{-1} to 7 c kl^{-1}. The increasing concentration of iron, manganese, algae and organic substances are most likely the cause of the excalating costs. Rainfall during summer months most probably contributed to increasing levels of contaminants such as iron, manganese and dissolved organic carbon. The high-pH lime process was shown to be approximately 2 c kl^{-1} more expensive than the other processes employed at the Balkfontein plant. Low concentrations (1 mg l^{-1}) of poly-electrolyte in combination with $FeCl_3$ produced acceptable final water at lower costs than the high-pH lime process.

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.

High-pH lime treatment was shown to remove turbidity, dissolved organic carbon and iron more efficiently than aluminum and chlorophyll (i.e. algal cells). Pre-chlorination improved algal removal. However, poly-electrolyte more efficiently removed organic substances such as humic acids, fulvic acids, protein and carbohydrates than the high-pH lime process.

Results showed that $FeCl_3$ and poly-electrolyte were efficient removal agents when centric diatoms were present in the raw water. One possible explanation for this observation may be that centric diatoms possibly excrete smaller amounts and fewer organic substances than green algal representatives. However, poly-electrolyte dosing was always needed when centric diatoms were present in the raw water. Diatoms reduced the removal of Fe, which had to be removed by higher dosages of poly-electrolyte.

Chlorination, as a pre-oxidative step, was found to adversely affect the removal of dissolved organic carbon.

The DAFF process was shown to be more efficient in the removal of Al, Fe and algal cells, while the conventional sedimentation-filtration line resulted in better removal of dissolved organic carbon. Poly-electrolyte improved the removal of dissolved organic substances in the DAFF process.

Results indicated that temperature affected the removal of organic substances. Threshold temperatures determined whether it was necessary to dose $FeCl_3$ or poly-electrolyte. Temperature was, however, not affecting the removal of algal cells.

The results clearly showed the necessity to qualify and quantify different fractions of dissolved organic substances in solution. Dissolved organic substances affected the removal of material in suspension, and different components were apparently requiring

different conditions for removal. The concentration of dissolved organic carbon and dissolved iron should be used in addition to turbidity as indicators of treatment efficiency.

Algal cells, colonies and filaments and purification processes

Green and blue-green algal representatives were in general removed less efficiently from the water in the treatment plant than representatives of the other algal groups because green and blue-green algae increased proportionate to the other groups from the raw water to the final water. In general, diatoms were reduced to a larger extend than green algae. Diatoms were removed more efficiently under the prevailing conditions of flow, coagulation, flocculation and filtration. The efficient removal of diatom cells is most probably partly explained by the cells being more dense and to silica-containing frustules. Surface characteristics apparently played an important role in the removal of algal cells, because green algae (cellulose cell walls) were better removed by $FeCl_3$ while diatoms (silica-frustules) were better removed by lime.

High phytoplankton biomass in the raw water increased the biomass and species diversity in the final water. *Synechococcus* sp., a blue-green alga, grew within the treatment plant because its concentration frequently increased from the river to the sand-filtered water. Sedimentation was shown to be primarily responsible for algal biomass removal, but not for reduction in species diversity.

The following algal species were removed less efficiently by sedimentation and filtration and should be considered problem species: *Carteria globosa, C. simplicissima, Chlamydomonas incerta, Crucigenia tetrapedia, Monoraphidium arcuatum, M. circinale, Oocystis lacustris* (all unicellular green algae) as well as *Chroococcus dispersus* and *Synechococcus cedrorum* (small semi-colonial blue-green algae). The *Carteria and Chlamydomonas* species may have partially avoided flocculation because they are able to move with flagella. The other green algae all deviate in shape from the sphere (being

elongated or triangular). The blue-green cells are much smaller than the other algae, and proved difficult to remove, even under high dosage concentrations.

Algal entities (cells, colonies, filaments) differ in a number of characteristics from colloidal entities. These differences include size, shape, density, surface charge and the presence or absence of appendages, internal charge, charge restoration, adsorptive and absorptive abilities, locomotive abilities, metabolic processes, excretion of organic substances and the relative importance of electrical, Van der Waals and gravitational interactions.

Jar test experiments showed that it is not necessary to dose Fe^{3+} in higher concentrations than 18 mg 1^{-1}. Low concentrations (below 4 mg 1^{-1}) of Fe^{3+} apparently provided too small amounts of Fe^{3+} to form positive charged Fe-hydroxo complexes for charge neutralisation.

Effective removal of dissolved organic carbon occurred in jar tests at pH 5 and 11.5 when $FeCl_3$ was used as flocculate at concentrations higher than 8 mg 1^{-1} (as $FeCl_3$). Removal of total suspended solids was most effective at pH 11.

Jar test experiments showed that *Monoraphidium minutum* and *Cyclotella meneghiniana* cells as well as *Pandorina morum* colonies were effectively removed at pH 11.5 and when Fe^{3+} was added at concentrations higher than 4 mg 1^{-1}.

Organic substances excreted by *Monoraphidium minutum* and *Cyclotella meneghiniana* apparently reduced the removal of algal cells at pH 6.4. At pH 11.5 excreted organic substances from *M. minutum* apparently improved the removal of chlorophyll, while excreted organic substances from C. *meneghiniana* had no effect at pH 11.5. Organic substances excreted by *Pandorina morum reduced* the removal of algal cells.

The results clearly showed that extracellular organic material differentially affect the coagulation of algal cells. The components of the excreted organic substances consisted of monocarboxylic, dicarboxylic, fatty and aromatic acids, as well as glycerol and phosphoric acid.

Apart from the effect organic substances can have on chlorination, the removal of suspended and dissolved substances, they most probably contribute negatively to the aesthetic quality of the water, such as producing unpleasant tastes and odours. The aesthetic aspects of the extracellular substances need to be investigated further.

Results from the jar tests illustrated that extracellular organic substances differentially affect the coagulation of suspended particles such as colloids and algal cells. It is known that organic substances in water affect the functioning of all unit processes, including pre- and post-chlorination. Therefore, results of the present study on the effect of extracellular substances should be investigated in bench-scale and pilot-scale models in order to ascertain the possible specific effect of the organic substances on full-scale plants.

Conclusion

Results presented in the present study clearly indicated that flocculation, filtration and flotation at the Balkfontein plant are affected by a complex array of conditions, processes, substances and organisms. These include the nature and origin of inorganic and organic substances as well as suspended particles, i.e. colloidal and algal entities. It is highly likely that these particles and substances mutually affect each other, as well as the processes involved in the purification of the water. All these aspects need to be investigated in detail in order to better understand the underlying principles in water purification so that new processes or new combinations can be developed in order to be able to continue producing potable water under conditions of dynamic changes in water quality occurring in source waters.

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ORGANIC COMPOUNDS EXCRETED BY ALGAE FROM THE VAAL RIVER

FLOCCULATION CHARACTERISTICS OF COLLOIDS AND ALGAL CELLS

ACKNOWLEDGMENTS

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Goudveld Water made all the facilities at the Balkfontein Plant available for research, and members of staff were responsible for the taking of samples and the analyses of various environmental variables.

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CHAPTER 1:
INTRODUCTION

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The Vaal River is eutrophied, polluted, salinised and mineralised because of the extensive utilisation of the water through household, mining and industrial activities and because of the release of effluents as well as because of specific agricultural practices. These effects have resulted, and will result, in large-scale algal blooms and, consequently, in serious ecological, aesthetic and water purification problems. Because of the increased load in dissolved substances, the water will most probably become clearer. Clearer water, with a high nutrient supply (through eutrophication), will result in more intensive algal blooms, sometimes possibly by algal species that have not, until now, caused such blooms. The occurrence of algal blooms may also have health consequences for people relying on the river as their only source of drinking water.

The Lesotho Highland Scheme, to be completed in the foreseeable future, will supply water to the Vaal River system to meet, for some time, increasing demands. It is not yet clear what the effect of Lesotho Highland water will be on the chemical and biological quality of the water in the middle Vaal River region, or how long it will last. In addition, recent infestations by water hyacinths may also affect environmental variables and phytoplankton populations, an aspect that has not been investigated to any significant degree.

Almost no information is available on the connections between morphological and physiological characteristics of phytoplankton species on the one hand, and aspects

of water purification processes such as oxidation, flocculation, sedimentation, filtration and flotation on the other hand. Morphological characteristics that could be of importance in the treatment of water to produce drinking water are, for example, different shapes and sizes of cells, colonies and filaments, whether the cells or colonies can move with flagella or change their shapes, or whether the cells have extensions like spines or other protuberances. Physiological characteristics that could be of importance are, for example, changes in the density or surface charges of cells, the uptake and release of carbon dioxide and oxygen during photosynthesis and respiration which could affect t e surface characteristics of the cells, as well as the excretion of organic compounds by the cells.

A complete, inclusive, integrated investigation of the connections between environmental variables and algae in the river as well as algae and the purification potential and purification problems of the water from the Vaal River, is therefore necessary in the South African context in general and in the Vaal River context in particular.

An integrated approach is considered necessary because the interrelationary nature of the different aspects strongly suggests that conditions unique to the environment in which the algae grow, select for specific algae with characteristics that cause specific problems in the different phases of the purification process. For this reason the investigation on the algae associated with the Goldfields Water purification plant at Balkfontein is done parallel with an investigation into the ecology of algal assemblages in the Vaal River. In addition, the integrated approach should result in a situation where scientific service could be rendered to organisations in need of, for example, information on specific algae.

Certain aspects of the effect of morphological and physiological characteristics of suspended algal cells on flocculation, sedimentation and filtration are also investigated in a joint research programme developed between Professor H Bernhardt

(now deceased, but continued by his colleagues) of the Wahnbachtalsperrenverband, Siegburg, Germany and Professor AJH Pieterse of the PU for CHE, Potchefstroom. The research programme is therefore also international and co-operative and resulted in the direct involvement in South Africa of scientists of international standing in the particular field of interest.

Aims of the research programme

The emphasis of the investigation was on dominant algal species in the Vaal River, as well. as on those algal species that are affected, or that are not affected, by the purification processes.

The aim of the investigation into algal species in water and related substances in the fullscale purification plant was to determine the nature and extent-of algal-related problems and the types of-algae involved, as well as the relationships between algae in the raw water and in different phases of the purification process. In addition, the contribution of algal cells to extracellular organic substances, substances posing health implications such as chlorinated hydrocarbons (e.g. THM substances), were also investigated. The importance in, and effect of, internal and external morphological characteristics of algal cells, colonies and filaments were investigated in relation to coagulation, flocculation, sedimentation and filtration processes. This approach will lead to a better understanding of the physical factors involved in settling and might provide additional explanations for differences in settling rates.

The following specific aspects were investigated:

- The identification and quantification of major algal groups and algal species as well as the total algal biomass in suspension in the raw water and in different phases of purification.

- Investigations into morphological characteristics of algal species in the purification plant:
    1. characteristics of size, shape, form drag and electrical as well as gravitational interactions of algal cells, and
    2. surface-associated characteristics of algal cells, such as electrical charge.
- Investigations into physiological characteristics of algal species in the purification plant, for example:
    1. photosynthetic and respiration uptake and release rates of carbon dioxide and oxygen, and
    2. density of algal cells, colonies and filaments,
- Potential of removal in relation to total algal biomass, specific algal species -and extracellular organic substances under conditions of
    1. excess lime in combination with different coagulants/flocculants,
    2. sedimentation, sand filtration, and
    3. flotation (dissolved-air-filter-flotation),
- The occurrence- of organic substances such as extracellular organic products posing a coagulant and oxidant demand, substances with possible health implications such as chlorinated carbohydrates (i.e. THMS), in the different unit processes.

CHAPTER 2:
CHARACTERISTICS OF VAAL RIVER WATER IN RELATION TO PURIFICATION AND TREATMENT PROCESSES AT THE BALKFONTEIN PLANT

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INTRODUCTION

The Balkfontein plant of Goudveld Water treats water for potable purposes from the middle Vaal River. The water in the river consists of a large fraction of recycled water from household, mining and industrial activities as well as a fraction arising from specific agricultural practices (Pieterse, 1986; Heynike & McCulloch, 1982; Basson & Pieterse, 1993).

The eutrophic nature of the raw water in the middle Vaal River (Pieterse, 1986) results in a constantly changing raw water quality which, together with the chemical characteristics of the raw water, high algal biomass or particular algal species at lower biomass concentrations as well as other unknown factors, are sometimes causing the impairment of flocculation and other processes in the different treatment phases in operation at the Balkfontein plant (Pieterse, 1989; Pieterse *et al.*, 1993; Bernhardt & Schell, 1989). Different algal species penetrate the entire purification process (Pieterse *et al.*, 1993).

The diversity of chemical substances in the water and rapid changes in the quality of the raw water, require that coagulant dosages sometimes have to be adjusted at short time intervals. Oftentimes high dosages of metallic salts, which traditionally are used with great success, are not able to efficiently purify the

water. Under such conditions other treatment options must be adopted at very high financial costs.

The possible effects of the raw water composition on water treatment are reviewed and discussed by various authors. The theory of coagulation, which also means an understanding of the chemistry of the coagulant in water, serves as the primary tool in explaining the behaviour of coagulants under certain conditions. Coagulation is, however, so complex that no easy and adequate explanation exists (AWWA, 1990; Johnson & Amirtharajah, 1983).

Flocculation and filtration are influenced by the nature of inorganic dissolved substances and colloidal particles as well as by the presence of phytoplankton, excreta from zooplankton and other faunal components of the riverine community, extracellular organic matter (EOM) released, amongst others, by algae as well as macromolecular organic substances attached to the surfaces of mineral particles (Bernhardt *et al.*, 1986; Bernhardt & Clasen, 1991; Lapin & Yedigarova, 1990; Abika *et al.*, 1991; Jiang *et al.*, 1993; Rebhun and Lurie, 1993).

Heavy metals, as well as the interaction of certain metals with EOM may play an important role in purification processes (Lapin & Yedigarova, 1990). The interrelationships between pH, chlorination, DOC products and subsequent formation of coagulant-organic matter complexes are mentioned by various authors. The adverse contribution of natural organic matter in water treatment is mainly due to its tendency to complexing, and various authors have attempted to examine the reactions amongst DOC and other contaminants in raw water. The effect of different coagulants, and the control of organic matter by coagulation have been researched by various authors. (*Sinsabaugh et al.*; 1986; *Hozalski et al.*, 1992; Jiang *et al.*, 1993; Amirtharajah *et al.*, 1993; Mc Knight *et al.*, 1992; Owen *et al.*, 1995; Lapin & Yedigarova, 1990; Rebhun & Lurie, 1993; Abika *et al.*, 1991; Knocke *et al.*, 1992; Knocke *et al.*, 1994; Krasner and Amy, 1996; Yen and Huang, 1993). The reactions between soluble iron and DOC and the impact

of DOC on iron removal is only described in literture by Knocke and co-writers (1992 and 1994).

Determinants such as total dissolved salts, turbidity, pH and various dissolved ions affect destabilisation mechanisms and coagulant dosages (Amirtharajah & O'Melia, 1990; Gregory, 1989). The distribution of free chlorine forms is affected by pH. Turbidity affects algal growth which, in turn, influences the carbonate system in the water.

The deteriorating quality of the Vaal River is the cause of many operational difficulties and high financial costs at the Balkfontein plant. Chemical coagulation is traditionally aimed at the removal of turbidity without necessarily addressing the cause of the problem neither being cost effective. The aim of this study is thus to determine raw water characteristics and the impact they have on the purification process.

A greater knowledge of interactions between different contaminants and alternative coagulants is needed if the plant is to be optimised. This knowledge must enable the plant manager to modify coagulation conditions in such a way that the process will still sustain effective turbidity removal while also achieving the removal of problematic contaminants which give rise to unnecessary cost increases in the operation of the treatment facility.

STUDY SITE, MATERIALS AND METHODS

The Water Purification Plant of Goudveld Water consists of three modules or lines that treat water in parallel fashion.

Operating characteristics of the Balkfontein purification plant are shown in Table 1.

Maximum G values (mean velocity gradient) of 2 100 s^{-1} can be obtained at the primary dosing points (Fig. 1) when operating at full capacity. Energy is obtained via a hydraulic jump. These dosing points are mainly used for lime dosing.

Table 1: Operating characteristics of the Balkfontein purification plant:

	MODULE 1 (FILTER 2)			MODULE 2 (DESIGN CAPACITY - 120 Ml/d)			MODULE 3 (DESIGN CAPACITY - 120 Ml/d)		
	G-Value s^{-1}	Retention Time	Volume m^3 (medium)	G-value s^{-2}	Retention Time	Volume m^3 (medium)	G-value s^{-1}	Retention Time	Volume m^3 (medium)
Primary dosing	2470	1.4 s		2469	1.4 s		2105	2.9 s	
Lime mixing channels	470	37.1 s		468	37.1 s		250	69.4 s	
Rapid Mixing units	4820	0.3 s		4817	0.3 s		4816	0.33 s	
Secondary dosing units	1450	2.9 s		1452	2.9 s		1721	2.9 s	
Split channels									
Channel	45	253.0 s		38	80.4 s		74	118.6 s	
Flume	920	2.9		1260	4.1 s		981	4.0 s	
Channel(2nd)							22	99.3 s	
Flume (2nd)							1584	3.0 s	
Serpentine channels									
30 Ml/d	45	966.8 s		45	966.1 s		45	967.0 s	
90 Ml/d				32	822.0 s				
Primary sedimentation tanks		15.2 h	7596		6.1 h	30386		6.1 h	30386
Secondary sedimentation tanks					4.0 h	18991		6.1 h	30386

Contact time is approximately 2,8 seconds. Poly-electrolytes are dosed at a second hydraulic jump. Rapid mixing is done by means of an in-line mixing system and the primary coagulant which is usually a metallic salt, is dosed here. G values of 4 800 s^{-1} can be reached at contact times of 0.33 seconds. Tables 1 and 2 summarise the operating characteristics of the Balkfontein plant.

The serpentine channels consist of 30 and 90 Ml/d units. The G values in the 30 Ml/d units are 45 s^{-1} and in the 90 Ml/d units 48 s^{-1} maximum, at contact times of approximately 820 and 9700 seconds respectively.

When the plant is being operated at full capacity the primary sedimentation time in Module II and Module III is 6 hours. In Module III secondary sedimentation time is also 6 hours, whereas for Module II it is only 4 hours. For the purpose of this study, Module 1 was changed to treat only 12 Ml/d, allowing for a primary sedimentation time of almost 15 hours.

The plant has 30 sandfilters with an open area of 100,8 m^2 each, and a total depth of 1m. Filtration speed is 5 m/h when operating at full capacity. During the experimental period grain size was determined by sieve analysis. The average effective size of the filter medium was 735 µm and the average uniformity coefficient was 1,3. Orginal values were 600 - 650 µm and 1,35 - 1,45 respectively. The increase in grain size is due to operating on the high lime process for many years.

The design capacity of the plant is 360 Ml/d; 120 Ml/d per module. The facility exists to use different chemical dosing points with different Camp numbers. Optimising on the plant also involves the evaluating of dosing points and energy values for a specific process.

Daily data were obtained by analysing the raw and final water for determinants such as total dissolved solids (TDS), turbidity, pH, electrical conductivity, alkalinity, hardness, chlorides, sulphates, iron, manganese, spectral absorbance coefficient (SAC) at 254 nm and chlorophyll-a.

A time-related sampling programme was used to sample a plug of water as it moved through the plant from the old pumping station. The water was analysed at the Balkfontein laboratory for the normal daily determinants. Dissolved organic carbon (DOC), THM (Trihalomethane) substances, metals and other organic substances were determined by the CSIR. These results from the time-related sampling programme represent the experimental data.

The daily data from 1993 to 1995 and the 1994-1996 experimental data were statistically analysed and plotted by using the Statgraphics Plus computer programme. Correlation's were determined and X-Y line graphs were used to determine relationships and tendencies. To draw conclusions based on the analyses of the time-related samples only, will not reflect the complete situation. The specific combination of chemicals used on scheduled days, was a choice based on the results of jar tests from the previous day. Many times this was no longer the most effective combination of coagulants due to the rapid changing of raw water quality. It was thus decided to use the experimental data to calculate reduction and to evaluate and compare different processes, but to incorporate daily data in order to relate chemical usage to water quality.

Module 3 was used as the control line. It was initially intended to use ferric chloride as the only coagulant in this module; where possible, this was done. Coagulation pH-values did, however, vary due to purification problems experienced in the plant. High concentrations of iron, manganese and DOC in the river created serious treatment problems and subsequent problems in the distribution system. Coagulation pH-values were raised to approximately 9,6 and pre-chlorination dosing concentrations were increased to such levels that free chlorine could be detected throughout the plant. Difficulties experienced with the removal of iron resulted in a cationic poly-electrolyte, U5000, being used as primary or secondary coagulant on all modules for an extended part of the experimental period.

Module 2 was used as an experimental line. The excess lime process, where water is treated at a pH of between 11 and 11,4, was run from 30 March to 19 July 1994. No pre-chlorination was applied. Lime sludge caused blockages in the different process units and this module had to be taken out of operation. It came back into operation by 26 October 1994, from which time onwards $FeCl_3$ was used as primary coagulant, and U5000 as secondary coagulant. The high lime process was run again from August 1995 to early October 1995. Due to water quality problems, U5000 had to be used for most of the remaining time.

One filter from Module 1 has been modified and used as a Dissolved Air Flotation and Filtration (DAFF) process. From 10 August to 21 September 1994, as for Module 3, $FeCl_3$ was used as the only coagulant. From 26 October 1994 onwards, coagulant dosing concentrations were the same as for Module 2, where U5000 was used as secondary coagulant. Due to various technical problems, it was not possible to run this filter continuously.

Jar tests were conducted to determine conditions for optimum operation of the plant. Coagulants were added to 1 liter water samples while stirring at 300 revolutions per minute (rpm) to simulate rapid mixing. The water was stirred at this rate for 2 minutes whereafter the flocculation process was simulated by stirring at 30 rpm. The water was then left to settle for 20 minutes and the supernatant analysed for the relevant parameters. To compare jar test results with sand filtered water, the supernatant was filtered through a Whatman No. 1 filter paper. Different coagulants were evaluated on laboratory scale as well as in the plant during the occurrence of purification problems. Raw water characteristics were carefully noted and deviations from expected correlation's were investigated.

Experimental methods as described in Standard Methods (1989), were used. Iron, manganese and aluminium were analysed by atomic absorption. Dissolved fractions were determined by first filtering the sample through a 0,45 µm filter, the

filtrate being regarded as the dissolved metal. The term total metal will be used for the acid soluble fraction.

RESULTS

Daily information

The daily data from January 1993 up to December 1995 were analysed and are illustrated in Figs 1 to 8.

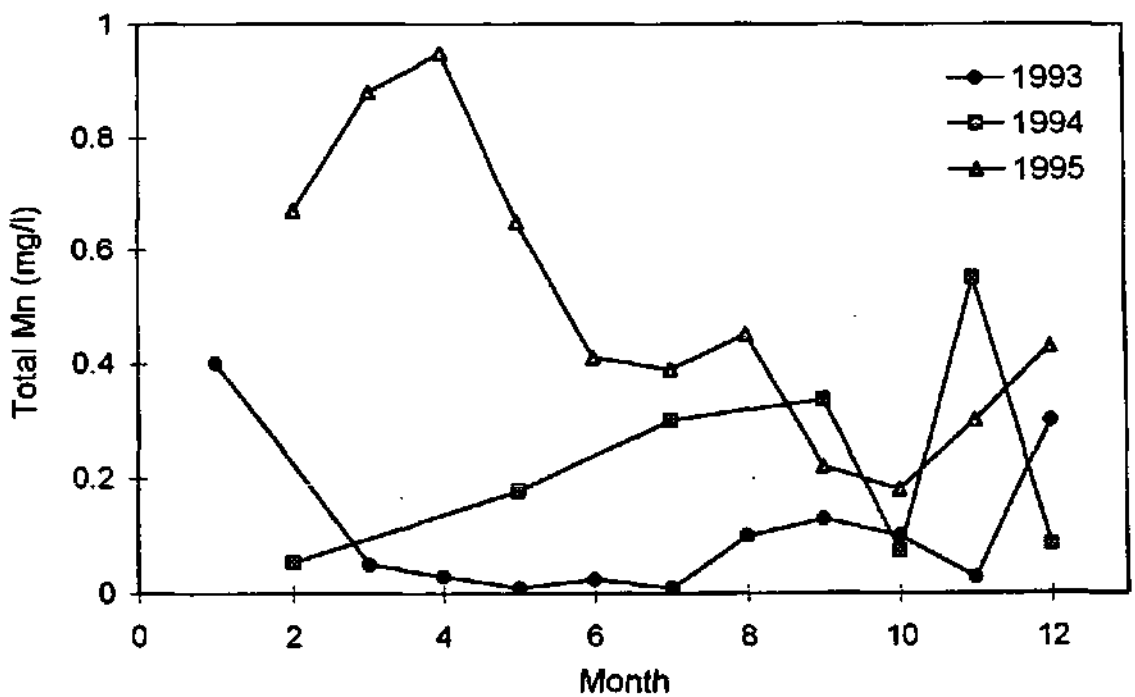

Figure 1: Monthly average manganese concentrations in raw water - 1993 to 1995

Total manganese concentrations (Fig. 1) in the raw water were fairly consistent, and much lower during 1993. Peaks occurred during January and December. For both 1994 and 1995, increasing manganese concentrations were observed towards the end of each year.

If a comparison is made between manganese values for the different years it can be seen that concentrations tend to decrease towards May, with peaks again during August and then again an upward trend towards December. No data is available for most of the first half of 1994.

It is clear from Fig. 1 that manganese concentrations in the raw water increased significantly since 1993 with very high levels occurring during the first half of 1995. Although results are reported as total manganese, dissolved manganese values, when determined, did not differ much for most of the time.

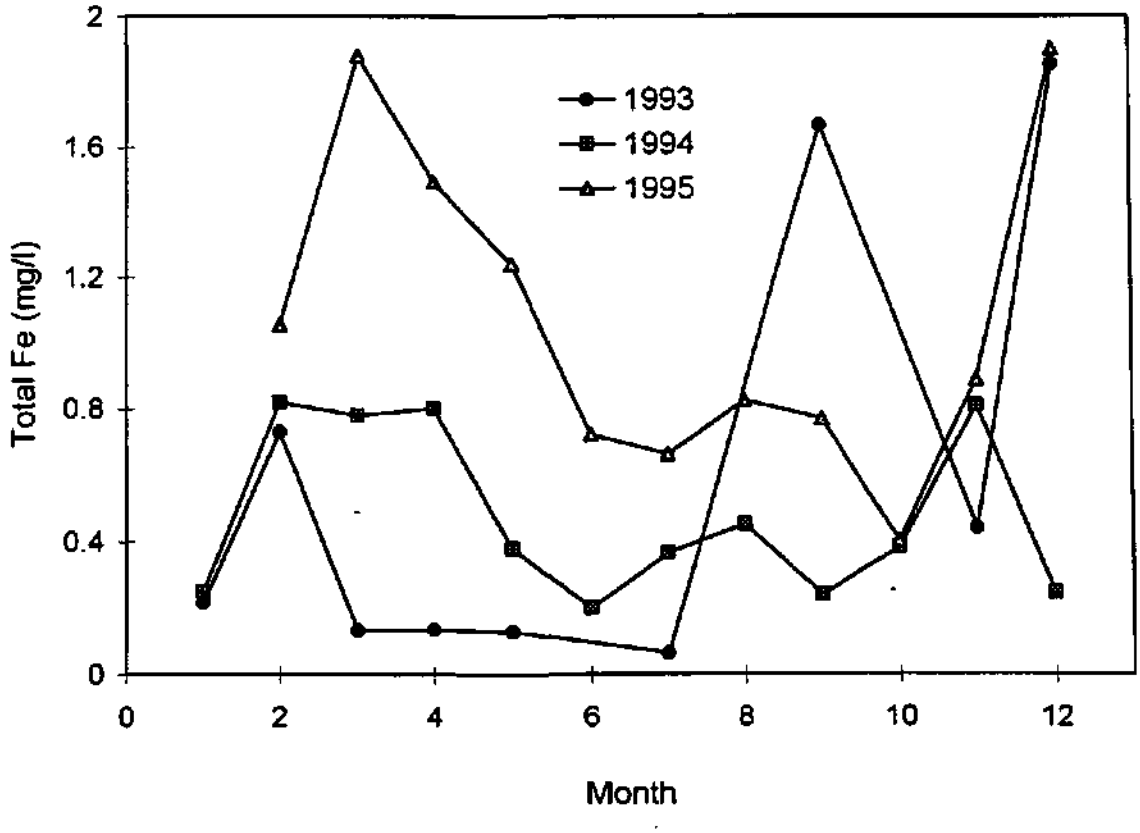

Figure 2: . Monthly average iron concentrations in raw water - 1993 to 1995

Total iron concentrations (Fig. 2) reached peak average values during the first three months of each year, thereafter concentrations decreased to reach lowest concentrations during June. Concentrations increased again over the last three months of the year. Concentrations were also higher during 1995 than during the previous years for most of the time.

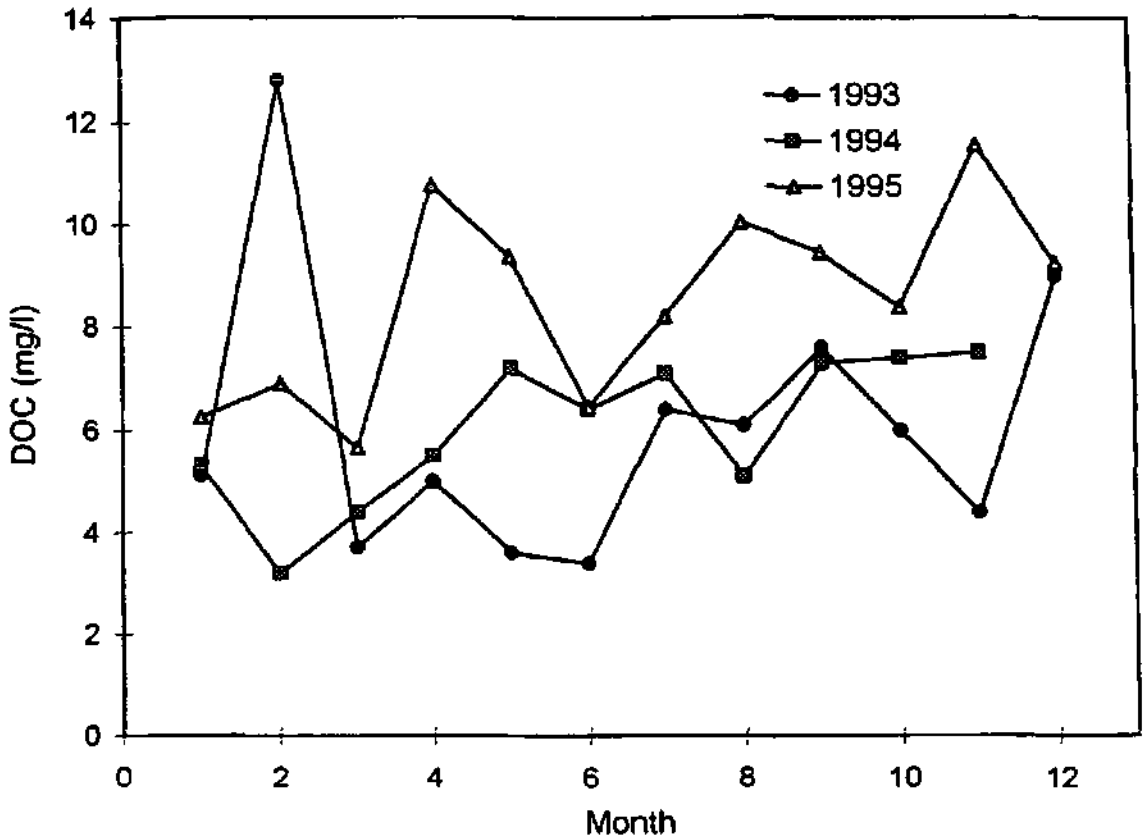

Figure 3: Monthly average DOC concentrations in raw water - 1993 to 1995

No definite pattern of DOC exists (Fig. 3). There is a slight tendency towards increasing concentrations during the last part of the year. DOC concentrations increased over the years, and from Fig. 3 it is clear that concentrations were much higher during 1995 than during the previous two years.

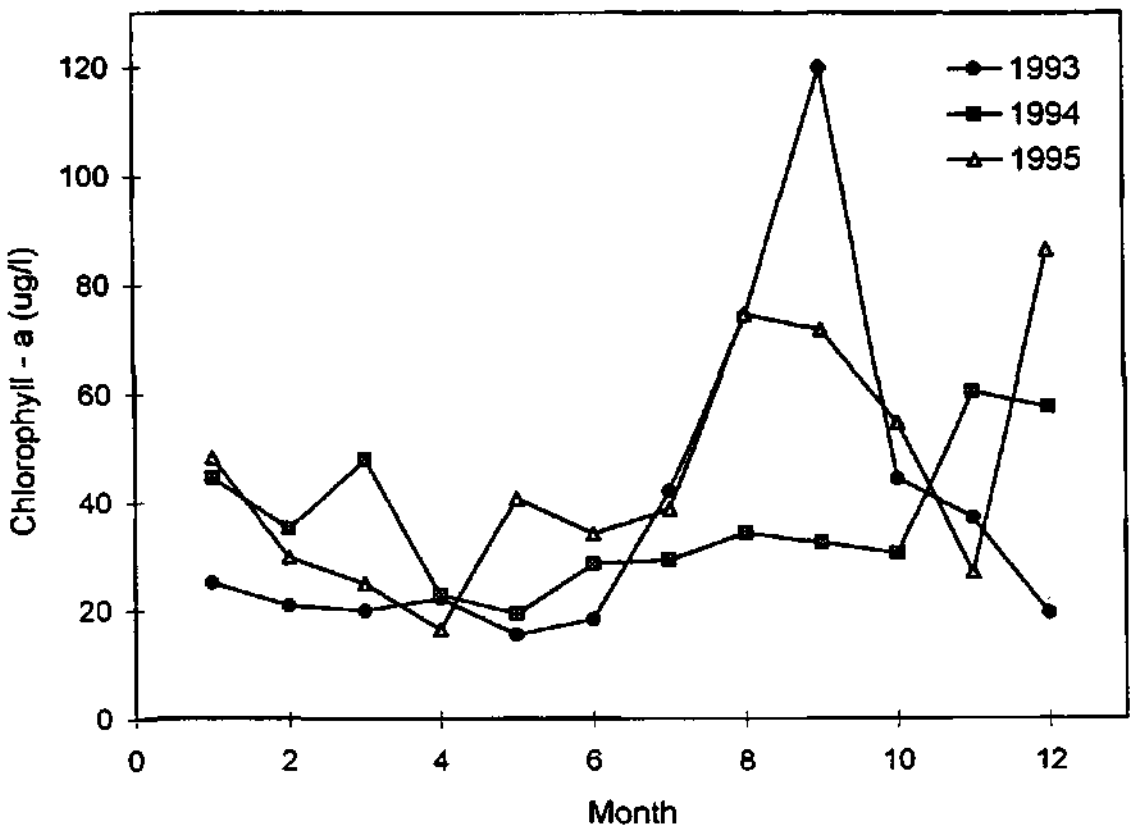

Figure 4: Monthly average chlorophyll - a concentrations in raw water - 1993 to 1995

Fig. 4 shows that increases in chlorophyll-a values are most likely to occur during August and September. Increasing concentrations were also observed during November and December. Average chlorophyll-a concentrations were much lower during 1994 with sharp increases noted only during March, November and December.

The EC of the water has changed since 1993 (Fig. 5). During 1993/1994 EC began to increase from January, reaching average peaks of 91 and 106 mS/m respectively. During 1995 the average value during May was 56 mS/m. During the corresponding month of the previous two years, EC values varied between 86 and 96 mS/m. During 1995 EC values were 56 mS/m or lower for 8 months of the year. The higher values (91>EC>76) were obtained from June to September, where-after values decreased to reach a minimum average value of 40 mS/m.

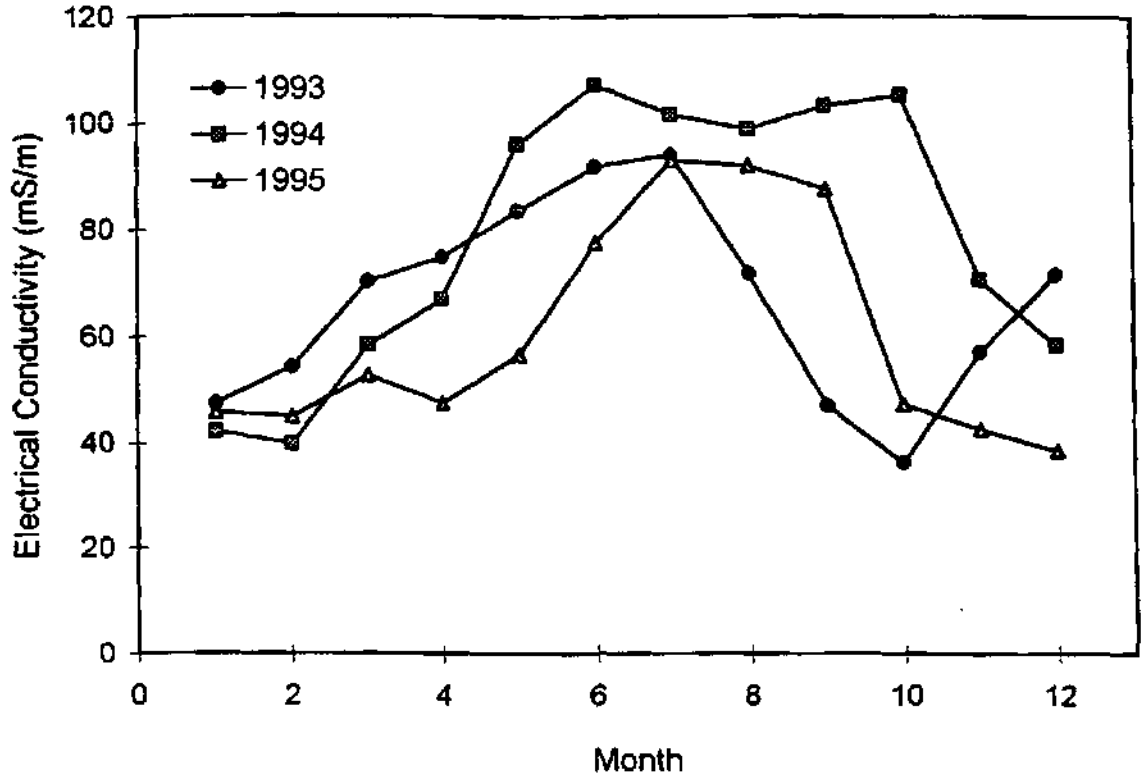

Figure 5: Monthly average values for raw water conductivity - 1993 to 1995

Fig. 6 shows that during 1995 total hardness values began to increase only in May, whereas increases were noted from March onwards during the previous two years. Downward trends were observed from June/July onwards each year. During 1993 an increase was observed during the last two months of the year, where as the downward trend continued during 1994/1995 for the same period. An average value of 165 mg/l was reached in September 1993 whereas values for the corresponding month during the following two years were greater than 300 mg/l.

Fig. 7 shows an increase in alkalinity over the first four months of 1993 and 1994. The opposite was observed during 1995 with average values of just above 100 mg/l being measured. A definite shift towards the later half of 1993 and 1994 can be seen in Fig. 7.

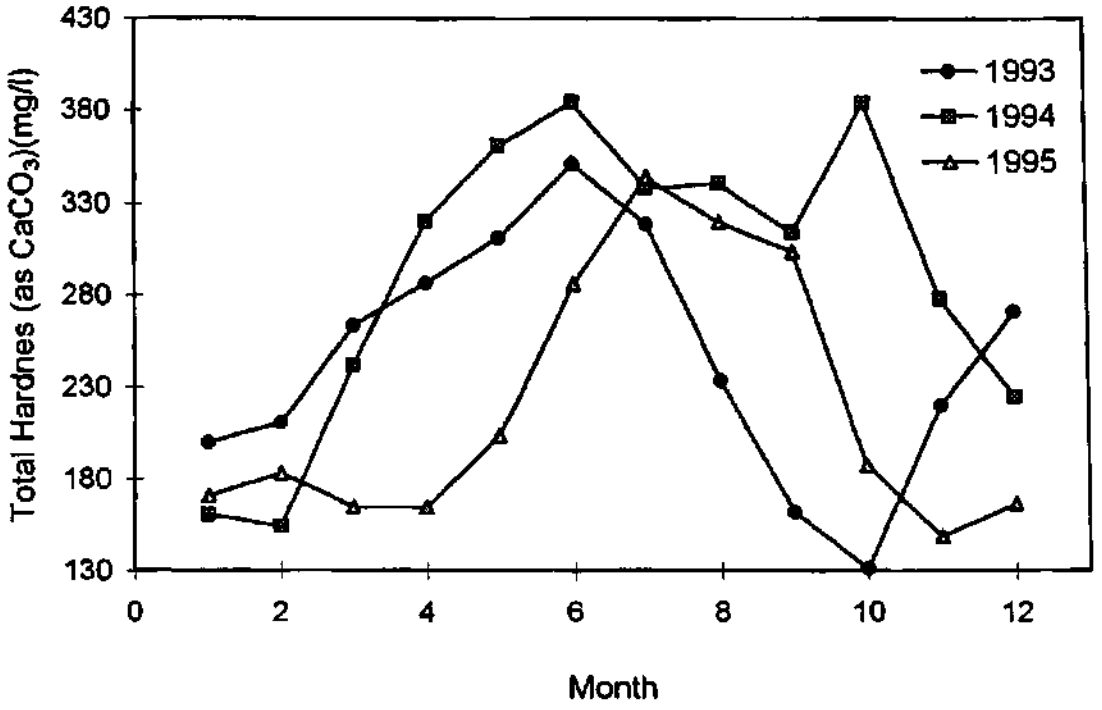

Figure 6: Monthly average total hardness concentrations in raw water - 1993 to 1995

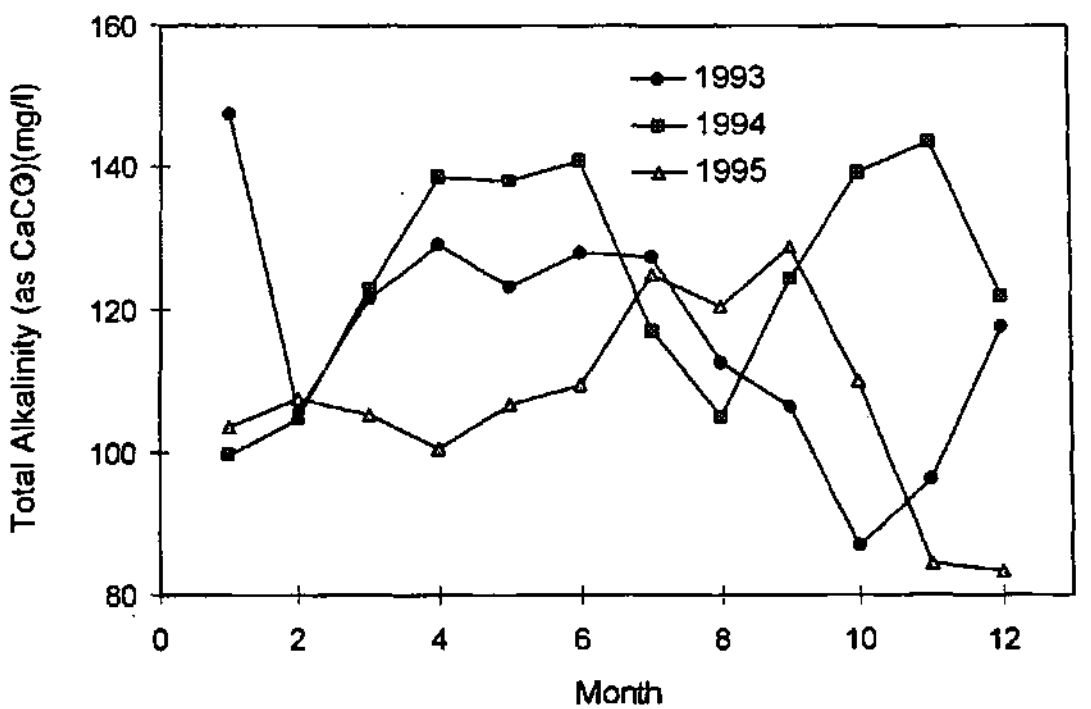

Figure 7: Monthly average total alkalinity values in raw water - 1993 to 1995

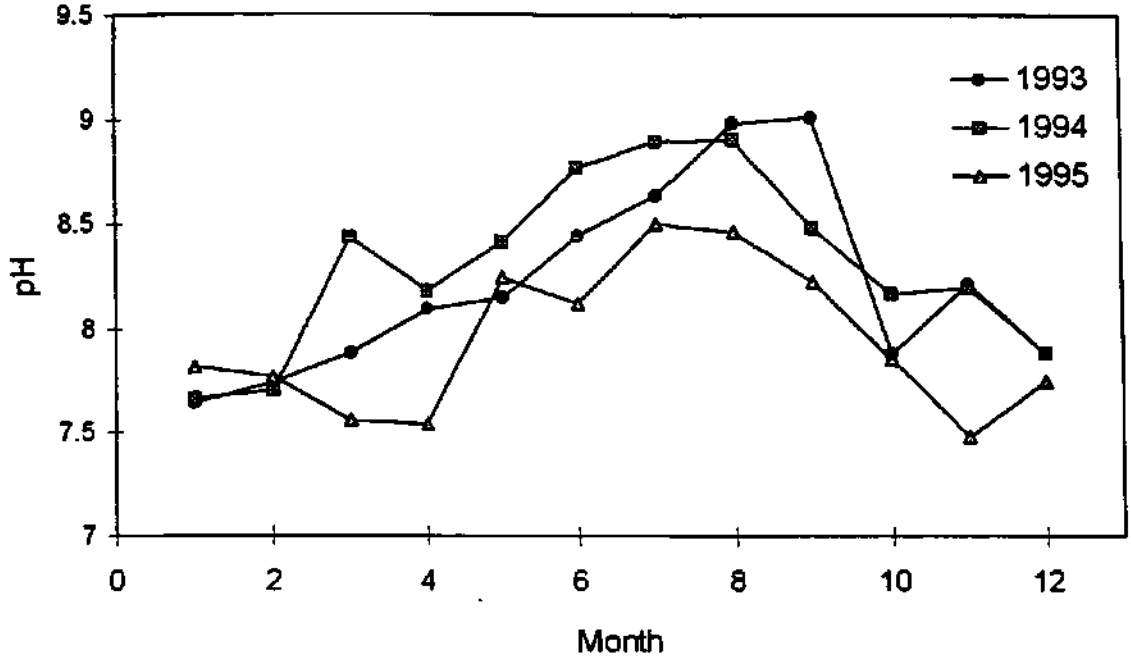

Figure 8: Monthly average raw water pH values - 1993 to 1995

pH values for 1995 were in general much lower than during the previous two years (Fig. 8).

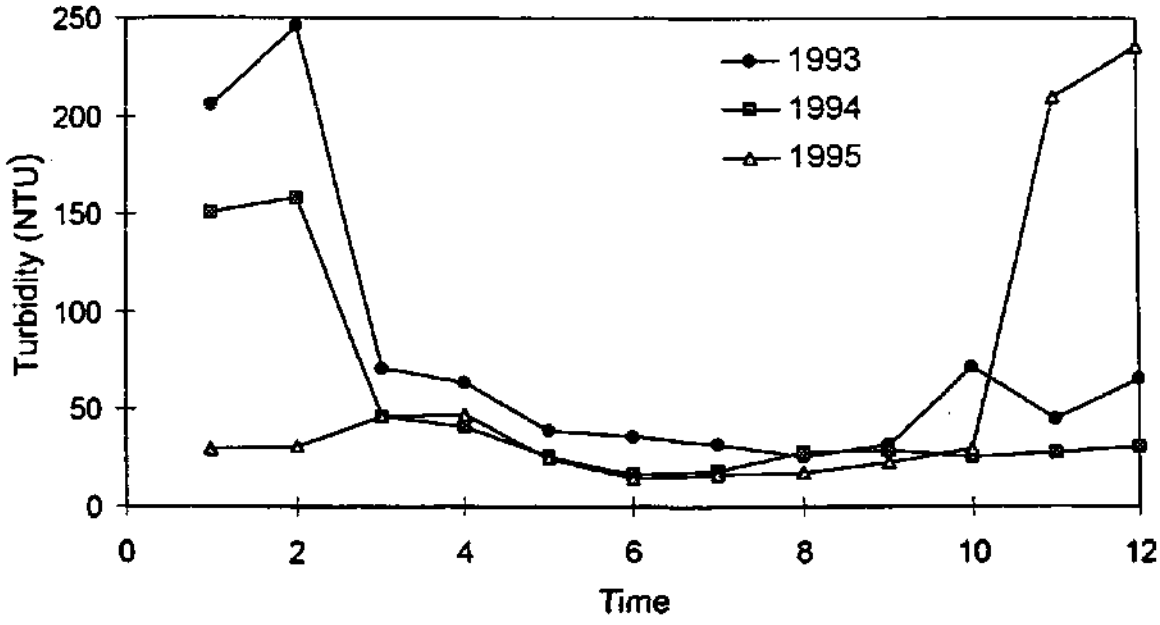

Figure 9: Monthly average raw water turbidity - 1993 to 1995

Fig. 9 shows the average raw water turbidity for the period 1993 to 1995. The higher turbidities usually occurred during the period October up to March of the following year.

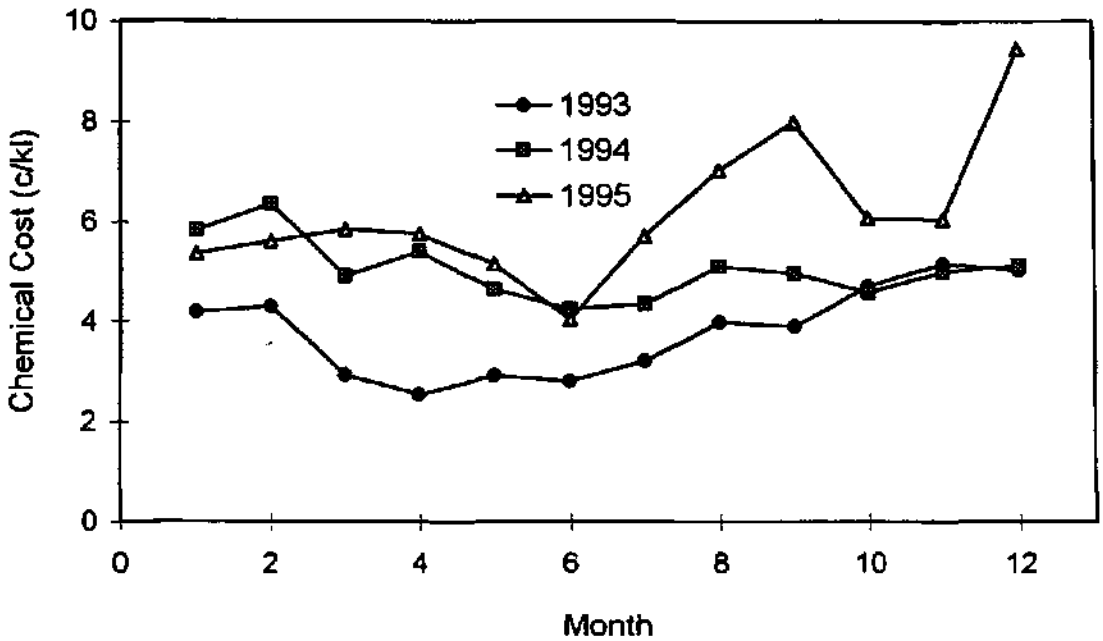

Figure 10: Monthly average chemical cost - 1993 to 1995

Fig. 10 shows the average chemical cost for the relevant period. It is clear that chemical costs were lower towards the winter months with the lowest average cost occurring in June of each year. From June onwards costs increased again, following almost the same pattern for each year.

The relationship between raw water turbidity and poly-electrolyte dosing concentrations during 1993 is shown in Fig. 11. High dosing concentrations were used during times of high turbidities. It, however, was sometimes also necessary to use poly-electrolyte at relatively low turbidities.

Fig. 12 shows the relationship between calcium concentration in the raw water and the $FeCl_3$ dosing concentration during 1993.

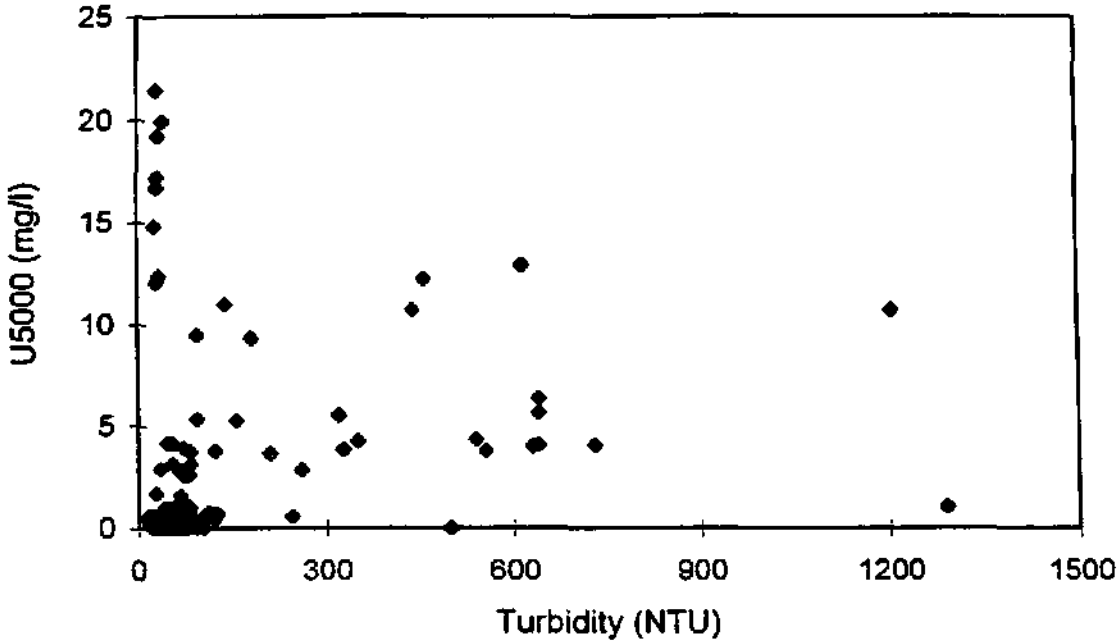

Figure 11: U5000 doses vs raw water turbidity for 1993

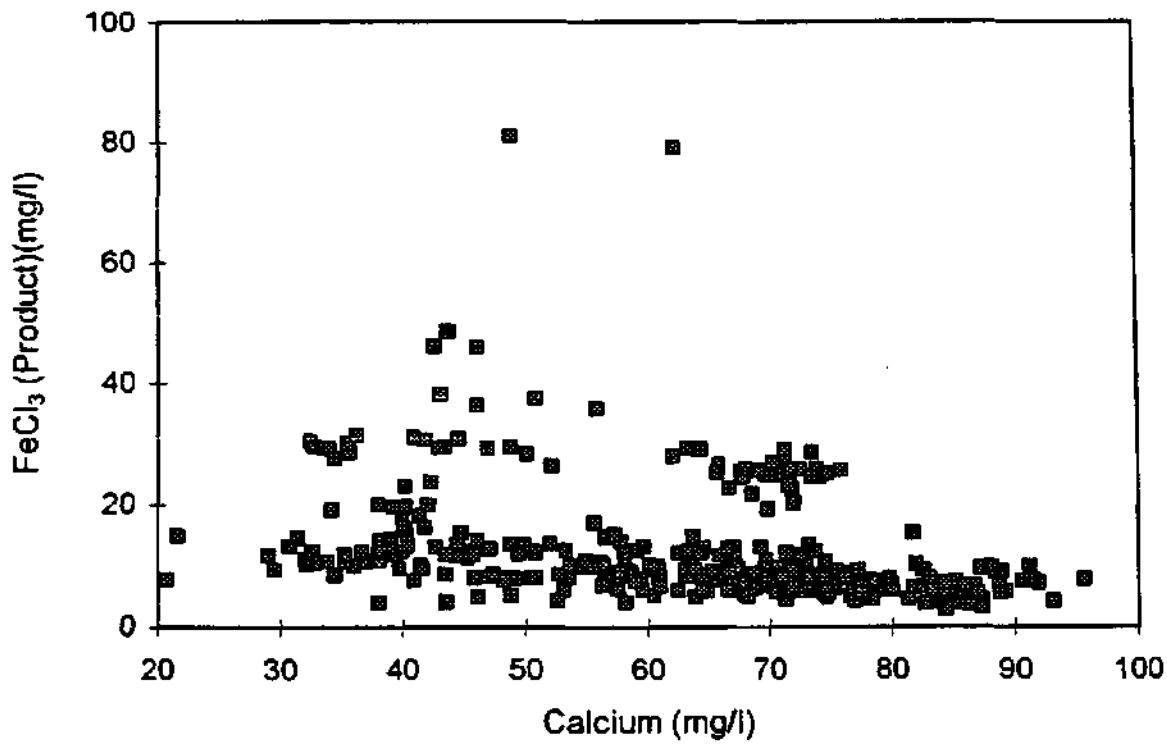

Figure 12: Iron doses vs calcium concentration in raw water in 1993

Water Quality

The quality of the raw water as per time-related sampling programme is shown in Figs 13 - 16.

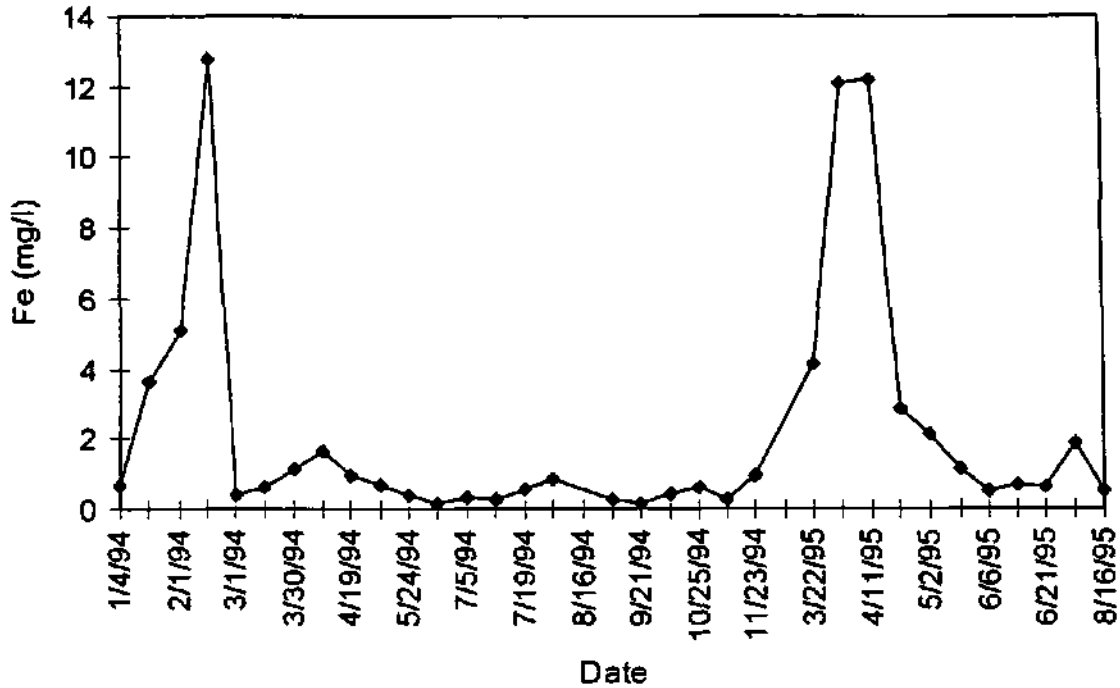

Figure 13: Iron in raw water for the period 4 January 1994 tot 16 August 1995

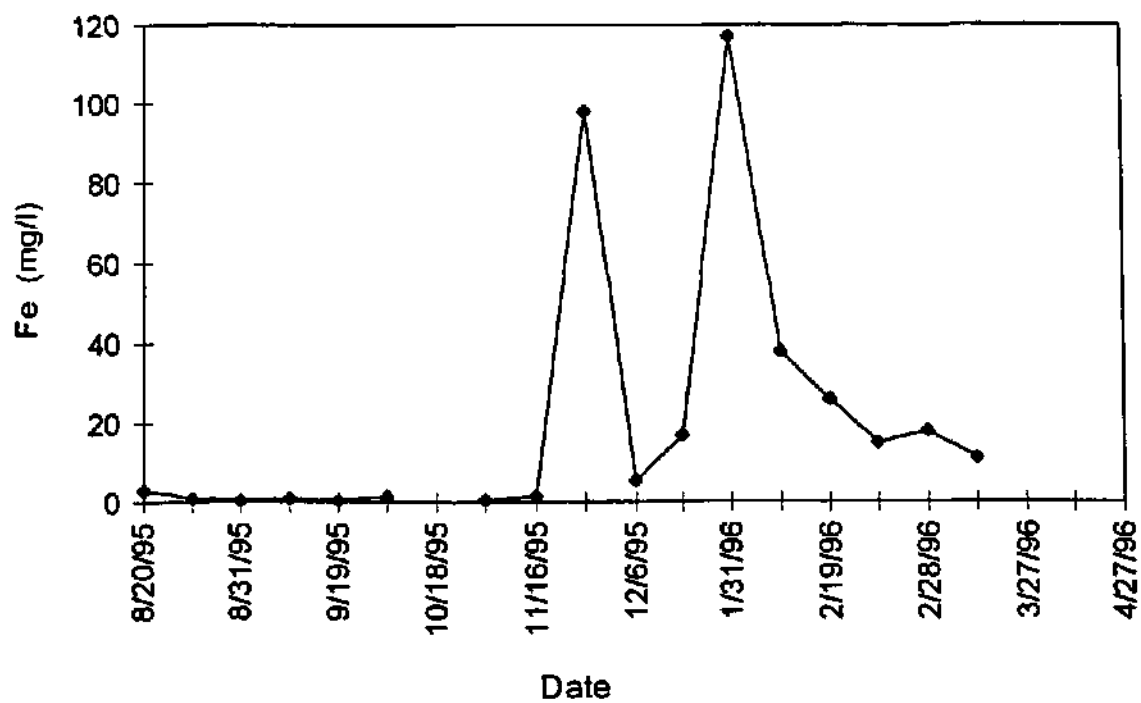

Figure 14: Total iron in the raw water for the period 20 August 1995 to 12 March 1996

High concentrations of iron were measured in the raw water.

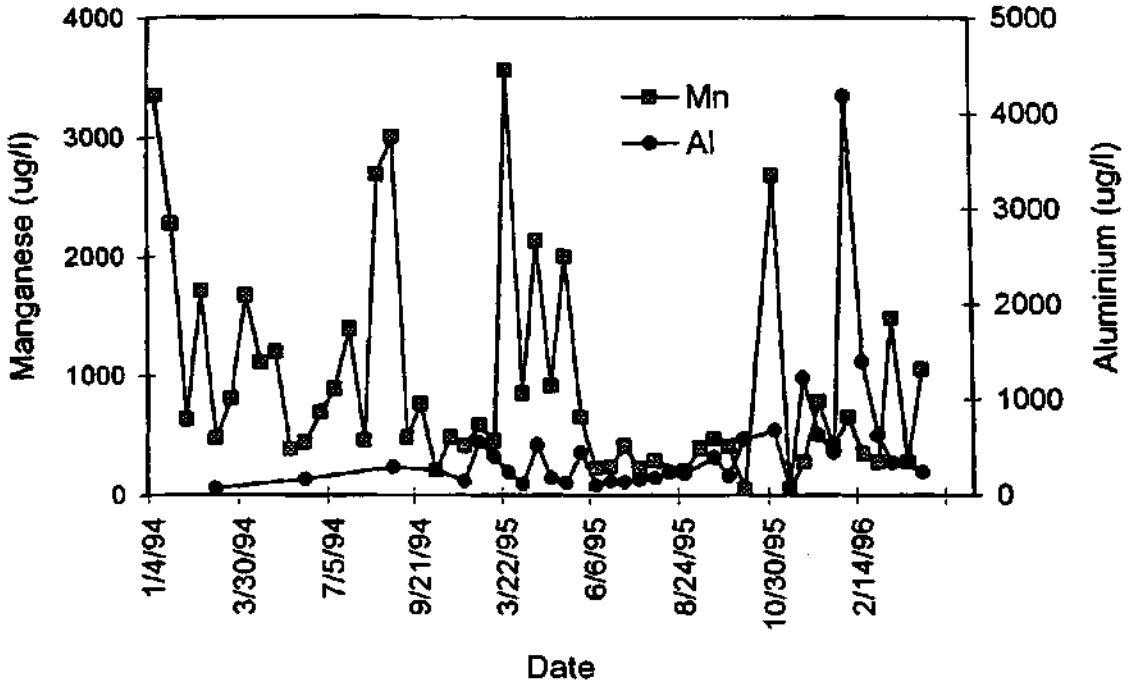

Figure 15: Manganese and aluminium in raw water for the period 4 January 1994 to 29 April 1995

Aluminium and manganese concentrations were high for most of the time (Fig. 15).

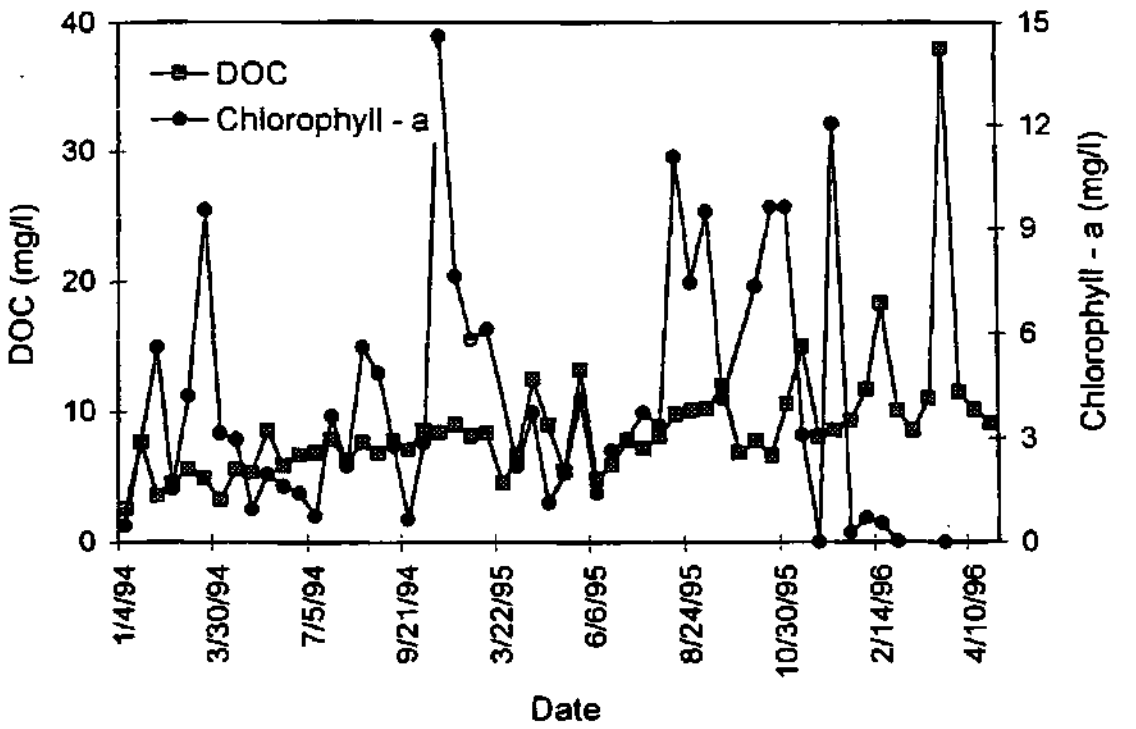

Figure 16: DOC and chlorophyll - a raw water for the period 4 January 1994 to 29 April 1996

Chlorophyll-a peaks (Fig. 16) were observed during January and March 1994, slight increases during August 1994 and peaks occurring again from 25 October 1994 towards the end of the year. From August 1995 to 6 December 1995 concentrations of greater than 90µg/l were measured most of the time.

DOC (Fig. 16) concentrations were below 8 mg/l for most of the observation dates during almost the first half of the experimental period. Peaks of up to 13 mg/l were observed during the period 22 March to 22 May 1995. The overall trend is a continuous increasing DOC concentration, with a peak of 38 mg/l occurring during March 1996.

Humic and fulvic acids, protein and carbohydrates were only measured from March 1995 onwards (Figs 17 and 18). High values of up to 18 mg/l of protein and humic acids were measured during the period March to May 1995. These peaks coincided with peaks in DOC and iron concentrations.

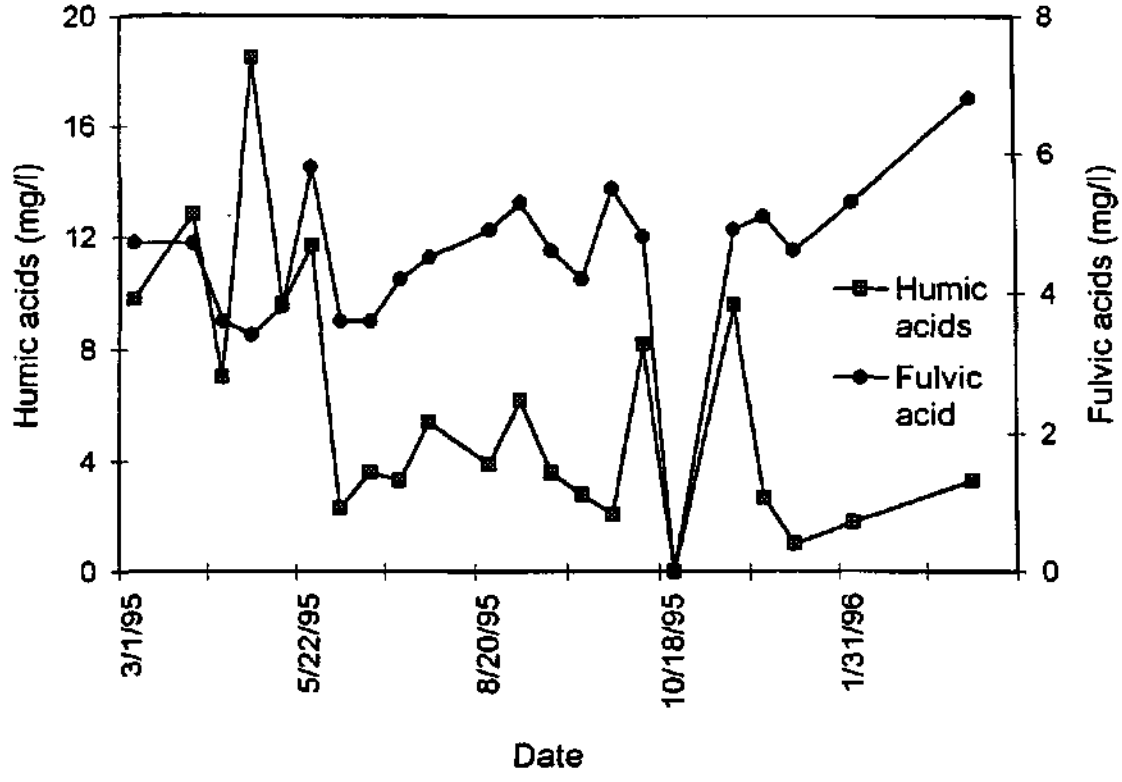

Figure 17: Humic acids and fulvic acids in raw water for the period March 1995 to March 1996

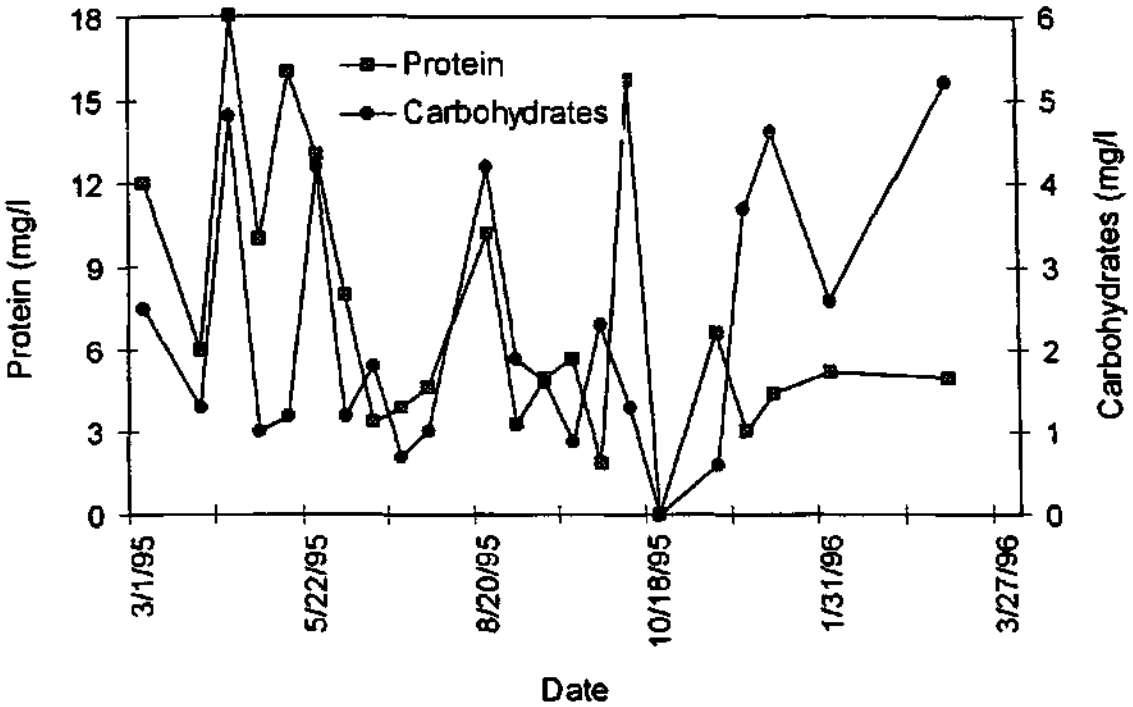

Figure 18: Carbohydrates and protein in raw water for the period March 1994 to March 1996

The experimental data was analysed to investigate the relationship between calcium concentrations in raw water and $FeCl_3$ dosing concentration (Fig. 19).

For certain periods $FeCl_3$ doses show no definite correlation with raw water calcium levels. Relationships were also investigated between temperature and chlorophyll-a reduction (Fig. 20) and temperature and iron reduction (Fig. 21).

Raw water turbidities as high as 230 NTU were measured on sampling dates during the period 4 January 1994 to 15 February 1994. Poly-electrolyte dosing concentrations ranged from 1,5 to 10 mg/l and $FeCl_3$ dosing concentrations from 0,8 to 2,7 mg/l, as Fe, during the same period. DOC concentrations of 9,0 mg/l and Fe concentrations of up to 1 800 µg/l were measured in the raw water.

The high lime process was evaluated on the plant from 30 March 1994 to 12 July 1994. Results obtained are illustrated in Tab. 1 and 2.

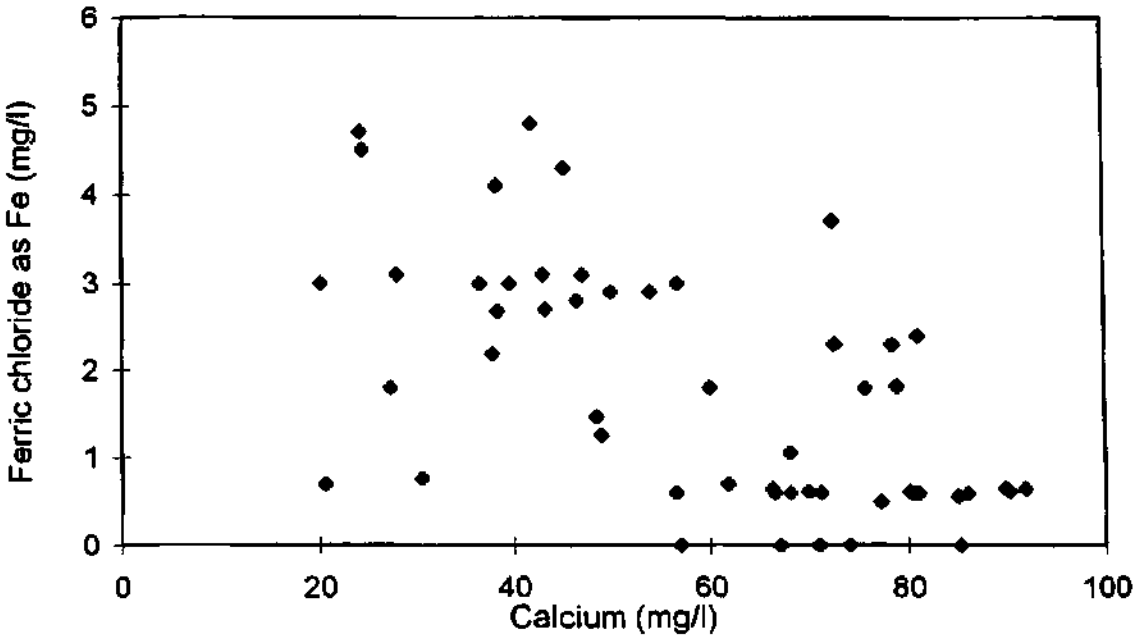

Figure 19: The relationship between raw water calcium and ferric chloride in Module 2

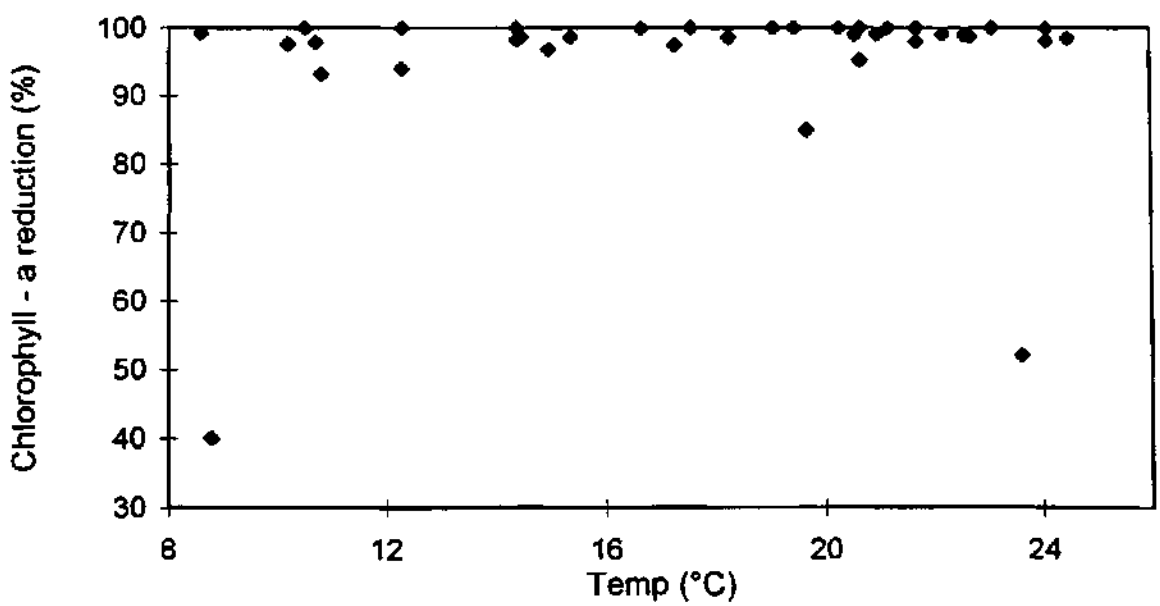

Figure 20: The relationship between raw water temperature and chlorophyll-a reduction in Module 2

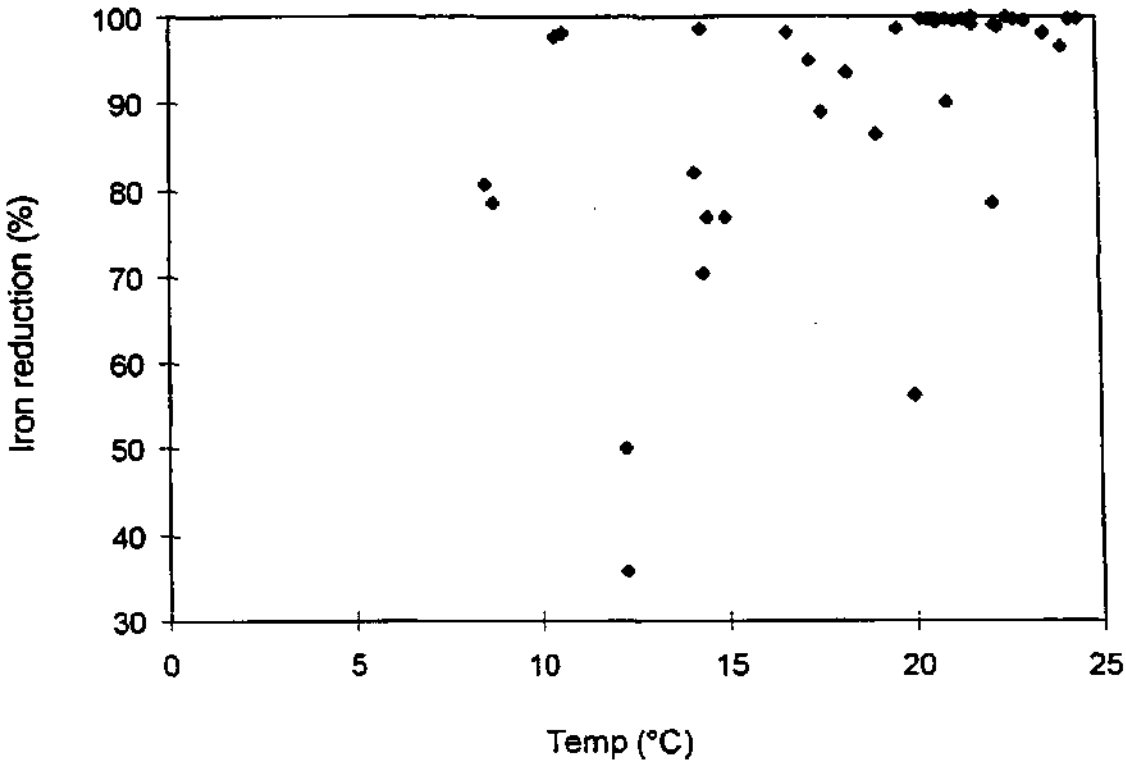

Figure 21: The relationship between raw water temperature and iron reduction in Module 2

Table 2 : Comparison of reduction between raw water and sedimentation for modules 2 and 3

Date 1994	Fe		Al		DOC		Chlorophyll-a	
	Module 2	Module 3	Module 2	Module 3	Module 2	Module 3	Module 2	Module 3
3.30	98.87	71.02	92.75	47.90	15.15	-36.36		97.43
4.12	94.20	83.54	88.55	85.12	35.71	3.57	92.27	96.15
4.19	98.69	68.62	92.55	91.72	29.63	11.11	88.06	79.06
5.11	98.16	95.13	41.04	96.10	40.70	-10.47	86.90	100.00
5.24	91.97	16.30	61.28	-3.64	25.42	0.00	92.92	96.49
6.07	18.75	-87.50	65.99	59.59	37.31	1.49	96.72	96.72
7.05	64.31	-39.23	63.41	74.09			36.17	69.99
7.12	73.36	-57.79	91.24	91.02			95.26	93.86
7.19	40.11	-3.96	59.60	-140.62			100.00	100.00

Table 3: Comparison of reduction between raw water and sand filtration for modules 2 and 3

Date	Fe		Al		DOC		Chlorophyll-a	
1994	Module 2	Module 3	Module 2	Module 3	Module 2	Module 3	Module 2	Module 3
3.30	98.87	79.57	88.68	86.41	-3.03	-69.70		98.79
4.12	99.23	99.23	83.50	82.15	33.93	5.36	95.17	100.00
4.19	98.69	98.69	94.06	97.32	40.74	7.41	85.03	100.00
5.11	98.16	83.63	27.27	96.10	60.47	40.70	100.00	100.00
5.24	70.32	40.63	-138.95	74.26	13.57	-42.37	98.21	98.21
6.07	50.00	50.00	60.32	60.90	40.30	4.48	100.00	100.00
7.05	78.46	74.92	65.68	77.50	34.78	15.94	39.97	92.53
7.12	80.62	84.78	57.76	92.53	34.18	16.46	99.20	94.46
7.19	97.75	85.97	89.40	63.80	11.11	9.52	100.00	100.00

Module 2 was used for high lime treatment. $FeCl_3$ was used as the only coagulant in Module 3 (the control line) at doses of 1 to 2 mg/l as Fe. Lime concentrations varied between 49 mg/l and 130 mg/l as $Ca(OH)_2$ in order to maintain the coagulation pH at approximately 11,3. Raw water pH-values increased up to 9,0 and alkalinity's of 145 mg/l, as $CaCO_3$, were measured. The raw water DOC concentrations were on average 9,0 mg/l and iron concentrations were below 100 µg/l. Chlorophyll-a peaks of 100 µg/l were measured.

Up to secondary sedimentation better reduction in iron concentration were obtained with the high lime process, where iron concentrations sometimes were reduced to below detection limits. Increases in iron concentrations were observed (control line) up to the sedimentation phase, but after sand filtration iron levels were, in some cases, similar to those in Module 2 (high lime process). Total iron reduction was, however, better with the high lime process (Fig. 22).

Reduction in aluminium were not constantly better with the high lime process after sedimentation. Reduction between secondary sedimentation and sand filtration

were constantly better in the control line than in the high lime process. Aluminium concentrations after sand filtration were thus lower in the control line for most of the time (Fig. 23).

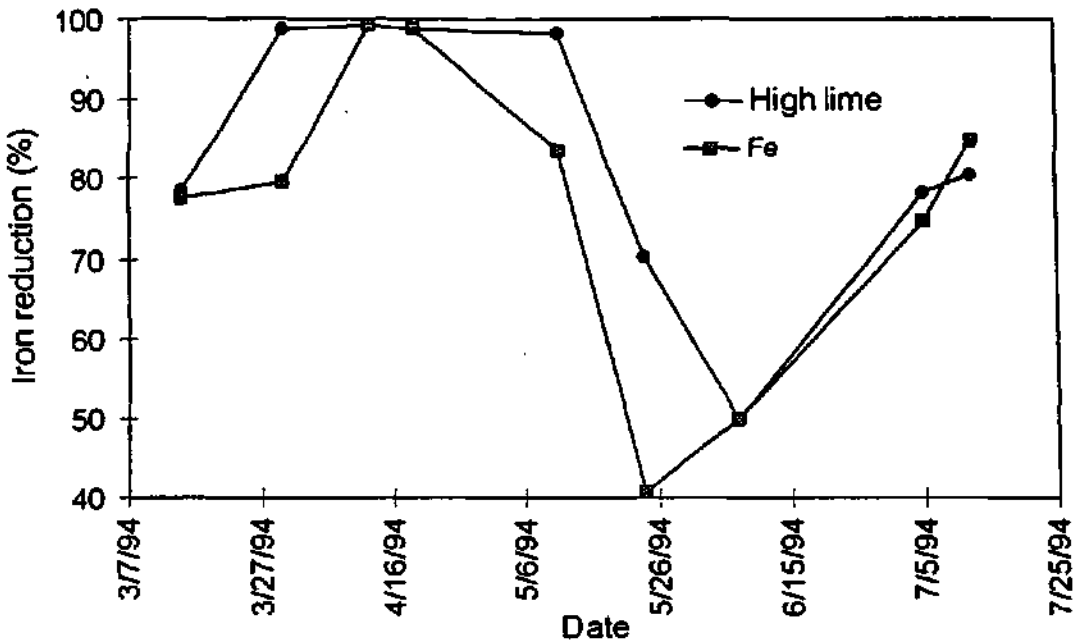

Figure 22: Iron reduction up to after sand filtration -a comparison between the high lime process and ferric chloride for the period 30 March 1994 to 19 July 1994

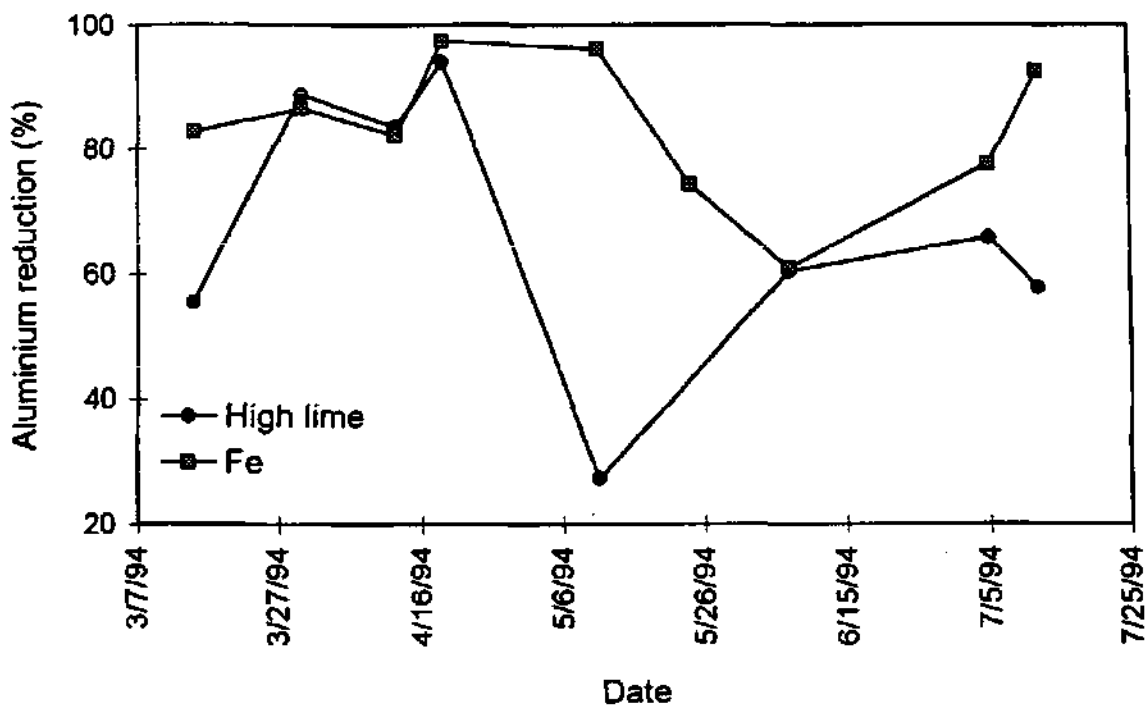

Figure 23: Aluminium reduction up to aftersand filtration - a comparison between the high lime process and ferric chloride for the period 30 March 1994 to 19 July 1996

Dissolved Organic Carbon (DOC) reduction up to secondary sedimentation ranged from 15-40% for Module 2 (high lime), whereas maximum reduction in Module 3 ($FeCl_3$) was 11%. Reduction obtained between secondary sedimentation and sand filtration were, in some cases, similar for both modules, thus resulting in an overall improved reduction in DOC for the high lime process (Fig. 24).

Trihalomethane (THM) values, after sand filtration, were continuously higher in the control line (Fig. 25). Total chlorophyll-a reduction was slightly better in the $FeCl_3$-line (Fig. 26). Colour, turbidity and suspended solids were removed better by the high lime process.

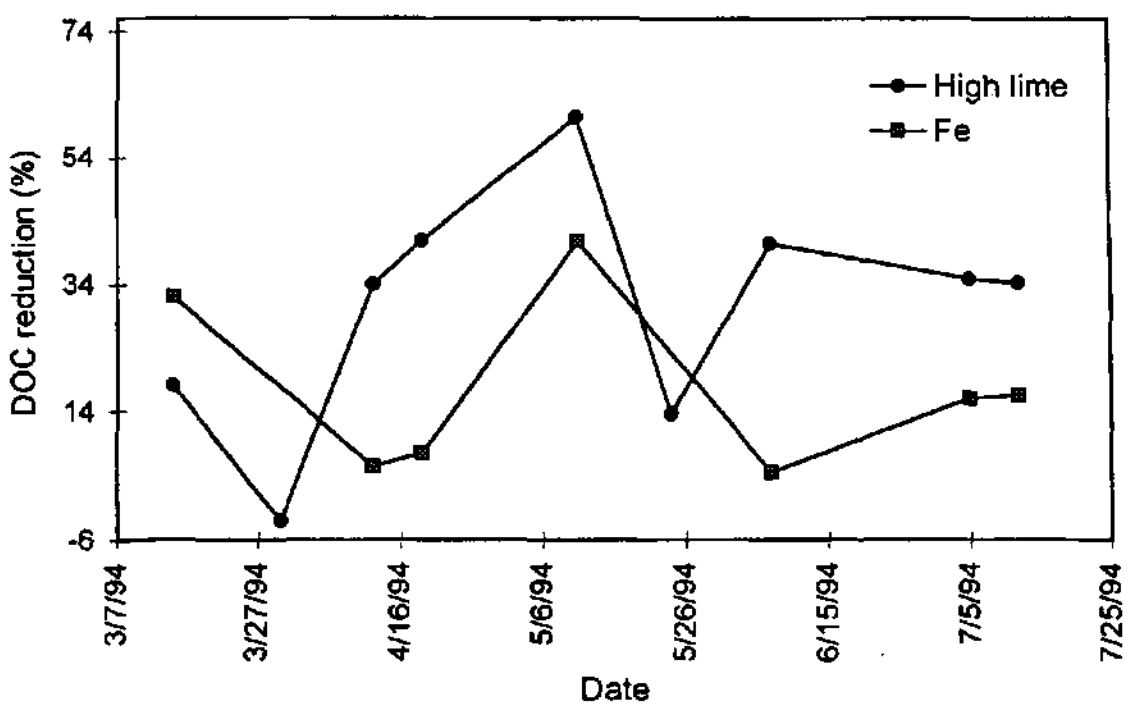

Figure 24: DOC reduction up to aftersand and filtration - a comparison between the high lime process and ferric chloride for the period 30 March 1994 to 19 July 1994

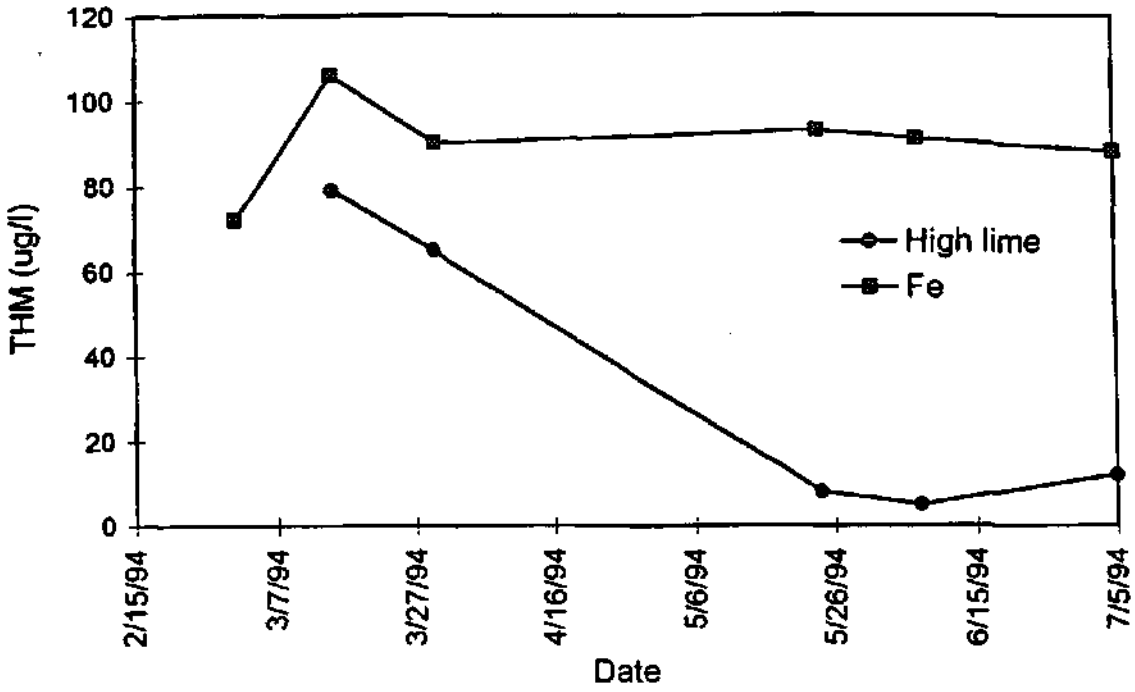

Figure 25: THM formation: Comparing the high lime process with ferric chloride for the period 30 March 1994 to 19 July 1994

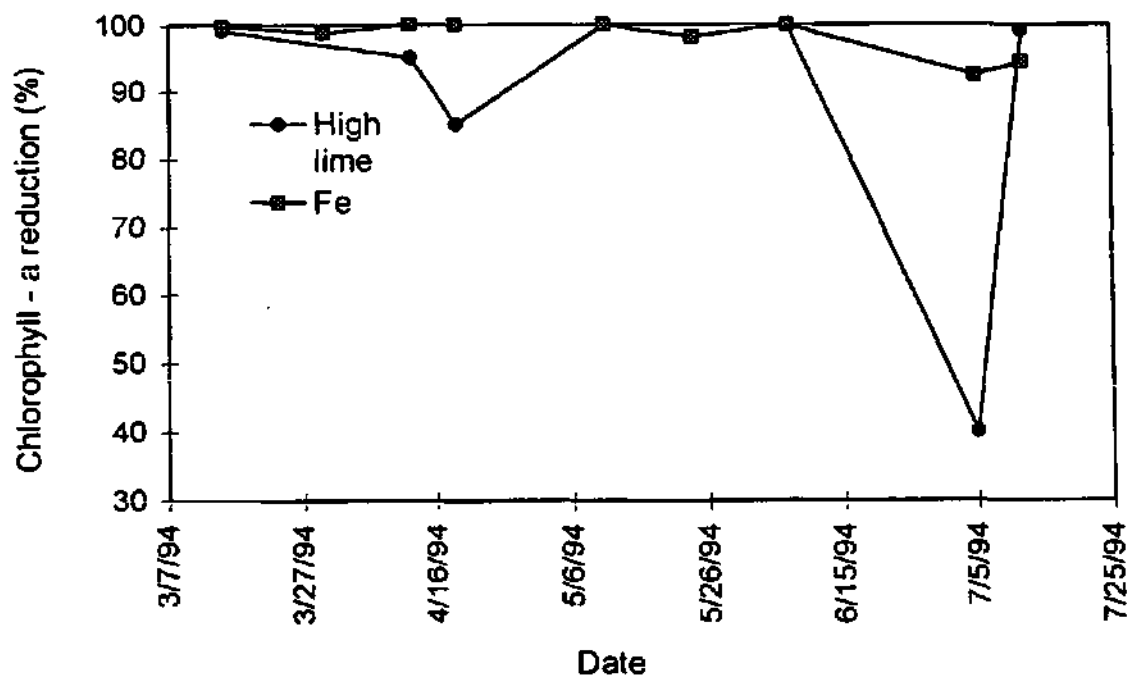

Figure 26: Chlorophyll - a reduction up to after sand filtration - a comparison between the high lime process and ferric chloride for the period 30 March 1994 to 19 July 1994

Reduction in iron decreased with decreases in lime dosing concentrations. It was noticed that decreases in aluminium reduction in general coincided with increases

in lime dosing concentrations. A slight negative correlation between DOC removal and changes in lime dosing was observed in both modules. Chlorophyll-a reduction increased when lime dosing concentrations were decreased. Due to lime sludge blockages Module 2 was taken out of operation for the period 10 August 1994 to 5 October 1994.

Because of the changing raw water quality, it was not possible to maintain continuity in the control line. From 25 October 1994 to 23 November 1994 no comparison studies with regard to different coagulants could be conducted due to water quality problems. Although a chlorophyll-a value of 145 µg/l was measured, the pH of the raw water was only approximately 7,5. Iron showed peak concentrations of 1 000 µg/l, DOC concentrations increased to 10 mg/l and turbidities reached values of 50 NTU. The performance of the DAFF process was evaluated under these conditions.

Tab. 4 shows results obtained in Modules 1 (DAFF) and 3 (control line) for the period 10 August to 23 November 1994. Alternative coagulants were used.

Table 4 : Comparison of reduction between raw water and sand filtered water for modules 1 and 3

Date	Fe		Al		DOC		Chlorophyll-a	
1994	Module 1	Module 3	Module 1	Module 3	Module 1	Module 3	Module 1	Module 3
8.10	98.54	94.86	99.59	83.71	15.58	9.09	100.00	100.00
8.16			92.00	93.70	23.19	40.58	98.83	97.64
8.31	95.19	46.15	78.93	64.52	3.85	7.69	100.00	96.93
9.21	92.94	92.94	75.59	63.84	14.08	18.31	100.00	100.00
10.05	52.56	74.42	4.37	13.59	4.65	5.81	98.01	100.00
10.26	97.95	68.14	85.80	58.04	2.38	3.57	100.00	99.42
11.02	95.83	95.83	71.46	84.63	22.22	20.00	99.25	97.75
11.23	98.70	98.70	80.17	80.34	26.83	7.32	100.00	100.00

Tab. 5 indicates the different coagulants used for the period 10 August 1994 to 3 October 1995.

Table 5 : Coagulants used during the period 10 August 1994 to 3 October 1995.

Date	Module 1	Module 2	Module 3
10 Aug. 1994 - 5 Oct. 1994	Fe Cl3	-	Fe Cl3
2 Nov. 1994 - 3 Jan. 1995	Fe Cl3 + U5000	-	Fe Cl3 + U5000
1 March 1995 - 30 Jun. 1995	Fe Cl3 + U5000	Fe Cl3 + U5000	Fe Cl3
20 Aug. 1995 - 3 Oct. 1995	Fe Cl3 + U5000	High Lime	Fe Cl3 + U5000

Fig. 27 shows the comparison in DOC removal by the DAFF process (Mod. 1), the high lime process and Ferric chloride.

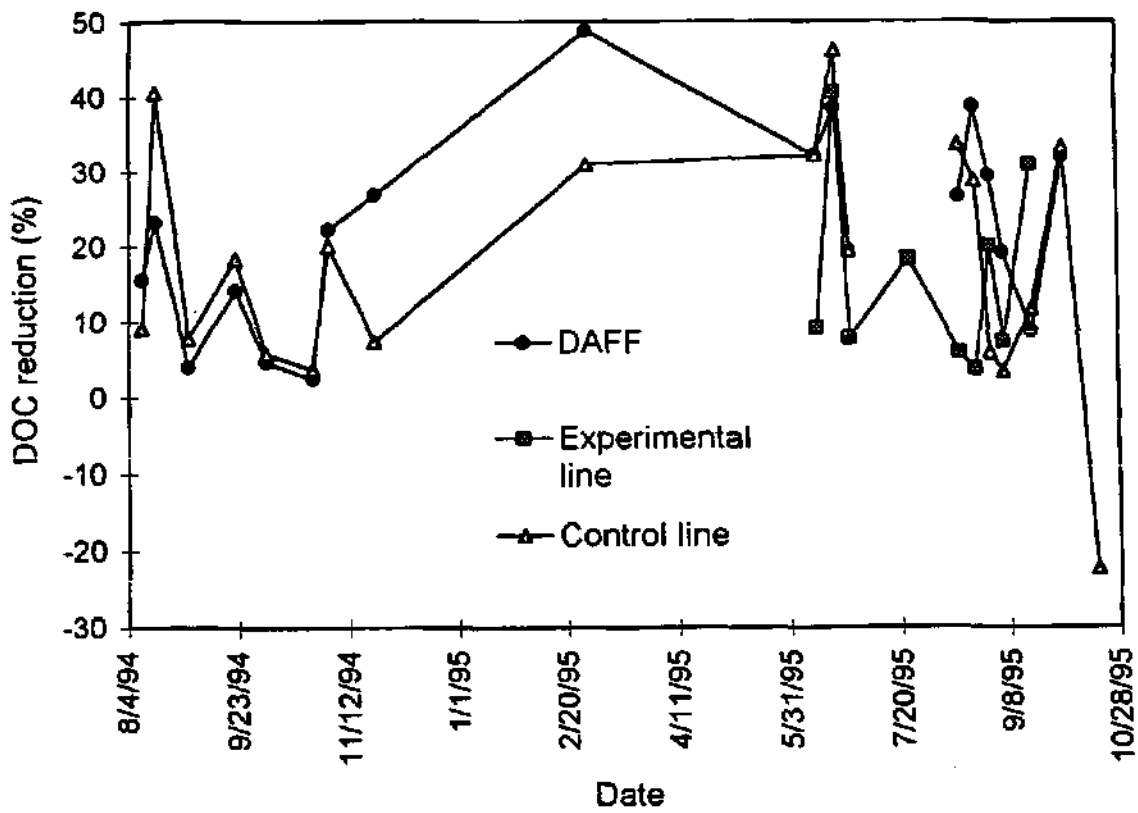

Figure 27: DOC reduction - comparing the three modules for the period 10 August 1994 to 3 October 1995

During the period 10 August to 5 October 1994 better DOC reduction were obtained in Module 3. $FeCl_3$ was used in module 3 and module 1. DOC reduction

in the DAFF process varied between 4 and 23 % and in the control line between 8 and 41 %. During the period 2 November to 3 January 1995 reduction in DOC were in general better for the DAFF process. Fe and Al reduction showed no constant pattern for the two modules. U5000 was used as secondary coagulant in both modules during this period. The DAFF process performed better than the high lime process in removing DOC for most of the time.

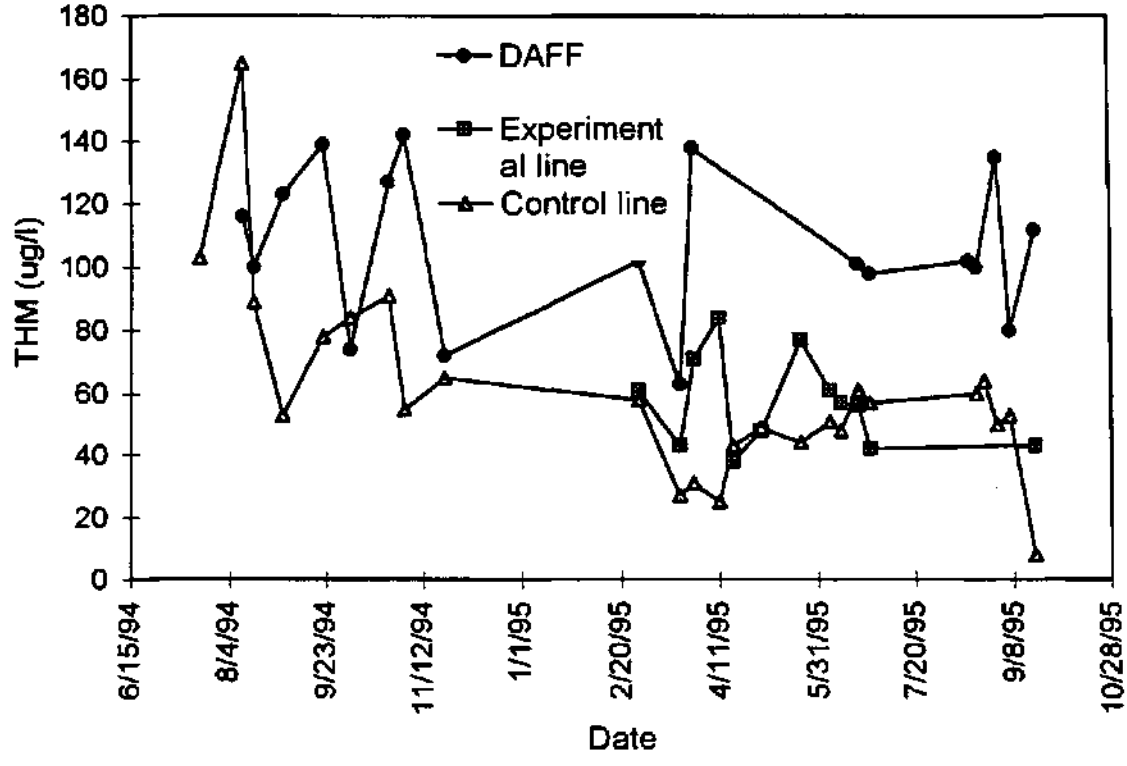

Figure 28: A comparison of THM formation (after sand filtration) in the three modules for the period 10 August 1994 to 3 October 1995

A comparison of THM formation in the three modules is shown in Fig. 28. Different combinations of coagulants were used for short times during this period. THM values were always lower in the control line than with the DAFF - process, regardless of the specific choice of process.

Slightly better reduction in Fe and Al concentrations were obtained by the DAFF process over this period. The removal of carbohydrates and humic acids were continuously the poorest in the DAFF process. The DAFF-process out-performed all other processes evaluated, in the removal of protein (Fig. 29).

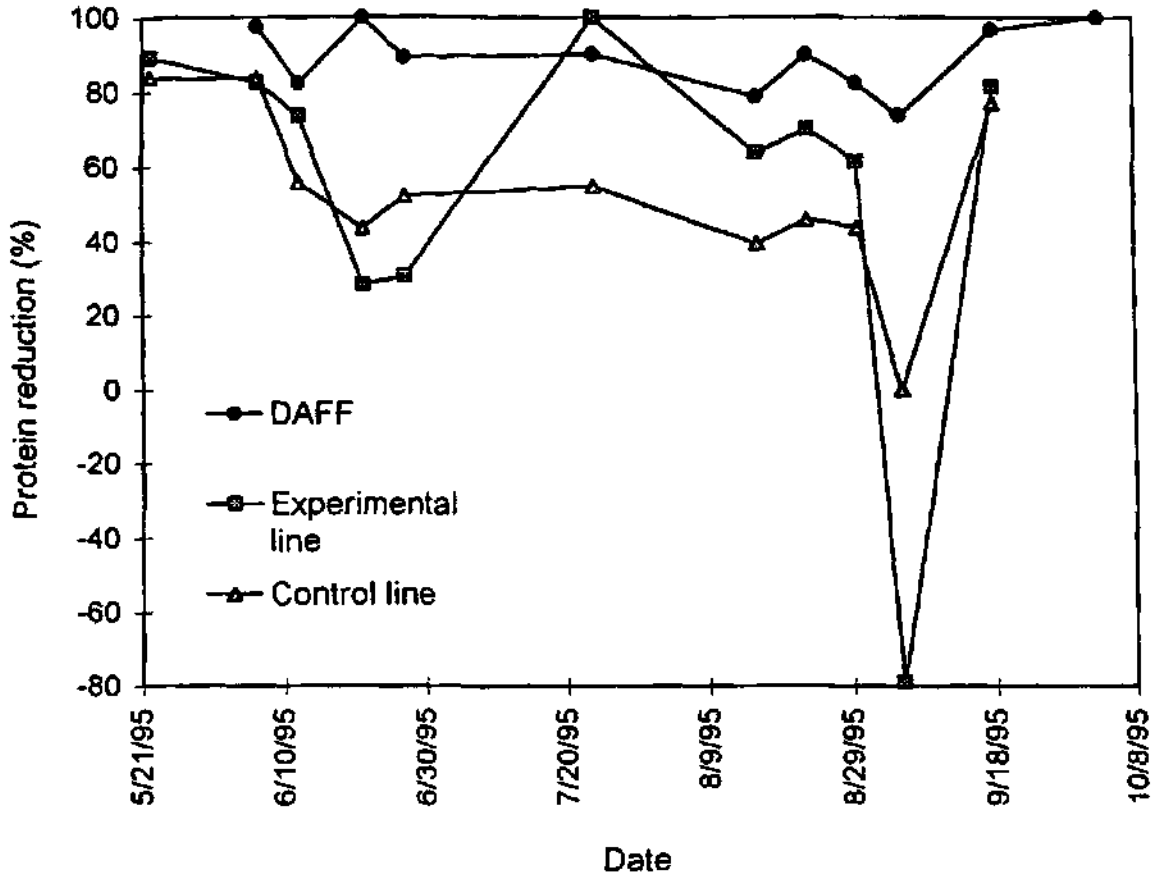

Figure 29: Protein reduction - comparing the three modules for the period 20 June 1995 to 3 October 1995

During January and February 1995 different coagulants could not be evaluated due to the raw water quality. Poly-electrolyte was used in both modules.

Module 3 was used as the control line from 1 March 1995 to 27 June 1995. $FeCl_3$ dosing concentrations were between 3,8 and 4,6 mg/l as Fe. Lime dosing concentrations ranged from 20-40 mg/l as $CaCO_3$. In modules 1 and 2 average $FeCl_3$ doses of 3 mg/l, as Fe, were maintained. The average U5000 dosing concentration in Modules 1 and 2 was 0,5 mg/l during this period. Raw water turbidities varied from about 20 NTU to 75 NTU. The raw water pH increased from 7,5 to 8,6. DOC concentrations varied between 4 and 14 mg/l and iron concentrations increased to 1 500 µg/l. Protein and humic acid concentrations were high, and peaks of 18 mg/l were measured.

Results from Modules 2 and 3 are compared in Tables 6, 7 and 8.

Table 6 : Comparison of reduction between raw water and sedimentation for modules 2 and 3

Date	Fe		Al		DOC		Chlorophyll-a	
1995	Module 2	Module 3	Module 2	Module 3	Module 2	Module 3	Module 2	Module 3
3.01			67.33	43.71			93.90	96.73
3.22	96.87		95.90	94.94				
3.29	98.43		85.88	85.88			100.00	96.13
4.11	97.70	97.54					98.81	96.94
4.18	87.85	93.40	82.26	82.26			100.00	100.00
5.02	82.25	68.22	86.35	86.35			93.32	93.32
5.22	42.86	48.21	70.99	58.79	78.79	-944.70	95.25	99.20
6.06	13.21	22.64	78.07	78.07			90.02	96.02
6.12	98.19	98.19	29.17	79.17	15.25	27.12	96.21	95.11
6.21			56.1	43.9	37.18	21.79	90.77	94.13
6.27			18.18	77.27	19.44	4.17	95.79	91.95

Table 7 : Comparison of reduction between raw water and sand filtered water for modules 2 and 3

Date	Fe		Al		DOC		Chlorophyll-a	
1995	Module 2	Module 3	Module 2	Module 3	Module 2	Module 3	Module 2	Module 3
3.01		99.70	69.09	69.09	16.67	30.95	98.12	99.07
3.22	99.70	99.90	92.53	97.75	-32.61	-45.65		
3.29	99.75	99.90	67.06	49.41	14.93	-17.91	100.00	94.81
4.11	99.75	99.57			49.60	-36.00	98.98	98.98
4.18	86.46	95.79	65.28	74.81	12.22	16.67	100.00	100.00
5.02	94.86	83.93	85.45	87.60	3.64	5.45	97.51	95.81
5.22	76.79	67.92	92.37	77.10	6.06	17.42	98.66	98.39
6.06	35.85	98.19	77.97	77.97	4.08	4.08	93.99	
6.12	98.19		79.17	79.17	27.12	32.2	97.84	
6.21			60.98	51.22	48.72	46.15	97.62	94.73
6.27				77.27	22.22	19.44	93.10	99.62

Small differences were noted in the total removal of iron and aluminium. A better removal in aluminium was, however, obtained in Module 2 ($FeCl_3$ + U5000) up to the sedimentation phase. Removal after sand filtration was also better for some of the observations. By increasing lime dosing concentrations better iron reduction was achieved in both modules for most of the time. Reduction in chlorophyll-a varied between 90 and 100% for both modules, with better removal being obtained for most of the time when U5000 was used (Fig. 30). The removal of protein, carbohydrates and humic- and fulvic acids were determined in the different modules. Tables 8 show the percentage reduction obtained for these substances.

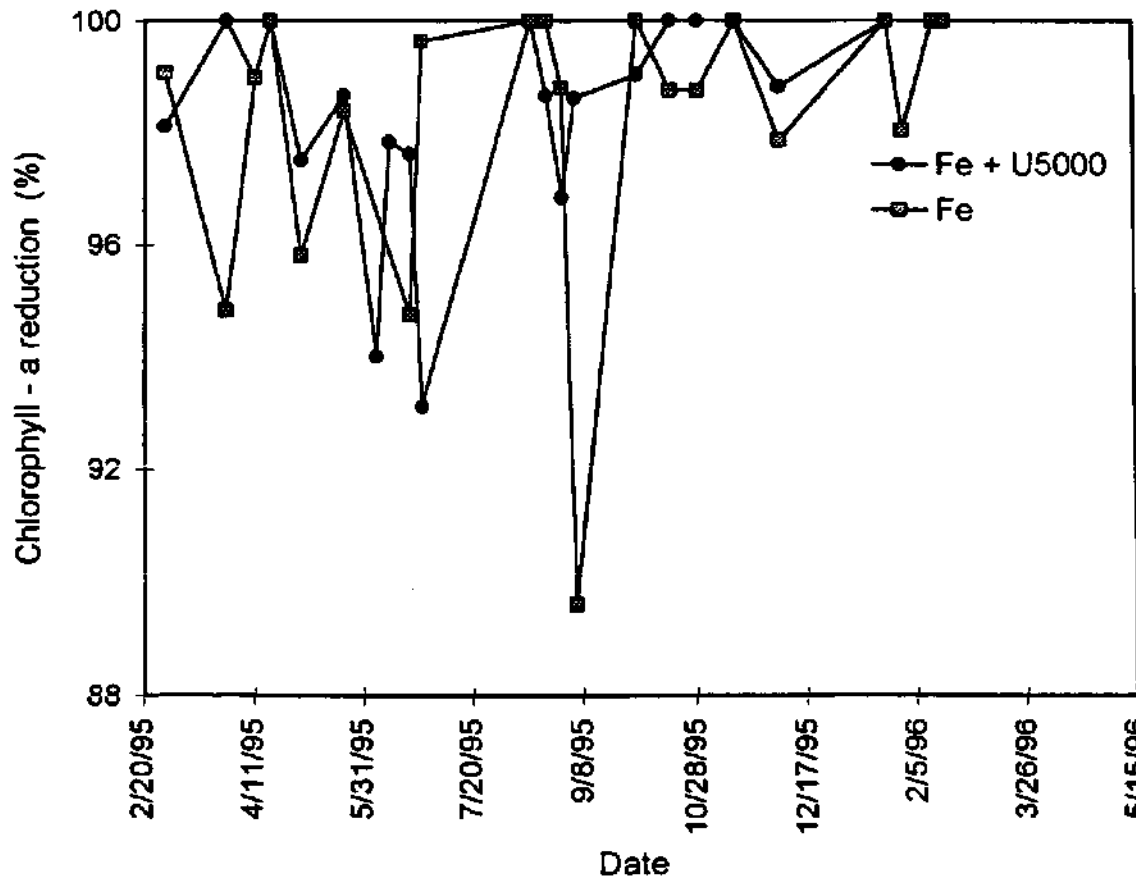

Figure 30: Chlorophyll - a reduction up to after sand filtration - a comparison between ferric chloride and ferric chloride plus U5000 for the period 1 March 1995 to 27 June 1995

Table 8: Humic- and Fulvic acid, carbohydrate and protein removal by coagulation, floculation, sedimentation and sand filtration

Date	HUMIC ACIDS			FULVIC ACIDS			CARBOHYDRATES			PROTEIN		
1995	Module 1	Module 2	Module 3	Module 1	Module 2	Module 3	Module 1	Module 2	Module 3	Module 1	Module 2	Module 3
3.01	91.84	88.78	91.84	61.86	47.03	49.15	83.33	58.33	66.67	72.00	64.00	80.00
3.29		99.22	96.09		34.04	31.91		50.00	50.00		38.46	23.08
4.11		98.86	98.57		44.44	30.56		61.11	72.22		97.92	93.75
4.18		97.30	96.76		26.47	29.41		40.00	4.00		80.00	10.00
5.02		94.79	94.79		44.74	34.21		43.75	56.25		83.33	100.00
5.22		93.16	95.73		60.34	55.17		*0.70	83.85		95.24	80.95
6.06	65.2	73.90	78.26	*0.50	38.89	36.11	97.50	82.50	83.75	16.67	58.33	8.33
6.12	91.7	83.33	86.11	47.22	27.78	33.33	82.35	73.53	55.88	88.89	100.00	83.33
6.21	48.5	84.85	87.88	35.71	33.33	38.10	100.00	28.21	43.59			
6.27	94.4	87.04	90.74	57.78	37.78	40.00	89.13	30.43	52.17	20.00	80.00	70.00
Average	78.33	90.12	91.67	50.60	39.48	37.80	90.46	51.98	56.84	49.39	77.48	61.05

** These results are not included.*

In the raw water protein and humic acids were always present in the highest and carbohydrates in the lowest concentrations. The use of U5000 at times slightly enhanced the removal of carbohydrates (Fig. 31) and fulvic acids (Fig. 32).

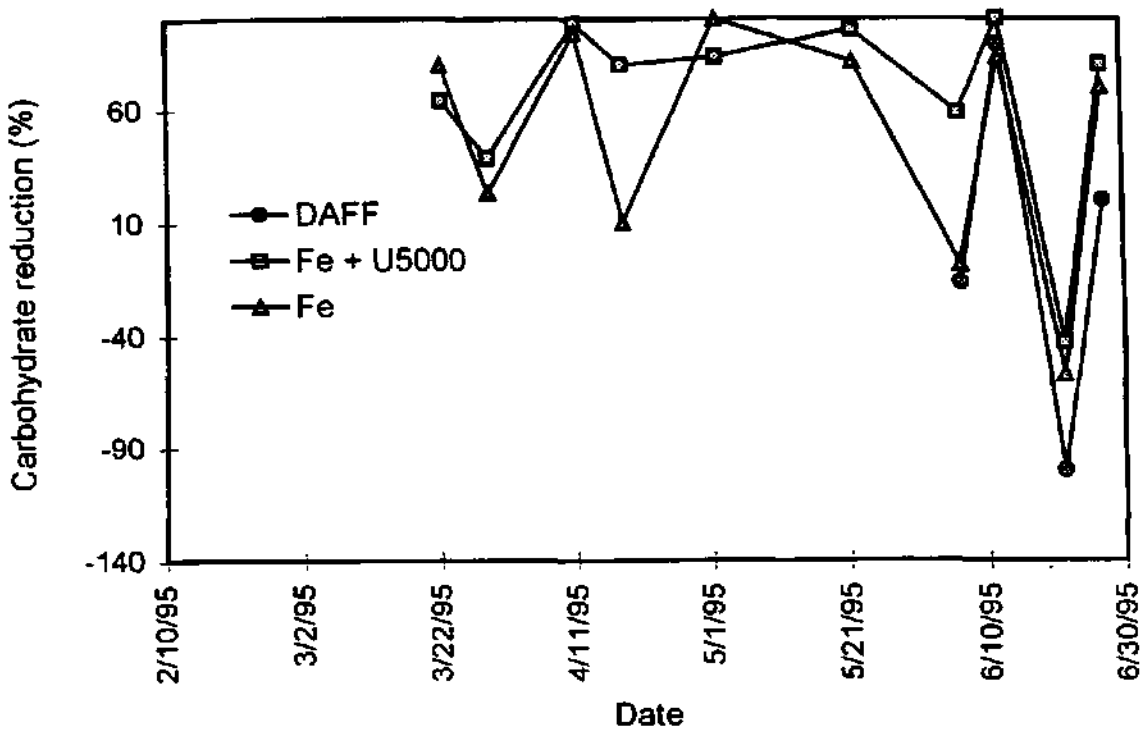

Figure 31: Carbohydrate reduction up to after sand filtration - a comparison between the three modules for the period 1 March 1995 to 27 June 1995

In June 1995 slightly better reduction in fulvic acid concentrations were obtained using $FeCl_3$ alone. Figs. 33 and 34 show that the reduction in protein and humic acids were not consistent for the same process. When comparing $FeCl_3$ with $FeCl_3$ plus U5000, protein reduction were better when only $FeCl_3$ was used. On 22 May and 12 June 1995, better reduction were, however, obtained when U5000 was used (Fig. 34). Fig. 35 shows that humic acids were removed better when U5000 was used as secondary coagulant from 22 March to 11 April 1995. Better reduction were obtained with only $FeCl_3$, from 22 May 1995 to 27 June 1996.

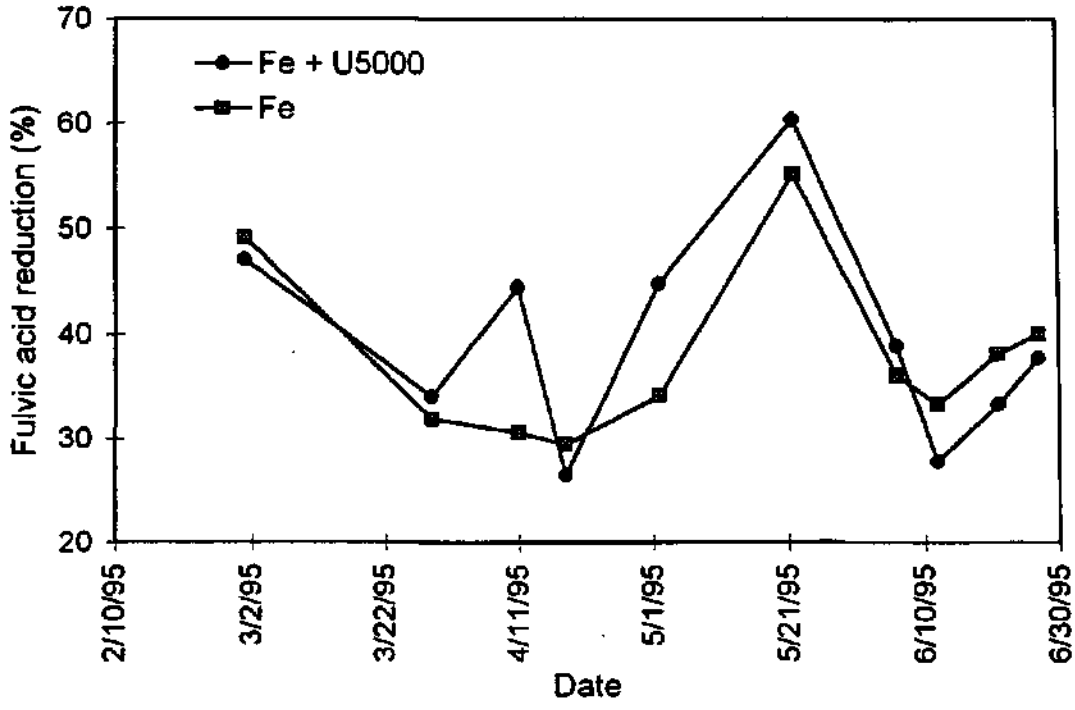

Figure 32: Fulvic acid reduction up to after sand filtration - a comparison between ferric chloride and ferric chloride plus U5000 for the period 1 March 1995 to 27 June 1995

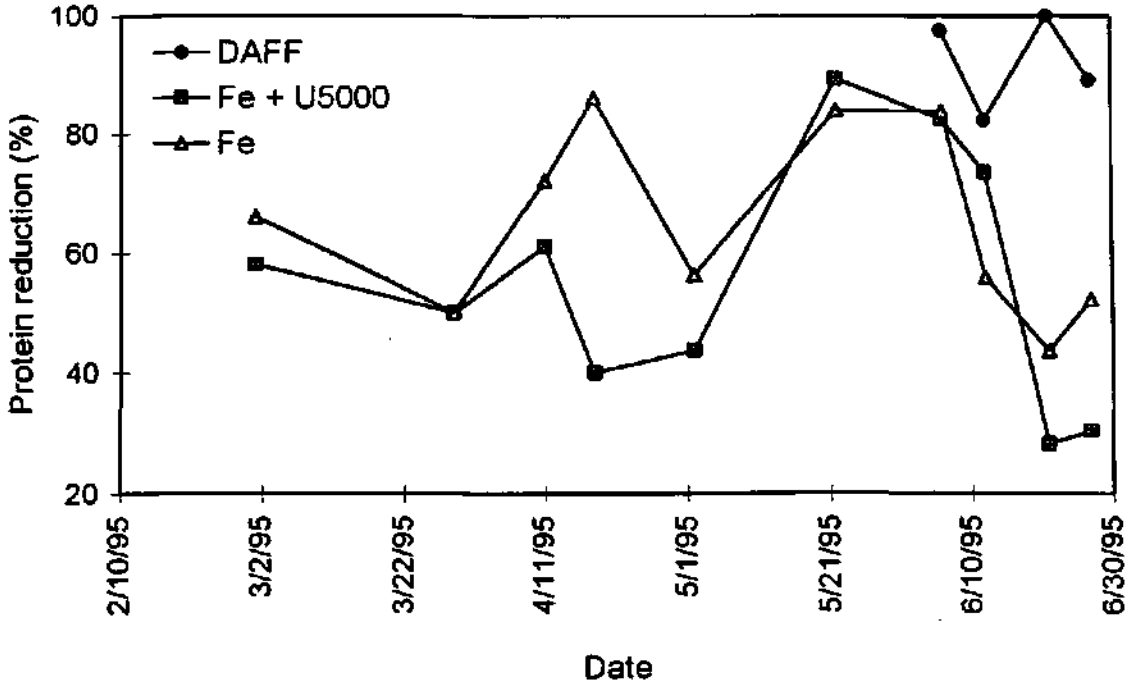

Figure 33: Protein reduction up to after sand and filtration - a comparison between the three modules for the period 1 March 1995 to 27 June 1995

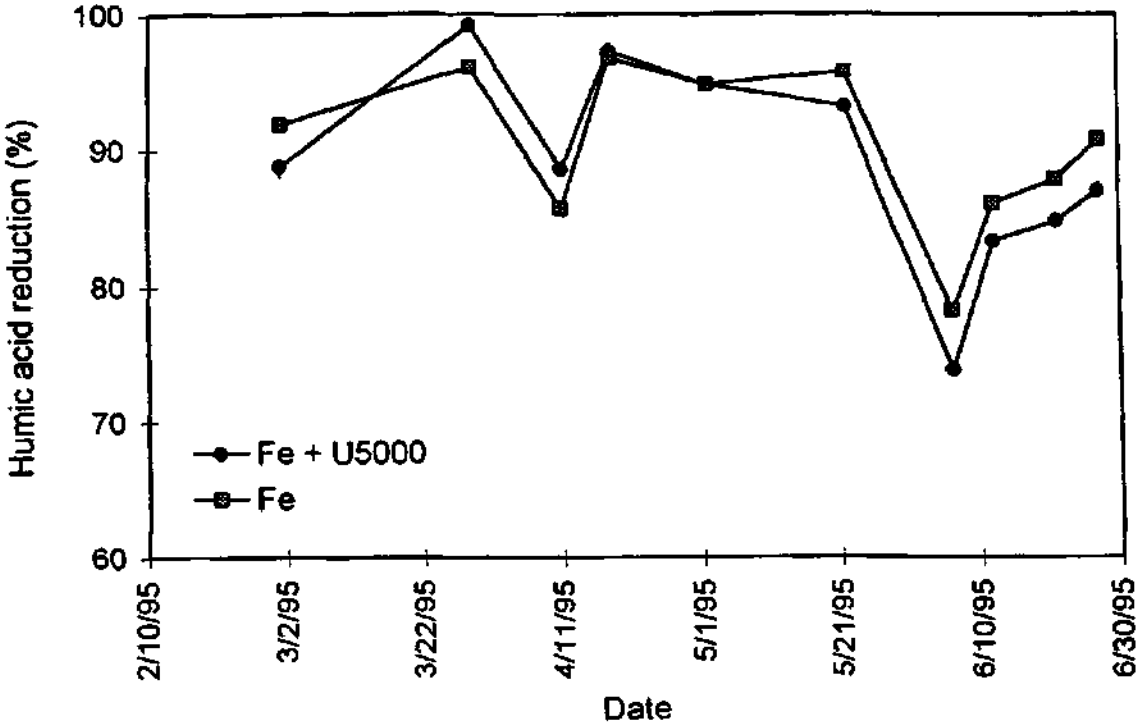

Figure 34: Humic acid reduction up to after sand filtration - a comparison between ferric chloride and ferric chloride plus U5000 for the period 1 March 1995 to 27 June 1995

increases in lime dosing concentrations coincided with decreasing DOC reduction when using $FeCl_3$ as the only coagulant for most of the observations. Inconsistencies or contradictions were obvious in the removal of DOC and iron.

The high lime process was again evaluated from 20 August 1995 to 3 October 1995. U5000 (0,5 mg/l) was used as secondary coagulant in the control line during this period. Lime dosing concentrations had to be increased to between 150 mg/l and 260 mg/l in order to maintain a pH of approximately 11,3. $FeCl_3$ dosing concentrations in Module 2 (control line) varied between 3,5 and 5,8 mg/l as Fe.

The iron concentration in the sand filtered water of the high lime process often exceeded the recommended limit of 100 µg/l. Only experimental data are shown in Fig.35.

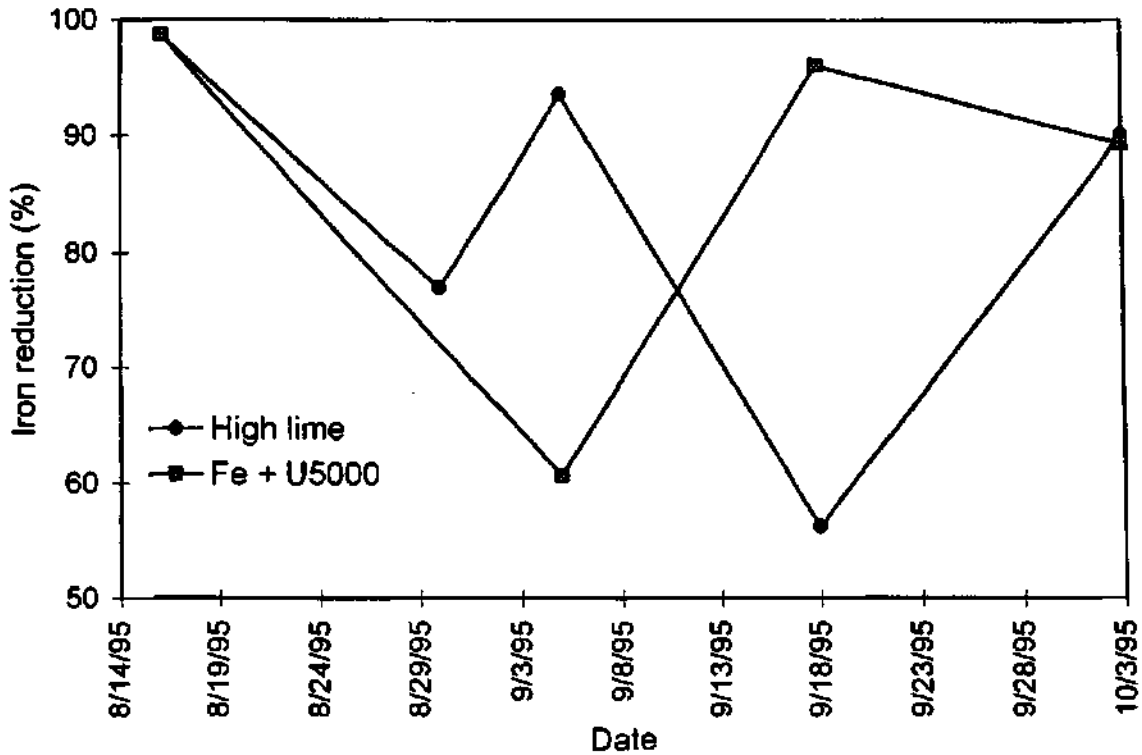

Figure 35: Iron reduction up to after sand filtration - a comparison between high lime and ferric chloride plus U5000 for the period 16 Augustus 1995 to 3 October 1995

The analyses of daily data showed that since the beginning of September better reduction of iron was obtained in the control line where U5000 was used as secondary coagulant. DOC reduction in the high lime process was less effective than during the previous experimental period. Daily SAC values also indicated the better removal of organic matter by the addition of U5000. Humic- and fulvic acids, protein and carbohydrates were removed better in the high lime process than with $FeCl_3$ plus U5000 for most of the time. Protein removals of approximately 90 % were obtained in the DAFF process. Since the beginning of September the high lime process was less effective (Figs 35-39) in removing iron and organic substances.

Raw water turbidities were consistently between 20 and 25 NTU during this period. pH Values were between 8,5 and 8,6 and alkalinity's increased from 70 mg/l to 138 mg/l as $CaCO_3$. Iron concentrations in the raw water did not exceed 500 µg/l. Increasing DOC concentrations were observed. Peaks of 12 mg/l were

measured during October 1995. At times the chlorophyll-a concentrations exceeded 100 µg/l.

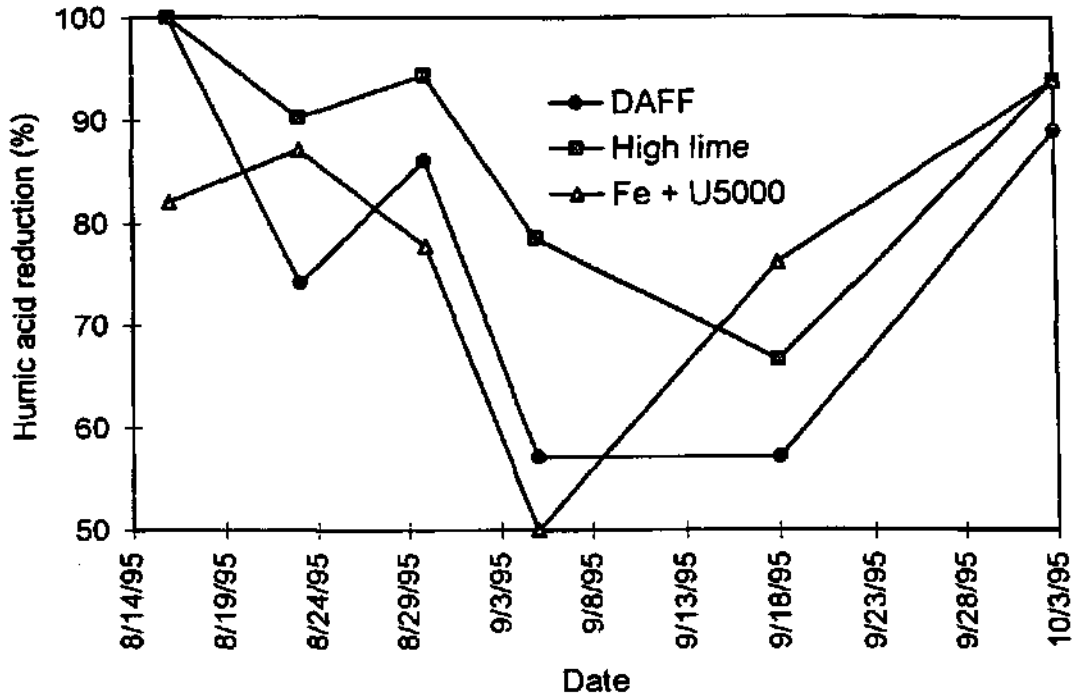

Figure 36: Humic acid reduction up to after sand filtration - comparing the three modules for the period 16 August 1995 to 3 October 1995

From 18 October 1995 to April 1996 the DOC concentration in the raw water increased consistently to reach peaks of almost 40 mg/l during March 1996. Chlorophyll-a values of as high as 120 µg/l were measured. Concentrations of 100 µg/l were measured from January 1996 onwards. Iron concentrations of between 100 and 110 mg/l were measured during the same time. Humic acids and protein levels also increased. Diatoms became dominant during this period. Raw water turbidities of 500-600 NTU were measured on the experimental dates during February 1996. $FeCl_3$ dosing concentrations of between 5 and 6 mg/l as Fe and U5000 concentrations of 0,5 mg/l were used during October 1995. During November 1995 U5000 dosing concentrations had to be increased to 10 mg/l with $FeCl_3$ doses still between 5 and 6 mg/l as Fe. During December 1995 and January and February 1996 U5000 dosing concentrations were increased to as high as 17 mg/l and $FeCl_3$ dosing concentrations could be decreased to between 3 and 4 mg/l as Fe, for certain periods. The average Fe dosed was, however, 5,5 mg/l. Lime was dosed at approximately 70 mg/l.

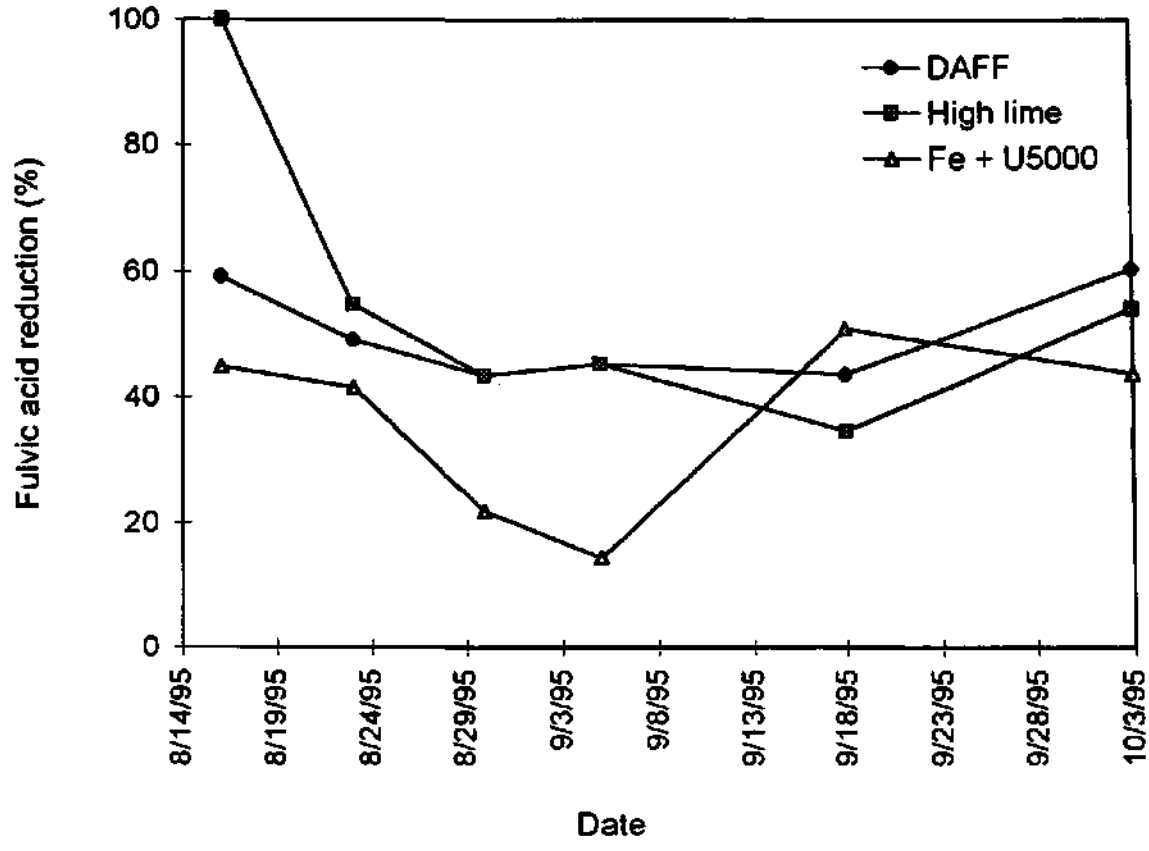

Figure 37: Fulvic acid reduction up to after sand filtration - comparing the three modules for the period 16 August 1995 to 3 October 1995

Jar Tests

Jar tests are traditionally used to optimise for coagulant doses based on turbidity removal. Water quality problems, however, gave rise to a different approach with respect to jar test evaluations for optimal coagulation.

Jar tests were conducted in the laboratory to investigate and confirm certain findings on the plant. The influence of temperature on the removal of iron and manganese is illustrated in Table 8 and Figs 40 and 41. Analyses were done on settled samples. A maximum reduction of 80% was obtained for dissolved iron at temperatures of approximately 13°C. A decrease in the reduction of total iron was observed for temperatures greater than 16°C. At 22°C the reduction was 51%.

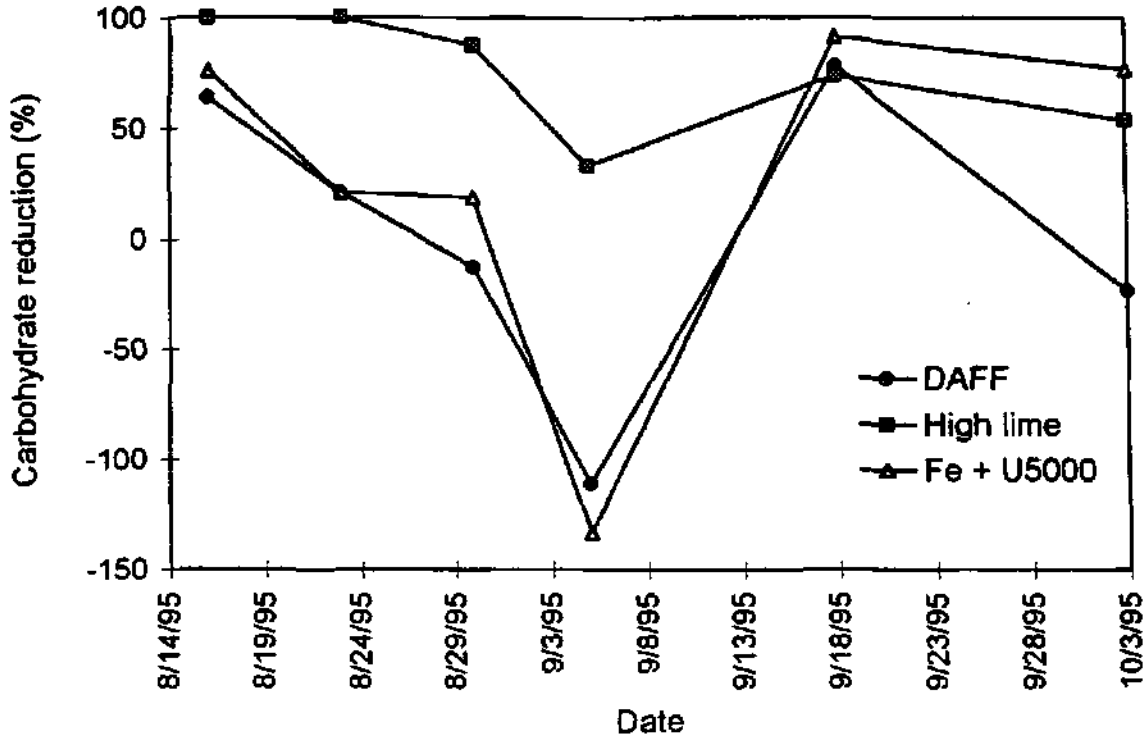

Figure 38: Carbohydrates reduction up to after sand filtration - comparing the three modules for the period 16 August 1995 to 3 October 1995

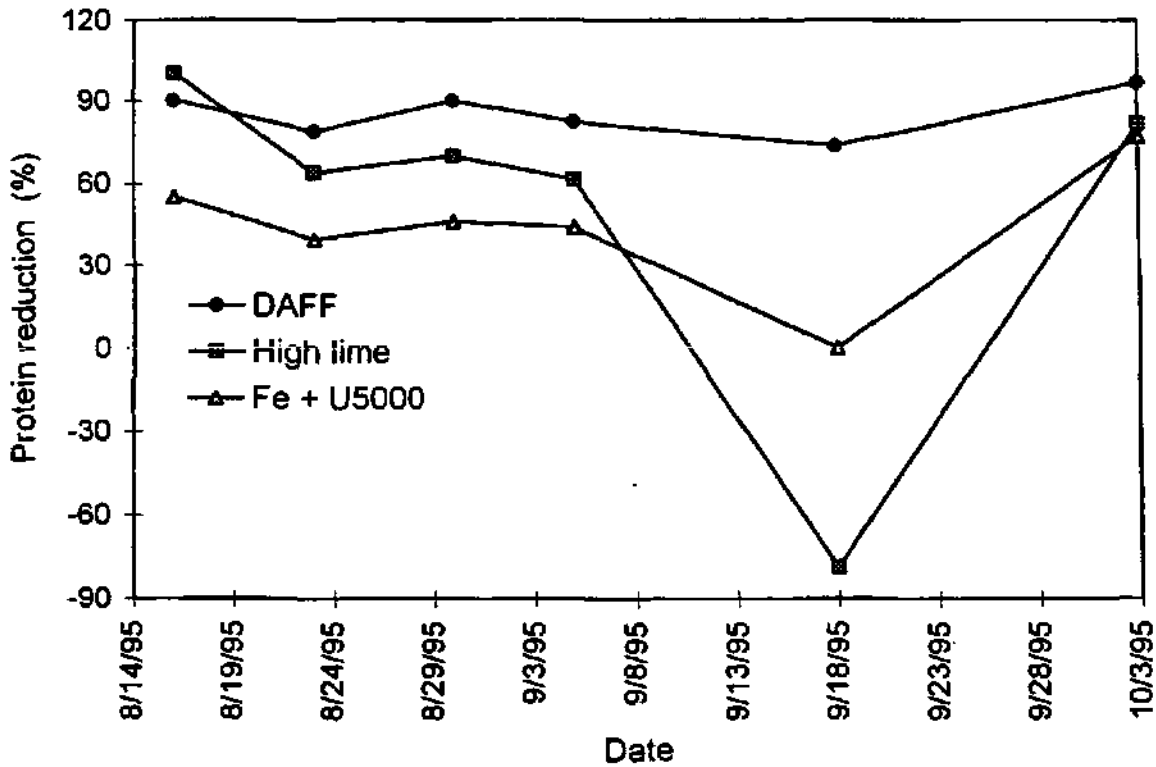

Figure 39: Protein reduction up to after sand filtration - a comparing the three modules for the period 16 August 1995 to 3 October 1995

Table 9 : Jar Tests to demonstrate the effect of temperature on the removal of iron and manganese on pre-chlorinated water

TEMP (°C)	pH	TOTAL Fe REDUCTION %	DISS. Fe REDUCTION %	TOTAL Mn REDUCTION %	DISS. Mn REDUCTION %
11.5	9.10	80.81	49.21	90.24	63.81
12.8	9.08	77.03	80.16	87.04	61.90
13.9	9.06	77.03	80.16	89.33	62.86
15.6	9.06	79.75	80.16	91.77	67.62
17.9	9.18	76.69	80.16	89.94	79.05
20.0	9.00	60.89	80.16	79.27	62.86
22.3	9.00	51.25	46.03	79.12	62.86

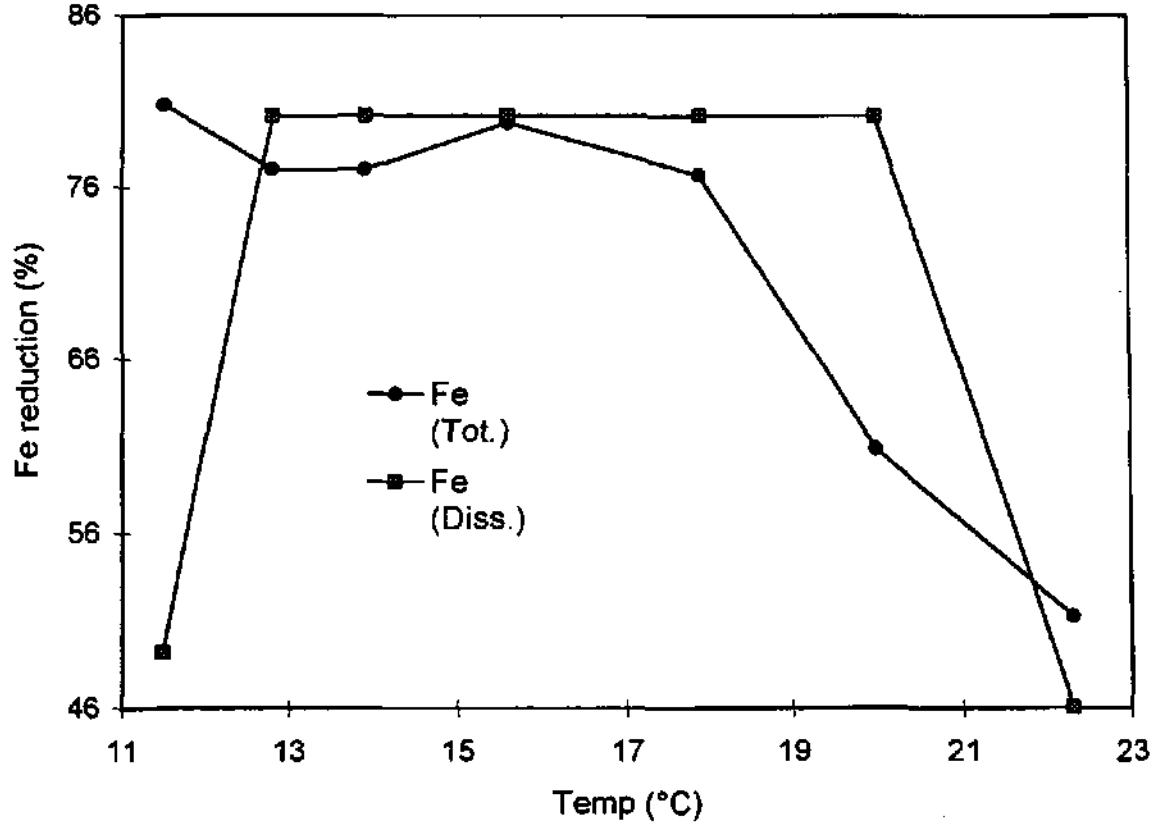

Figure 40: The influence of temperature on iron removal - jar results for settled samples

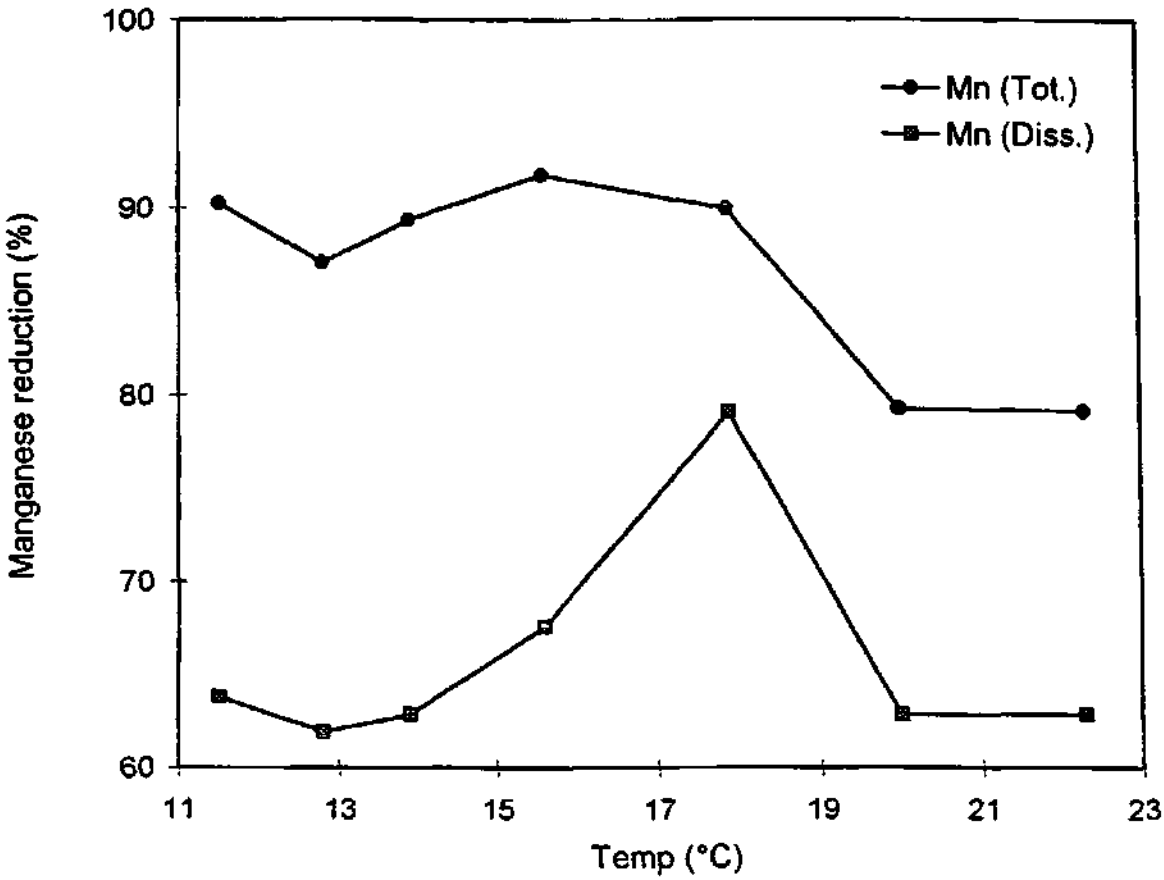

Figure 41: The influence of temperature on manganese removal - jar test results for settled sampled

The removal of total and dissolved manganese decreased with the increase of temperatures above approximately 18°C. Above 20°C no further decrease was observed. The removal of dissolved manganese increased up to a temperature of 18°C and then decreased with further increases in temperature. Removals stabilised at temperatures above 20°C. Fig. 41 shows a decrease in the reduction of total and dissolved manganese between 11°C and 13°C.

The influence of the addition of lime, and thus pH, on Fe and Mn removal is illustrated in Tab. 10. Pre-chlorinated water was used, and analyses were done on settled samples.

Table 10 : Jar Tests to demonstrate the effect of pH and coagulant dosing concentrations on the removal of iron and manganese on pre-chlorinated water

pH	Fe mg/l	CaO mg/l	TOTAL Fe REDUCTION %	DISS. Fe REDUCTION %	TOTAL Mn REDUCTION %
7.52	3.75		46.52	0	59.91
8.40	3.75	25	51.04	80.16	67.38
9.12	3.75	50	49.43	80.16	66.46
9.50	3.75	75	67.30	80.16	81.55
9.70	3.75	100	68.58	80.16	92.99
10.40	0.90	100	93.53	80.16	100.00
11.30	0.90	175	99.76	80.16	100.00

The effect of pH on the removal of iron and manganese is shown in Fig. 42.

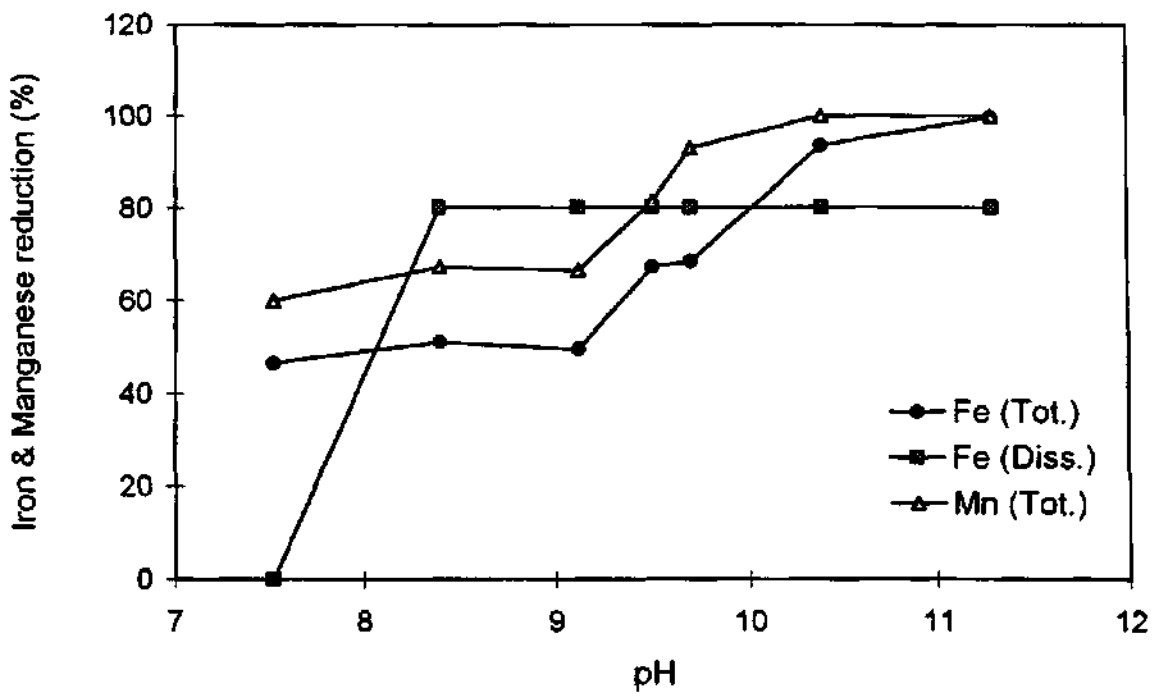

Figure 42: The effect of pH on the removal of iron and manganese jar test results for settled samples.

No improvement in the reduction of dissolved iron was observed for pH values above 8,5. Reduction in total iron increased from approximately 50% at pH 9,0 to approximately 70% at pH 9,8. Reduction of 90% and higher were obtained at pH values between 10,4 and 11,4. Total manganese removal improved from 65% to 95% when the pH was increased from 9,0 to 9,8. DOC on the raw water was not determined.

Tab. 11 illustrates the effect of pH, poly-electrolyte concentrations and chlorine on the removal of iron, manganese and organic matter. The raw water DOC concentration was 9,8 mg/l and the Fe concentration 990µg/l. The results are from settled samples.

Table 11 : Jar Tests to demonstrate the effect of pH, chlorine and coagulant concentration on the removal of iron, manganese and organic matter

pH	Fe (mg/l)	U5000 (mg/l)	Chlo-rine (mg/l)	Turbi-dity (%)	DOC (%)	Fe (Total) (%)	Fe (Diss.) (%)	Mn (Total) (%)	Mn (Diss.) (%)	SAC (%)
7.51	2.22	0.50	3.70	42.86	2.08	93.66	ND	3.33	0.80	11.01
7.49	0.59	10.00	3.70	91.71	15.64	97.73	ND	36.67	26.09	37.42
8.74	2.22	0.50	3.70	92.86	7.39	64.99	ND	6.67	39.13	10.69
8.68	0.59	10.00	3.70	91.71	12.03	81.52	ND	51.67	47.83	34.28
9.87	2.22	0.50	3.70	94.86	3.952	87.84	ND	7.50	60.87	24.21
9.85	0.59	10.00	3.70	91.43	12.20	93.35	ND	65.00	69.57	33.65
7.78	2.22	0.50	0.00	66.57	9.52	88.04	ND	2.30	1.00	17.59
7.91	0.59	10.00	0.00	89.71	22.75	97.68	ND	9.09	14.29	43.04
8.59	2.22	0.50	0.00	92.57	6.70	68.93	ND	3.45	16.39	17.06
8.63	0.59	10.00	0.00	89.43	17.8	90.71	ND	6.20	27.14	36.75
9.82	2.22	0.50	0.00	90.86	6.66	79.64	ND	22.73	7.14	28.08
9.79	0.59	10.00	0.00	92.57	12.70	85.36	ND	22.73	57.14	42.26

The results in Tab. 11 show that better DOC and Fe removal was obtained with higher doses of U5000 and without pre-chlorination. Significant Mn removal was only obtained with pre-chlorination at pH 9.8 and with a higher dose of U5000. Turbidity removal was poor at low pH values.

DOC and Fe concentrations increased since November 1995 to reach peak values during the first three months in 1996. The results of jar tests which demonstrate the effect of pH, oxidant and coagulant concentration on the removal of Fe, chlorophyll-a and SAC under these conditions are shown in Tab. 11. The Fe concentration in the raw water was 3249 µg/l and the SAC was 28.8m^{-1}. The results are from filtered samples.

Table 12 : Jar Tests to demonstrate the effect of pH, chlorine and coagulant concentration on the removal of iron, chlorophyll-a and SAC

pH	Fe (mg/l)	U5000 (mg/l)	Chlorine (mg/l)	Turbidity (%)	Chlorophyll a (%)	Fe (Total) (%)	SAC (%)
7.70	7.00	0	4.2	41.00	89.90	71.1	6.00
7.80	1.18	12	4.2	80.40	89.90	87.3	20.16
8.85	7.00	0	4.2	50.00		69.0	21.10
8.70	1.18	12	4.2	89.00		81.4	24.30
9.78	7.00	0	4.2	83.90	91.19	76.5	14.30
9.76	1.18	12	4.2	90.61	94.90	90.0	25.20
7.78	7.00	0	0.0	40.65	25.35	53.1	6.00
7.80	1.18	12	0.0	91.23	59.23	99.0	54.80
8.85	7.00	0	0.0	41.10		54.3	18.00
8.70	1.18	12	0.0	90.94		99.1	52.80
9.78	7.00	0	0.0	42.06	57.04	68.1	34.80
9.76	1.18	12	0.0	92.00	68.90	99.6	55.50

From the results in Tab. 12 it is clear that better reduction in Fe were obtained with U5000 as primary coagulant when no pre-chlorination was performed. The removal of chlorophyll-a, however, was enhanced by pre-chlorination.

DISCUSSION

Fig. 10 shows that chemical cost on the plant had increased significantly since 1993. The increasing concentrations of iron, manganese and organics present in the raw water, are most likely to be the cause of the escalating costs. It is also

evident from Figs 1-3 and fig. 10 that costs follow the pattern of the occurrence of these determinants in the raw water. Poly-electrolyte concentrations of 10 mg/l and more had to be dosed to effectively treat the water when high levels of iron and DOC were present. This caused an increasing treatment cost.

Turbidity and iron, manganese and DOC levels in the river increased during periods of rain. Increases in EC, hardness and alkalinity during winter are a known seasonal pattern. Changes in rainfall and temperature patterns must have contributed to the annual difference in peak occurrences and consequently to various treatment problems (Figs 43 and 44).

Fig. 10 shows that the raw water was much more susceptible to conventional treatment processes during winter. The conclusion can be drawn from these graphs that rainfall during summer months most probably contributed to the increasing levels of contaminants such as iron, manganese and DOC in the river (Fig. 44).

The lower $FeCl_3$ dosing concentrations needed with increasing raw water calcium concentrations, probably relates to the findings of Bernhardt and co-workers (1984). The authors described the enhancement of flocculation by calcium. Fig. 45a shows that no clear relationship exists between dosing concentrations and raw water calcium concentrations for the last four months of 1993.

This was due to various treatment options which had to be implemented during that period, as result of, at that stage, unknown water quality problems. High turbidities, coinciding with low calcium values, were also treated with lower $FeCl_3$ doses plus U5000.

By further analysing the data for the first eight months, as illustrated in Fig. 45b, it became clear that by excluding raw water pH values below 7,5, there was a definite downward trend in $FeCl_3$ required as the calcium concentration in the raw water increased (Figs 46a and 46b).

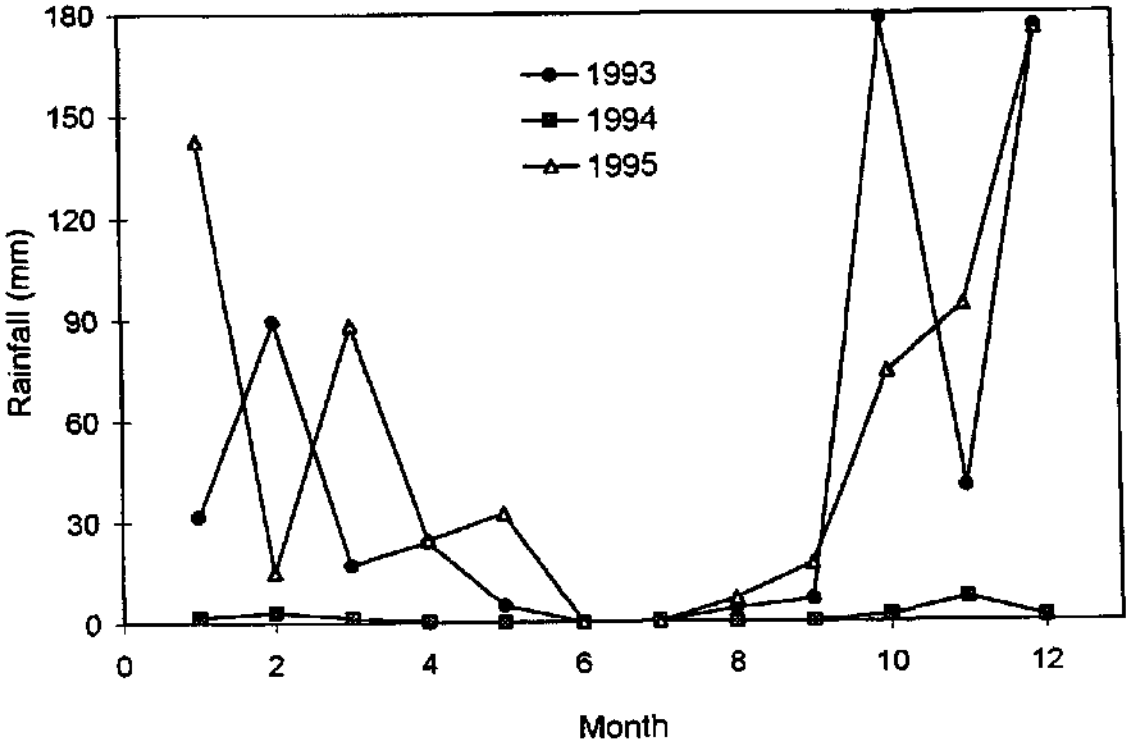

Figure 43: Monthly average rainfall - 1993 to 1995

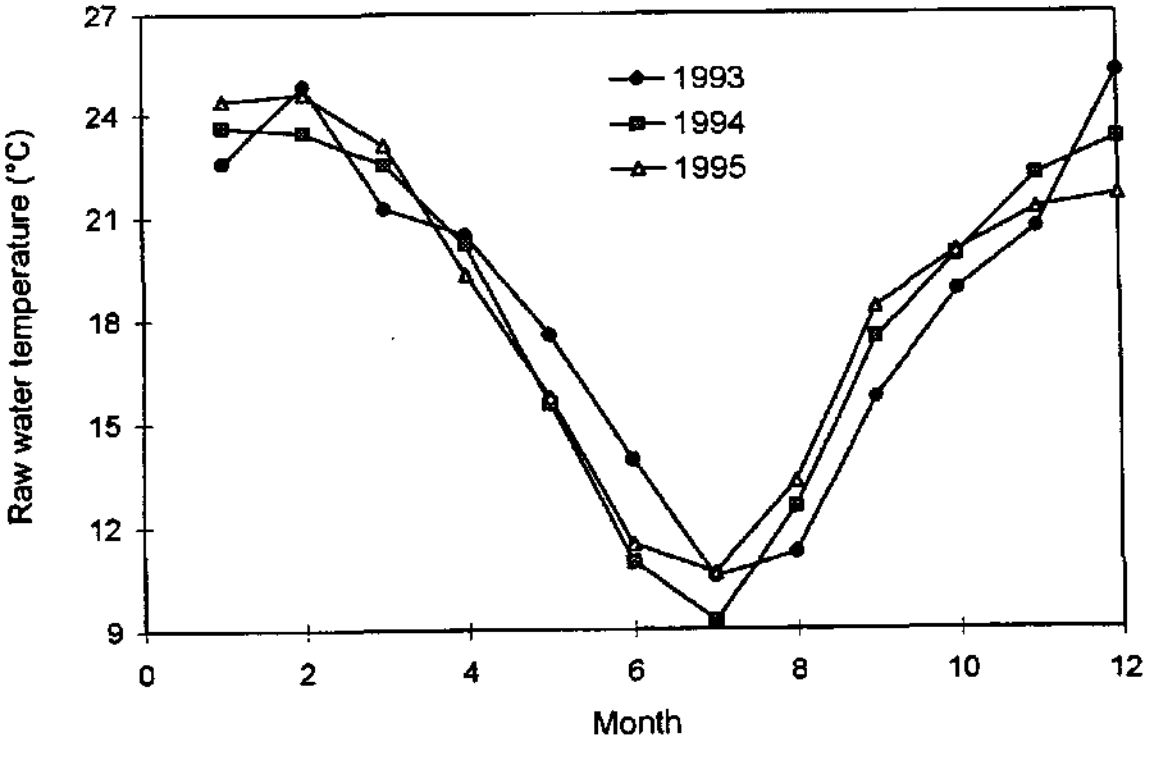

Figure 44: Monthly average raw water temperature - 1993 to 1995

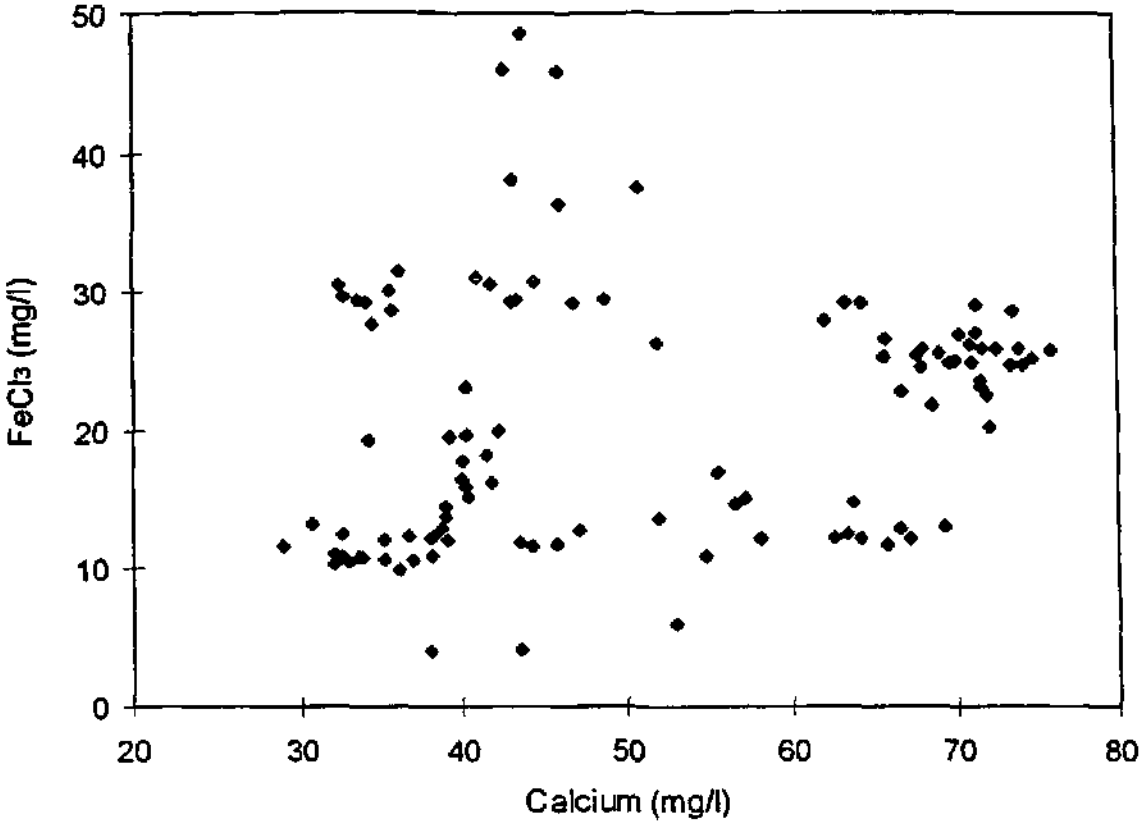

Figure 45a: The relationship between raw water calcium concentration and iron dosing concentrations for the period January 1993 to August 1993

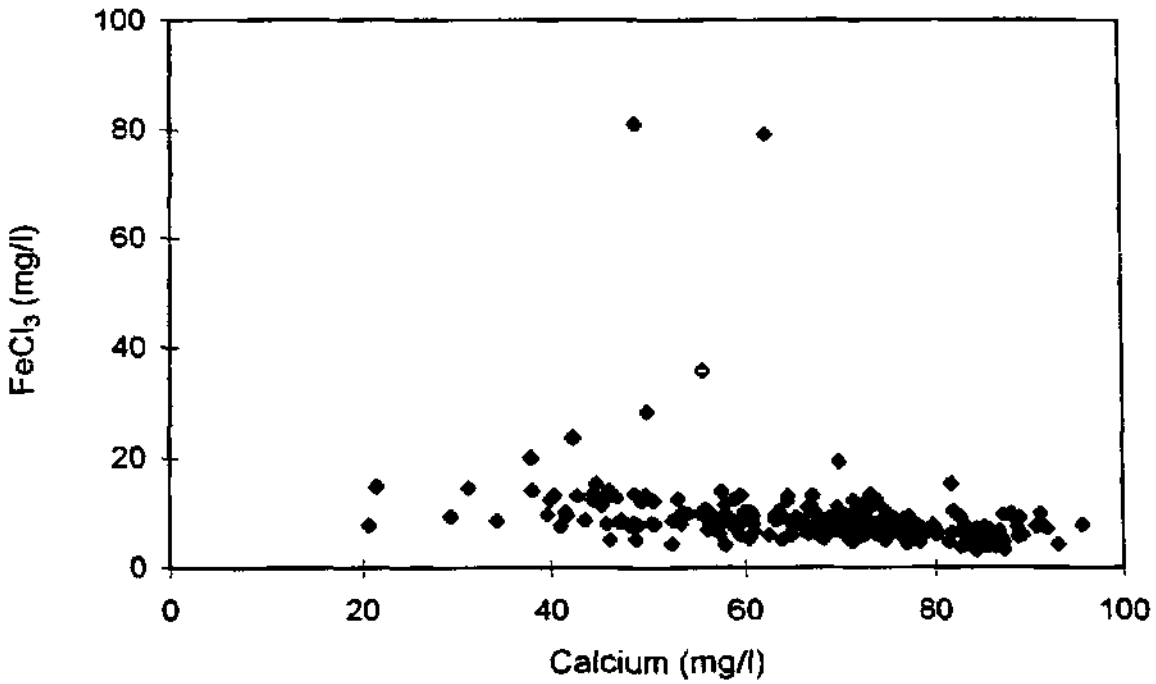

Figure 45b: The relationship between raw water calcium concentration and iron dosing concentrations for the period September 1993 to December 1993

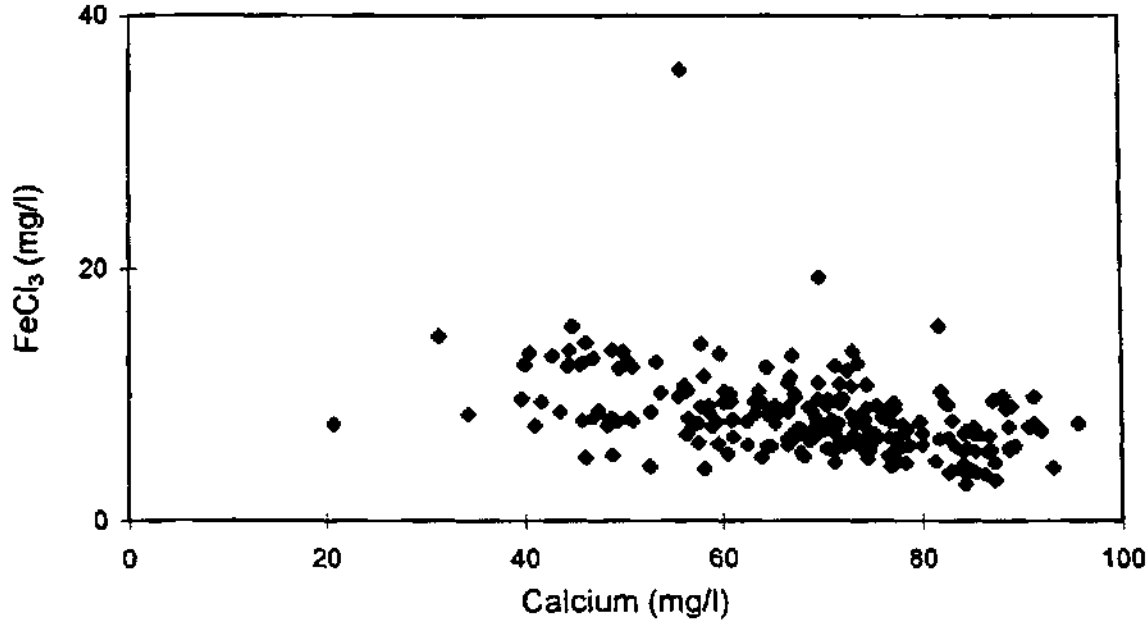

Figure 46a: The relation between raw water calcium concentration and $FeCl_3$ dosing concentrations for the period January 1993 to August 1993 with pH - values bigger and equal to 7.5

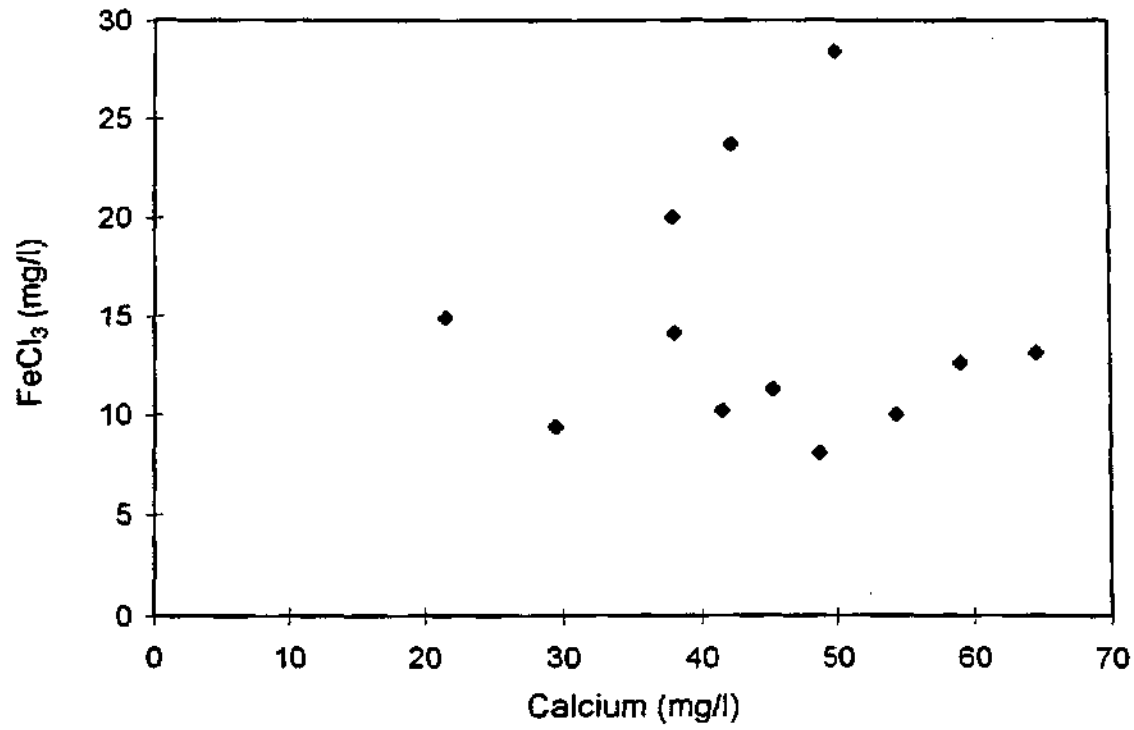

Figure 46b: The relation between raw water calcium concentrations and iron dosing concentrations for the period January 1993 to August 1993 with pH-values smaller than 7.5

High turbidities in the raw water, which coincided with low pH values and low calcium levels, were treated with U5000, thus resulting in lower $FeCl_3$

concentrations being used. The experimental data shows that $FeCl_3$ dosages were not always in direct correlation with calcium levels in the raw water. The use of the high lime process and U5000 for certain periods caused the non-correlation's.

Figs 47a and 47b show that the high poly-electrolyte dosing concentrations, were not always related to high turbidities.

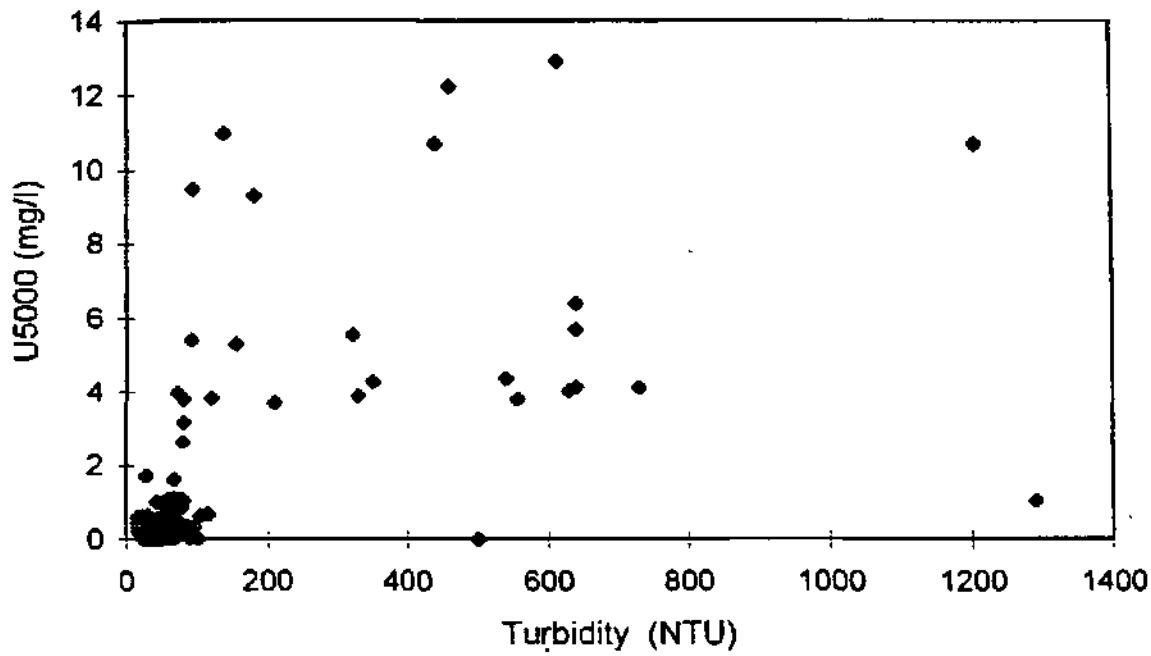

Figure 47a: The relationship between raw water turbidity and U5000 dosing concentrations for the period January 1993 to August 1993

Turbidities very seldom exceeded 100 NTU during the last four months of 1993. U5000, however, had to be dosed. This coincided with the other non-correlations due to water quality problems (Fig. 45a).

High poly-electrolyte dosing concentrations were used in modules 2 and 3 from 4 January to 15 February 1994 due to raw water turbidities of between 200 and 250 NTU, DOC concentrations of 15 to 25 mg/l and iron concentrations of 1500 µg/l.

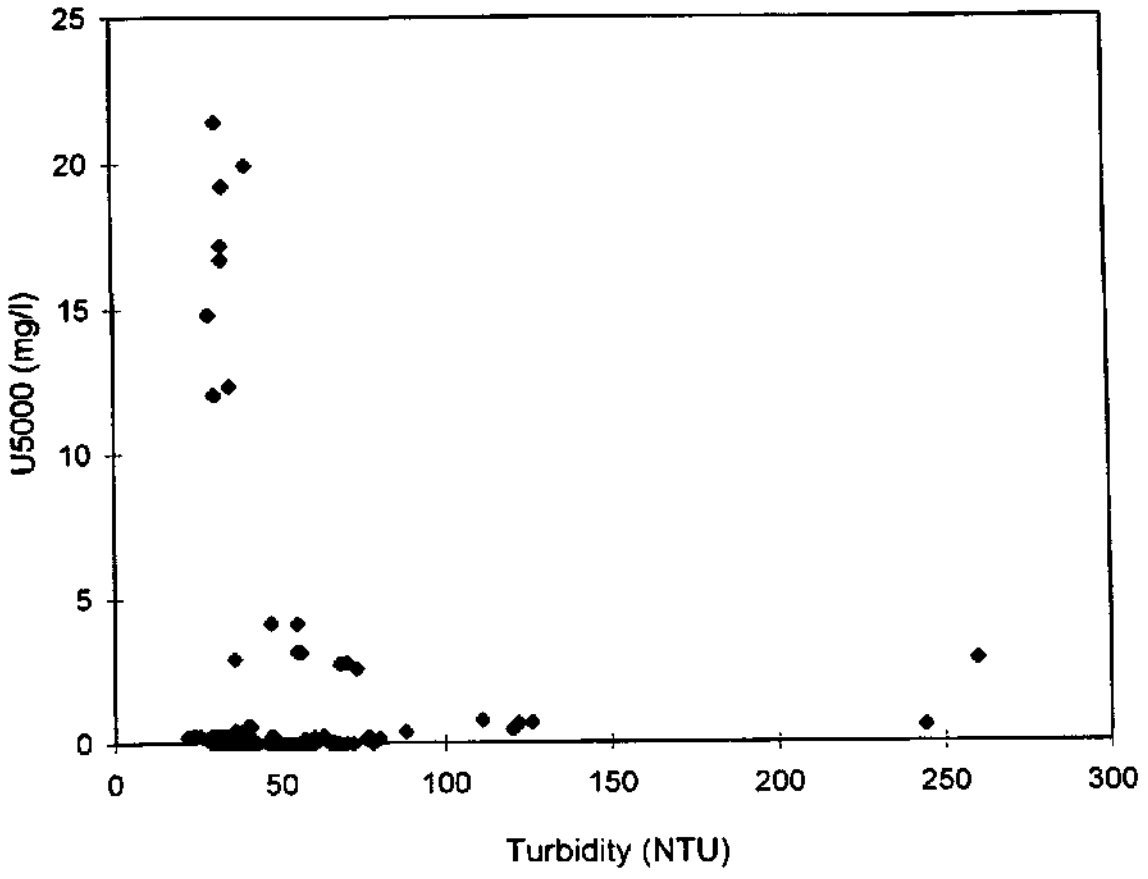

Figure 47b: The relationship between raw water turbidity and U5000 dosing concentrations for the period September 1993 to December 1993.

It is evident from results obtained that, for most of the time contaminants relevant to this study were removed better by the high lime process except for the removal of aluminium and chlorophyll-a. The low turbidity of the water after sedimentation caused filamentous algal growth in the secondary sedimentation tanks in Module 2, which could have contributed to higher chlorophyll-a levels obtained in the high lime process. The positive effect of pre-chlorination on the removal of chlorophyll-a, as illustrated in Tab. 11, could possibly also have contributed to the poorer removal of chlorophyll-a in the high lime process where no pre-chlorination was performed. Although protein was removed better in the high lime process when compared with ferric chloride plus U5000, slightly better reduction of chlorophyll-a was obtained with U5000. This is in contradiction with the findings of Al-Layla and Middlebrooks (1974) stating that algal organic matter is composed mainly of protein. Chlorophyll-a reduction were > 96% in both modules and an explanation can probably be that the protein originating from algal organic matter was in any

case removed efficiently in both modules. The fraction of protein which was removed better in the high lime process could thus have been from a different source.

Aluminium is least soluble at a pH of about 6,2 (AWWA), most probably the reason for the weaker removal by the high lime process. It must be pointed out that the difference between the two modules, in reduction of aluminium, was significant only after sand filtration. This aspect was not investigated further.

A significant difference in DOC removal was observed between the high lime process and the ferric chloride process. DOC levels in the raw water never exceeded 9,0 mg/l during this period. The absence of pre-chlorination in the high lime process could possibly also have played a positive role in the removal of DOC (Yen and Huang, 1993). In Scandinavian countries the use of tertiary lime flocculation is very popular for raw wastewater treatment (Rebhun and Lurie, 1993). The removal of colloidal matter and dissolved organic macromolecules (DOM) are effected only when the pH is raised to above 10,5 in order to work in the range of $Mg(OH)_2$ (s) precipitation. Adsorptive coagulation is favoured and it might be assumed, according to Leentvaar and Rebhun (1992), and as described by Rebhun and Lurie (1993), that the $Mg(OH^+)_{aq}$ complex reacts with the DOM and the product adsorbs on the $Mg(OH)_2$ (s).

Bernhardt *et al.*, (1986) described the addition of calcium to reduce the impairment of flocculation which can result in turbidities not being lowered to acceptable levels by sand filtration in addition to problems due to high residual iron in the filtrate. According to these authors the flocculant cations (Fe^{3+} in the case of the Balkfontein plant) react with the EOM to form polynuclear mixed ligand complexes and/or EOM reacts with the hydrolytically formed trivalent metal hydroxo-complexes and oxide hydroxides to yield surface complexes. The formation of these ligand complexes hinders the formation of positively charged iron hydroxo- complexes necessary for destabilisation. The complexes are soluble or in colloidal form which passes through the filter. This results in an increasing residual iron content in the filtrate.

The formation of coagulant - organic matter complexes is also described by abika *et al.*, (1991). By adding Ca^{++} ions the positive charge of the iron hydroxo-complexes increases as a result of the attachment of the ions to the negatively charged polynuclear iron hydroxo complexes. Calcium ions also promote the adsorption of negatively charged EOM macromolecules to negatively charged FeOOH surfaces and to negatively charged inorganic particles, improving the removal of macromolecules and particulate matter.

When using $FeCl_3$ as the only coagulant, lime dosing, and consequently the increase of pH, did not always result in acceptable final residual iron during the experimental period. Bernhardt *et al.* (1986) suggested the addition of approximately 2mmol/l of Ca^{++} when flocculation is carried out at pH above the iso-electrical potential. At Balkfontein calcium ions were always added in the form of $Ca(OH)_2$ to increase the coagulation pH. Under these alkaline conditions the concentration of Ca^{++} was apparently not always sufficient to enhance flocculation in the presence of EOM. Specific attention was not given to this aspect on the plant, which could have attributed to inconsistency in results obtained from the same process at different times. Jar tests were conducted but the constantly changing raw water quality and the lack of detailed organic analyses made it impossible to find proper explanations for the variations experienced. The importance of pH in the reduction of iron was however confirmed by jar tests and is illustrated in Figures 40 and 48. Lime was used for pH adjustment and the role of Ca^{++} must be taken into consideration. The good results obtained with the high lime process could probably be a result of the presence of the high concentration of calcium ions under alkaline conditions.

When $FeCl_3$ was used in jar tests, a slightly better removal (32 %) of DOC was obtained with jar tests at pH 7,5 than at pH 9,1 (23 %). At a pH of 10,3 an increase in reduction was observed (28 %). This could indicate that the removal of organic substances varies within certain pH-ranges, which could be the result of the impact of Ca^{++} (Bernhardt *et al.*, 1986), or as the result of the relationship between the effectiveness of chlorine and pH. The increase in reduction at pH > 10,3 can be explained in terms of the adsorption theory according to Leentvaar

and Rebhun (1992). Tab. 10 and 11 show the same pattern for different pH values.

When using U5000 as secondary coagulant in Module 3 and compared with the high lime process, humic- and fulvic acids, protein and carbohydrates were, however, removed better in Module 3 than in the high lime process (Figs 36-39) during the period when increasing DOC concentrations were observed in the raw water.The increasing DOC concentrations also coincided with the poorer removal of iron in the high lime process.

Rebhun and Lurie (1993) indicated that the inhibition of the formation of separable $Mg(OH)_2(s)$ precipitate at pH above 10,5, is inhibited in the presence of DOM. A higher iron activity product is thus required to obtain a good precipitate in the presence of DOM. Increasing DOC concentrations in the raw water during the period 95/08/20 tot 95/10/03 could possibly be responsible for the inhibition of $Mg(OH)_2(s)$ precipitate formation and thus the weaker reduction in DOC over this period. Reduction were in general low. It must be pointed out that the dominant algal population in the raw water for the first part of this second evaluation of the high lime process differed from the population during the last part. Centric diatoms were found to be dominant during the last part and this possibly explains the better performance of $FeCl_3$ plus U5000 in removing organic substances and iron during this period. Throughout this study it was found that U5000 had to be used when centric diatoms were dominant. The interaction of EOM's from aquatic organisms with metal ions in natural water is described by Lapin & Yedigarova (1990).

Total alkalinity values of 110-120 mg/l and average pH values of 8,5 were measured in the raw water during the period 20 August 1995 to 3 October 1995 compared to average pH values of 9,5 and average alkalinities of 100 mg/l measured during the period 30 March 1994 to 19 July 1994. This probably explains why lime dosing concentrations of 150-250 mg/l were needed during the 1995 evaluation of the high lime process for obtaining the required pH of 11,3.

During 1993 high poly-electrolyte concentrations were applied to deal with problems experienced with the removal of iron and turbidity. Jar tests performed with $FeCl_3$ during the presence of DOC levels exceeding 10 mg/l, sometimes produced a gelatine like slimy floc. Bernhardt *et al.*, (1986) mentioned the disturbance of flocculation by EOM as result of a mechanism whereby the particle is enclosed in a gel due to molecular interlacing and co-precipitation together with the metal hydrolysates used as flocculant. In periods during 1994 and 1995 iron could not be removed below 100 µg/l by using $FeCl_3$ as the only coagulant even at pH values of approximately 9,6. Lapin and Yedigarova (1990) emphasised the fact that EOM (also from blue-green algae) effectively binds and retains Fe(111) when pH $\geq$ 8. The problems experienced with iron removal could be as result of these bindings at pH values of this order measured in the raw water source.

According to Bernhardt and co-writers sufficient calcium ions should be added and Rebhun and Lurie (1993) described the neccessity of a higher ione activity product for the formation of a $Mg(OH)_2$ (s) precipitate in the presence of DOC. The indication is thus that poly-electrolyte had to be used because the process as described by the various authors were not applied in the Balkfontein plant. The increase of calcium ions in the form of lime, were not practical nor cost effective and it was thus not concentrated on these options during laboratory bench work. Fig. 51 shows iron and manganese removals of 90% at pH values of 10,5. The operating pH in the high lime process is 11,4 and iron dosing concentrations are <1 mg/l as Fe.

The use of poly-electolytes for the removal of organic substances is described in literature and correlates with findings in the laboratory and in the plant, where the addition of U5000 presented better results than only $FeCl_3$ in the removal of fulvic- and humic acids, carbohydrates and chlorophyll-a. Differences observed, as can be seen in Fig. 32 and 33, are related to temperature. Protein was removed better with $FeCl_3$ at temperatures between 24,5°C and 16,5°C. Between 16°C and 12°C better results were obtained with the addition of U5000. At temperatures

below 12°C $FeCl_3$, without U5000, performed better. The removal of humic acids was better at the temperatures below 16°C when only $FeCl_3$ as used. The addition of U5000 contributed to the better removal of humic acids at temperatures above 16°C.

According to Rebhun and Lurie (1993) cationic organic poly-electrolytes can act as primary coagulants for humic substances. The authors found doses of about 15 mg/l to be effective in the removal of organic substances. At the Balkfontein plant concentrations of 10 mg/l were found to be efficient for iron removal for most of the time. During times when DOC concentrations were between 15 and 40 mg/l, U5000 doses had to be increased to an average of 18 mg/l. Destabilisation takes place by means of charge neutralisation and it is important that additional flocculant should be dosed at iso-electric point in order to yield good flocculation and form settleable flocs. The lack of detailed analyses with respect to DOC and Fe adversely affected decision making in choosing a process. The evaluation of the high lime process during the presence of unusually high levels of DOC in the raw water could not be implemented due to the fact that it was not practically possible to raise the pH to 11,4 during this period. This could possibly be due to the low pH values measured in the raw water at that time.

Properties of flocs with organic matter are different from mineral particle flocs. They are fluffy and more fragile (Rebhun and Lurie 1993), and the floc breakup constant for humic flocs were found to be two times higher than for clay mineral flocs. The poly-electrolyte possibly served as a strengthening floc aid under these conditions.

Jiang *et al.*, (1993) found a prepolymerised metal salt coagulant (polyferric sulphate) to be superior to other metal salts in the removal of algae and algae-derived organic matter. The superior performance is partly attributable to charge effects. These authors also found that greater coagulation performance was achieved at doses above that required for colloid charge neutralisation. The

effective use of cationic poly-electrolytes for algal flocculation is also mentioned by Al-Layla and Middlebrooks (1974).

During the experimental period the high levels of iron in the final water did, however, not always coincide with high turbidities in the final water as was the case during 1993. In both cases, however, poly-electrolyte was dosed in order to reduce iron concentrations to acceptable levels. The removal of iron, down to acceptable levels, was obtained in jar tests where U5000 was used with $FeCl_3$, as either primary or secondary coagulant. U5000 was then used successfully on the plant. The problem with the removal of Fe occurred again during January and February 1995 and then again from September 1995 up to early 1996. Diatoms was the dominant algal group during this time. The benefit of the use of a poly-electrolyte in the removal of chlorophyll-a, DOC, same organic fractions and iron was evident from the better results obtained in the plant when using U5000 during the presence of high DOC and iron levels in the raw water. From the results obtained at the Balkfontein plant and from jar tests conducted, it is clear that $FeCl_3$, as dosed in the plant, did not present optimal flocculation for certain periods of the year. These periods coincide with the presence of diatoms in the raw water. DOC concentrations were also high during these periods. Concentrations exceeded 20 mg/l at times to reach peak values of 38 mg/l.

Organic complexation of iron was possibly the reason for this poor removal. Knocke *et al.* (1993) mentioned that many authors have stated that a high degree of complexation may occur when significant DOC is present in conjuction with soluble iron. Knocke *et al.* (1992) described the impact of DOC on the removal of iron and concluded that the lack of observed iron removal when significant DOC is present, is related to the interaction of the iron and DOC and is not due to the competitive oxidant demand of the organic matter. The authors indicated that when iron was complexed by higher molecular weight organic species, efficient iron removal was observed at chemical dosing concentrations which optimised DOC removal. This is in agreement with jar tests conducted at the Balkfontein laboratory (Tab. 10) and findings on the plant during times of high DOC levels in

the raw water where effective iron removals were obtained coinciding with better DOC removals.

Knocke and co-workers described the inefficient removal of iron by using chlorine when significant amounts of DOC were present. They found free chlorine to be a very inefficient oxidant for the removal of complexed iron, except when oxalate was the source of DOC. Jar tests confirmed the findings of these authors (Tab. 11). Better reduction in total iron and DOC were obtained with high doses of U5000 (12mg/l) and no pre-chlorination when high concentration of organic matter were present. DOC concentrations measured in the plant varied between 20 and 40 mg/l. The authors also stated that the oxidation of iron by O_2 is also retarded in the presence of humic and tannic acids due to the forming of complexes. Whether oxidant addition will prove to be of any advantage is possible to assess, only when appropriate speciation of iron is done.

Pre-chlorination was performed in the plant almost throughout the experimental period in order to enhance the removal of Mn and chlorophyll-a. It was therefore not possible to properly evaluate the role of pre-chlorination in the removal of DOC and Fe. It is not possible to conclude from jar tests and a short evaluation period on the plant that pre-chlorination is in fact detrimental to the removal of DOC and Fe and all conditions.

Jar tests conducted in the laboratory (Tables 10 and 11) indicated that better removal of organic substances is obtained when no pre-chlorination was performed. This could be one of the reasons for the better reduction obtained by the high lime process, as no pre-chlorination was done during this process. The effect of pre-chlorination on DOC removal was also tested in the plant by running both modules on $FeCl_3$ plus U5000, the only difference being that no chlorine was added to Module 2. Better DOC reduction was obtained in Module 2. DOC values exceeding 12 mg/l were measured in the plant. Jar tests showed most of the time that pre-chlorination had some adverse effect on DOC removal. Yeh and Huang (1993) indicated that the removal of hydrophilic fractions are limited and that pre-

chlorination probably transforms some organics from other fractions into hydrophilic-neutral fractions.

From the middle of October 1995 high turbidities and high levels of iron and DOC in the raw water were the reasons for poly-electrolyte dosing concentrations to be increased. Abnormal rainfall, causing flood conditions, must have contributed to the high levels of iron and DOC measured in the raw water. Centric diatoms were dominant.

By analysing the results in Tab.10 it is clear that in order to obtain final manganese concentrations in compliance with the guidelines, the coagulation pH had to be raised to at least 9,6 and an oxidant had to be used (Fig. 48).The higher poly electrolyte dosing concentration enhanced the removal of dissolved manganese at a pH-value of 9,8 without the use of an oxidant. (Tab. 10)

When U5000 was used in dosing concentrations of 10 mg/l and at pH > 9,6, good removal of iron was obtained. When optimising for pH in the reduction of iron, it was found that the poorest removal occurred at a pH value of approxamitally 9,0. Effective iron removal was possible without pre-chlorination (Fig. 49).

The good removals of iron obtained at pH values of 7,5 coincided with the better reduction in DOC at this pH (Fig. 51). The best reduction in DOC was obtained with the high dose of U5000 and without pre-chlorination. This confirms the adverse effects of oxidation on DOC removal as described in literature.

Results obtained in the laboratory and in the plant showed the adverse effects of chlorination on DOC removal. This possibly explains the problems experienced with the removal of iron in the presence of high DOC and manganese and with $FeCl_3$ as coagulant. It was thus necessary to resolve to other treatment options under such conditions.

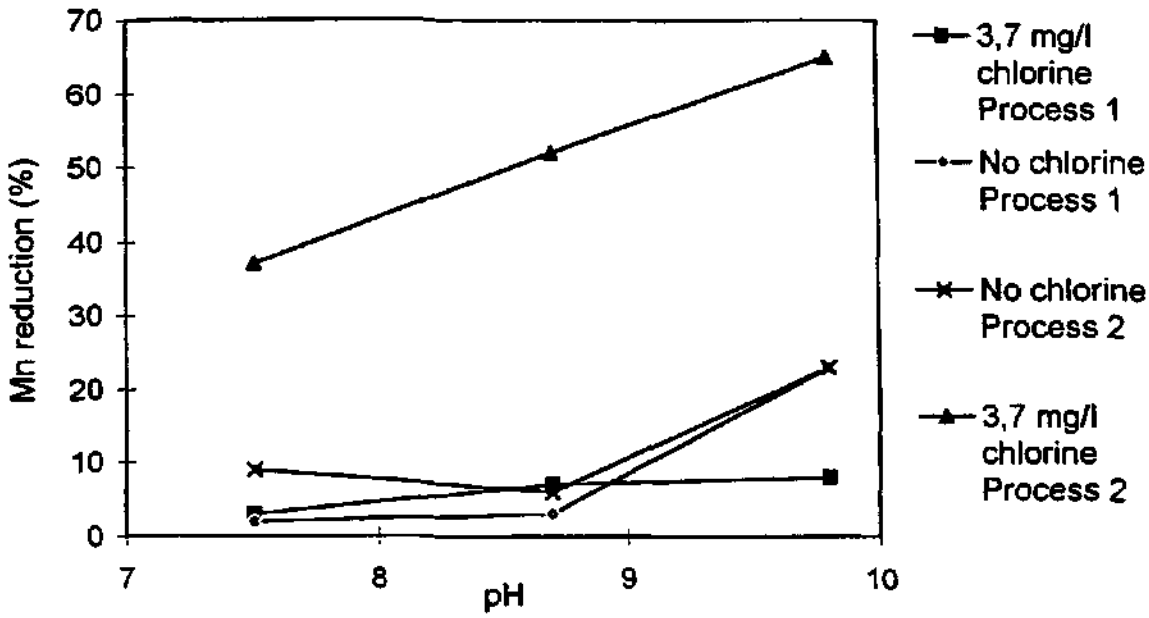

Figure 48: Mn reduction vs pH

Process 1: Mn 2,2 mg/l; U5000 0,5 mg/l
Process 2: Mn 0,59 mg/l; U5000 10 mg/l

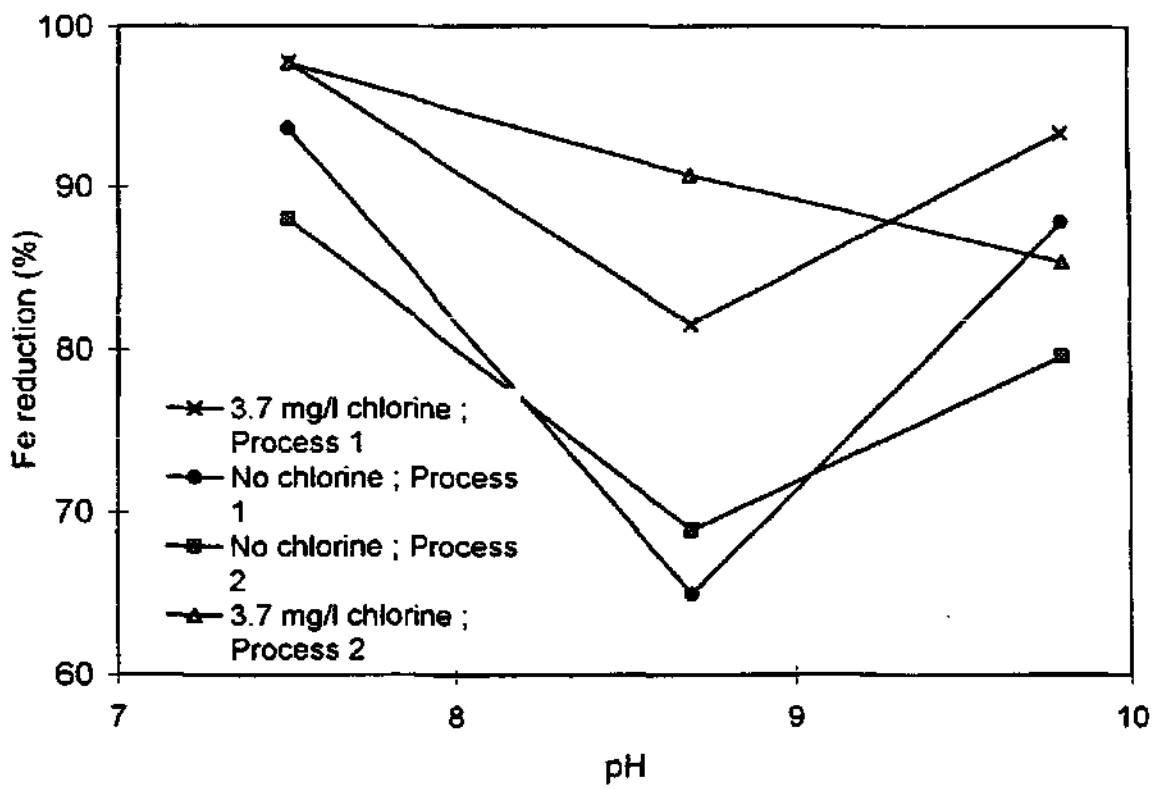

Figure 49: Fe reduction vs pH
Process 1: Fe = 2,2 mg/l; U5000 = 0,5 mg/l
Process 2: Fe = 0,59 mg/l; U5000 = 10 mg/l

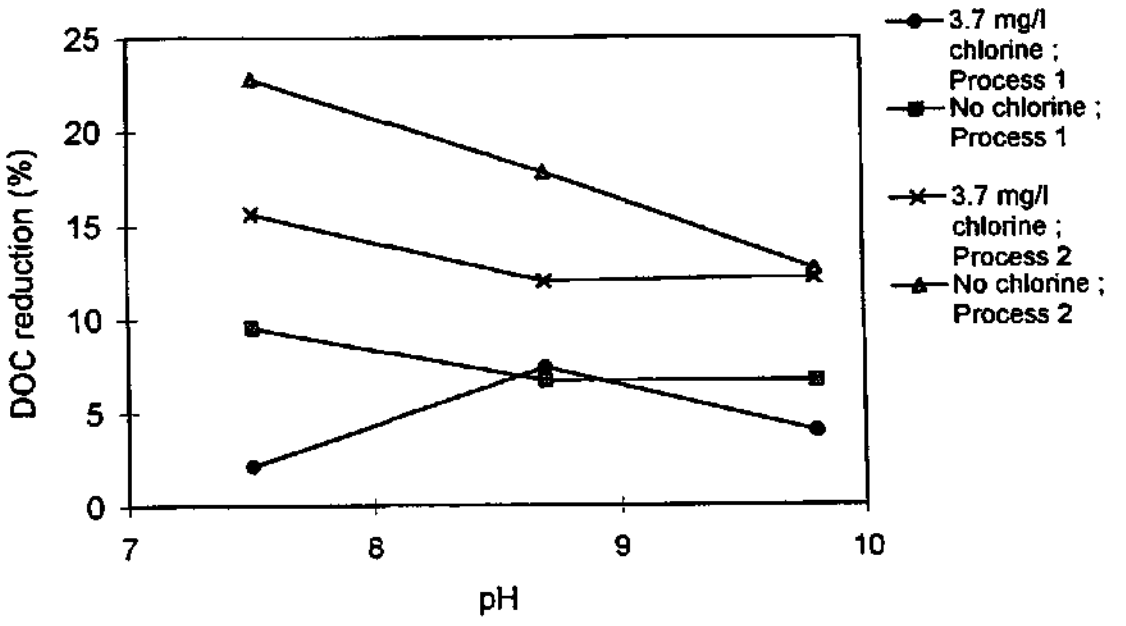

Figure 50: DOC reduction vs pH

Process 1: Fe = 2,2 mg/l; U5000 - 0,5 mg/l
Process 2: Fe = 0,59 mg/l U5000 = 10 mg/l

The best reduction, however, was obtained by using the high lime process (without pre-chlorination) when raw water DOC levels were below 10 mg/l. From experience on the plant, the presence of DOC concentrations exceeding 10 mg/l mostly resulted in the use of U5000 for the efficient removal of iron. These conditions often times coincided with diatoms being abundant in the raw water.

It must, however, be kept in mind that jar tests results are only applicable to conditions at the time of analyses. Jar test findings were practised in the plant. It was clear from results in the plant that iron reduction, with $FeCl_3$ as only coagulant, were only effective at pH values ≥ 9,6. The presence of high concentrations of DOC in the raw water at times had a negative influance on the removal of iron. The effect of pH 7,5 on DOC and iron reduction was not evaluated on the plant.

Lower concentrations of poly-electrolyte with or without pre-chlorination did not work as effectively as the higher dosing concentrations (e.g. 10 mg/l). Good reduction in iron and manganese concentrations were also obtained with a stabilised aluminium based product, even without pre-chlorination. These finding

were successfully evaluated on the plant. Knocke and co-writers (1994) stated that DOC adsorps onto ferric hydroxide colloids, stabilises them and hinders their ability to aggregate into larger particles for removal by sedimentation. Some other form of coagulation is necessary to remove these colloids and this is possibly also a reason why poly-electrolyte and alum perform better in the removal of organic matter under specific conditions.

The removal efficiency of iron by oxidation could be influenced by pH as well as DOC to Fe(11) ratio (Knocke *et al.*, 1994). Molecular weight distribution and/or the different fractions of DOC and iron species present were not known. This makes it impossible to explain these different findings. According to Knocke *et al.*, (1994), it is thus important to determine the DOC concentration in each of the particulate, colloidal and soluble iron fraction in the raw water to provide insight into how DOC might be affecting particle formation. The authors stated that the presence of DOC affects the iron speciation obtained by the addition of an oxidant. The importance of characterising DOC in order to optimise the removal thereof is also mentioned by Sinsabaugh and co-workers (1986). The authors indicated that the efficacy of conventional treatment for organic removal depends on the nature of the organic material itself. Removal may directly be affected by size, charge and solubility characteristics. The fate of DOC and to a certain extent, iron, in a treatment process can thus not be explained properly without determining the types of organic matter. The unpredictable behaviour of these contaminants, what seemed to be inconsistencies or non-correlation's, was probably due to the fact that specific information with respect to the different fractions of organic matter and iron was not available and therefore could not be explained.

The DAFF process performed better than the control line in removing Al, Fe and chlorophyll-a. DOC removal in the control line was better (Fig. 27). When using U5000, however, as a secondary coagulant in the DAFF process, DOC removal was better than in the control line where only $FeCl_3$ was used. The removal of chlorophyll-a in the control line compared well with the removal in the DAFF process on two occasions when poly-electrolyte had to be used on both

modules. It seems that U5000, as secondary coagulant, for these specific periods, enhanced the removal of DOC and chlorophyll-a. Al-Layla and Middlebrooks (1974) stated that algal organic matter is composed mainly of protein, which possibly explains the better reduction of both chlorophyll-a and protein by the DAFF process with U5000 as secondary coagulant.

Carbohydrates and protein are classified under the non-humic fraction of natural organic matter (Owen *et al.*, 1995) and are less hydrophobic in character. These authors mentioned that a significant percentage of disinfection by-products can be formed from the non-humic fraction. The poor removal of carbohydrates could thus have contributed to the higher THM values in the DAFF process (Fig. 28). Organic matter excreted by phytoplankton and capable of complexing reactions with heavy metal ions is described by Lapin and Yedigarova (1990). The removal or non-removal of certain algal species by different treatment processes could be of significance when trying to understand the efficiency of the different processes in the removal of the different fractions of organic material. The role of oxidants in changing humic fractions into non-humic fractions (Owen *et al.*, 1995 and Yeh and Huang, 1993) must also be kept in mind when evaluating the DAFF process where overflow from primary sedimentation is chlorinated before entering the process. The higher THM values obtained in the DAFF process (Fig. 28) is most probably the result of chlorination after sedimentation.

The influence of temperature on the removal of iron, chlorophyll-a and DOC was investigated. No correlation between the reduction of chlorophyll-a and temperature was observed statistically in all modules as can be seen from Fig. 31 for Module 3. Jar tests were conducted to confirm this and chlorophyll-a concentrations were used as an indication of the removal of algae. No correlation could be found. The findings differ from the findings of Al-Layla and Middlebrooks (1974). These authors demonstrated that the removal of algae was less efficient at higher temperatures and at longer settling times. Pre-chlorination performed at the Balkfontein plant is the main reason for chlorophyll-a reduction of greater than 95 % for most of the time and the influence of temperature is thus not observed. Jar tests were also not conducted at high temperatures. In Module 2, both the

high lime process and when U5000 was used, a slight downward trend in DOC reduction occurred together with increasing temperatures. The reduction of total iron in Module 3 however, improved with increasing temperature to reach almost 100 % reduction at 20°C (Fig. 21). DOC removal in Module 3 showed a slight negative correlation with increasing temperature up to 19°C. The analyses of reduction in organic substances showed a downward trend in the reduction of fulvic and humic adics with temperatures increasing to approximately 16°C.

Jar tests confirmed some of these findings (Tab. 8). With $FeCl_3$ as coagulant and at a pH of 9,0, results from the laboratory tests showed an increase in iron and manganese reduction together with increasing temperatures up to approximately 17°C-18°C, whereafter increasing temperatures resulted in decreasing reduction (Figs 39 and 40). Increasing temperatures had no significant effect on the dissolved iron. The decrease in the removal of organic substances together with increasing coagulation temperatures was also confirmed by laboratory experiments. The increases in total iron and manganese values, after sedimentation at temperatures of 18°C and higher are probably because of particulate material being carried to the surface as a result of solubility of air in water being temperature dependant.

The role of electrical conductivity on iron reduction were investigated. When evaluating all the experimental data for Module 3, fair to excellent iron reduction was obtained at conductivity's below 80 mS/m. At conductivity's above 80 mS/m iron reduction varied from bad to excellent (40 - 100%) and did not seem to be temperature related. Temperatures varied from 12°C to 24°C. (Fig. 51).

Results from this study showed that the use of U5000 improved the removal of aluminium by sedimentation. In the control line good reduction was obtained mostly after sand filtration. This can be seen from results throughout the experimental period. More laboratory work needs to be done on the removal of aluminium.

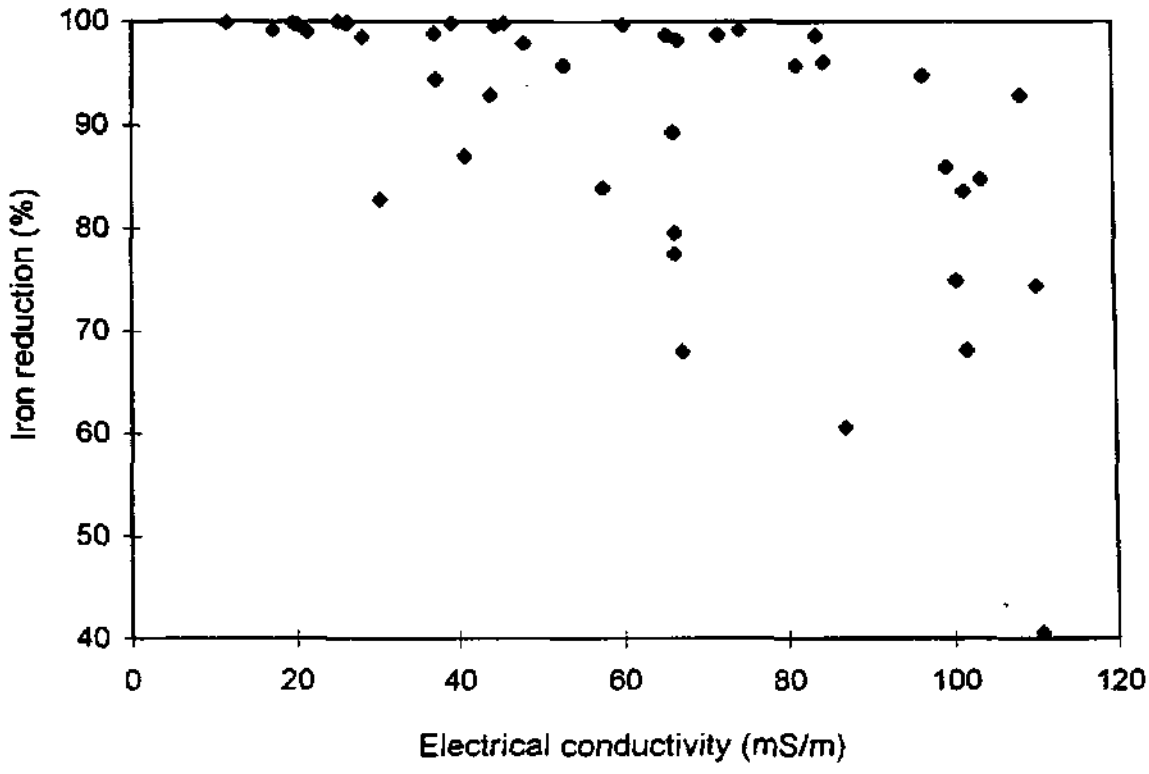

Figure 51: The relationship between raw water conductivity and iron reduction in Module 3

Figs 52-54 show the chemical dosing costs in c/kl for the different modules. It is evident that the high lime process is much more expensive than any of the other processes. Good results were obtained at a lower cost by using poly-electrolyte (Figs 53 and 54).

The increasing chemical cost is mainly due to the increasing concentrations of iron, manganese and organic matter in the source water. These contaminants were efficiently removed by using U5000 at lower costs. High turbidities, iron and DOC in the raw water from October 1995 onwards, were responsible for the sharp increase in costs as shown in Fig. 55.

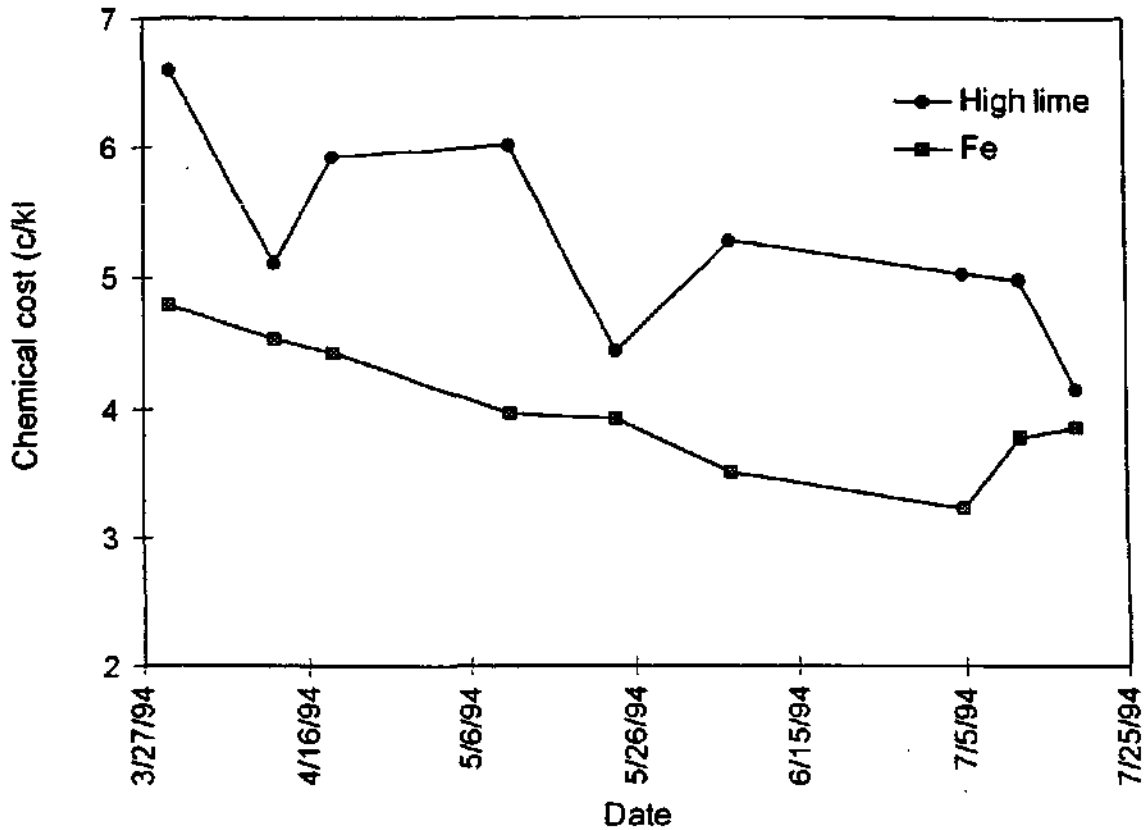

Figure 52: Chemical cost

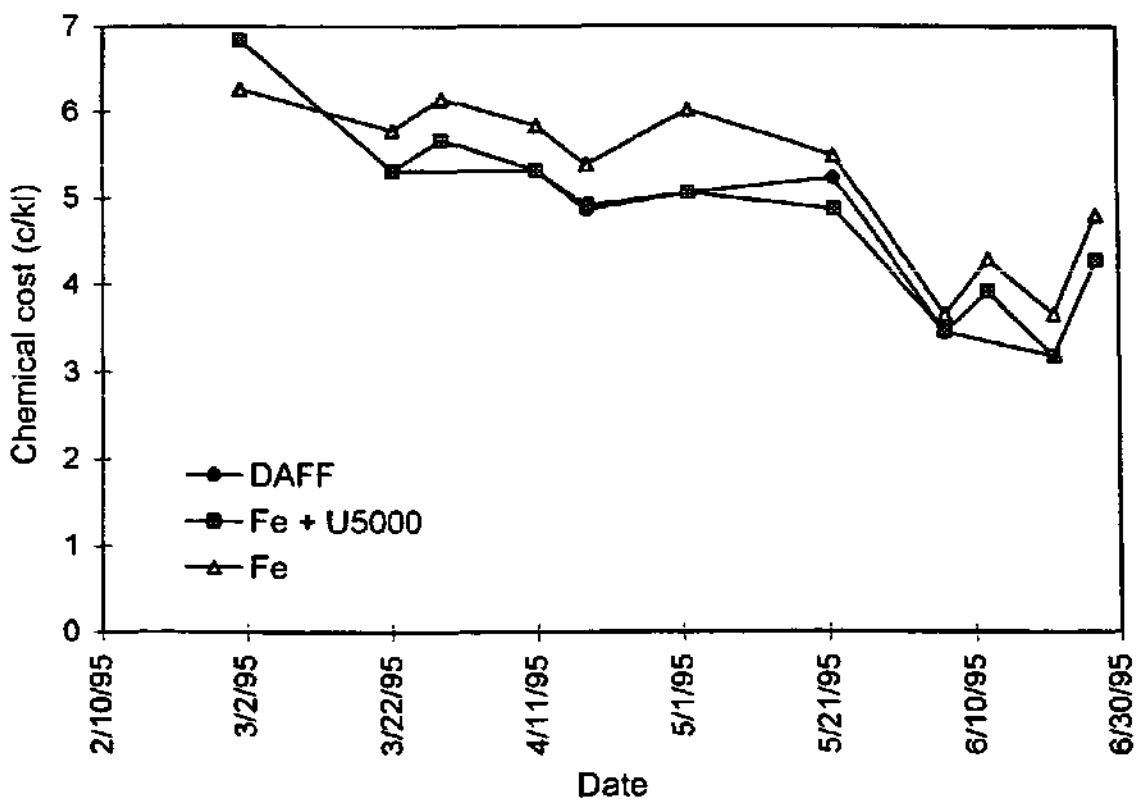

Figure 53: Chemical Cost

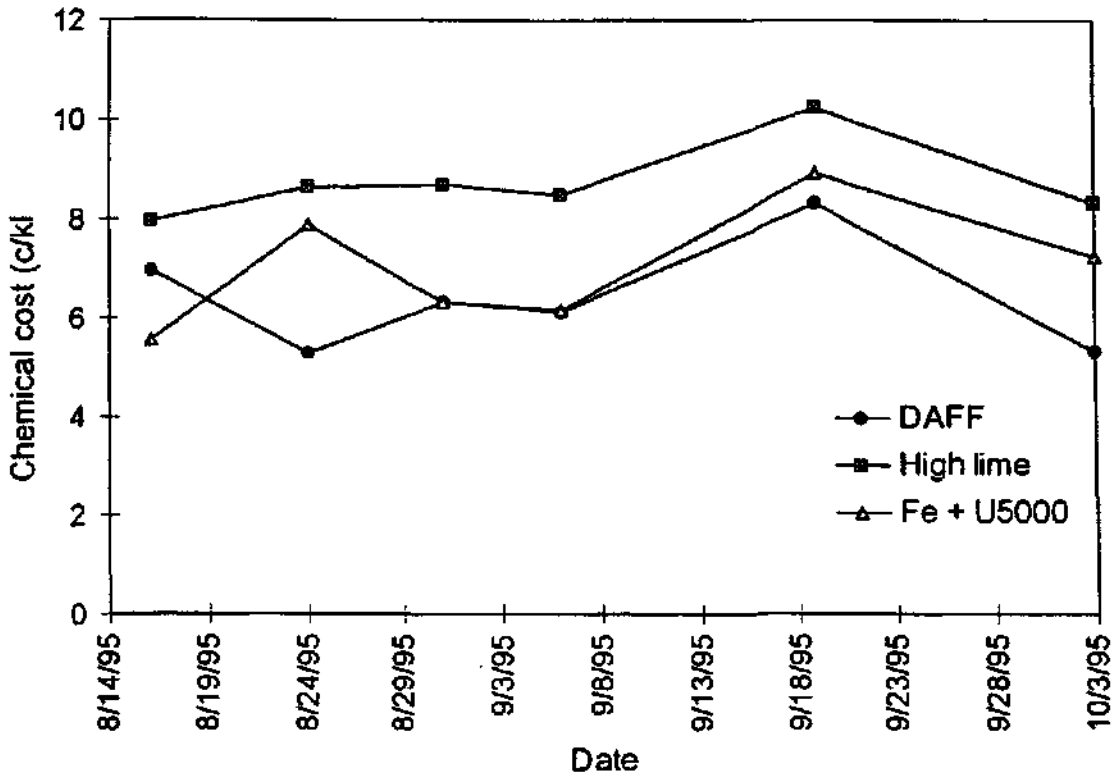

Figure 54: Chemical cost

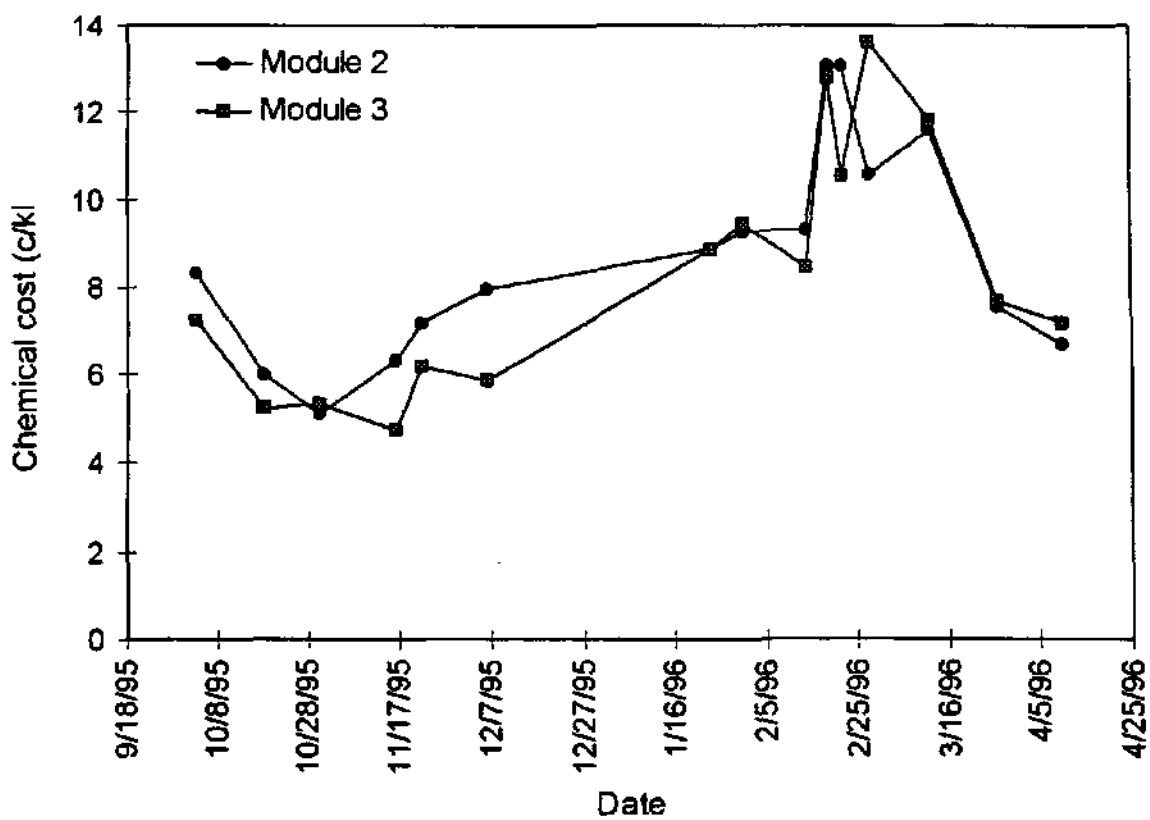

Figure 55: Average chemical cost for ferric chloride and U5000

It was not possible to raise the pH sufficiently in order to run the high lime process and a cost comparison between the high lime process and high U5000 dosing concentrations was not possible.

CONCLUSIONS

On-going water quality problems made it impossible to employ the same process for the entire experimental period. It was therefore difficult to evaluate a process under these continuously changing conditions. However, important conclusions can be drawn from this study:

The deteriorating raw water quality is of concern. High concentrations of iron and DOC in the raw water are causing serious problems in so far as usually efficient treatment practices are no longer capable of removing these contaminants to acceptable levels. This results in increasing chemical costs.
Different processes were evaluated under different conditions. The high lime process was found to be the most effective for the removal of iron and DOC except when high levels of DOC were present in the raw water. Low concentrations (less than 1 mg/l) of U5000 in combination with Ferric chloride produced an acceptable final water at lower cost than the high lime process. The effective reduction of iron was obtained when using U5000 as secondary coagulant with DOC concentrations as high as 13mg/l. During periods of unusually high levels of DOC, turbidity and iron in the raw water it was found that U5000 in the 15 - 20 mg/l dosage range was the only practical treatment option found to achieve an acceptable final water quality. The DAFF process was found to outperform the other processes for the removal of protein.

What was achieved through this study is possibly identifying what could be the most important contaminant in relation to the treatment of water from the middle Vaal River. Water quality characteristics vary widely. It is therefor necessary to conduct a sampling and detailed analyses program to discern the variations in the water quality that may affect treatment and are associated with serious cost implications.

Not much information is available in the literature regarding the impact of DOC on the removal of iron. Inconsistencies in the results achieved by the same process on what seemed to be similar raw water characteristics cannot be explained and research studies should be carried out to evaluate the role of DOC or EOM and the effect of molecular weight distribution on iron complexation. The importance of defining the different DOC fractions (or molecular weight distribution) and speciation of iron must be emphasised as this knowledge will enable plant managers to understand mechanisms, broaden coagulation objectives and adjust treatment processes accordingly.

It is traditional practice to use the reduction of turbidity as a measure of effective coagulation. From this study it became clear that the specific choice of coagulant/s and dosage should be based, in the case of the middle Vaal River, not only on turbidity but on other controlling factors such as DOC and iron as well. Effective turbidity removal must still be obtained, but it is critical to evaluate the performance of coagulants, in the removal of these contaminants, under specific problematic situations.

The DAFF process was found to be cost effective in the removal of protein and chlorophyll-a. The formation of THM substances is, however, of concern.

Pre-chlorination forms an important part of the treatment process at Balkfontein in enhancing the coagulation of algae. The increasing concentration, and the nature of organic matter in the raw water give rise to the occurrence of much higher concentrations of THM's in the finished drinking water. Unacceptable concentrations will eventually force the water utility to optimise coagulation to enhance DOC removal. This will then also result in optimising the removal of complexed iron.

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APPENDIX A

Sampling dates for the experimental period

1. 94-01-04
2. 94-01-18
3. 94-02-01
4. 94-02-15
5. 94-03-01
6. 94-03-15
7. 94-03-30
8. 94-04-12
9. 94-04-19
10. 94-05-11
11. 94-05-24
12. 94-06-07
13. 94-07-05
14. 94-07-12
15. 94-07-19
16. 94-08-10
17. 94-08-16
18. 94-08-31
19. 94-09-21
20. 94-10-05
21. 94-10-25
22. 94-11-02
23. 94-11-23
24. 95-03-01
25. 95-03-22
26. 95-03-29
27. 95-04-11
28. 95-04-18
29. 95-05-02
30. 95-05-22
31. 95-06-06
32. 95-06-12
33. 95-06-21
34. 95-06-27
35. 95-08-16
36. 96-08-20
37. 95-08-24
38. 95-08-31
39. 95-09-06
40. 95-09-19
41. 95-10-03
42. 95-10-18
43. 95-10-30
44. 95-11-16
45. 95-11-22
46. 95-12-06
47. 96-01-24
48. 96-01-31
49. 96-02-14
50. 96-02-19
51. 96-02-22
52. 96-02-28
53. 96-03-12
54. 96-03-27
55. 96-04-10
56. 96-04-29

CHAPTER 3:
ALGAL SPECIES PENETRATING UNIT PROCESSES IN THE BALKFONTEIN WATER PURIFICATION PLANT

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INTRODUCTION

Algal blooms cause different problems in conventional water purification plants. Algal blooms can result, amongst others, in aesthetically unacceptable situations and increased purification cost of water for potable purposes, because filters become clogged and scums are formed in purification plants (Bruwer et al., 1985), increased chemical dosages are necessary and more sophisticated treatment processes are required to remove tastes, odours and other side-effects (Wnorowski, 1992). Algae causing taste and odour problems are, for example, *Anabaena*, *Microcystis* and *Oscillatoria* species of the blue-green algae; *Actinastrum*, *Ankistrodesmus*, *Chlamydomonas*, *Pediastrum* and *Scenedesmus* species of the green algae and *Euglena* species of the euglenophytes (Tate & Arnold, 1990).

Major blooms, primarily by *Micractinium*, *Stephanodiscus*, *Carteria*, *Chlamydomonas* and *Oscillatoria* species, occur annually between June and October, apparently triggered by increased nitrogen supply (Pieterse, 1986b). Phytoplankton in river water supplies consists essentially of diatom and other algal cells, some of which with so little colouring matter in them that the water appears to be relatively clear and colourless (Vosloo & Langenegger, 1987).

In general, algal species penetrate the different phases of purification (Bernhardt, 1984a & b; Dickens & Slatter, 1991; Palmer, 1980; Bruwer *et al.*, 1985; Pieterse, 1989), and may be involved in the production of THM precursors (Basson & Pieterse, 1993). Algal biomass and species of the river water affect the number of algal cells and species that penetrate the entire treatment system (Pieterse, 1989).

Algae are generally not of serious health concern, but certain species may produce endo- or exotoxins which, if ingested at high concentrations, may be harmful (DWA, 1993). Three species of blue-green algae, namely *Anabaena flos-aquae*, *Microcystis aeruginosa* and *Aphanizomenon flos-aquae* may produce such toxins (Tate & Arnold,

1990). Recent occurrences of *Microcystis aeruginosa* in the Vaal River apparently posed no problems (Pieterse, 1986b).

Processes like flocculation, flotation and rapid sand filtration have to be employed to treat algal-rich river water (Bernhardt & Clasen, 1990). Goldfield water at Balkfontein purifies turbid, polluted water from the Middle Vaal River for potable purposes (Basson & Pieterse, 1993). The following phases constitute the purification process at Balkfontein (compare N.I.W.R., 1981). The first phase is an oxidation phase known as pre-chlorination. After pre-chlorination, the water is pumped to the chemical house where chemical dosing occur. Chemicals such as $FeCl_3$, lime and poly-electrolytes are added as coagulants or flocculants. After chemical dosing, the water is rapidly mixed, coagulation and flocculation are allowed to occur, after which the water flows to sedimentation tanks or clarifiers where flocculated particles are allowed to settle out. The water then goes through rapid sand filters, and before it is stored in reservoirs, the water is post-chlorinated (Compare Tebutt, 1977; N.I.W.R., 1981; Gregory, 1989). From the reservoir the water is pumped to different geographical areas such as the Free State Goldfields and the western parts of the North West Province. An average of 300 Ml/d is supplied over 8000 km^2 from Makwassie in the North West Province to Theunissen and Ventersburg in the Free State (Basson & Pieterse, 1993).

The physical process of producing contact between destabilised particles is termed flocculation, and it occurs primarily in flocculation tanks, therefore flocculation occurs when physical processes transform smaller particles into larger aggregates or flocs (Amirtharajah & O'Melia, 1990). Flocculation occurs only if particles can collide with each other and can adhere when brought together by collision (Gregory, 1989). Flocculation of algal cells is not subject to specific laws. This means that spherical diatoms, green algae and blue-green algae can be coagulated and aggregated according to the same mechanisms as inorganic colloids and dispersed particles (Bernhardt & Clasen, 1991).

Deviations from the normal flocculation process also occur if algal cells are not spherical, but have other forms such as filamentous or spikes. Where this is the case, an agglomeration of algal units during aggregation will be very difficult or even impossible (Bernhardt, 1965; Bernhardt & Clasen, 1967; Richard & Rizet, 1989).

There are some types of algae which have pectin or polysaccharide components attached to their surfaces which can induce the formation of gelatinous slime. In these instances, the peripheric cell wall structures exert an influence on the flocculation

process on account of their chemical structure, irrespective of their charge density (Lüsse, 1988; Bernhardt & Clasen, 1967; Richard & Rizet, 1989; Janssens *et al*, 1989). Slime producing algae are, for example, *Oscillatoria simplicissima* and *Euglena* spp. (Palmer, 1980). Some algae even have microscopic vacuoles of gas within their cells, with which they can change their specific gravity at will (Vosloo & Langenegger, 1987). Extracellular substances from algal cells also influence the flocculation of suspended particles (Bernhardt *et al*., 1985a & b)

Most species have mechanically resistant cell coverings (i.e. cell walls, pellicle plates and bands, frustules or thecal plates) which may give them a competitive advantage over fragile species in the riverine situation. The mechanically resistant cells most probably contribute to difficulties experienced in removing algae from the water during purification (Pieterse, 1993)

Sedimentation processes promote gravity settling of solid particles to the bottom of the water column where accumulated solids are removed. The density of planktonic algal cells is normally slightly greater than that of water so that the cells settle out (Pieterse, 1993). Sedimentation of algal cells or all suspended material may be affected by the type and number of algae present (Dickens & Slatter, 1991). Sedimentation is generally used subsequent to coagulation and flocculation to remove flocculated particles and improve subsequent filtration efficiency (Hamann *et al*., 1990). Sand filtration followed by disinfection is normally the final steps in water purification.

Previous observations at the Balkfontein purification plant indicated that if algal biomass is high in the river water, then algal biomass is also high in the final water (Pieterse, 1989). In addition, high diversity of species occur in the final water when algal biomass in the river water is high (Pieterse, 1989; Pieterse & Roos, 1991). Umgeni found that when the algal number in the river water increases, the algal number in the final water also increases (Dickens & Slatter, 1991). Previous observations also indicated that $FeCl_3$ appeared to have been more efficient in the removal of green algae than high pH lime treatment which appeared to remove diatoms more efficiently

Research indicated that the sedimentation phase is of primary importance in the removal of algae (Pieterse, 1989). Preliminary observations on the penetration of purification processes by algal species showed that representatives of six different algal groups were present in the river water as well as in water treated in the different stages of the purification process (Pieterse *et al*., 1993). The groups were Cyanophyceae (blue-green

algae), Bacillariophyceae (diatoms), Chlorophyceae (green algae), Euglenophyceae (euglenophytes), Chrysophyceae (golden algae) and Dinophyceae (dinoflagellates).

As already indicated, algal species penetrate different unit processes of water purification. Virtually no information is available on the connection between morphological and physiological characteristics of phytoplankton species on the one hand, and aspects of water purification, such as oxidation, flocculation, sedimentation, filtration and flotation, on the other hand.

The main aim of the investigation into the penetration of algal species in the water purification plant at Balkfontein is, therefore, to determine the nature and extent of algal-related problems and the types of algae involved as well as the relations between algae in the river water and algae in different phases of the purification process.

The penetration of the different unit processes by algal species and aspects of different interrelationships between purification processes and morphological characteristics of phytoplankton cells will, therefore, be investigated because different morphological features may affect coagulation and sedimentation. Results from the study will be used to determine whether the different unit processes of the purification plant is operating efficiently.

During the current study three modules of the Balkfontein plant were investigated to determine the effect of different treatments on the penetration of algal species. Module I included the flotation unit, Module II was used to conduct different experiments with, and Module III was used as the control unit.

STUDY AREA, MATERIALS AND METHODS

Sampling localities

Fig. 1 (Chapter 1) represents a map of the purification plant, operated by Goldfield Water at Balkfontein. The localities of pumping stations (Old PS = Old Pumping Station, New PS = New Pumping Station), chemical dosing and rapid mixing, the three Modules (Modules I, II, III), sedimentation tanks of the three modules, filter blocks with the filters of the three modules and the reservoirs where the water is stored before it is pumped to the different areas, are shown on the map. For the purpose of this study, nine sampling localities were selected in the purification plant at Balkfontein (Fig. 1), namely at the Intake (1), after Secondary sedimentation for Modules I, II & III (1.3, 2.4 & 3.4

respectively), after Flotation for Module I (1.4a), after Sand filtration for Modules I, II & III (1.6, 2.5 & 3.5 respectively) and the Final water (4).

Phytoplankton

Taxonomical groups

Water samples were taken every two weeks from August 1993 to April 1996 at the different sampling localities. The overall study period was from August 1993 to April 1996 but in Module I it was only from July 1994 to October 1996. Module II was investigated from August 1993 to July 1994 and again from March 1995 to April 1996. Module III was investigated from August 1993 to October 1994 and again from March 1995 to April 1996. The different periods of investigation coincided with periods during which the modules were in operation. Retention time was taken into account when water samples were collected. The reason why retention time was taken into account was to ensure that the same plug of water that was collected at the intake was also collected at the other sampling localities. A 100 ml water sample was taken for qualitative analysis, which was fixed with two percent formaldehyde (final concentration).

In certain instances sampling was not don biweekly resulting in gaps in the illustration of the data, i.e. fig. 3.1. There are two reasons for missing data during the study period. Firstly the different Modules were not in operation during the entire study period. These modules were taken out of operation to be cleaned. It was sometimes impossible for the staff to collect water late at night or early in the morning.

Where possible, all algae present (excepting the unicellular centric diatoms) were identified to species level with a light microscope and texts such as Geitler (1932), Huber-Pestalozzi (1950, 1955, 1961, 1962a, b, c), Prescott (1951), Bourelly (1966, 1968, 1970), Prescott el al. (1981, 1982), Förster (1982), Komárek & Fott (1983) and Starmach (1985).

After identification each sample was shaken in order to suspend the algae uniformly through the water. Gas vacuoles of blue-green algae were pressure deflated in a special container. Equal volumes, usually 0.5 to 6.0 ml (depending on the density of the algae) of water from the different sampling localities were then pipetted into two identical sedimentation tubes with diameters of 16.5 mm. Two sedimentation tubes were used for each sample so that counting for a specific sample was done in duplicate. The sedimentation tubes were filled with distilled water and covered with circular glass cover

slips. The sedimentation tubes were left in a desiccator (filled with distilled water in the bottom section) for two days in order to allow the algal cells to settle and to avoid evaporation of water in the sedimentation tubes (Lund *et al.*, 1958). Settling times of one centimeter length per day of the sedimentation tubes were allowed. These procedures were repeated for each water sample taken.

Algal cells were counted by means of the technique described by Utermöhl (1931 & 1958) and modified by Lund *et al.* (1958), which employs an inverted Zeiss light microscope. One of the eyepieces of the inverted microscope contained a Whipple grid. The glass bottom of the sedimentation tubes were examined in strips, while a count of all the cells, colonies and filaments inside the Whipple grid was made. The counts were thus recorded as number of algal units per unit volume of water.

Centric diatoms were not identified while counting (excepting the filamentous centric diatom, *Melosira granulata*). A total count of all other unidentified centric diatoms were made. The cell counts, together with the original sub-sample volumes transferred to the sedimentation tubes, as well as the number of strips counted in the sedimentation tubes, were used to calculate the concentration of individual phytoplankton species in units/ml (i.e. cells, colonies or filaments/ml) with the aid of a standard computer programme.
The phytoplankton counts were used to determine species number, biomass, percentage composition of different species at a given time. For the purpose of this study the concept dominant species is used for the species with the highest concentration.

Morphological groups

For comparative purposes the algal species identified from the different sampling localities were grouped into the following general morphological types. Size-ranges for some species are given in brackets (l=length; b=breadth, d=diameter).

Unicellular algae with flagellated cells (UnFl)

Carteria globosa (17-30 µm l; 13-22 µm b), *Carteria simplicissima* (17-30 µm l; 13-22 µm b), *Chlamydomonas bicocca* (12-25 µm l; 5 µm b), *Chlamydomonas incerta* (12-25 µm l; 5 µm b), *Chlamydomonas* sp. (12-25 µm l; 5 µm b), *Cryptomonas major* (10-80 µm l), *Lepocinclis salina* (36-60 µm l; 26-45 µm b), *Peridinium penardiforme* (30-34 µm l; 26-30 µm b), *Phacotus lenticularis* (13-20 µm d), *Phacus acuminatus* (100µm l; 26-70 µm b), *Phacus longicauda* (100µm l; 26-70 µm b), *Phacus pyrum* (100µm l; 26-70 µm b), *Pteromonas aculeata* (10-34 µm l; 14-24 µm b), *Sphaerodinium ravumfluvium*,

Strombomonas fluviatilis (100 µm l), *Strombomonas jaculata* (100 µm l), *Strombomonas lanceolata* (100 µm l), *Strombomonas longicauda* (100 µm l), *Strombomonas ovalis* (100 µm l), *Strombomonas verrucosa* (100 µm l), *Trachelomonas intermedia* (19-32 µm l; 15-23 µm b), *Trachelomonas scabra* (19-32 µm l; 15-23 µm b), *Trachelomonas volvocina* (19-32 µm l; 15-23 µm b), *Thoracomonas feldmannii* (10-14 µm l; 8-13 µm b).

Unicellular algae with spheric cells (UnSp)

Chlorococcum infusionum (10-20 µm d), *Cosmarium laeve* (20-35 µm l; 13-25 µm b), *Oocystis lacustris* (6.4-25 µm l; 3.2-14 µm b), *Polytomella citri*, *Synechococcus cedrorum* (5-10 µm l; 3-4 µm b), *Synechocystis* sp., *Tetraedron limneticum* (5-22 µm d; spines 2-4-(6) µm l), *Tetraedron mediocris* (5-22 µm d; spines 2-4-(6) µm l), *Tetraedron planctonicum* (5-22 µm d; spines 2-4-(6) µm l), *Tetraedron regulare* (5-22 µm d; spines 2-4-(6) µm l).

Unicellular algae with elongated cells (UnEl)

Ankistrodesmus bibraianus (16-105 µm l; 1.2-8 µm b), *Ankistrodesmus falcatus* (16-105 µm l; 1.2-8 µm b), *Ankistrodesmus stipitatus* (16-105 µm l; 1.2-8 µm b), *Cerasterias irregularis*, *Characium limneticum* (15-70 µm l; 2.5-33 µm b), *Euglena clavata* (42-172 µm l; 9-28 µm b), *Euglena elastica* (42-172 µm l; 9-28 µm b), *Euglena hemichromata* (42-172 µm l; 9-28 µm b), *Euglena pusilla* (42-172 µm l; 9-28 µm b), *Euglena* sp. (42-172 µm l; 9-28 µm b), *Lagerheimia balatonica* (4.8-12 µm l; 2-7.8 µm b), *Monoraphidium arcuatum* (11-27.5 µm l; 3-5 µm b), *Monoraphidium circinale* (11-27.5 µm l; 3-5 µm b), *Monoraphidium griffithi* (11-27.5 µm l; 3-5 µm b), *Monoraphidium minutum* (11-27.5 µm l; 3-5 µm b), Unidentified pennate diatom, *Schroederia indica* (44 µm l; 4.4-12.3 µm b).

Unicellular algae with discoidal cells (UnDi)

Centric diatoms for example *Cyclostephanos dubius* (5-35 µm d), *Cyclotella meduanae* (5-50 µm d), *Cyclotella meneghiniana* (5-50 µm d), *Stephanodiscus hantzschii* (8-20 µm d), *Stephanodiscus* sp. (8-20 µm d), *Thalassiosira duostra* (15-40 µm d), *Thalassiosira weissflogii* (15-40 µm d).

Colonial algae, individual cells with spines (CoSpi)

Golenkinia radiata (10-18 µm d; spines 25-45 µm l), *Micractinium pusillum* (3-20 µm d; spines 10-65 µm l), *Scenedesmus acuminatus* (3.5-30 µm l; 1.5-9 µm b), *Scenedesmus disciformis* (3.5-30 µm l; 1.5-9 µm b), *Scenedesmus intermedius* (3.5-30 µm l; 1.5-9 µm b), *Scenedesmus lefevrii* (3.5-30 µm l; 1.5-9 µm b), *Scenedesmus opoliensis* (3.5-30 µm l; 1.5-9 µm b), *Scenedesmus smithii* (3.5-30 µm l; 1.5-9 µm b), *Tetrastrum*

heteracanthum (6-15 μm l; 5-12 μm b), *Tetrastrum staurogeniaeforme* (6-15 μm l; 5-12 μm b), *Treubaria quadrispina* (8-12 μm d; spines 15-22 μm l).

Colonial algae with spherical cells (CoSp)

Actinastrum hantzschii (9-36 μm l; 1.5-6 μm b), *Chroococcus dispersus* 5-6 μm d), *Coelastrum carpaticum* (8-30 μm d - cells; 100 μm across - colony), *Coelastrum pseudomicroporum* (8-30 μm d - cells; 100 μm across - colony), *Dictyosphaerium elegans* (3.5-5.5 μm l; 2-3 μm b), *Eudorina elegans* (16-25 μm d - cells; 200 μm across - colony), *Kirchneriella* sp. (6-18 μm l; 3-8 μm b - cells), *Microcystis aeruginosa* (9 μm d), *Microcystis flos-aquae* (9 m d), *Microcystis incerta* (9 μm d), *Oocystis marssonii* (6.4-25 μm l; 3.2-14 μm b - cells), *Oocystis pusilla* (6.4-25 μm l; 3.2-14 μm b - cells), *Pandorina morum* (63-73 μm l; 55-64 μm b).

Colonial algae with discoidal cells (CoDi)

Crucigenia lauterbornii (6-30.5 μm d - colony), *Crucigenia tetrapedia* (6-30.5 μm d - colony), *Crucigeniella rectangularis* (4-11 μm l; 3-7 μm b), *Merismopedia minima* (0.5-17 μm d), *Pediastrum duplex* (246 μm d - colony), *Pediastrum simplex* (246 μm d - colony), *Pediastrum tetras* (246 μm d - colony), *Staurastrum tetracerum* (130 μm l).

Filamentous algae (Fila)

Anabaena circinales (8-10 μm b), *Melosira granulata* (5-21 μm d - cells; 20 μm l), *Oscillatoria simplicissima* (2-4-(15) μm l; (2)-8-9 μm b).

Environmental variables

Water from the different sampling localities were analysed for turbidity and chlorophyll-*a*. Turbidity and chlorophyll-*a* were determined at the purification plant employing standard methods.

Computer programmes and analysis of Data

In South Africa the decimal SI system was adopted which makes the use of the comma (,) mandatory. However, in this study decimals are indicated by a point (.). The point notation was adopted in order to maintain compatibility with text and graphics generated by computer software requiring this format for numerical calculations and representations. All other abbreviations and units are in accordance with the SI system. Data on algal counts were entered into QUATTRO PRO4. Graphical presentations were made by SIGMAPLOT 4.0 and HARVARD GRAPHICS 3.0. Graphics were exported as

Hewlett Packard Graphics Language (HPGL) files and as such imported into MSWORD 5.5. All programmes were registered versions available for use in the Vaal River Research Group of the Department of Plant and Soil Science of the Potchefstroom University for Christian Higher Education, Potchefstroom.

Percentage removal

Percentage removal were calculated for the different phases as well as for the entire process. The percentage removal during sedimentation represents the percentage of, for example, chlorophyll-*a* removed from the river water by secondary sedimentation. The percentage removal of the combined processes represents the percentage of, for example, chlorophyll-*a* removed from the river water through to filtration.

Diversity index

The diversity index were calculated for the different phases by using the formula of Margalef (1968), namely D = S-1/Log N.
S = Total species number and N = Total cells/ml. The diversity index was used to give additional information about the different types of algae.

RESULTS AND DISCUSSION

River water

Major Taxonomical groups

Representatives of six different algal groups were present in the water from the Vaal River from August 1993 to April 1996 (Tables 4, 9 & 12). The groups were Cyanophyceae (blue-green algae), Chlorophyceae (green algae), Bacillariophyceae (diatoms), Euglenophyceae (euglenophytes), Dinophyceae (dinoflagellates) and Cryptophyceae (cryptophytes).

The diatoms were dominant in the river water and were gradually removed by the different purification processes (Figs 1 & 2). The dominant species were the centric diatom *Melosira granulata*, an unidentified pennate diatom and an unidentified centric diatom.
During the beginning of August 1993, the end of December 1993, the end of October 1994 and the beginning of August 1995 the Chlorophyceae (green algae) was dominant

in the river water (Figs 1 & 2). The dominant species were *Chlamydomonas bicocca*, *Chlamydomonas incerta*, *Chlamydomonas* sp., *Oocystis marssonii* and *Oocystis lacustris*.

Small quantities of euglenophytes, blue-green algae, dinoflagellates and cryptophytes were present in the river water (Figs 1 & 2). The dominant euglenophytes were *Trachelomonas intermedia*, *Trachelomonas scabra* and *Strombomonas fluviatilis* and the dominant blue-green algae were *Synechococcus cedrorum* and *Microcystis flos-aquae*. The dominant dinoflagellate was *Sphaerodinium ravumfluvium* and the dominant cryptophyte was *Cryptomonas major*.

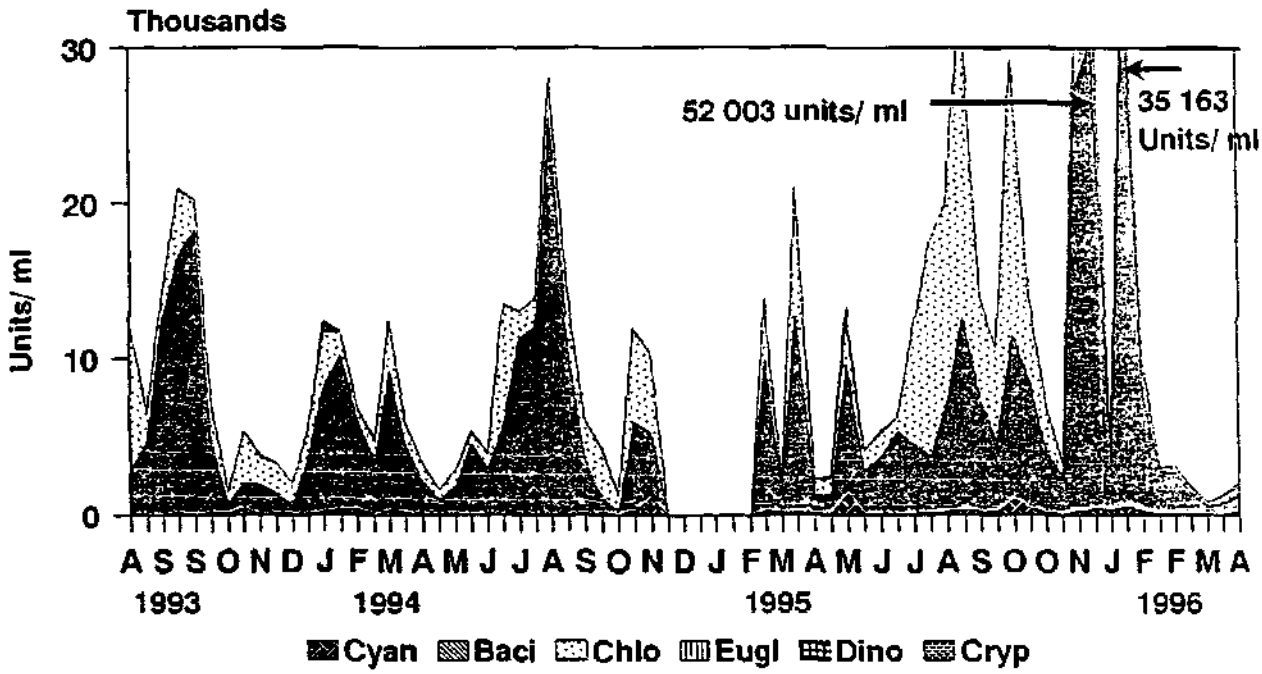

Figure 1: Phytoplankton counts of major taxonomical groups of the river water from August 1993 to April 1996.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Dino = Dinophyceae, Cryp = Cryptophyceae.

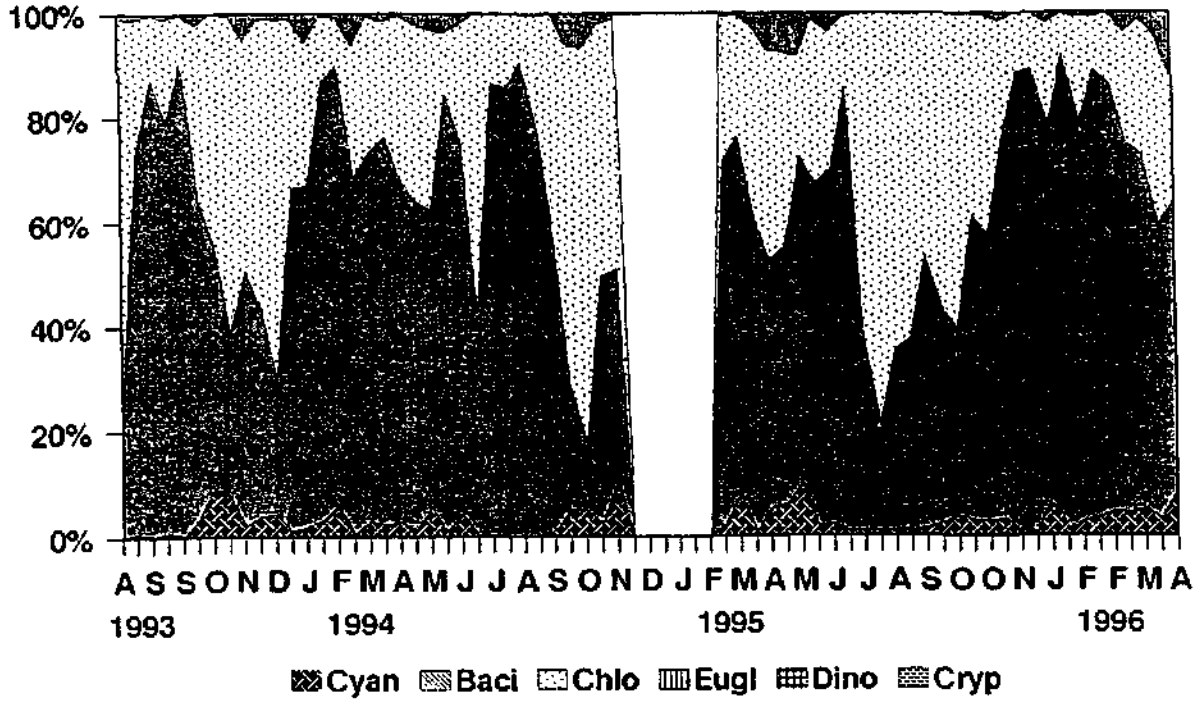

Figure 2: Phytoplankton composition (%) of major taxonomical groups of the river water from August 1993 to April 1996.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Dino = Dinophyceae, Cryp = Cryptophyceae.

Phytoplankton biomass and Species diversity

During the study period chlorophyll-*a* and algal units concentration followed similar patterns in the river water (Fig. 3). The chlorophyll-*a* concentration varied throughout the study period in the river water (Fig. 3). The highest chlorophyll-*a* concentration occurred at the end of September 1993 (Fig. 3, Table 1; 130 µg/l).

During the end of November 1995, during the end of February 1996 and during March 1996 the chlorophyll-*a* concentration was below detection limits (Fig. 3). The dominant algal species were an unidentified centric diatom and *Melosira granulata* during the end

of February 1996 and an unidentified centric diatom and *Monoraphidium arcuatum* during March 1996. The water was too turbid during the end of November 1995 to make algal counts.

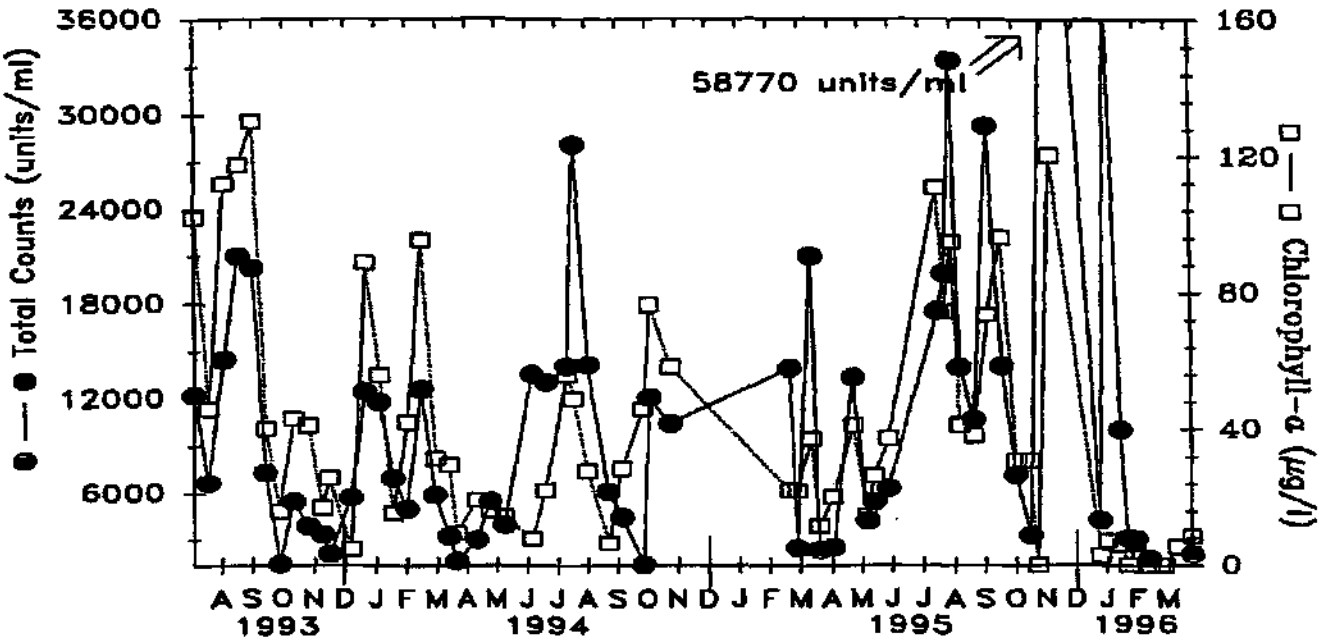

Figure 3: Phytoplankton biomass in µg/l chlorophyll-*a* and total counts in algal units/ml of the river water from August 1993 to April 1996.

The total algal counts in the river water showed variation during the study period (Fig. 3). The total counts was below 2 000 units/ml while the chlorophyll-a concentration was above 40 µg/l during the end of October 1994 (Fig. 3). The dominant algal species were *Chlamydomonas incerta* and *Scenedesmus intermedius*.

The highest total algal count occurred during the beginning of December 1995 (Fig. 3, 58770 units/ml). The dominant algal species were *Melosira granulata* and an unidentified centric diatom. There was therefore a bloom of *Melosira granulata* in the water during December 1995.

On four occasions, namely the end of October 1993, beginning of January 1994, the end of October 1995, during the end of January 1996 and the beginning of February 1996, the turbidity of the river water was above 200 NTU (Fig. 4). The dominant algal species were an unidentified centric diatom and *Melosira granulata*. From the end of February 1994 to the end of October 1995 the turbidity was below 50 NTU most of the time (Fig. 4).

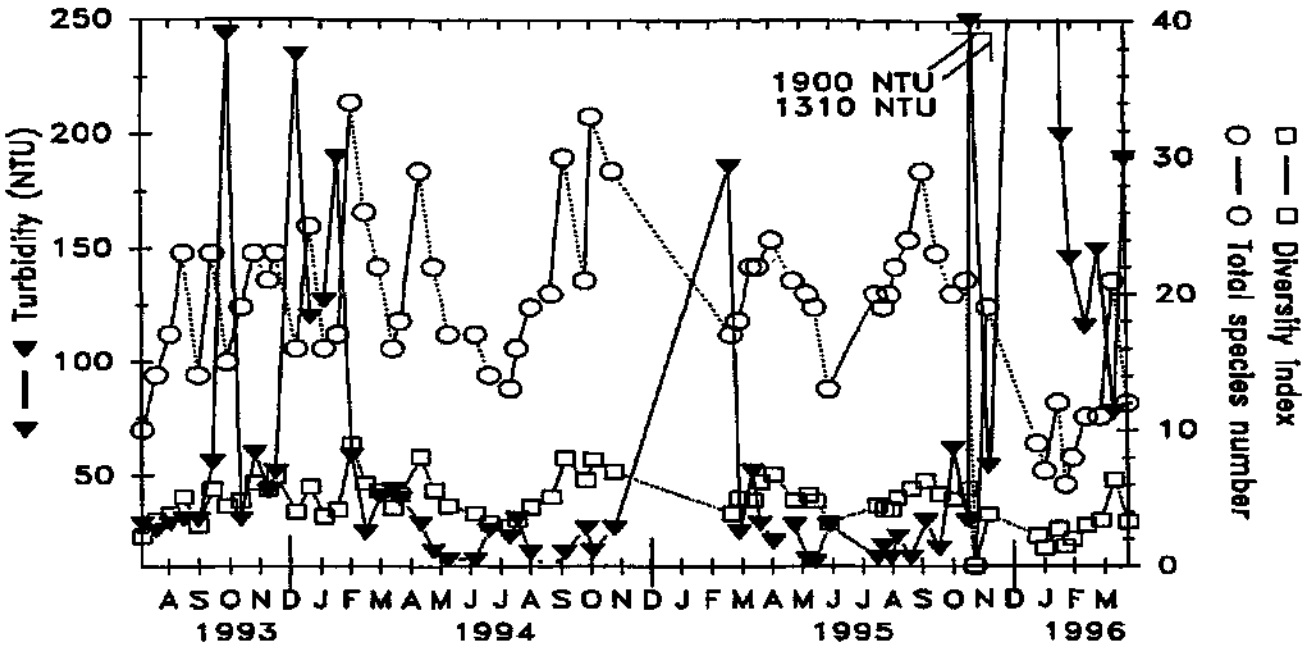

Figure 4: Species diversity in total species number, turbidity in NTU and diversity index of the river water from August 1993 to April 1996.

The total species number showed variation in the river water during the entire study period (Fig. 4). There were only two occasions when the total species number was above 30 species, namely at the end of February 1994 and at the end of October 1994 (Fig. 4). The dominant species were an unidentified centric diatom and *Melosira granulata* during the end of February 1994 and *Chlamydomonas incerta* and *Scenedesmus intermedius* (green algae) during the end of October 1994.

The diversity index followed the same pattern as the total species number and was below 10 during the entire study period (Fig. 4).

Morphological groups

Unicellular discoidal cells (Undi) was most of the time dominant in the river water during the study period (Figs 5 & 6). The dominant species comprised unidentified centric diatoms.

Colonial algae, individual cells with spines (Cospi) were dominant at the beginning of November 1993 and the beginning of October 1995 in the river water (Figs 5 & 6). The dominant species were *Scenedesmus acuminatus* and *Scenedesmus opoliensis*.

Unicellular flagellated cells (Unfl) were dominant at the beginning of August 1993, during October 1994 and during the beginning of August 1995 in the river water (Figs 5 & 6). The dominant species were *Chlamydomonas incerta*, *Chlamydomonas bicocca*, *Chlamydomonas* sp. and *Trachelomomas intermedia*.

At the beginning of February 1994, during the middle of March 1994 and during December 1995 filamentous algae were dominant in the river water (Figs 5 & 6). The dominant species were *Melosira granulata*, *Oscillatoria simplicissima* and *Anabaena circinale*.

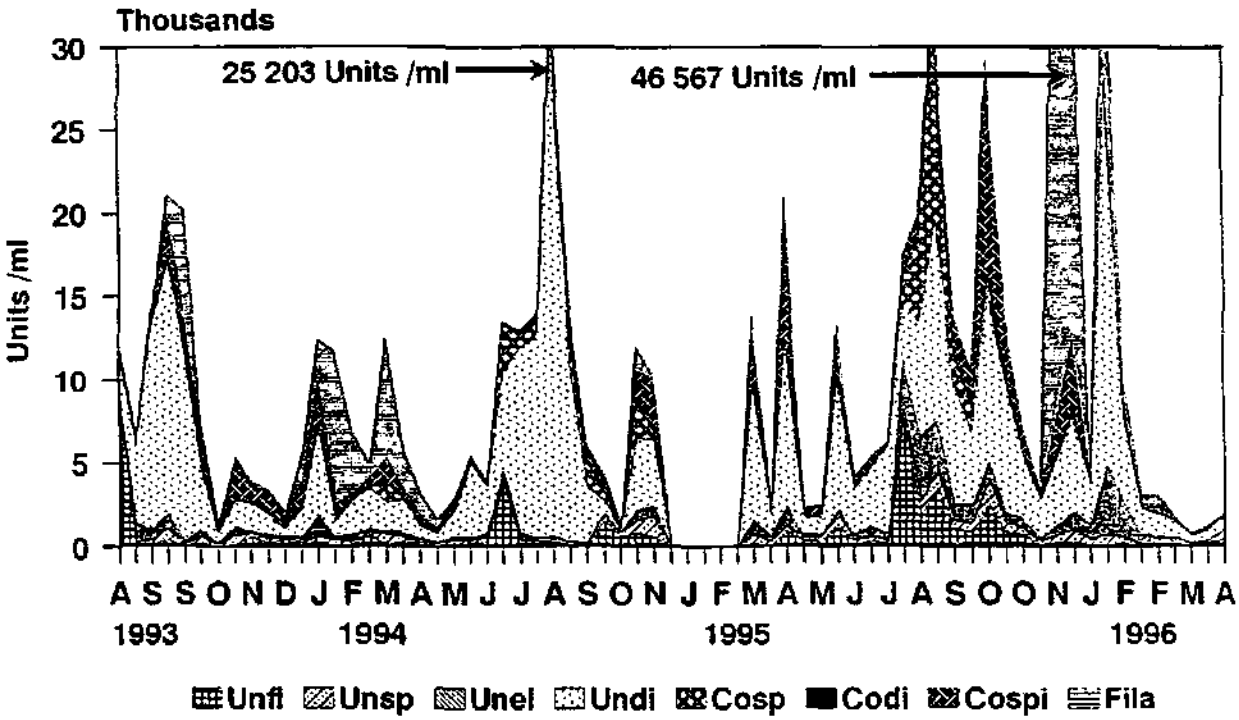

Figure 5: Phytoplankton counts of morphological groups of the river water from August 1993 to April 1996.
Unfl = Unicellular flagellated cells, Unsp = Unicellular spherical cells, Unel = Unicellular elongated cells, Undi = Unicellular discoidal cells, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Cospi = Colonial algae individual cells with spines, Fila = Filaments.

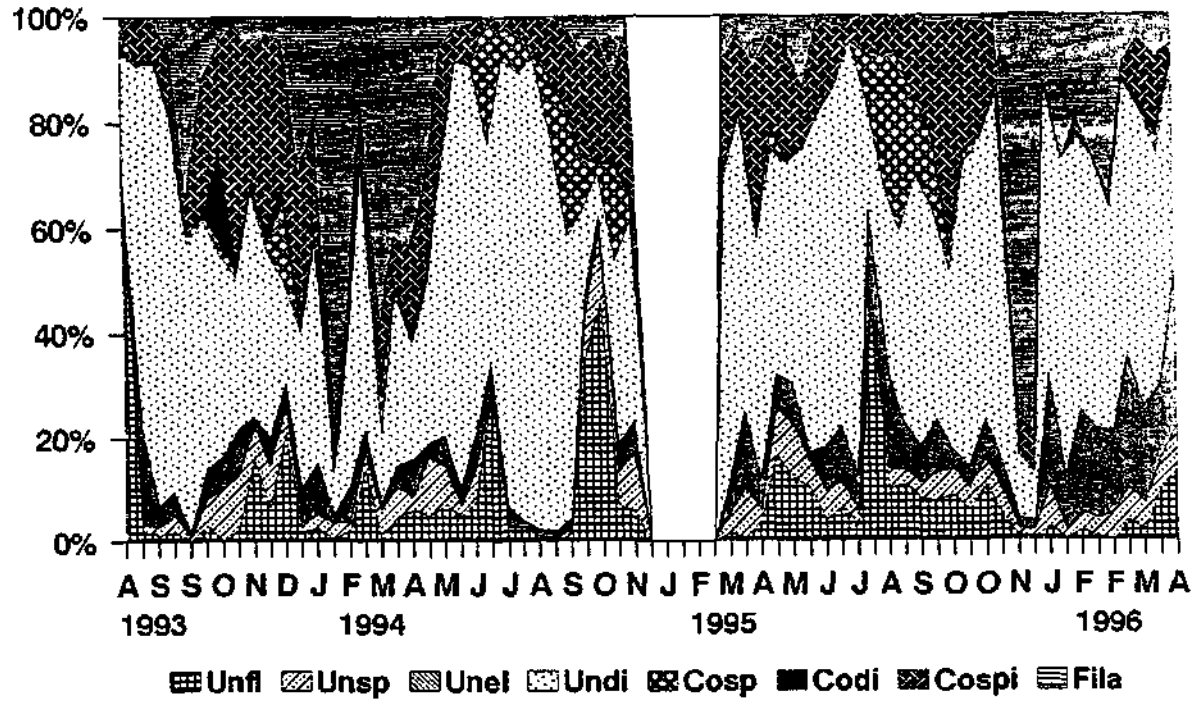

Figure 6: Phytoplankton composition (%) of morphological groups of the river water from August 1993 to April 1996.
Unfl = Unicellular flagellated cells, Unsp = Unicellular spherical cells, Unel = Unicellular elongated cells, Undi = Unicellular discoidal cells, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Cospi = Colonial algae individual cells with spines, Fila = Filaments.

Module I

Major taxonomical groups

Representatives of six different algal groups were present in the different stages of purification processes of Module I from July 1994 to October 1995 (Table 4). The groups were Cyanophyceae (blue-green algae), Bacillariophyceae (diatoms), Chlorophyceae (green algae), Euglenophyceae (euglenophytes), Dinophyceae (dinoflagellates) and Cryptophyceae (cryptophytes).

The diatoms were dominant during the beginning of August 1994 in the sedimentation effluent of Module I (Figs 7 & 8). The dominant algal species were an unidentified centric and an unidentified pennate diatom. A small peak of diatoms occurred at the end of July 1995 in the sedimentation effluent of Module I (Figs 7 & 8). The dominant diatom was an unidentified centric diatom.

From the middle of August 1994 to the end of October 1995 the green algae were dominant in the sedimentation effluent of Module I (Figs 7 & 8). The dominant algal species were *Monoraphidium arcuatum*, *Chlamydomonas* sp., *Actinastrum hantzschii*, *Ankistrodesmus stipitatus* and *Carteria simplicissima*.

A peak of diatoms occurred during the middle of August 1994 in the flotation effluent of Module I (Figs 9 & 10). The dominant diatom was an unidentified centric diatom. A smaller peak of diatoms occurred at the end of July 1995 in the flotation effluent of Module I (Figs 9 & 10). The dominant species was unidentified centric diatom.

The green algae were dominant in the flotation effluent from the end of August 1994 to the end of October 1995 (Figs 9 & 10). The dominant algal species were *Monoraphidium arcuatum*, *Oocystis lacustris*, *Scenedesmus opoliensis*, *Chlamydomonas* sp. and *Actinastrum hantzschii*.

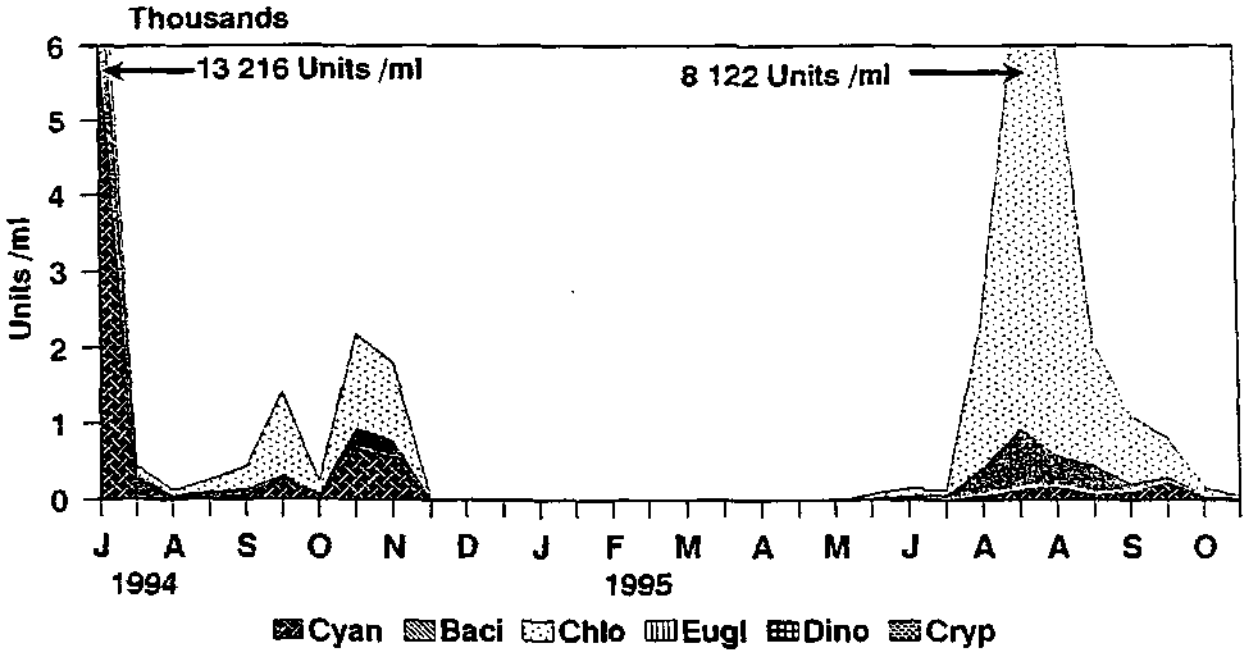

Figure 7: Phytoplankton counts of major taxonomical groups of the sedimentation effluent of Module I from July 1994 to October 1995.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Dino = Dinophyceae, Crypt = Cryptophyceae.

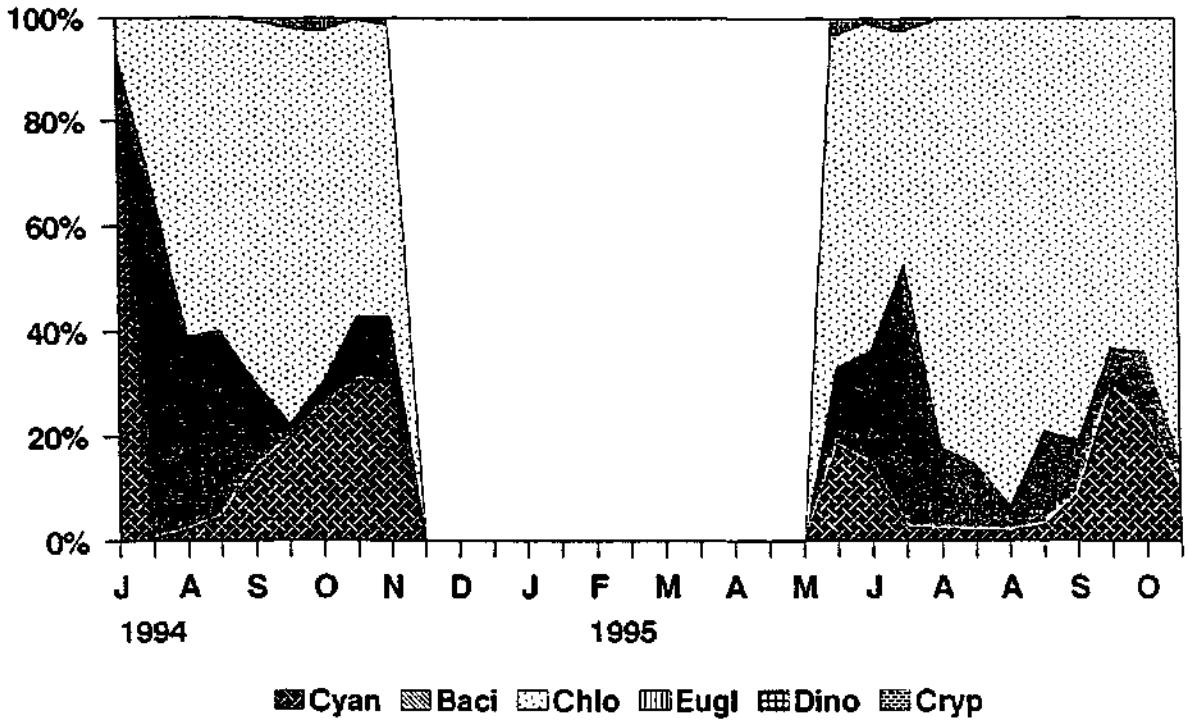

Figure 8: Phytoplankton composition (%) of major taxonomical groups of the sedimentation effluent of Module I from July 1994 to October 1995.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Dino = Dinophyceae, Crypt = Cryptophyceae.

The peak of diatoms, which occurred in the beginning of August 1994 in the sedimentation and flotation effluent, was almost entirely removed by flotation-filtration (Figs 11 & 12). The dominant diatom was an unidentified centric diatom. A peak of diatoms occurred during the middle of August 1994 in the flotation-filtration effluent of Module I (Figs 11 & 12). The dominant diatom was an unidentified centric diatom.

A peak of green algae occurred during the beginning of August 1994 at the flotation-filtration effluent (Figs 11 & 12). The dominant species were *Oocystis lacustris*, *Actinastrum hantzschii* and *Monoraphidium arcuatum*.

From the end of August 1994 to the end of October 1995 the green algae were dominant in the flotation-filtration effluent (Figs 11 & 12). The dominant green algae were *Monoraphidium arcuatum*, *Oocystis lacustris*, *Chlamydomonas incerta*, *Chlamydomonas* sp. and *Actinastrum hantzchii*.

The blue-green algae increased proportionate to the other groups from the river water to the flotation-filtration effluent of Module I (Figs 1 & 2, 7-12). The dominant algal species were *Synechococcus cedrorum*, *Microcystis flos-aquae* and *Synechosystis* sp.

The blue-green algae were dominant during July 1994 in the sedimentation, flotation and flotation-filtration effluents of Module I (Figs 7-12). The dominant blue-green algae were *Synechocystis* sp. and *Synechococcus cedrorum*.

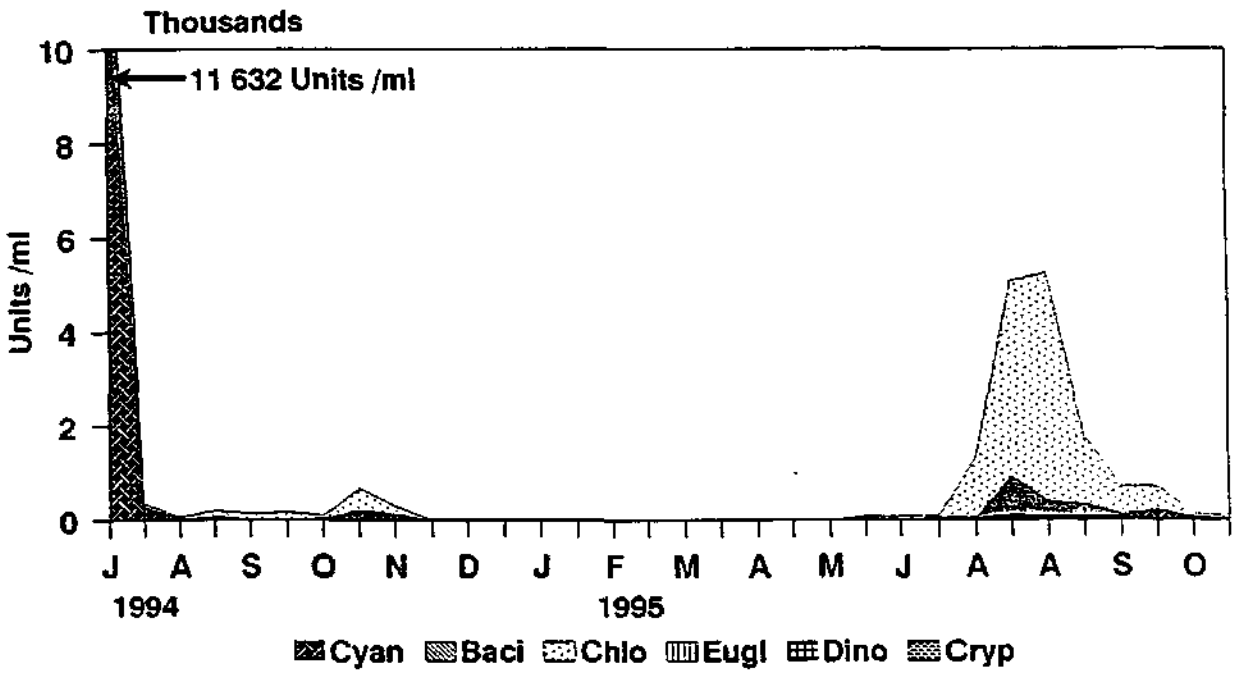

Figure 9: Phytoplankton counts of major taxonomical groups of the flotation effluent of Module I from July 1994 to October 1995.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Dino = Dinophyceae, Crypt = Cryptophyceae.

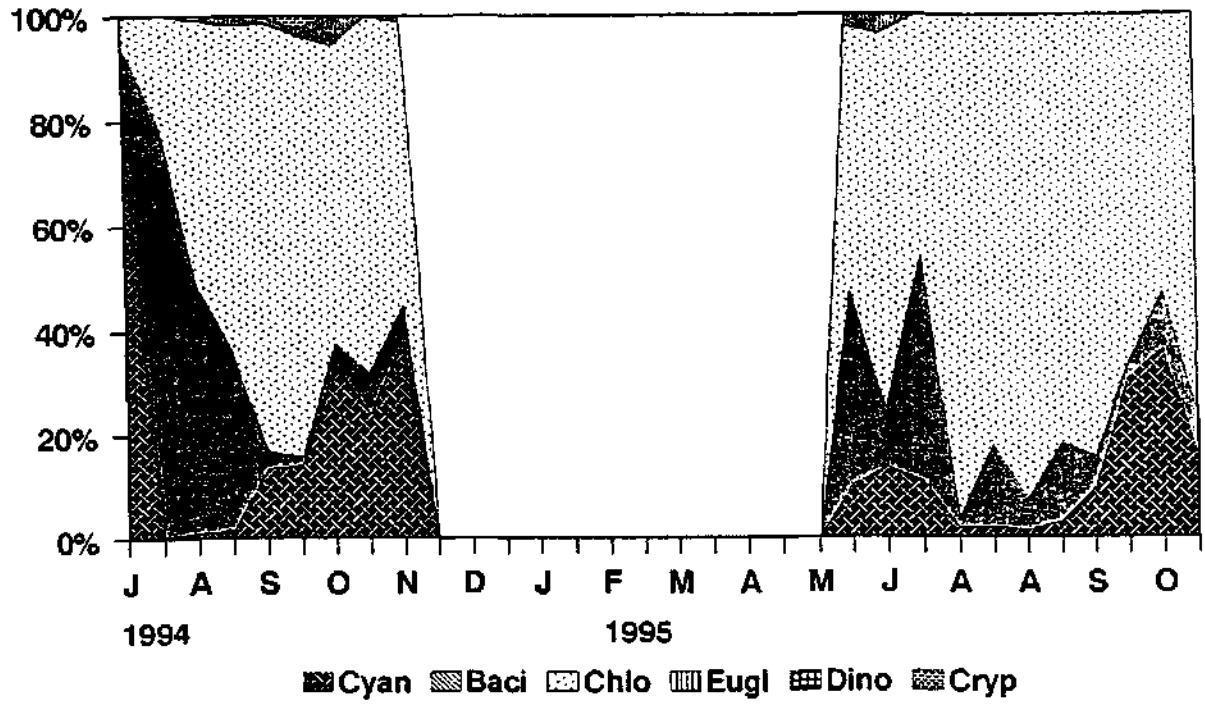

Figure 10: Phytoplankton composition (%) of major taxonomical groups of the flotation effluent of Module I from July 1994 to October 1995.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Dino = Dinophyceae, Crypt = Cryptophyceae.

Three peaks of blue-green algae occurred at the flotation-filtration effluent of Module I, namely at the beginning of October 1994, the beginning of November 1994 and the beginning of October 1995 (Figs 11 & 12). The dominant blue-green algal species were *Synechococcus cedrorum, Microcystis flos-aquae* and *Chroococcus dispersus.*

Small amounts of euglenophytes, dinoflagellates and cryptophytes were present in the sedimentation, flotation and flotation-filtration effluents of Module I (Figs 7-12). The dominant euglenophyte species were *Trachelomonas intermedia, Phacus pyrum, Euglena* sp. and *Trachelomonas scabra,* the dominant dinoflagellate species was *Sphaerodinium ravumfluvium* and the dominant cryptophyte species was *Cryptomonas major.*

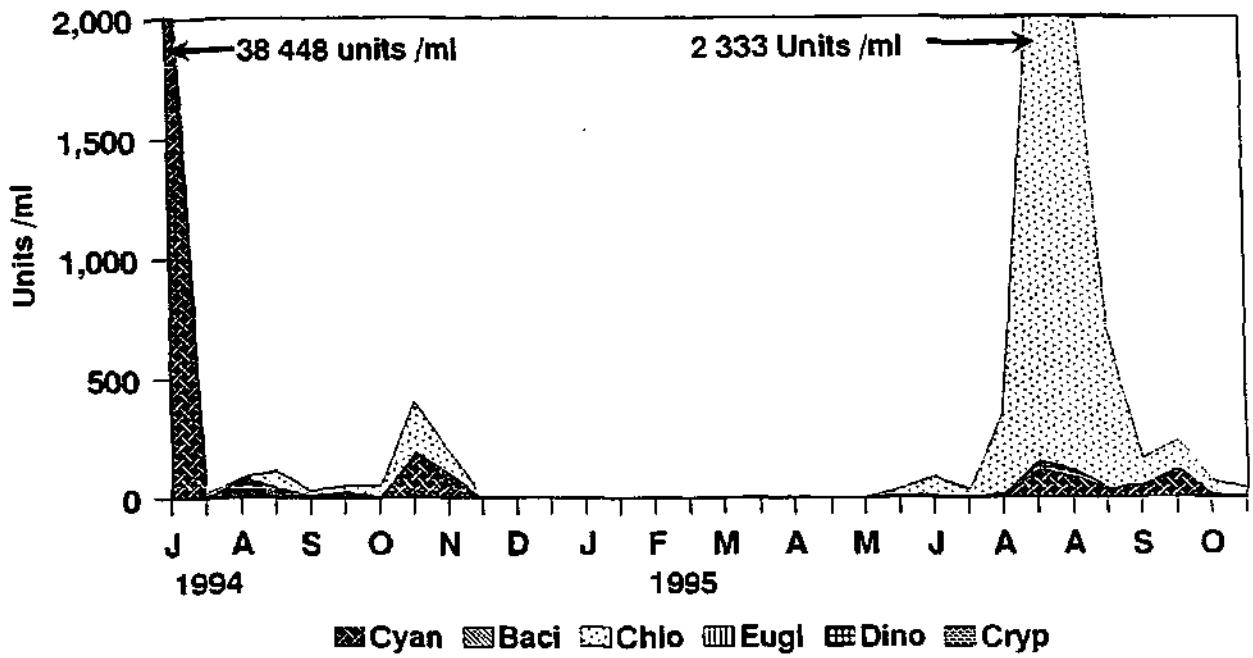

Figure 11: Phytoplankton counts of major taxonomical groups of the flotation-filtration effluent of Module I from July 1994 to October 1995.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Dino = Dinophyceae, Crypt = Cryptophyceae.

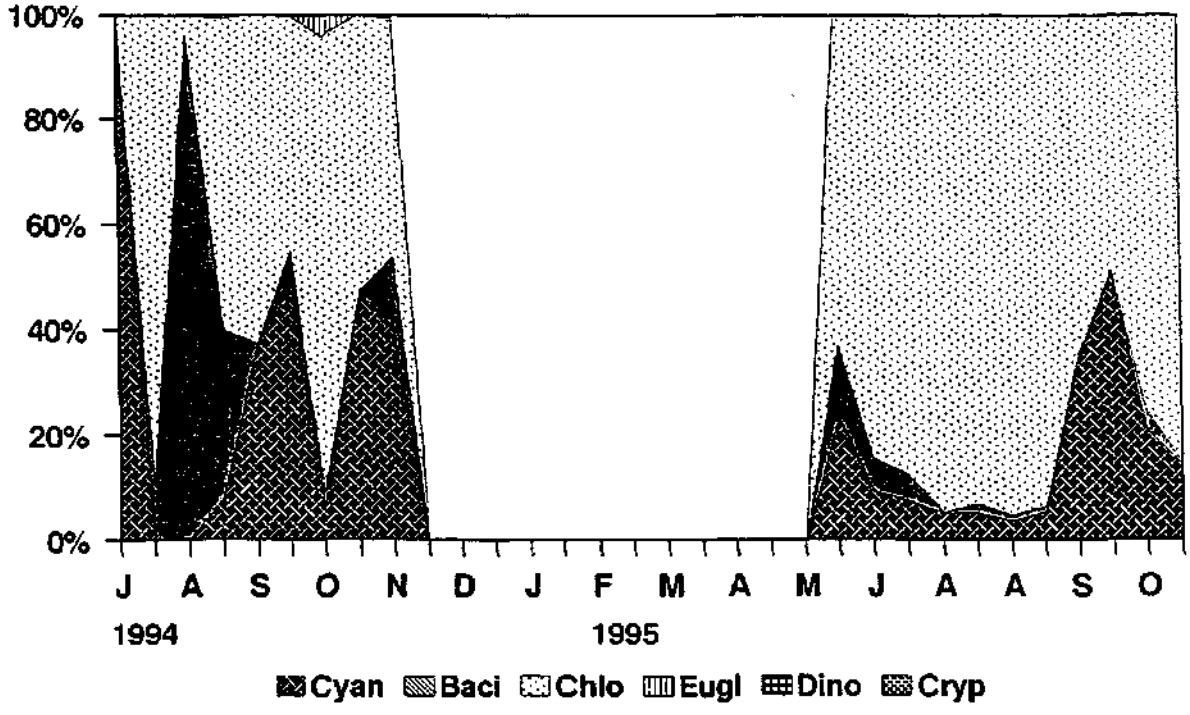

Figure 12: Phytoplankton composition of major taxonomical groups of the flotation-filtration effluent of Module I from July 1994 to October 1995.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Dino = Dinophyceae, Crypt = Cryptophyceae.

Phytoplankton biomass, Species diversity and Turbidity

The chlorophyll-*a* concentration of the sedimentation effluent of Module I was below 10 µg/l during the study period except during the middle and end of August 1994 when it was 12 µg/l and 32 µg/l respectively (Fig. 13). The chlorophyll-a concentration was relatively low (8 µg/l) during the end of July 1994 in the sedimentation effluent, while the algal unit concentration was the highest during the end of July 1994 in the sedimentation effluent (Fig. 13). The dominant algal species were *Synechococcus cedrorum* and *Synechocystis* sp.

The algal unit concentration of the sedimentation effluent of Module I was below 2 500 units/ml during the study period, except during the end of July 1994 and the end of August 1995 when it was above 6 000 units/ml (Fig. 13). The highest algal unit concentration of the sedimentation effluent of Module I occurred during the end of July 1994 (Fig. 13, Table 1; 16 017 units/ml). The dominant algal species was *Synechocystis* sp. The algal unit concentration was relatively high (2 250 units/ml) during the beginning

of November 1994, while the chlorophyll-a concentration was relatively low (3 μg/l). The dominant algal species was *Chroococcus dispersus*.

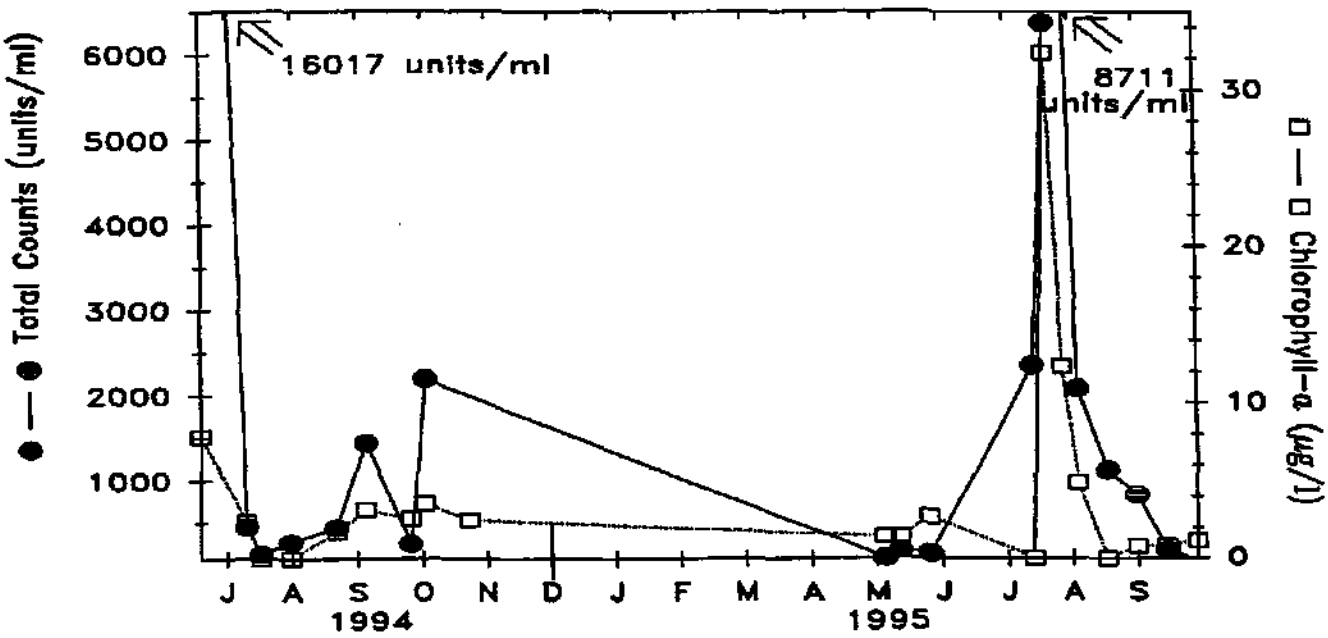

Figure 13: Phytoplankton biomass in μg/l chlorophyll-*a* and total counts in algal units/ml of the sedimentation effluent of Module I from July 1994 to October 1995.

The chlorophyll-a concentration varied throughout the study period in the flotation effluent (Fig. 14). The highest chlorophyll-a concentration in the flotation effluent occurred during the middle of September 1994 while the algal unit concentration was very low during this period (Fig. 14, Table 1; 3.43 μg/l). The dominant algal species were *Monoraphidium arcuatum* and *Scenedesmus opoliensis*.

The algal unit concentration was relatively low (below 250 units/ml) from the middle of August 1994 to the end of October 1994, during June 1995 and during October 1995 in the flotation effluent of Module I (Fig. 14). The dominant algal species were an unidentified centric diatom, *Monoraphidium arcuatum* and *Chlamydomonas* sp.

At Balkfontein chlorophyll-a concentrations in excess of 1 μg/l in the filtration effluent are considered to be problematic. There were only two periods when the chlorophyll-a concentration of the flotation-filtration effluent was above 1 μg/l, namely at the end of June 1995 (3 μg/l) and the beginning of September 1995 (Fig. 15; 1.2 μg/l).

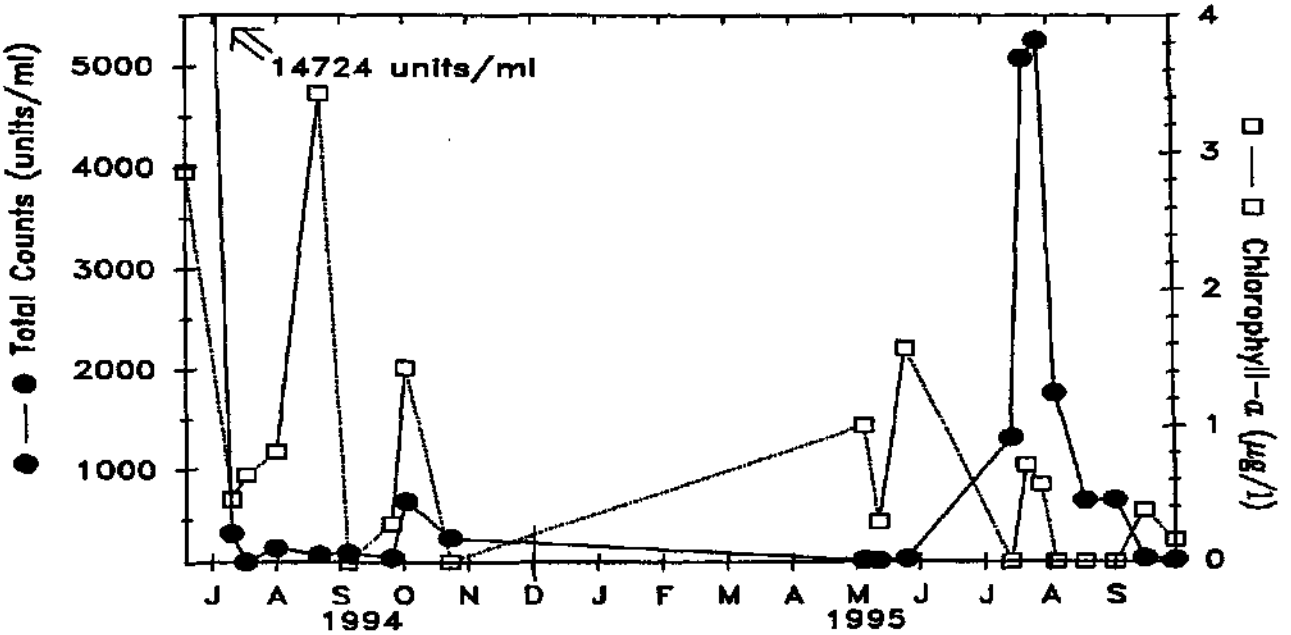

Figure 14: Phytoplankton biomass in µg/l chlorophyll-*a* and total counts in algal units/ml of the flotation effluent of Module I from July 1994 to October 1995.

The algal unit concentration was high in the flotation-filtration effluent during July 1994. This was due to a high concentration of *Synechocystis* sp. in the flotation-filtration effluent (Figs 11 & 12). The lowest algal unit concentration of the flotation-filtration effluent occurred at the beginning of August 1994 (below 25 units/ml), the chlorophyll-a concentration was below detection limit during this period in the flotation-filtration effluent of Module I (Fig. 15). The dominant algal species were *Oocystis lacustris* and *Actinastrum hantzschii*.

The turbidity of the sedimentation effluent varied throughout the study period (Fig. 16). The turbidity was the highest during the end of August 1994 (Fig. 16, Table 2; 4 NTU). There were two occasions when the turbidity was below 1 NTU, namely at the end of August 1995 and the end of September 1995 (Fig. 16). The total species number of the sedimentation effluent of Module I ranged between 9 and 29 during the study period (Fig. 16 & Table 2). The diversity index of the sedimentation effluent of Module I was below 10 during the study period (Fig. 16 & Table 2). The total counts was most of the time low when the turbidity was high in the secondary sedimentation effluent of Module I (Figs 13 & 16).

Table 1: Minimum, maximum and mean values of algal unit concentration and chlorophyll-*a* of the different sampling localities of Module I (See also Figs 3, 13, 14, 15, 60). nd = not detectable

Sampling localities	Algae (unit/ml)			Chlorophyll-a (μg/l)		
	Min	Max	Mean	Min	Max	Mean
River water	842	58 770	10 295	nd	130	39.86
Sedimentation	55	16 017	2 274	nd	32.38	4.08
Flotation	73	14 724	1 599	nd	3.43	0.73
Flotation-filtration	19	38 829	2 313	nd	3.0	0.42
Final water	10	8129	433	nd	3.43	0.26

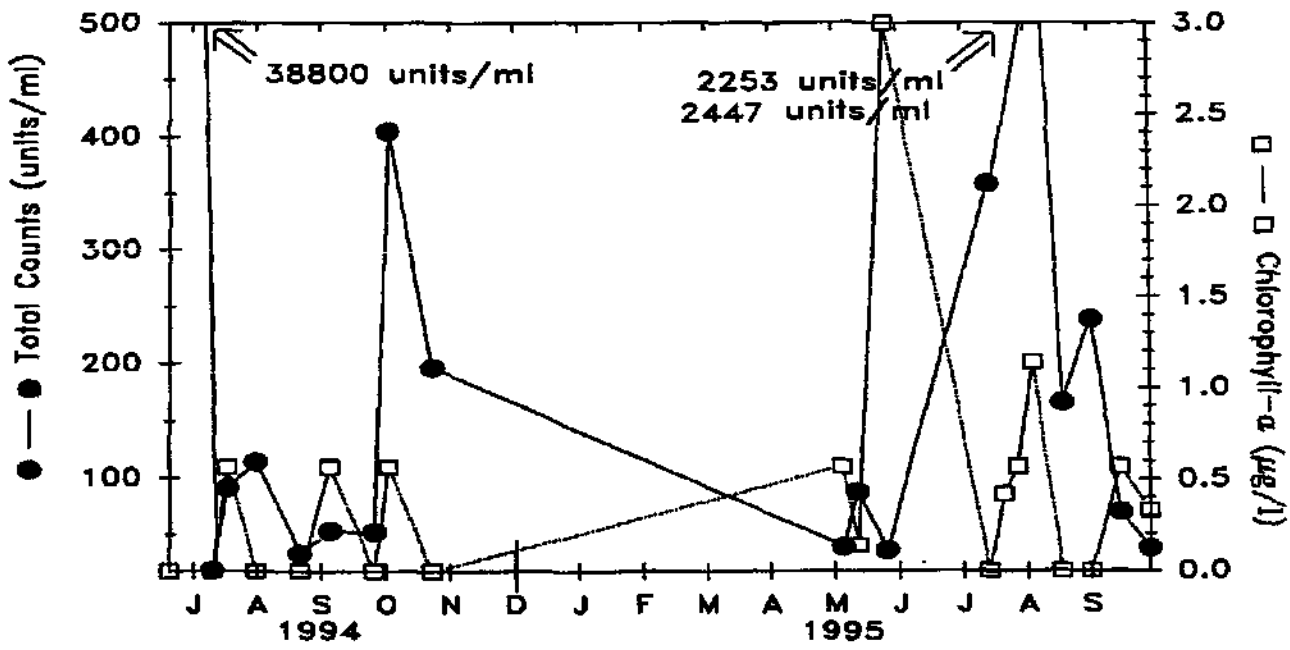

Figure 15: Phytoplankton biomass in μg/l chlorophyll-*a* and total counts in algal units/ml of the flotation-filtration effluent of Module I from July 1994 to October 1995.

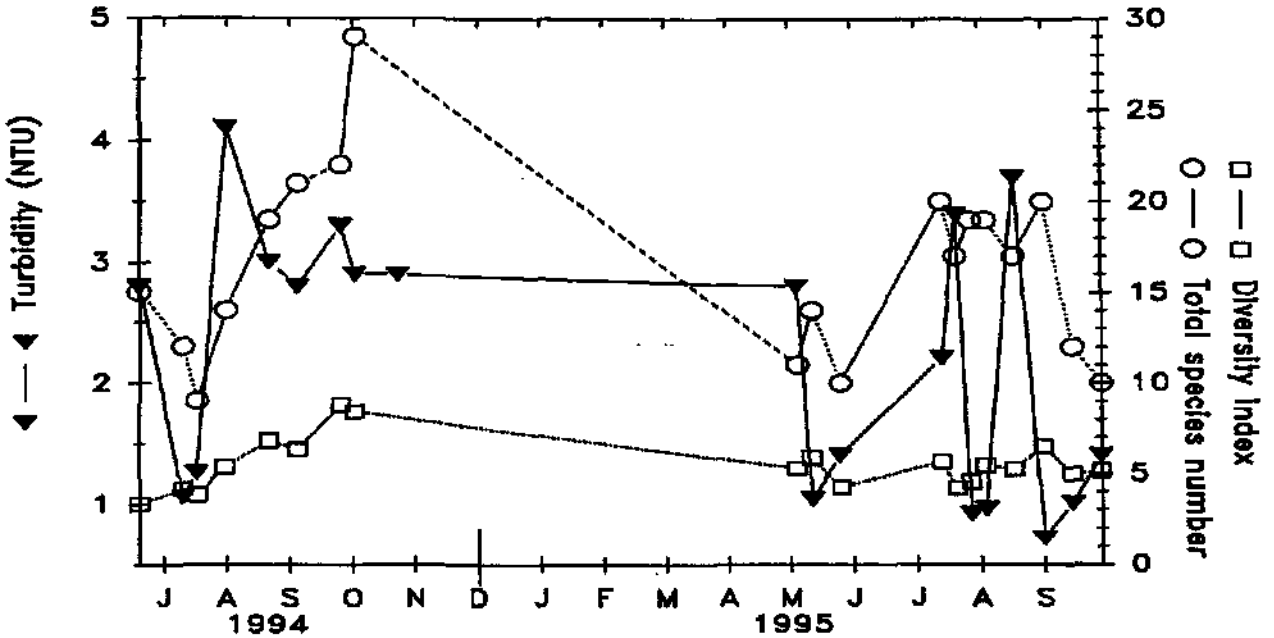

Figure 16: Species diversity in total species number and turbidity in NTU of the Sedimentation effluent of Module I from July 1994 to October 1995.

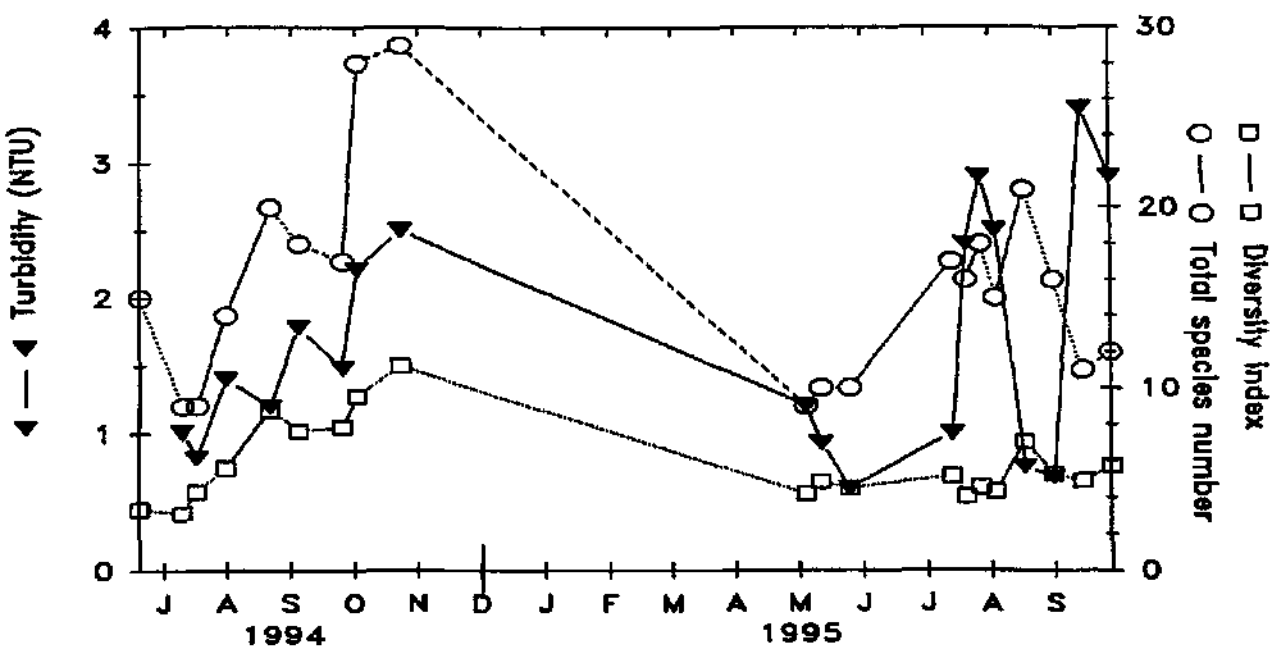

Figure 17: Species diversity in total species number and turbidity in NTU of the flotation effluent of Module I from July 1994 to October 1995.

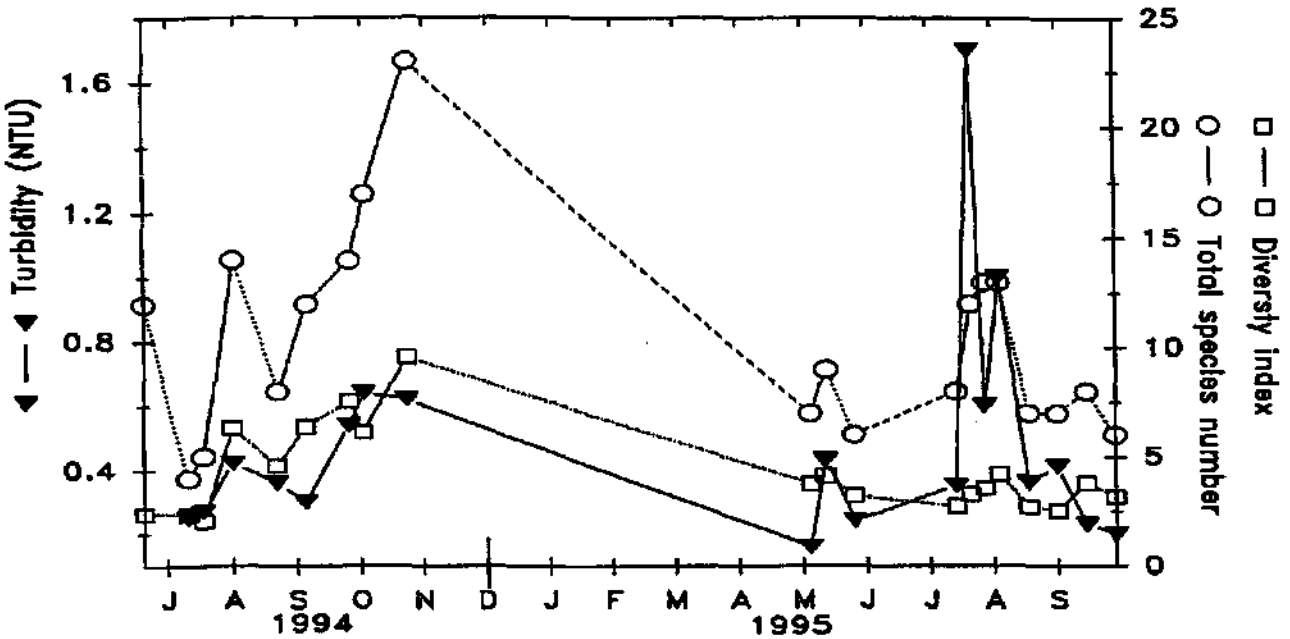

Figure 18: Species diversity in total species number and turbidity in NTU of the flotation-filtration effluent of Module I from July 1994 to October 1995.

Table 2: Minimum, maximum and mean values of turbidity, diversity index and total species number of the different sampling localities of Module I (See also Figs 4, 16, 17, 18, 61).

Sampling localities	Turbidity			Total species number			Diversity index		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
River water	7.9	1900	111.3	6	34	18.74	0	8.9	4.6
Sedimentation	0.72	4.1	2.18	9	29	16.32	3	8.7	5.5
Flotation	0.6	3.4	1.67	9	29	15.7	3	11	5.8
Flotation-filtration	0.10	0.95	0.40	3	24	11.02	1	8.06	4.7
Final water	0.13	2.3	0.58	3	23	11.7	1	9.6	5.2

Turbidity and species number varied throughout the study period in the flotation and flotation-filtration effluents of Module I.

The diversity index of the flotation effluent was below 11 and the diversity index of the flotation-filtration effluent was below 10 during the study period (Figs 17, 18 & Table 2).

Percentage removal

The percentage removal of chlorophyll-*a* during sedimentation, flotation and flotation-filtration varied throughout the study period, but the percentage removal of chlorophyll-*a* during the combined processes remained more or less constant and above 90% (Fig. 19).

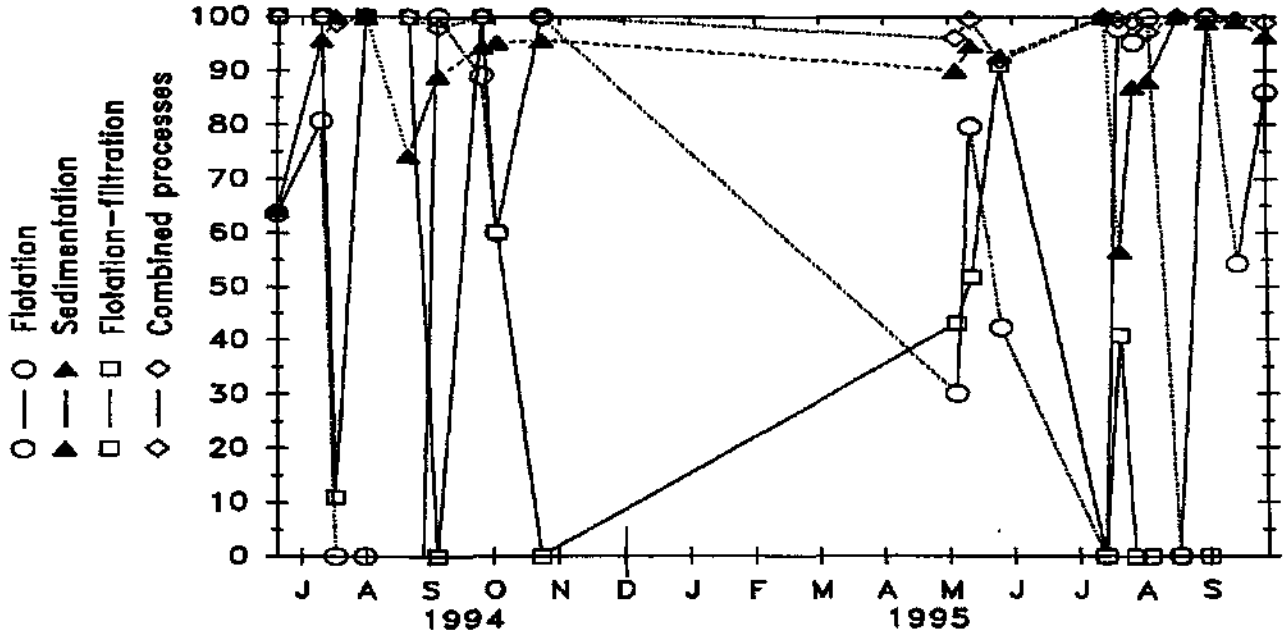

Figure 19: Percentage removal of chlorophyll-*a* by sedimentation, flotation, flotation-filtration and the combined processes of Module I from July 1994 to October 1995.

The percentage removal of chlorophyll-*a* during flotation was 0 during the middle and end of August 1994, the beginning of August 1995 and the middle of September 1995 (Fig. 19). The dominant algal species were *Chlamydomonas* sp. during August and September 1995 and an unidentified centric diatom during August 1994.

The percentage removal of chlorophyll-*a* during flotation-filtration was also 0 at the beginning of September 1994, end of November 1994, the beginning and end of August

1995 and September 1995 (Fig. 19). The dominant algal species were *Oocystis lacustris* during the beginning of September 1994, *Synechococcus cedrorum* during the end of November 1994 and *Chlamydomonas* sp. during August and September 1995.

Table 3 represents the minimum, maximum and mean values of four parameters of percentage removal of chlorophyll-*a*, algal units and turbidity being used here, namely during sedimentation, flotation, flotation-filtration separately and combined.

Table 3: Percentage removal of chlorophyll-*a*, algal units and turbidity by sedimentation, flotation, flotation-filtration and the combined processes of Module I (See also Figs 19, 20, 21).

Sampling localities	Chlorophyll-a (%)			Algal units (%)			Turbidity (%)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Sedimentation	57	100	91	-203*	99	84	62	98	87
Flotation	-100*	100	54	-51*	88	32	-236*	99	-8*
Flotation-filtration	-106*	100	32	-163*	95	40	29	93	68
Combined processes	92	100	99	-198*	99	83	91	99	97

* = negative removal indicates algal growth within the system.

The percentage removal of algal units during the combined processes remained more or less constant while the percentage removal of algal unit concentration during sedimentation, flotation and flotation-filtration varied throughout the study period (Fig. 20).

During the beginning of July 1994 an increase in algal unit concentration occurred between the river water (13 013 units/ml) and the flotation-filtration effluent (38 829 units/ml); therefore a negative percentage removal was demonstrated (Fig. 20, Table 3). This was due to an increase in the concentration of *Synechocystis* sp.

During June 1995 a negative percentage removal of algal units by flotation and flotation-filtration occurred due to an increase in algal units from the sedimentation to the flotation-filtration effluent of Module I. The dominant algal species were *Monoraphidium arcuatum*, an unidentified centric diatom and *Synechococcus cedrorum*.

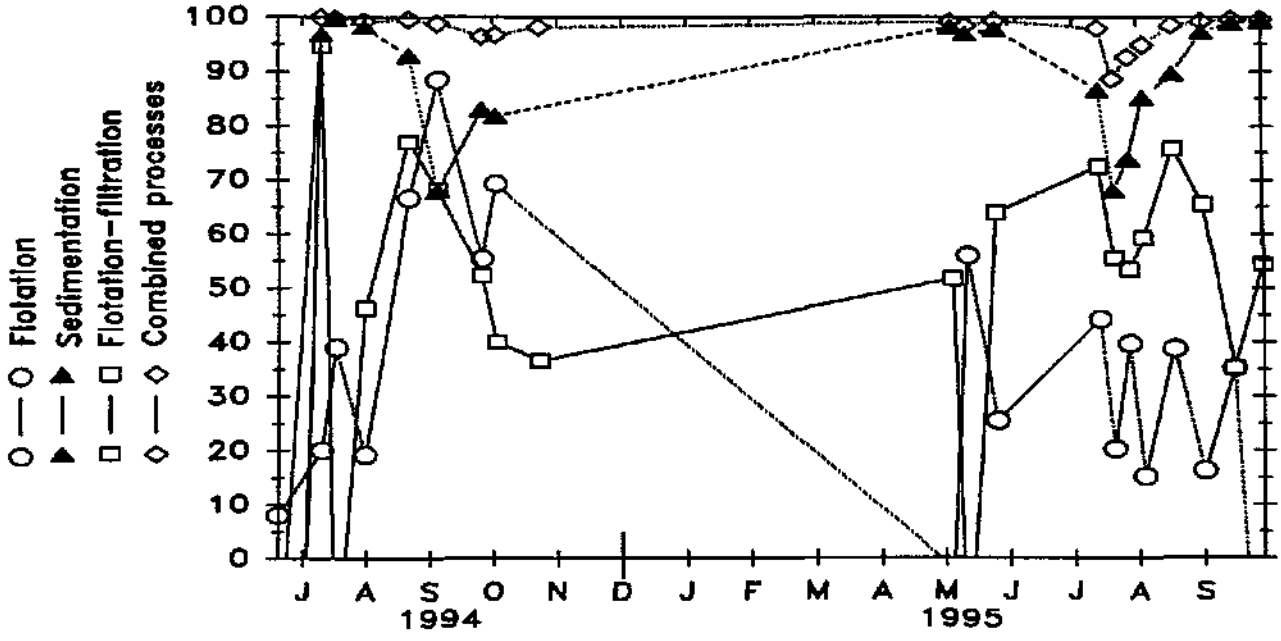

Figure 20: Percentage removal of algal units by sedimentation, flotation, flotation-filtration and the combined processes of Module I from July 1994 to October 1995.

The percentage removal of turbidity during sedimentation, flotation and flotation-filtration varied throughout the study period, while the percentage removal during the combined processes remained more or less constant throughout the study period (Fig. 21). The percentage removal of turbidity was above 60% during the study period (Fig. 21). The percentage removal of turbidity during flotation was negative during the end of July and the beginning of August 1995 due to an increase in turbidity from the sedimentation to the flotation effluent of Module I (Fig. 21).

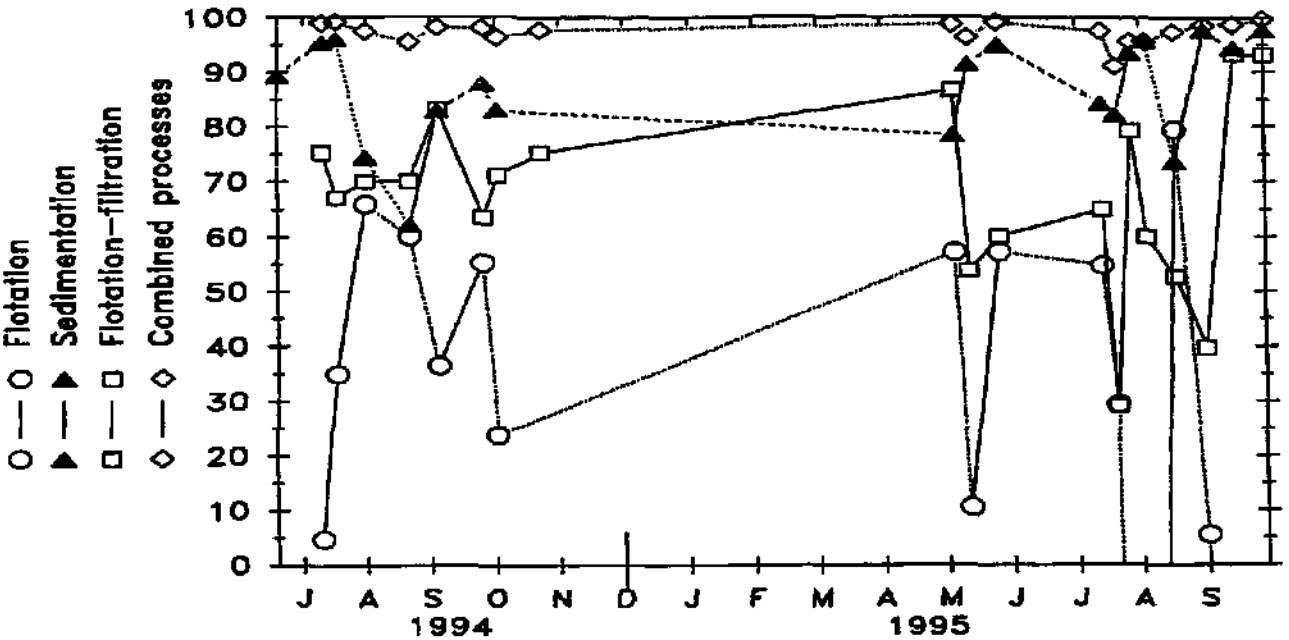

Figure 21: Percentage removal of turbidity by sedimentation, flotation, flotation-filtration and the combined processes of Module I from July 1994 to October 1995.

Morphological groups

A peak of unicellular spherical cells (Unsp) occurred during July 1994 in the sedimentation effluent of Module I (Figs 22 & 23). The dominant algal species were *Synechocystis* sp. and *Synechococcus cedrorum*.

Four peaks of unicellular flagellated cells (Unfl) occurred in the sedimentation effluent of Module I, namely at the beginning of October 1994, the beginning of August 1995, the beginning of September 1995 and at the end of October 1995 (Figs 22 & 23). The dominant species were *Chlamydomonas* sp. and *Chlamydomonas incerta*.

Three peaks of unicellular discoidal cells (Undi) occurred in the sedimentation effluent of Module I, namely at the beginning of August 1994, the end of August 1994 and the end of July 1995 (Figs 22 & 23). The dominant algal species was an unidentified centric diatom.

A peak of colonial algae with spherical cells (Cosp) occurred during the middle of August 1995 in the sedimentation effluent of Module I (Figs 22 & 23). The dominant species were *Actinastrum hantzschii* and *Coelastrum carpaticum*.

During the beginning of August 1994 unicellular discoidal cells (Undi) were dominant in the flotation effluent (Figs 24 & 25). The dominant algal species was an unidentified centric diatom.

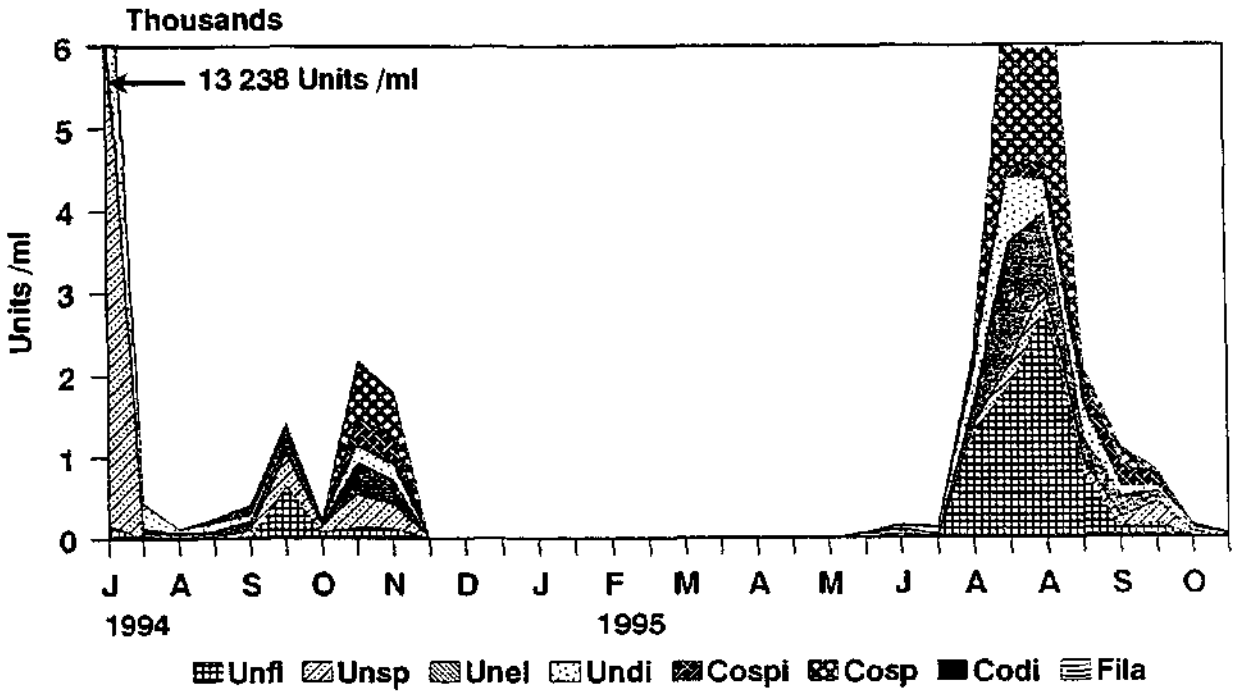

Figure 22: Phytoplankton counts of morphological groups of the sedimentation effluent of Module I from July 1994 to October 1995.
Unfl = Unicellular flagellated cells, Unsp = Unicellular spherical cells, Unel = Unicellular elongated cells, Undi = Unicellular discoidal cells, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Cospi = Colonial algae individual cells with spines, Fila = Filaments.

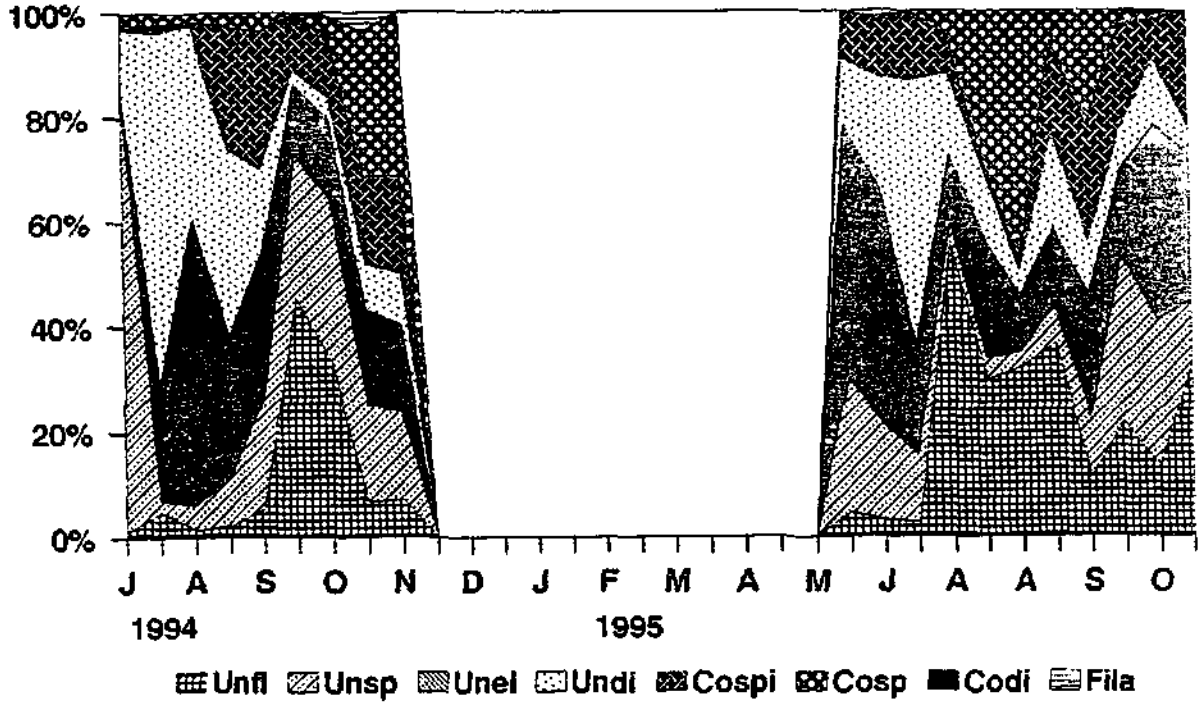

Figure 23: Phytoplankton composition (%) of morphological groups of the sedimentation effluent of Module I from July 1994 to October 1995.
Unfl = Unicellular flagellated cells, Unsp = Unicellular spherical cells, Unel = Unicellular elongated cells, Undi = Unicellular discoidal cells, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Cospi = Colonial algae individual cells with spines, Fila = Filaments.

Unicellular elongated cells (Unel) were dominant in the flotation effluent during the middle of August 1994 (Figs 24 & 25). The dominant algal species was *Trachelomonas intermedia*.

The unicellular spherical cells (Unsp) was dominant during July 1994 in the flotation effluent of Module I (Figs 24 & 25). The dominant algal species were *Synechocystis* sp. and *Synechococcus cedrorum*.

The unicellular flagellated cells (Unfl) was dominant in the flotation effluent of Module I during the beginning of August 1995 and during September and October 1995 (Figs 24 & 25). The dominant species were *Chlamydomonas* sp. and *Chlamydomonas incerta*.

Unicellular discoidal cells (Undi) were more efficiently removed when compared to the other groups during flotation (Figs 24 & 25).
A peak of unicellular discoidal cells (Undi) occurred during the middle of August 1994 in the flotation-filtration effluent (Figs 26 & 27). The dominant algal species was an unidentified centric diatom.

The unicellular flagellated cells (Unfl) were dominant during July 1994 and from the beginning of August 1995 to the end of September 1995 in the flotation-filtration effluent of Module I (Figs 26 & 27). The dominant species were *Chlamydomonas* sp. and *Chlamydomonas incerta*.

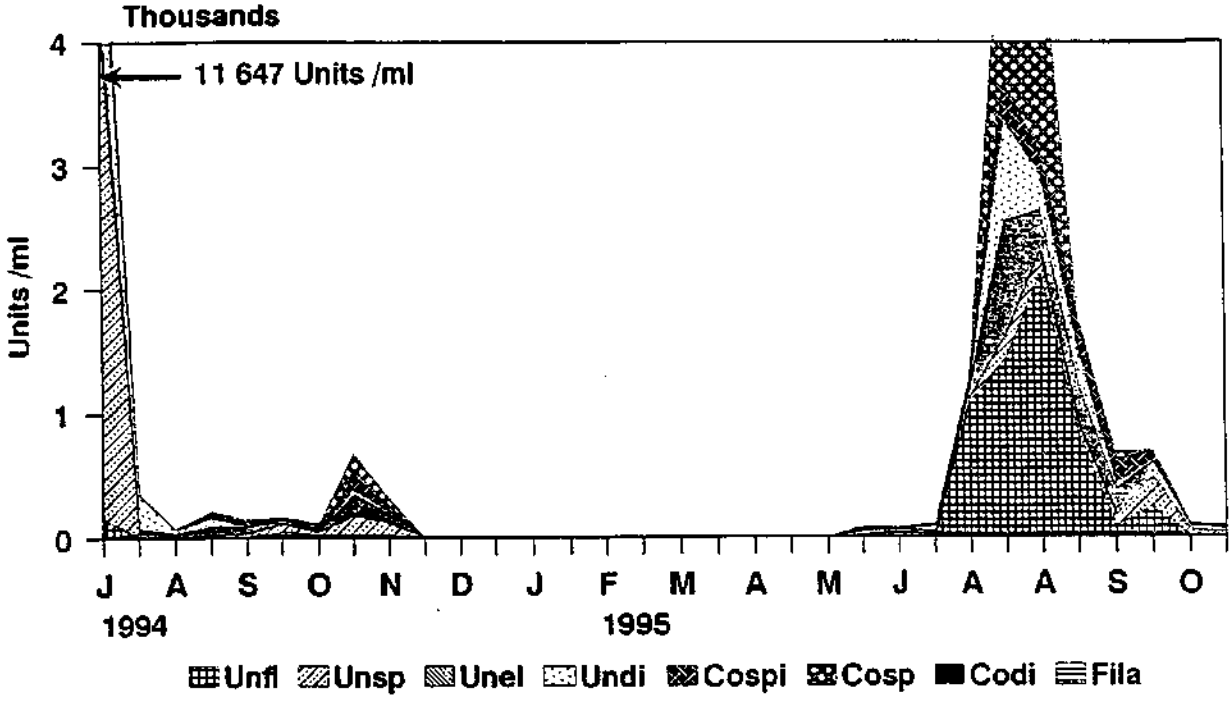

Figure 24: Phytoplankton counts of morphological groups of the flotation effluent of Module I from July 1994 to October 1995.
Unfl = Unicellular flagellated cells, Unsp = Unicellular spherical cells, Unel = Unicellular elongated cells, Undi = Unicellular discoidal cells, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Cospi = Colonial algae individual cells with spines, Fila = Filaments.

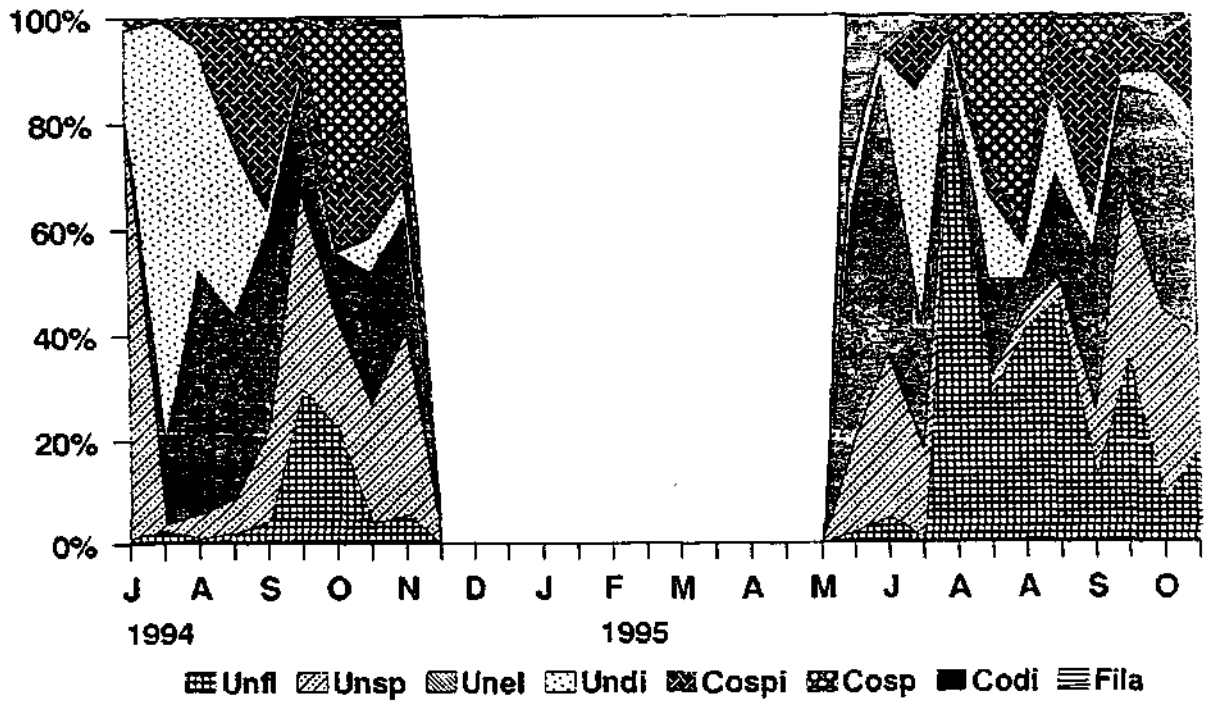

Figure 25: Phytoplankton composition (%) of morphological groups of the flotation effluent of Module I from July 1994 to October 1995.
Unfl = Unicellular flagellated cells, Unsp = Unicellular spherical cells, Unel = Unicellular elongated cells, Undi = Unicellular discoidal cells, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Cospi = Colonial algae individual cells with spines, Fila = Filaments.

The unicellular elongated cells were dominant in the flotation-filtration effluent of Module I during June and July 1995 (Figs 26 & 27). The dominant algal species were *Monoraphidium arcuatum* and *Monoraphidium minutum*.

Colonial algae, individual cells with spines (Cospi) were efficiently removed by flotation-filtration when compared with the other groups (Figs 26 & 27).

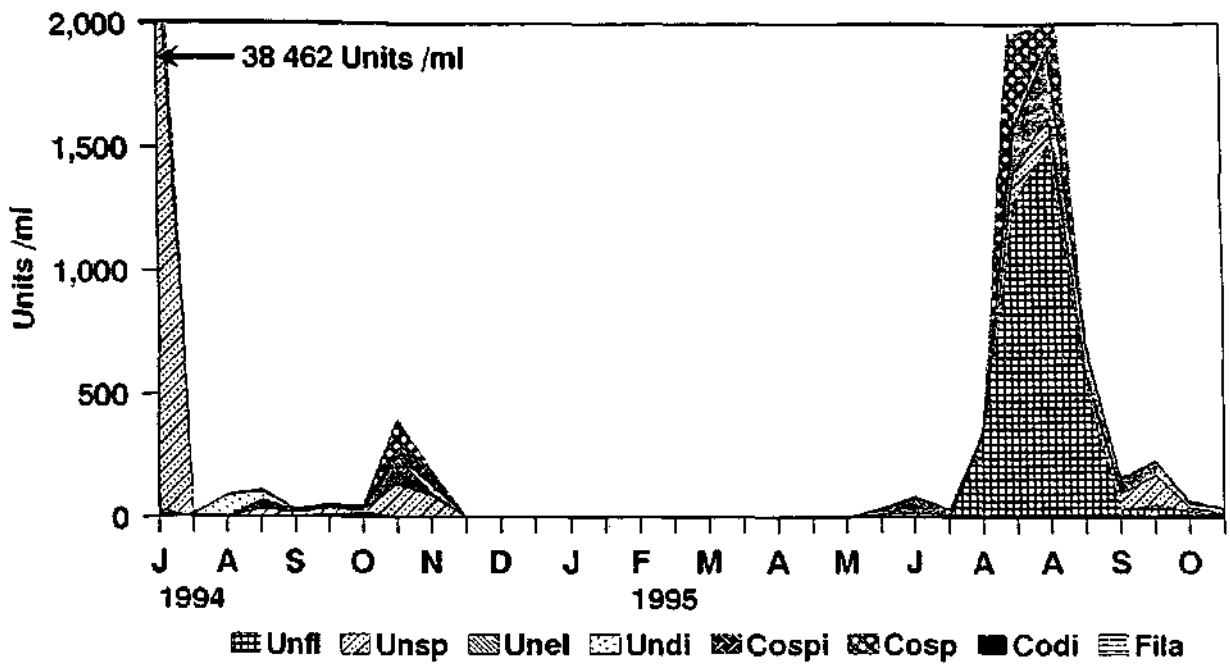

Figure 26: Phytoplankton counts of morphological groups of the flotation-filtration effluent of Module I from July 1994 to October 1995.
Unfl = Unicellular flagellated cells, Unsp = Unicellular spherical cells, Unel = Unicellular elongated cells, Undi = Unicellular discoidal cells, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Cospi = Colonial algae individual cells with spines, Fila = Filaments.

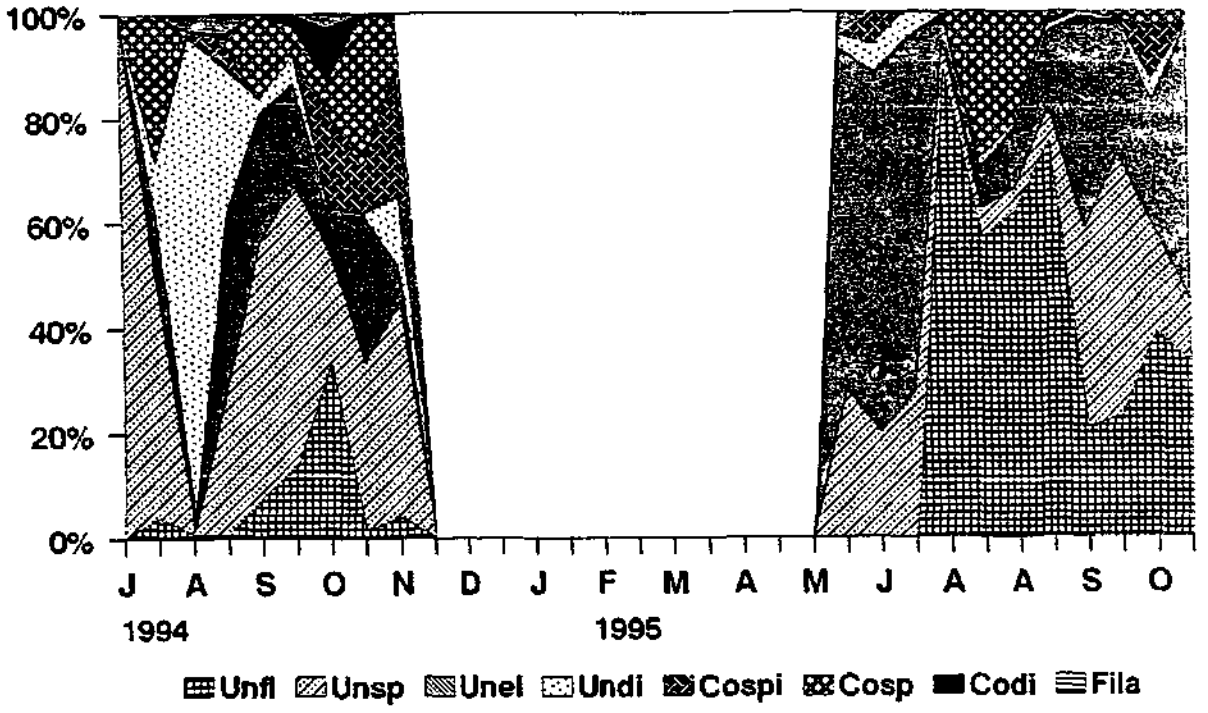

Figure 27: Phytoplankton composition (%) of morphological groups of the flotation-filtration effluent of Module I from July 1994 to October 1995.
Unfl = Unicellular flagellated cells, Unsp = Unicellular spherical cells, Unel = Unicellular elongated cells, Undi = Unicellular discoidal cells, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Cospi = Colonial algae individual cells with spines, Fila = Filaments.

Discussion of results of Module I

During July 1994 high algal unit concentrations occurred in the sedimentation, flotation and flotation-filtration effluent of Module I (Figs 13, 14, 15). High chlorophyll-*a* concentrations occurred in the sedimentation and flotation effluents of Module I during this period (Figs 13, 14). The flow through the Module was low, possibly allowing algal cells to grow in the system. This could be a reason for the high concentrations of the blue-green alga, *Synechocystis* sp., in the water (Table 5). During this period no pre-lime, carbon dioxide and polymer were dosed (Table 5). According to Bernhardt &

Clasen (1995) lower removal rates were obtained with respect to small algal cells like *Synechocystis* sp. (a small cell-sized blue-green alga).

Vosloo and Langenegger (1987) found that certain blue-green algae are small enough to pass through the sand filter when floc-formation was inefficient. Inefficient flocculation could, therefore, be another reason for the high concentrations of *Synechocystis* sp. in the flotation-filtration effluent.

During the end of June 1995 the chlorophyll-a concentration was the highest (3 μg/l) in the flotation-filtration effluent of Module I (Fig. 15, Table 1). During this period the green algae were dominant in the flotation-filtration effluent of Module I (Figs 11 & 12). The diatoms were removed by flotation-filtration during this period. The percentage removal of chlorophyll-*a* by flotation and flotation-filtration was very low (0 %). The concentration of polymer dosed was below 1 mg/l and the concentration of $FeCl_3$ dosed was below 3 mg/l during this period. The pre-chlorine dosage was relatively low (below 4 mg/l). This particular dosage concentration and combination were therefore not successful in the removal of the green algae from the water, but removed the diatoms successfully in relation to the green algae. The dominant green algae were *Monoraphidium arcuatum* and *Oocystis lacustris*.

During the beginning of September 1995 the chlorophyll-a concentration of the flotation-filtration effluent was above 1 μg/l (Fig. 15) and with regard to the Balkfontein operation protocol a chlorophyll-a concentration of more than 1 μg/l in the filtration effluent is considered to be too high. The concentration of polymer dosed was low (0.2 mg/l) during this period. The pre-chlorine dosage was high (4 mg/l) and the $FeCl_3$ dosage was 3 mg/l. The green algae were dominant in the flotation-filtration effluent of Module I during this period (Figs 11 & 12). The diatoms was efficiently removed by flotation-filtration. The percentage removal of chlorophyll-*a* by flotation-filtration was very low (0%) during this period (Fig. 19).

The following list gives an indication of the species which penetrated the sedimentation (Sed), flotation (Flot) and flotation-filtration (Flot-filtr) processes of Module I.

	Sed	Flot	Flot-Filt
Green algae:			
Monoraphidium arcuatum (Unel)*	X	X	X
Monoraphidium circinale (Unel)	X	X	X

Oocystis lacustris (Unsp)	X	X	X
Carteria simplicissima (Unfl)	X	X	X
Chlamydomonas incerta (Unfl)	X	X	X
Chlamydomonas sp. (Unfl)	X	X	X
Actinastrum hantzschii (Cosp)	X	X	
Blue-green algae:			
Synechococcus cedrorum (Unel)	X	X	X
Synechocystis sp. (Unsp)	X	X	X
Microcystis flos-aquae (Cosp)	X	X	X
Diatoms:			
Centric diatom (Undi)	X	X	X
Melosira granulata (Fila)	X	X	X
Pennate diatom (Unel)	X	X	X
Euglenophytes:			
Phacus pyrum (Unfl)	X	X	
Trachelomonas intermedia (Unfl)	X	X	X
Trachelomonas scabra (Unfl)	X	X	
Euglena sp. (Unel)		X	

*Unfl = Unicellular flagellated cells, Unsp = Unicellular spherical cells, Unel = Unicellular elongated cells, Undi = Unicellular discoidal cells, Cosp = Colonial algae with spherical cells, Fila = Filaments.

It is clear that almost the same species of unicellular algae penetrated the flotation and flotation-filtration phases of Module I. Unicellular algal species are therefore removed less efficiently from the water during sedimentation, flotation and flotation-filtration.

Only a small amount of colonial algae with discoidal cells (Codi), colonial algae with spherical cells (Cosp), colonial algae individual cells with spines and filaments penetrated the sedimentation, flotation and flotation-filtration effluents of Module I (Figs 22-27), indicating that these morphological forms are removed more efficiently than the unicellular forms.

Table 5 gives an indication of the algal species that penetrated the different phases of Module I under certain dosing conditions. During August and September 1995

Chlamydomonas sp., *Monoraphidium arcuatum* and *Actinastrum hantzcshii* (green algae) were not successfully removed in Module I. The species that were present in large quantities in the river water were difficult to remove during the different phases. Exceptions were *Synechocystis* sp. and *Chroococcus dispersus* (blue-green algae) which were not present in the river, but they were observed after secondary sedimentation and in the following phases of purification.

Table 4: Occurrence of phytoplankton species in the raw, sedimentation, flotation, sand filtration and final water of Module I of the Goldfield Water purification plant at Balkfontein.

	River*	Sed*	Flot*	Filtr*	Finw*
CYANOPHYCEAE (Cyano)**					
Anabaena circinales	X	-	-	-	-
Chroococcus dispersus	-	X	X	X	X
Merismopedia minima	-	-	-	X	X
Microcystis aeruginosa	X	X	X	X	X
Microcystis flos-aquae	X	X	X	X	X
Microcystis incerta	-	X	X	X	X
Oscillatoria simplicissima	X	X	X	X	X
Synechococcus cedrorum	X	X	X	X	X
Synechocystis sp.	-	X	X	X	X
BACILLARIOPHYCEAE (Baci)**					
Centric diatoms	X	X	X	X	X
Melosira granulata	X	X	X	X	X
Pennate diatoms	X	X	X	X	X
CHLOROPHYCEAE (Chlo)**					
Actinastrum hantzschii	X	X	X	X	X

Table 4 continued

	River*	Sed*	Flot*	Filtr*	Finw*
Ankistrodesmus bibraianus	X	X	-	-	-
Ankistrodesmus falcatus	-	-	-	-	X
Ankistrodesmus stipitatus	X	X	X	X	X
Carteria globosa	X	X	X	-	X
Carteria simplicissima	X	X	X	X	X
Characium limneticum	-	-	-	-	X
Chlamydomonas bicocca	X	X	X	X	X
Chlamydomonas incerta	X	X	X	X	X
Chlamydomonas sp.	X	X	X	X	X
Chlorococcum infusionum	X	X	X	X	X
Coelastrum carpaticum	X	X	X	X	X
Coelastrum pseudomicroporum	X	X	X	X	X
Cosmarium laeve	X	X	X	X	X
Crucigenia lauterbornii	X	-	-	-	-
Crucigenia tetrapedia	X	X	X	-	X
Crucigeniella rectangularis	X	-	-	X	X
Dictyosphaerium elegans	X	X	X	X	X
Eudorina elegans	X	X	X	-	-
Golenkinia radiata	X	X	X	-	-
Kirchneriella sp.	X	X	X	-	X
Lagerheimia balatonica	X	X	X	X	X
Micractinium pusillum	X	X	X	X	-
Monoraphidium arcuatum	X	X	X	X	X
Monoraphidium circinale	X	X	X	X	X
Monoraphidium griffithi	X	X	X	-	X
Monoraphidium minutum	X	X	X	X	X

Table 4 continued

	River*	Sed*	Flot*	Filtr*	Finw*
Oocystis lacustris	X	X	X	X	X
Oocystis marssonii	X	X	X	X	X
Pandorina morum	X	X	-	X	-
Pediastrum duplex	X	X	X	X	X
Pediastrum simplex	X	X	X	-	X
Pediastrum tetras	X	-	X	-	-
Pteromonas aculeata	X	X	X	X	X
Scenedesmus acuminatus	X	X	X	X	X
Scenedesmus disciformis	X	X	X	X	X
Scenedesmus intermedius	X	X	X	X	X
Scenedesmus lefevrii	X	X	X	X	X
Scenedesmus opoliensis	X	X	X	X	X
Scenedesmus smithii	-	-	-	-	X
Schroederia indica	X	-	-	-	-
Tetraedron limneticum	-	-	X	-	X
Tetraedron mediocris	X	X	X	X	X
Tetraedron planctonicum	X	-	-	-	X
Tetraedron regulare	X	-	-	-	-
Tetrastrum heteracanthum	X	-	-	-	X
Tetrastrum staurogeniaeforme	X	X	X	-	X
CRYPTOPHYCEAE (Crypto)**					
Cryptomonas major	X	X	X	X	-
DINOPHYCEAE (Dino)**					
Peridinium penardiforme	X	-	-	-	-

Table 4 continued

	River*	Sed*	Flot*	Filtr*	Finw*
Sphaerodinium ravumfluvium	X	X	X	X	X
EUGLENOPHYCEAE (Eugl)**					
Euglena clavata	-	-	X	X	-
Euglena hemichromata	X	X	-	-	-
Euglena pusilla	X	-	-	-	-
Euglena sp.	X	X	X	-	X
Lepocinclis salina	X	X	-	-	X
Phacus acuminatus	X	-	-	X	X
Phacus longicauda	X	-	X	-	X
Phacus pyrum	X	X	X	-	X
Strombomonas fluviatilis	X	X	-	-	X
Strombomonas ovalis	X	-	-	-	-
Strombomonas verrucosa	X	-	-	-	-
Trachelomonas intermedia	X	X	X	X	X
Trachelomonas scabra	X	X	X	-	X
Trachelomonas volvocina	X	-	-	-	-
TOTAL	68	56	55	44	59

*River = water from the river; Sed = effluent from secondary sedimentaton tank; Flot = water that has been flotated prior to filtration; Filtr = effluent from sand filter; Final water = final water, post-chlorinated

** Cyano = Cyanophyceae, blue-green algae; Baci = Bacillariophyceae, diatoms; Chlo = Chlorophyceae, green algae; Crypto = Cryptophyceae; Dino = Dinophyceae; Eugl = Euglenophyceae.

Table 5: Dosage concentration and algal species penetrating sedimentation, flotation and sand filtration phases of Module I

DATE	DOSAGE CONCENTRATION	SEDIMENTATION		FLOTATION		FILTRATION	
		Algal species	Chl-*a*	Algal species	Chl-*a*	Algal species	Chl-*a*
19/7/94	No Pre-lime No Polymer Pre-chlorine (4 mg l^{-1}) $FeCl_3$ (2 mg^{-1})	***Synechocystis* sp. (blue-green alga)	7.88 µg l^{-1}	***Synechosystis* sp. (blue-green alga)	2.87 µg l^{-1}	***Synechocystis* sp. (blue-green alga)	0 µg l^{-1}
5/10/94	No Pre-lime Polymer (0.7 mg l^{-1}) Pre-chlorine (5.9 mg l^{-1}) $FeCl_3$ (1.9 mg l^{-1})	**Carteria simplicissima* (green alga)	3.15 µg l^{-1}	**Oocystis lacustris* (green alga)	0 µgl^{-1}	**Synechococcus cedrorum* (blue-green alga)	0.57 µg l^{-1}
26/10/94	No Pre-lime Polymer (0.7 mg l^{-1}) Pre-chlorine (4.4 mg l^{-1}) $FeCl_3$ (1.8 mg l^{-1})	**Synechococcus cedrorum* (blue-green alga)	2.57 µg l^{-1}	***Chroococcus dispersis* (blue-green alga)	0.28 µg l^{-1}	**Chlamydomonas incerta* (green alga)	0 µg l^{-1}
2/11/94	No Pre-lime Polymer (0.7 mg l^{-1}) Pre-chlorine (6.1 mg l^{-1}) $FeCl_3$ (1.8 mg l^{-1})	***Chroococcus dispersis* (blue-green alga)	3.58 µg l^{-1}	**Monoraphidium circinale* (green alga)	1.43 µg l^{-1}	**Monoraphidium circinale* (green alga)	0.57 µg l^{-1}
23/8/95	Pre-lime (55.9 mg l^{-1}) Polymer (0.3 mg l^{-1}) No Pre-chlorine $FeCl_3$ (3.0 mg l^{-1})	**Chlamydomonas* sp. (green alga)	32.4 µg l^{-1}	**Chlamydomonas* sp. (green alga)	0.71 µg l^{-1}	**Chlamydomonas* sp. (green alga)	0.42 µg l^{-1}

16/8/95	Pre-lime (62.4 mg l^{-1}) Polymer (0.3 mg l^{-1}) Pre-chlorine (7.0 mg l^{-1}) $FeCl_3$ (3.0 mg l^{-1})	**Chlamydomonas* sp. (green alga)	0 $\mu g l^{-1}$	**Chlamydomonas* sp. (green alga)	0 $\mu g l^{-1}$	**Chlamydomonas* sp. (green alga)	0 $\mu g\ l^{-1}$
18/9/95	Pre-lime (53.9 mg l^{-1}) No Polymer Pre-chlorine (4 mg l^{-1}) $FeCl_3$ (5.8 mg l^{-1})	**Monoraphidium arcuatum* (green alga)	0 $\mu g l^{-1}$	**Monoraphidium arcuatum* (green alga)	0 $\mu g l^{-1}$	*Monoraphidium arcuatum (green alga)	0 $\mu g\ l^{-1}$
3/10/95	Pre-lime (37.1 mg l^{-1}) Polymer (0.1 mg l^{-1}) Pre-chlorine (1.4 mg l^{-1}) $FeCl_3$ (4.9 mg l^{-1})	**Synechococcus cedrorum* (blue-green alga)	0.76 $\mu g\ l^{-1}$	**Synechococcus cedrorum* (blue-green alga)	0 $\mu g l^{-1}$	**Synechococcus cedrorum* (blue-green alga)	0 $\mu g\ l^{-1}$
30/8/95 5/9/95	Pre-lime (38.7 mg l^{-1}) Polymer (0.25 mg l^{-1}) Pre-chlorine (4.0 mg l^{-1}) $FeCl_3$ (3.4 mg l^{-1})	**Actinastrum hantzschii* (green alga)	8.6 $\mu g\ l^{-1}$	**Actinastrum hantzschii* (green alga)	0.5 $\mu g\ l^{-1}$	**Actinastrum hantzschii* (green alga)	0.86 $\mu g\ l^{-1}$

* Species present in river water in large quantities

** Species not present in river water

Module II

Major taxonomical groups

Representatives of six different algal groups were present in the different stages of the purification process of Module II from August 1993 to April 1996 (Table 9). The groups were Cyanophyceae (blue-green algae), Bacillariophyceae (diatoms), Chlorophyceae (green algae), Euglenophyceae (euglenophytes), Dinophyceae (dinoflagellates) and Cryptohyceae (cryptophytes).

The diatoms were dominant during the end of August 1993, December 1995 in the sedimentation effluent of Module II and the dominant species was an unidentified centric diatom and *Melosira granulata* (Figs 28 & 29).

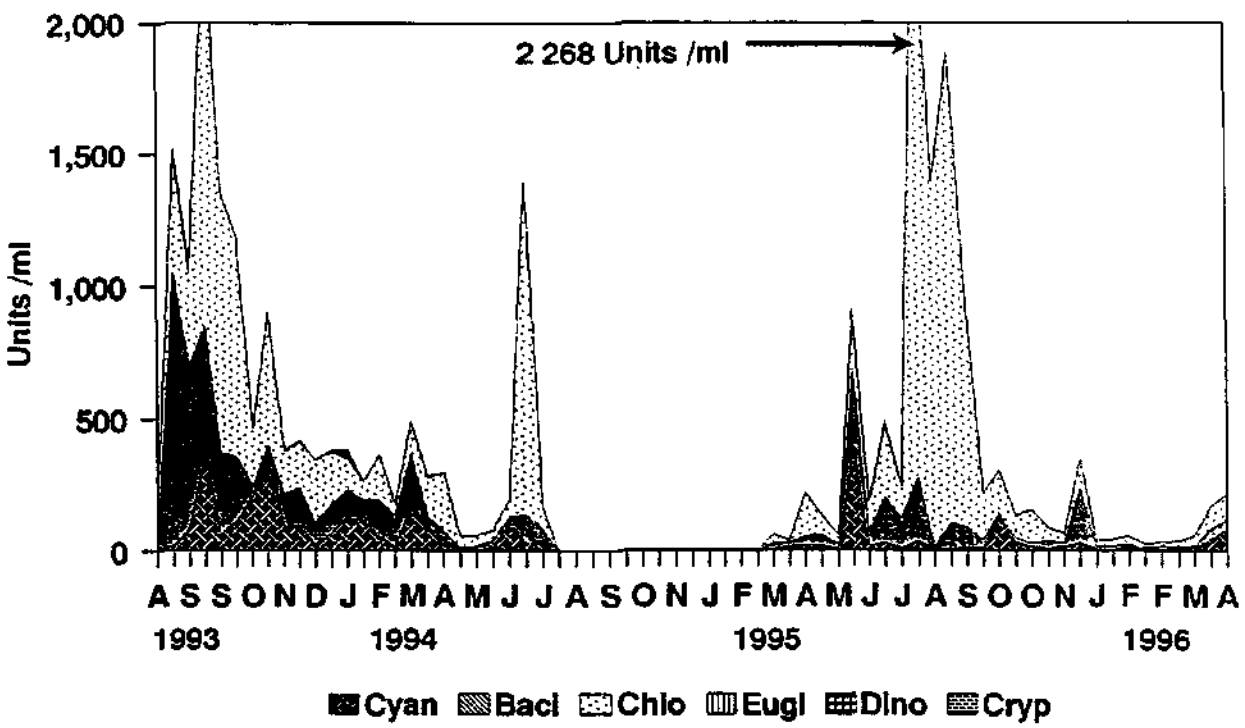

Figure 28: Phytoplankton counts of the major taxonomical groups of the secondary sedimentation effluent of Module II from August 1993 to April 1996.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Dino = Dinophyceae, Cryp = Cryptophyceae.

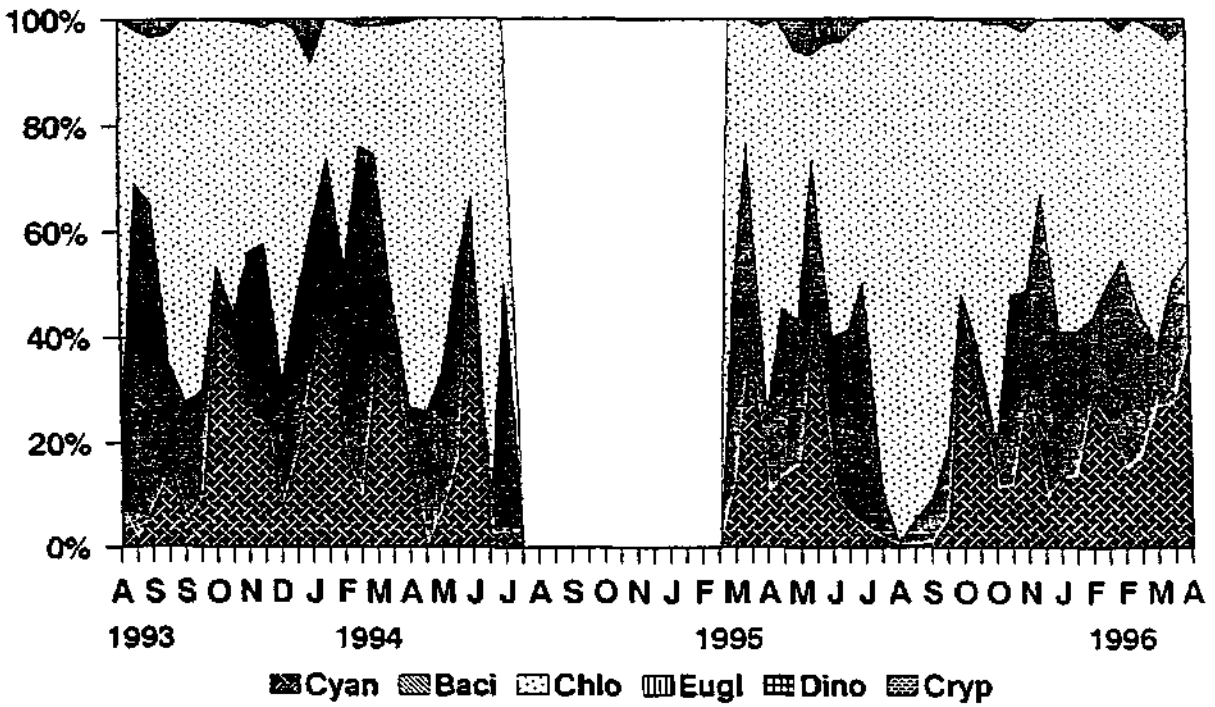

Figure 29: Phytoplankton composition (%) of the major taxonomical groups of the secondary sedimentation effluent of Module II from August 1993 to April 1996. Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Dino = Dinophyceae, Cryp = Cryptophyceae.

The diatoms were dominant during the end of February 1994 and at the beginning of March 1994 in the secondary sedimentation and sand filtration effluents of Module II (Figs 28-31). The greatest amount of diatoms was removed through sedimentation, therefore sedimentation was more efficient in removing centric diatoms (Figs 1 & 2, 28-31, 58 & 59). The dominant diatom species in the sedimentation effluent were *Melosira granulata* and an unidentified pennate diatom. In the sand filtration effluent unidentified pennate diatoms were also dominant.

The green algae increased in relation to other groups from the river water to the sedimentation effluent of Module II (Figs 1 & 2, 28 & 29). The green algae were dominant during the following periods in the sedimentation effluent of Module II namely, the beginning of August 1993, during September 1993, the end of December 1993, during April and the beginning of May 1994, beginning of July 1994, beginning of April 1995, during August and September 1995 and during the end of October 1995 (Figs 28

& 29). The dominant algal species were *Monoraphidium arcuatum, Chlamydomonas incerta, Chlamydomonas* sp. and *Oocystis lacustris.*

Blue-green algae were dominant during the beginning of June 1994 in the sedimentation effluent (Figs 28 & 29). The dominant algal species were *Chroococcus dispersus* and *Synechococcus cedrorum.*

A peak of diatoms occurred during the end of July 1994 and at the end of February 1996 in the filtration effluent of Module II (Figs 30 & 31). The dominant species were an unidentified centric, an unidentified pennate diatom and *Melosira granulata.*

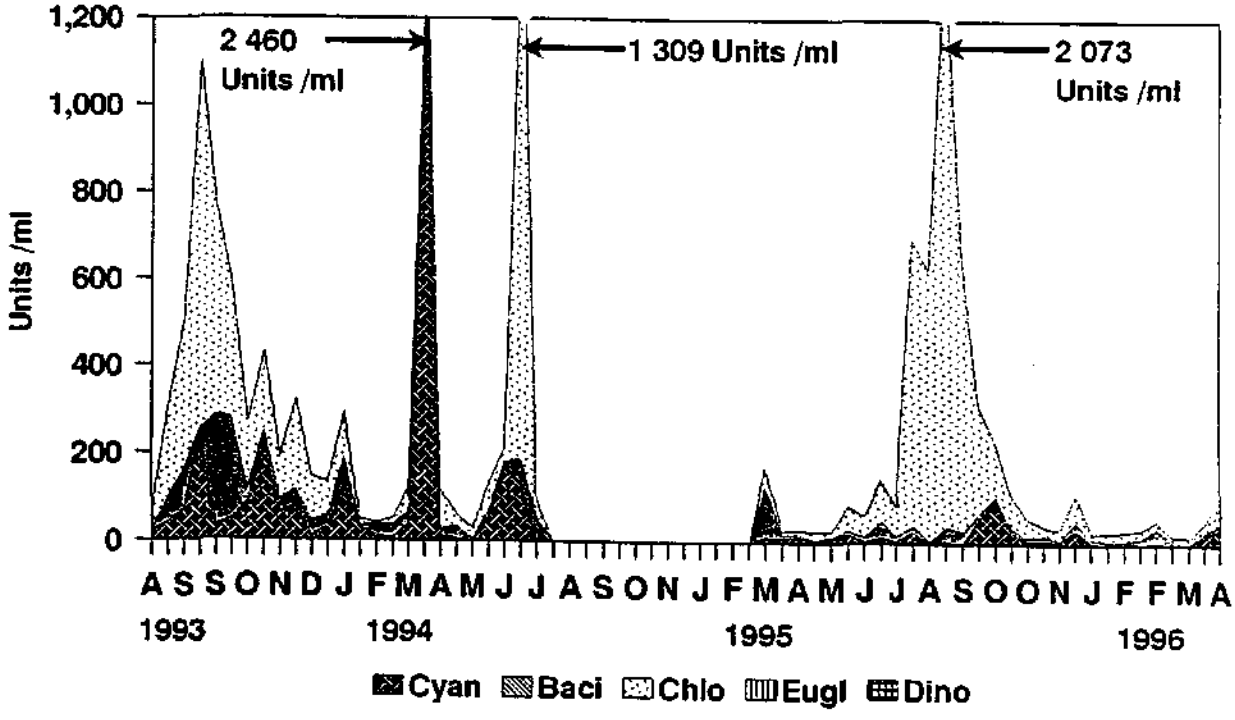

Figure 30: Phytoplankton counts of the major taxonomical groups of the sand filtration effluent of Module II from August 1993 to April 1996.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Dino = Dinophyceae.

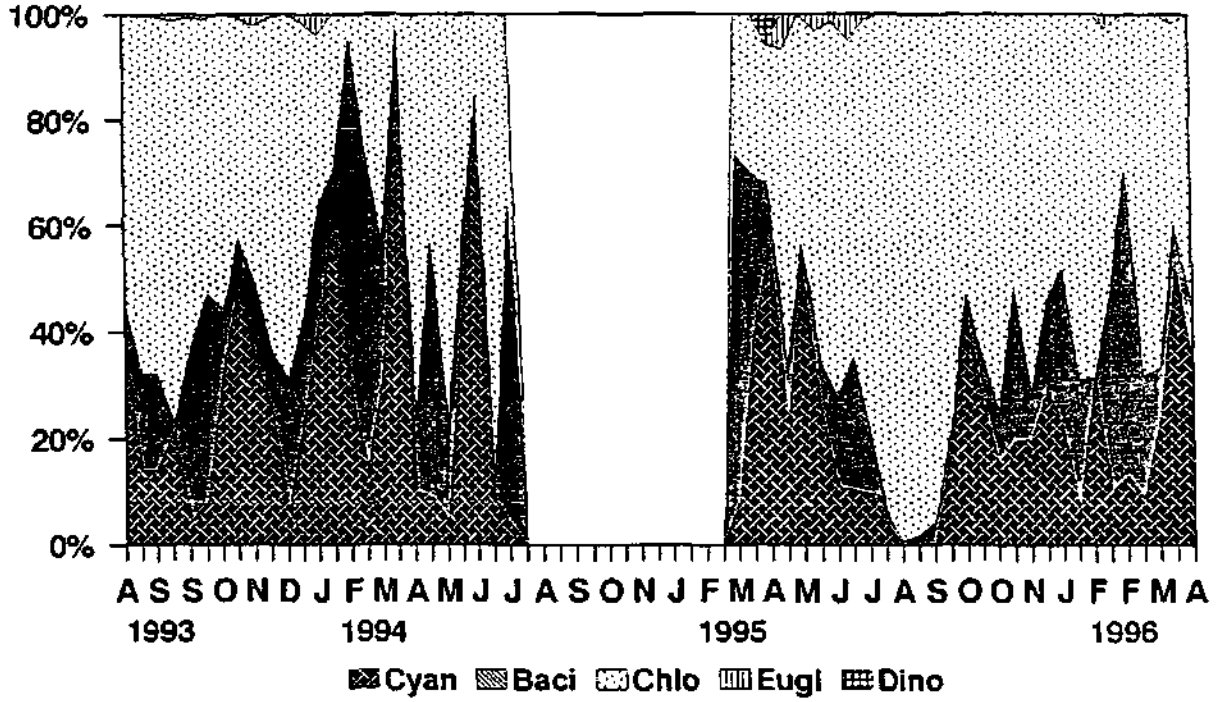

Figure 31: Phytoplankton composition (%) of the major taxonomical groups of the sand filtration effluent of Module II from August 1993 to April 1996.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Dino = Dinophyceae.

The green algae again increased from the sedimentation effluent to the filtration effluent of Module II and was dominant except for the periods when the diatoms and the blue-green algae were dominant (Figs 30 & 31). The dominant algal species were *Monoraphidium arcuatum, Chlamydomonas incerta* and *Chlamydomonas* sp.

Blue-green algae were dominant during the beginning of November 1993, the beginning of February 1994, the end of March 1994, the beginning of June 1994, the beginning of April 1995 and during the beginning of April 1996 in the filtration effluent of Module II (Figs 30 & 31). The dominant species were *Synechococcus cedrorum*, *Chroococcus dispersus* and *Microcystis flos-aquae.*

Euglenophytes, dinoflagellates and cryptophytes were present in small quantities at the different sampling localities. The dominant euglenophyte species were *Trachelomonas intermedia*, *Trachelomonas scabra* and *Strombomonas fluviatillis*, the dominant

dinoflagellates were *Peridinium penardiforme* and *Sphaerodinium ravufluvium* and the dominant cryptophyte species was *Cryptomonas major*.

Phytoplankton biomass, Species diversity and Turbidity

The chlorophyll-a concentration of the sedimentation effluent varied throughout the study period and the highest chlorophyll-a concentration occurred during the end of August 1995 (Fig. 32, Table 6; 11 µg/l). The dominant algal species were *Chlamydomonas* sp. and *Chlamydomonas incerta*.

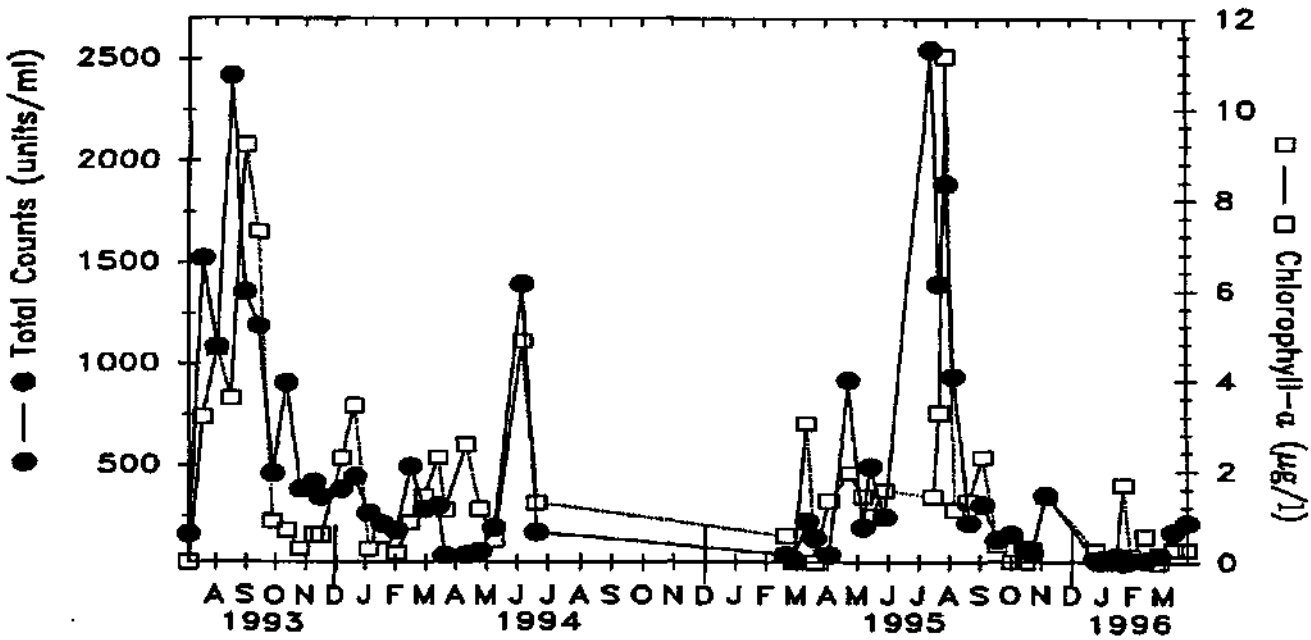

Figure 32: Phytoplankton biomass in µg/l chlorophyll-*a* total counts in algal units/ml of the sedimentation effluent of Module II from August 1993 to April 1996.

On five occasions the chlorophyll-a concentration were above 4 µg/l in the sedimentation effluent, namely at the beginning of September 1993, during October 1993, during June 1994 and during August 1995. The rest of the time the chlorophyll-a concentration was below 4 µg/l (Fig. 32). The dominant algal species during the five periods mentioned above were *Chroococcus dispersus* and *Chlamydomonas* sp.

On two occasions the algal unit concentration was very high (above 2 400 units/ml), while the chlorophyll-a concentration was relatively low (below 4 µg/l) in the sedimentation effluent of Module II, namely, during the middle of September 1993 and

the beginning of August 1995 (Fig. 32). The dominant algal species were *Chlamydomonas incerta, Chlamydomonas* sp. and an unidentified centric diatom.

The highest algal unit concentration in the sedimentation effluent of Module II occurred at the beginning of August 1995 (Fig. 32 & Table 6; 2 547 units/ml). The dominant algal species were *Chlamydomonas* sp. and *Chlamydomonas incerta*.

From January 1996 to the end of April 1996 the algal unit and chlorophyll-*a* concentration of the sedimentation effluent was low (below 250 units ml^{-1} & below 2 $\mu g\ l^{-1}$; Fig. 32). The dominant algal species were *Synechococcus cedrorum* and *Monoraphidium arcuatum*.

During the beginning of July 1994 the algal unit concentration and chlorophyll-*a* concentration were relatively high (above 1200 units ml^{-1} & above 4 $\mu g\ l^{-1}$) in the sedimentation and filtration effluent of Module II (Figs 32, 33). This corresponded with a peak of green algae in the sedimentation and filtration effluent (Figs 28-31). The dominant algal species were *Chlamydomonas incerta*, *Oocystis lacustris* and *Monoraphidium arcuatum*.

The chlorophyll-*a* concentration of the filtration effluent of Module II varied throughout the study period (Fig. 33). The highest chlorophyll-*a* concentration of the filtration effluent of Module II occurred during June 1994 (Fig. 33 & Table 6; 4.6 $\mu g/l$). The dominant algal species was *Chroococcus dispersus*.

The chlorophyll-*a* concentration of the filtration effluent was most of the time below 1 $\mu g/l$ (Fig. 33), which is very good because, as already mentioned, a chlorophyll-*a* concentration of below 1 $\mu g/l$ in the filtration effluent is prefered at Balkfontein as a managment tool.

The highest algal unit concentration in the filtration effluent occurred during the end of March 1994 (Fig. 33, Table 6; 2 545 units/ml). The chlorophyll-a concentration was below 1 g l^{-1} during this period. The dominant algal species was *Chroococcus dispersus*, a blue-green alga.

Table 6 represents the minimum, maximum and mean concentrations of chlorophyll-*a* and algal units in the different sampling localities of Module II.

Table 6: Minimum, maximum and mean values of algal unit concentration and chlorophyll-*a* of the different sampling localities of Module II (See also Figs 3, 32, 33, 60). nd = not detectable

Sampling localities	Algal unit/ml			Chlorophyll-a(µg/l)		
	Min	Max	Mean	Min	Max	Mean
River water	842	58 770	10 295	nd	130	39.86
Secondary sedimentation	27.15	2 547	481	nd	11.2	1.68
Sand filtration	19.01	2 545	299	nd	4.6	0.72
Final water	9.79	8 129	433	nd	3.4	0.26

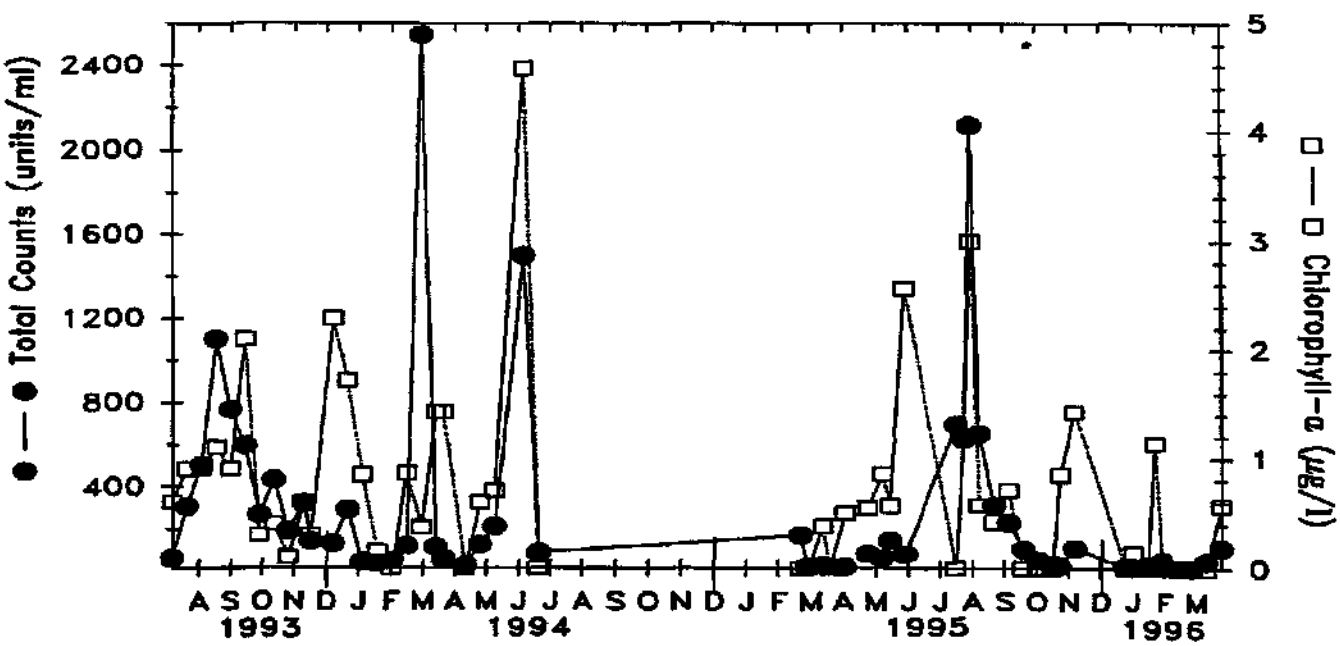

Figure 33: Phytoplankton biomass in µg/l chlorophyll-*a* and total counts in algal units/ml of the sand filtration effluent of Module II from August 1993 to April 1996.

The algal unit concentration very low and the chlorophyll-a concentration relatively low during February 1994, May 1994 and during March and April 1995 and from February to

the beginning of April 1996 in the filtration effluent of Module II (Fig. 33). The dominant algal species were *Chroococcus dispersus* and *Synechococcus cedrorum* during February and May 1994, during April 1995 and the beginning of April 1996, and *Melosira granulata* was dominant during March 1995 and *Monoraphidium arcuatum* was dominant during February and March 1996.

At the end of March 1994 the algal unit concentration was high while the chlorophyll-a concentration was low (0.57 µg/l) at the sand filtration effluent (Fig. 33). The dominant species was *Chroococcus dispersus*.

The chlorophyll-a concentration and the algal unit concentration were relatively high during the end of August 1995 in the filtration effluent of Module II (Fig. 33). The dominant algal species were *Chlamydomonas* sp. and *Monoraphidium arcuatum*.

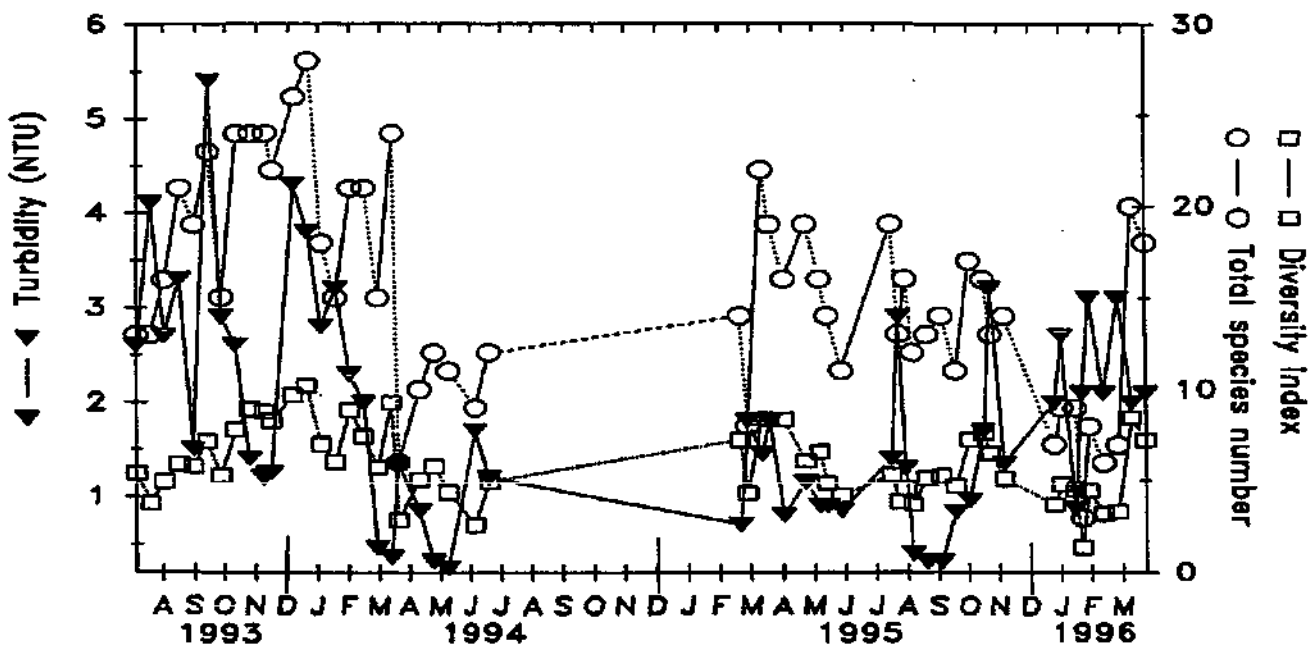

Figure 34: Species diversity in total species number, turbidity in NTU and diversity index of the secondary sedimentation effluent of Module II from August 1993 to April 1996.

Table 7 represents the minimum, maximum and mean values of the turbidity, total species number and diversity index of the different sampling localities of Module II. The turbidity of the secondary sedimentation effluent was the highest during the beginning of October 1993 (5.4 NTU) and the lowest (0.35 NTU) during the beginning of June 1994 (Fig. 34 & Table 7).

The turbidity of the sedimentation effluent was below 2 NTU from March 1995 to October 1995 (Fig. 34). The dominant algal species were *Chlamydomonas* sp., *Chlamydomonas incerta* and *Synechococcus cedrorum*.

The total species number of the sedimentation effluent of Module II varied throughout the study period (Fig. 34). The highest total species number (28) occurred during the end of January 1994 (Fig. 34).

The diversity index was below 10 in the sedimentation effluent of Module II throughout the study period (Fig. 34). The diversity index was the highest (10) during January 1994 and the lowest (2.54) during June 1994 (Fig. 34).

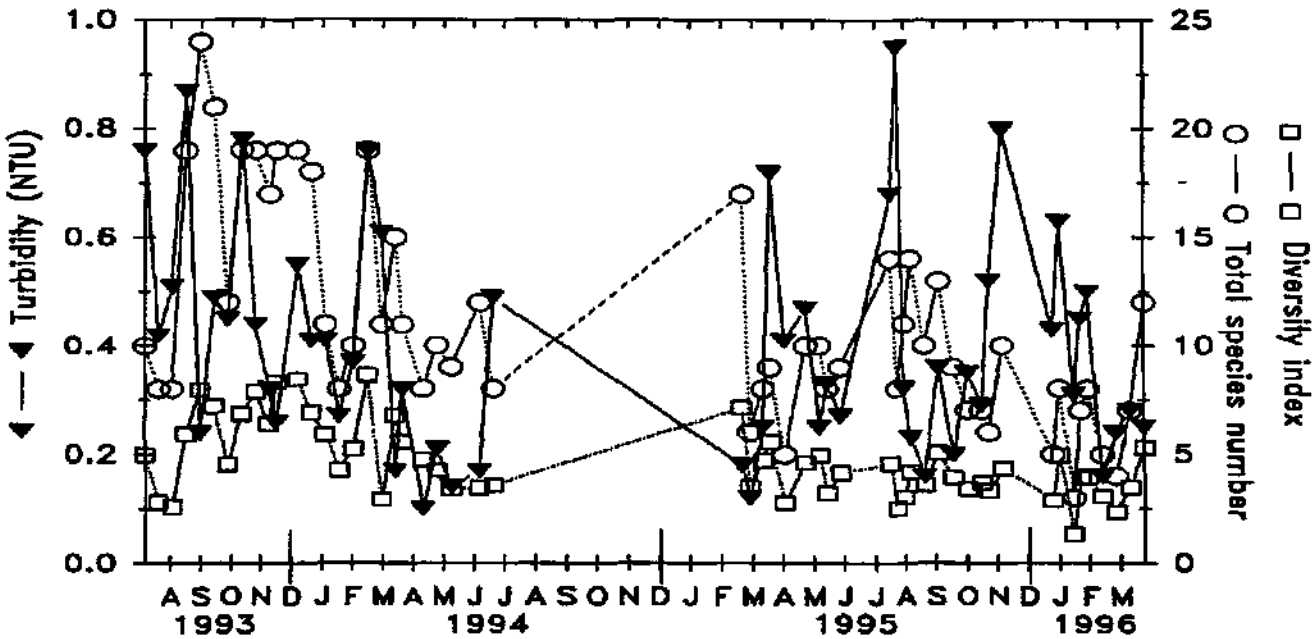

Figure 35: Species diversity in total species number, turbidity in NTU and diversity index of the sand filtration effluent of Module II from August 1993 to April 1996.

The turbidity of the filtration effluent was below 0.6 NTU during the study period except on seven occasions when the turbidity was above 0.7 NTU, namely during the beginning of August 1993, middle of September 1993 and the beginning of November 1993, middle of March 1994, end of April 1995 and December 1995 (Fig. 35).

The total species number varied throughout the study period. The highest total species number (24) occurred during the end of September 1993 and lowest species number (4) occurred during the end of March 1996 (Fig. 35).

The diversity index followed almost the same pattern as the total species number (Fig. 35).

Table 7: Minimum, maximum and mean values of the turbidity, total species number and diversity index of the different sampling localities of Module II (See also Figs 4, 34, 35, 61).

Sampling localities	Turbidity			Total species number			Diversity index		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
River water	7.9	1 900	111.3	6	34	18.74	0	8.9	4.6
Secondary sedimentation	0.25	5.4	1.83	3	28	15.30	1.4	10.2	5.9
Sand filtration	0.1	0.95	0.4	3	24	11.02	1.3	8.64	4.7
Final water	0.13	2.3	0.58	3	23	11.7	1.2	9.56	5.2

Percentage removal

Table 8 represents the minimum, maximum and mean values of percentage removal, namely during sedimentation and filtration separately as well as combined.

The percentage removal of chlorophyll-*a* during sedimentation remained more or less constant and above 80% during the study period except during the beginning of January 1994, during the end of June 1994, the end of November 1995 and during the end of February and March 1996 (Fig. 36).

The percentage removal of chlorophyll-a during filtration varied throughout the study period. During the end of January 1994, the beginning of February 1994, during April 1994, during June 1994 and during June and July 1995 the percentage removal was negative due to an increase in chlorophyll-a from the sedimentation to the filtration effluent (Fig. 36). The dominant algal species were *Synechococcus cedrorum* during

January and February 1994, *Monoraphidium arcuatum* during April 1994 and *Chroococcus dispersus* during June and July 1995.

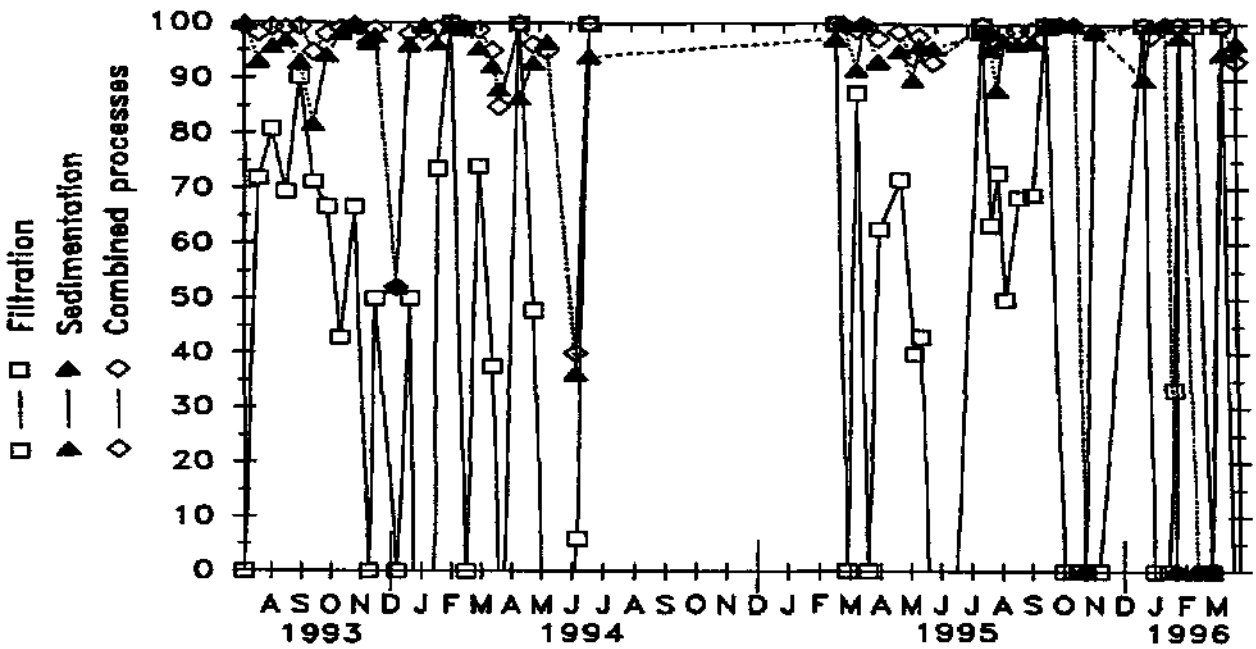

Figure 36: Percentage removal of chlorophyll-*a* by sedimentation, filtration and the combined processes of Module II from August 1993 to April 1996.

The percentage removal of chlorophyll-*a* by the combined processes remained more or less constant during the study period except during the beginning of January 1994 and during the end of June 1994 (Fig. 36).

The percentage removal of algal units by sedimentation varied throughout the study period (Fig. 37). The percentage removal of algal units by sedimentation was above 80% during the study period, except during the end of August 1993 and the end of October 1993 when it was below 70% (Fig. 37).

The percentage removal of algal units by filtration varied throughout the study period (Fig. 37). During the middle of March, April 1994 and during May and June 1994, during the beginning of March 1995, again during the end of August and the middle of September 1995 and during the end of January 1996 the percentage removal of algal units by filtration was negative due to an increase in algal cells from the river water to the filtration effluent (Fig. 37). The dominant species were *Monoraphidium arcuatum* during March, April and May 1994 and the end of January 1996, *Chroococcus dispersus* during

June 1994 and *Chlamydomonas* sp. during the end of August 1995 and the middle of September 1995.

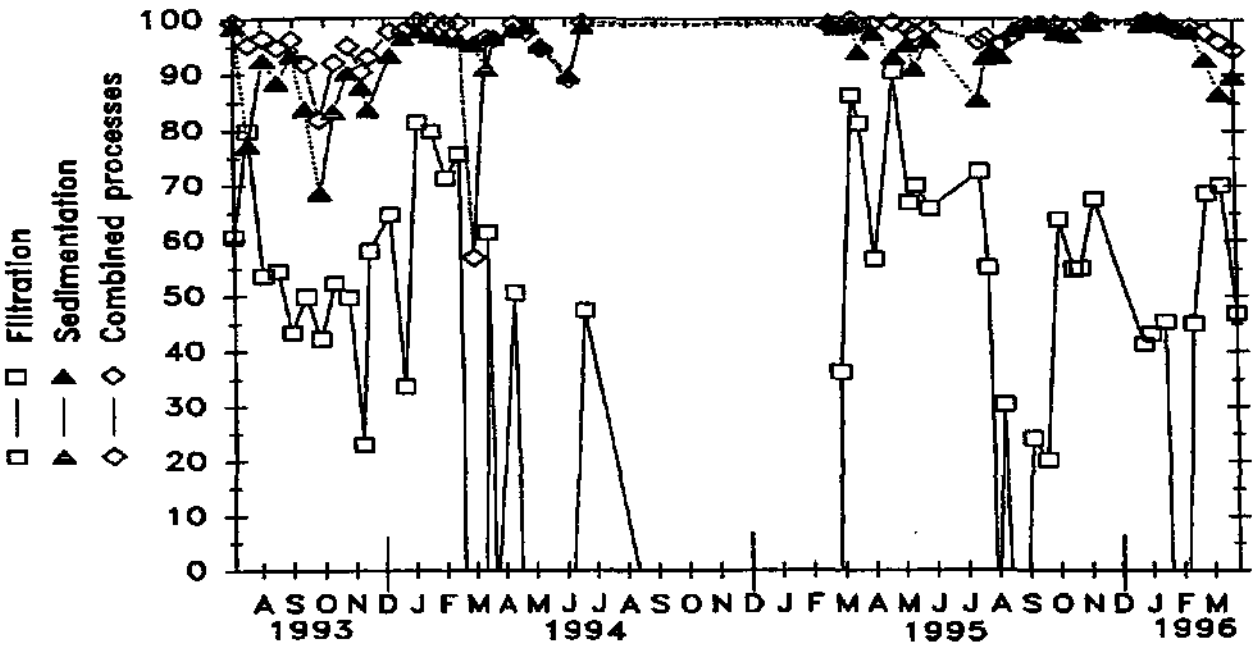

Figure 37: Percentage removal of algal units by sedimentation, filtration and the combined processes of Module II from August 1993 to April 1996.

Table 8 shows increases of algal unit concentration during filtration. The reason for the negative percentage removal from the end of March 1994 to the end of July 1994 is because there was an increase in algal unit concentration from the sedimentation effluent to the filtration effluent. The same can be seen in Fig. 37. The increase in algal unit concentration from the sedimentation to the filtration effluent during March 1994 was due to the blue-green alga *Chroococcus dispersus* which increased drastically (from 84 algal units/ml to 2 403 algal units/ml). Increases in algal unit concentration during July 1994 was due to the green algae *Chlamydomonas incerta*, *Carteria simplicissima* and *Monoraphidium arcuatum*.

The percentage removal of algal units by the combined processes was above 90% throughout the study period, except during the end of October 1993 when it was almost 80% (Fig. 37).

The percentage removal of turbidity during sedimentation was above 80% during the study period (Fig. 38, Table 8). The percentage removal during sedimentation was

higher than the percentage removal of turbidity by filtration throughout the study period (Fig. 38).

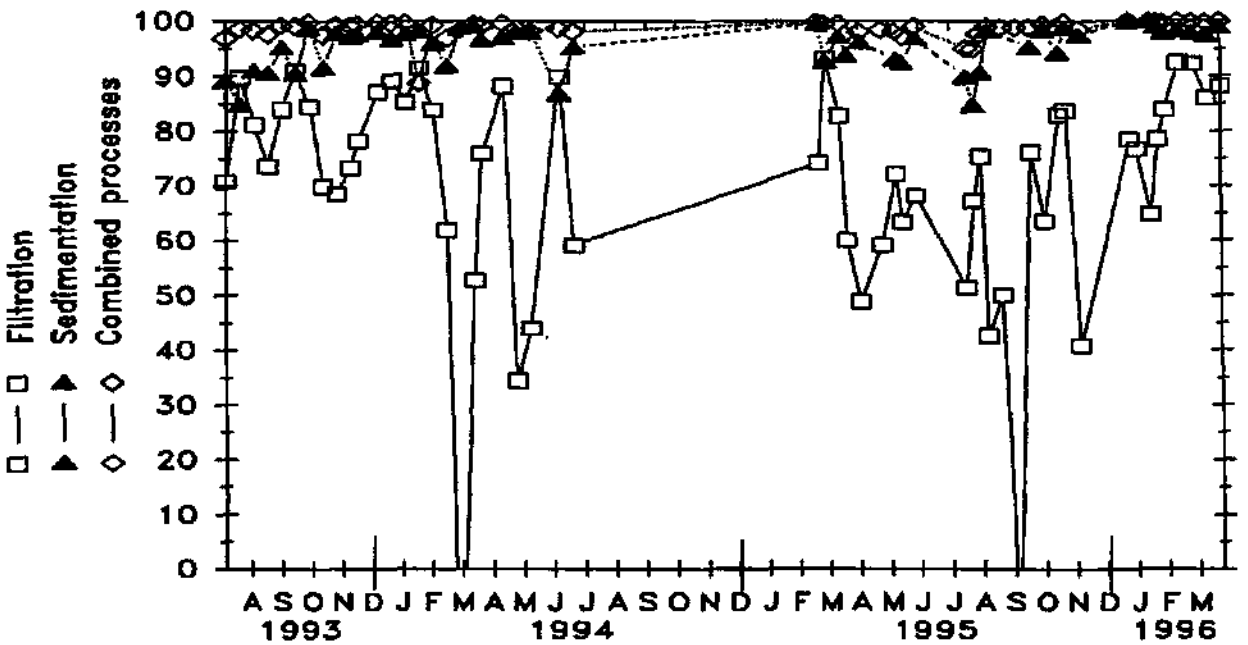

Figure 38: Percentage removal of turbidity by sedimentation, filtration and the combined processes of Module II from August 1993 to April 1996.

Table 8: Percentage removal of chlorophyll-*a*, algal unit concentration and turbidity by sedimentation, sand filtration and the combined processes of Module II (See also Figs 36, 37, 38).

Sampling localities	Chlorophyll-*a* (%)			Algal units (%)			Turbidity (%)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Sedimentation	0	100	87	68	100	94	85	99	95
Filtration	-203*	100	35	-802*	91	24	-33*	93	70
Combined processes	0	100	89	57	100	96	89	100	99

* = negative removal indicates algal growth within the system.

The percentage removal of turbidity during filtration varied throughout the study period (Fig. 38). The percentage removal of turbidity by filtration was negative during the end of March 1994 and the beginning of October 1995 (Fig. 38).

The percentage removal of turbidity during the combined processes remained more or less constant and above 90% during the study period (Fig. 38, Table 8).

Morphological groups

Unicellular spherical cells (Unsp) and unicellular elongated cells (Unel) increased proportionate to the other morphological types from the river to the secondary sedimentation effluent between the end of August 1993 to the end of May 1994 and again from the middle of October 1995 to the end of April 1996 (Figs 5 & 6, 39 & 40). The dominant Unsp cells were *Synechococcus cedrorum*, *Chroococcus dispersus* and *Oocystis lacustris*, while the dominant Unel cells were *Monoraphidium arcuatum* and an unidentified pennate diatom.

From the middle of September 1993 the unicellular discoidal cells (Undi) were efficiently removed in relation to the other groups by secondary sedimentation (Figs 39 & 40).

The unicellular flagellated cells (Unfl) were dominant in the beginning of August 1993, the beginning of July 1994 and from August 1995 to the end of September 1995 in the sedimentation effluent of Module II (Figs 39 & 40). The dominant species were *Chlamydomonas incerta*, *Chlamydomonas bicocca* and *Chlamydomonas* sp.

A peak of unicellular spherical cells (Unsp) occurred during the end of April 1994 and the beginning of October 1995 in the sedimentation effluent of Module II (Figs 39 & 40). The dominant species were *Oocystis lacustris* and *Synechococcus cedrorum*. A peak of colonial algae with spherical cells (Cosp) occurred during the beginning of June 1994 in the sedimentation effluent (Figs 39 & 40) and the dominant species was *Chroococcus dispersus*.

Some of the filaments which were dominant in the river water during the end of February 1994, the middle of March 1994 and during December 1995, were removed by secondary sedimentation (Figs 39 & 40). The dominant filamentous algae in the secondary sedimentation effluent were *Oscillatoria simplicissima* and *Melosira granulata*.

Unicellular spherical cells (Unsp) and unicellular elongated cells (Unel) were dominant in the filtration effluent from the beginning of August 1993 to the middle of March 1994, from the end of May 1994 to the end of July 1994 and from the beginning of October 1995 to the end of April 1996 (Figs 41 & 42). The dominant Unsp species were *Oocystis lacustris*, *Synechococcus cedrorum*, *Chroococcus dispersus* and *Chlorococcum infusionum*. The dominant Unel cells were *Monoraphidium arcuatum*, *Monoraphidium circinale*, *Ankistrodesmus falcatus* and an unidentified pennate diatom.

During the end of October 1993 and the beginning of February 1996 a peak of colonial algae with discoidal cells (Codi) occurred in the filtration effluent of Module II (Figs 41 & 42). The dominant species was *Crucigenia tetrapedia*.

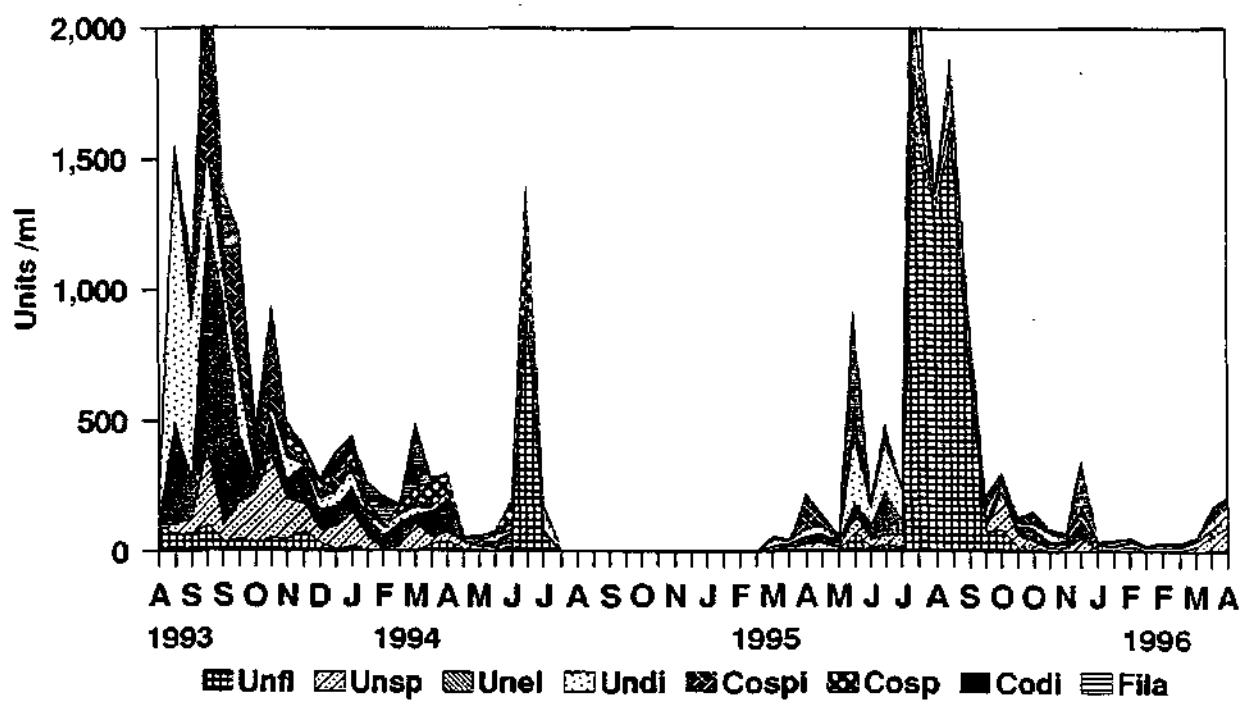

Figure 39: Phytoplankton counts of morphological groups of the secondary sedimentation effluent of Module II from August 1993 to April 1996.
Unfl = Unicellular flagellated algae, Unsp = Unicellular spherical algae, Unel = Unicellular elongated algae, Undi = Unicellular discoidal algae, Cospi = Colonial algae individual cells with spines, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Fila = Filament.

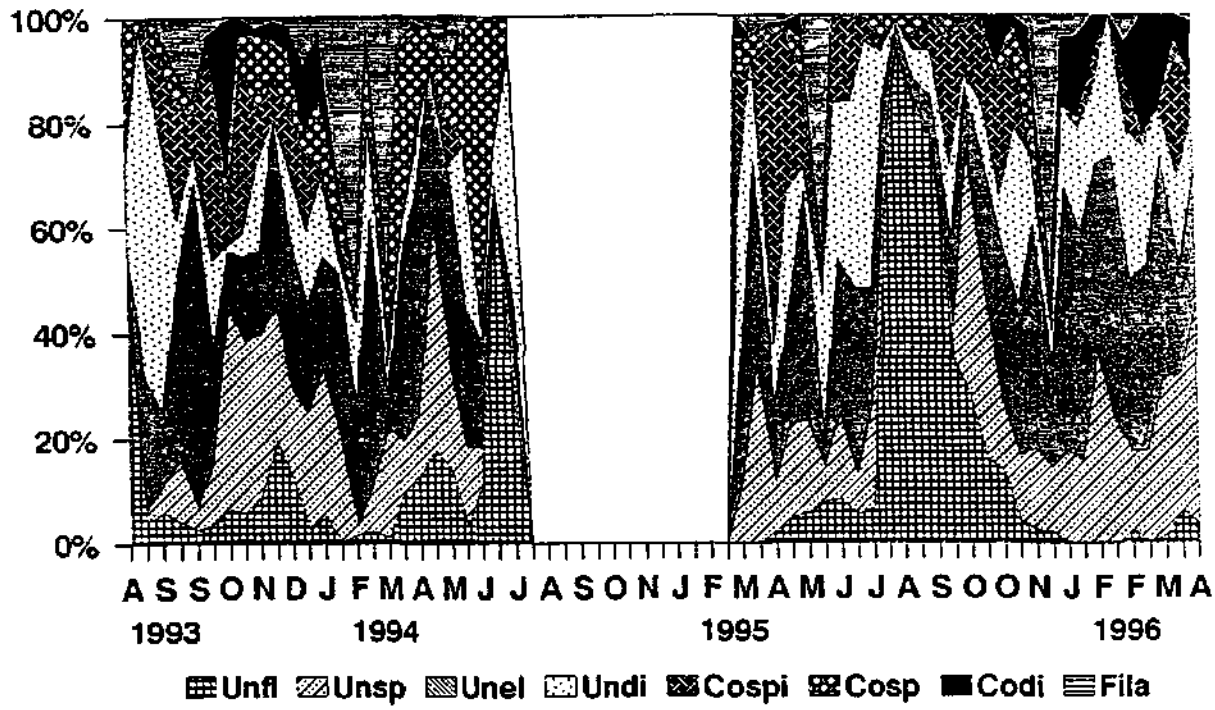

Figure 40: Phytoplankton composition (%) of morphological groups of the secondary sedimentation effluent of Module II from August 1993 to April 1996.
Unfl = Unicellular flagellated algae, Unsp = Unicellular spherical algae, Unel = Unicellular elongated algae, Undi = Unicellular discoidal algae, Cospi = Colonial algae individual cells with spines, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Fila = Filament.

Four peaks of Unicellular flagellated cells (Unfl) occurred in the filtration effluent of Module II, namely during December 1993, the beginning of May 1994, the beginning of July 1994 and from the beginning of August 1995 to the end of September 1995 (Figs 41 & 42). The dominant species were *Carteria simplicissima*, *Carteria globosa* and *Chlamydomonas incerta* and *Chlamydomonas* sp.

Almost all of the filaments which were dominant during the end of February and the middle of March 1994 and during December 1995 were removed by sand filtration (Figs 41 & 42). The dominant species were *Oscillatoria simplicissima* and *Melosira granulata*.

During the end of April 1994 a peak concentration of filaments occurred in the filtration effluent (Figs 41 & 42), the dominant species were *Melosira granulata* and *Oscillatoria simplicissima*.

A peak of colonial algae with spherical cells (Cosp) occurred during the end of March 1994 and the beginning of June 1994 in the filtration effluent of Module II (Figs 41 & 42), the dominant species were *Chroococcus dispersus*, *Coelastrum pseudomicroporum* and *Microcystis flos-aquae*.

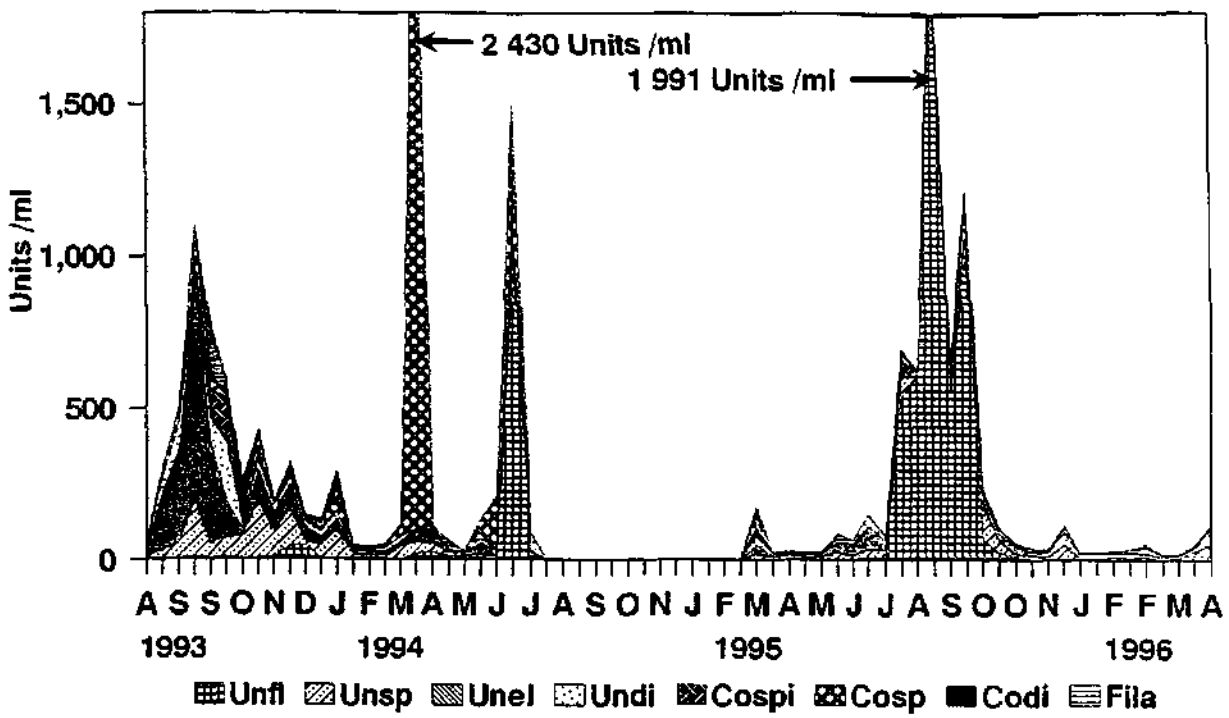

Figure 41: Phytoplankton counts of morphological groups of the sand filtration effluent of Module II from August 1993 to April 1996.
Unfl = Unicellular flagellated algae, Unsp = Unicellular spherical algae, Unel = Unicellular elongated algae, Undi = Unicellular discoidal algae, Cospi = Colonial algae individual cells with spines, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Fila = Filament.

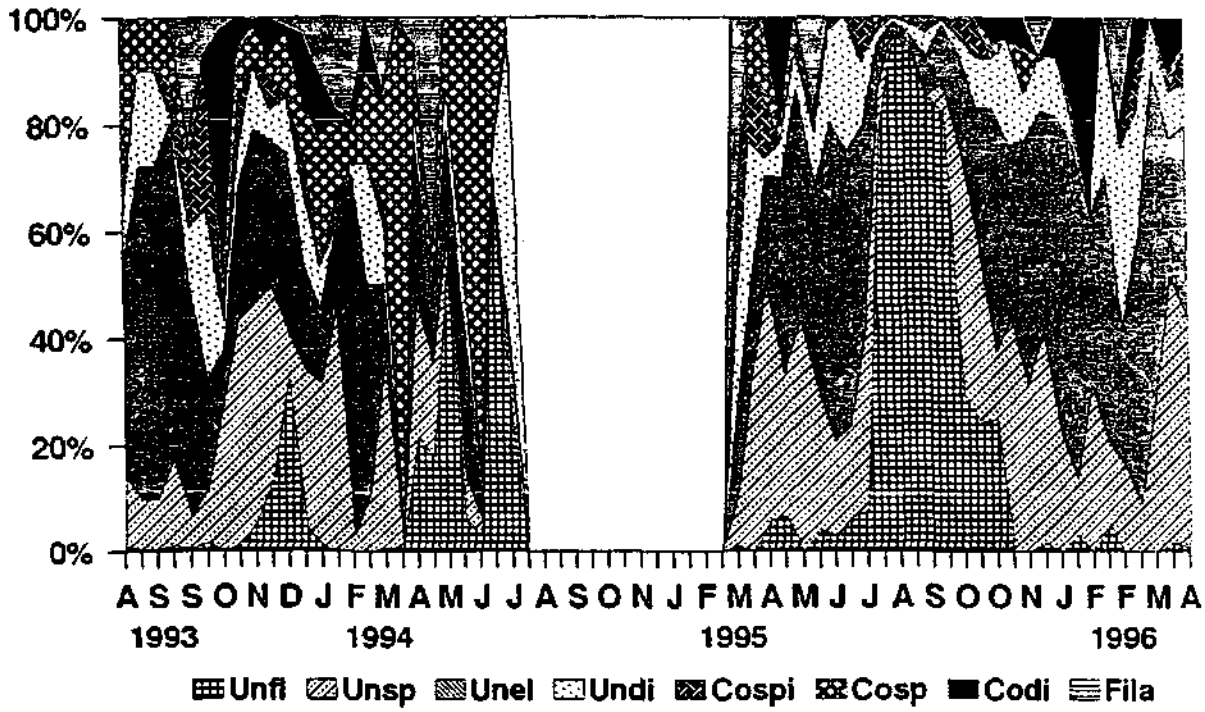

Figure 42: Phytoplankton composition (%) of morphological groups of the sand filtration effluent of Module II from August 1993 to April 1996.
Unfl = Unicellular flagellated algae, Unsp = Unicellular spherical algae, Unel = Unicellular elongated algae, Undi = Unicellular discoidal algae, Cospi = Colonial algae individual cells with spines, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Fila = Filament.

Discussion of the results of Module II

At the beginning of August 1993 and the middle of September 1993 $Fe_2(SO_4)_3$ was dosed instead of $FeCl_3$. The turbidity of the river water was low (29 and 31 NTU), but the chlorophyll-a concentration of the river water was high (102.35 and 117.5 µg/l; Figs 3 & 4). The high chlorophyll-a concentration of the river water was due to green algae (Figs 1 & 2). The dominant species were *Chlamydomonas incerta* (Unfl), *Chlamydomonas bicocca* (Unfl) and *Oocystis marssonii* (Cosp).

The $Fe_2(SO_4)_3$ dosage was accompanied by a high pre-chlorine dosage (5.9 mg/l) during the beginning of August 1993. During the middle of September 1993 the pre-chlorine dosage was not as high (3.9 mg/l) as during the beginning of August 1993.

There was not a noticeable difference between the total dosage cost when $Fe_2(SO_4)_3$ was dosed than when $FeCl_3$ was dosed.

Almost the same species (exceptions were *Chlamydomonas incerta* and *Crucigenia tetrapedia*) penetrated the sedimentation and filtration phases when $Fe_2(SO_4)_3$ and $FeCl_3$ were dosed. There was, therefore no significant difference between the affects of the $Fe_2(SO_4)_3$ and $FeCl_3$ in Module II.

The following list compares the species which penetrated the different purification processes when $Fe_2(SO_4)_3$ and $FeCl_3$ were dosed.

Location	**$Fe_2(SO_4)_3$**	**$FeCl_3$**
Sedimentation		
Chlamydomonas incerta (Unfl)*	X	
Oocystis marssonii (Cosp)		X
Oocystis lacustris (Unsp)	X	
Monoraphidium arcuatum (Unel)	X	X
Monoraphidium circinale (Unel)	X	X
Scenedesmus opoliensis (Cospi)	X	X
Scenedesmus intermedius (Cospi)	X	
Chlamydomonas sp. (Unfl)		X
Filtration		
Monoraphidium arcuatum (Unel)	X	X
Monoraphidium circinale (Unel)	X	X
Oocystis lacustris (Unsp)	X	X
Scenedesmus intermedius (Cospi)	X	X
Crucigenia tetrapedia (Codi)	X	
Chlamydomonas sp. (Unfl)		X

*Unfl = Unicellular flagellated algae, Unsp = Unicellular spherical algae, Unel = Unicellular elongated algae, Cospi = Colonial algae individual cells with spines, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells.

During the beginning of November 1993 the pre-chlorine and pre-lime dosage was relatively high (6.2 & 27.8 mg/l). The turbidity of the river water was relatively low (Fig. 4; 31 NTU).

The diatoms were the best removed by sedimentation during the beginning of November 1993 in relation to the other groups when the pre-chlorine and pre-lime dosages were high. The dominant diatom during the beginning of November 1993 was an unidentified centric diatom.

During the beginning of October 1993 the pre-chlorine dosage was relatively low and no pre-lime was dosed (1.9 & 0 mg/l). The unidentified centric diatoms were dominant in the river water together with a relatively low chlorophyll-a concentration (Figs 1, 2 & 25). The unidentified centric diatoms were not as efficiently removed by sedimentation as during the beginning of November 1993 when the pre-lime and pre-chlorine dosage was relatively high.

The chlorophyll-a concentration of the filtration effluent of Module II was above 1 μg/l during the end of April 1994 (Fig. 33). The diatoms were dominant in the filtration effluent of Module II during this period (Figs 30 & 31). No pre-chlorine and polymer were dosed, and a low concentration of $FeCl_3$ was dosed (below 1 mg/l). These results indicate that diatoms are not sufficiently removed from the water when no pre-chlorine and polymer together with a low $FeCl_3$ concentration are being dosed.

From the end of March 1994 to the end of July 1994 the pre-chlorine dosage was 0 mg/l, while the pre-lime and carbon dioxide dosage was high and the $FeCl_3$ dosage low. During this period the excess lime treatment programme was run at Module II. During this period the algal unit concentration increased from the sedimentation to the filtration effluent causing a negative percentage removal of algal unit concentration during filtration (Fig. 37). Therefore it can be concluded that filtration was not successful in removing the algal cells (green algae, blue-green algae and diatoms) from the water in the absence of pre-chlorination and under low $FeCl_3$ dosage. It can also be concluded that high concentrations of pre-lime dosage are not sufficient for the efficient removal of algal cells from the water.

When the pre-lime dosage was low (below 30 mg/l) and the $FeCl_3$ dosage high (above 1 mg/l) the algal cells were removed much more efficiently from the water than when the pre-lime dosage was high (above 30 mg/l) and the $FeCl_3$ dosage low (below 1 mg/l).

During the end of January 1994 the chlorophyll-a concentration of the filtration effluent of Module II was above 1 μg/l (Fig. 33; 1.7 μg/l). During this period the blue-green algae were dominant in the filtration effluent of Module II and the dominant species was *Synechococcus cedrorum*. The pre-chlorine dosage was above 4 mg/l. The polymer

dosage was above 2 mg/l and the $FeCl_3$ dosage was below 2 mg/l. Low $FeCl_3$ dosage concentration did not efficiently remove the blue-green algae from the water (Table 4.10).

Two peaks of blue-green algae occurred in the filtration effluent of Module II, namely at the end of March 1994 and during the end of May and beginning of June 1994 (Figs 30 & 31). The $FeCl_3$ dosage concentration was below 1 mg/l during these periods. No pre-chlorine and polymer were dosed during these periods. These results can therefore indicate that low $FeCl_3$ dosage concentrations in the absence of pre-chlorine and polymer do not remove the blue-green algae efficiently.

During the end of August 1995 the chlorophyll-*a* concentration of the filtration effluent of Module II was extremely high (Fig. 33; 3 μg/l). No pre-chlorine or polymer was dosed during this period, while the $FeCl_3$ dosage was below 1 mg/l. The pre-lime dosage concentration was extremely high (± 180 mg/l). The green algae were dominant in the filtration effluent of Module II during this period and the dominant algal species was *Chlamydomonas* sp. There was a negative percentage removal of algal units by filtration due to an increase in algal cells (*Chlamydomonas* sp.) from the sedimentation to the filtration effluent of Module II. Therefore it can be concluded that a high concentration of pre-lime dosage did not efficiently remove the green algae, *Chlamydomonas* sp. from the water (Table 4.10).

The following list gives an indication of the species which penetrated the sedimentation and filtration processes of Module II.

	Sedimentation	**Filtration**
Green algae :		
Oocystis lacustris (Unsp)	X	X
Monoraphidium arcuatum (Unel)	X	X
Monoraphidium circinale (Unel)	X	X
Scenedesmus opoliensis (Cospi)	X	X
Scenedesmus intermedius (Cospi)	X	
Crucigenia tetrapedia (Codi)	X	X
Chlamydomonas sp. (Unfl)	X	X
Carteria globosa (Unfl)	X	X
Coelastrum pseudomicroporum (Cosp)	X	
Carteria simplicissima (Unfl)		X

Blue-green algae:		
Microcystis flos-aquae (Cosp)	X	X
Synechococcus cedrorum (Unsp)	X	X
Oscillatoria simplicissima (Fila)	X	
Chroococcus dispersus (Cosp)	X	X
Diatoms:		
Centric diatom (Undi)	X	X
Melosira granulata (Fila)	X	X
Pennate diatom (Unel)	X	X
Euglenophytes:		
Trachelomonas intermedia (Unfl)	X	X
Trachelomonas scabra (Unfl)	X	X
Phacus longicauda (Unfl)	X	
Euglena sp. (Unel)	X	X

Unfl = Unicellular flagellated algae, Unsp = Unicellular spherical algae, Unel = Unicellular elongated algae, Undi = Unicellular discoidal algae, Cospi = Colonial algae individual cells with spines, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Fila = Filament.

Representatives of all eight morphological groups were occassionally not removed by sedimentation. The prominant and dominant penetrating groups were, however, unicellular elongated cells (Unel), unicellular spherical cells (Unsp), unicellular flagellated cells (Unfl) and the filaments. The filters were also penetrated by all the morphological groups. The dominant groups were unicellular spherical (Unsp) and unicellular elongated cells (Unel). It is, therefore, clear that the unicellular algae penetrated the processes more frequently than the colonial algae.

Table 10 shows algal species which were difficult to remove during the different treatment processes in Module II under different dosing concentrations. Green and blue-green algae penetrated the different phases of Module II. All the species in the table is unicellular except for the filamentous diatom *Melosira granulata* and the colonial blue-green alga *Chroococcus dispersus*. *Chroococcus dispersus* was not present in the river water but was observed after secondary sedimentation and in the sand filtration effluent of Module II. *Melosira granulata* was successfully removed during sand filtration (Table 10).

Table 9: Occurrance of phytoplankton species in the raw water, sedimentation, sand filtration and final water of Module II of the Goldfield Water purification plant at Balkfontein. Abbreviations explained in Table 4.

	River*	Sed*	Filtr*	Finw*
CYANOPHYCEAE (Cyano)**				
Anabaena circinales	X	X	X	-
Chroococcus dispersus	-	X	X	X
Merismopedia minima	-	-	-	X
Microcystis aeruginosa	X	X	-	X
Microcystis flos-aquae	X	X	X	X
Microcystis incerta	-	X	X	X
Oscillatoria simplicissima	X	X	X	X
Synechococcus cedrorum	X	X	X	X
Synechocystis sp.	-	-	-	X
BACILLARIOPHYCEAE (Baci)**				
Centric diatoms	X	X	X	X
Melosira granulata	X	X	X	X
Pennate diatoms	X	X	X	X
CHLOROPHYCEAE (Chlo)**				
Actinastrum hantzschii	X	X	X	X
Ankistrodesmus bibraianus	X	-	X	-
Ankistrodesmus falcatus	-	X	X	X
Ankistrodesmus stipitatus	X	X	X	X
Carteria globosa	X	X	X	X
Carteria simplicissima	X	X	X	X

Table 9 continued

	River*	Sed*	Filtr*	Finw*
Cerasterium irregularis	-	-	X	-
Characium limneticum	-	X	X	X
Chlamydomonas bicocca	X	X	-	X
Chlamydomonas incerta	X	X	X	X
Chlamydomonas sp.	X	X	X	X
Chlorococcum infusionum	X	X	X	X
Coelastrum carpaticum	X	X	X	X
Coelastrum pseudomicroporum	X	X	X	X
Cosmarium laeve	X	X	X	X
Crucigenia lauterbornii	X	X	-	-
Crucigenia tetrapedia	X	X	X	X
Crucigeniella rectangularis	X	X	X	X
Dictyosphaerium elegans	X	-	-	X
Eudorina elegans	X	X	X	-
Golenkinia radiata	X	X	X	-
Kirchneriella sp.	X	X	X	X
Lagerheimia balatonica	X	X	X	X
Micractinium pusillum	X	X	X	-
Monoraphidium arcuatum	X	X	X	X
Monoraphidium circinale	X	X	X	X
Monoraphidium griffithi	X	X	X	X
Monoraphidium minutum	X	X	X	X
Oocystis lacustris	X	X	X	X
Oocystis marssonii	X	X	X	X
Pandorina morum	X	X	X	-
Pediastrum duplex	X	X	X	X

Table 9 continued

	River*	Sed*	Filtr*	Finw*
Pediastrum simplex	X	X	X	X
Pediastrum tetras	X	X	-	-
Polytomella citri	-	X	-	-
Pteromonas aculeata	X	X	X	X
Scenedesmus acuminatus	X	X	X	X
Scenedesmus disciformis	X	X	X	X
Scenedesmus intermedius	X	X	X	X
Scenedesmus lefevrii	X	X	X	X
Scenedesmus opoliensis	X	X	X	X
Scenedesmus smithii	-	-	-	X
Schroederia indica	X	-	-	-
Tetraedron limneticum	-	X	X	X
Tetraedron mediocris	X	X	X	X
Tetraedron planctonicum	X	-	X	X
Tetraedron regulare	X	-	-	-
Tetrastrum heteracanthum	X	X	X	X
Tetrastrum staurogeniaeforme	X	X	X	X
Thoracomonas feldmannii	X	-	-	X
Treubaria quadrispina	-	X	-	-
CRYPTOPHYCEAE (Crypto)**				
Cryptomonas major	X	X	-	-
DINOPHYCEAE (Dino)**				
Peridinium penardiforme	X	X	-	-
Sphaerodinium ravumfluvium	X	X	X	X

Table 9 continued

	River*	Sed*	Filtr*	Finw*
EUGLENOPHYCEAE (Eugl)**				
Euglena clavata	-	X	-	-
Euglena elastica	-	X	-	-
Euglena hemichromata	X	-	-	-
Euglena pusilla	X	-	-	-
Euglena sp.	X	X	X	X
Lepocinclis salina	X	X	X	X
Phacus acuminatus	X	-	-	X
Phacus longicauda	X	X	-	X
Phacus pyrum	X	X	X	X
Strombomonas fluviatilis	X	X	X	X
Strombomonas ovalis	X	X	-	-
Strombomonas verrucosa	X	X	X	-
Trachelomonas intermedia	X	X	X	X
Trachelomonas scabra	X	X	X	X
Trachelomonas volvocina	X	X	X	-
TOTAL	68	69	58	59

Table 10: Dosage concentration and algal species penetrating sedimentation, sand filtration phases of Module II

DATE	DOSAGE CONCENTRATION	SEDIMENTATION		FILTRATION	
		Algal species	Chl-*a*	Algal species	Chl-*a*
4/8/93	Pre-lime (13.8 mg l^{-1}) Polymer (0.3 mg l^{-1}) Pre-chlorine (5.9 mg l^{-1}) $Fe_2(SO_4)_3$ (2 mg l^{-1})	**Chlamydomonas incerta* (green alga)	0 $\mu g\ l^{-1}$	**Monoraphidium arcuatum* (green alga)	0.6 $\mu g\ l^{-1}$
Jan 1994	Pre-lime (4.6-7.6 mg l^{-1}) Polymer (1.7-2.4 mg l^{-1}) Pre-chlorine (1.4 mg l^{-1}) $FeCl_3$ (1.3-2.7 mg l^{-1})	**Synechococcus cedrorum* (blue-green alga)	2.87 $\mu g\ l^{-1}$	**Synechococcus cedrorum* (blue-green alga)	2.0 $\mu g\ l^{-1}$
15/2/94	No Pre-lime Polymer (10.3 mg l^{-1}) Pre-chlorine (4 mg l^{-1}) $FeCl_3$ (0.8 mg l^{-1})	**Melosira granulata* (green alga)	0.57 $\mu g\ l^{-1}$	* Pennate diatom	0.15 $\mu g\ l^{-1}$

June 1994	Pre-lime (49-69 mg l^{-1}) No Polymer No Pre-chlorine $FeCl_3$ (0.6 mg l^{-1})	****Chroococcus dispersis*** (blue-green alga)	2.21 µg l^{-1}	****** *Chroococcus dispersis* (blue-green alga)	1.76 µg l^{-1}
23/8/95 until 18/9/95	Pre-lime (166-264 mg l^{-1}) No Polymer No Pre-chlorine $FeCl_3$ (0.6 mg l^{-1})	***Chlamydomonas* sp.** (green alga)	4.23 µg l^{-1}	***Chlamydomonas* sp.** (green alga)	1.21 µg l^{-1}
16/8/95	Pre-lime (142 mg l^{-1}) No Polymer Pre-chlorine (7.0 mg l^{-1}) $FeCl_3$ (0.6 mg l^{-1})	***Chlamydomonas* sp.** (green alga)	1.43 µg l^{-1}	***Chlamydomonas* sp.** (green alga)	0 µg l^{-1}
3/10/95	Pre-lime (177 mg l^{-1}) No Polymer Pre-chlorine (1.4 mg l^{-1}) $FeCl_3$ (0.7 mg l^{-1})	***Synechococcus cedrorum*** (blue-green alga)	2.29 µg l^{-1}	***Synechococcus cedrorum*** (blue-green alga)	0 µg l^{-1}

22/2/96	Pre-lime (55 mg l^{-1}) Polymer (17 mg l^{-1}) Pre-chlorine (0.5 mg l^{-1}) No $FeCl_3$	* *Monoraphidium arcuatum* (green alga)	1.71 µg l^{-1}	**Monoraphidium arcuatum* (green alga)	1.14 µg l^{-1}

* Species present in river water in large quantities

** Species not present in river water

Module III

Major Taxonomical groups

Representatives of six algal groups were present in the different stages of the purification process of Module III from August 1993 to April 1996 (Table 14). The groups were Cyanophyceae (blue-green algae), Bacillariophyceae (diatoms), Chlorophyceae (green algae), Euglenophyceae (euglenophytes), Dinophyceae (dinoflagellates) and Cryptophyceae (cryptophytes).

On four occasions, namely the end of August 1993, the middle of March 1994, during August 1994 and the end of January 1996 the diatoms were dominant in the secondary sedimentation effluent of Module III (Figs 43 & 44). The dominant species were an unidentified centric diatom, *Melosira granulata* and an unidentified pennate diatom.

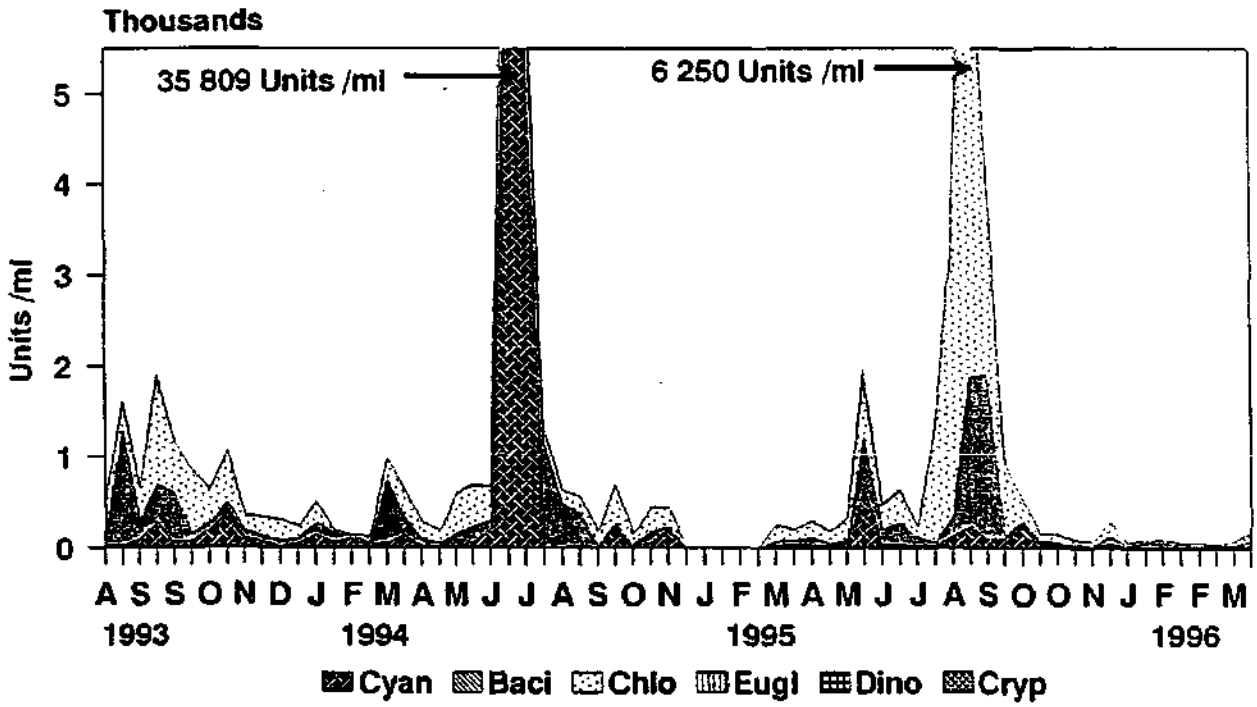

Figure 43: Phytoplankton counts of major taxonomical groups of the secondary sedimentation effluent of Module III from August 1993 to April 1996.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Dino = Dinophyceae, Cryp = Cryptophyceae.

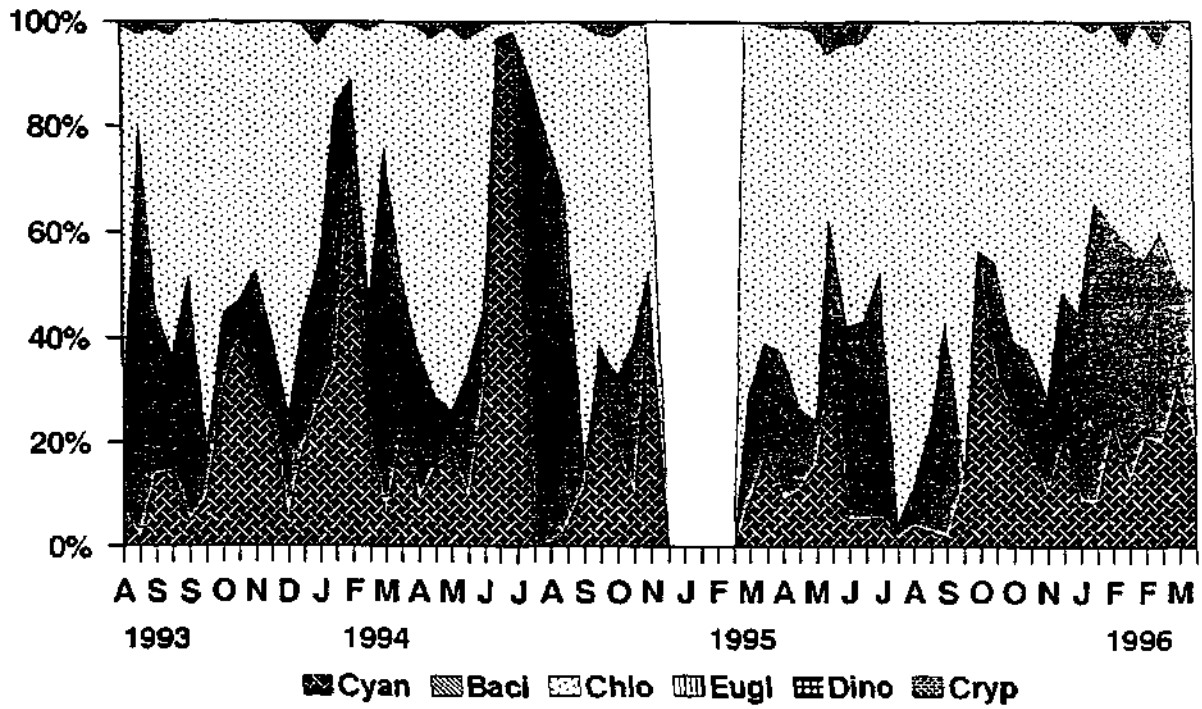

Figure 44: Phytoplankton composition (%) of major taxonomical groups of the secondary sedimentation effluent of Module III from August 1993 to April 1996.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Dino = Dinophyceae, Cryp = Cryptophyceae.

During the end of February 1994, during July 1994 and at the beginning of October 1995 the blue-green algae were dominant in the sedimentation effluent of Module III (Figs 43 & 44); the dominant species were *Oscillatoria simplicissima*, *Synechocystis* sp., *Synechococcus cedrorum* and *Microcystis flos-aquae*.

The green algae were dominant in the secondary sedimentation effluent, except for the periods mentioned above (end of August 1993, end of February 1994 and the middle of March 1994, July 1994, August 1994 beginning of October 1994 and the end of January 1996). The dominant species were *Monoraphidium arcuatum*, *Scenedesmus opoliensis*, *Scenedesmus acuminatus*, *Oocystis lacustris* and *Chlamydomonas* sp.

On four occasions, namely the end of February 1994, the end of March 1994, during August 1994 and December 1995 the diatoms were dominant in the filtration effluent (Figs 45 & 46). The dominant species was an unidentified pennate diatom, *Melosira granulata* and an unidentified centric diatom.

Six peaks of blue-green algae occurred in the filtration effluent, namely in the beginning of November 1993, the end of January 1994, during July 1994, in the beginning of October 1994, the end of November 1994 and the beginning of October 1995 (Figs 45 & 46). The dominant algal species were *Synechococcus cedrorum*, *Synechocystis* sp. and *Microcystis flos-aquae*.

The green algae were dominant in the filtration effluent of Module III except for the periods when the diatoms or blue-green algae were dominant (Figs 45 & 46). The dominant species were *Monoraphidium arcuatum*, *Chlamydomonas* sp., *Carteria globosa* and *Oocystis lacustris*.

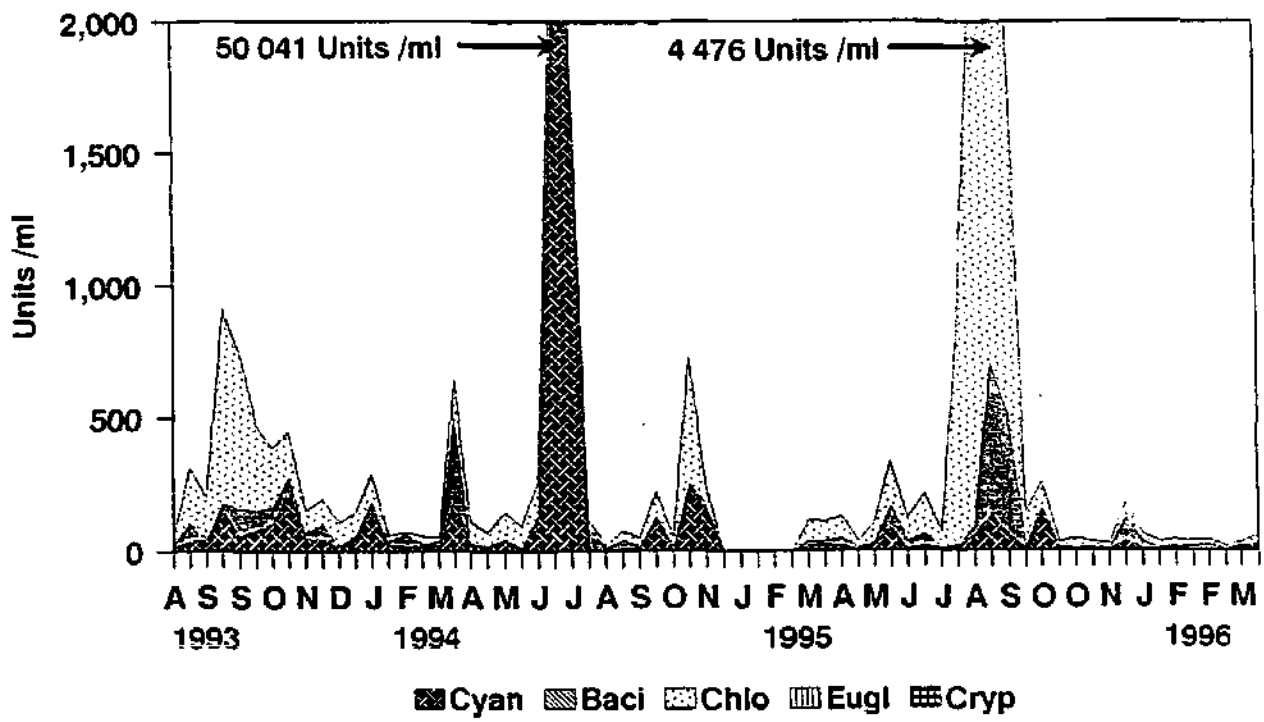

Figure 45: Phytoplankton counts of major taxonomical groups of the sand filtration effluent of Module III from August 1993 to April 1996.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Cryp = Cryptophyceae.

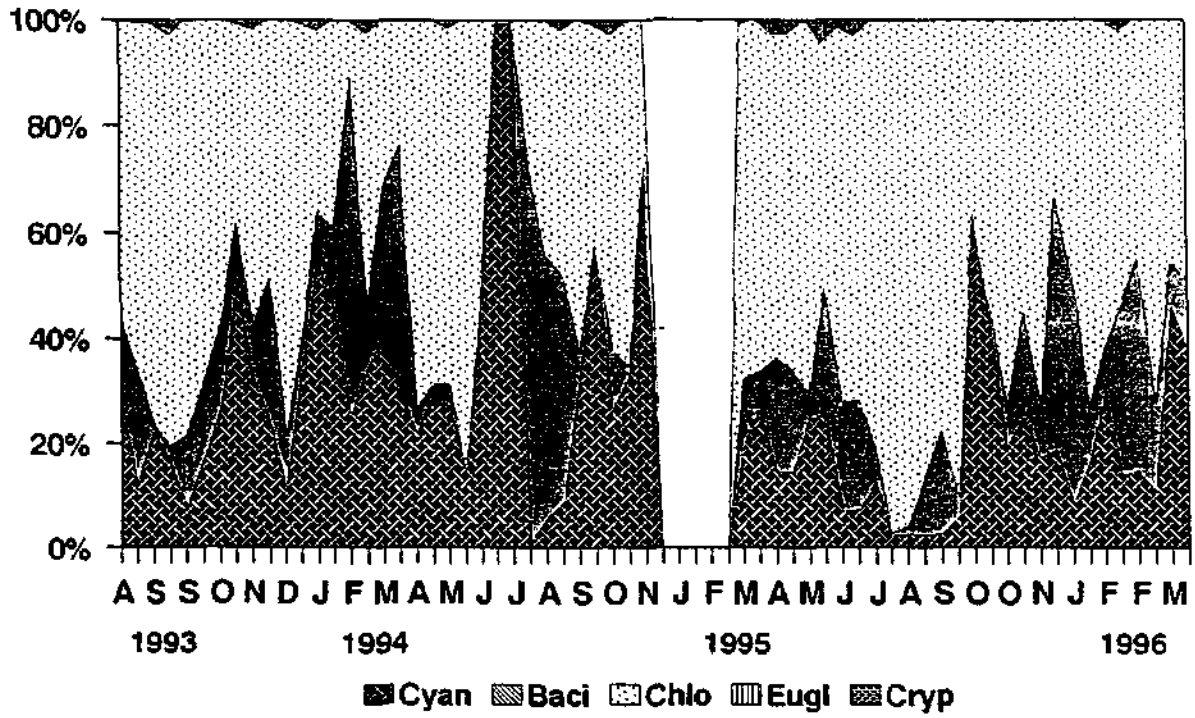

Figure 46: Phytoplankton composition (%) of major taxonomical groups of the sand filtration effluent of Module III from August 1993 to April 1996.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Cryp = Cryptophyceae.

Low concentrations of euglenophytes, dinoflagellates and cryptophytes were present in the sedimentation and filtration effluents of Module III. The dominant euglenophyte species were *Trachelomonas intermedia*, *Trachelomonas scabra*, *Euglena* sp, *Phacus pyrum* and *Lepocinclis salina*, the dominant dinoflagellates were *Peridinium penardiforme* and *Sphaerodinium ravumfluvium* and the dominant cryptophyte was *Cryptomonas major*.

Phytoplankton biomass, Species diversity and Turbidity

The chlorophyll-a concentration of the sedimentation effluent varied throughout the study period and the highest chlorophyll-a concentration occurred during the middle of September 1993 (Fig. 47, Table 11; 5 µg/l). The dominant algal species was *Scenedesmus opoliensis*, a colonial green alga.

The highest algal unit concentration of the sedimentation effluent of Module III occurred during June and July 1994 (Fig. 47, 37 600 units/ml). The high concentration of algal

units was due to high concentrations of the blue-green algae *Synechocystis* sp. in the sedimentation effluent of Module III.

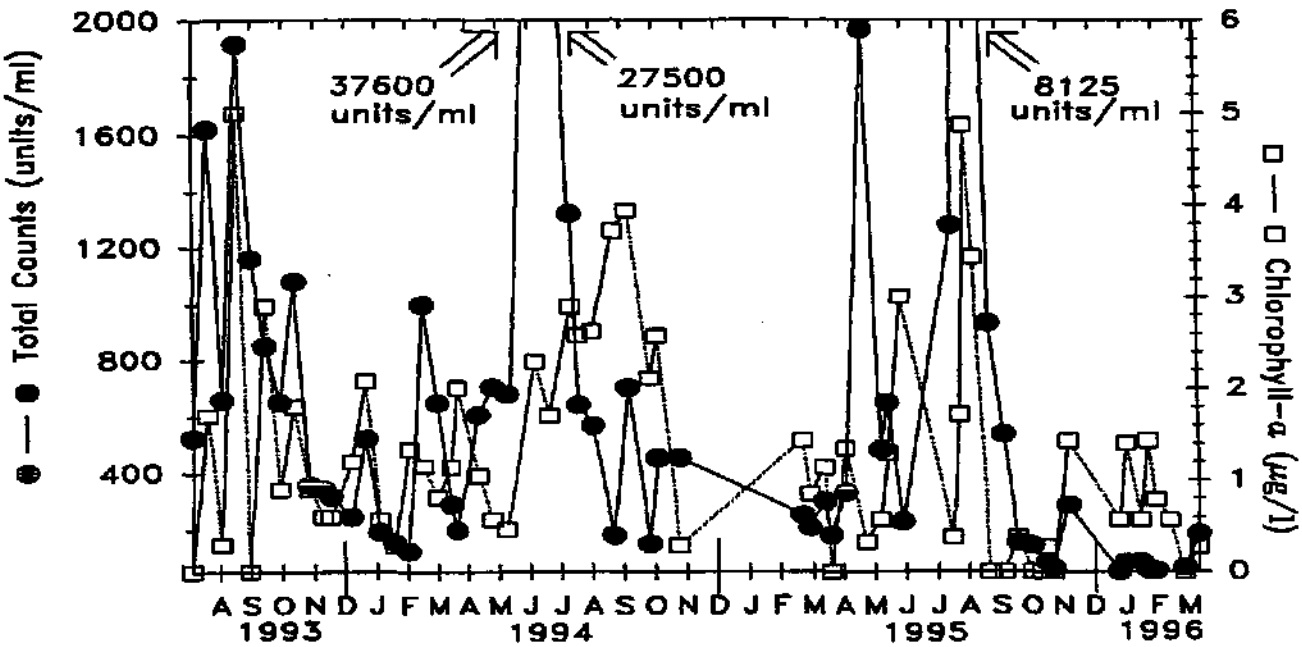

Figure 47: Phytoplankton biomass in µg/l chlorophyll-*a* and total counts in algal units/ml of the secondary sedimentation effluent of Module III from August 1993 to April 1996.

On four occasions the chlorophyll-a concentration was below detection limits, while the algal unit concentration was relatively high in the sedimentation effluent of Module III (Fig. 47), namely at the beginning of August 1993, the end of September 1993, the end of April 1995, during the end of September 1995 and the beginning of October 1995 (Fig. 47). The dominant algal species were *Chlamydomonas incerta* during August 1993, *Monoraphidium arcuatum* during the end of September 1993, *Scenedesmus opoliensis* during the end of April and the end of September 1995 and *Synechococcus cedrorum* during the beginning of October 1995.

The chlorophyll-a concentration of the filtration effluent varied throughout the study period and the highest chlorophyll-a concentration occurred at the end of August 1995 (Fig. 48, Table 11; 4.3 µg/l). The chlorophyll-a concentration of the filtration effluent of Module III was most of the time below 1 µg/l (Fig. 48).

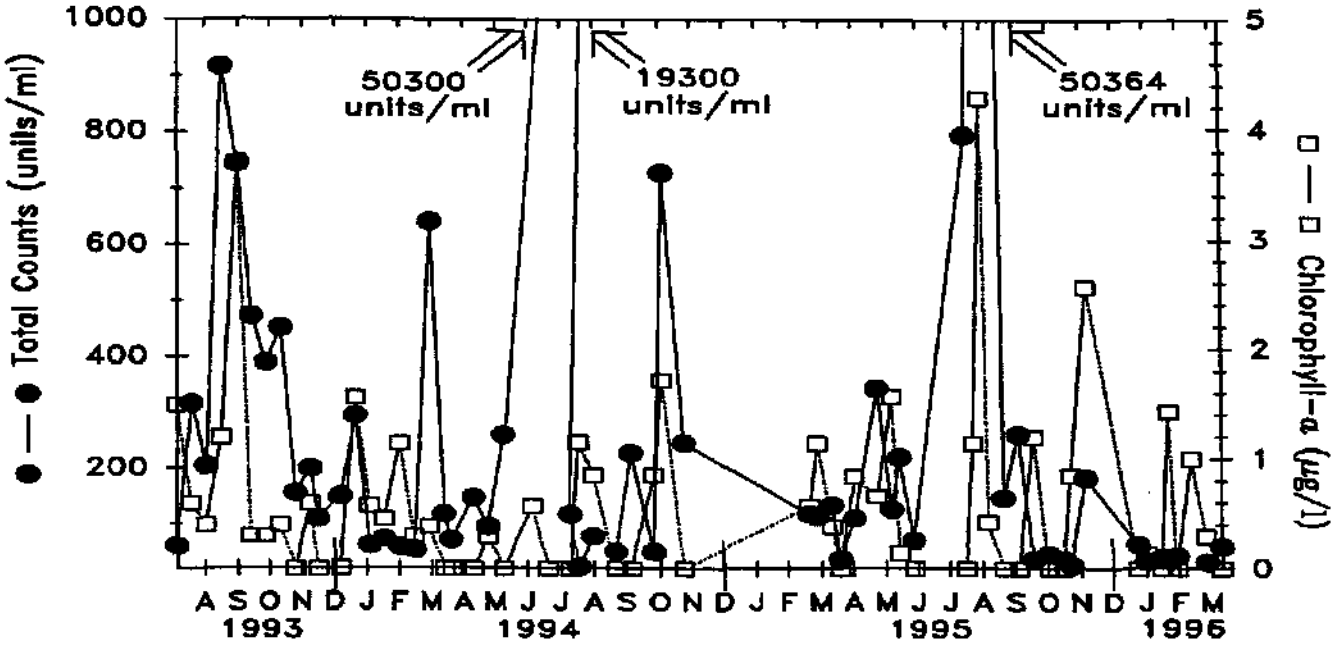

Figure 48: Phytoplankton biomass in µg/l chlorophyll-*a* and total counts in algal units/ml of the sand filtration effluent of Module III from August 1993 to April 1996.

The highest algal unit concentration of the filtration effluent occurred during June and July 1994 and during August 1995 (Fig. 48, 50 300 units/ml). The dominant algal species was *Synechocystis* sp. during June and July 1994 and *Chlamydomonas* sp. during August 1995. The chlorophyll-*a* concentration was also the highest during August 1995.

During the beginning of August 1994, middle of April 1995 and during the end of October 1995, the end of January 1996 and during February 1996 the algal unit concentration and chlorophyll-a concentration was relatively low (Fig. 48). The dominant algal species were an unidentified centric diatom during the beginning of August 1994, *Monoraphidium arcuatum* during the middle of April 1995 and the end of October 1995, *Melosira granulata* during January and February 1996.

The turbidity varied during the study period in the sedimentation effluent of Module III (Fig. 49). The highest turbidity (7.8 NTU) occurred during the end of February 1996 (Fig. 49, Table 12).

Table 11: Minimum and maximum values of the algal unit and chlorophyll-*a* concentrations of the different sampling localities of Module III (See also Figs 3, 47, 48, 60). nd = not detectable

Sampling localities	Algae (unit/ml)			Chlorophyll-a (µg/l)		
	Min	Max	Mean	Min	Max	Mean
River water	842	58 770	10 295	nd	130	39.86
Sedimentation	36.2	37 601	1 786	nd	5.0	1.31
Filtration	16.29	50 364	1 475	nd	4.29	0.61
Final water	9.79	8 129	433	nd	3.43	0.26

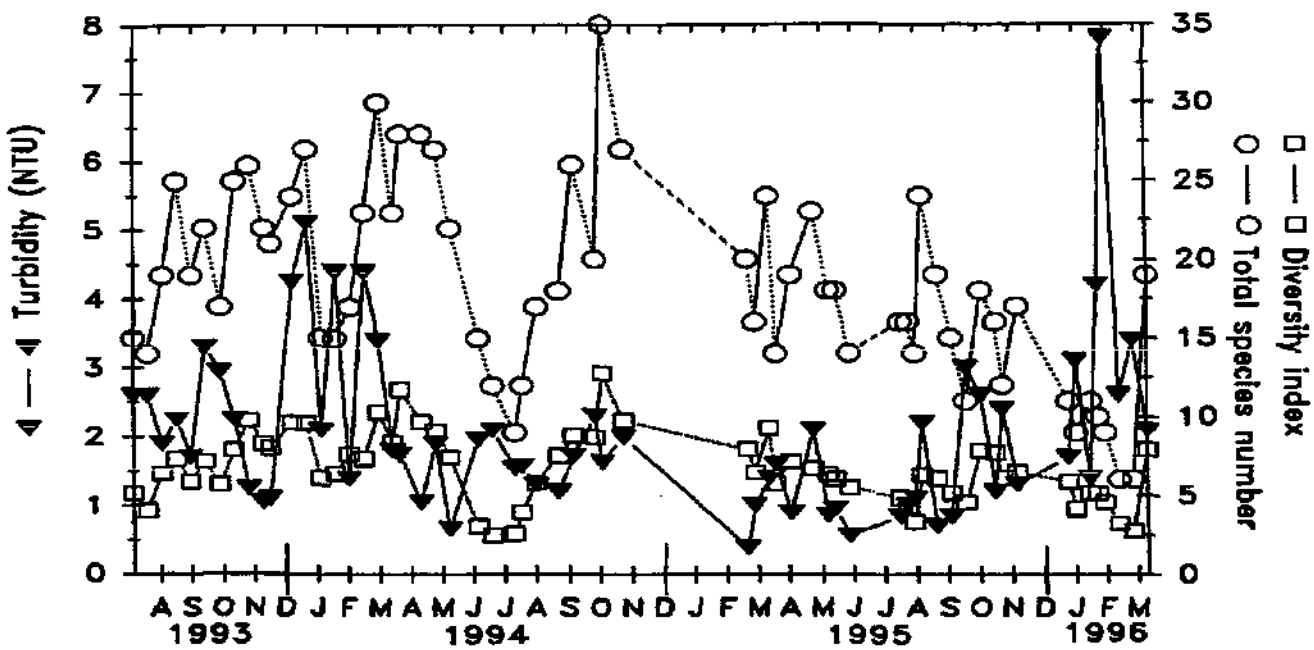

Figure 49: Species diversity in total species number, turbidity in NTU and diversity index of the secondary sedimentation effluent of Module III from August 1993 to April 1996.

The total species number varied between 5 and 35 species during the study period in the sedimentation effluent of Module III. (Fig. 49, Table 12). The diversity index was

below 15 throughout the study period and the highest diversity index occurred during the beginning of November 1995 (Fig. 49, Table 12; 12.8).

Table 12: Minimum and maximum values of turbidity, total species number and diversity index of the different sampling localities of Module III (See also Figs 4, 49, 50, 61).

Sampling localities	Turbidity (NTU)			Total species number			Diversity index		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
River water	7.9	1900	111.3	6	34	18.74	0	8.9	4.6
Secondary sedimentation	0.39	7.8	2.06	6	35	18.36	2.5	12.8	6.6
Sand filtration	0.1	1.1	0.5	3	26	12.54	1.2	9.7	5.3
Final water	0.13	2.3	0.58	3	23	11.7	1.2	9.6	5.2

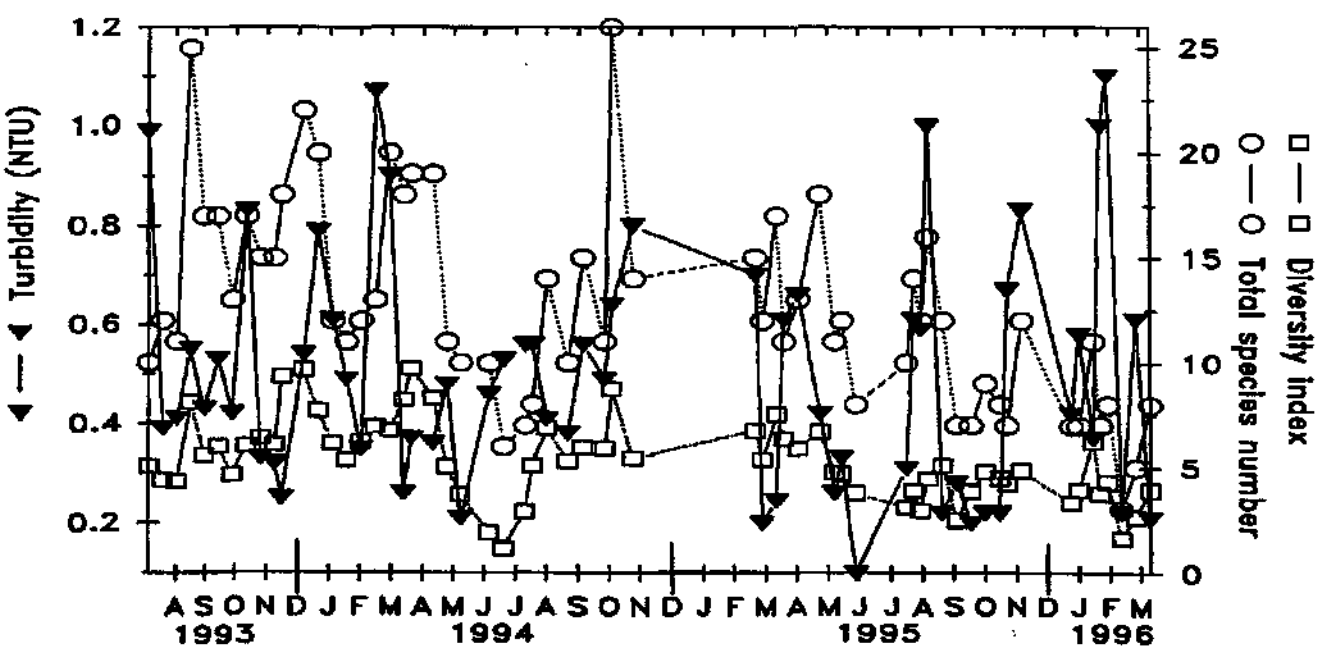

Figure 50: Species diversity in total species number, turbidity and diversity index in NTU of the sand filtration effluent of Module III from August 1993 to April 1996.

The turbidity of the filtration effluent of Module III varied throughout the study period (Fig. 50). There were five occasions where the turbidity was above 0.9 NTU, namely at the

beginning of August 1993, during March 1994 and the beginning of September 1995 and the middle and end of February 1996 (Fig. 50). The turbidity of the filtration effluent was the lowest during the end of June 1995 (Fig. 50, 0.1 NTU).

The total species number and diversity index varied throughout the study period in the filtration effluents of Module III (Fig. 50).

Percentage removal

The percentage removal of chlorophyll-*a* during sedimentation remained more or less constant and above 70% except for the end of September 1994 (44%), the end of November 1995 (0%), end of February 1996 and during March 1996 when the percentage removal during sedimentation was lower than during the rest of the study period (Fig. 51).

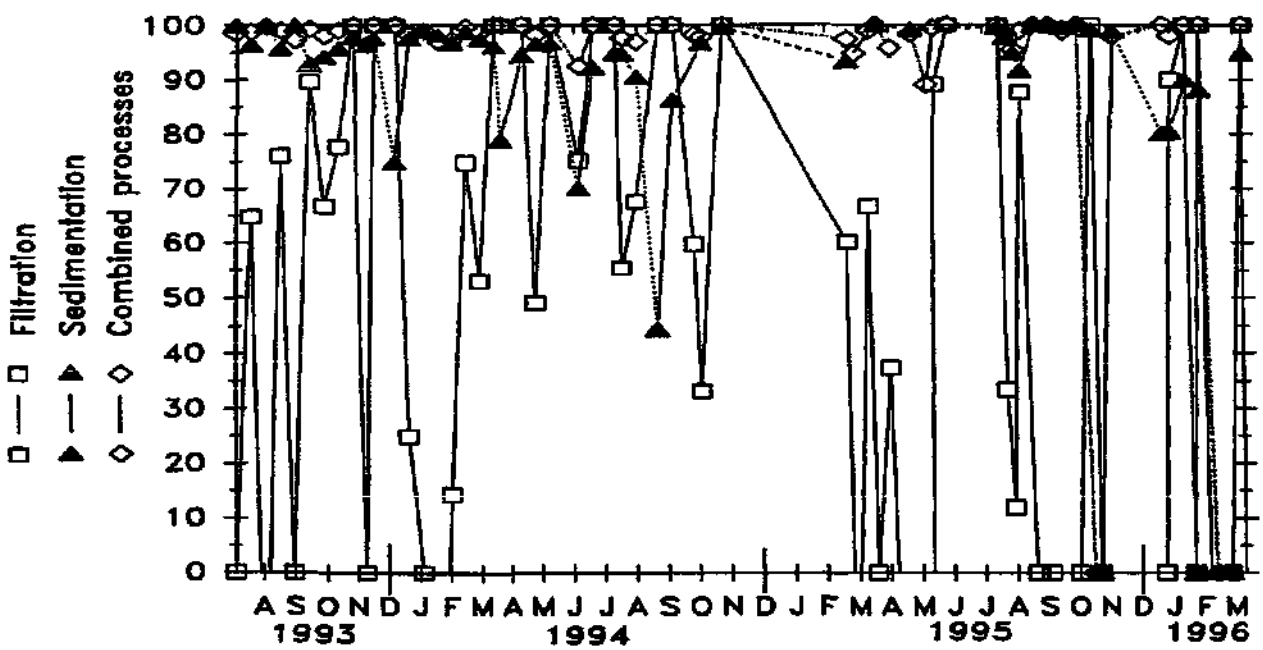

Figure 51: Percentage removal of chlorophyll-*a* by sedimentation, filtration and the combined processes of Module III from August 1993 to April 1996.

On four occasions, namely at the beginning of September 1993, the end of February 1994, during the end of March 1995 and during May and June 1995, the percentage removal of chlorophyll-*a* during filtration was negative. The negative removals were because of an increase in chlorophyll-a concentration between the sedimentation and the filtration effluents of Module III (Fig. 51).

During the end of November 1995, the end of February 1996 and during March 1996 the percentage removal of chlorophyll-*a* during sedimentation was 0 (Fig. 51).

The percentage removal of chlorophyll-*a* during the combined processes remained more or less constant during the study period
(Fig. 51).

The percentage removal of algal units by sedimentation, filtration and the combined processes showed great variation during the study period (Fig. 52).

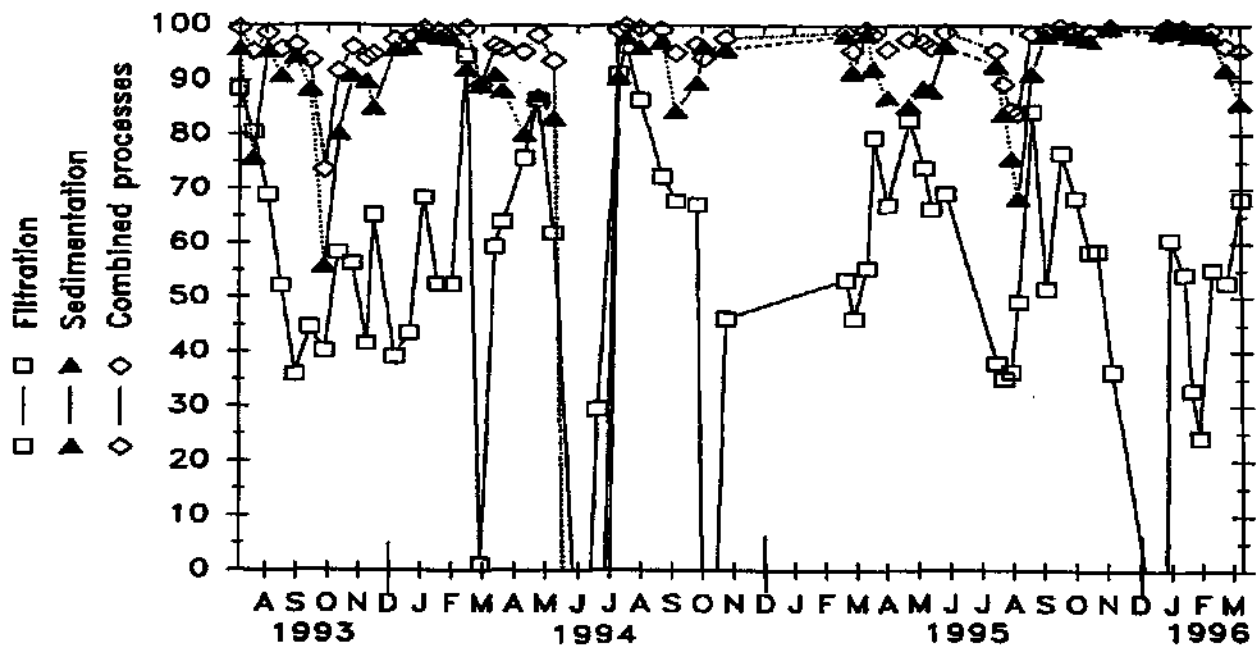

Figure 52: Percentage removal of algal units by sedimentation, filtration and the combined processes of Module III from August 1993 to April 1996.

The percentage removal of algal units by sedimentation, filtration and the combined processes were negative during June and July 1994 due to an increase in algal unit concentration from the river water to the final water (Fig. 52). The dominant algal species was the blue-green algae *Synechocystis* sp.

During November 1994, and during January 1996 the percentage removal of algal units by filtration was negative due to an increase in algal units from the river water to the filtration effluent (Fig. 52). The dominant algal species was *Synechococcus cedrorum*.

During the end of March 1994 no algal cells were removed from the water by filtration because the percentage removal of algal units by filtration was 0 (Fig. 52).

Table 13 represents the minimum, maximum and mean values of percentage removal during sedimentation, filtration separately and for the combined process.

Table 13: Percentage removal of chlorophyll-*a*, algal units and turbidity by sedimentation, sand filtration and the combined processes of Module III (See also Figs 51, 52, 53).

Sampling localities	Chlorophyll-a (%)			Algal units (%)			Turbidity (%)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Sedimentation	0	100	86	-177*	99	83	82	99	95
Filtration	-215*	100	39	-60*	96	54	-79*	93	70
Combined processes	0	100	90	-272*	100	88	95	100	98

* = negative removal indicates algal growth within the sytem.

The percentage removal of turbidity by sedimentation varied throughout the study period. The percentage removal by sedimentation was higher than the percentage removal by filtration (Fig. 53). The percentage removal of turbidity by sedimentation was above 80% during the study period.

The percentage removal of turbidity by filtration varied during the study period (Fig. 53). The percentage removal of turbidity was negative during the beginning of March 1995 due to an increase in turbidity from the sedimentation to the filtration effluent of Module III (Fig. 53).

The percentage removal of turbidity by the combined processes remained more or less constant and above 90% during the study period (Fig. 53).

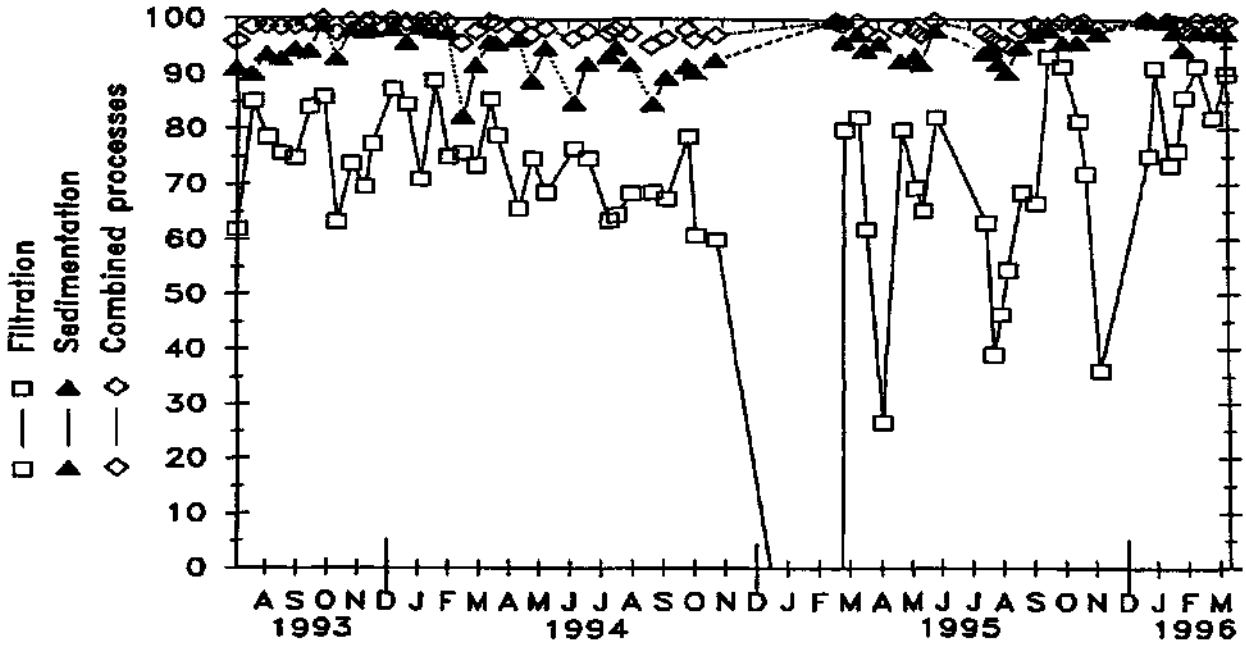

Figure 53: Percentage removal of turbidity by sedimentation, filtration and the combined processes of Module III from August 1993 to April 1996.

Morphological groups

Most of the unicellular discoidal cells (Undi) which were present in the river water were removed by secondary sedimentation during the study period except during the end of August 1993, during August 1994 and June and July 1995 (Figs 54 & 55).

Unicellular discoidal cells (Undi) were dominant during the end of August 1993 and during August 1994 in the sedimentation effluent (Figs 54 & 55). The dominant algal species was an unidentified centric diatom.

Peaks of filament concentration occurred at the end of September 1993, the end of February 1994 and the middle of March 1994 in the sedimentation effluent (Figs 54 & 55). The dominant species were *Melosira granulata* and *Oscillatoria simplicissima*.

During August 1993, December 1993, the beginning of October 1994 and during August 1995 peaks of unicellular flagellated cells (Unfl) occurred in the sedimentation effluent (Figs 54 & 55). The dominant species were *Carteria globosa*, *Carteria simplicissima* and *Chlamydomonas incerta*, *Chlamydomonas* sp.

The unicellular spherical cells (Unsp) and unicellular elongated (Unel) cells increased from the river water to the sedimentation and filtration effluent from the end of August 1993 to the end of July 1994 and again from September 1995 to the middle of April 1996 (Figs 5 & 6, 54-57). The dominant Unsp species were *Synechocystis* sp., *Synechococcus cedrorum* and *Oocystis lacustris*. The dominant Unel species were *Monoraphidium arcuatum*, *Monoraphidium circinale* and unidentified pennate diatoms.

Four peaks of unicellular spherical cells (Unsp) occurred during July 1994, at the beginning of October 1994, the beginning of November 1994 and the beginning of October 1995 in the sedimentation effluent (Figs 54 & 55). The dominant algal species were *Synechocystis* sp., *Synechococcus cedrorum* and *Oocystis lacustris*.

During the end of November 1994 and during March and April 1995 the colonial algal cells with spines (Cospi) was dominant in the sedimentation effluent of Module III (Figs 54 & 55). The dominant algal species *Scenedesmus opoliensis* and *Scenedesmus intermedius*.

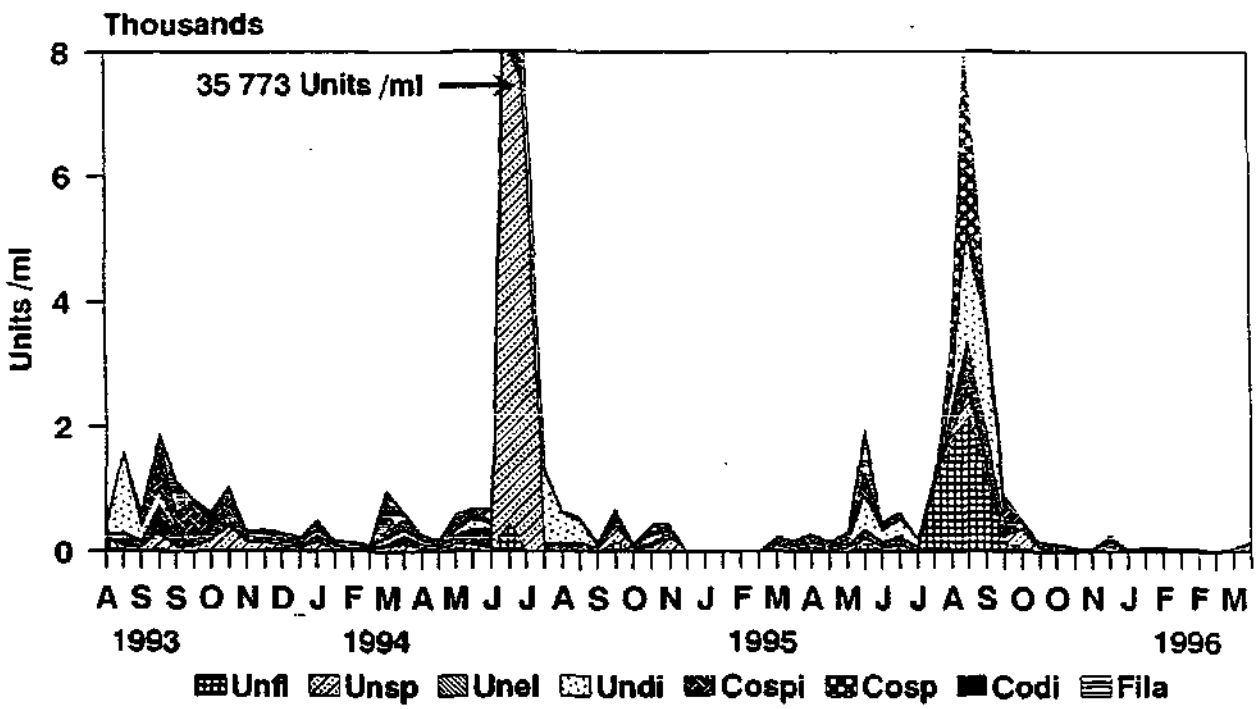

Figure 54: Phytoplankton counts of morphological groups of the secondary sedimentation effluent of Module III from August 1993 to April 1996.
Unfl = Unicellular flagellated algae, Unsp = Unicellular spherical algae, Unel = Unicellular elongated algae, Undi = Unicellular discoidal algae, Cospi = Colonial algae individual cells with spines, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Fila = Filament.

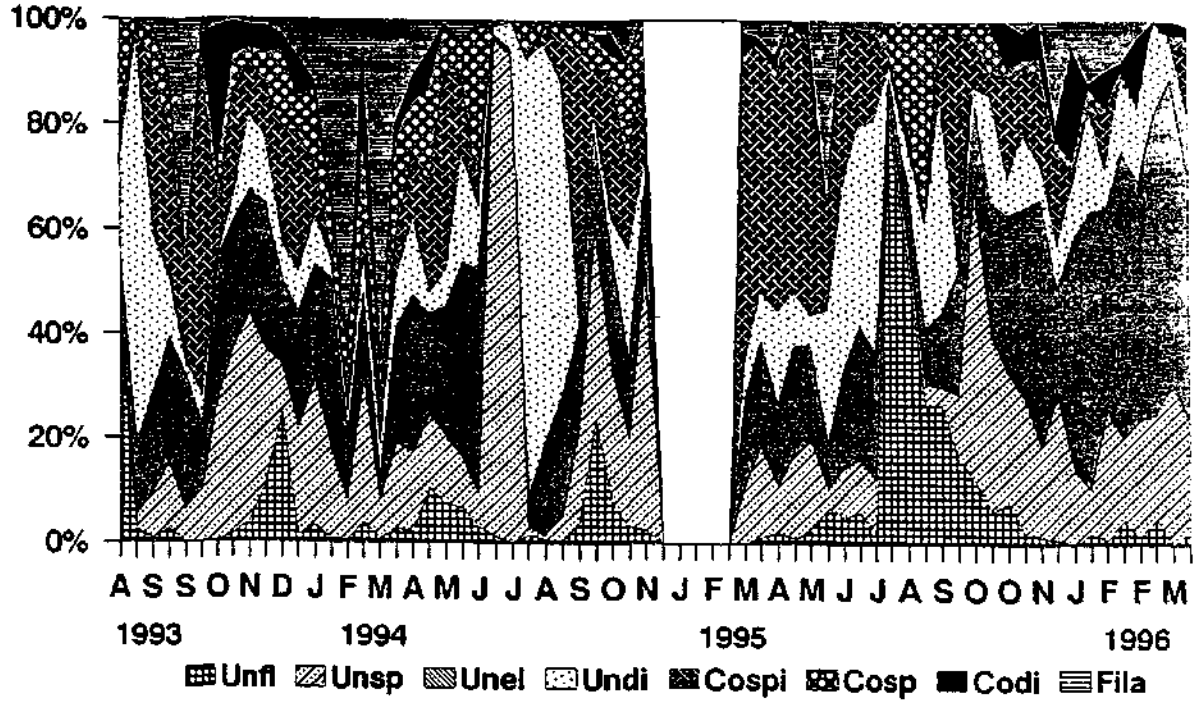

Figure 55: Phytoplankton composition (%) of morphological groups of the secondary sedimentation effluent of Module III from August 1993 to April 1996.
Unfl = Unicellular flagellated algae, Unsp = Unicellular spherical algae, Unel = Unicellular elongated algae, Undi = Unicellular discoidal algae, Cospi = Colonial algae individual cells with spines, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Fila = Filament.

A peak concentration of unicellular discoidal cells (Undi) occurred during the beginning of August 1994 in the filtration effluent (Figs 56 & 57). The dominant algal species was an unidentified centric diatom.

Only a small percentage of the filaments were present in the filtration effluent during the end of September 1993, end of February 1994 and middle of March 1994 (Figs 56 & 57), indicating that filtration removed the filaments effectively.

A peak of filaments occurred during the end of March 1994 and December 1995 in the filtration effluent (Figs 56 & 57), the dominant species was *Melosira granulata*.

Five peaks of unicellular flagellated (Unfl) cells occurred in the filtration effluent during the end of November 1993, the end of December 1993, the beginning of October 1994,

during August 1995 and the beginning of September 1995. The dominant species were *Carteria globosa*, *Carteria simplicissima*, *Chlamydomonas incerta* and *Chlamymonas* sp.

From the beginning of August 1993 to the end of October 1993 and again from November 1995 to March 1996 the unicellular elongated (Unel) cells were dominant in the filtration effluent of Module III (Figs 56 & 57). The dominant species were *Ankistrodesmus falcatus*, *Monoraphidium arcuatum*, *Monoraphidium circinale* and unidentified pennate diatoms.

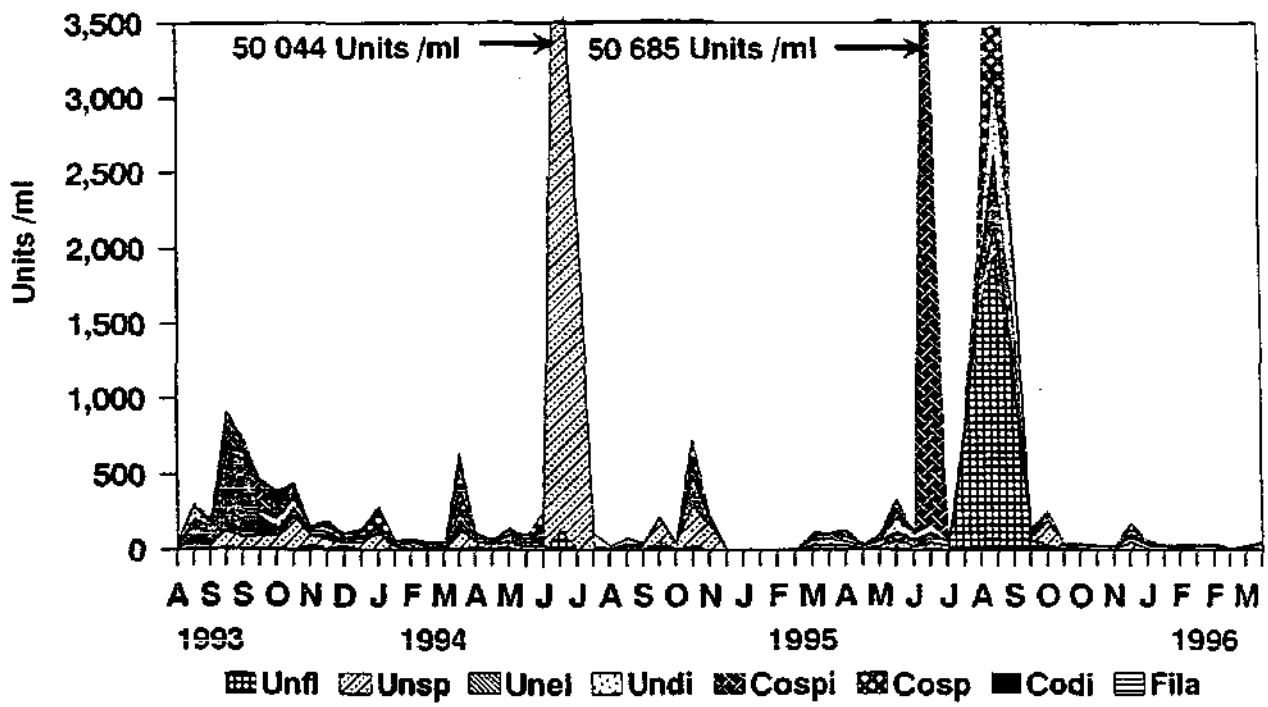

Figure 56: Phytoplankton counts of morphological groups of the sand filtration effluent of Module III from August 1993 to April 1996.
Unfl = Unicellular flagellated algae, Unsp = Unicellular spherical algae, Unel = Unicellular elongated algae, Undi = Unicellular discoidal algae, Cospi = Colonial algae individual cells with spines, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Fila = Filament.

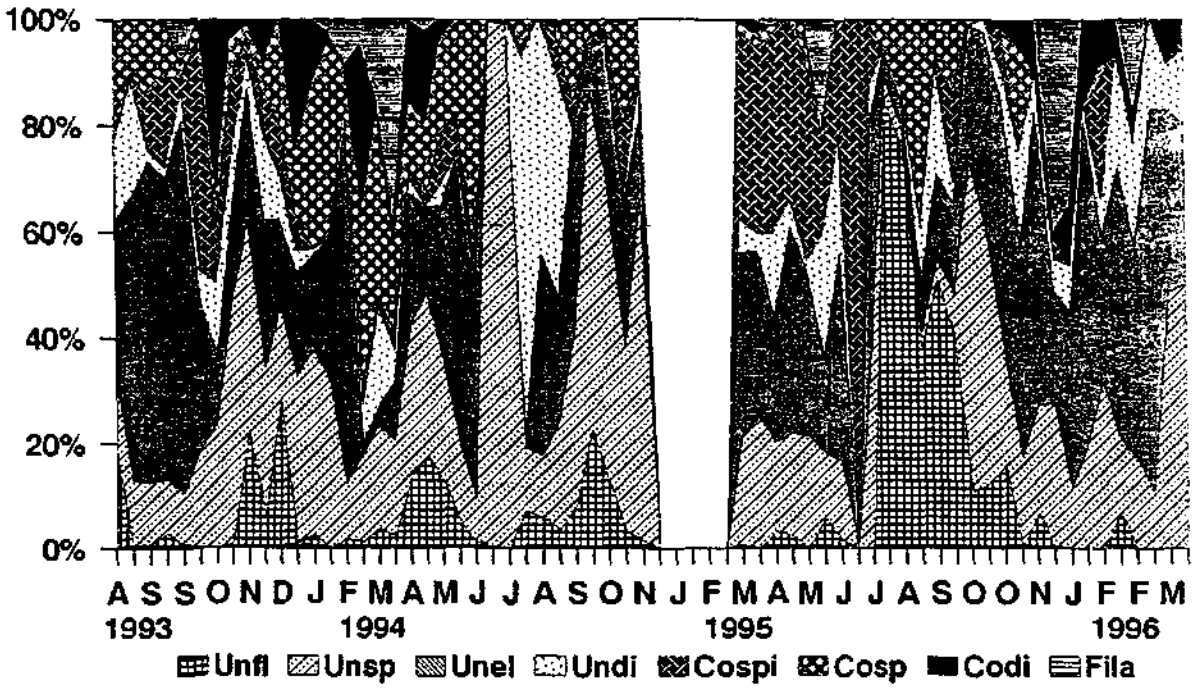

Figure 57: Phytoplankton composition (%) of morphological groups of the sand filtration effluent of Module III from August 1993 to April 1996.
Unfl = Unicellular flagellated algae, Unsp = Unicellular spherical algae, Unel = Unicellular elongated algae, Undi = Unicellular discoidal algae, Cospi = Colonial algae individual cells with spines, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Fila = Filament.

Four peaks of unicellular spherical cells (Unsp) occurred during July 1994, at the beginning of October 1994, the beginning of November 1994 and the beginning of October 1995 in the filtration effluent (Figs 56 & 57). The dominant algal species were *Synechocystis* sp., *Synechococcus cedrorum* and *Oocystis lacustris.*

There were three peaks of colonial algae with discoidal cells (Codi) namely, at the end of October 1993, the beginning of January 1994 and the beginning of March 1994 in the filtration effluent (Figs 56 & 57). The dominant species was *Crucigenia tetrapedia.*

Discussion of the results of Module III

The best removal of diatoms in relation to the other groups was by secondary sedimentation (Figs 1 & 2, 43-46, 58 & 59). The green algae increased proportionally from the river water to the sedimentation effluent.

During the beginning of August 1993 when the pre-chlorine dosage was high, the chlorophyll-*a* concentration of the filtration effluent was high (1.5 μg/l) while the algal unit concentration was very low (Fig. 48, below 100). During the same period the green algae were dominant in the filtration effluent (Figs 45 & 46). The reason for the high chlorophyll-*a* concentration occurring together with low algal unit concentrations, was probably because the green algal cells may have had a high chlorophyll-*a* content per cell unit. The dominant species was *Chlamydomonas incerta*.

During the end of December 1993 no pre-lime, carbon dioxide, $FeCl_3$, $Fe_2(SO_4)_3$ and polymer were dosed. Only chlorine was dosed.

The green algae were dominant in the different stages of the purification process during the end of December 1993 when only chlorine was dosed (Figs 43-46, 58 & 59). The dominant species were *Carteria simplicissima*, *Monoraphidium arcuatum*, *Carteria globosa* and *Monoraphidium circinale*.

A peak of unicellular flagellated cells (Unfl) occurred at all the different stages of the purification process during the end of December 1993 (Figs 5 & 6, 54-57, 62 & 63). The dominant species were *Carteria simplicissima* and *Carteria globosa*. The results indicate that these green algae are least affected by chlorine dosage.

During the middle of March 1994 no pre-lime was dosed, but only a relatively high (3 mg/l) polymer dosage was applied. Fig. 47 shows that the chlorophyll-*a* concentration and algal units of the sedimentation effluent was high (2,9 μg/l & 1000 units/ml) during this (middle of March) period. The diatoms were dominant in the sedimentation effluent during mid- March 1994. The dominant diatom species was *Melosira granulata*.

During the middle of February 1994 no pre-lime and carbon dioxide were dosed but a very high (10.9 mg/l) dosage of polymer occurred. The diatoms were removed by sedimentation, but there was a peak of blue-green algae in the sedimentation effluent (Figs 43 & 44 ; Table 15). The dominant diatom was an unidentified centric diatom, and the dominant blue-green alga was *Oscillatoria simplicissima*. These results indicated

that a high polymer dosage effectively removed the diatoms, but not the blue-green algae present.

The reason for the difference between the middle of March 1994 (where the polymer dosage was not effective in removing the diatoms) and the middle of February (where the polymer was effective in removing the diatoms), could be because the polymer dosage of mid February was higher (10.9 mg/l) than the polymer dosage (3 mg/l) of mid March 1994.

A small percentage of the blue-green algae were removed by filtration (Figs 45 & 46), but there were still blue-green algae present in the final water (Figs 58 & 59). The dominant species in the final water was *Oscillatoria simplicissima*.

A bloom of the diatom *Melosira granulata* occurred in the water during December 1995 (Figs 1 & 2, 43-46). The diatom was dominant in the filtration effluent of Module III during this period (Figs 45 & 46). High concentrations of pre-chlorine (3.8 mg/l) and $FeCl_3$ (5 mg/l) was dosed during this period. The polymer dosage concentration was not so high (1,2 mg/l) in the same period. The dosage concentrations was apparently not sufficient to remove the diatom, *Melosira granulata*, from the water.

The diatoms were dominant in the filtration effluent of Module III during the middle of August 1994 (Figs 45 & 46). A bloom of diatoms occurred in the river water during this period (Figs 1 & 2). The pre-chlorine dosage concentration was high (4 mg/l) and the $FeCl_3$ dosage was also high (3 mg/l), while no polymer was dosed during this period. Therefore, it can be concluded that polymer dosage is necessary for the removal of diatoms.

During the end of January 1994 the blue-green algae were dominant in the filtration effluent of Module III (Figs 45 & 46). The chlorophyll-*a* concentration of the filtration effluent was above 1 μg/l (Fig. 48; 1.6 μg/l). The pre-chlorine dosage concentration was high (4 mg/l). The polymer dosage was above 1 (2.2 mg/l) and the $FeCl_3$ dosage concentrations approximately 1.1 mg/l. A low $FeCl_3$ dosage concentration together with high pre-chlorine and polymer dosage was not successful in the removal of the blue-green algae from the water.

The green algae were most of the time dominant in the filtration effluent of Module III when the chlorophyll-a concentrations was above 1 μg/l.

During June and July 1994 a peak of blue-green algae occurred in the sedimentation and filtration effluents of Module III (Figs 43-46). The dominant species was *Synechocystis* sp. (Unsp) (Table 15). The algal unit concentration of the sedimentation and filtration effluent was extremely high (Figs 56, 57). The percentage removal of algal units during sedimentation, filtration and the combined processes was negative due to an increase in algal units from the river water to the final water.

The following list compares the species which penetrated the sedimentation and filtration processes of Module III.

	Sedimentation	Filtration
Green algae:		
Monoraphidium arcuatum (Unel)*	X	X
Monoraphidium circinale (Unel)		X
Oocystis lacustris (Unsp)	X	X
Scenedesmus opoliensis (Cospi)	X	X
Scenedesmus acumunatis (Cospi)	X	
Scenedesmus lefevrii (Cospi)	X	
Carteria globosa (Unfl)	X	
Carteria simplicissima (Unfl)		X
Crucigenia tetrapedia (Codi)		X
Chlamydomonas incerta (Unfl)	X	X
Blue-green algae:		
Microcystis flos-aquae (Cosp)	X	X
Synechococcus cedrorum (Unsp)	X	X
Oscillatoria simplicissima (Fila)	X	X
Synechocystis sp. (Unel)	X	X
Chroococcus dispersus (Cosp)	X	X
Diatoms:		
Centric (Undi)	X	X
Melosira granulata (Fila)	X	X
Pennate (Unel)	X	X
Euglenophytes:		
Trachelomonas intermedia (Unfl)	X	X
Trachelomonas scabra (Unfl)	X	X
Euglena sp. (Unel)	X	X

Phacus pyrum (Unfl)	X	
Lepocinclis salina (Unfl)	X	
Trachelomonas volvocina (Unfl)		X

*Unfl = Unicellular flagellated algae, Unsp = Unicellular spherical algae, Unel = Unicellular elongated algae, Undi = Unicellular discoidal algae, Cospi = Colonial algae individual cells with spines, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Fila = Filament.

Sedimentation and filtration were penetrated by all the morphological groups. However, the groups which were removed less effectively in relation to the other groups were unicellular elongated cells (Unel), unicellular spherical cells (Unsp), filaments (Fila) colonial algae and individual cells with spines (Cospi).

Table 15 shows different dosing concentrations and some of the species which were not successfully removed during the different phases of Module III. Two major taxonomical groups, namely the green and blue-green algae, were generally difficult to remove. All the algal species in Table 15 are small unicellular algae except for the filamentous blue-green alga *Oscillatoria simplicissima*. *Oscillatoria simplicissima* was successfully removed during sand filtration.

Most of the time the same species that was dominant in the river water was difficult to remove during the different treatment processes. Most of the time if a species was not successfully removed during sedimentation it was also present in the sand filtration and final water.

Table 14: Occurrance of phytoplankton species in the raw, sedimentation, sand filtration and final water of Module III of the Goldfield Water purification plant at Balkfontein. Abbreviations explained in Table 4.

	River*	Sed*	Filtr*	Finw*
CYANOPHYCEAE (Cyano)**				
Anabaena circinales	X	X	-	-
Chroococcus dispersus	-	X	X	X
Chroococcus schizodermaticus	-	X	-	-

Table 14 continued

	River*	Sed*	Filtr*	Finw*
Merismopedia minima	-	X	X	X
Microcystis aeruginosa	X	X	X	X
Microcystis flos-aquae	X	X	X	X
Microcystis incerta	-	X	X	X
Oscillatoria simplicissima	X	X	X	X
Synechococcus cedrorum	X	X	X	X
Synechocystis sp.	-	X	X	X
BACILLARIOPHYCEAE (Baci)**				
Centric diatoms	X	X	X	X
Melosira granulata	X	X	X	X
Pennate diatoms	X	X	X	X
CHLOROPHYCEAE (Chlo)**				
Actinastrum hantzschii	X	X	X	X
Ankistrodesmus bibraianus	X	-	-	-
Ankistrodesmus falcatus	-	X	X	X
Ankistrodesmus stipitatus	X	X	X	X
Carteria globosa	X	X	X	X
Carteria simplicissima	X	X	X	X
Cerasterium irregularis	-	X	-	-
Characium limneticum	-	X	X	X
Chlamydomonas bicocca	X	X	X	X
Chlamydomonas incerta	X	X	X	X
Chlamydomonas sp.	X	X	X	X
Chlorococcum infusionum	X	X	X	X

Table 14 continued

	River*	Sed*	Filtr*	Finw*
Coelastrum carpaticum	X	X	X	X
Coelastrum pseudomicroporum	X	X	X	X
Cosmarium laeve	X	X	X	X
Crucigenia lauterbornii	X	X	-	-
Crucigenia tetrapedia	X	X	X	X
Crucigeniella rectangularis	X	X	X	X
Dictyosphaerium elegans	X	X	X	X
Eudorina elegans	X	X	X	-
Golenkinia radiata	X	X	X	-
Kirchneriella sp.	X	X	X	X
Lagerheimia balatonica	X	X	X	X
Micractinium pusillum	X	X	X	-
Monoraphidium arcuatum	X	X	X	X
Monoraphidium circinale	X	X	X	X
Monoraphidium griffithi	X	X	X	X
Monoraphidium minutum	X	X	X	X
Oocystis lacustris	X	X	X	X
Oocystis marssonii	X	X	X	X
Oocystis pusilla	-	-	X	-
Pandorina morum	X	X	X	-
Pediastrum duplex	X	X	-	X
Pediastrum simplex	X	X	X	X
Pediastrum tetras	X	-	-	-
Pteromonas aculeata	X	X	X	X
Scenedesmus acuminatus	X	X	X	X
Scenedesmus disciformis	X	X	X	X

Table 14 continued

	River*	Sed*	Filtr*	Finw*
Scenedesmus intermedius	X	X	X	X
Scenedesmus lefevrii	X	X	X	X
Scenedesmus opoliensis	X	X	X	X
Scenedesmus smithii	-	-	-	X
Schroederia indica	X	-	-	-
Staurastrum tetracerum	-	-	X	-
Tetraedron limneticum	-	X	X	X
Tetraedron mediocris	X	X	X	X
Tetraedron planctonicum	X	X	X	X
Tetraedron regulare	X	-	-	-
Tetrastrum heteracanthum	X	X	X	X
Tetrastrum staurogeniaeforme	X	X	X	X
Thoracomonas feldmannii	X	X	-	X
Treubaria quadrispina	-	X	-	-
CRYPTOPHYCEAE (Crypto)**				
Cryptomonas major	X	X	X	-
DINOPHYCEAE (Dino)**				
Peridinium penardiforme	X	-	-	-
Sphaerodinium ravumfluvium	X	X	-	X
EUGLENOPHYCEAE (Eugl)**				
Euglena clavata	-	X	-	-
Euglena elastica	-	X	-	-
Euglena hemicromata	X	X	-	-

Table 14 continued

	River*	Sed*	Filtr*	Finw*
Euglena pusilla	X	-	-	-
Euglena sp.	X	X	X	X
Lepocinclis salina	X	X	X	X
Phacus acuminatus	X	-	-	X
Phacus longicauda	X	X	-	X
Phacus pyrum	X	X	X	X
Strombomonas fluviatilis	X	X	X	X
Strombomonas ovalis	X	X	-	-
Strombomonas verrucossa	X	X	X	-
Trachelomonas intermedia	X	X	X	X
Trachelomonas scabra	X	X	X	X
Trachelomonas volvocina	X	-	X	-
TOTAL	68	72	62	59

Table 15: Dosage concentration and algal species penetrating sedimentation, sand filtration phases of *Module III*

DATE	DOSAGE CONCENTRATION	SEDIMENTATION		FILTRATION	
		Algal species	Chl-*a*	Algal species	Chl-*a*
27/10/93	Pre-lime (8.1 mg l^{-1}) Polymer (0.6 mg l^{-1}) Pre-chlorine (4.0 mg l^{-1}) $FeCl_3$ (3.6 mg l^{-1})	**Crucigenia tetrapedia* (green alga)	0.9 $\mu g\ l^{-1}$	**Crucigenia tetrapedia* (green alga)	0.3 $\mu g\ l^{-1}$
10/11/93	Pre-lime (27.4 mg l^{-1}) Polymer (0.2 mg l^{-1}) Pre-chlorine (6.0 mg l^{-1}) $FeCl_3$ (3.8 mg l^{-1})	**Synechococcus cedrorum* (blue-green alga)	1.8 $\mu g\ l^{-1}$	**Synechococcus cedrorum* (blue-green alga)	0.4 $\mu g\ l^{-1}$
24/11/93	Pre-lime (20.1 mg l^{-1}) No Polymer Pre-chlorine (4 mg l^{-1}) $FeCl_3$ (0.8 mg l^{-1})	**Synechococcus cedrorum* (blue-green alga)	0.9 $\mu g\ l^{-1}$	* *Synechococcus cedrorum* (blue-green alga)	0 $\mu g\ l^{-1}$
15/9/93	Pre-lime (7.8 mg l^{-1}) Polymer (0.2 mg l^{-1}) Pre-chlorine (4 mg l^{-1}) $Fe_2(SO_4)_3$ (2.5 mg l^{-1})	**Scenedesmus intermedius* (green alga)	5 $\mu g\ l^{-1}$	**Monoraphidium arcuatum* (green alga)	1.2 $\mu g\ l^{-1}$

15/2/94	No Pre-lime Polymer (10.9 mg l^{-1}) Pre-chlorine (4 mg l^{-1}) $FeCl_3$ (0.8 mg l^{-1})	* *Oscillatoria simplicissima* (blue-green alga)	0.28 µg l^{-1}	*Pennate diatom	0.45 µg l^{-1}
July 1994	Pre-lime (0.8-1.6 mg l^{-1}) No Polymer Pre-chlorine (4.0 mg l^{-1}) $FeCl_3$ (1.2-2.1 mg l^{-1})	***Synechocystis* sp. (blue-green alga)	1.96 µg l^{-1}	***Synechocystis* sp. (blue-green alga)	0.29 µg l^{-1}
23/11/94	No Pre-lime Polymer (0.9 mg l^{-1}) Pre-chlorine (5.0 mg l^{-1}) $FeCl_3$ (1.7 mg l^{-1})	**Synechococcus cedrorum* (blue-green alga)	0.29 µg l^{-1}	**Synechococcus cedrorum* (blue-green alga)	0 µg l^{-1}
May 1994	Pre-lime (1.5-6.4 mg l^{-1}) No Polymer Pre-chlorine (4.0 mg l^{-1}) $FeCl_3$ (1.5 mg l^{-1})	* *Monoraphidium arcuatum* (green alga)	0.81 µg l^{-1}	**Monoraphidium arcuatum* (green alga)	0.29 µg l^{-1}
23/8/95	Pre-lime (56.4 mg l^{-1}) Polymer (4 mg l^{-1}) Pre-chlorine (7.4 mg l^{-1}) $FeCl_3$ (2.7 mg l^{-1})	**Chlamydomonas* sp. (green alga)	1.71 µg l^{-1}	**Chlamydomonas* sp. (green alga)	1.14 µg l^{-1}

3/10/95	Pre-lime (37.1 mg l^{-1}) Polymer (0.2 mg l^{-1}) Pre-chlorine (6.3 mg l^{-1}) $FeCl_3$ (5.1 mg l^{-1})	**Synechococcus cedrorum* (blue-green alga)	0 μg l^{-1}	**Synechococcus cedrorum* (blue-green alga)	0 μg l^{-1}
18/10/95	No Pre-lime Polymer (0.2 mg l^{-1}) Pre-chlorine (4.0 mg l^{-1}) $FeCl_3$ (5.3 mg l^{-1})	**Synechococcus cedrorum* (blue-green alga)	0.38 μg l^{-1}	**Synechococcus cedrorum* (blue-green alga)	1.2 μg l^{-1}
22/11/95	Pre-lime (66.5 mg l^{-1}) Polymer (1.3 mg l^{-1}) No Pre-chlorine $FeCl_3$ (5.5 mg l^{-1})	**Monoraphidium arcuatum* (green alga)	0 μg l^{-1}	**Monoraphidium arcuatum* (green alga)	0.85 μg l^{-1}

* Species present in river water in large quantities

** Species not present in river water

Final water

Major Taxonomical groups

Representatives of five different algal groups were present in the final water of the purification process between August 1993 and April 1996 (Tables 4, 9 & 14). The groups were Cyanophyceae (blue-green algae), Bacillariophyceae (diatoms), Chlorophyceae (green algae), Euglenophyceae (euglenophytes) and Dinophyceae (dinoflagellates).

The percentage blue-green and green algae increased from the river water to the final water where they were dominant (Figs 58 & 59). The dominant blue-green algal species in the final water were *Synechococcus cedrorum*, *Synechocystis* sp., *Microcystis flos-aquae* and *Oscillatoria simplicissima*, and the dominant green algal species were *Crucigenia tetrapedia*, *Monoraphidium arcuatum*, *Oocystis lacustris* and *Carteria globosa*.

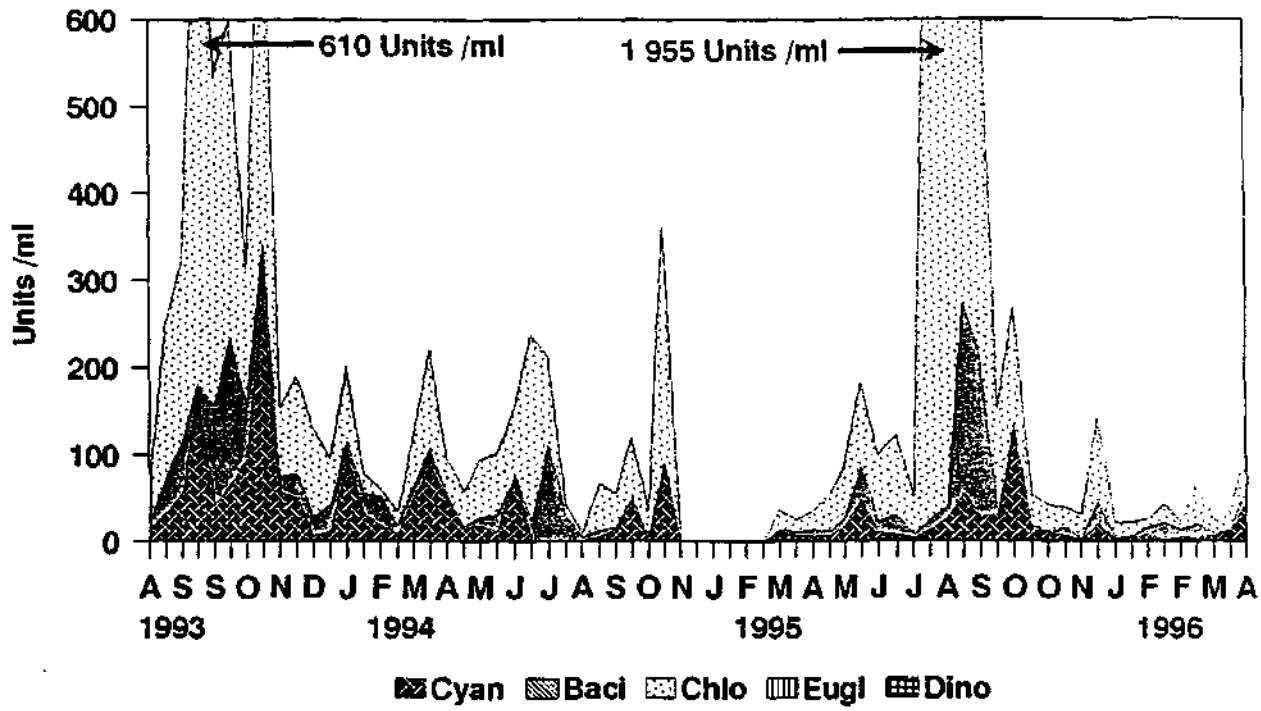

Figure 58: Phytoplankton counts of major taxonomical groups of the final water from August 1993 to April 1996.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Dino = Dinophyceae.

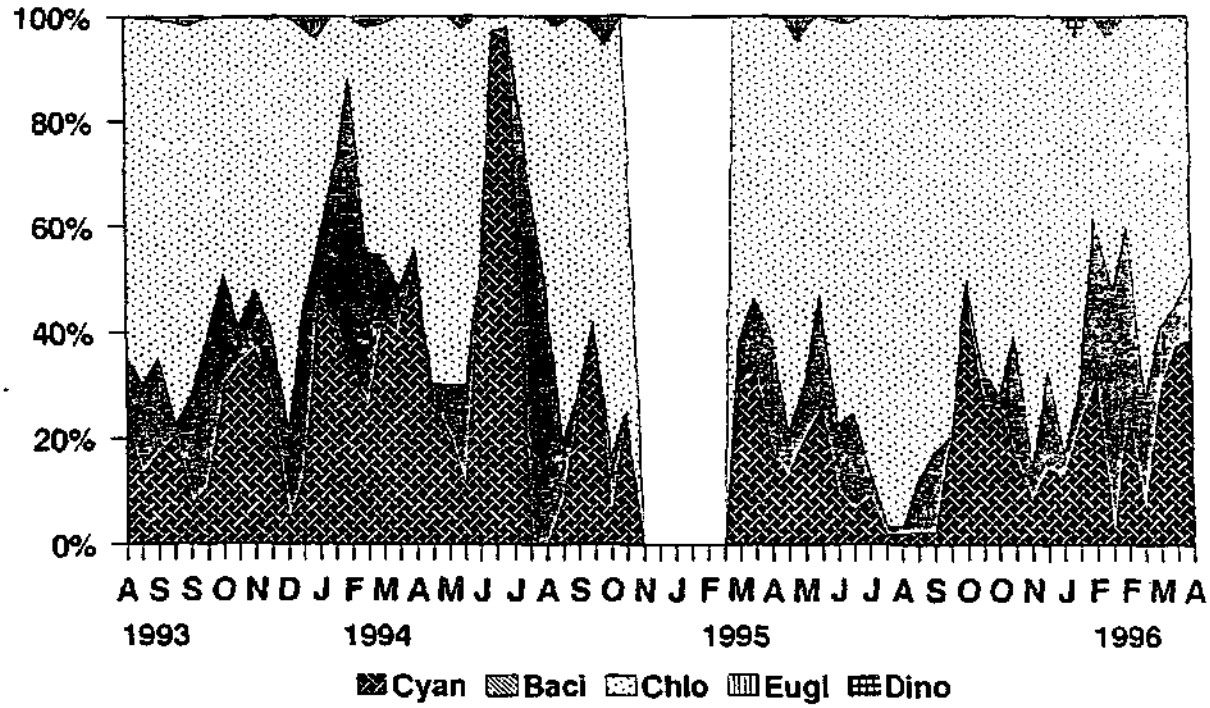

Figure 59: Phytoplankton composition (%) of major taxonomical groups of the final water from August 1993 to April 1996.
Cyan = Cyanophyceae, Baci = Bacillariophyceae, Chlo = Chlorophyceae, Eugl = Euglenophyceae, Dino = Dinophyceae.

A Peak of diatom cells was observed during the end of February 1994 and during the beginning of August 1994 in the final water, the dominant species of which were an unidentified pennate diatom and an unidentified centric diatom (Figs 58 & 59).

A peak of blue-green algae was observed during June and July 1994 in the final water (Figs 58 & 59). The dominant algal species were *Synechocystis* sp. and *Synechococcus cedrorum*.

Small amounts of Euglenophytes and dinoflagellates were present in the final water (Figs 58 & 59), the dominant euglenophyte species were *Trachelomonas intermedia*, *Phacus pyrum* and *Euglena* sp. and the dominant dinoflagellate species were *Peridinium penardiforme* and *Sphaerodinium ravumfluvium*.

Phytoplankton biomass, Species diversity and Turbidity

The chlorophyll-a concentration varied during the study period and the highest chlorophyll-*a* concentration occurred during the middle of September 1995 (Fig. 60; 3.43 μg/l).

The chlorophyll-*a* concentration could not be detected during June 1994 while the algal unit concentration was the highest (8 100 & 4 920 units/ml) during this period (Fig. 60). The dominant algal species was *Synechocystis* sp.

There were three occasions when the chlorophyll-*a* concentration was above 1 μg/l in the final water namely, during the beginning of November 1994, the middle of September 1995 and the end of November 1995 (Fig. 60).

The algal unit concentration varied during the study period and was below 1000 units/ml except during June 1994 and during August and the beginning of September 1995 (Fig. 60). The dominant algal species during June 1994 was *Synechocystis* sp. and the dominant algal species during August and the beginning of September was *Chlamydomonas* sp.

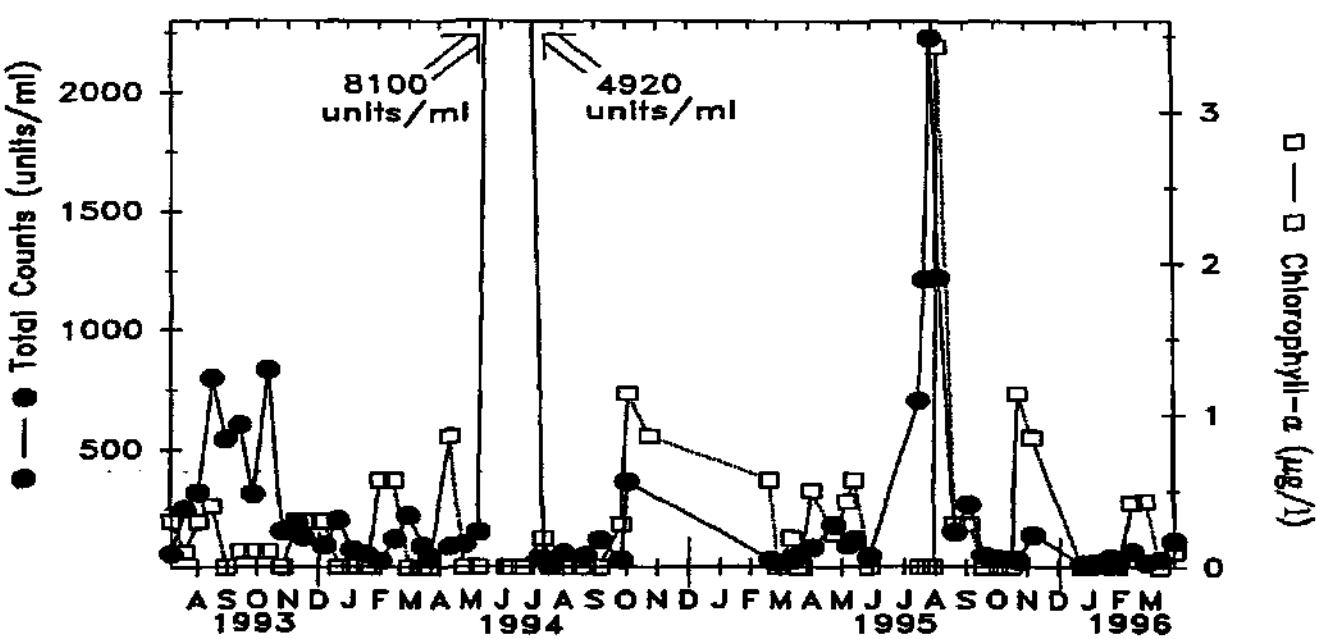

Figure 60: Phytoplankton biomass in μg/l chlorophyll-*a* and total counts in algal units/ml of the final water from August 1993 to April 1996.

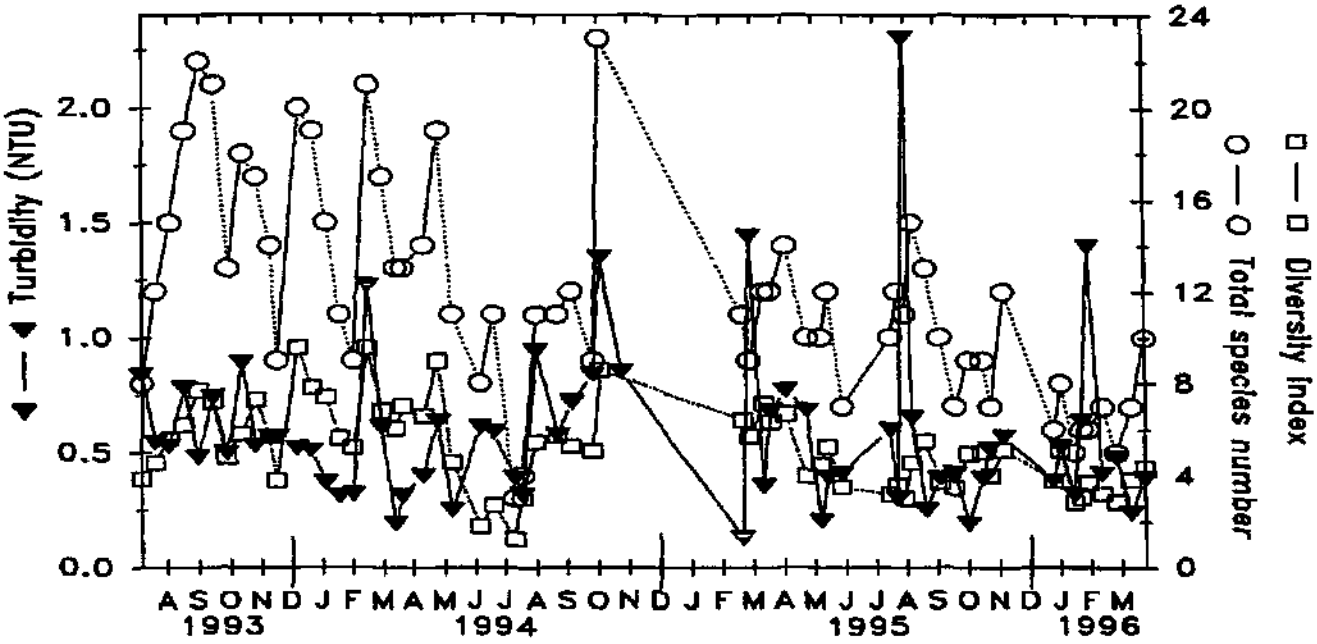

Figure 61: *Species diversity in total species number, turbidity in NTU and diversity index of the final water from August 1993 to April 1996.*

The turbidity showed great variation during the study period (Fig. 61). The highest turbidity (2.3 NTU) occurred during the end of August 1995 and the lowest turbidity (0.13 NTU) was during the end of March 1995 (Fig. 61).

The total species number and diversity index varied throughout the study period (Fig. 61). The highest total species number (23) was during the end of October 1994 (Fig. 61). The diversity index was below 9 during the study period (Fig. 61).

Morphological groups

There was four peaks of unicellular flagellated (Unfl) cells during November 1993, the beginning of May 1994, the end of October 1994 and during August and September 1995 in the final water (Figs 62 & 63). The dominant species were *Chlamydomonas incerta*, *Chlamydomonas* sp. and *Carteria globosa*.

Only a small percentage of the unicellular discoidal cells (Undi) were present in the final water (Figs 62 & 63), except for a peak of unicellular discoidal cells (Undi) during the

beginning of August 1994. The dominant algal species was an unidentified centric diatom.

From August 1993 to the end of September 1993 and again from the end of October 1995 to the end of April 1996 the unicellular elongated cells (Unel) were dominant in the final water (Figs 62 & 63). The dominant species were *Monoraphidium arcuatum*, *Monoraphidium circinale* and *Ankistrodesmus falcatus*.

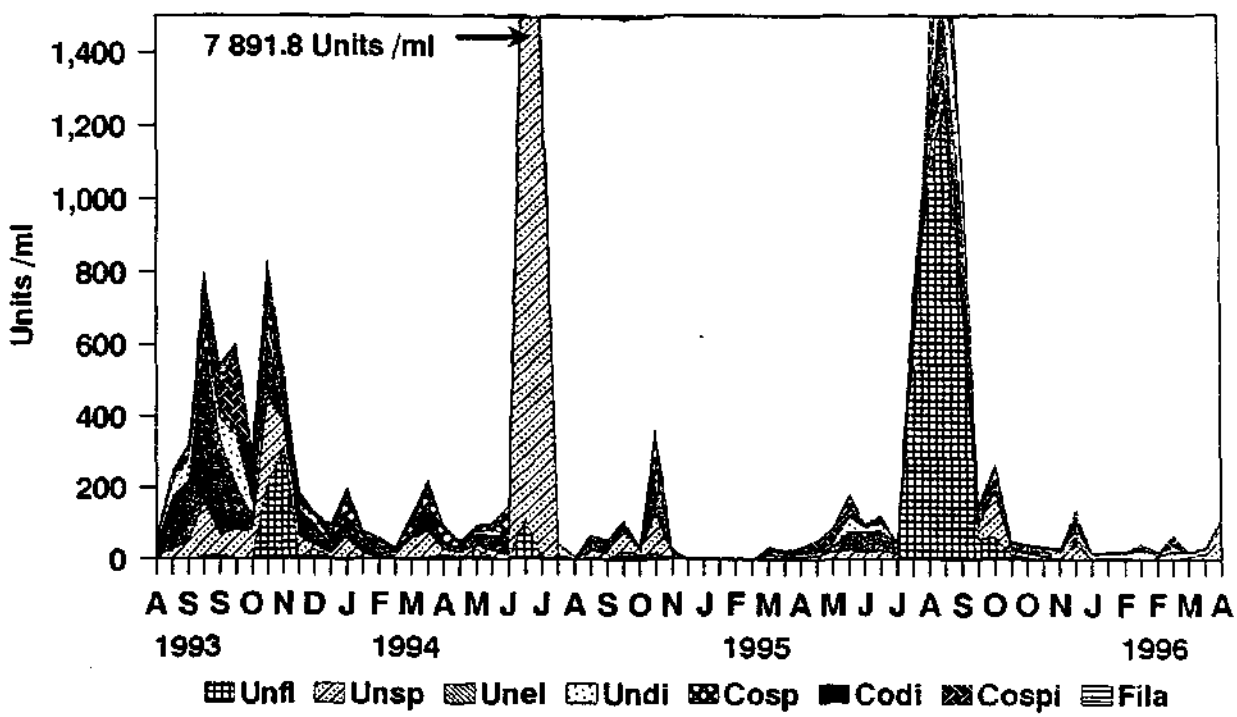

Figure 62: Phytoplankton counts of morphological groups of the final water from August 1993 to April 1996.
Unfl = Unicellular flagellated algae, Unsp = Unicellular spherical algae, Unel = Unicellular elongated algae, Undi = Unicellular discoidal algae, Cospi = Colonial algae individual cells with spines, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Fila = Filament.

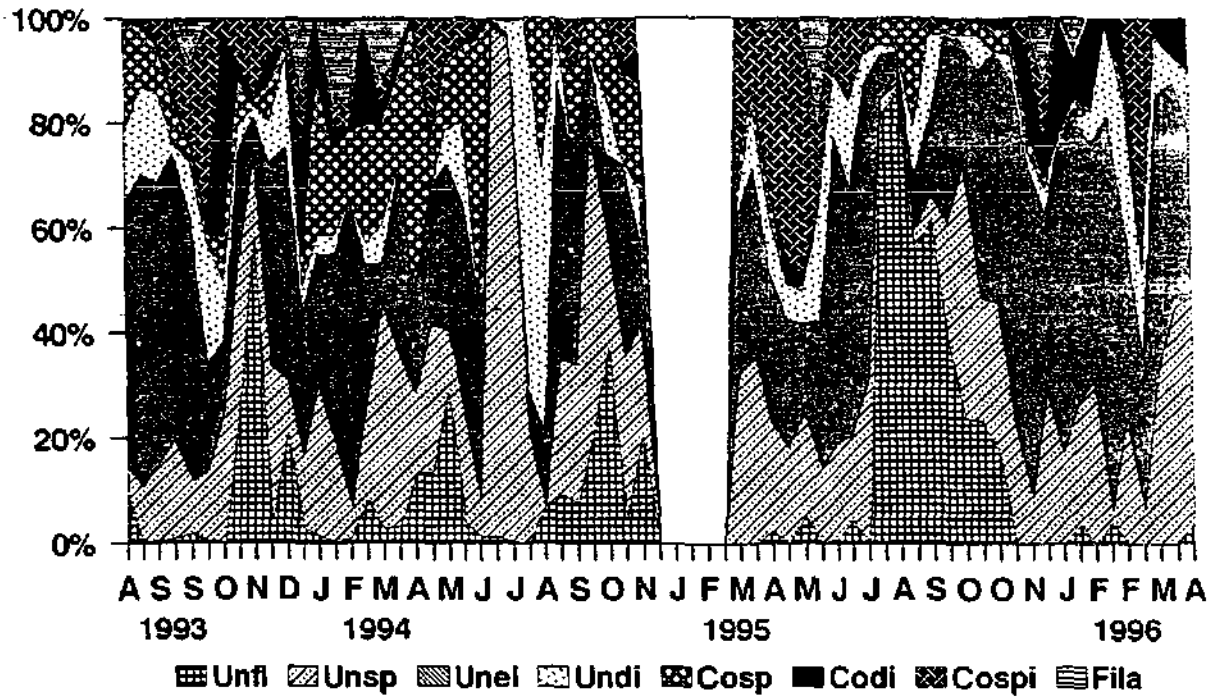

Figure 63: Phytoplankton composition (%) of morphological groups of the final water from August 1993 to April 1996.
Unfl = Unicellular flagellated algae, Unsp = Unicellular spherical algae, Unel = Unicellular elongated algae, Undi = Unicellular discoidal algae, Cospi = Colonial algae individual cells with spines, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells, Fila = Filament.

A peak of unicellular spherical cells (Unsp) occurred during July 1994 and the beginning of October 1994 in the final water (Figs 62 & 63). The dominant algal species were *Synechocystis* sp. and *Synechococcus cedrorum*.

The colonial algae, individual cells with spines (Cospi), was dominant in the final water during March and April 1995 (Figs 62 & 63). The dominant species was *Scenedesmus opoliensis*.

SUMMARY

In the previous sections the different results were presented, illustrated and described. At the end of each section representing the different modules, the findings were discussed and conclusions were drawn. This section gives a summary of the different conclusions.

The results of the present study showed that when the algal biomass in the river water was high, then a high diversity of species occurred in the final water. Therefore, high biomass in the river water apparently resulted in less efficient removal of the total species number.

The results of the present study indicated that sedimentation is primarily responsible for biomass removal (more than 50%), but not for the reduction in the number of algal species.

Six major algal groups were described from the different sampling localities during the study period, namely blue-green algae, diatoms, green algae, cryptophytes, dinoflagellates and the euglenophytes. The cryptophytes were present in very small quantities during the entire study period.

The green algae and diatoms were the main dominating groups and succeeded each other during the study period at the different sampling localities within the treatment plant. The diatoms were most of the time dominant in the river water and were removed by the different purification processes.

More than 60 % of the diatoms present in the river water were removed by sedimentation and the rest of the diatoms were removed by flotation and filtration. Large amounts of diatoms were seldom present in the final water.

The green algae were most of the time in relative small quantities present in the river water (Figs 1 & 2), but increased proportionate to the other groups through the purification processes to the final water (Figs 58 & 59) where they reached dominant proportions. These results indicated that green algae in general are less efficiently removed by the unit processes employed at Balkfontein.

Blue-green algae, similar to green algae, also increased proportionate to the other groups from the river to the final water (Figs 1 & 2, 58 & 59).

The euglenophytes, cryptophytes and dinoflagellates were only in small quantities present at the different sampling localities during the study period. All the cryptophytes present in the water was removed during purification because no cryptophytes were present in the final water.

Differential removal of algae occurred in the processes employed in the purification plant. The Bacillariophyceae (diatoms) were reduced to a larger extent than the Chlorophyceae. Therefore, the Bacillariophyceae was removed more efficiently in relation to the Chlorophyceae under the prevailing conditions of flow, coagulation-flocculation and filtration.

Bacillariophyceae cells (unicellular discoidal cells) are probably more dense because of the frustules containing silicate. Chlorophyceae cells, on the other hand, showed different shapes. The denser diatoms cells are expected to settle out easier than green algal cells which are possibly less dense. Therefore, as indicated previously, it is important to investigate morphological characteristics of algal cells in relation to their ability or inability to be removed during purification processes.

The diatoms and more specifically the unidentified centric diatoms was effectively removed during sedimentation. Large amounts of diatoms were seldom present in the final water.

Synechococcus cedrorum (blue-green alga) and *Monoraphidium* spp. (green algae) were not sufficiently removed during purification because they were most of the time dominant in the final water.

The dominant species in the sedimentation effluent of Module's I, II and III were:

	Module I	**Module II**	**Module III**
Blue-green algae			
Synechocystis sp.(Unsp)*	X	-	X
Synechococcus cedrorum (Unsp)	X	X	X
Microcystis flos-aquae (Cosp)	X	X	X
Oscillatoria simplicissima (Fila)	-	X	X
Chroococcus dispersus (Cosp)	-	X	X
Green algae			
Monoraphidium arcuatum (Unel)	X	X	X
Oocystis lacustris (Unsp)	X	X	X

Carteria simplicissima (Unfl)	X	-	-
Chlamydomonas incerta (Unfl)	X	-	X
Scenedesmus opoliensis (Cospi)	X	X	X
Monoraphidium circinale (Unel)	-	X	-
Scenedesmus intermedius (Cospi)	-	X	-
Scenedesmus acumunatis (Cospi)	-	-	X
Carteria globosa (Unfl)	-	X	X
Chlamydomonas sp. (Unfl)	-	X	X
Diatoms			
Centric diatom (Undi)	X	X	X
Melosira granulata (Fila)	X	X	X
Pennate diatom (Unel)	X	X	X
Euglenophytes			
Trachelomonas intermedia (Unfl)	X	X	X
Trachelomonas scabra (Unfl)	X	X	X
Phacus pyrum (Unfl)	X	-	X
Euglena sp. (Unel)	X	X	X

*Unfl = Unicellular algae with flagellated cells, Unsp = Unicellular algae with spherical cells, Unel = Unicellular algae with elongated cells, Undi = Unicellular algae with discoidal cells, Cospi = Colonial algae, individual cells with spines, Cosp = Colonial algae with spherical cells and Fila = Filamentous algae.

The dominant species in the filtration effluent of Module's I, II and III were:

	Module I	**Module II**	**Module III**
Blue-green algae:			
Synechocystis sp. (Unsp)*	X	-	X
Synechococcus cedrorum (Unsp)	X	X	X
Microcystis flos-aquae (Cosp)	X	X	X
Chroococcus dispersus (Cosp)	-	X	X
Oscillatoria simplicissima (Fila)	-	-	X
Green algae:			
Monoraphidium arcuatum (Unel)	X	X	X
Monoraphidium circinale (Unel)	-	X	X
Crucigenia tetrapedia (Codi)	-	X	X

Oocystis lacustris (Unsp)	X	X	X
Carteria simplicissima (Unfl)	X	X	X
Actinastrum hantzschii (Cosp)	X	-	-
Scenedesmus opoliensis (Cospi)	-	X	X
Carteria globosa (Unfl)	-	X	-
Chlamydomonas incerta (Unfl)	-	-	X
Chlamydomonas sp. (Unfl)	-	X	X
Diatoms:			
Centric diatom (Undi)	X	X	X
Pennate diatom (Unel)	X	X	X
Melosira granulata (Fila)	X	X	X
Euglenophytes:			
Trachelomonas intermedia (Unfl)	X	X	X
Trachelomonas scabra (Unfl)	-	X	X
Euglena sp. (Unel)	-	X	X
Trachelomonas volvocina (Unfl)	-	-	X

*Unfl = Unicellular algae with flagellated cells, Unsp = Unicellular algae with spherical cells, Unel = Unicellular algae with elongated cells, Undi = Unicellular algae with discoidal cells, Cospi = Colonial algae, individual cells with spines, Cosp = Colonial algae with spherical cells, Codi = Colonial algae with discoidal cells and Fila = Filamentous algae.

Algal species were grouped into morphological groups in order to determine what type of algal cells penetrated the system more frequently. The results indicated that all the morphological groups penetrated the different phases of the purification process.

Small unicellular algal cells (for example *Monoraphidium* spp., green algae and *Synechococcus cedrorum*, blue-green alga) are the algal cells which were the most difficult to remove from the water during the purification process. The cells possibly did not flocculate efficiently and therefore penentrated the purification processes. The small unicellular algal cells were most of the time dominant in the final water.

The unicellular discoidal cells (Undi) were removed more efficiently in relation to the other groups during sedimentation and filtration.

The colonial algae (for example *Scenedesmus* or other, green algae species and *Microcystis* or other blue-green algae species) were removed more easily during sedimentation and filtration than the unicellular groups. The colonial algae are present in the final water in very small amounts.

Filamentous algae, for example *Melosira granulata* (diatom) and *Oscillatoria simplicissima* (blue-green alga), were most of the time effectively removed during filtration because the algae were not present in the filtratrion effluent of the different modules.

Algal cells with flagella (for example *Chlamydomonas* spp.) are motile which makes it more difficult to remove. The flagella may prevent the cells from forming flocs and it is, therefore, difficult to remove the cells during sedimentation.

Some species have the ability to change their shapes (for example *Euglena* spp.). This morphological characteristic makes it very difficult to remove these algal cells from the water during sedimentation, flotation and filtration.

The fact that chlorophyll-*a* concentration after sedimentation, flotation, sand filtration and in the final water of Modules I, II and III were at times below detection limits (indicated by nd = not detectable), suggested that the method for determining chlorophyll-*a* is possibly not sensitive enough at low concentrations because total algal counts of algal cells from the same samples indicated that cells were present in the water. It is, therefore, important to determine whether the cells that were present in the latter stages of purification, were alive or not. In addition, more sensitive methods for the estimation of chlorophyll-*a* concentrations must be employed.

The results of the present study clearly indicated that differences in algal removal occurred between the Modules. The three Modules received the same river water, therefore the observed difference must have developed during the different purification processes.

A major difference between the three Modules at Balkfontein was the presence of *Synechocystis* sp. in Modules I and III during June and July 1994 and not in Module II. Green algae and diatoms were dominant during June and July 1994 only in Module II. Conditions in Module I and III must have been ideal for the growth of *Synechocystis* sp. because no *Synechocystis* sp. occurred in the river water. *Synechocystis* cells have

multiplied in Module I while the module was not in operation until June 1994. This could not have been the case for Module III because Module III was continually in operation.

Different algal cells react differently to chemical dosage and dosage concentrations. It was therefore necessary to investigate the effect of different chemicals and different concentrations and combinations of chemicals on the removal of algal cells from the water.

The following results about the chemical dosage and the removal of algal cells from the water were obtained during the study period.

Similar species penetrated the sedimentation and filtration phases irrispective of $Fe_2(SO_4)_3$ or $FeCl_3$ dosed. The results therefore do not indicate a significant difference between the effect of $Fe_2(SO_4)_3$ and the effect of $FeCl_3$ on the removal of algal cells from the water.

Low $FeCl_3$ dosage concentrations (below 1 mg l^{-1}) together with high (above 4 mg l^{-1} pre-chlorine and above 1 mg l^{-1} polymer) or low (below 4 mg l^{-1} pre-chlorine and above 1 mg l^{-1} polymer) pre-chlorine (applied as pre-oxidant) and polymer dosage concentrations did not effectively remove the blue-green algae from the water, because blue-green algae was present in the final water. High pre-lime (above 60 mg l^{-1}) dosage concentrations also did not remove the blue-green algae efficiently from the water.

It was demonstrated that the purification process was not successful in the removal of algal cells under low $FeCl_3$ (below 1 mg l^{-1}) dosage conditions in the absence of pre-chlorination.

When the pre-lime dosage was low (below 20 mg l^{-1}) and the $FeCl_3$ dosage high (above 1 mg l^{-1}), algal cells were better removed from the water than when the pre-lime dosage was high (above 20 mg l^{-1}) and the $FeCl_3$ dosage low (below 1 mg l^{-1}).

A high pre-lime and CO_2 dosage (above 30 mg l^{-1} for both) alone (without additional coagulants) were not successful in the removal of algal cells from the water.

The high excess lime treatment programme, together with $FeCl_3$ and carbon dioxide were inefficient in the removal of algal cells from the water.

High pre-chlorine dosage contributed to the removal of the diatoms efficiently from the water. Pre-chlorine dosage was not successful in the removal of the blue-green algae from the water.

The diatoms were the best removed by sedimentation when the polymer dosage was high (approximetly 11 mg l^{-1}) or when the pre-chlorine (above 4 mg l^{-1}) and pre-lime (above 20 mg l^{-1}) dosages were high, but high polymer dosage (approximetly 11 mg l^{-1}) did not remove the blue-green algae effectively in relation to the other groups.

The results of the present study therefore indicated that different algal species or morphological groups required different treatment conditions to be successfully removed during water purification.

The results of the present study give the operators at water purification plants an indication of which coagulant to use when a specific algal group/species is present (dominant) in the raw water of the Vaal River, at least at Balkfontein. The results, when applied to purification plants, could provide an increase in our understanding of the treatment procedures of Vaal River water.

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CHAPTER 4:
COAGULATION AND SEDIMENTATION OF WATER-BORNE PARTICLES FROM THE VAAL RIVER

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INTRODUCTION

NaOH and Lime as pH-adjustment chemicals

NaOH and lime are two pH-adjustment chemicals. In this study, lime was compared with NaOH to determine the efficiency of the pH-adjustment chemicals as coagulant aids.

Lime clarification is widely applied in water treatment. In general, lime treatment has the following effects on the treated effluent: removal of suspended and colloidal matter and partial removal of DOC, precipitation of phosphorus (as calcium phosphate compounds) and heavy metals (as their hydroxides), and elevation of the pH to enable ammonia removal in subsequent stages (Ronen, 1981).

In coagulation, rapid mixing disperses the lime homogeneously to enable good contact between it and the raw liquid in order to affect destabilisation and aggregation of the dispersed phase present in sewage or secondary effluent. This phase consist mainly of a large amount of negatively charged, non-settleable, colloidal material, usually ranging in size from 10^{-3} to 102 µm. The following chemical reactions (providing sufficient reaction time is allowed) are involved:

$$Ca(OH)_2 + Ca(HCO_3)_2 \longrightarrow 2\,CaCO_3 + 2\,H_2O$$
$$5\,Ca^{2+} + 3\,HPO_4^{-} + 4\,OH^{-} \longrightarrow Ca_5OH(PO_4)_3 + 3\,H_2O$$
$$Mg^{2+} + 2\,OH^{-} \longrightarrow Mg(OH)_2$$

During the application of lime, the pH of the treated effluent is raised to the desired level (Ronen, 1981).

The addition of lime to the water in the pH range 10.5 to 11.5 has the following effect on its inorganic composition. The alkalinity is increased due to the addition of hydroxide ions (OH^-), but is subsequently reduced by the precipitation of carbonate as calcium carbonate and hydroxide as magnesium hydroxide. Therefore, the calcium concentration is initially increased owing to the lime addition, but subsequently reduced. The magnesium concentration is not affected by the lime addition, but it is reduced as a result of the precipitation of magnesium hydroxide when pH levels increase to above 10.5.

Although some removal of micro-organisms take place during the lime-treatment stage, this process is not aimed at the removal of micro-organisms from untreated water. Bacteria and viruses are generally removed together with the suspended and colloidal matter and could be killed as a result of the high pH level (Grabow *et al.*, 1969).

There is evidence in the literature that lime treatment affects the molecular mass distribution of the organic matter, which means that hydrolysis of organic matter occurs during this stage (Ronen, 1981). This phenomenon was not observed or studied during the present investigation.

Effect of high pH conditions pH > 11.

Apart from coagulation by $FeCl_3$ and $Fe_2(SO_4)_3$, lime-magnesium coagulation are also being employed. A number of investigations on treatment technologies involving an alkaline medium have studied the contribution of calcium carbonate and magnesium hydroxide to coagulation (both precipitate in lime coagulation). The contributing effect of the two substances was first reported on in the late twenties (Flentje, 1927). The study led to the following findings, namely that lime increases clarification and that the relationship between lime dosage and clarifying effects should be attributed to the properties of magnesium hydroxide formed from magnesium salts present in the water. Since the Flentje study, a number of experimental studies have made use of the coagulating and absorbing properties of magnesium hydroxide. These approaches yielded a water treatment method in which magnesium carbonate (precipitated to magnesium hydroxide in the presence of lime) acted as a coagulant (Black and Thompson, 1971, 1975). Two other investigators (Oldham and Rush, 1978) showed the following: magnesium hydroxide results in the removal of coloured matter and turbidity which is comparable to that achieved by alum, while the suspended particles produced *via*

this route are easier to settle. Experiments on municipal sewage samples (Leentvaar and Rebhun, 1982) have supported these findings on the contribution of calcium carbonate and magnesium hydroxide to the removal of organic matter. Taking these findings into account, it can be concluded that the final effect of water treatment at high pH is a joint contribution of the calcium carbonate and magnesium hydroxide particles.

The primary objective of high-lime coagulation (Parker *et al.*, 1975; Dziubek and Kowal, 1984) is an alkalisation of the water or waste water to achieve a pH level of pH 11.5, thus making the precipitation of magnesium hydroxide quicker. The process, however, has two inherent limitations set by economic factors, namely the high consumption of lime (specifically when the influent stream displays high alkalinity levels), and the overalkalisation of the water under treatment, which calls for a two-stage recarbonation in order to decrease the levels of salts. There is an important disadvantage of applying high-lime coagulation, namely the removal of magnesium, an important microelement for humans (Dziubek and Kowal, 1989).

In this study, high-lime experiments will be used to investigate the effect of pH between 10.5 and 12 on the removal of dissolved organic carbon. Experience at the Goudveld purification plant showed that when the pH was raised to above 11.4, DOC concentrations were effectively decreased.

Ferric (III) salts as coagulants

$FeCl_3$ and $Fe_2(SO_4)_3$ are chemical coagulants that can bring about the destabilisation of suspensions in natural waters. Leprince *et al.* (1984) reported that partially neutralised "polymeric" $FeCl_3$ solutions were superior to untreated solutions in removing turbidity from synthetic suspensions at low temperatures.

The efficiency of coagulants can be determined with the aid of the jar test apparatus. The jar test is universally recognised for coagulation control, and may be used for coagulant selection, dosage selection, coagulant aid selection, dosage selection and the determination of optimum pH. In addition, the jar test can be used in the determination of the addition point of pH adjustment chemicals and coagulant aid, the optimisation of mixing energy and duration time for rapid mixing and slow mixing, as well as the determination of dilution of coagulant and similar measurements.

When the optimum pH for coagulation is determined, it is possible to compare $FeCl_3$ with other iron salts, therefore it is possible to conduct a study where ferric chloride is compared with ferric sulphate. The ferric ions of $FeCl_3$ and $Fe_2(SO_4)_3$ have identical charges, but the chemicals are not identical as coagulants.

The $(SO_4)^{2-}$ ions in solution assist in destabilisation of negatively charged particles, as illustrated in Fig. 1. The negatively charged particles are destabilised by Fe through the process of charge neutralisation. The destabilised particles in the water have the ability to restabilise by excess iron hydrolysis species. The restabilised particle can be stabilised by adsorption of sulphate ions. This is illustrated in Fig. 1 (D).

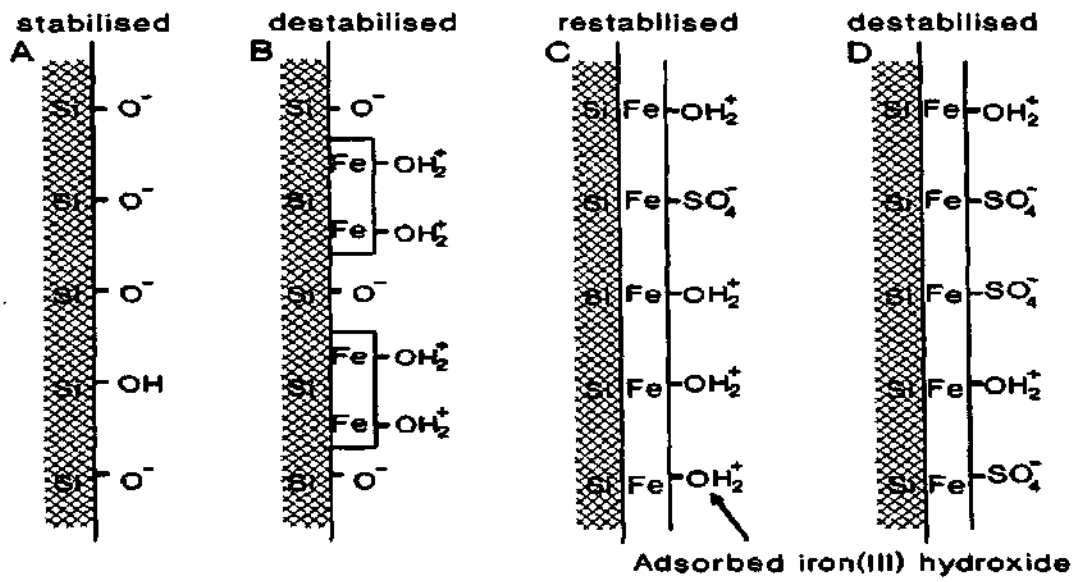


Figure 1. Schematic diagram of destabilisation and restabilisation of Ferric-treated particles; (A) surface of negatively charged particle (stabilised), (B) particle destabilised by charge neutralisation, (C) particle restabilised by excess ferric hydrolysis species and (D) destabilisation by adsorption of sulphate ions (Letterman and Vanderbrook, 1983).

Ferric chloride coagulation for removal of dissolved organic carbon

The need for optimising the removal of dissolved organic carbon (DOC) during drinking water treatment has become important due to the health risks associated with disinfection by-products. Coagulation often provides substantial removal of

DOC. Numerous detailed investigations have focused on the treatment of natural waters containing DOC (Black and Christman, 1963; Hall and Packman, 1965; Dempsey *et al.*, 1984; Edwards and Amirtharajah, 1985; Sinsabaugh *et al.*, 1986). These investigations showed that coagulation of DOC was dependent on the pH conditions, the coagulant dose, and the concentration of DOC. Effective removal of DOC occurred at lower pH conditions than turbidity removal. The optimum pH conditions for coagulation of organic matter were around pH 4 for Fe(III) salts. Except at low pH values, the optimum coagulant dose was proportional to the concentration of organic matter (Dempsey *et al.*, 1984).

The removal of DOC by coagulation was influenced by its charge, solubility, and molecular size characteristics (Sinsabaugh *et al.*, 1986). The efficiency of removal of DOC was found to be proportional to molecular size with larger molecular weight components being more effectively removed. Sinsabaugh *et al.* (1986) determined that acidic and basic components of the DOC in natural waters were twice as likely to be removed by coagulation than nonpolar, neutral compounds. The removal of neutral compounds was dependent on their polarity and the number of available low-polarity adsorption sites on the flocs.

The removal of DOC was thought to occur by both adsorption onto the solid hydroxide precipitate and complexation between coagulant and DOC. Edwards and Amirtharajah (1985) proposed two mechanisms by which DOC is removed from solution during coagulation with metal salts, namely precipitation by cationic species and adsorption on organic and inorganic solids.

Recently researchers (Gray, 1988; Gregory, 1989; Dempsey, 1989) concluded that the removal of DOC by coagulation with metal salts involves a combination of both adsorption to solid hydroxide and chemical precipitation (i.e. coprecipitation of metal-DOC and metal hydroxide). Both Gray (1988) and Gregory (1989) regarded the removal of DOC by coagulation using metal salts as a combination of precipitation of a metal-DOC complex and adsorption onto the surface of solid hydroxide precipitate. Gray (1988) reported that below pH 6, removal occurs by coprecipitation of ferric-organic matter/ferric hydroxide precipitate and concluded that effective removal of DOC with iron(III) occurs primarily by the formation of an iron-organic precipitate rather than the formation of ferric hydroxide.

In this study the removal of DOC plays an important part, because experience at the Goudveld water purification plant showed that DOC was effectively removed at

pH conditions of 11.4 and higher. It is also important to investigate the effect of DOC on the removal of suspended particles including algal cells in Vaal River water.

Coagulation and settling of different algae

Many problems in water supply are caused by algae in eutrophicated water sources like the Vaal River (AWWA, 1990). There are problems of tastes and odours, toxicity, obstruction to coagulation and sand filter clogging.

The influence of algae in water treatment processes is experienced in general water treatment processes such as coagulation, sedimentation and filtration. A rapid sand filtration system is generally not suitable to remove the algae, because it has been developed for treatment of high density inorganic substances (Konno, 1993). Because the density of algae is low (Reynolds, 1975), algogenic substances cause obstruction to coagulation and sedimentation of inorganic matter such as clay (Bernhardt, 1982; Magara et al., 1986). The effect of algae on the conditions for coagulation is to unstabalise the flocs, while the size of algae is larger than colloidal matter (Konno, 1993).

In this investigation three types of algae which may cause obstruction to coagulation or filter clogging were studied. Two of the algae belong to the Chlorophyta or greenalgae, namely *Monoraphidium minutum* and *Pandorina morum* and one, *Cyclotella meneghiniana*, a diatom, belongs to the Chrysophyta, sub phylum Bacillariophyceae.

Monoraphidium minutum

M. minutum cells are small, elongated and crescent shaped which can be responsible for the possibility that the compactness of the flocs formed will be low and that sedimentation would be ineffective

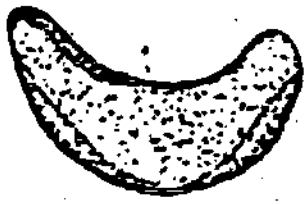


Figure 2. Schematic diagram of a *Monoraphidium minutum* cell

Pandorina morum

P. morum colonies are motile by means of flagella and the movement of these flagella may break up the flocs in which the colonies were concentrated or may "swim" out of flocs.

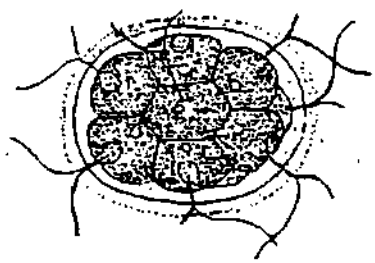


Figure 3. Schematic diagram of a *Pandorina morum* colony

Cyclotella meneghiniana

C. meneghiniana cells are circular in valvar view and narrowly rectangular in the girdle view. The cells consist of radiate costae with striae between them which consist of areolae. (Costae: ribs; enlongated, solid thickinings of the valve of a diatom frustule; Frustule: the shell or cell covering of diatoms; Striae: delicate, long, narrow markings, streaks, bands, groove or channel, a row of pores, areolae, or an elongate chamber in the frustule of a diatom; Areolae: the regularly repeated perforation through the siliceous layer of a frustule usually covered on one side by a velum; Velum: a membrane or structure similar to a veil.). These areolae can capture oxygen during photosinthesis which could apparently be responsible for the poorer sedimentation of flocs in which the cells are concentrated.

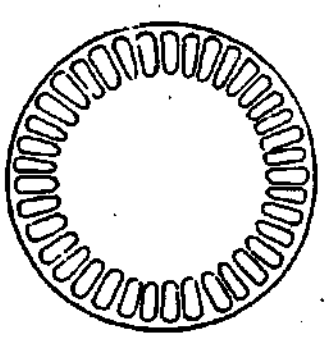


Figure 4. Schematic diagram of a *Cyclotella meneghiniana* cell in valvar view

Motivation for research

At present various water treatment plants experience algal-related problems during treatment and are using, amongst others, iron(III) salts as coagulants. A project was, therefore, developed to investigate the effect of different coagulants at various concentrations, using different pH adjustment chemicals in a pH range of 5 to 11. The first phase of the study involved only water taken from the Vaal River. The effect of different coagulation and sedimentation conditions on naturally occurring suspended particles (i.e. colloidal and algal) were investigated. In the second phase of the study different algal species grown in culture and representing selected morphological and physiological conditions, were added to Vaal River water. The effect of comparable coagulation and sedimentation conditions on these suspensions was investigated.

The following aspects received special attention:

The optimum Fe^{3+} concentration for the effective removal of dissolved organic matter and other suspended particles.

The removal efficiency of $FeCl_3$ and $Fe_2(SO_4)_3$ as coagulants.

The pH adjustment chemical (i.e. HCl, NaOH and lime) most suitable for the coagulation processes.

The effect of high algal concentrations, and the organic substances excreted by them, on removal efficiencies.

MATERIALS AND METHODS

The Jar Test apparatus

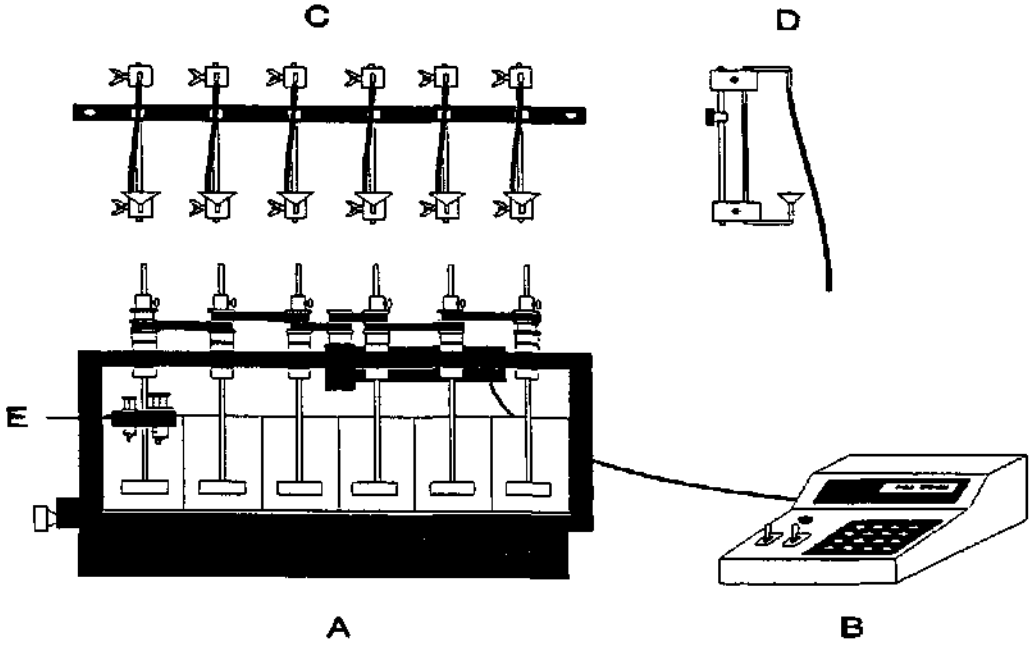


Figure 5. The Jar Test Apparatus used in this investigation with (A) the Jar Test Apparatus with six standard jars, (B) the control unit, (C) multiple funnels (front view), (D) multiple funnels (side view) and (E) syringes in a syringe holder.

Equal volumes (1 litre) Vaal River water were treated with different Fe^{3+} concentrations at various pH conditions. Water samples were taken at Balkfontein near Bothaville. The turbidity, chlorophyll-a concentrations and spectral absorption coefficient at 254 nm (SAC 254) were measured after each treatment.

The jar test apparatus used for the experiments is illustrated in Fig. 5. This apparatus consists of several standard jars (19,9 X 9,5 X 9,5 cm) and a mixing device with standard mixing paddles (stirrer flaps 2,5 X 7,5 cm) as seen in Fig 5(a). The jars are made of clear plastic, sometimes with a sampling tap 10 cm below the water level to withdraw water. In addition, water can be withdrawn from the jars with multiple funnels (Fig. 5, C and D).

The sampling taps or funnels enable the sampling of supernatant water without sampling the sedimented material. The jars and all glassware were cleaned before each experiment.

Iron(III) salts, i.e. ferric chloride ($FeCl_3$) and ferric sulphate ($Fe_2(SO_4)_3$), were used as flocculants. The $FeCl_3$ stock solution contained 4,8376 g $FeCl_3.6H_2O$ (1 g l^{-1} Fe^{3+}) and the $Fe_2(SO_4)_3$ stock solution 3.578 g $Fe_2(SO_4)_3.XH_2O$ (1 g l^{-1} Fe^{3+}) to which 2,5 ml l^{-1} 15% HCl was added to stabilise the solution.

The pH range for flocculation with Fe^{3+} was adjusted to between 5 and 11. The pH adjustment chemicals used were 0.1 M HCl, 0.1 M and 0.4M NaOH and lime.

In one treatment, water from the Vaal River was put through the jar test while following exactly the same experimental procedures as for the different treatments, but without the addition of any flocculant. Only pH adjustment was done. For the control treatment, raw water was analysed without being put through the jar test. Neither flocculant nor pH adjustment chemicals were added.

During experimentation the following procedures were followed. Samples were thoroughly mixed prior to the experiment. The volume of pH adjustment chemicals was determined prior to the experiment by a standard titration method. To achieve different Fe^{3+} concentrations, the $FeCl_3$ solution was added to 250 ml of Vaal River water. Due to the acidity of the $FeCl_3$ stock solution, the pH of the water for each Fe^{3+} concentration had to be adjusted. This adjustment was done with either HCl, NaOH or lime.

Multiple syringes were used to add the flocculant and pH adjustment chemicals to the 12 jars (of two Jar test apparatii). A syringe holder (Fig. 5E) was used for this purpose.

The following procedures were followed to fill the syringes with the appropriate volumes. The flocculant ($FeCl_3$) or pH adjustment chemicals were drawn into the syringe and ejected repeatedly until the syringe tip was filled without any bubbles. The plunger with rubber bulb was removed and the exact volume of chemicals were pipetted into the syringe. The plunger was replaced without ejecting the chemicals.

Each jar was filled with 1 litre thoroughly mixed Vaal River water. Tests for the optimisation of the coagulant dosage was conducted in the following way.

1. While rapid mixing (350 rpm) the water for one minute, the pH adjustment chemicals were added near the impeller with multiple syringes as illustrated in

Fig. 5E into the twelve jars of two jar test apparatii that contain the same raw water.

2. The water was rapidly mixed for another 30 seconds at the maximum mixing intensity (350 rpm) and, while mixing, the coagulant ($FeCl_3$) was added simultaneously near the impeller, also with multiple syringes.
3. To allow flocculation to proceed, the suspension was then slowly mixed for 10 minutes at 40 rpm.
4. After flocculation, the flocs were allowed to settle for 30 minutes without stirring.
5. Settled water was withdrawn with multiple funnels (Fig. 5 C and D).

Chlorophyll-*a* concentrations, turbidity and spectral absorption coefficient (SAC 254) of the settled water were determined.

Chlorophyll-*a* determination

Settled water samples were taken from the jars and chlorophyll-*a* was measured by a pigment extraction method described by Sartory (1982). 250 ml of the 1000 ml (1 litre Vaal River water) was filtered through a Whatman - GF/C filter.

Chlorophyll-*a* was extracted from the algal cells in suspension in 10 ml of 95% ethanol for a period of 5 minutes at 78°C. After the ethanol samples were allowed to cool, the absorption of the dissolved chlorophyll was determined at 750 and 665 nm with a spectrophotometer. 100 µl of 0,3 N HCl was added to the extract and the absorption was again determined at 665 nm. The chlorophyll-*a* concentration (µg l^{-1}) was then determined with the following formula (Sartory, 1982):

$$\text{Chl } a\ (\mu g\ l^{-1}) = \frac{[(665_o-750_o)-(665_a-750_a)] \times 28{,}66 \times 10\ ml}{250\ ml}$$

where 665_o = adsorption before addition of acid
665_a = adsorption after addition of acid
750_o = background value before addition of acid
750_a = background value after addition of acid

Spectral absorption coefficient (SAC) determination

Settled water samples were taken from the jars and SAC was measured in a way slightly modified from the method used by Bernhardt *et al.* (1985). 10 ml of the

supernatant was filtered through a Whatman membrane filter (pore size, 0.65 µm). Absorbance, here taken as SAC (SAC m^{-1}), was measured of the membrane-filtered water at 254 nm in a quarts cuvet.

The SAC 254 of the membrane filtered water was taken to represent total particulate and dissolved organic matter, and is often used as a simple surrogate method for dissolved organic carbon (DOC; Edzwald *et al.*, 1985). SAC 254 of the membrane filtered water was taken to represent DOC. SAC 254 (m^{-1}) was calculated using the following formula:

$$\text{SAC 254 (SAC } m^{-1}) = \frac{\text{Absorbance (254 nm) X 100 (cm)}}{\text{1 (cm; cuvet length)}}$$

Turbidity determination

The turbidity of the raw and chemically treated water was determined with a Aqualytic Turbidimeter AL 1000.

Addition of algal cells to increase the chlorophyll-*a* concentration

Algal cells and colonies (*Monoraphidium minutum* and *Pandorina morum* respectively) were grown in culture medium, GBG 11, for a period of 10 days. The light intensity was 43 µE m^{-1} s^{-1} and the temperature 18° C. Due to the fact that the growth rate of *Cyclotella meneghiniana* is lower than that of the other algal species, *C. meneghiniana* was grown for a period of 18 days before the cells were added to Vaal River suspensions.

The algal cells were centrifuged at 5500 rpm for 10 minutes to concentrate the cultures so that 5 ml contained ±60 µg l^{-1} chlorophyll-*a*. Because of low cell numbers it was difficult to concentrate the chlorophyll-*a* of *C. meneghiniana* to 60 µg l^{-1}; therefore the *C. meneghiniana* culture was concentrated so that 7.5 ml contained ±30 µg l^{-1}. The volume of culture medium that was needed to add ±60 µg l^{-1} of chlorophyll-*a* to Vaal River water was calculated (in case of *C. meneghiniana*, ±30 µg l^{-1}). The cells were allowed for 30 minutes to adapt to the conditions in which they were concentrated.

Different treatments were applied in an attempt to distinguish between the effects of algal cells separate from the excreted material. After the cells were centrifuged,

the supernatant of the culture medium was kept for control experiments to determine the effect of the cations (not adsorbed by algal cells) as well as excreted organic sustances present in the culture medium, on the flocculation process. Autoclaved culture medium was added to determine what effect the dissolved inorganic matter, present in the culture medium in which cells did not grow, had on the flocculation process.

Experiments were also conducted where the algal cells were removed from the culture medium (by centrifugation) and resuspended in distilled water. The algal cells were centrifuged and resuspended three times to make sure that the original culture medium and all dissolved substances were effectively removed. These algal cells were then suspended in distilled water and added to Vaal River water in the volume and concentrations given above. The aim was to determine what effect algal cells only had on the flocculation processes.

In addition, experiments were conducted where only distilled water, the same volume as given above (5 ml for *Monoraphidium minutum* and *Pandorina morum*, and 7.5 ml for *Cyclotella meneghiniana*), was added to Vaal River water. This was to determine the (possibly small) effect of dilution when algal cells suspended in distilled water, were added to Vaal River water.

Composition of GBG 11

The composition of the growth medium, GBG 11 (Krüger and Eloff, 1978), a modified BG 11 (Stanier *et al.*, 1971), used for all three algal species are given in Tables 1 and 2. The addition of culture medium changed the ion composition of the Vaal River water and the added ions may act as point charges, which could influence the coagulation process.

However, when culture medium in which algal cells grew, were added to Vaal River water, organic substances excreted by the algal cells were also added. To determine the possible effect of excreted organic material on coagulation and sedimentation, results of added medium in which cells grew were compared with results of added medium in which cells did not grow.

Table 1. Composition of GBG 11, major elements

Constituents	Stock-solution	Volume of stock
$NaNO_3$	15.00 g l^{-1}	10 ml l^{-1}
$K_2HPO_4.3H_2O$	6.93 g l^{-1}	10 ml l^{-1}
$MgSO_4.7H_2O$	7.50 g l^{-1}	10 ml l^{-1}
$CaCl_2.2H_2O$	3.60 g l^{-1}	10 ml l^{-1}
$NaSiO_3$	10.00 g l^{-1}	10 ml l^{-1}
Na_2CO_3	2.00 g l^{-1}	10 ml l^{-1}
EDTA	0.10 g l^{-1}	10 ml l^{-1}
Citric acid	1.20 g l^{-1}	10 ml l^{-1}
$FESO_4.7H_2O$	1.10 g l^{-1}	10 ml l^{-1}
Minor elements	*	1 ml l^{-1}

* see Table 2

Table 2. Composition of GBG 11, minor elements

Constituents	Stock-solution
H_3BO_3	2.86 g l^{-1}
$MnCl_2.4H_2O$	1.13 g l^{-1}
$ZnSO_4.7H_2O$	0.22 g l^{-1}
$NaMoO_4.5H_2O$	0.39 g l^{-1}
$Co(NO_3)_2.6H_2O$	0.049 g l^{-1}
$CuSO_4.5H_2O$	0.079 g l^{-1}

Analysis of extracellular organic substances

As described earlier, algal cells were removed from the culture medium by centrifugation. The supernatant of each culture was freeze-dried and 80 mg of the weighed, dried substrate was dissolved in 1.0 ml distilled water. Organic substances were extracted in ether and analysed for using the methods described in Van Rooyen *et al.* (1994). The concentration of the different excreted organic acids was determined and normalised to the chlorophyll content of the respective culture. In the present study all individual components were summed into, and

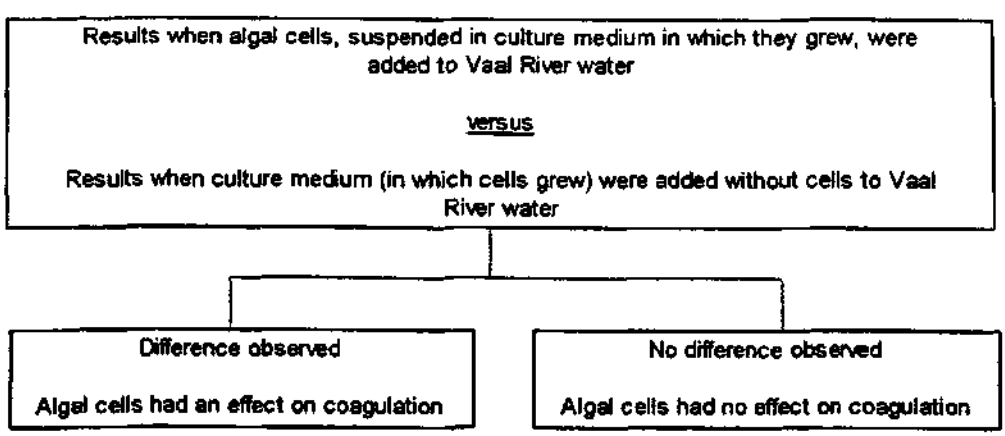
listed in major categories, i.e. monocarboxylic acids, dicarboxylic acids and aromatic acids. In addition, glycerol and phosphoric acid, present respectively in *Monoraphidium minutum* and *Pandorina morum* cultures, were listed separately. The composition of the extracellular organic substances will be given in detail elsewhere in this study (see section by Pieterse, Mienie and Traut).

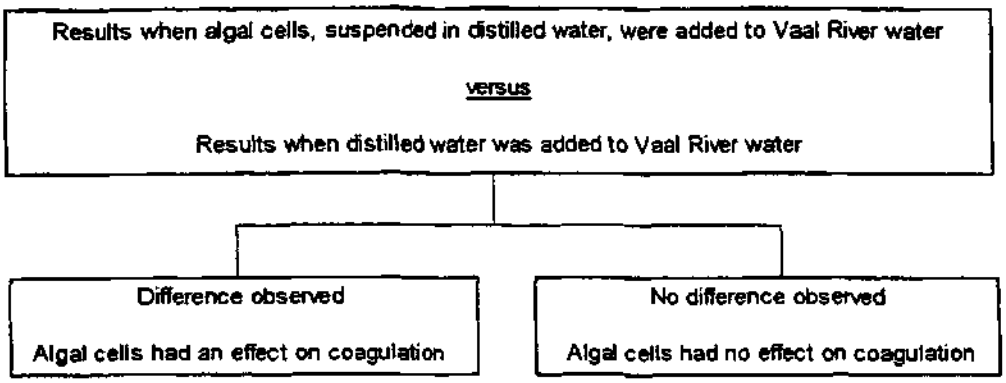
It is possible that the supernatant of the cultures have contained intact algal and bacterial cells from which organic substances could also have been extracted. It can, however, be asumed that these cells made a minor contribution, if at all, to the organic substances actually excreted by the live cells that grew in the culture.

Interpretation of results

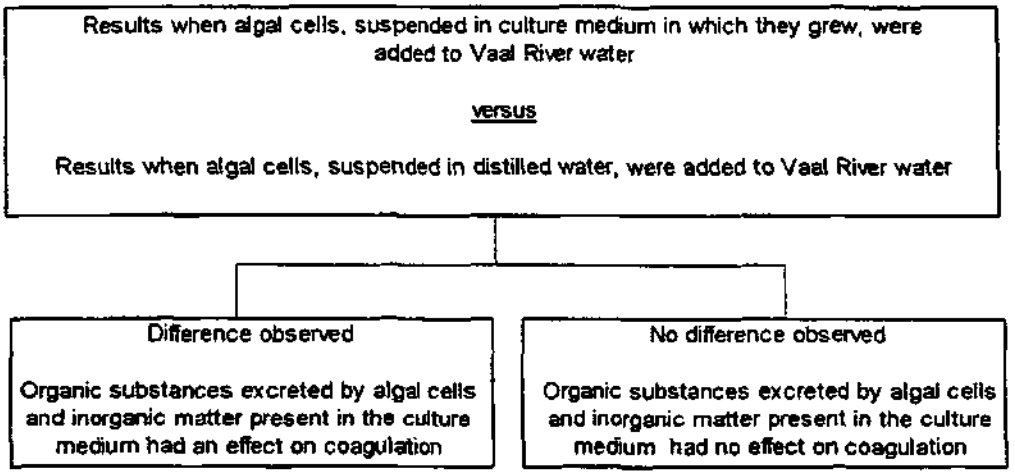
The interpretation of the results where algal cells together with culture medium were added to Vaal River water was done very carefully. The experiments were conducted to determine the effect of increased algal concentration and excreted dissolved organic carbon (DOC) on the coagulation conditions of Vaal River water. The addition of excreted DOC to Vaal River water was done by adding culture medium in which the cells grew to Vaal River water. This gave rise to an important problem, because removal was then not only affected by DOC excreted by algal cells, but also by inorganic substances present in the culture medium. For this reason, medium in which algal cells did not grow, was also added to Vaal River water. The following illustrations explains the way in which the the results from the different treatments were interpreted.

1. The effect of algal cells only

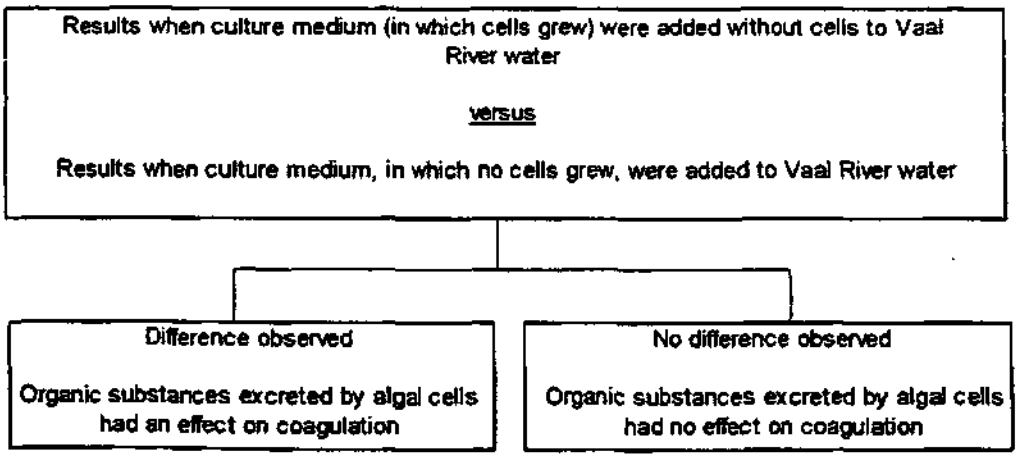




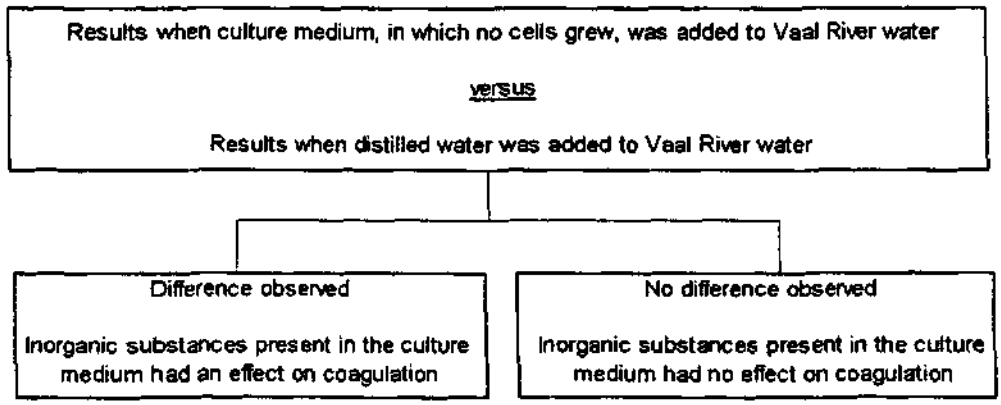
2. The effect of organic and inorganic substances



3. The effect of organic substances only



4. The effect of inorganic substances only



RESULTS

The effect of increased iron concentration on the removal of total suspended solids and dissolved organic carbon

The aim of the experiment was to determine the efficiency of $FeCl_3$ as flocculant by using the jar test apparatus, and to determine the optimum pH for coagulation with various Fe^{3+} concentrations.

The pH was adjusted to 5 and 7 with 0.1 M HCl, to 9 with 0.1 M NaOH, and to 11 with 0.4 M NaOH. The various Fe^{3+} concentrations used in this experiment was between 2 and 22 mg l^{-1} in steps of 2 mg l^{-1}. Chlorophyll-*a*, turbidity and SAC 254 was determined, and the results are illustrated in Figs 6-d. The formation of flocs, floc size and amount of flocs was visually observed. No flocks formed with the addition of 2 mg l^{-1} Fe^{3+} when the pH was adjusted to 5 with 0.1 M HCl.

After the flocculation period, the treated water seemed turbid. With the addition of higher flocculant concentrations, increase in the floc size were observed together with increased Fe^{3+} concentration. The amount of small flocs formed on the surface of the treated water increased with an increase in Fe^{3+} concentration, possibly an indication of flocculant overdose.

As illustrated in Fig. 6, a decrease in chlorophyll-*a* and turbidity levels occurred with the addition of 4 mg l^{-1} Fe^{3+}. At higher concentrations an effective removal of suspended solids and chlorophyll-*a* were observed. There was also a total

removal of chlorophyll-*a* when 18 mg l^{-1} Fe^{3+} was added, leading to the conclusion that phytoplankton was effectively removed with the addition of 18 mg l^{-1} Fe^{3+}.

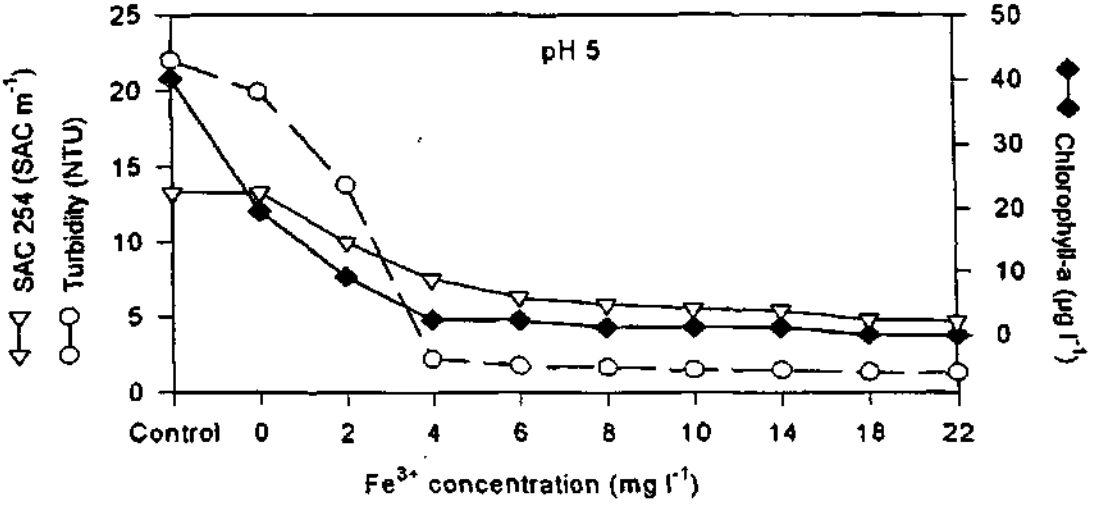


Figure 6. Variation of turbidity (NTU), chlorophyll-*a* concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased iron concentrations (mg l^{-1}) for pH adjusted to 5 with HCl. The turbidity of the raw water was 22 NTU, chlorophyll-*a* was 40.124 µg l^{-1}, and SAC was 13.3 SAC m^{-1}.

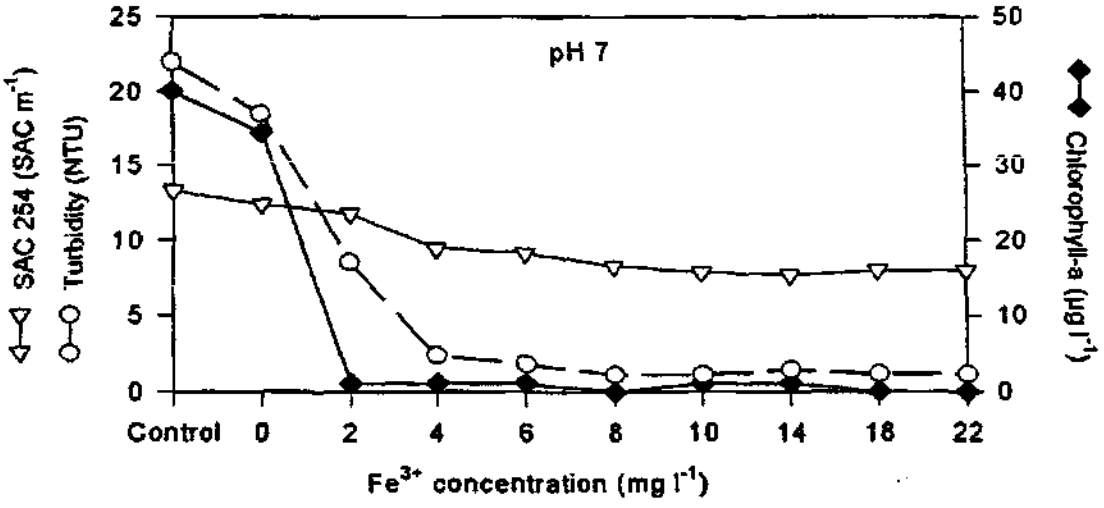


Figure 7. Variation of turbidity (NTU), chlorophyll-*a* concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased iron concentrations (mg l^{-1}) for pH adjusted to 7 with HCl. The turbidity of the raw water was 22 NTU, chlorophyll-*a* was 40.124 µg l^{-1}, and SAC was 13.3 SAC m^{-1}.

Flocs were formed with the addition of 4 mg l^{-1}, when the pH was adjusted to 7 with 0.1 M HCl, but the floc size was probably insufficient for effective sedimentation. An increase in the amount of flocs formed on the surface of the treated water was observed together with an increase in Fe^{3+} concentration, an indication that flocculant overdosing possibly occurred.

A decrease in chlorophyll-*a* levels with the addition of flocculant at pH 7 and at Fe^{3+} concentrations above 4 mg l^{-1} was observed as illustrated in Fig. 7.

The removal of total suspended solids, as indicated by turbidity, was more gradual in contrast to chlorophyll-a, but more effective than the removal of DOC, as indicated by SAC 254.

With the adjustment of the pH to 9 (Fig. 8) with 0.1 M NaOH, only small flocs formed when 2 mg l^{-1} flocculant was added. The size of the flocs was apparently insufficient for sedimentation, but after a 30 min sedimentation period, the turbidity of the treated water was lower.

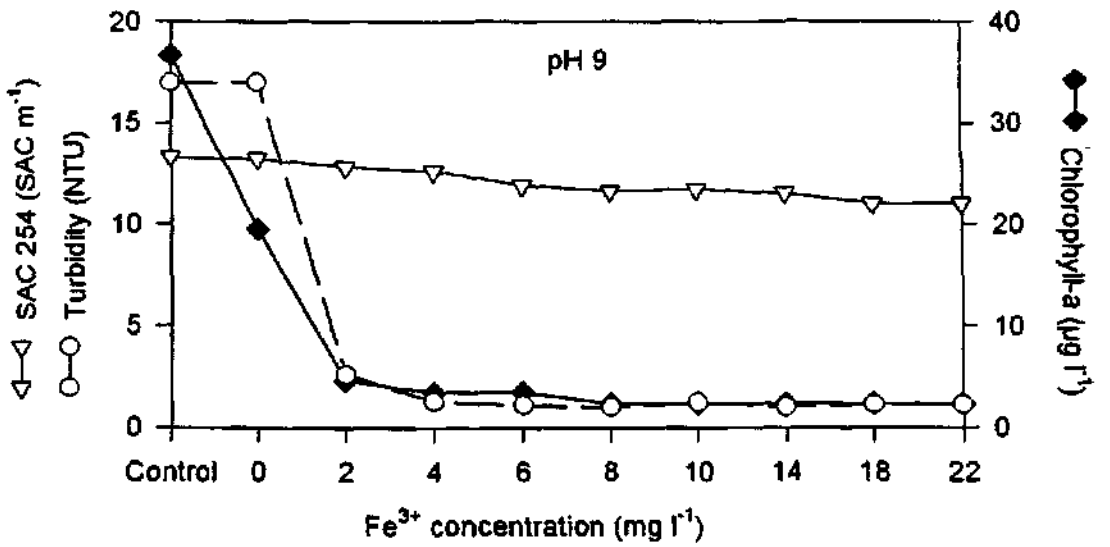


Figure 8. Variation of turbidity (NTU), chlorophyll-*a* concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased iron concentrations (mg l^{-1}) for pH adjusted to 9 with NaOH. The turbidity of the raw water was 17 NTU, chlorophyll-*a* was 36.68 µg l^{-1}, and SAC was 13.3 SAC m^{-1}.

As illustrated in Fig. 8, high Fe^{3+} concentrations displayed effective removal of total suspended solids in the water, but not the removal of DOC. With the addition of 2 mg l^{-1} Fe^{3+} at pH 9, a decrease in chlorophyll-*a* and turbidity levels occurred. At high concentrations a slight additional decrease with the addition of Fe^{3+} was observed. The Chlorophyll-*a* was not as effectively removed at pH 9 when compared with pH 5 and 7 (see Figs 6 and 7).

In the jar test at pH 11, flocs formed without the addition of $FeCl_3$ (Fig. 9). The pH was adjusted with 0.4 M NaOH and the ions produced by NaOH in solution may have acted as point charges, which may have been responsible for floc formation. An increase in floc size and number, occurring together with an increase in Fe^{3+} concentration, was visually observed.

As illustrated in Fig. 9, the removal of total suspended solids was ineffective with the addition of lower Fe^{3+} (up to 6 mg l^{-1}) concentrations. A decrease in chlorophyll-a values with the addition of 2 mg l^{-1} Fe^{3+} occurred at pH 11. The removal of DOC occurred, but was ineffective in contrast with total suspended solids.

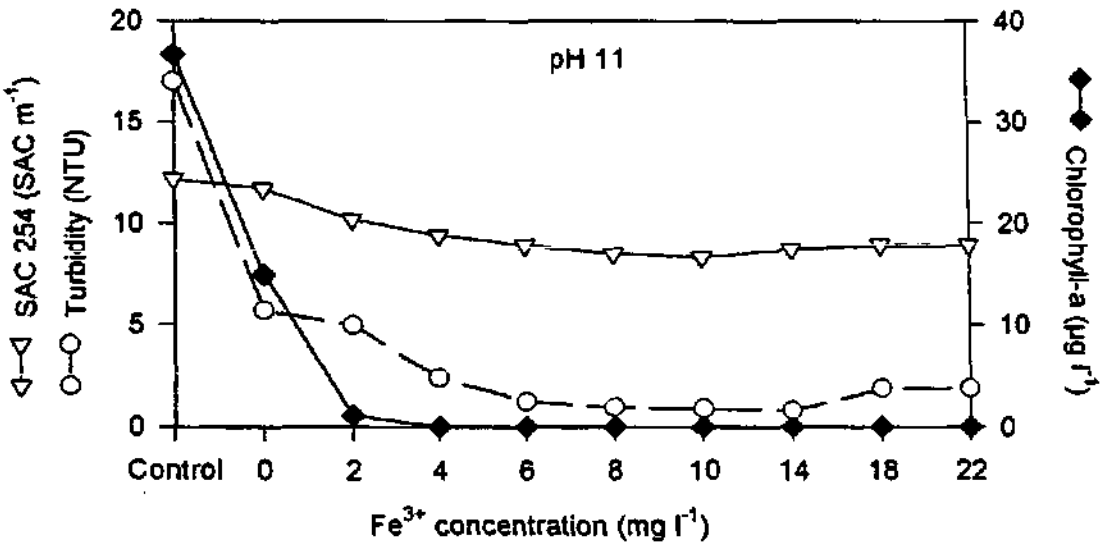


Figure 9. Variation of turbidity (NTU), chlorophyll-*a* concentration (µg l^{-1}) and spectral absorption coefficient (SAC. m^{-1}) with increased iron concentrations (mg l^{-1}) for pH adjusted to 11 with NaOH. The turbidity of the raw water was 17 NTU, chlorophyll-*a* was 36.68 µg l^{-1}, and SAC was 12.2 SAC m^{-1}.

The effect of NaOH and lime as pH-adjustment chemicals

The aim of the next group of experiments was to compare the use of NaOH and Lime as pH adjustment chemicals.

The pH for flocculation with Fe^{3+} was tested at 9 and 11. The pH adjustment chemicals used was 0.1 M NaOH, 0.4 M NaOH, lime supernatant solution and a supersaturated lime suspension. The supersaturated lime suspension was acquired from the Western Transvaal Regional Water Company. The lime supernatant used in this experiment was withdrawn with a pipette from the supersaturated lime suspension. The lime suspension was diluted 4:1 with distilled water. The same Fe^{3+} concentrations as in the previous experiment were used, except that the highest concentration was 18 mg l^{-1}. Chlorophyll-*a*, turbidity and SAC 254 was determined as described in the materials and methods section, and the results are illustrated in Figs 10-f. The formation of flocs, floc size and amount of flocs were visually observed.

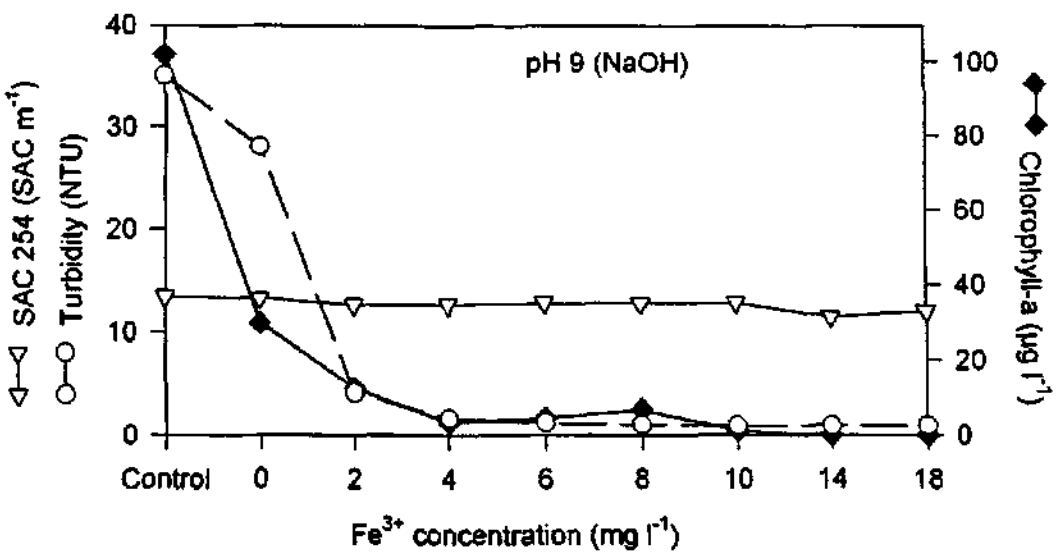


Figure 10. Variation of turbidity (NTU), chlorophyll-*a* concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased iron concentrations (mg l^{-1}) for pH adjusted to 9 with NaOH. The turbidity of the raw water was 35 NTU, chlorophyll-*a* was 102.03 µg l^{-1}, and SAC was 13.4 SAC m^{-1}.

When the pH was adjusted to 9 with 0.1 M NaOH, the size of the flocs was insufficient for sedimentation when small amounts of flocculant was added. A decrease in chlorophyll-*a*, as illustrated in Fig. 10, together with the addition of increased Fe^{3+} concentrations was observed, but high Fe^{3+} concentrations (> 14 mg l^{-1}) was necessary for the removal of total suspended solids. Dissolved organic matter was not removed from the treated water with the addition of $FeCl_3$ at pH 9.

At pH 11 (Fig. 11), the NaOH solution used caused the formation of flocs without the addition of $FeCl_3$. With the addition of flocculant, large flocs formed. After a sedimentation period of 30 min, there were still flocs in suspension and attached to the sides of the jars.

Fig. 11 shows a decrease in chlorophyll-*a* and turbidity with the addition of 2 mg l^{-1} Fe^{3+} and more. The removal of chlorophyll-*a* was most effective with the addition of high Fe^{3+} concentration (≥ 6 mg l^{-1}). Almost no removal of dissolved organic matter was observed, as indicated by SAC 254 values.

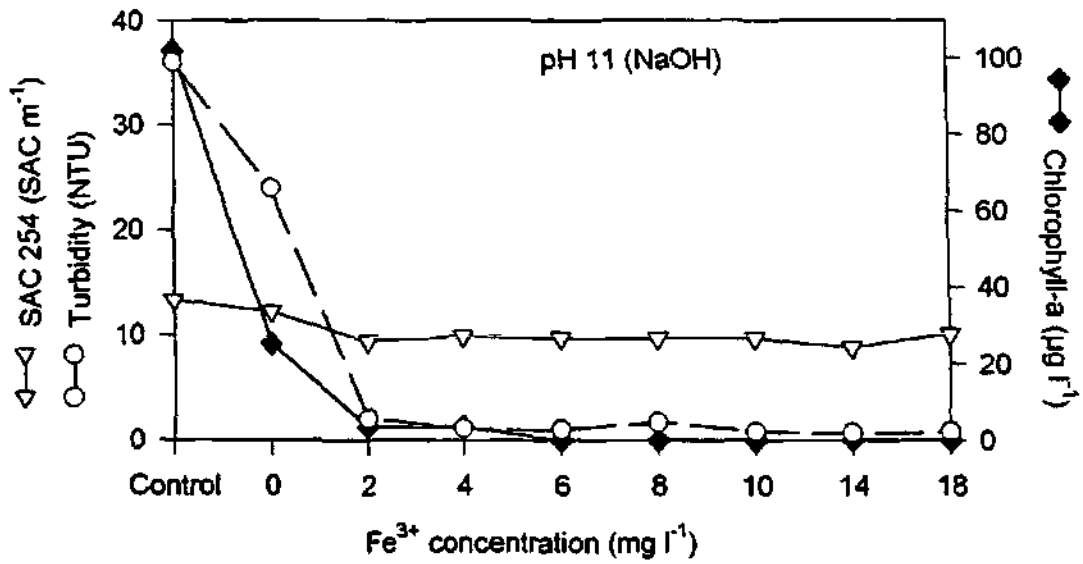


Figure 11. Variation of turbidity (NTU), chlorophyll-*a* concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased iron concentrations (mg l^{-1}) for pH adjusted to 11 with NaOH. The turbidity of the raw water was 35 NTU, chlorophyll-*a* was 102.03 µg l^{-1}, and SAC was 13.4 SAC m^{-1}.

Results from the experiment where pH was adjusted with NaOH and lime supernatant were in general similar (compare Figs 10 and 12; 11 and 13). After the lime supernatant was added as pH adjustment chemical at pH 9, the time period in which the flocs were formed, was longer than with the addition of NaOH.

A removal of chlorophyll-*a* and suspended solids in the treated water together with the addition of 2 mg l^{-1} Fe^{3+} was observed (Fig. 12). No removal of dissolved organic matter at pH 9 was observed.

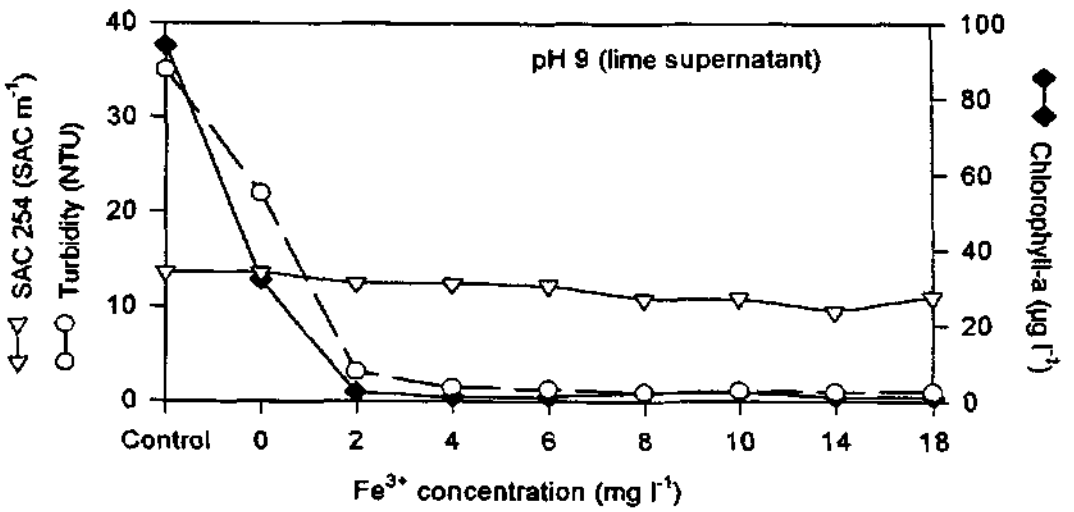


Figure 12. Variation of turbidity (NTU), chlorophyll-*a* concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased iron concentrations (mg l^{-1}) for pH adjusted to 9 with lime supernatant. The turbidity of the raw water was 35 NTU, chlorophyll-*a* was 94.01 µg l^{-1}, and SAC was 13.6 SAC m^{-1}.

When the pH was adjusted to 11 with lime supernatant (Fig. 13), a noticeable removal of chlorophyll-*a*, without the addition of $FeCl_3$,occurred. The removal of chlorophyll-*a* and other suspended particles was effective with the addition of increased Fe^{3+} concentration (above 4 mg l^{-1}). The flocculation and removal of dissolved organic matter was inefficient at pH 11, as indicated by SAC 254.

The addition of the supersaturated lime suspension caused an increase in the formation of flocs, observed visually, in contrast with the previous treatments. The size of the flocs also increased visually with the addition of lime as pH adjustment chemical.

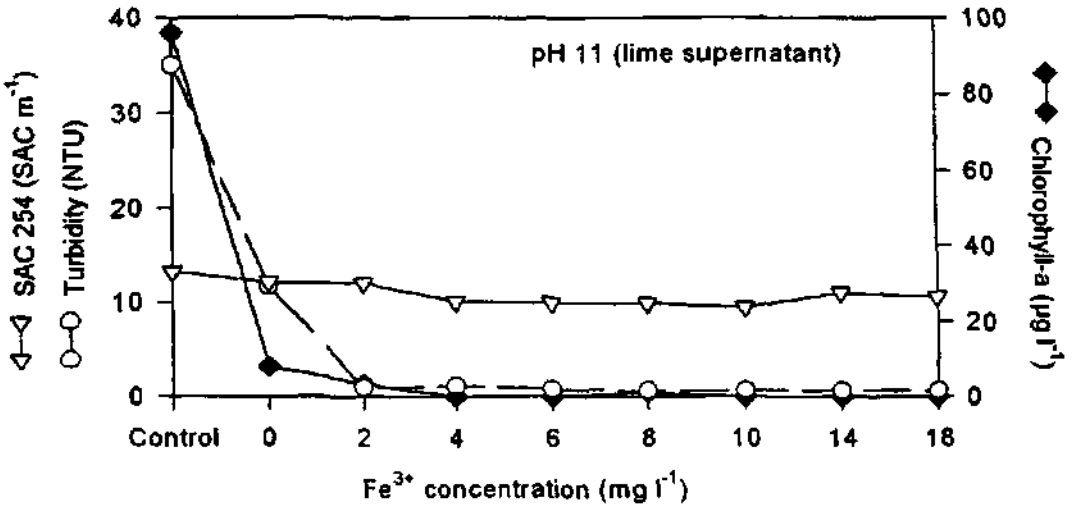


Figure 13. Variation of turbidity (NTU), chlorophyll-*a* concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased iron concentrations (mg l^{-1}) for pH adjusted to 11 with lime supernatant. The turbidity of the raw water was 35 NTU, chlorophyll-*a* was 96.29 µg l^{-1}, and SAC was 13.2 SAC m^{-1}.

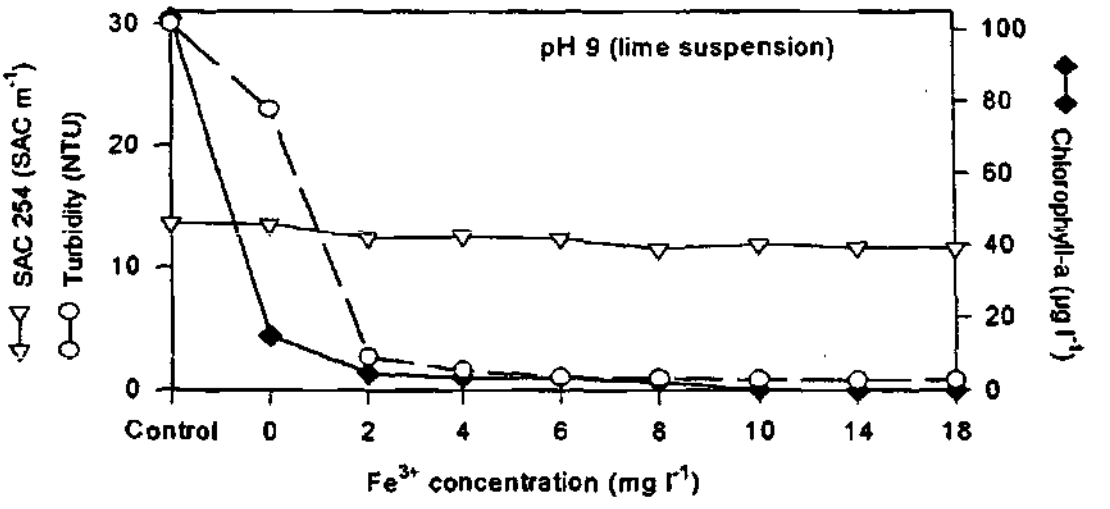


Figure 14. Variation of turbidity (NTU), chlorophyll-a concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased iron concentrations (mg l^{-1}) for pH adjusted to 9 with Lime suspension. The turbidity of the raw water was 30 NTU, chlorophyll-a was 103.18 µg l^{-1}, and SAC was 13.6 SAC m^{-1}.

As illustrated in Fig. 14, a decrease in total suspended solids in the treated water with the addition of 2 mg l^{-1} Fe^{3+} was observed at pH 9. A total removal of chlorophyll-*a* with the addition of 10 mg l^{-1} Fe^{3+} and higher concentrations was observed. The removal of total suspended solids was decreased to 0.79 NTUs with the addition of 14 mg l^{-1} Fe^{3+}.

No removal of dissolved organic matter at pH 11 was observed (Fig. 14).

It was extremely difficult to keep particles of the lime suspension in suspension before it was added to the untreated water. After the sedimentation period, the treated water was turbid (due to suspended particles in the lime suspension) when no flocculant was added.

An increase in turbidity with the addition of lime to the untreated water was observed (Fig.15), but with the addition of increased Fe^{3+} concentration, the turbidity decreased to a minimum of 0.59 NTUs.

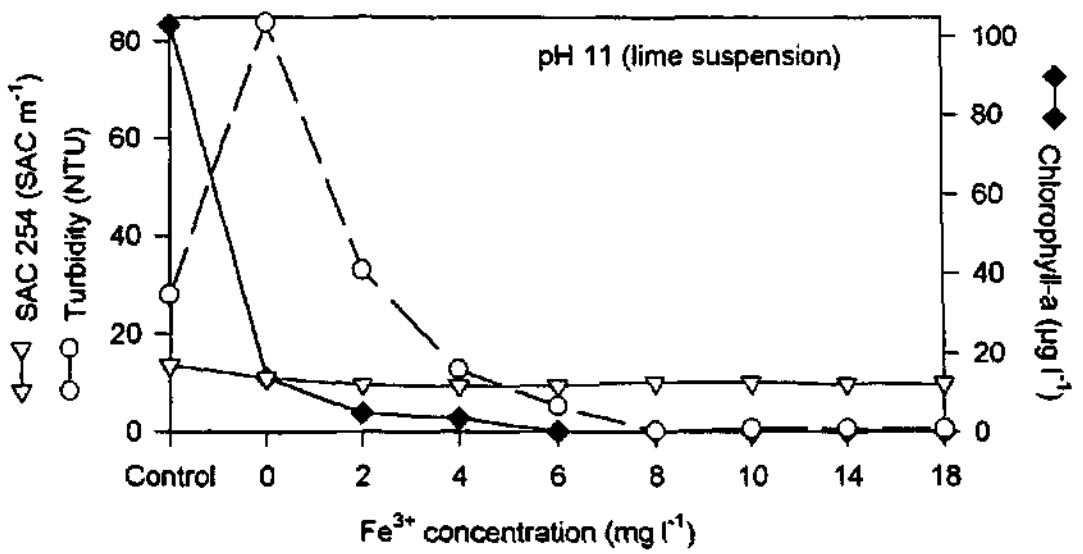


Figure 15. Variation of turbidity (NTU), chlorophyll-*a* concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased iron concentrations (mg l^{-1}) for pH adjusted to 11 with Lime suspension. The turbidity of the raw water was 28 NTU, chlorophyll-*a* was 103.18 µg l^{-1}, and SAC was 13.6 SAC m^{-1}.

Chlorophyll-*a* was efficiently removed at higher Fe^{3+} concentrations ($\geq$ 6 mg l^{-1}). As illustrated in Fig. 15, in accordance with the previous experiments, dissolved organic matter was unsuccessfully removed at pH 11.

The effect of $FeCl_3$ and $Fe_2(SO_4)_3$

The aim of the experiment was to compare the effects of $Fe_2(SO_4)_3$ (ferric-sulphate) and $FeCl_3$ (ferric-chloride) when used as coagulants. The experiment was conducted to compare the ability of the two coagulants at various pH levels when lime was used as pH adjustment chemical. The concentrations used in this experiment was the same as those used in the previous experiment. The $Fe_2(SO_4)_3$ stock solution contained 3.578 g $Fe_2(SO_4)_3.H_2O$ (1g.l^{-1} Fe^{3+}) to which 2.5 ml l^{-1} 15% HCl was added to stabilise the solution. The pH for flocculation with Fe^{3+} as $FeCl_3$ and $Fe_2(SO_4)_3$ was tested at 9 and 11. The pH adjustment chemical used was lime suspension.

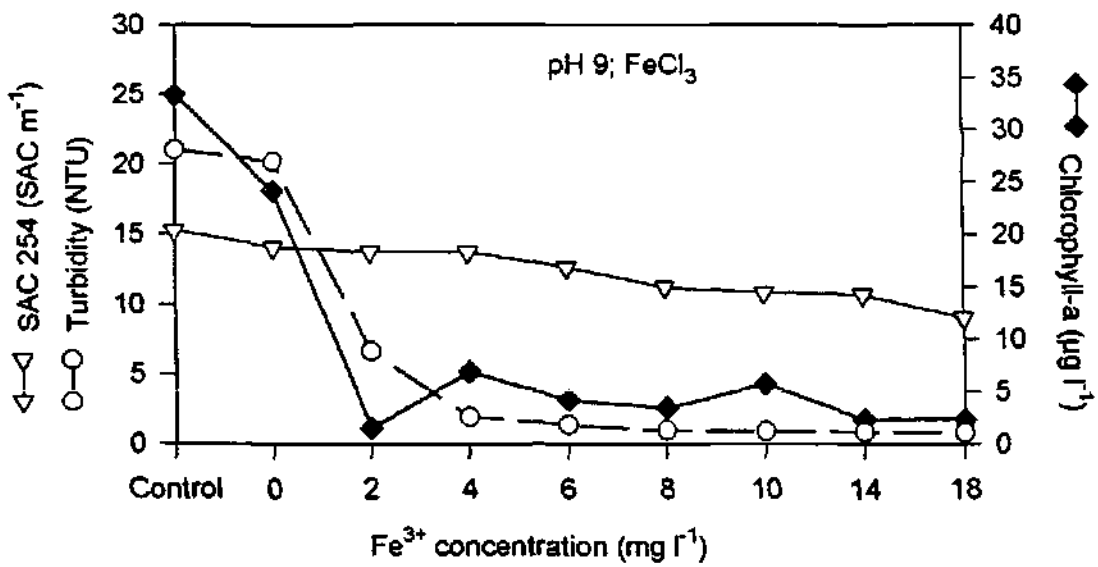


Figure 16. Variation of turbidity (NTU), chlorophyll-*a* concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased iron concentrations (mg l^{-1}) for pH adjusted to 9 with Lime suspension. The turbidity of the raw water was 22.1 NTU, chlorophyll-*a* was 33.25 µg l^{-1}, and SAC was 15.2 SAC m^{-1}.

When $FeCl_3$ was used as flocculant at pH 9, as illustrated in Fig. 16, a decrease in total suspended solids was observed together with an increase in Fe^{3+} concentration.

The actual removal of chlorophyll-*a* and suspended inorganic matter in the treated water occurred under higher Fe^{3+} concentrations ($\geq$ 6-18 mg l^{-1}). Slight removal of dissolved organic matter occurred (Fig. 16) at 6 mg l^{-1} Fe^{3+} and higher concentrations.

As illustrated in Fig. 17, when $FeCl_3$ was used as flocculant, the lime suspension, used as pH adjustment chemical, caused an increase in turbidity in the absence of flocculant. With the addition of increased Fe^{3+} concentrations ($\geq$ 4 mg l^{-1}), the turbidity was efficiently decreased to NTUs lower than 1.0. More than 80 % of the chlorophyll-a of the Vaal River water was removed without the addition of flocculant. This can be due to the aid of lime as flocculant.

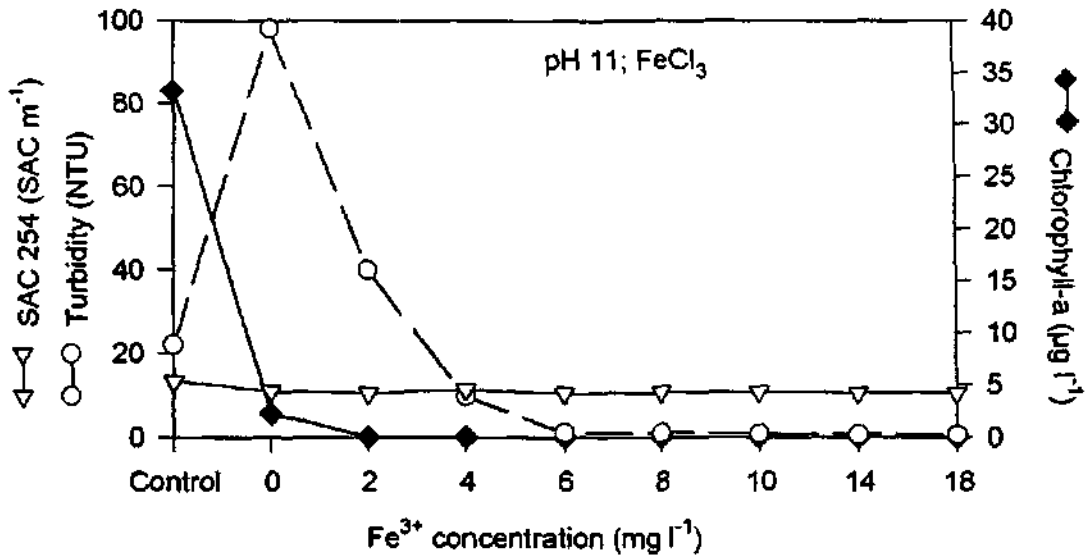


Figure 17. Variation of turbidity (NTU), chlorophyll-*a* concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased iron concentrations (mg l^{-1}) for pH adjusted to 11 with Lime suspension. The turbidity of the raw water was 22.1 NTU, chlorophyll-*a* was 33.25 µg l^{-1}, and SAC was 13.4 SAC m^{-1}.

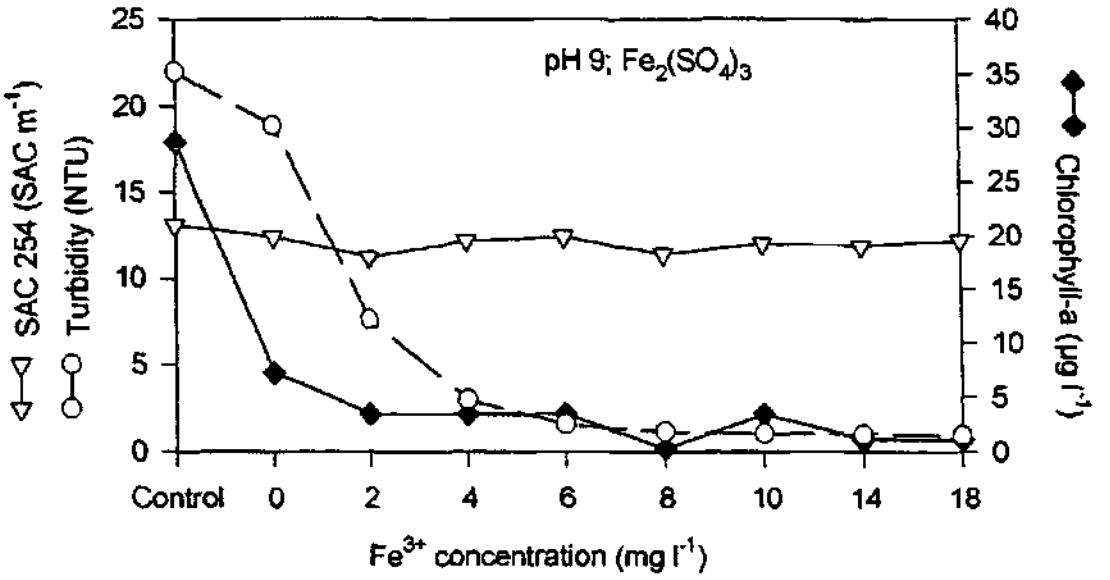


Figure 18. Variation of turbidity (NTU), chlorophyll-*a* concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased iron concentrations (mg l^{-1}) for pH adjusted to 9 with Lime suspension. The turbidity of the raw water was 22 NTU, chlorophyll-*a* was 28.66 µg l^{-1}, and SAC was 13.1 SAC m^{-1}.

As illustrated in Fig. 17, dissolved organic matter was not removed from the treated water at pH 11.

When $Fe_2(SO_4)_3$ was used as flocculant (Fig. 18), the results obtained was similar to the results obtained from the addition of Fe^{3+} as $FeCl_3$ at pH 9 adjusted with lime.

The difference between the different treatments could be observed in the removal of chlorophyll-*a*. With the addition of 14 mg l^{-1} Fe^{3+} as $Fe_2(SO_4)_3$, chlorophyll-*a* was decreased to 4% of that of the raw water. Therefore, the addition of a high concentration of $Fe_2(SO_4)_3$ was effective in the removal of chlorophyll-*a* in the untreated water. This is possibly an indication of effective removal of phytoplankton.

When lime suspension was added at pH 11, as illustrated in Fig. 19, as in the case of the previous experiment where lime was added to pH 11 (Fig. 15), turbidity increased initially. With an increase in $Fe_2(SO_4)_3$ concentration, turbidity

decreased. Chlorophyll-*a* was effectively removed with the addition of increased $Fe_2(SO_4)_3$ concentrations (above 14 mg l^{-1}).
A slight removal of dissolved organic matter was observed at pH 11 with the addition of increased flocculant concentrations. This can be due to the effect of lime in the flocculation and removal of dissolved organic matter. This aspect need to be investigated further.

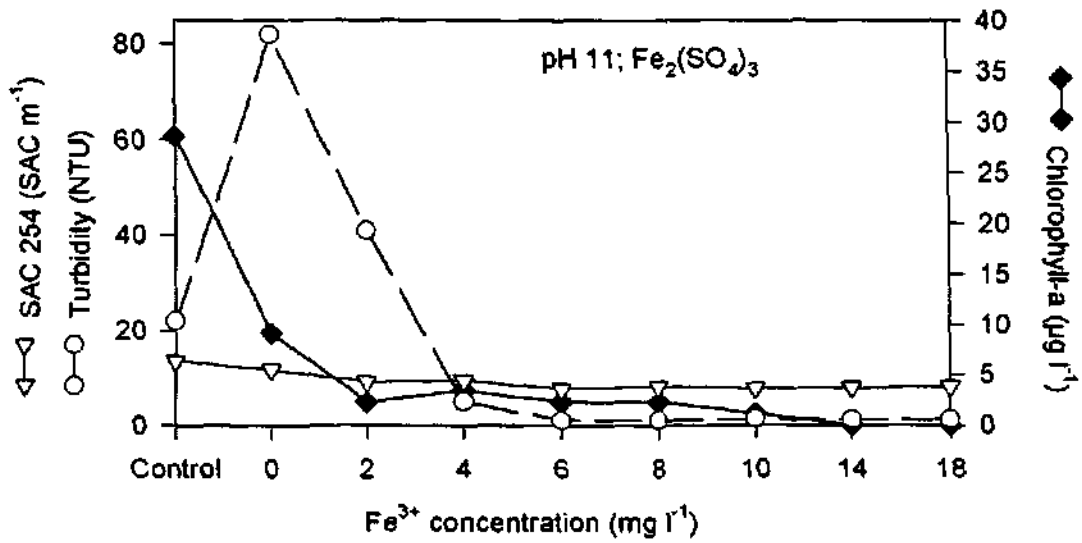


Figure 19. Variation of turbidity (NTU), chlorophyll-a concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased iron concentrations (mg l^{-1}) for pH adjusted to 11 with Lime suspension. The turbidity of the raw water was 22 NTU, chlorophyll-a was 28.66 µg l^{-1}, and SAC was 13.1 SAC m^{-1}.

The effect pH > 11 on removal of suspended material

The aim of this experiment was to determine the effect of the removal of chlorophyll-*a*, suspended solids and dissolved organic matter when the pH was raised above 11. At the Balkfontein purification plant, experience showed that DOC was effectively removed when the pH was raised to 11.4.

When the pH was adjusted with NaOH and no flocculant was added, removal of chlorophyll-*a* increased with an increase in pH (Fig. 20). Total removal of chlorophyll-*a* was observed at pH 11.5. When the pH was raised to 12, the

removal decreased slightly. Suspended solids were also effectively removed at pH 11.5, with almost no removal at pH 10.5. DOC removal was not effective, which can be due to the absence of added Fe^{3+}, but the best removal was observed at pH 11.5

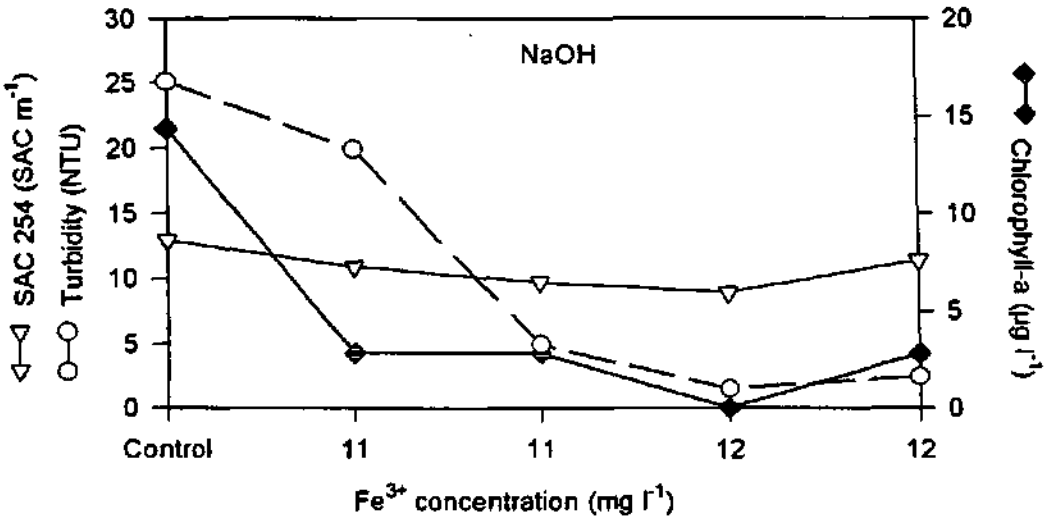


Figure 20. Variation of turbidity (NTU), chlorophyll-a concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased pH. pH adjusted with NaOH.

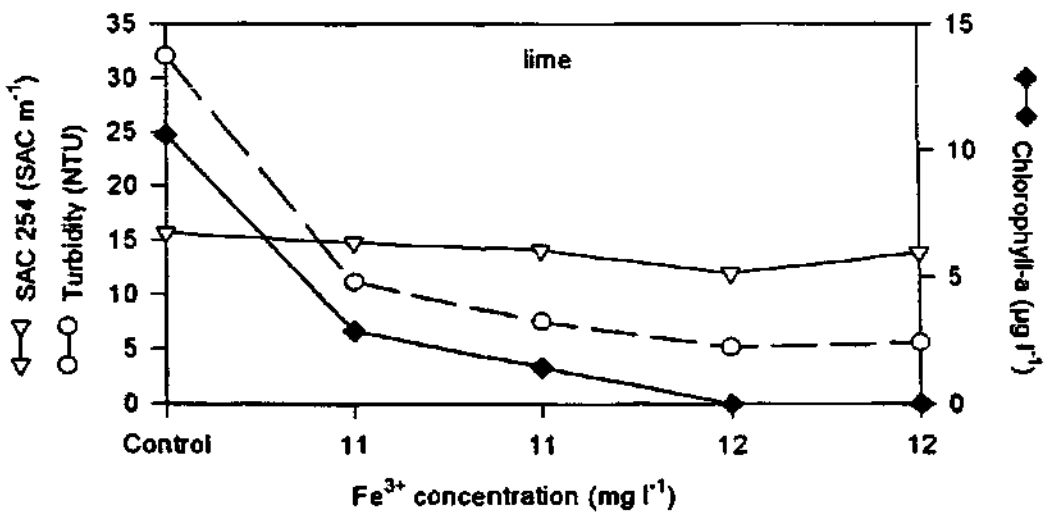


Figure 21. Variation of turbidity (NTU), chlorophyll-a concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased pH. pH adjusted with lime.

When the pH was adjusted with lime, the removal of chlorophyll-a was ineffective at pH 10.5, but when the pH was increased to 11.5 and higher, total removal of chlorophyll-*a* occurred (Fig. 21). The removal of suspended solids was ineffective when the pH was adjusted with lime (compare Figs 20 and 21) which can be due to the suspended particles in the lime suspension which may have increased the turbidity. Fe^{3+} was not added and previous experiments (Figs 15 and 17) showed that lime increase turbidity when Fe^{3+} was not added as coagulant. The lowest turbidity values were obtained when the pH was adjusted to 11.5. DOC was also ineffectively removed when pH was adjusted with lime, but lower SAC values were obtained at pH 11.5

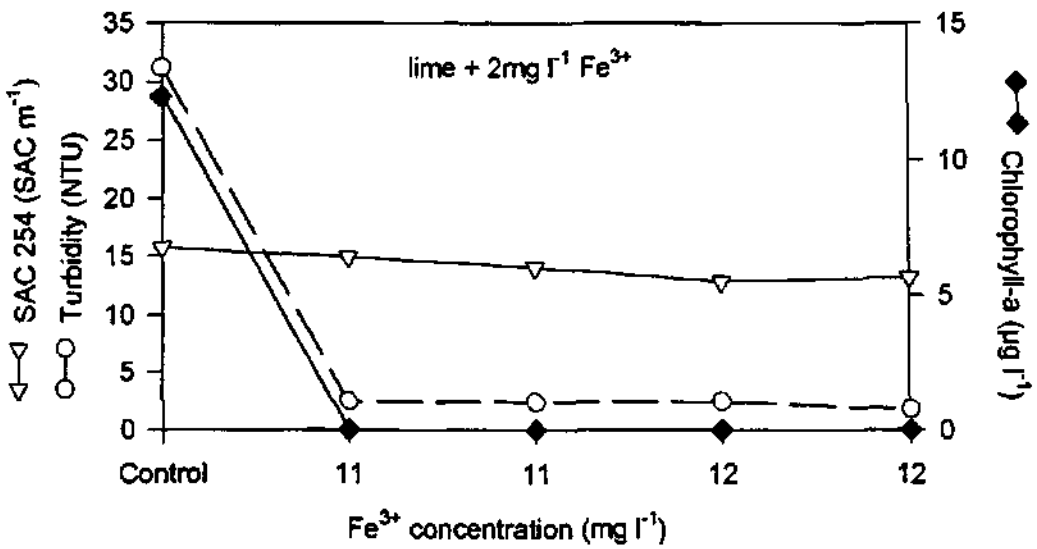


Figure 22. Variation of turbidity (NTU), chlorophyll-a concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased pH. pH adjusted with lime and 2 mg l^{-1} was added to Vaal River water.

When 2 mg l^{-1} Fe^{3+} was added together with increase pH, total removal of chlorophyll-a occurred. The removal of suspended solids was effective and almost the same for all pH conditions (Fig. 22). DOC was again not effectively removed. The lowest SAC value was observed at pH 11.5 (Fig. 22).

The effect of the Ca^{2+} ions present in lime on the flocculation processes

In the high pH lime experiment, high concentrations of Ca^{2+} was added to the untreated Vaal River water in the form of lime. The aim of the next experiment was to determine the effect of this added Ca^{2+} ions on the flocculation processes.

The calcium concentration of the supersaturated lime suspension (acquired from the Western Transvaal Regional Water Company), that was used for pH adjustment, was determined by the Soil Laboratory of the PU for CHE. The Ca^{2+} concentration of the lime which was added as pH adjustment agent in the previous experiments was then calculated. The highest calculated Ca^{2+} concentration (volume of lime added to Vaal River water to raise the pH to 12) was 0.741 mg l^{-1}. The various Ca^{2+} concentrations used in this experiments were 0.55, 0.65, 0.75, 0.85 and 1 mg l^{-1}. Ca^{2+} as $CaCl_2$ was added to Vaal River water, without pH adjustment, and also when the pH was adjusted to 11.5 with NaOH.

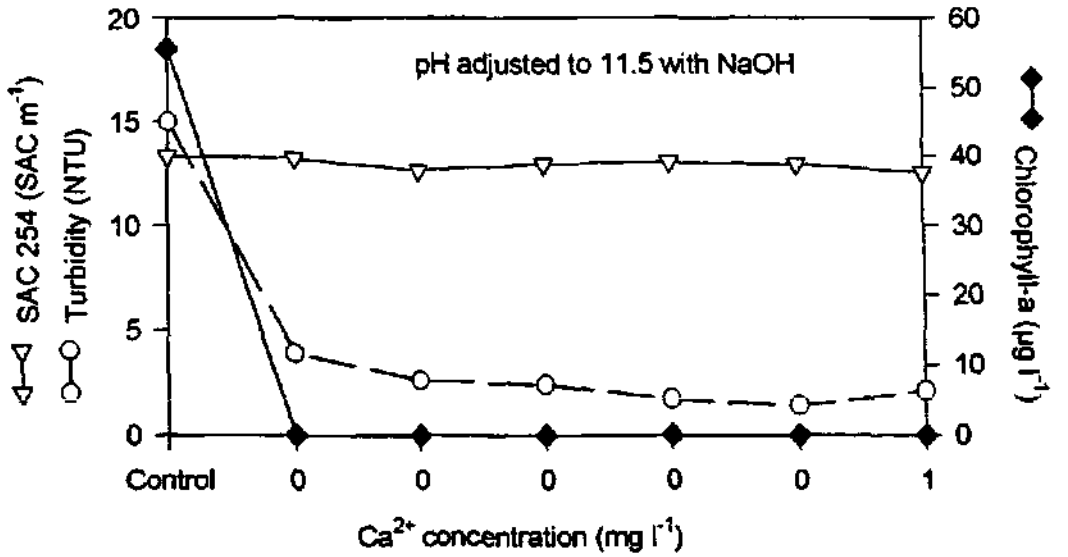


Figure 23. Variation of turbidity (NTU), chlorophyll-a concentration (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased Calcium concentrations (mg l^{-1}) for pH adjusted to 11.5 with NaOH.

When the pH was adjusted to 11.5 (Fig. 23), total removal of chlorophyll-a was observed in all the treatments. The removal of suspended solids was also effective, with the best removal observed at Ca^{2+} concentrations 0.75-0.85 mg l^{-1}. DOC was,

however, poorly removed when Ca^{2+} ions were added as $CaCl_2$ (Fig 23) when pH was adjusted to 11.5. Ca^{2+} had no effect on chlorophyll-*a* removal, because when 0 mg l^{-1} was added, chlorophyll-*a* removal was also total. The removal was , therefore, the result of high pH conditions.

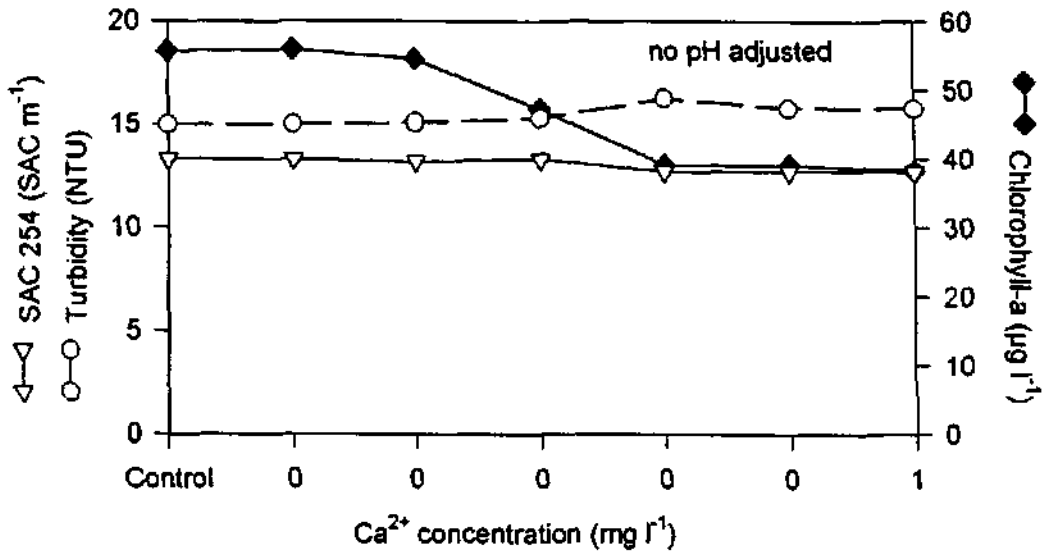


Figure 24. Variation of turbidity (NTU), chlorophyll-a concentrations (µg l^{-1}) and spectral absorption coefficient (SAC m^{-1}) with increased Calcium concentrations (mg l^{-1}). pH was not adjusted.

When the pH was not adjusted, and increased calcium concentrations was added to raw Vaal River water, almost no visually observed flocs formed. Slight removal of chlorophyll-a occurred at high Ca^{2+} concentrations (> 0.75 mg l^{-1}). The removal of DOC did not occur, and the turbidity values increased with the addition of high calcium concentrations (Fig. 24).

Figs 23 and 24 indicated that Ca^{2+} had no effect on the removal of chlorophyll-a, suspended solids and dissolved organic matter. pH played an important part in flocculation or it can be possible that pH 11.5 caused calcium ions (and magnesium ions present in Vaal River water) to form precipitates which assist in flocculation, because suspended particles can be adsorbed by these precipitates (Parker *et al.*, 1975; Dziubek and Kowal, 1984).

Organic substances excreted by algal cells

Table 3 illustrate major categories of organic substances excreted by algae in culture. *Monoraphidium minutum* excreted five major organic substances, *Pandorina morum* four and *Cyclotella meneghiniana* only three. *C. meneghiniana* cells excreted more mono and dicarboxylic acids per unit chlorophyll than the other two species, while *Monoraphidium minutum* excreted more fatty and aromatic acids.

Table 3. Extracellular organic substances from uni-algal cultures of *Monoraphidium minutum* (Monmin; 10 days old), *Cyclotella meneghiniana* (Cycmen; 18 days old), and *Pandorina morum* (Panmor; 10 days old) isolated from the Vaal River

Compound	Concentration µg l^{-1}			ng/µg chlorophyll-*a*$^{-1}$		
	Monmin	Cycmen	Panmor	Monmin	Cycmen	Panmor
Monocarboxylic acids	354.8	188.9	34.4	99.8	219.1	10.8
Dicarboxylic acids	266.0	348.0	266.1	74.8	403.6	83.9
Fatty acids	331.4	39.9	-	93.3	46.3	-
Aromatic acids	231.8	-	109.6	65.2	-	34.6
Glycerol	34.3	-	-	9.7	-	-
Phosphoric acid	-	-	6.7	-	-	2.1

The effect of *Monoraphidium minutum* cells on coagulation and flocculation

The aim of this experiment was to determine what effect added *M. minutum* cells (representing a *M. minutum* dominance under natural conditions) had on flocculation processes.

Removal of biomass (i.e. chlorophyll-a)

M. minutum cells suspended in culture medium in which the cells grew (concentrated so that 5.0 ml contains 60 µg l^{-1} chlorophyll-*a*), the same concentration suspended in distilled water, culture medium without cells in which the cells grew, culture medium in which no cells grew and distilled water only, were added to Vaal River water.

Small flocs formed when HCl was added as pH adjustment chemical. The treated water was more turbid when lime was added, although larger flocs formed. The treated water, after lime dosing, was visually clearer at the end of the sedimentation period (30 min.). When no Fe^{3+} was added, and only pH adjustment chemicals (HCl and NaOH), almost no removal occurred. When lime was added, total removal of chlorophyll-*a* occurred (Fig. 25).

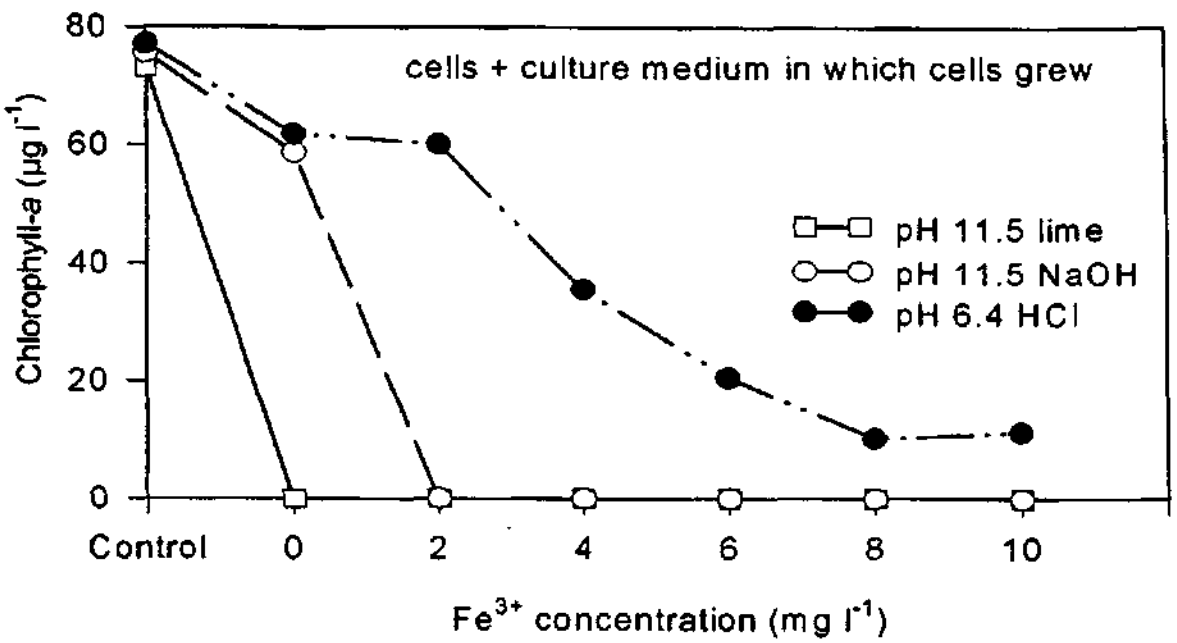


Figure 25. Variation in chlorophyll-*a* concentration (µg l^{-1}) with increased Fe^{3+} concentrations. *Monoraphidium minutum* cells, suspended in culture medium in which the cells grew, were added to Vaal River water.

The addition of low Fe^{3+} concentrations at pH 6.4 was inefficient in the removal of chlorophyll-*a*, when compared to when pH adjustment was made with NaOH and lime. The best removal of chlorophyll-*a*, at pH 6.4, was obtained when 8 mg l^{-1} Fe^{3+} and higher concentrations were added. Effective removal occurred at pH 11.5 (adjusted with NaOH) when Fe^{3+} was added. The same results were obtained when lime was used (Fig. 25).

When *M. minutum* cells were suspended in distilled water and added to Vaal River water, the floc size of the differently treated water was the same as when cells,

suspended in culture medium, were added to Vaal River water. The number of flocs formed on the surface of the treated water was, however, visually less.

As illustrated in Fig. 26, when lime was added as pH adjustment chemical, total removal of chlorophyll-*a* did not occur at Fe^{3+} < 6 mg l^{-1} (compare with Fig. 25). The Fe^{3+} treatment at pH 6.4 was ineffective in the removal of chlorophyll-*a*. The best removal occurred at the addition of high Fe^{3+} concentrations, with the most effective removal occurring when 10 mg l^{-1} Fe^{3+} was added. At pH 11.5, adjusted with NaOH, total removal of chlorophyll-a did not occur, but effective removal was obtained when 4 mg l^{-1} Fe^{3+} and higher iron concentrations were added (Fig. 26). Total removal of chlorophyll-a was, however, observed when 6 mg l^{-1} and higher iron concentrations were added to raw water, when the pH was adjusted to 11.5 with lime (Fig 26).

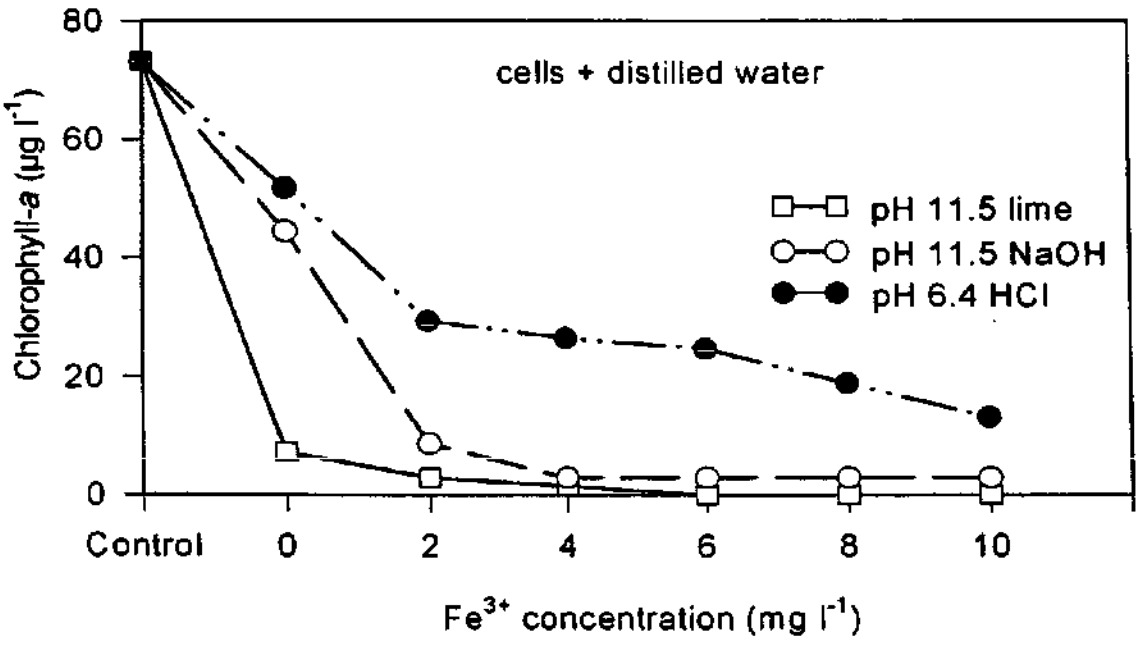


Figure 26. Variation in chlorophyll-*a* concentration (µg l^{-1}) with increased Fe^{3+} concentrations. *Monoraphidium minutum* cells, suspended in distilled water, were added to Vaal River water.

When the culture medium in which the cells grew was added to Vaal River water, the initial chlorophyll-a concentration was less, compared with Figs 25 and 26,

because the chlorophyll-*a* concentration was not increased with the additional 60 µg l^{-1} (Fig. 27).

The removal of natural occurring algal cells (present in raw Vaal River water) was not effective at pH 6.4 when low Fe^{3+} concentrations were used as flocculants, i.e. < 6 mg l^{-1} Fe^{3+} (Fig. 27). At pH 11.5, when the pH was adjusted with NaOH, total removal of chlorophyll-*a* was obtained when iron was added as flocculant. At pH 11.5, when lime was used as pH adjustment chemical, total removal of chlorophyll-*a* occurred even when Fe^{3+} was not added (Fig. 27). Therefore, lime was apparently responsible for the coagulation and removal of chlorophyll-a. Total removal of chlorophyll-*a* also occurred at pH 6.4 when 6.0 mg l^{-1} and higher iron concentrations were added (Fig. 27).

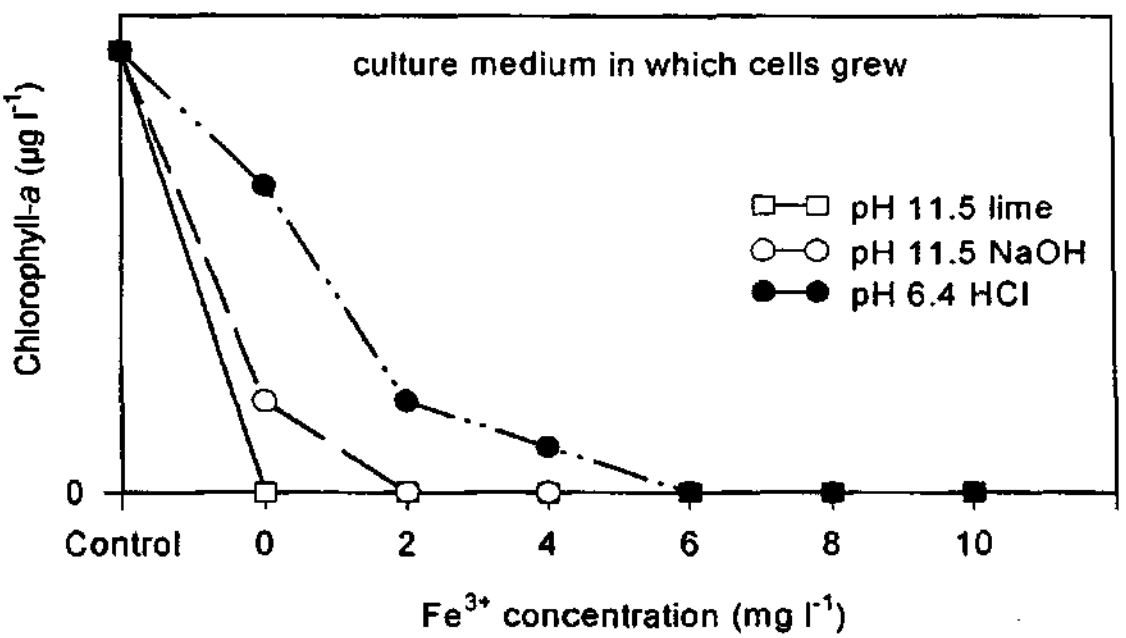


Figure 27. Variation in chlorophyll-*a* concentration (µg l^{-1}) with increased Fe^{3+} concentrations. Culture medium, in which *Monoraphidium minutum* cells grew, was added to Vaal River water.

When only culture medium in which cells never grew, containing no algal cells, was added to raw water, the initial chlorophyll-*a* values were also low (Fig. 28). At pH 6.4 small flocs formed during slow mixing, but when the pH was adjusted to 11.5,

the floc size increased and the treated water appearred visually more turbid. The number of flocs formed on the surface layer also increased from pH 6.4 to pH 11.5.

Slight removal occurred when pH was adjusted to 6.4 when no Fe^{3+} was added, but total removal of chlorophyll-a occurred when 4 mg l^{-1} and higher Fe^{3+} concentrations were added (Fig. 28).

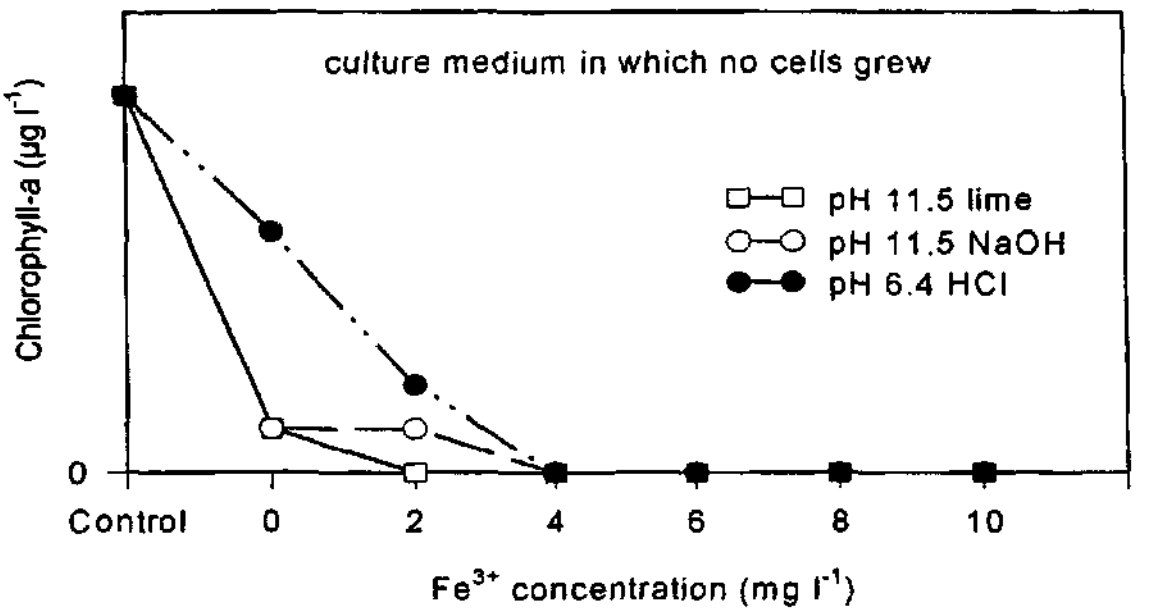


Figure 28. Variation in chlorophyll-*a* concentration (µg l^{-1}) with increased Fe^{3+} concentrations. Culture medium, in which no cells grew, was added to Vaal River water.

Effective removal of chlorophyll-a occurred at pH 11.5 when adjusted with NaOH (Fig. 28). The removal was the same when 2 mg l^{-1} Fe^{3+} was added, but total removal of chlorophyll occurred when 4 mg l^{-1} and higher concentrations were added.

Effective removal of chlorophyll was observed when lime (pH 11.5) was used as pH adjustment chemical. Total removal occurred when Fe^{3+} (>2 mg l^{-1}) was added to the untreated water (Fig. 28).

When only distilled water was added to the Vaal River water (Fig. 29), unsuccessful coagulation and removal of natural occurring chlorophyll-*a* occurred when the pH was adjusted to 6.4. Total removal of chlorophyll-*a* was observed when 8 mg l^{-1} and higher Fe^{3+} concentrations were added.

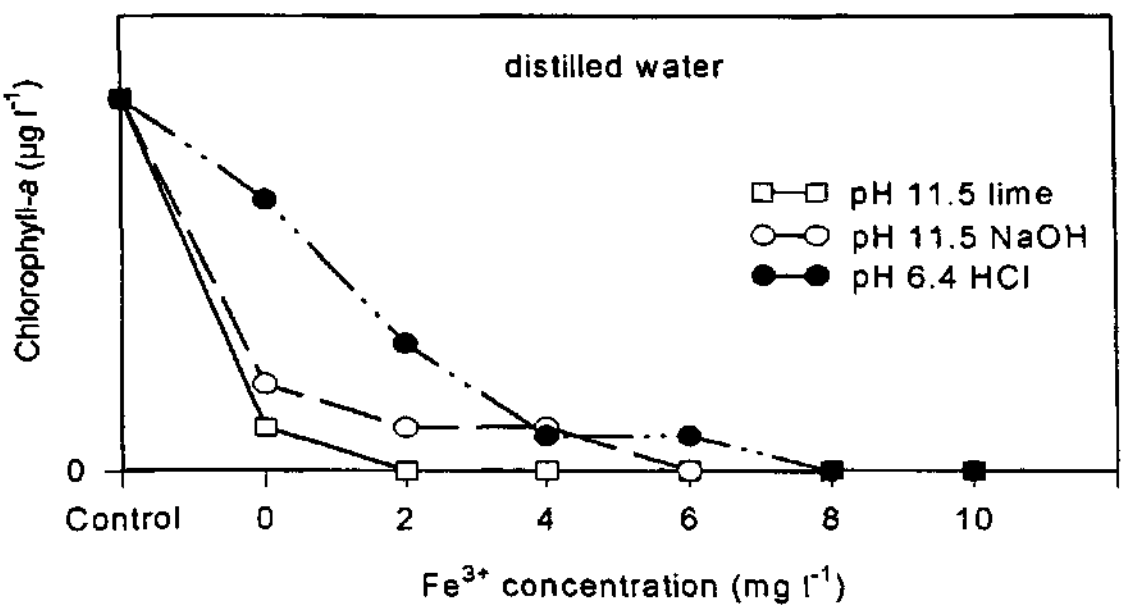


Figure 29. Variation in chlorophyll-*a* concentration (µg l^{-1}) with increased Fe^{3+} concentrations. Distilled water only was added to Vaal River water.

Similar results were obtained when the pH was adjusted to 11.5 with NaOH; lower Fe^{3+} concentrations did not remove chlorophyll-*a*. Total removal of chlorophyll-*a* occurred when 6 mg l^{-1} Fe^{3+} and higher concentrations were added as flocculant (Fig. 29).

In the absence of flocculant, lime (at pH 11.5) removed chlorophyll-*a* more effectively than when pH was adjusted with NaOH (pH 11.5) and HCl (pH 6.4). The addition of Fe^{3+} (2 mg l^{-1} and higher), together with lime, gave total removal of chlorophyll-*a* (Fig. 29).

The following conclusions can be drawn to summarise observations on the removal of chlorophyll-*a* when *M. minutum* was added to Vaal River water. The addition of

M. minutum cells increased the chlorophyll-*a* concentrations with approximately 60 µg l^{-1}. The high concentration of chlorophyll-*a* was removed less efficient at pH 6.4 (see Figs 25 and 26). When algal cells were added which were suspended in culture medium in which the cells grew (excreted organic substances present), the removal of the cells at pH 11.5 was more effective than when the cells were suspended in distilled water (compare Figs 25 and 26). Therefore, culture medium in which the cells grew apparently assist in flocculation. The assistance could be due to the dissolved inorganic components of the nutrient medium, or the excreted organic substances.

When the chlorophyll-*a* concentration was increased by adding cells suspended in culture medium, and the pH was adjusted to 6.4, then high Fe^{3+} concentrations, possibly higher than 10 mg l^{-1},were necessary for effective removal of chlorophyll-*a* (Figs 25). When the chlorophyll-*a* concentrations were low (approximately 12 µg l^{-1} in the untreated water), and culture medium in which the cells grew was added to Vaal River water (Fig. 27), effective removal occurred at Fe^{3+} concentrations of 6 mg l^{-1} and higher. Therefore, algal cells apparently obstructed the flocculation process when high chlorophyll-*a* concentration occurred in the water.

When culture medium in which the cells grew (Fig. 27) was added to Vaal River water, poorer removal of chlorophyll-*a* was observed at pH 6.4 than when culture medium in which no cells grew (Fig. 28) was added to Vaal River water. Therefore, organic substances excreted by the cells apparently caused poorer removal of chlorophyll-*a*. At pH 11.5 better removal was observed when organic substances were present.

When culture medium in which no cells grew (Fig. 28) was added to Vaal River water, removal of chlorophyll-*a* was better at pH 6.4 and 11.5 than when distilled water only was added to Vaal River water. Therefore, inorganic components of the nutrient medium assist in removal of chlorophyll-*a*.

High pH in conjunction with Fe^{3+} removed *M. minutum* cells effectively (Figs 25 and 26). When cells suspended in culture medium in which they grew, was added to Vaal River water, pH 11.5 (adjusted with lime) effectively removed chlorophyll-*a* without Fe^{3+} addition (Fig. 25).

Removal of suspended solids

The effect of *M. minutum* cells on the removal of suspended solids will be illustrated in the following figures.

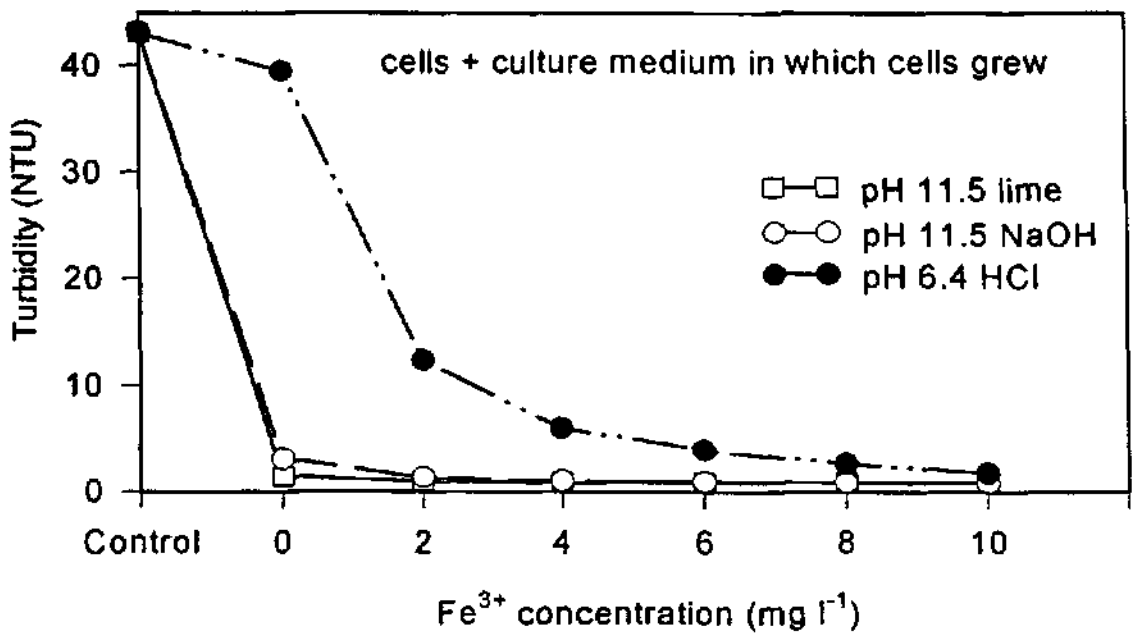


Figure 30. Variation in turbidity (NTU) with increased Fe^{3+} concentrations. *Monoraphidium minutum* cells, suspended in culture medium in which cells grew, was added to Vaal River water.

When *M. minutum* cells suspended in culture medium in which they grew were added to Vaal River water, removal of suspended particles (illustrated as turbidity in Figs 30-34), together with algal cells, were ineffective when the pH was adjusted to 6.4, although effective removal occurred at Fe^{3+} concentrations of 8 mg l^{-1} and higher (Fig. 30). pH (11.5) adjusted with NaOH did improve the removal of suspended solids, and with the addition of increased Fe^{3+} (>2 mg l^{-1}) concentrations, suspended material was effectively removed. At pH 11.5, when the pH was adjusted with lime, effective removal of suspended material was obtained with increased Fe^{3+} concentrations. Even when no $FeCl_3$ was dosed, effective removal occurred (Fig. 30).

When *M. minutum* cells were suspended in distilled water and added to Vaal River water, removal of suspended material occurred at pH 6.4, but was ineffective when compared with pH 11.5 (Fig. 31). At pH 11.5, when the pH was adjusted with lime, effective removal of suspended material was observed.

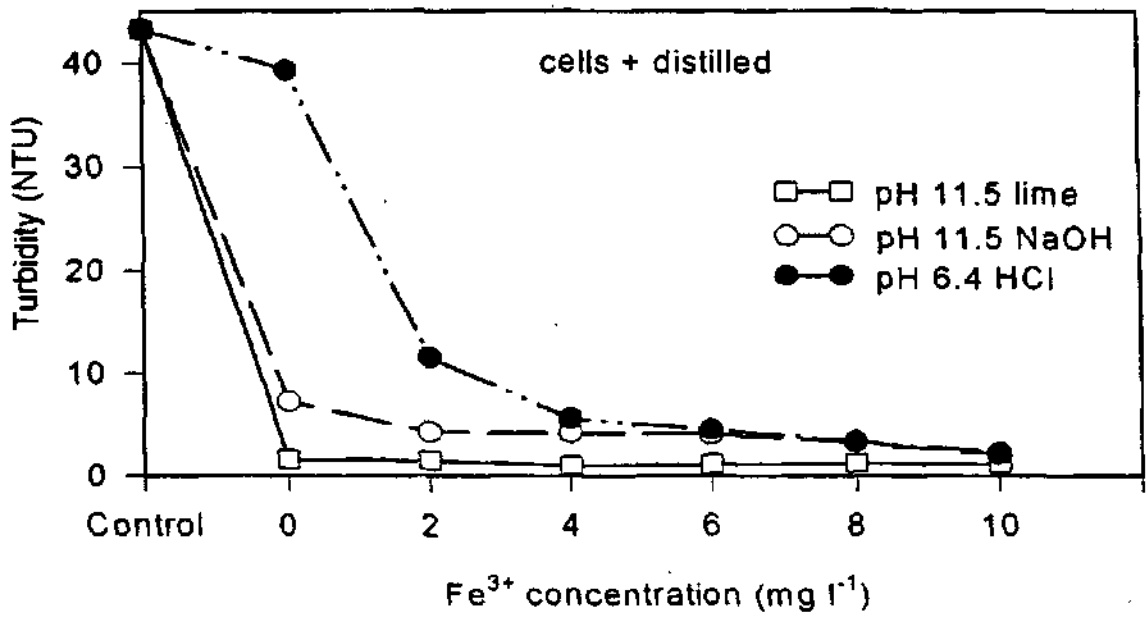


Figure 31. Variation in turbidity (NTU) with increased Fe^{3+} concentrations. *Monoraphidium minutum* cells, suspended in distilled water, were added to Vaal River water.

Results illustrated in Figs 32 (when culture medium in which cells grew were added to Vaal River water), 8I (when culture medium in which no cells grew were added to Vaal River water) and 34 (when distilled water only was added to Vaal River water) are more or less the same, except for a few small differences.

At pH 6.4, when low iron concentrations were added, the most effective removal of suspended solids occurred when culture medium in which cells did grow (Fig. 32) was added to Vaal River water. When 5 ml culture medium in which no cells grew was added (Fig. 33), the removal was more effective than when only 5 ml distilled water was added (compare Figs 33 and 34). This observation confirms a previous one, namely that inorganic components present in the nutrient medium positively effected coagulation and sedimentation.

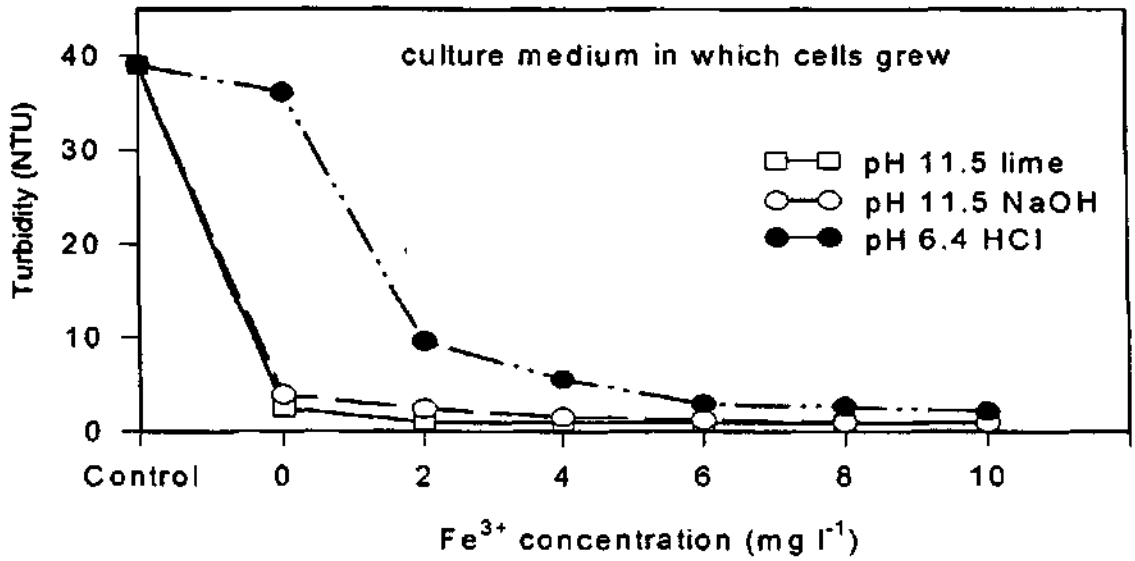


Figure 32. Variation in turbidity (NTU) with increased Fe^{3+} concentrations. Culture medium, in which *Monoraphidium minutum* cells grew, was added to Vaal River water.

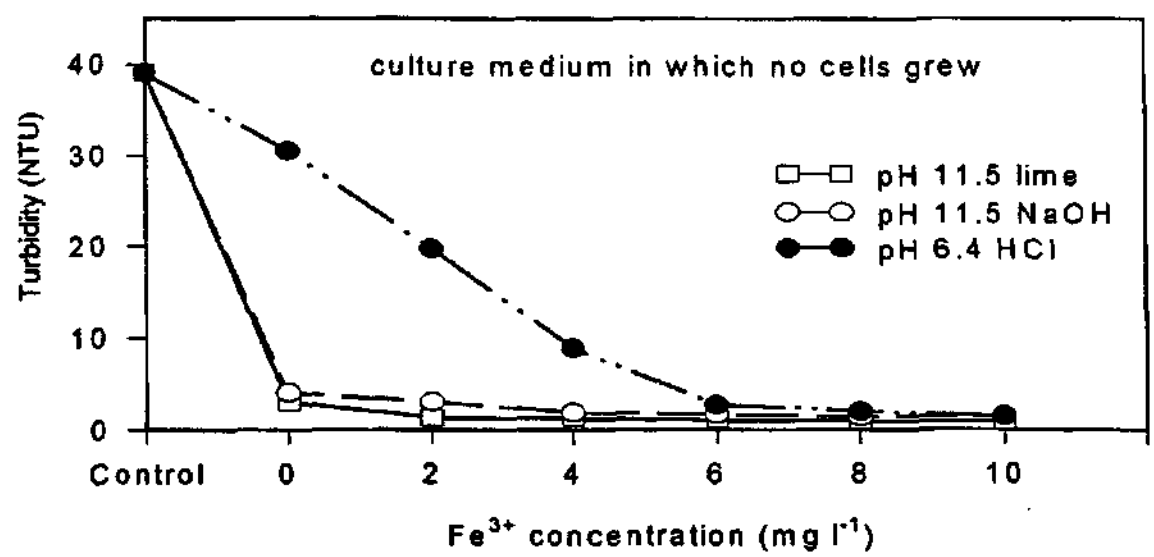


Figure 33. Variation in turbidity (NTU) with increased Fe^{3+} concentrations. Culture medium, in which no cells grew, was added to Vaal River water.

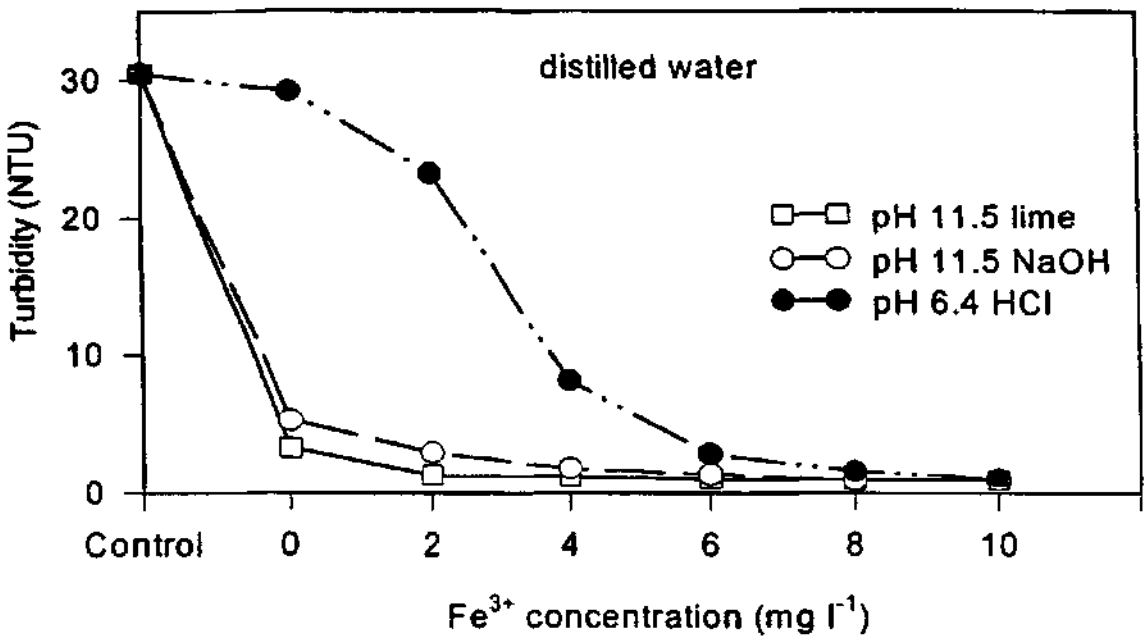


Figure 34. Variation in turbidity (NTU) with increased Fe^{3+} concentrations. Distilled water only was added to Vaal River water.

When culture medium in which cells grew (Fig. 32), culture medium in which no cells grew (Fig. 8I) or distilled water only (Fig. 34) was added to Vaal River water, effective removal at pH 6.4 occurred only when the flocculant concentration was higher than 6 mg l^{-1}. At pH 11.5, for both pH adjustment chemicals, the most effective removal was observed at iron concentrations higher or equal to 4 mg l^{-1} Fe^{3+}.

The following conclusions can be drawn to summarise observations on the removal of suspended solids when *M. minutum* cells were added to Vaal River water. When *M. minutum* cells were added as 60 µg l^{-1} chlorophyll-*a*, turbidity was 13 NTU units higher than the initial turbidity of the Vaal River water (30.2 NTU; Figs 30 and 31). When culture medium in which cells grew (Fig. 32) or did not grow (Fig. 8I) was added, turbidity was 8 NTUs higher than the initial Vaal River water. Therefore it is possible that turbidity was not only increased by algal cells, but also by the culture medium. When distilled water was added to Vaal River water, turbidity was unchanged. Figs 30 to 34 indicated that a pH of 11.5 was more

effective in the removal of suspended solids as was the case with chlorophyll-a. At pH 6.4 removal was ineffective, except when Fe^{3+} was dosed in high concentrations (6 mg l^{-1} and higher). At pH 11.5, when *M. minutum* cells together with culture medium in which they grew, was added to Vaal River water, little difference in the removal was observed compared to when NaOH or lime was added (Fig. 30).
When *M. minutum* cells suspended in culture medium in which they grew was added to Vaal River water (Fig. 30), better removal of suspended solids was observed at pH 11.5 (adjusted with NaOH) than when *M. minutum* cells suspended in distilled water was added to Vaal River water. Therefore, dissolved inorganic components of the nutrient medium or the excreted organic substances apparently assisted in flocculation of suspended solids.

When *M. minutum* cells suspended in culture medium in which they grew was added to Vaal River water (Fig. 30), removal of suspended solids was similar than when only the culture medium in which cells grew was added to Vaal River water. Therefore, *M. minutum* cells apparently did not affect removal of suspended solids.

When culture medium in which no cells grew was added to Vaal River water (Fig. 33), removal of suspended solids was similar than when distilled water only (Fig. 34) was added to Vaal River water. Therefore, inorganic components of the nutrient medium did not effect removal of suspended solids.

When culture medium in which cells grew was added to Vaal River water (Fig. 32), slightly better removal of suspended solids was observed than when culture medium in which no cells grew (Fig. 33) was added to Vaal River water. Therefore, organic substances excreted by the algal cells apparently assisted in removal of suspended matter.

Removal of dissolved organic carbon

The removal of dissolved organic carbon (DOC) when *M. minutum* cells were added to Vaal River water, are illustrated and discussed in the following paragraphs.

When *M. minutum* cells suspended in culture medium in which cells grew were added to Vaal River water, removal of DOC increases with increase in Fe^{3+} concentration and pH. At pH 6.4, the same removal as illustrated earlier occurred

(Figs 6 and b), i.e. at lower pH conditions, but if the removal is compared with pH 11.5 (when lime was used), it is clear that a pH of 11.5 gave slightly better removal of DOC (Fig. 35). The most effective removal occurred at pH 11.5 when lime was used and 4 mg l^{-1} and higher Fe^{3+} concentrations were used (Fig. 35).

When *M. minutum* cells were suspended in distilled water before being added to Vaal River water, the results of DOC removal (Fig. 36) appeared to be the same as when cells were suspended in culture medium in which cells grew (Fig. 35). The removal of DOC at pH 11.5 when lime was added as pH adjustment chemical was more effective, probably due to the possibility that DOC was not added together with the cells, or that organic matter was washed off the cells and that the cells adsorbed the natural occurring DOC of the Vaal River.

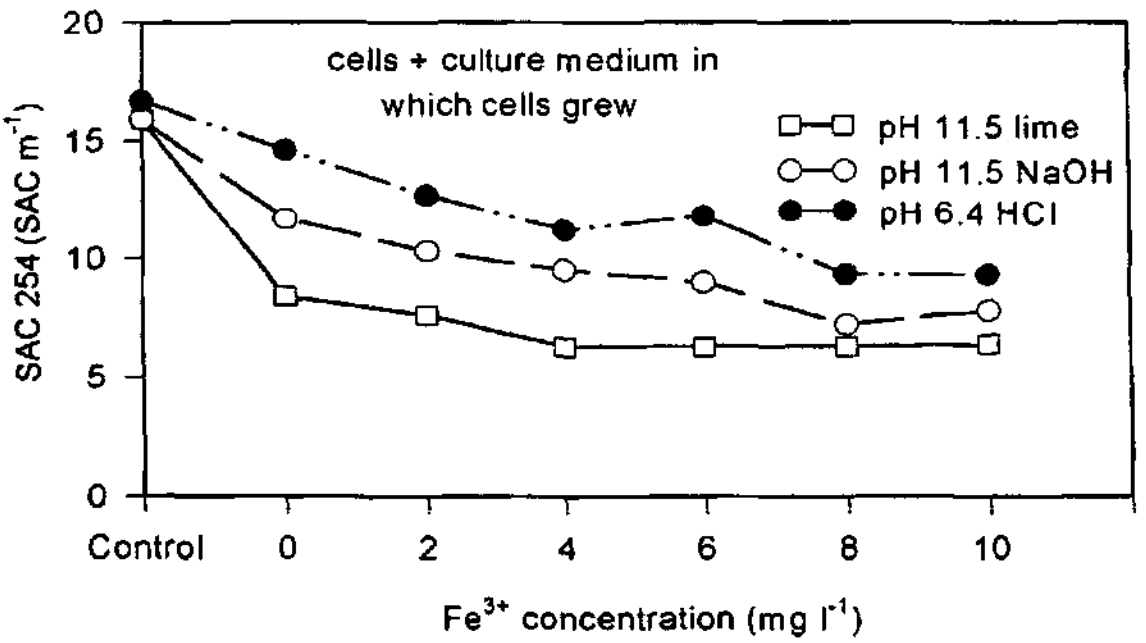


Figure 35. Variation in spectral absorption coefficient (SAC m^{-1}) with increased Fe^{3+} concentrations. *Monoraphidium minutum* cells, suspended culture medium in which cells grew, were added to Vaal River water.

When no *Monoraphidium* cells were added to Vaal River water, but only culture medium (Fig. 38) or distilled water (Fig. 39), the results differ greatly from when cells suspended in culture medium in which they grew were added to Vaal River

water (Fig 35) and when cells suspended in distilled water were added to Vaal River water (Fig. 36).

The removal of DOC was lower when *M. minutum* cells were not added to Vaal River water (Figs 37, 38 and 39). It appeared that pH had no effect on the removal of DOC. Increased Fe^{3+} concentrations increase the removal of DOC, and effective removal of DOC occurred only when 10 mg l^{-1} and higher Fe^{3+} concentrations were added (Figs 37, 38 and 39).

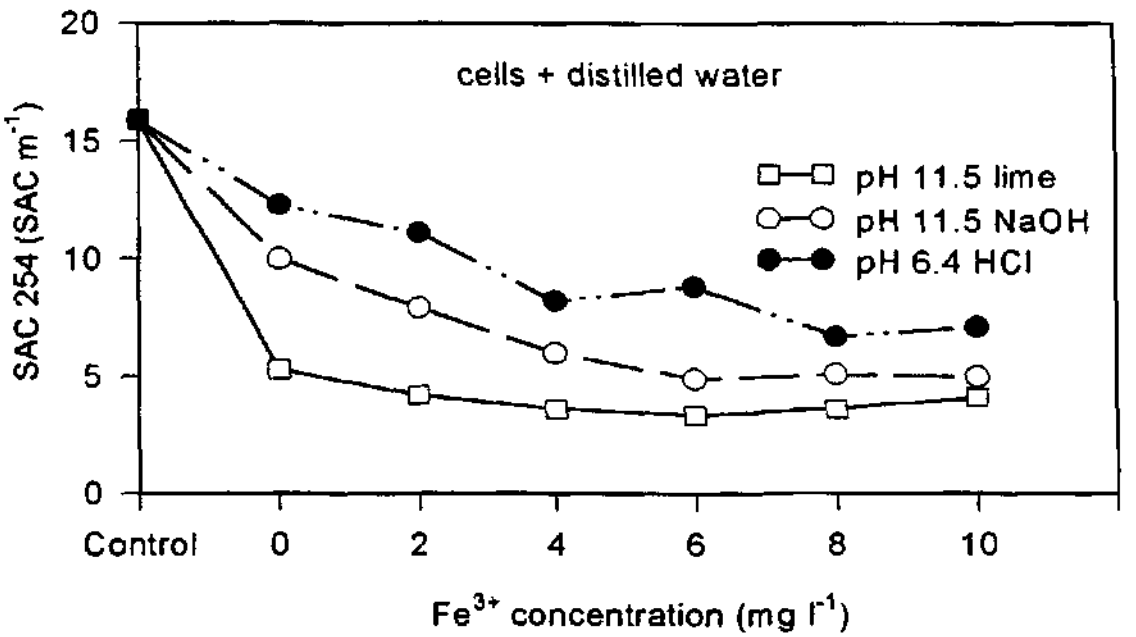


Figure 36. Variation in spectral absorption coefficient (SAC m^{-1}) with increased Fe^{3+} concentrations. *Monoraphidium minutum* cells, suspended in distilled water, were added to Vaal River water.

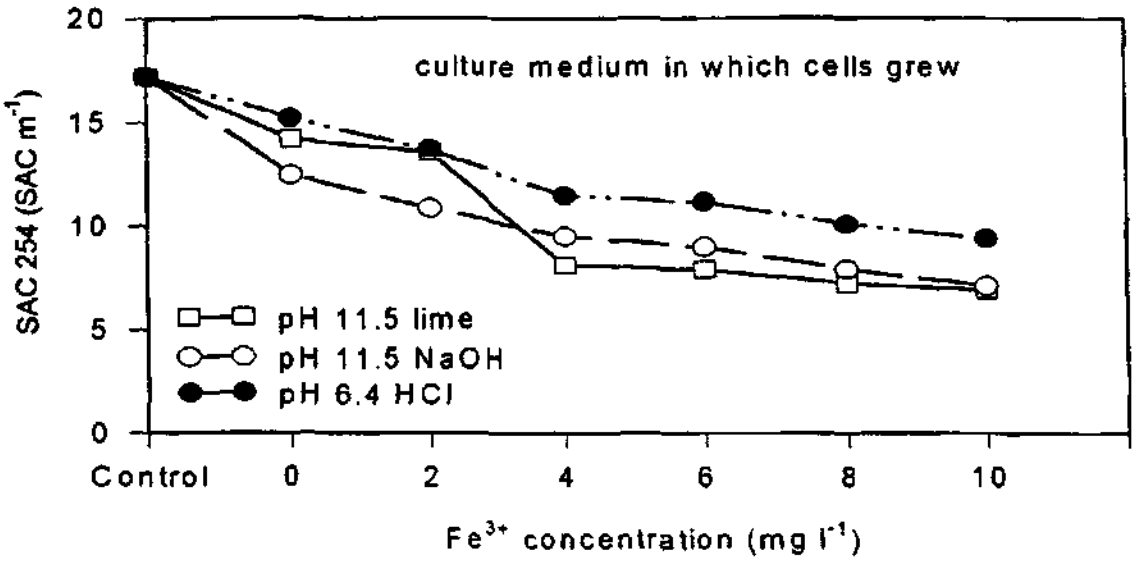


Figure 37. Variation in spectral absorption coefficient (SAC m^{-1}) with increased Fe^{3+} concentrations. Culture medium, in which *Monoraphidium minutum* cells grew, was added to Vaal River water.

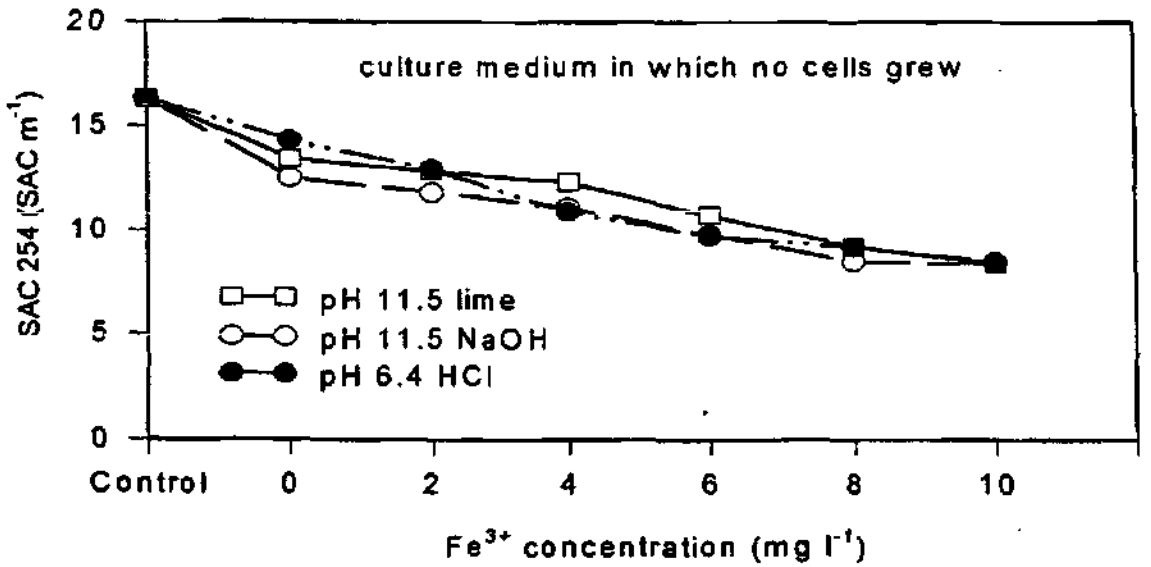


Figure 38. Variation in spectral absorption coefficient (SAC m^{-1}) with increased Fe^{3+} concentrations. Culture medium, in which no cells grew, was added to Vaal River water.

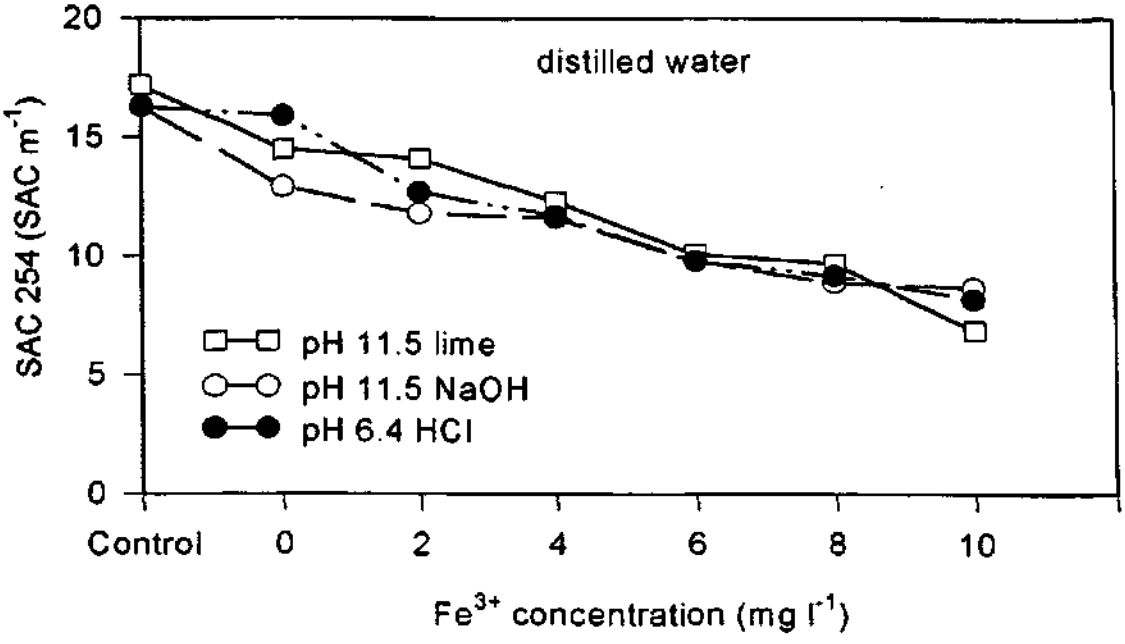


Figure 39. Variation in spectral absorption coefficient (SAC m^{-1}) with increased Fe^{3+} concentrations. Distilled water only was added to Vaal River water.

The following conclusions can be drawn to summarise observation on the removal of dissolved organic matter when *M. minutum* was added to Vaal River water. Figs 35 to 39 showed that in the initial Vaal River water SAC 254 values were little affected by the addition of *M. minutum* cells and culture medium in which cells grew. It was expected that SAC 254 would increase when algal cells and culture medium in which they grew, was added.

When *M. minutum* cells, suspended in culture medium in which they grew, was added to Vaal River water (Fig. 36), removal of DOC was better than when only culture medium in which cells grew was added to Vaal River water (Fig. 37). Therefore, *M. minutum* cells apparently assisted in the removal of DOC.

When culture medium in which no cells grew was added to Vaal River water (Fig. 38), removal of suspended solids was similar to when distilled water only (Fig. 39) was added to Vaal River water. Therefore, inorganic components of the nutrient medium apparently did not affect removal of DOC.

When culture medium in which cells grew was added to Vaal River water (Fig. 37), similar removal of DOC was observed than when culture medium in which no cells grew (Fig. 38) was added to Vaal River water. Therefore, organic substances excreted by the algal cells apparently did not affect the removal of DOC.

The effect of *Cyclotella meneghiniana* cells on caogulation and flocculation

The aim of this experiment was to determine what effect added *C. meneghiniana* cells (representing a *C. meneghiniana* dominance under natural conditions) had on flocculation processes

Cyclotella meneghiniana cells grown in culture (concentrated so that 7.5 ml contains approximately 30 µg l^{-1} chlorophyll-*a*) were added to Vaal River water. The chlorophyll-*a* concentration of the raw water was fairly low, and the turbidity values were high, caused by fine silt particles.

Removal of biomass (i.e. chlorophyll-*a*)

When the pH was adjusted to 6.4 with HCl, small flocs formed initially, but the floc size increased with time during the flocculation or slow mixing (40 rpm) period. When pH was adjusted with either NaOH or lime to 11.5, larger flocs formed immediately.

When *C. meneghiniana* and culture medium in which cells grew were added to Vaal River water (Fig. 40) and the pH was adjusted to 6.4 with HCl, almost no removal of chlorophyll-*a* occurred. When flocculant (Fe^{3+}) was added, chlorophyll-*a* concentration decreased with increased Fe^{3+} concentrations. The removal of chlorophyll-*a* was, however, effective only when high (>8 mg l^{-1}) Fe^{3+} concentrations were added (Fig. 40). The removal of *C. meneghiniana* was, however, better than the removal of *Monoraphidium minutum* at similar conditions (see Fig. 25). With the adjustment of pH to 11.5 with either lime or NaOH, total removal of chlorophyll-*a* occurred.

When *C. meneghiniana* cells were suspended in distilled water and then added to Vaal River water (Fig. 41), the results appeared to be the same as when cells were suspended in culture medium in which cells grew before added to Vaal River water (Fig. 40). At pH 6.4 removal increased together with increase in Fe^{3+} concentration; total removal of chlorophyll-*a* occurred when 8 mg l^{-1} and higher

Fe^{3+} was dosed. When the pH was adjusted to 11.5 with NaOH, chlorophyll-*a* was not removed completely, but when flocculant was added, total removal occurred. At pH 11.5, when lime was used as pH adjustment chemical, total removal, even without flocculant, was observed (Fig. 41).

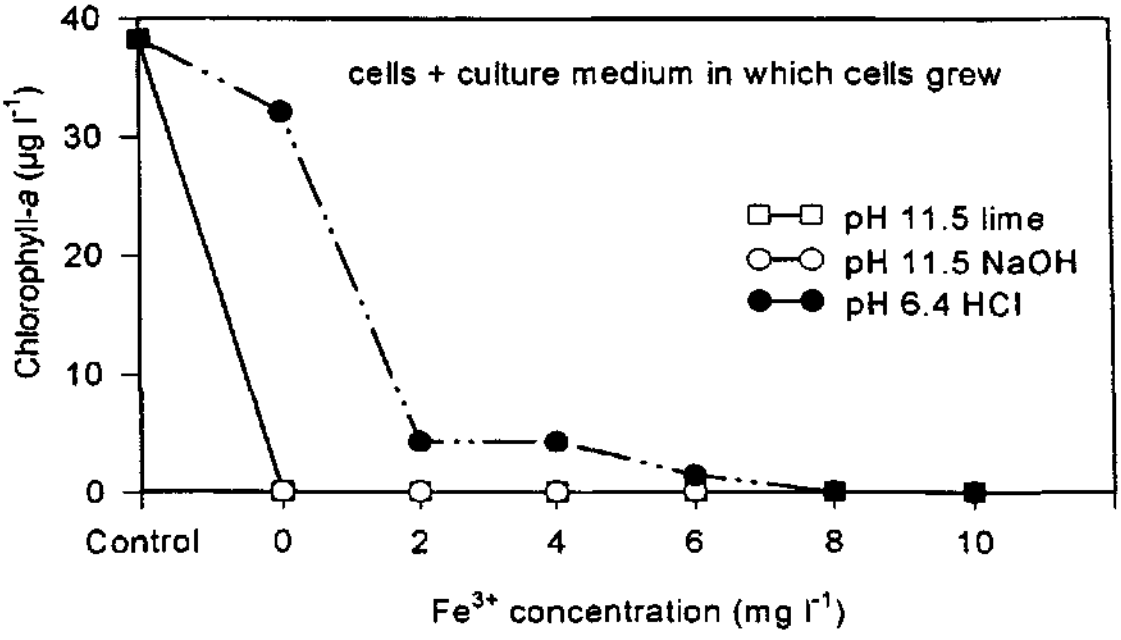


Figure 40. Variation in chlorophyll-a concentration (µg l^{-1}) with increased Fe^{3+} concentrations. *Cyclotella meneghiniana* cells, suspended in culture medium in which cells grew, were added to Vaal River water.

When culture medium in which the cells grew was added to Vaal River water (Fig. 42), the removal was more or less the same as when cells were added (Fig. 40), but the initial chlorophyll-a values were less due to the fact that no algal cells were added to the Vaal River water. The algal cells that were present in the raw water was, however, removed inefficiently at pH 6.4 when low Fe^{3+} concentrations were added (2 mg l^{-1}). Total removal of chlorophyll occurred when the pH was adjusted to 11.5.

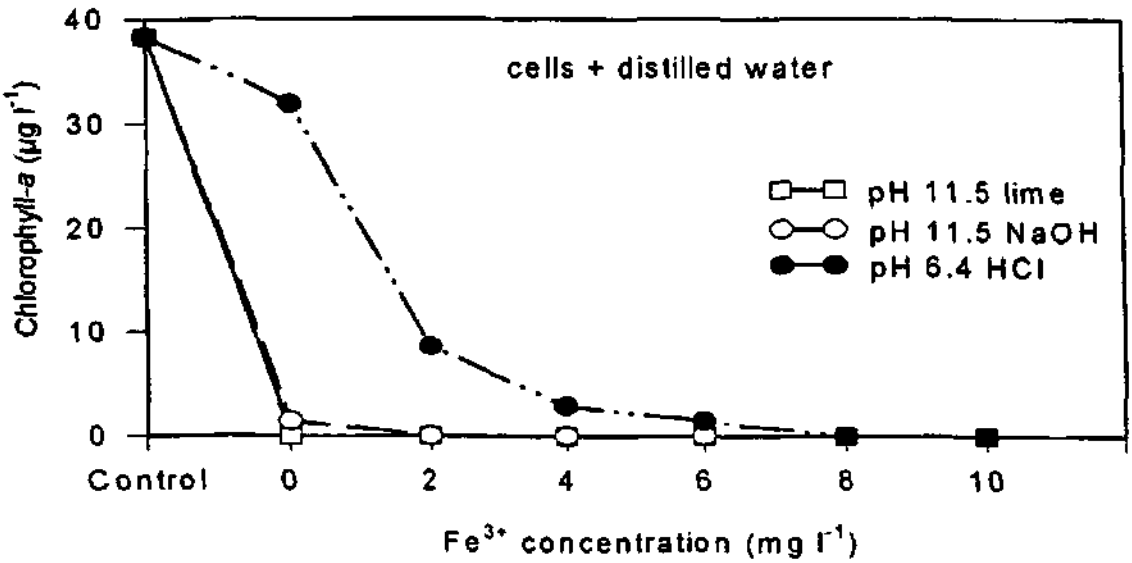


Figure 41. Variation in chlorophyll-a concentration (µg l^{-1}) with increased Fe^{3+} concentrations. *Cyclotella meneghiniana* cells, suspended in distilled water, were added to Vaal River water.

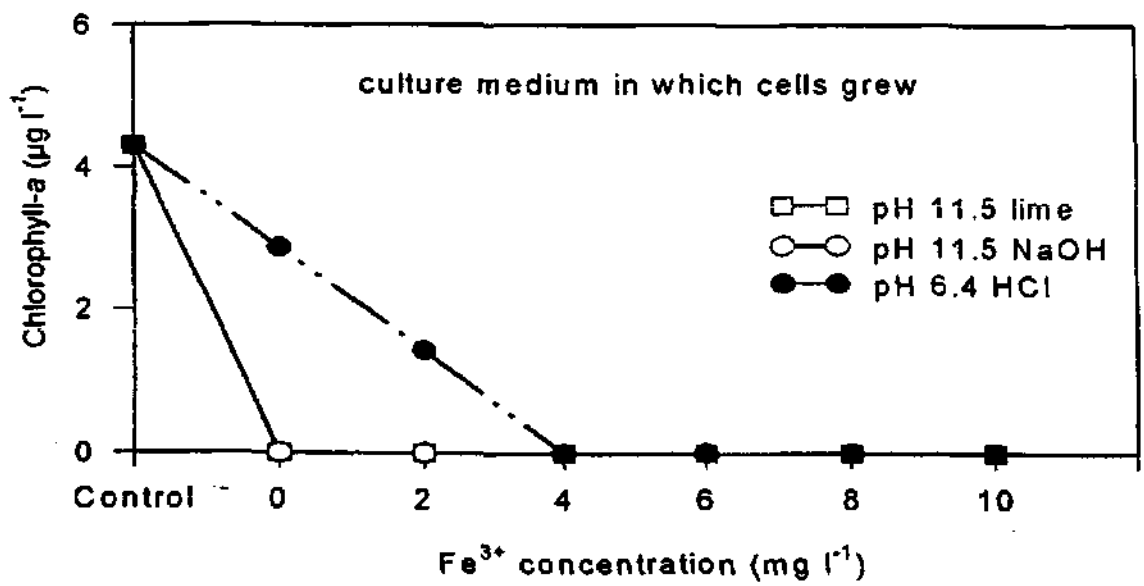


Figure 42. Variation in chlorophyll-a concentration (µg l^{-1}) with increased Fe^{3+} concentrations. Culture medium, in which *Cyclotella meneghiniana* cells grew, was added to Vaal River water.

Because of the fact that there were only small amounts of chlorophyll-*a* present in the raw water, and because the chlorophyll-*a* was effectively removed with the addition of chemicals, the effect of the different treatments could not be illustrated clearly. Fig. 43 represent results obtained for the treatments where culture medium in which cells did not grow, as well as when distilled water were added. The chlorophyll-*a* that was present, was effectively removed.

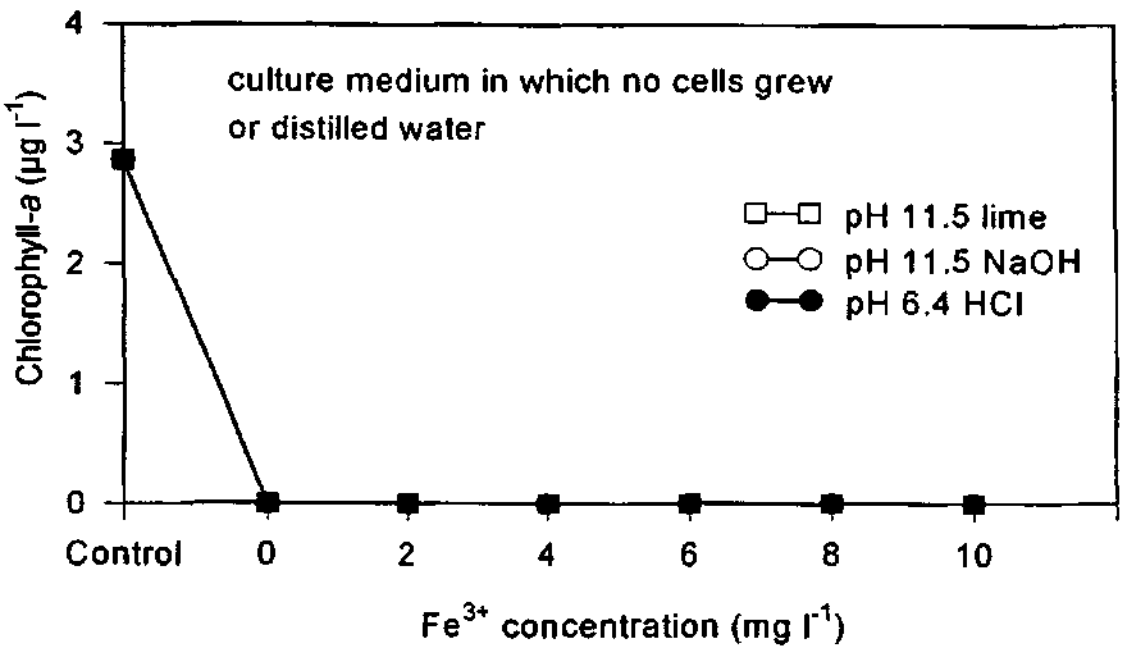


Figure 43. Variation in chlorophyll-a concentration (µg l^{-1}) with increased Fe^{3+} concentrations. Either culture medium, in which no cells grew, or distilled water was added to Vaal River water.

The following conclusions can be drawn to summarise observations on the removal of chlorophyll-*a* when *Cyclotella meneghiniana* cells were added to Vaal River water. The addition of *C. meneghiniana* cells increased the chlorophyll-*a* concentration with approximately 30 µg l^{-1}. The increased chlorophyll-*a* was less efficiently removed at pH 6.4 when lower iron concentrations (< 6 mg l^{-1}) was added (Figs 40 and 41).

When *C. meneghiniana* were suspended in culture medium in which cells grew or in distilled water, and added to Vaal River water, chlorophyll-*a* was removed when

the pH was adjusted to 11.5 (Figs 40 and 41). This removal at pH 11.5 indicates that *C. meneghiniana* can easily be removed at this pH.

When *C. meneghiniana* cells suspended in culture medium in which they grew was added to Vaal River water (Fig. 40), similar removal of chlorophyll-*a* was observed than when *C. meneghiniana* cells suspended in distilled water (Fig.41) was added to Vaal River water. Therefore, dissolved inorganic components of the nutrient medium or the excreted organic substances possibly did not affect in flocculation.

When *C. meneghiniana* cells suspended in culture medium in which they grew was added to Vaal River water (Fig. 40), removal of chlorophyll-*a* was similar at pH 11.5 and slightly poorer at pH 6.4 than when culture medium in which cells grew (Fig. 42) was added to Vaal River water. Therefore, *C. meneghiniana* cells did not affect removal of chlorophyll-*a* at pH 11.5. At pH 6.4, *C. meneghiniana* cells were inefficiently removed.

When culture medium in which no cells grew was added to Vaal River water (Fig. 43), removal of chlorophyll-*a* was similar to when distilled water only (Fig. 43) was added to Vaal River water. Therefore, inorganic components of the nutrient medium did not affect removal of chlorophyll-*a*.

When culture medium in which cells grew was added to Vaal River water (Fig. 42), slightly poorer removal of chlorophyll-*a* was observed at pH 6.4 than when culture medium in which no cells grew (Fig. 43) was added to Vaal River water. Therefore, organic substances excreted by the algal cells inhibited the removal of chlorophyll-*a* at pH 6.4. At pH 11.5, when culture medium in which cells grew were added to Vaal River water (Fig. 42), removal of chlorophyll-a was similar than when culture medium in which no cells grew (Fig. 43) were added to Vaal River water. Therefore, organic substances excreted by the algal cells did not affect the removal of chlorophyll-*a* at pH 11.5.

When the chlorophyll-*a* concentrations was low (approximately 4 μg l^{-1}), chlorophyll-*a* was effectively removed with the addition of Fe^{3+} (2 mg l^{-1} and higher concentrations) at pH 6.4 and pH 11.5 (Fig. 43).

Removal of suspended solids

Although the initial turbidity was high, the removal of suspended solids were generally effective (Figs. 44-9l). Removal was generally less effective at pH 6.4.

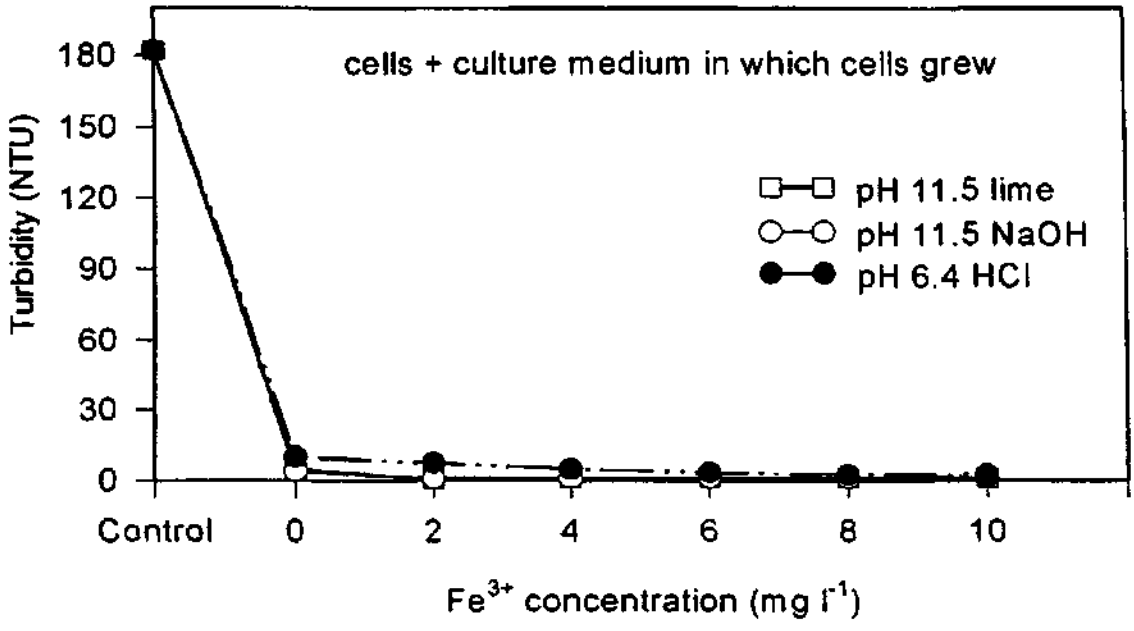


Figure 44. Variation in turbidity (NTU) with increased Fe^{3+} concentrations. *Cyclotella meneghiniana* cells, suspended in culture medium in which cells grew, were added to Vaal River water.

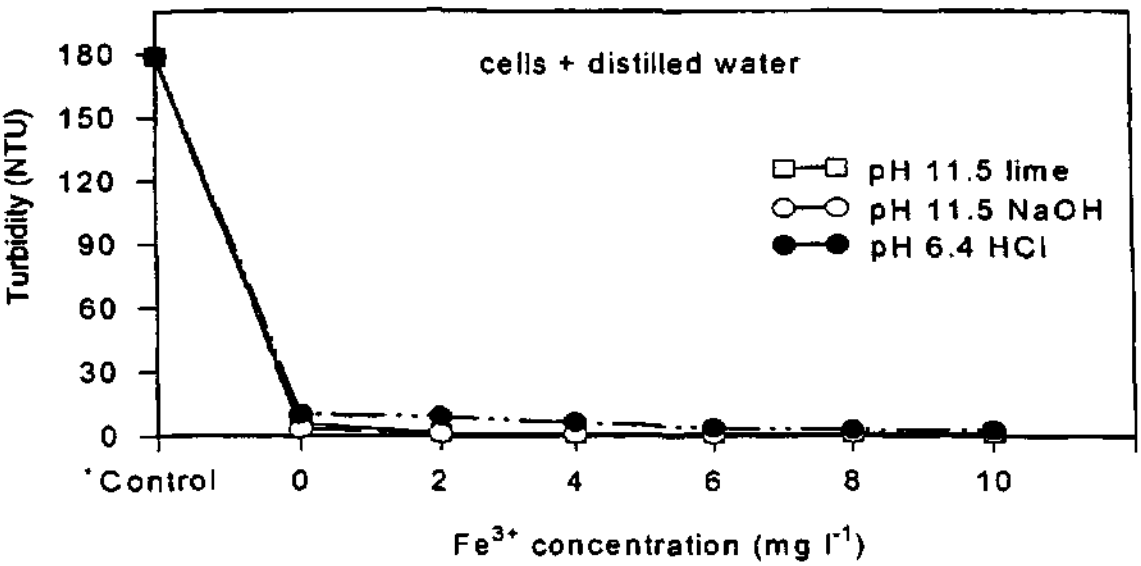


Figure 45. Variation in turbidity (NTU) with increased Fe^{3+} concentrations. *Cyclotella meneghiniana* cells, suspended in distilled water, were added to Vaal River water.

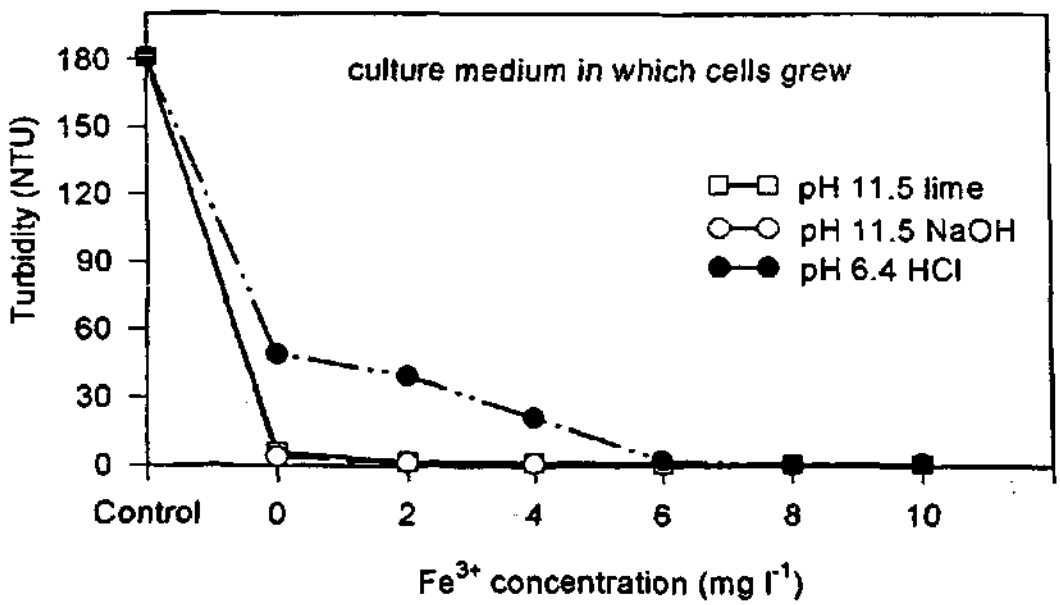


Figure 46. Variation in turbidity (NTU) with increased Fe^{3+} concentrations. Culture medium, in which *C. meneghiniana* cells grew, was added to Vaal River water.

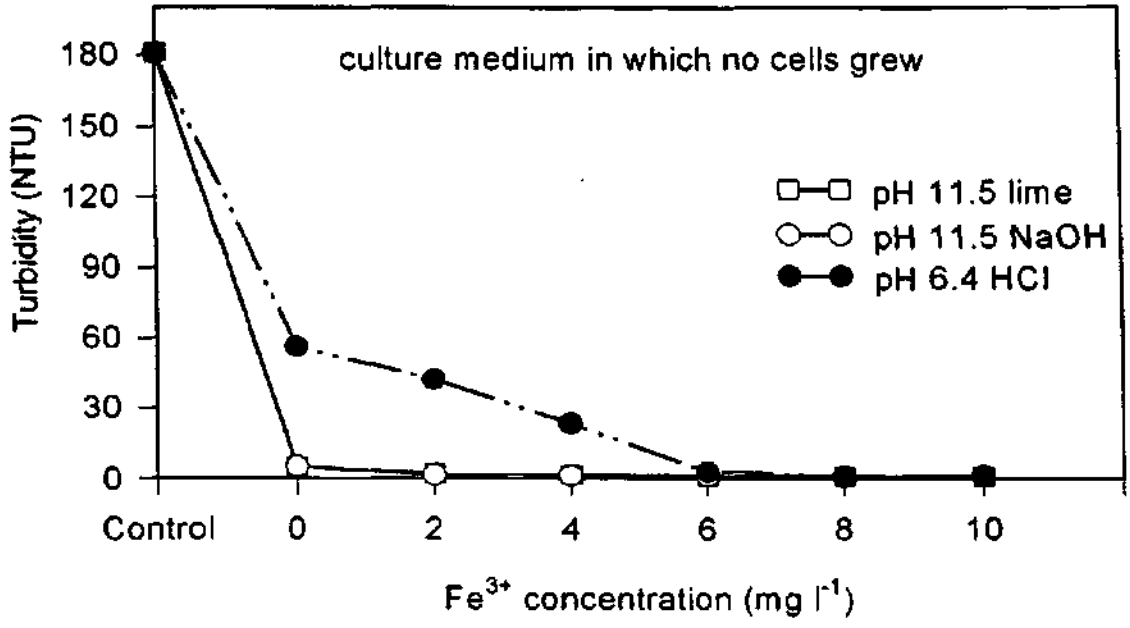


Figure 47. Variation in turbidity (NTU) with increased Fe^{3+} concentrations. Culture medium, in which no cells grew, was added to Vaal River water.

When culture medium in which cells grew, culture medium in which no cells grew or distilled water only was added to Vaal River water and the pH was adjusted to 6.4, only high Fe^{3+} concentrations (> 6 mg l^{-1}) removed suspended particles (Figs 46, 47 and 48). During the jar tests, almost no flocs were formed when low iron concentrations were dosed (i.e. 2-4 mg l^{-1}). This poor formation of flocs were usually observed at pH 6.4 when the turbidity was high.

When the pH was adjusted to 11.5 with either lime or NaOH, effective removal of suspended matter occurred, even without the addition of $FeCl_3$ (Figs 47 to 48)

The following conclusions can be drawn to summarise observations on the removal of suspended solids when *C. meneghiniana* cells were added to Vaal River water. When *C. meneghiniana* cells were added as 30 µg l^{-1} chlorophyll-*a*, or when culture medium was added to Vaal River water, the initial Vaal River water turbidity remained unchanged. It is possible that the high concentration of suspended solids in the Vaal River water was the reason why the turbidity remained unchanged. Figs 44 to 48 indicated that pH 11.5 played an important part in the

removal of suspended solids as was the case when *M. minutum* cells were added (Figs 30 to 34). pH 6.4 was ineffective in the removal of suspended matter except when high Fe^{3+} (> 6 mg l^{-1}) was added. Effective removal occurred at pH 11.5 at increased Fe^{3+} concentrations, and little difference was observed when NaOH or lime was added.

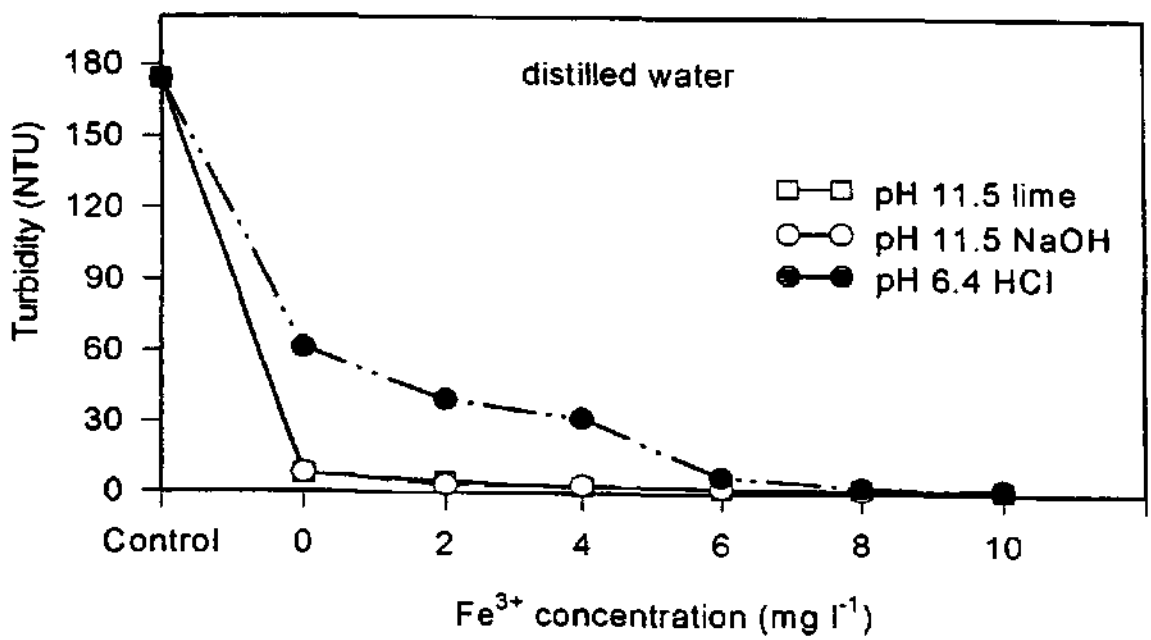


Figure 48. Variation in turbidity (NTU) with increased Fe^{3+} concentrations. Distilled water only was added to Vaal River water.

When algal cells suspended in culture medium in which they grew (Fig. 44) or distilled water (Fig. 45) were added to Vaal River water, suspended solids was more effectively removed at pH 6.4 than when culture medium without cells (Fig. 46) or distilled water only (Fig. 48) was added to Vaal River water. This indicates that *C. meneghiniana* cells possibly assist in the removal of suspended solids at pH 6.4.

When culture medium in which no cells grew was added to Vaal River water (Fig. 47), removal of suspended solids was similar to when distilled water only (Fig. 48) was added to Vaal River water. Therefore, inorganic components of the nutrient medium apparently did not affect removal of suspended solids.

When culture medium in which cells grew was added to Vaal River water (Fig. 46), similar removal of suspended solids was observed than when culture medium in which no cells grew (Fig. 47) was added to Vaal River water. Therefore, organic substances excreted by the algal cells did not assist in removal of suspended matter.

Removal of dissolved organic carbon

The removal of DOC was effective when *C. meneghiniana* cells were added to Vaal River water. SAC values of less than 3 SAC m^{-1} were obtained when the pH was adjusted to 11.5 with lime.

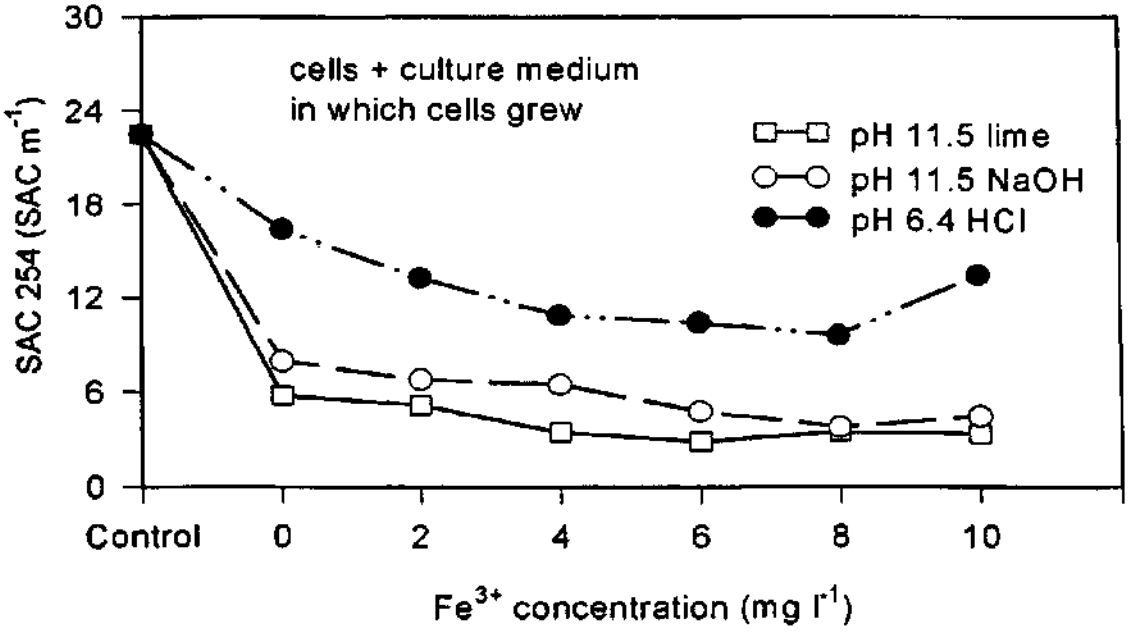


Figure 49. Variation in spectral absorption coefficient (SAC m^{-1}) with increased Fe^{3+} concentrations. *Cyclotella meneghiniana* cells, suspended in culture medium in which cells grew, were added to Vaal River water.

When *C. meneghiniana* cells and culture medium in which cells grew were added to Vaal River water, and the pH adjusted to 6.4, the removal of DOC was ineffective compared to the removal at a pH of 11.5 (Fig. 49). When the pH was adjusted to

11.5, very low SAC values were obtained. When *C. meneghiniana* cells were suspended in distilled water and added to Vaal River water, effective removal was observed, except when pH was adjusted to 6.4 (Fig. 50).

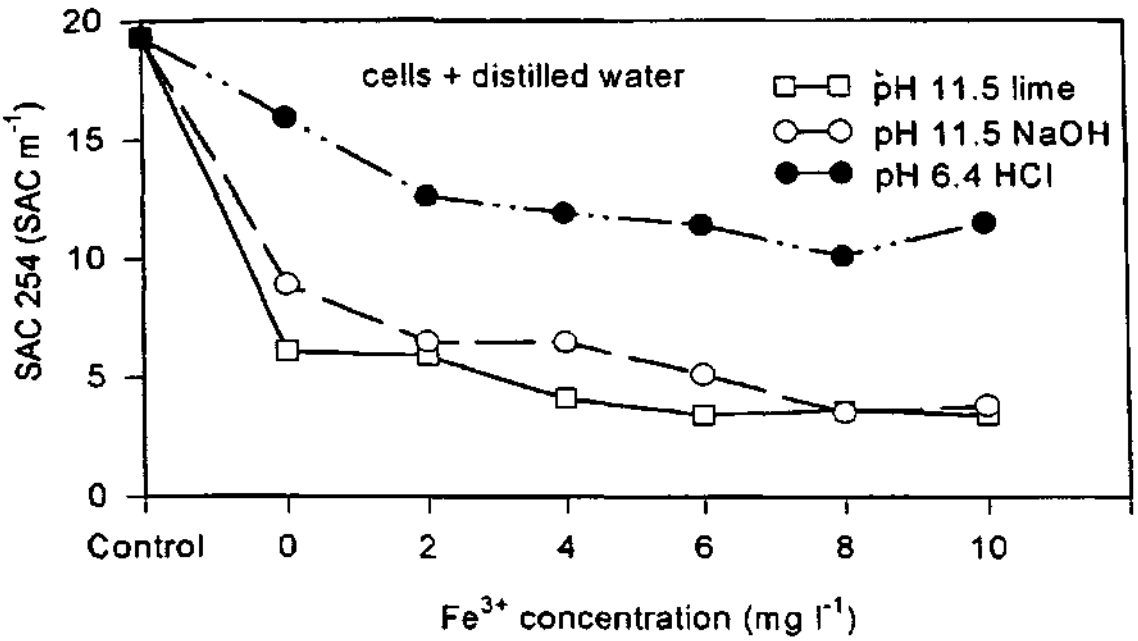


Figure 50. Variation in spectral absorption coefficient (SAC m^{-1}) with increased Fe^{3+} concentrations. *Cyclotella meneghiniana* cells, suspended in distilled water, were added to Vaal River water.

When culture medium in which the cells grew (Fig. 51), culture medium in which no cells grew (Fig. 52) or distilled water (Fig. 53) was added to Vaal River water, the removal of DOC increased at pH 6.4 when higher iron concentrations (> 6 mg l^{-1}) were added. When culture medium in which cells grew was added to Vaal River water (Fig. 51), removal was still effective at pH 11.5 when lime was used as pH adjustment chemical and high Fe^{3+} concentrations (> 6 mg l^{-1}) were added.

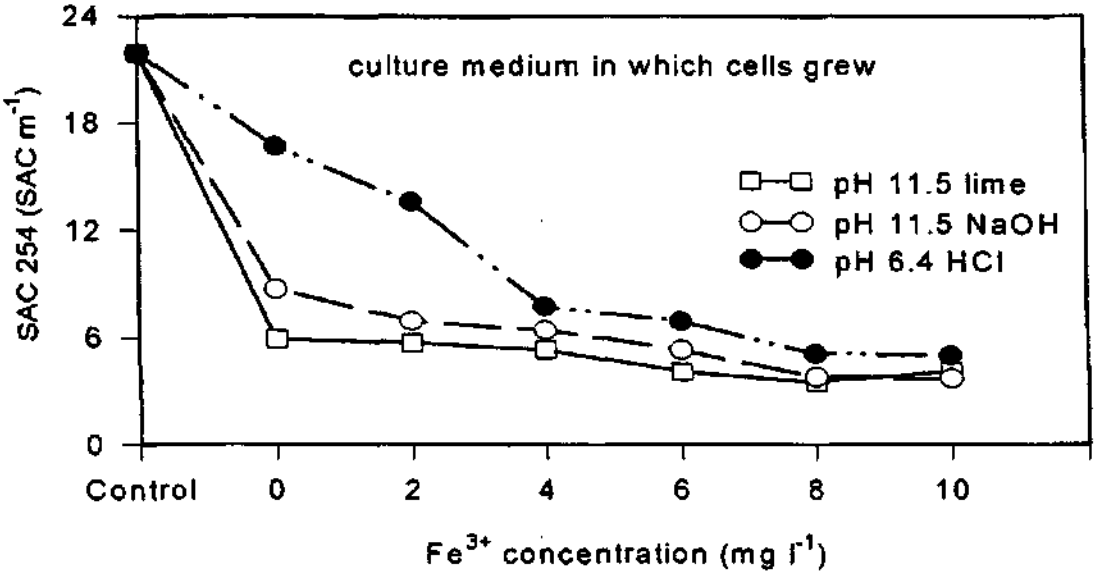


Figure 51. Variation in spectral absorption coefficient (SAC m^{-1}) with increased Fe^{3+} concentrations. Culture medium, in which *C. meneghiniana* cells grew, was added to Vaal River water.

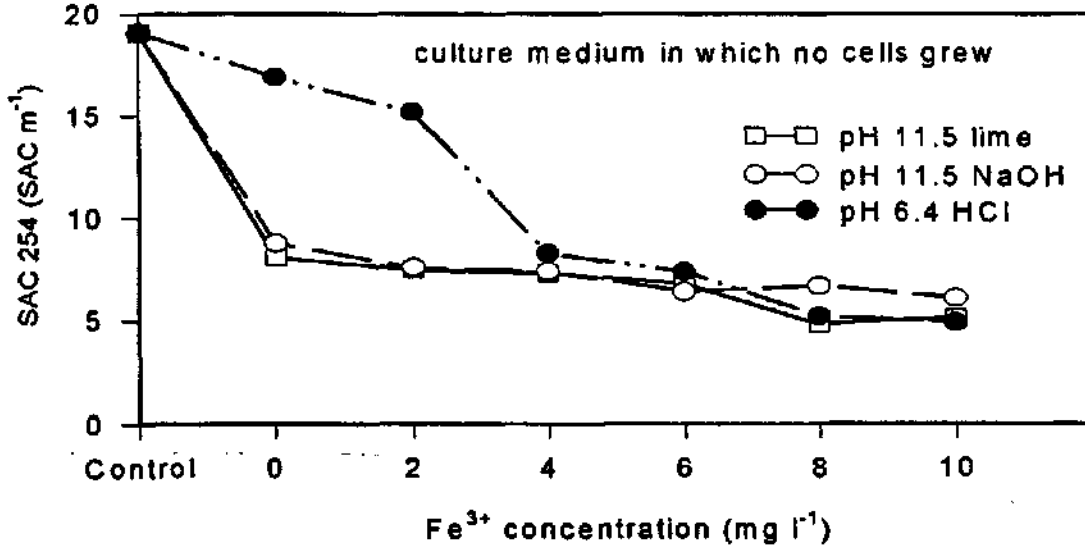


Figure 52. Variation in spectral absorption coefficient (SAC m^{-1}) with increased Fe^{3+} concentrations. Culture medium, in which no cells grew, was added to Vaal River water.

When culture medium in which no cells grew (Fig. 52) or distilled water (Fig. 53) was added to Vaal River water the removal of DOC was ineffective at pH 11.5 when compared with the situation when algal cells were added to Vaal River water (see Figs 49 and 50). When the pH was adjusted to 6.4 and Fe^{3+} concentration was higher than 4 mg l^{-1} (Figs 51, 52 and 53), effective removal of DOC was observed.

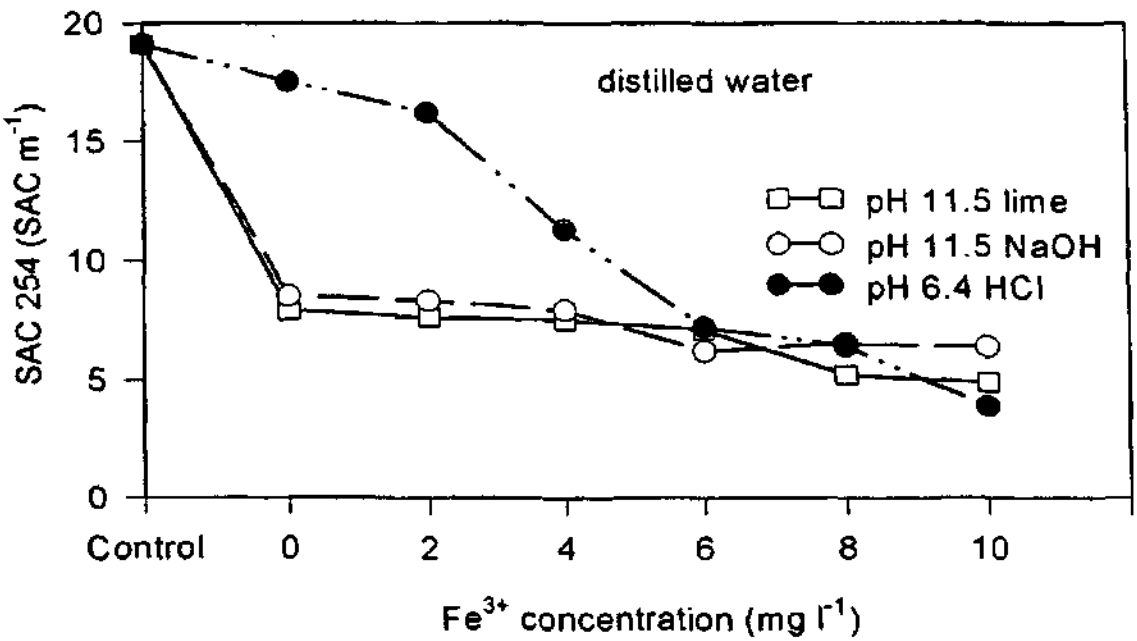


Figure 53. Variation in spectral absorption coefficient (SAC m^{-1}) with increased Fe^{3+} concentrations. Distilled water only was added to Vaal River water.

The following conclusions can be drawn to summarise observations on the removal of DOC when *C. meneghiniana* cells were added to Vaal River water. Figs 49 and 51 showed that the initial Vaal River SAC 245 values were increased by approximately 5 units when culture medium in which cells grew were added to Vaal River water.

When *C. meneghiniana* cells suspended in culture medium were added to Vaal River water (Figs 49), DOC was similarly removed at pH 11.5 than when culture medium in which cells grew (Fig. 51) was added. At pH 6.4 better removal was observed when no cells were added This ineffective removal at pH 6.4 when cells

were present, was possibly caused by specific characteristics of *C. meneghiniana* cells.

When *C. meneghiniana* cells suspended in distilled water were added to Vaal River water (Fig. 50), DOC was better removed at pH 11.5 than when distilled water only (Fig. 53) was added. Therefore, *C. meneghiniana* possibly assisted in the removal of DOC at pH 11.5. At pH 6.4 better removal was observed when no cells were added. Therefore, removal of DOC was inhibited at pH 6.4 when *C. meneghiniana* cells were present.

When culture medium in which no cells grew was added to Vaal River water (Fig. 52), removal of DOC was similar to when distilled water only (Fig. 53) was added to Vaal River water. Therefore, inorganic components of the nutrient medium apparently did not affect the removal of DOC.

When culture medium in which cells grew was added to Vaal River water (Fig. 51), better removal of DOC was observed than when culture medium in which no cells grew (Fig. 52) was added to Vaal River water. Therefore, organic substances excreted by the algal cells possibly assisted in removal of natural occurring DOC in Vaal River water.

At pH 6.4 ineffective removal of DOC occurred when cells (suspended in culture medium or distilled water) were added to Vaal River water. At pH 11.5 effective removal of DOC was observed. Thus pH 6.4 and pH 11.5 had an effect on the removal of DOC.

When culture medium in which cells grew (Fig. 51) or no cells grew (Fig. 52) or distilled water only (Fig. 53), were added to Vaal River, the removal of DOC was ineffective at pH 6.4 when low Fe^{3+} concentrations (2 mg l^{-1}) were added. At pH 11.5 effective removal of DOC occurred.

The effect of *Pandorina morum* colonies on coagulation and flocculation

The aim of this experiment was to determine what effect added *P. morum* colonies (representing a *P. morum* dominance under natural conditions) had on flocculation processes.

P. morum colonies suspended in culture medium in which they grew (concentrated so that 5.0 ml culture medium contains approximately 60 µg l^{-1} chlorophyll-*a*), the same concentration suspended in distilled water, culture medium without colonies in which the colonies grew, culture medium in which no colonies grew and distilled water only, were added to Vaal River water. The chlorophyll-*a* concentrations of the raw water was increased to ± 67 µg l^{-1}.

Removal of biomass (i.e. chlorophyll-*a*)

When *P. morum* colonies suspended in culture medium in which they grew were added to Vaal River water (Fig 54), and the pH was adjusted to 11.5 with lime, total removal of chlorophyll-*a* was observed. When the pH was adjusted with NaOH, low chlorophyll-*a* concentration was observed when 2 mg l^{-1} iron was added, but total removal occurred at higher iron concentrations. At pH 6.4, chlorophyll-*a* was effectively removed with the addition of high iron (> 6 mg l^{-1}) concentrations (Fig. 54). The removal was, however, better than the removal of *Monoraphidium minutum* at similar conditions (see Fig. 25).

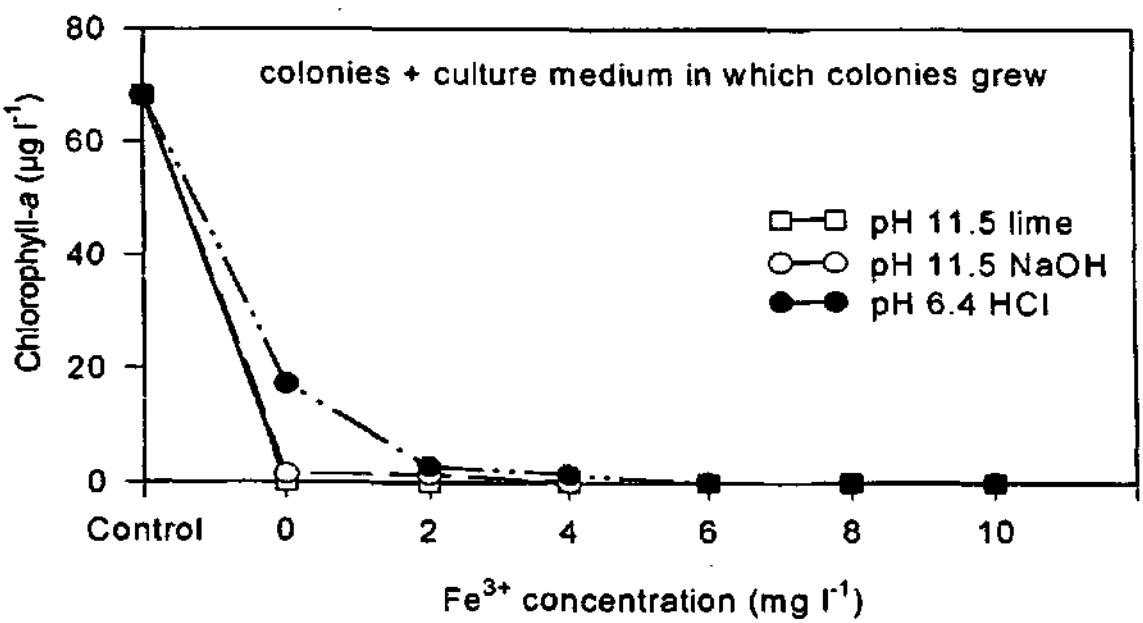


Figure 54. Variation in chlorophyll-a concentration (µg l^{-1}) with increased Fe^{3+} concentrations. *Pandorina morum* colonies, suspended in culture medium in which colonies grew, were added to Vaal River water.

When *P. morum* colonies were suspended in distilled water and added to Vaal River water (Fig. 55), the same removal occurred as when colonies suspended in culture medium in which they grew were added to Vaal River water (Fig. 54), except that chlorophyll-a was completely removed when the pH was adjusted to 11.5 with NaOH and iron was added.

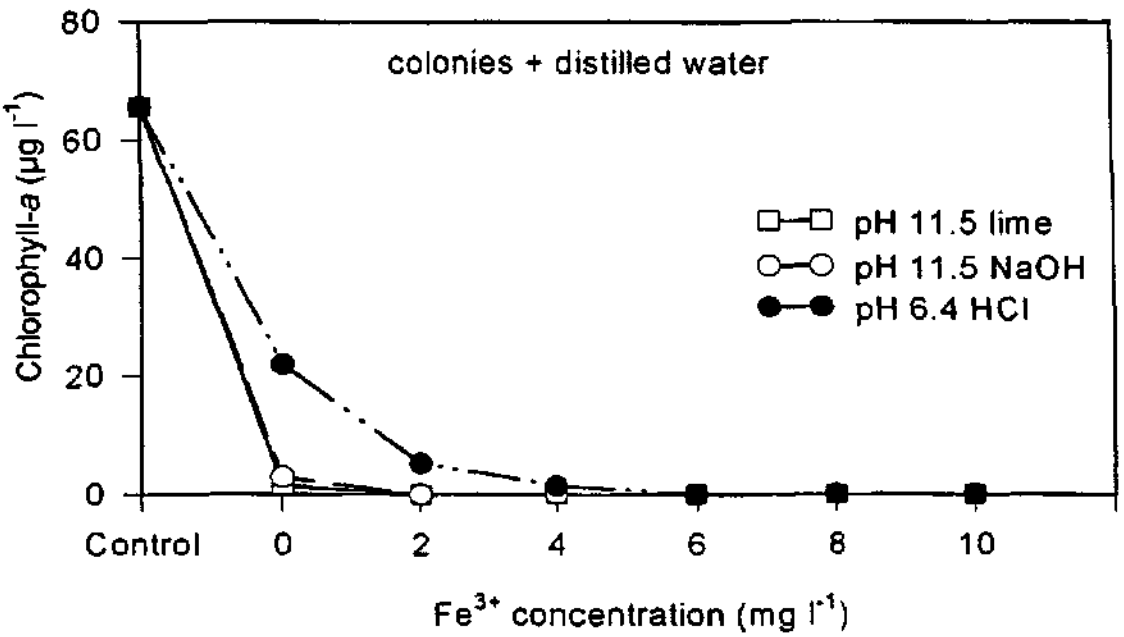


Figure 55. Variation in chlorophyll-a concentration (µg l^{-1}) with increased Fe^{3+} concentrations. *Pandorina morum* colonies, suspended in distilled water, were added to Vaal River water.

When culture medium in which colonies grew was added to Vaal River water (Fig. 56) of which the chlorophyll-*a* concentration was low, effective removal of chlorophyll-*a* occurred when the pH was adjusted to 11.5 with lime. At pH 11.5, when NaOH was added, chlorophyll-a was effectively removed when iron was added at concentrations higher than 2 mg l^{-1}. At pH 6.4 effective removal was observed when Fe^{3+} concentrations were higher than 4 mg l^{-1}.

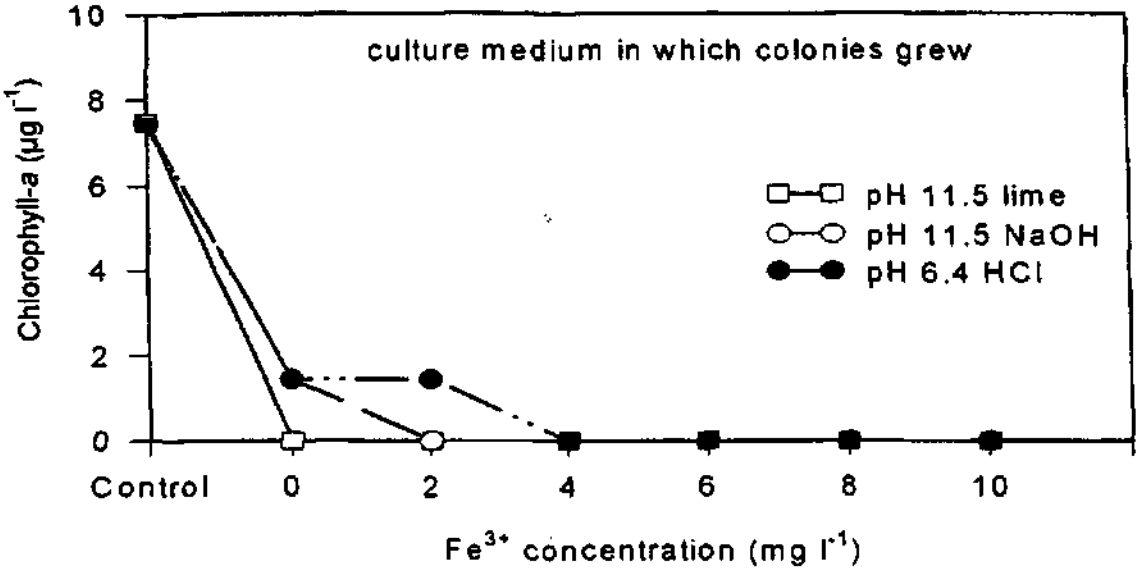


Figure 56. Variation in chlorophyll-a concentration (µg l^{-1}) with increased Fe^{3+} concentrations. Culture medium, in which *Pandorin morum* colonies grew, was added to Vaal River water.

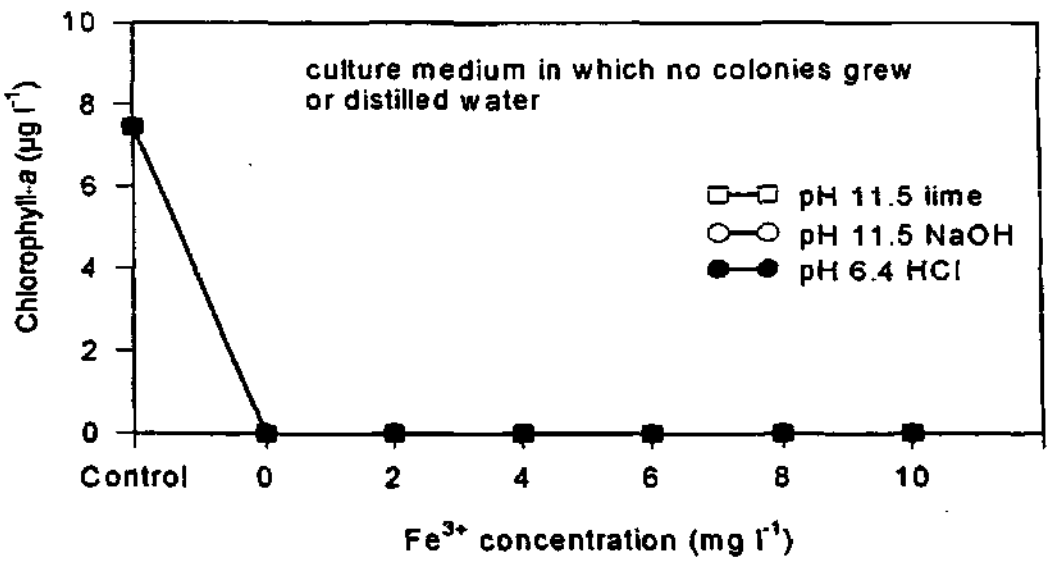


Figure 57. Variation in chlorophyll-a concentration (µg l^{-1}) with increased Fe^{3+} concentrations. Either culture medium, in which no colonies grew, or distilled water was added to Vaal River water.

Due to the fact that there were only small amounts of chlorophyll-*a* present in the raw Vaal River water, and that these chlorophyll-*a* was effectively removed by the addition of different chemicals, the effect of the different treatments could not be illustrated. Fig. 57 represents the results obtained for the treatments where culture medium in which no colonies grew or when distilled water were added. The chlorophyll-*a* that was present, was effectively removed.

The following conclusions can be drawn to summarise observations on the removal of chlorophyll-*a* when *Pandorina morum* colonies were added to Vaal River water. The addition of *P. morum* colonies increased the chlorophyll-a concentrations with approximately 60 µg l^{-1}. This increase in chlorophyll-*a* was less efficiently removed at pH 6.4 when lower iron concentrations (< 4 mg l^{-1}) were added (Figs 54 and 55).

When *P. morum* colonies suspended in culture medium in which colonies grew were added to Vaal River water, chlorophyll-*a* was effectively removed when the pH was adjusted to 11.5 (Fig. 54) and increased Fe^{3+} concentrations (> 2 mg l^{-1}) were added. When culture medium in which colonies grew (Fig. 56) was added to Vaal River water, removal was better when *P. morum* colonies suspended in culture medium in which the colonies grew, were added to Vaal River water (Fig. 54). Therefore, *P. morum* colonies apparently inhibited the removal of chlorophyll-*a*, or were removed less efficiently, probably because of the ability to move.

When *P. morum* colonies suspended in distilled water (Figs 55) were added to Vaal River water, chlorophyll-*a* was removed less efficiently than when distilled water only (Fig. 57) was added. Therefore, as already shown, *P.morum* colonies apparently inhibited the removal of chlorophyll-*a*.

When culture medium in which no colonies grew was added to Vaal River water (Fig. 57), removal of chlorophyll-*a* was similar than when distilled water only (Fig. 57) was added to Vaal River water. Therefore, inorganic components of the nutrient medium did not affect removal of chlorophyll-*a*.

When culture medium in which colonies grew was added to Vaal River water (Fig. 56), slightly poorer removal of chlorophyll-*a* was observed than when culture medium in which no colonies grew (Fig. 57) was added to Vaal River water. Therefore, organic substances excreted by the algal colonies possibly inhibited the removal of chlorophyll-*a*.

Removal of suspended solids

As illustrated in Figs 58-10l, suspended particles in the Vaal River water were removed for most of the treatments when *P. morum* colonies were added to Vaal River water.

When *P. morum* colonies suspended in culture medium in which they grew (Fig. 58) were added to Vaal River water and the pH was adjusted to 6.4, higher iron (> 6 mg l^{-1}) concentrations were necessary for the effective removal of suspended particles in the raw water. At pH 11.5, adjusted with NaOH or lime, removal was effective with the addition of increased iron concentrations (> 2 mg l^{-1}).

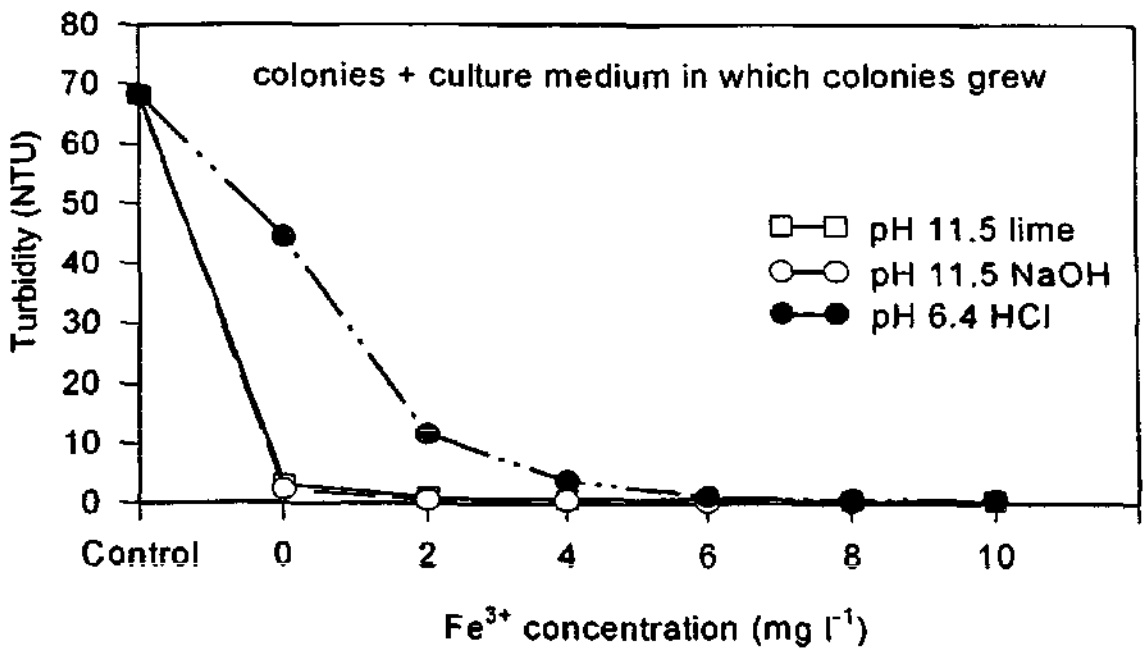


Figure 58. Variation in turbidity (NTU) with increased Fe^{3+} concentration. *Pandorina morum* colonies, suspended in culture medium in which colonies grew, were added to Vaal River water.

When *P. morum* colonies suspended in distilled water (Fig. 59) was added to Vaal River water and the pH adjusted to 6.4, higher iron (> 6 mg l^{-1}) concentrations were necessary for the effective removal of suspended particles in the raw water. At pH

11.5, adjusted with NaOH or lime, removal was effective with the addition of increased iron concentrations.

When culture medium in which colonies grew (Fig. 60) was added to Vaal River water and the pH was adjusted to 6.4, higher iron (> 6 mg l^{-1}) concentrations were necessary for the effective removal of suspended particles in the raw water. At pH 11.5,adjusted with NaOH or lime, removal was effective with the addition of increased iron concentrations.

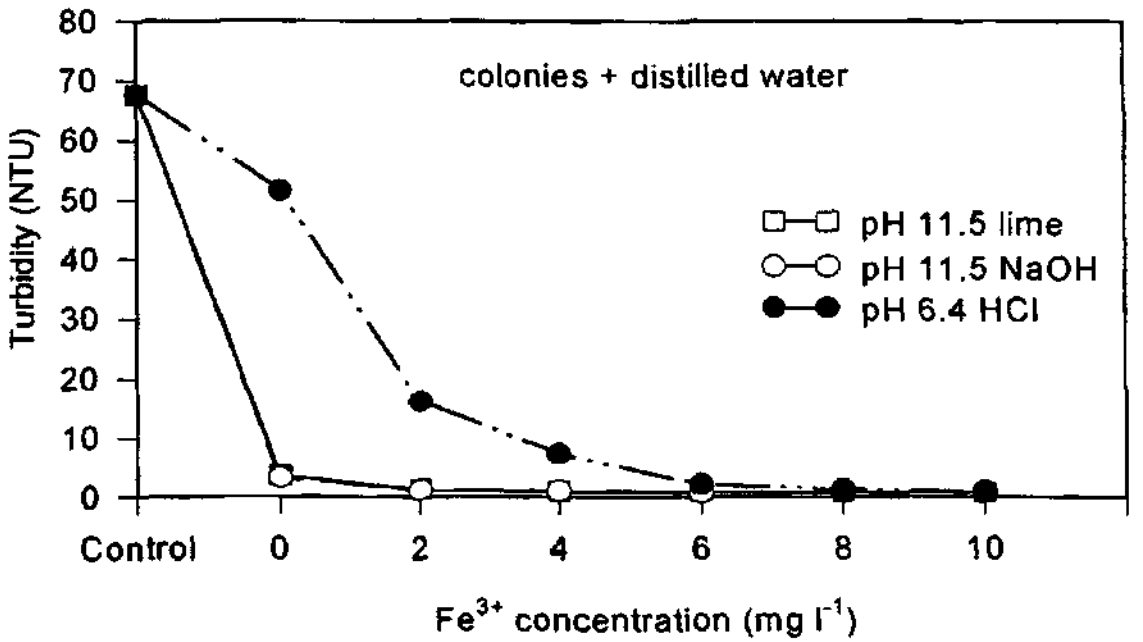


Figure 59. Variation in turbidity (NTU) with increased Fe^{3+} concentrations. *Pandorina morum* colonies, suspended in distilled water, were added to Vaal River water.

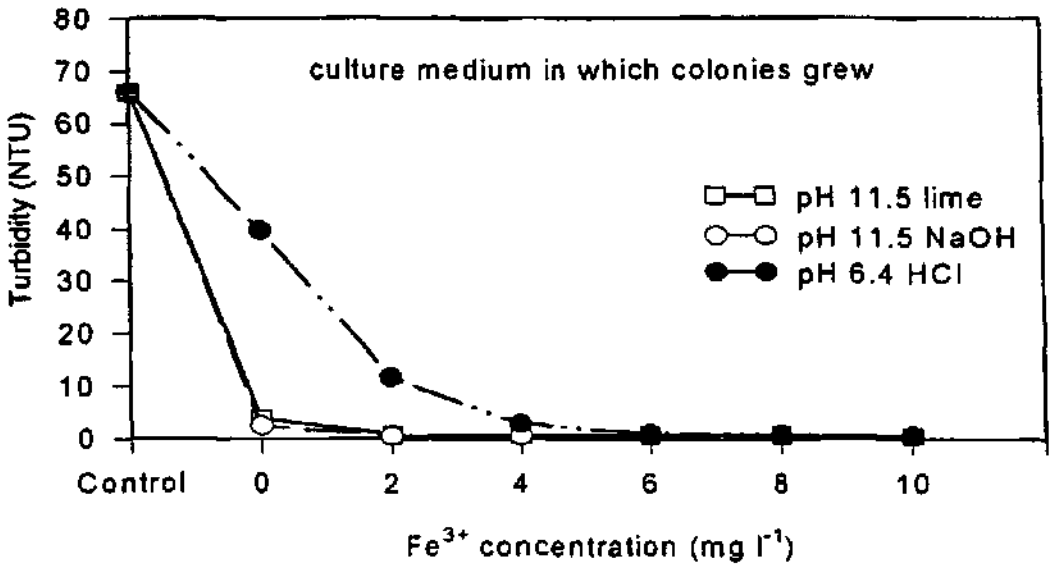


Figure 60. Variation in turbidity (NTU) with increased Fe^{3+} concentrations. Culture medium, in which *Pandorina morum* colonies grew, was added to Vaal River water.

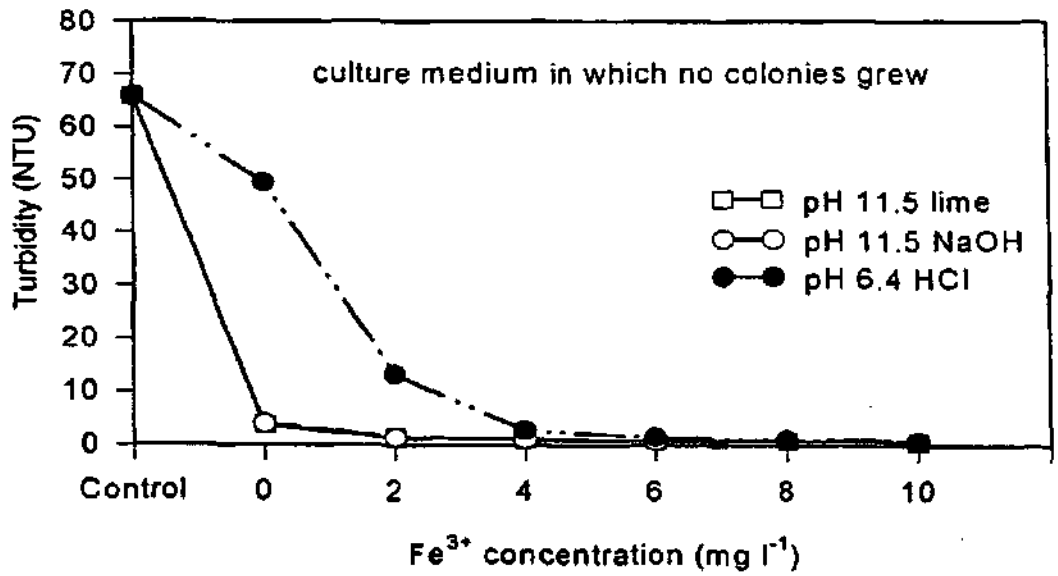


Figure 61. Variation in turbidity (NTU) with increased Fe^{3+} concentrations. Culture medium, in which no colonies grew, was added to Vaal River water.

When culture medium in which no colonies grew (Fig. 61) was added to Vaal River water and the pH was adjusted to 6.4, higher iron (> 6 mg l^{-1}) concentrations were necessary for the effective removal of suspended particles in the raw water. At pH 11.5,adjusted with NaOH or lime, removal was effective with the addition of increased iron concentrations.

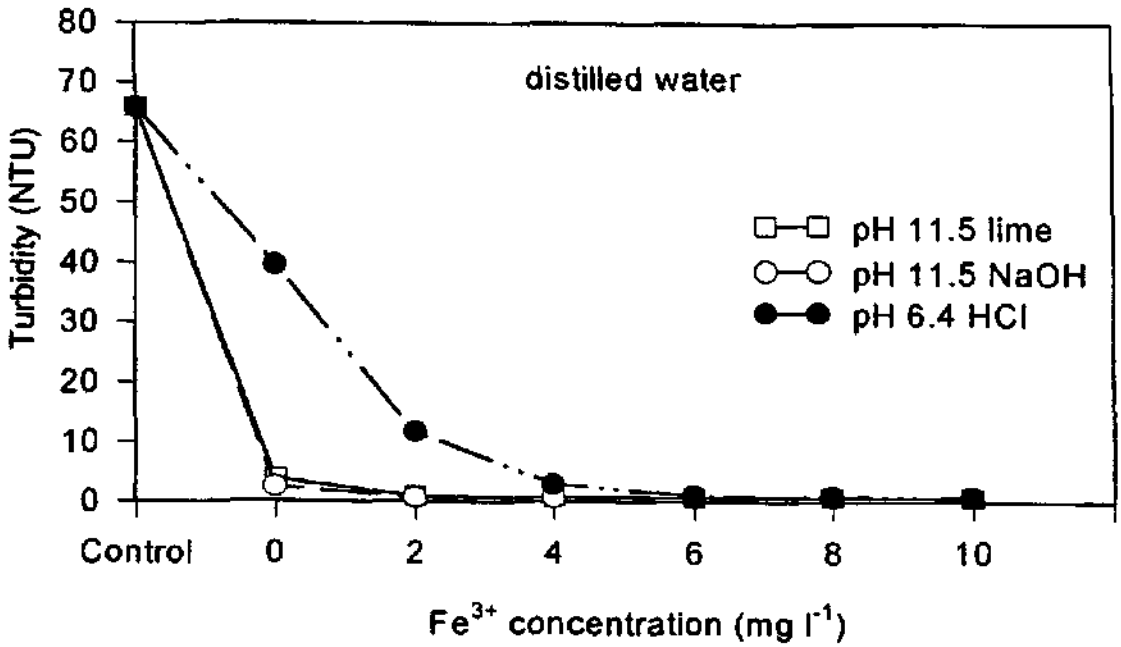


Figure 62. Variation in turbidity (NTU) with increased Fe^{3+} concentrations. Distilled water only was added to Vaal River water.

When distilled water only (Fig. 62) was added to Vaal River water and the pH was adjusted to 6.4, higher iron (> 6 mg l^{-1}) concentrations were necessary for the effective removal of suspended particles in the raw water. At pH 11.5,adjusted with NaOH or lime, removal was effective with addition the of increased iron concentrations.

The following conclusions can be drawn to summarise observations on the removal of suspended solids when *Pandorina morum* colonies were added to Vaal River water. When *P. morum* colonies were added as 60 µg l^{-1} chlorophyll-a or when culture medium was added to Vaal River water, the initial turbidity of Vaal River water remained unchanged. It is possible that the high concentration of suspended

solids in the Vaal River water was the reason why the turbidity remained unchanged. Figs 58 to 62 indicated that pH 11.5 played an important role in the removal of suspended solids. pH 6.4 was ineffective in the removal of suspended matter except when high Fe^{3+} (> 6 mg l^{-1}) concentrations were added. Effective removal occurred at pH 11.5 with increased Fe^{3+} concentrations, and little difference was observed when NaOH or lime was added.

Figs 58 to 62 showed that the removal of suspended solids was similar for all the treatments. Therefore, removal of suspended solids was apparently not affected by excreted organic substances or *P. morum* colonies.

Removal of dissolved organic carbon

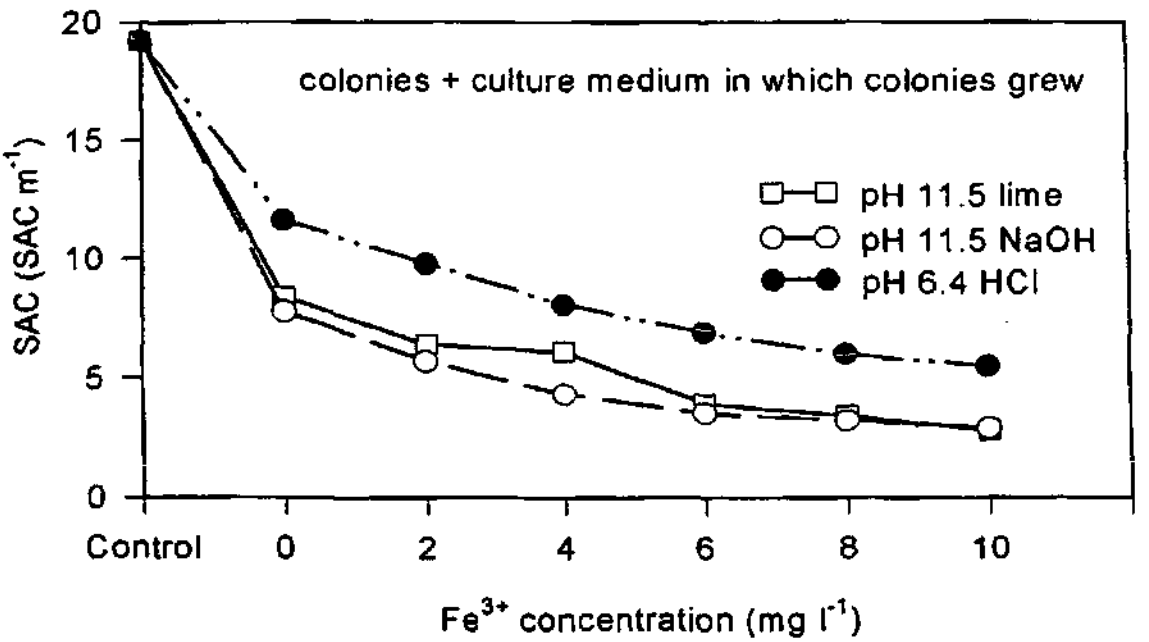


Figure 63. Variation in spectral absorption coefficient (SAC m^{-1}) with increased Fe^{3+} concentrations. *Pandorina morum* colonies, suspended in culture medium in which colonies grew, were added to Vaal River water.

When *P. morum* colonies were added to Vaal River water, the DOC concentration did not increase more than 1 SAC unit (Figs 63 and 64). When *P. morum* colonies

suspended in culture medium in which they grew, were added to Vaal River water (Fig. 63), effective removal of DOC concentrations occurred only with high iron concentrations were added (10 mg l^{-1} and higher). The removal was not as effective at pH 6.4. The best removal occurred when the pH was adjusted to 11.5 with NaOH, but when lime was used with 10 mg l^{-1} Fe^{3+}, the most effective removal was observed.

When *P. morum* colonies were suspended in distilled water and added to Vaal River water, the removal of DOC seemed to be the same as when algal colonies were added suspended in culture medium (compare Figs 63 and 64). When the pH was adjusted to 11.5 with lime, the removal of DOC was slightly less than when *P. morum* colonies suspended in culture medium were added (Fig. 64).

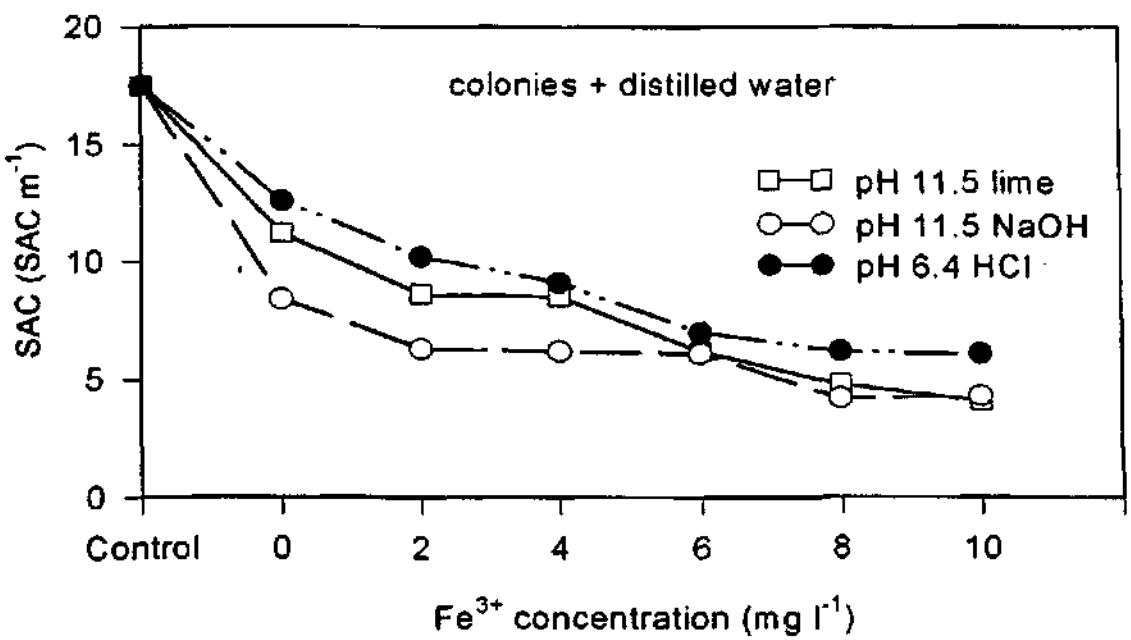


Figure 64. Variation in spectral absorption coefficient (SAC m^{-1}) with increased Fe^{3+} concentrations. *Pandorina morum* colonies, suspended in distilled water, were added to Vaal River water.

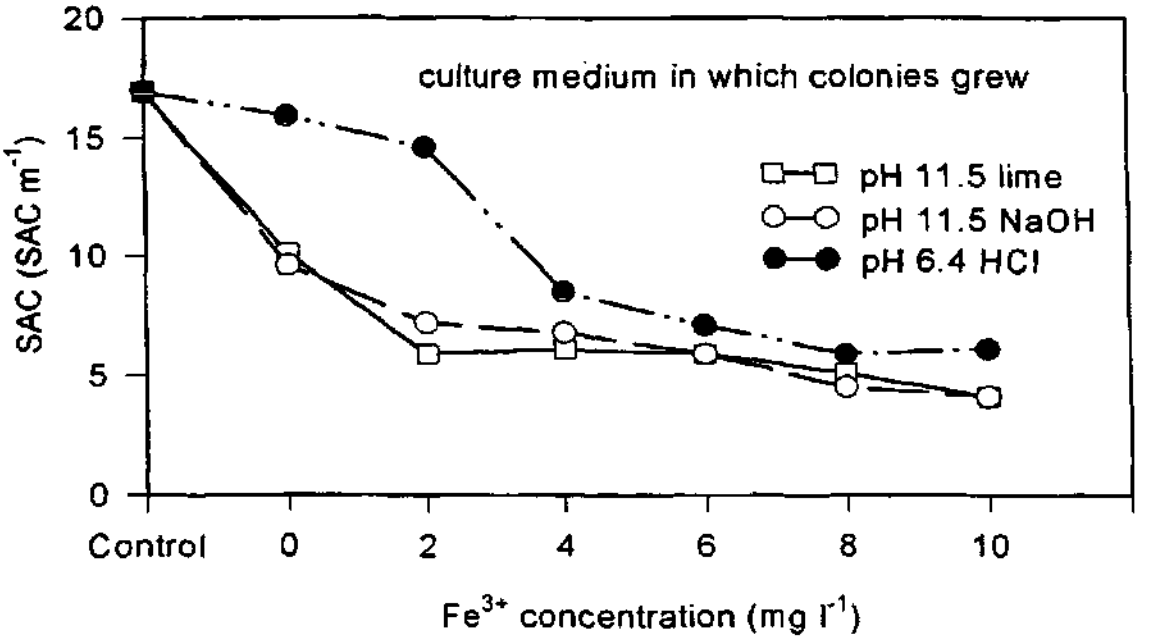


Figure 65. Variation in spectral absorption coefficient (SAC m^{-1}) with increased Fe^{3+} concentrations. Culture medium, in which *Pandorina morum* colonies grew, was added to Vaal River water.

When culture medium in which the colonies, grew or culture medium in which no colonies grew, was added to Vaal River water, the results illustrated in Figs 65 and 66 were comparable with results obtained when only colonies were added (Figs 63 and 64). The removal of DOC was, however, poorer when the pH was adjusted to 6.4 and low Fe^{3+} concentrations (< 4 mg l^{-1}) were dosed.

When distilled water was added to Vaal River water (Fig.67), the removal of DOC was slightly less effective than when *P. morum* colonies (suspended in culture medium or in distilled water) or culture medium (in which colonies did or did not grow) were added. When pH was adjusted to 6.4, only high iron concentrations (i.e. > 8 mg $l^{-1}$of Fe^{3+}) removed DOC effectively (Fig. 67).

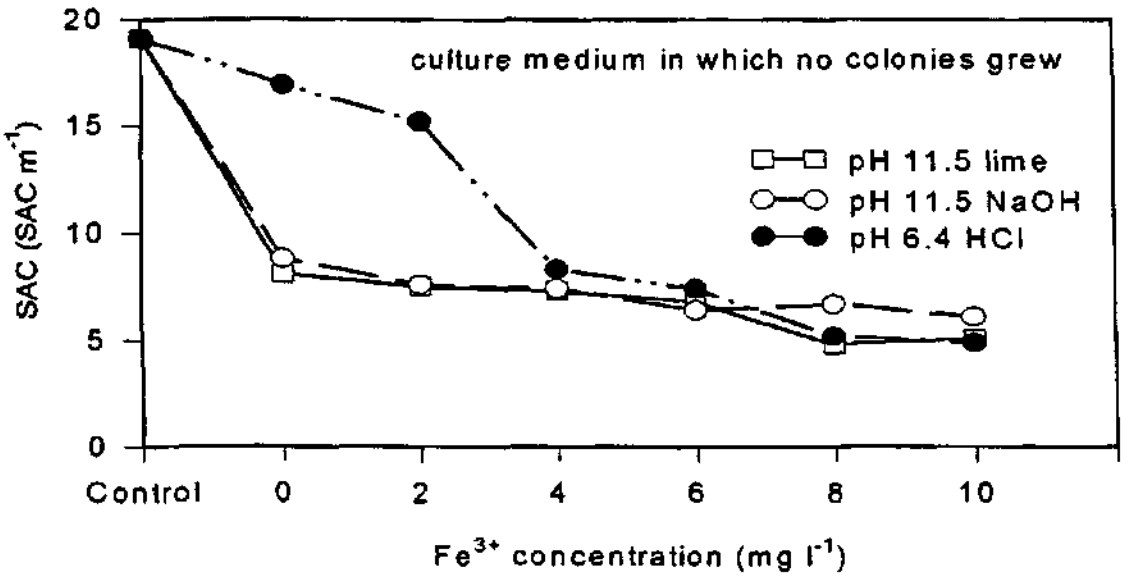


Figure 66. Variation in spectral absorption coefficient (SAC m^{-1}) with increased Fe^{3+} concentrations. Culture medium, in which no colonies grew, was added to Vaal River water.

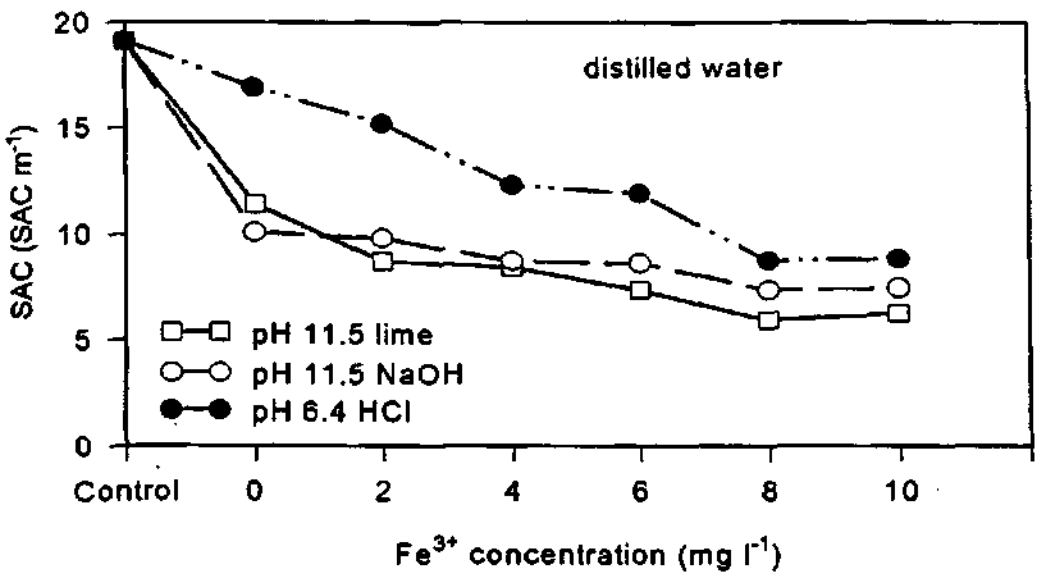


Figure 67. Variation in spectral absorption coefficient (SAC m^{-1}) with increased Fe^{3+} concentrations. Distilled water only was added to Vaal River water.

The following conclusions can be drawn to summarise observations on the removal of DOC when *P. morum* colonies were added to Vaal River water. When *P. morum* colonies (suspended in culture medium or distilled water) were added to Vaal River water (Figs 49 and 50), DOC was more effectively removed at pH 6.4 than when culture medium in which the colonies grew (Fig.65) or distilled water (Fig. 53) was added and the pH was adjusted to 6.4. The removal was possibly enhanced by added *P. morum* colonies. At pH 11.5 the removal of DOC was almost the same for all the treatments, except when colonies were added together with culture medium (Fig. 63) in which case better removal was observed. The slight improvement in removal when colonies were added together with culture medium in which colonies grew, indicate that algal colonies possibly assisted in the removal of DOC.

When culture medium in which no colonies grew was added to Vaal River water (Fig. 66), removal of DOC was slightly better than when distilled water only (Fig. 67) was added to Vaal River water. Therefore, inorganic components of the nutrient medium assisted in the removal of DOC.

When culture medium in which colonies grew was added to Vaal River water (Fig. 65), similar removal of DOC was observed than when culture medium in which no colonies grew (Fig. 66) was added to Vaal River water. Therefore, organic substances excreted by the algal colonies apparently did not affect the removal of DOC.

At pH 6.4 ineffective removal of DOC occurred when colonies (suspended in culture medium or distilled water), culture medium in which colonies grew, culture medium in which no colonies grew or distilled water only were added to Vaal River water. At pH 11.5 effective removal of DOC was observed.

When culture medium in which colonies grew (Fig. 51) or no colonies grew (Fig. 52), were added to Vaal River water, removal of DOC was ineffective at pH 6.4 when low Fe^{3+} concentrations (< 4 mg l^{-1}) were added. When distilled water was added (Fig. 67), removal was ineffective at pH 6.4 when low Fe^{3+} concentrations (<8 mg l^{-1}) was added. At pH 11.5 effective removal of DOC occurred.

The following conclusions can be drawn to summarise the effect of the three algal species, and the organic substances excreted by them, on the removal of

chlorophyll-a, suspended solids and dissolved organic matter present in Vaal River water:

1. *Monoraphidium minutum* addition reduced the removal of chlorophyll-*a* (algal cells). The organic matter excreted by the cells possibly improved the removal of chlorophyll-a at pH 11.5, but inhibited removal at pH 6.4. Organic matter excreted by *M. minutum* apparently assisted in the removal of suspended matter present in Vaal River water. The organic substances excreted by *M. minutum* cells reduced the removal of DOC, or had no effect. The culture medium in which *M. miutum* grew contained higher concentrations of monocarboxylic, fatty and aromatic acids in addition to glycerol than the culture media of the other algae (Table 3).
2. *Cyclotella meneghiniana* cells were more effectively removed than *Monoraphidium minutum* cells. Organic substances excreted by *Cyclotella meneghiniana* reduced the removal of chlorophyll-*a* (algal cells) at pH 6.4. The culture medium in which *C. meneghiniana* grew had higher concentrations of dicarboxylic acids than the culture media of the other algae (Table 3). *C. meneghiniana* cells apparently enhanced the removal of suspended particles at pH 6.4. When the pH was adjusted to 11.5, *C. meneghiniana* apparently enhanced the removal of DOC.
3. Although *Pandorina morum* colonies are motile by means of flagellar movements, the colonies were more effectively removed when compared with the removal of *Monoraphidium minutum* cells. Organic substances excreted by *Pandorina morum* colonies apparently reduced the removal of chlorophyll-*a* (algal colonies). *P. morum* colonies, and the organic substances excreted by them, did not affect the removal of suspended particles in Vaal River water. *P. morum* colonies apparently enhanced the removal of DOC slightly. The organic substances excreted by *P. morum* did not affect the removal of DOC. The culture medium of *P. morum* had less monocarboxylic and aromatic acids in solution than the media of the other algae (Table 3).
4. Although the extracellular substances of the different algae differed markedly, and while it is tempting to suggest that the differences in effect might might have been attributable to the differences in concentration and relative ratios of the extracellular organic substances, the present investigation cannot provide conclusive answers.

DISCUSSION AND CONCLUSIONS

The results obtained in the experiments showed that the methods and conditions used here were generally effective for coagulation, flocculation and sedimentation of algal cells, algal colonies and suspended solids. The removal of dissolved organic substances occurred at specific conditions.

The experimental procedures followed in these experiments allowed comparison between different variables measured in untreated and chemically treated water. In the experiments it was possible to establish how much material has been removed by flocculation and what effect pH and different coagulants had on the processes.

The results, on the water used in this study, showed that it is not necessary to dose Fe^{3+} in higher concentrations than 18 mg l^{-1} because of the small additional effect 20 and 22 mg l^{-1} Fe^{3+} had.

Low Fe^{3+} concentration (lower than approximately 4 mg l^{-1}) dosages gave lower flocculation and removal efficiencies. These results apparently show the effect of to little Fe^{3+} available to form positive charged Fe-hydroxo complexes for charge neutralisation. With higher Fe^{3+} concentrations, flocculation and removal occurred more efficiently.

The main factor responsible for the formation of flocs on the surface of the water could be flocculant overdose. The optimum flocculant concentration, based on the results of the experiments, was between 8 and 10 mg l^{-1} Fe^{3+} for a pH range between 5 and 11.

The formation and concentration of flocs or aggregates on the surface of the treated water could also be an indication that the phytoplankton in the water produce gas vacuoles which enable the cells in the flocs to float on the water surface. In addition, the concentration at the surface could also be due to mucilage material present around some algal cells which entraps gasses such as O_2 and CO_2 released by the cells. Differences in densities between the mucilage material and the water could also have resulted in the concentration of material at the surface of the water.

The results showed that the flocculation and removal of DOC decreased with an increase in pH (Figs. 6-9). The most efficient removal of DOC occurred at pH 5,

which is an indication that $FeCl_3$ as sole flocculant was insufficient in the removal of DOC at pH conditions between 7 and 11. However, when the pH was raised to 11.5, the removal of DOC increased. This increase in removal of DOC was enhanced with the addition of iron.

Ca^{2+} ions apparently did not participate directly in flocculation processes when the pH was unchanged (Fig. 24). When the pH was adjusted to 11.5, algal cells and suspended particles were effectively removed even when no Ca^{2+} was added. The removal was, therefore, the result of the high pH conditions. It is, however, possible that a pH of 11.5, in conjunction with the added Ca^{2+}, resulted in the formation of precipitates (calcium carbonate and magnesium hydroxide) which can possibly assist in flocculation. It was shown in other studies that suspended particles can be adsorbed onto these precipitates (Parker *et al.*, 1975; Dziubek and Kowal, 1984).

The use of high Fe^{3+} concentrations (> 6 mg l^{-1}) under low pH conditions (< 7) for the water used in this study may have contributed to the relatively efficient removal of DOC. Investigations by Black and Christman (1963), Hall and Packham (1965), Dempsey *et al.* (1984), Edwards and Amirtharajah (1985) and Sinsabaugh *et al.* (1986) showed that coagulation of DOC was dependent primarily on pH conditions, the coagulant dose, and the concentration of DOC. Effective removal of DOC occurred at lower pH conditions than turbidity. The optimum pH conditions for coagulation of organic matter was around pH 4 for Fe(III) salts. Gray (1988) reported that below pH 6, removal occurs by coprecipitation of ferric-organic matter/ferric hydroxide precipitates and concluded that effective removal of DOC with iron(III) occurs primarily by the formation of an iron-organic precipitate rather than the formation of ferric hydroxide. This investigation showed that DOC was also effectively removed at pH 11.5 in conjunction with increased Fe^{3+} concentrations (> 8 mg l^{-1}).

The experiments demonstrated that low Fe^{3+} concentrations (< 6 mg l^{-1}) gave lower flocculation and removal efficiencies. With an increase in Fe^{3+} concentration (i.e. 8 to 18 mg l^{-1}), an increase in the efficiency of flocculation and removal were observed. It was possible to determine the optimum Fe^{3+} concentration (approximately 8 mg l^{-1}) necessary for efficient flocculation and removal of algal biomass (indicated by chlorophyll-a), DOC and total suspended solids for the water and conditions of the present study.

The experiments enable the determination of the optimum pH for flocculation with $FeCl_3$ as flocculant. Except for the removal of DOC, the removal of total suspended solids in the water was optimal at pH 11. Therefore, it is possible to conclude that optimal conditions for flocculation with $FeCl_3$ as flocculant is at pH 11 at a Fe^{3+} concentration of 8 mg l^{-1}. Ferric chloride was more efficient in affecting the coagulation process than ferric sulphate.

The results obtained from the comparison between lime and sodium hydroxide showed that lime was more efficient in affecting flocculation. This can be due to the increase in suspended particles and possibly calcium concentrations which may possibly assist in flocculation as a result of calcium carbonate precipitates which forms at pH conditions higher than 10.5 (Ronen, 1981).

Monoraphidium minutum cells were ineffectively removed at pH 6.4, but effective removal occurred at pH 11.5. *M. minutum* cells are elongated and cresent shaped which can be responsible for the possibility that the compactness of the flocs in which they were included was low and that sedimentation would be affected. *Cyclotella meneghiniana* cells were effectively removed when added to Vaal River water, except when pH was adjusted to 6.4 and low iron concentrations (< 4 mg l^{-1}) was added. The areolae in the frustules, which can capture oxygen during photosinthesis, could possibly be responsible for the ineffective removal at pH 6.4 when low Fe^{3+} concentrations (< 4 mg l^{-1}) was added. *C. meneghiniana* cells apparently enhanced the removal of suspended matter at pH 6.4.

Pandorina morum colonies were effectively removed when the pH was adjusted to 11.5 and Fe^{3+} concentrations higher than 4 mgl^{-1} were added. Ineffective removal occurred at pH 6.4 when low Fe^{3+} concentrations (< 2 mg l^{-1}) were added. The ineffective removal at pH 6.4 can possibly be due to the presence of the mucilage sheath around the colonies. The mucilage density is lower than the density of water (Reynolds, 1975) and, therefore, sedimentation would be slower. The ineffective removal can also be due to the movement of the colonies by means of flagella.

The organic substances excreted by *Monoraphidium minutum* improved the removal of chlorophyll-*a* at pH 11.5, but chlorophyll-*a* removal was inhibited at pH 6.4. Organic matter excreted by *M. minutum* possibly improve the removal of suspended matter present in Vaal River water, but reduced the removal of DOC.

Organic substances excreted by *Cyclotella meneghiniana* cells apparently reduced the removal of chlorophyll-a at pH 6.4, but the removal of chlorophyll-*a* was not affected at pH 11. 5 by excreted organic matter. The organic substances excreted by *Pandorina morum* colonies also apparently reduced the removal of chlorophyll-*a*.

The results showed that algal cells, especially of *Monoraphidium minutum* and *Cyclotella meneghiniana* (at pH 11.5) and *Pandorina morum* colonies themselves, possibly assist in the removal of DOC.

It can in general be concluded that increase in biomass together with the excreted organic matter from the algal cells, affect the removal of biomass, suspended matter and dissolved organic carbon. However, more detailed studies are needed to determine the exact effect of the algal cells and colonies as well as their excreted organic substances on coagulation and sedimentation.

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CHAPTER 5:
ORGANIC COMPOUNDS EXCRETED BY ALGAE FROM THE VAAL RIVER

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INTRODUCTION

Algae are common inhabitants of surface waters exposed to sunlight where they often give rise to large quantities of organic material. This material is causing various problems in rivers and lakes, such as aesthetically unacceptable situations and sometimes by producing toxic substances (Palmer, 1980). In South Africa, problems related to the overabundance of algae in rivers are well recognised, but poorly understood.

Massive developments of phytoplankton are experienced in certain sections of the Vaal River, resulting in aesthetic problems, health hazards, interferences with treatment processes and problems in water distribution systems. In water purification systems, algae may clog sand filters and distribution pipes, shorten filter runs, impart unpleasant tastes and odors, resist sedimentation and interfere with industrial use (Pieterse, 1989). Reduction in phytoplankton and other suspended material are being achieved in the Balkfontein plant, but the treated water deteriorated during the occurrence of algal blooms in the river (raw) water (Pieterse, 1989).

The present research programme focus on algae which possibly resist oxidation and sedimentation. Certain algal species penetrate purification processes in full-scale water treatment plants (Pieterse *et al.*, 1993). Because algae probably resist oxidation and sedimentation, additional oxidant and flocculant must be added to bleach or remove the remaining algal cells. One of the possible reasons for the penetration of algal cells in purification processes is the possible effects of algal-extracellular products.

Algal-extracellular products could influence water purification by affecting the following processes or characteristics of the suspended particles. Because algal cells generally carry negative surface charges (Tebutt, 1977: Ronen, 1981), positively charged ions (e.g. Al^{3+} or Fe^{3+}) are added during purification. The purpose of the positive ions is to

bind by means of an attraction force, to the negative charged particles in suspension. In this way biotic and abiotic particles agglomerate and increase in size so that removal by sedimentation becomes possible. Negative charged substances can be biotic (e.g. algae and bacteria cells) or abiotic (e.g. colloids, and dissolved ions such as SO_4^{2-} and NO_3^-).

The characteristics of the biotic particles are not the same as that of the abiotic particles, because biotic particles are alive and can excrete different substances (Lüsse *et al.*, 1985). These extracellular organic substances can go into suspension or attach to the cell wall and influence their surface characteristics, such as the surface charge. If the excreted substances go into suspension, it could remain stable or dissolve in the water or react with other substances, such as with chlorine, to form trihalomethanes (THMs) which are considered to be potentially carcinogenic compounds. The occurrence of THM substances have been demonstrated in the Balkfontein purification plant as well as in raw water from the middle Vaal River (Basson & Pieterse, 1993).

Algal-extracellular organic substances in suspension contribute to the particulate organic carbon (POC) fraction in the water, while algal-extracellular products which dissolve in the water, contribute to the dissolved organic carbon (DOC) fraction. The POC and DOC may compete with the algal cells for the oxidation reagent. e.g. chlorine. One possibility is when algal cells are under stress, as might happen under the influence of the added oxidation chemicals, more algal extracellular excretion could occur, providing organic substances which can react with the oxidation reagent. In certain fragile species the cells may break up to release their constituents into the external medium. The result is that the algal-extracellular products are most probably oxidised in preference to algal cells which may cause some algal cells not to be oxidised.

If algal-extracellular products occur, they would contribute to the total organic carbon (TOC) fraction in the water. The particulate organic carbon fraction in the water together with the dissolved organic carbon fraction, gives the total organic fraction in the water. If the TOC concentration is less than 1-2 mg l^{-1}, flocculation is generally improved, but if the concentration is in excess of 1-2 mg l^{-1} , flocculation is disturbed (Lüsse *et al.*, 1985; Hoyer *et al.*, 1985). It must be remembered, however, that POC and DOC of non-algal origin are always present in the water which will also affect the processes reviewed here.

Charge neutralisation is necessary for the formation of flocs. Algal-extracellular products which attach to the cell wall may affect the surface charge characteristics of the algal cells. If the algal-extracellular product concentration is high, the effect on the surface charge characteristics will possibly be more extensive. The net result of the effects of algal-extracellular products is that charge neutralisation possibly does not occur completely and flocs containing algal cells are not readily formed or are destabilised.

Some algal-extracellular products could be polysaccharides. Polysaccharidic substances serve as precursors of humin-like compounds containing aliphatic and aromatic structures with phenolic polymers. Portions of aliphatic structures in humic acids can be considerably larger than portions of aromatic structures, particularly when the humic substances originate in aquatic environments.

Particularly towards the end of prolonged and extensive algal biomass production, increased amounts of cell wall material are found in the water. Substances comprising the cell wall material are mainly macromolecular, acidic polysaccharides which contain sulfonic acid esters, uronic acid esters and glucoproteins as functional groups (Leppard & Colvin, 1972; Colvin & Leppard, 1973; Leppart *et al.*, 1977; Burnison, 1978 and Massalski & Leppard, 1979). Acidic polysaccharides are found in waters of eutrophic lakes and glucose molecules make up the greatest part of the carbohydrates.

Different studies were done on the mechanisms involved in unit processes in a water purification plant (Tebutt, 1977; Hart, 1981; Ronen, 1981; Van Vuuren, 1981; Van Leeuwen, 1981a and 1981b; Hatting *et al.*, 1981; Van Vuuren *et al.*, 1981 and Gregory, 1989). Based on these studies, an understanding of the influence of algal-extracellular substances on the water purification process is necessary.

In order to develop such an understanding, different characteristics of algae must be investigated, such as the reaction of algal cells to flocculation and sedimentation and the characteristics of cell walls and mucilages (O'Colla, 1962) excreted by algal cells. In terms of the possible reaction of algal cells, it is important to know whether algal cells excrete organic substances in reaction to oxidation flocculation chemicals.

Based on aspects referred to in the previous paragraphs, the aim of the research into organic substances excreted by algal cells was to identify and quantify extracellular products. Special attention will be given to the isolation and characterisation of extracellular organic matter from algae (Hoyer *et al.*, 1985; Lüsse *et al.*, 1985; Fogg, 1962: Hellebust, 1974).

MATERIAL AND METHODS

Algal species

Organic compounds from five different algal species, isolated in uni-algal culture from the Vaal River, were quantified and identified. The algal species were *Monoraphidium minutum* (a unicellular green alga), *Chlamydomonas* sp. (a unicellular green flagellate), *Pandorina morum* (a coloniat green flagellate), *Cosmarium laeve* (a unicellular green desmid), and *Cyclotella meneghiniana* (a centric diatom). The algae were grown in an artificial growth medium called GBG11 (Krüger & Eloff, 1978). Because of slow growth by *C. meneghiniana*, 18 day old cultures were used for analyses, while 10 day old cultures were used for the other, faster-growing algae. The algae were removed from the medium by centrifugation (5500 rpm for 10 minutes). The supernatant from each culture were used to determine the composition and concentration of the excreted organic substances. In a parellel study (see section by Traut and Pieterse), centrifuged algal cells and excreted organic compounds were added to Vaal River water in order to investigate their effect on coagulation and sedimentation.

Analysis of extracellular organic substances

The supernatant of each culture was freeze-dried and 80 mg of the weighed, dried substrate was dissolved in 1.0 ml distilled water. Organic substances were extracted and analysed for using the methods described by Van Rooyen *et al.* (1994). Very little proteins and carbohydrates were found in the cultures. The concentration of different excreted organic acids were normalised to the chlorophyll content of the relavant culture.

It is possible that the supernatant of the cultures have contained intact algal and bacterial cells from which organic substances could also have been extracted. It can, however, be assumed that these cells made a minor contribution, if at all, to the organic substances actually excreted by the live cells hat grew in the cultures.

RESULTS

Organic acids, excreted by the different algal species, are given in Tables 1 to 5. Almost undetectable amounts of proteins, aminoacids and carbohydrates (not given in the tables) were found in the culture media. A diverse amount of organic, fatty and aromatic acids as well as dimers, glycerol and phosphoric acid were found in the

media. *Monoraphidium minutum* excreted the largest number of substances (Table 1), followed by *Cosmarium laeve* (Table 4), *Chlamydomonas* sp. (Table 2), *Pandorina morum* (Table 3) and *Cyclotella meneghiniana* (Table 5).

High concentrations of hydroxy-Acetic/Glycolic acid, 3,4-dihydroxy-Butyric acid, Oxalic acid, Lauric acid and Hydroxy-propylenediphenol were excreted by *Monoraphidium minutum* (Table 1). *Chlamydomonas* sp. (Table 2) excreted high concentrations of Decanoic and Octanoic acids, while *Pandorina morum* excreted high concentrations of Oxalic and Benzoic acids (Table 3). *Cosmarium laeve* excreted several carboxylic and fatty acids in high concentrations; a high concentration of 1236 µg l^{-1} of Octanoic acid was demonstrated. *Cyclotella meneghiniana* excreted high concentrations of Lactic and Oxalic acids.

Table 1 : Components of extracellular organic substances from a uni-algal culture of *Monoraphidium minutum* (10 days old), a unicellular green alga, isolated from the Vaal River

Compound	Formula	Mol. Weight	Concentration (µg l^{-1})	ng/µg chlorophyll-a
1. Monocarboxylic acids				
Lactic acid	$CH_3CHOHCO_2H$	90.08	34.4	9.7
hydroxy-Acetic/ Glycolic acid	$HOCH_2CO_2H$	76.05	135.7	38.2
3-hydroxy-Propanoic acid	$HOCH_2CH_2CO_2H$	90.08	47.7	13.4
3,4-dihydroxy-Butyric acid	$HOCH_2CHOHCH_2CO_2H$	104.11	137.0	38.5
2. Dicarboxylic acids				
Oxalic acid	HO_2CCO_2H	90.04	251.8	70.9
Succinic acid	$HO_2CCH_2CH_2CO_2H$	118.09	14.2	4.0
3. Fatty acids				
Lauric acid	$CH_3(CH_2)_{10}CO_2H$	200.32	131.5	37.0
Myristic acid	$CH_3(CH_2)_{12}CO_2H$	228.36	79.4	22.3
Palmitic acid	$CH_3(CH_2)_{14}CO_2H$	256.43	58.7	16.5
Stearic acid	$CH_3(CH_2)_{16}CO_2H$	284.49	61.8	17.4
4. Dimers				
Absent				
5. Aromatic acids				
Methylenediphenol	$C_{13}H_{12}O_2$	344	51.5	14.5
Hydroxyethylene-diphenol	$C_{14}H_{14}O_3$	446	76.9	21.6
Hydroxy-propylenediphenol	$C_{15}H_{16}O_3$	460	103.4	29.1
6. Other				
Glycerol	$HOCH_2CHOHCH_2OH$	92.1	34.3	9.7

Table 2 : Components of extracellular organic substances from a uni-algal culture of *Chlamydomonas* sp. (10 days old), a unicellular green flagellate, isolated from the Vaal River

Compound	Formula	Mol. Weight	Concentration ($\mu g\ l^{-1}$)	ng/µg chlorophyll-a
1. Monocarboxylic acids				
Lactic acid	$CH_3CHOHCO_2H$	90.08	35.8	9.9
hydroxy-Acetic/ Glycolic acid	$HOCH_2CO_2H$	76.05	26.1	7.2
2. Dicarboxylic acids				
Oxalic acid	HO_2CCO_2H	90.04	95.4	26.3
Succinic acid	$HO_2CCH_2CH_2CO_2H$	118.09	76.8	21.2
Aconic acid	$HO_2CCHCCO_2HCH_2CO_2H$	128.08	25.2	6.9
3. Fatty acids				
Octanoic acid	$CH_3(CH_2)_6CO_2H$	144.22	715.3	197.0
Decanoic acid	$CH_3(CH_2)_8CO_2H$	172.27	294.8	81.2
4. Dimers				
Diglycolic acid	$O(CH_2CO_2H)_2.H_2O$	152.11	85.9	23.7
5. *Aromatic acids*				
Absent				

Table 3 : Components of extracellular organic substances from a uni-algal culture of *Pandorina morum* (10 days old), a colonial green flagellate, isolated from the Vaal River

Compound	Formula	Mol. Weight	Concentration ($\mu g\ l^{-1}$)	ng/µg chlorophyll-a
1. Monocarboxylic acids				
Lactic acid	$CH_3CHOHCO_2H$	90.08	34.4	10.8
2. Dicarboxylic acids				
Oxalic acid	HO_2CCO_2H	90.04	251.8	79.4
Succinic acid	$HO_2CCH_2CH_2CO_2H$	118.09	14.3	4.5
3. Fatty acids				
Absent				
4. Dimers				
Absent				
5. Aromatic acids				
Benzoic acid	$C_6H_5CO_2H$	122.12	109.6	34.6
6. Other				
Phosphoric acid	$(C_2H_5O)_2POOH$	118.09	6.7	2.1

Table 4 : Components of extracellular organic substances from a uni-algal culture of *Cosmarium laeve* (10 days old), a unicellular green alga (desmid), isolated from the Vaal River

Compound	Formula	Mol. Weight	Concentration ($\mu g\ l^{-1}$)	ng/µg chlorophyll-a
1. Monocarboxylic acids				
Lactic acid	$CH_3CHOHCO_2H$	90.08	188.9	91.5
hydroxy-Acetic/ Glycolic acid	$HOCH_2CO_2H$	76.05	167.4	81.1
3-hydroxy-Propanoic acid	$HOCH_2CH_2CO_2H$	90.08	236.4	114.6
2. Dicarboxylic acids				
Oxalic acid	HO_2CCO_2H	90.04	226.4	109.7
Succinic acid	$HO_2CCH_2CH_2CO_2H$	118.09	65.9	31.9
3. Fatty acids				
Octanoic acid	$CH_3(CH_2)_6CO_2H$	144.22	1235.7	598.8
Decanoic acid	$CH_3(CH_2)_8CO_2H$	172.27	365.6	177.2
4. Dimers				
Absent				
5. Aromatic acids				
Benzoic acid	$C_6H_5CO_2H$	122.12	35.4	17.2
6. Other				
Glycerol	$HOCH_2CHOHCH_2OH$	92.10	34.3	16.6
Phosphoric acid	$(C_2H_5O)_2POOH$	154.10	29.8	14.4

Table 5 : Components of extracellular organic substances from a uni-algal culture of *Cyclotella meneghiniana* (18 days old), a unicellular centric diatom, isolated from the Vaal River

Compound	Formula	Mol. Weight	Concentration ($\mu g\ l^{-1}$)	ng/µg chlorophyll-a
1. Monocarboxylic acids				
Lactic acid	$CH_3CHOHCO_2H$	90.08	188.9	219.1
2. Dicarboxylic acids				
Oxalic acid	HO_2CCO_2H	90.04	236.4	274.2
Succinic acid	$HO_2CCH_2CH_2CO_2H$	118.09	65.9	76.4
Citric acid	$HO_2C(CH_2CO_2H)_2CO_2H$	192.12	45.7	53.0
3. Fatty acids				
Palmitic acid	$CH_3(CH_2)_{14}CO_2H$	256.43	39.9	46.3
4. Dimers				
Absent				
5. Aromatic acids				
Absent				

DISCUSSION AND CONCLUSIONS

Planktonic organisms release organic compounds into the water. These compounds are polysaccharides, uronic acids and some mono- and oligosaccharides as well as organic nitrogen compounds with amino acid structures and polypeptides. Amino sugars such as glucosamine were also identified from algae (Lüsse *et al.*, 1985). In the present study five different algae isolated from the Vaal River excreted a diverse amount of monocarboxylic, dicarboxylic and fatty acids, while glycerol and phosphoric acid were demonstrated in culture media of two species. Apart from affecting chlorination, the removal of suspended and dissolved substances, the excreted substances most probably contribute negatively to the aesthetic quality of the water, such as producing tastes and odours.

Although it was demonstrated that the extracellular organic substances most probably affected coagulation (and sedimentation; see section by Traut and Pieterse) of algal cells and colonies as well as colloidal particles, the effect of the individual substances were not investigated. This aspect needs to be studied in detail in future investigations.

In the present study no distinction were made between adhesion substances on the cell walls and the algal-extracellular substances in suspension or in solution. Adhesion substances could possibly affect the surficial charge characteristics, an aspect that also needs to be investigated. The charge of the substances can be measured by the isoelectric focussing method (Garfin, 1990). The charge on the surface of the algal cells can be measured with a zeta potential meter and by the titration method developed by Schell & Bernhardt (1986).

It is also necessary to identify and quantify organic compounds in Vaal River water and in the various phases of the treatment process, as well as whether these compounds are oxidised preferentially to algal cells. Other aspects that need to be investigated are to determine how changes in charge characteristics affect the characteristics of the flocs formed during coagulation, the possible change in algal-extracellular products when the cells are exposed to stress conditions, e.g. by oxidation reagents (chlorine) and other chemicals e.g. $FeCl_3$, and what effect different purification chemicals in different concentrations and combinations has on the floc formation with algal cells.

Investigations are also necessary to determine whether extracellular products, consisting of proteins, are excreted by algal cells. Protein identification and quantification will be done by the Sodium dodecyl sulfate-polyacrylamide

electrophoresis (SDS-PAGE) method (Zehr *et al.*, 1989). The adhesion proteins must be removed from the cell walls and an acceptable removal reagent must be chosen. In the normal technique $CaCl_2$ or KCl are used (Wong *et al.*, 1977; Müder & Schloss, 1979; Huber & Nevens, 1981; Fukuda & Komamine, 1982; Lienard & Barnoud, 1985 and Fry, 1988), but calcium and potassium have specific metabolic effects so that other agents, such as LiCl, may have to be used. Experiments will be done to find a suitable reagent for this purpose. Attempts must be made to label specific proteins occurring on the cell walls. The distribution of particular proteins on the cell wall can then be investigated with a transmission electron microscope (TEM). If the charge of the proteins are known, the influence of its charge on the surface charge of the algal cell could be determined.

Special investigations should be done to identify polysaccharides by chromatographic methods such as column chromatography, depending on the type of complex (Deutcher, 1990).

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CHAPTER 6:
FLOCCULATION CHARACTERISTICS OF COLLOIDS AND ALGAL CELLS

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INTRODUCTION

Flocculation is an important step in many solid-liquid separation processes and is widely used in water treatment. Processes such as filtration, flotation and sedimentation are more effective when the size of the particles is increased. If the size of the particles to be removed is too small for effective separation, increasing their size can be achieved by aggregation. This aggregation process is known as coagulation and flocculation (Amirtharajah & O'Melia, 1990).

Regarding removal by flocculation, two broadly defined classes of material can be distinguished, namely inorganic material or colloids, and material of organic nature, i.e. algal and bacterial cells. The efficiency of the flocculation process, in relation to organic and inorganic particles, is influenced by the probability of two particles colliding with each other as well as the ability of these particles to adhere after they were brought together by collision.

Since the pioneering work of Von Smoluchowski (1917), who described the kinetics of flocculation of monodispersed, spherical colloidal particles by means of Brownian movement, much research has been done towards the understanding and modelling of colloid stability (Batchelor, 1972; Overbeek, 1977; Van de Ven & Mason, 1977; Adler, 1981; Melik & Fogler, 1981).

When reviewing information obtained during the last 75 years of investigation, it became clear that when two colloidal particles approach each other, different types of interactions come into play which have major effects on the dynamics of the flocculation process and which directly affects the collision efficiency, i.e. the probability that a pair of particles will form a permanent aggregate. Two types of interactions can be distinguished, namely viscous (or hydrodynamical) interactions and electrical (and/or electromagnetical) interactions.

Viscous interactions

Hydrodynamical interactions occur during the approach of particles suspended in the fluid, and account for the existence of fluid viscosity (Acrivos & Taylor, 1964; Goldman *et al.*, 1966; Cooley & O'Neill, 1969; Lin *et al.*, 1970; Brenner & O'Neill, 1972; Wacholder & Sather, 1974; Jeffrey & Onishi, 1984). Hydrodynamic interactions, together with external forces, such as gravitational, are responsible for the movement of the particles when they are far away from each other, but also play an important role when the particles are close to each other.

The movement of the particles induced by the fluid (translation and rotation; O'Neill, 1970) is not only a function of fluid properties, but it is also intimately linked to the geometry of the particles. These forces and torques exerted on the particle by the fluid can be described fully and explicitly by means of 21 independent parameters (Brenner, 1964a-d). Unfortunately, the determination of the analytical expression for these coefficients is, for a complex-shaped particle, almost impossible. Only special cases of particles with specific symmetries have received attention. These particles are the sphere, the ellipsoid and the slightly deformed sphere. For other geometries, like toroids, lens-shaped (hemisphere and spherical caps) particles, two spheres and spindles, only a part of the 21 relevant coefficients are known (Brenner, 1966).

Electrical and electromagnetical interactions

Whenever particles are brought in close vicinity of each other by means of hydrodynamical interactions, additional short-range interactive forces have to be taken into account. These interactions are, in the framework of colloidal particles, essentially of electrical and electromagnetical nature (Curtis & Hocking, 1970; Zeichner & Schowalter, 1977; Valioulis & List, 1984a; Gregory, 1989; Han & Lawler, 1991), and are either attractive (Van der Waals forces in general) or repulsive (electrical double layers). The strength of these forces is mainly dependent on the size and the physical properties of the particle (Hamaker, 1937; Van Oss *et al.*, 1979. The result of the combination of the effects of these different interactions (see Fig. 1) will determine whether the two particles will collide, and when they do collide, whether they will adhere after the collision to form an aggregate. If an aggregate is formed, flocculation occurred and the colloidal suspension is said to be unstable. If, after colliding, the particles separate, the colloidal suspension is said to be stable (no flocculation).

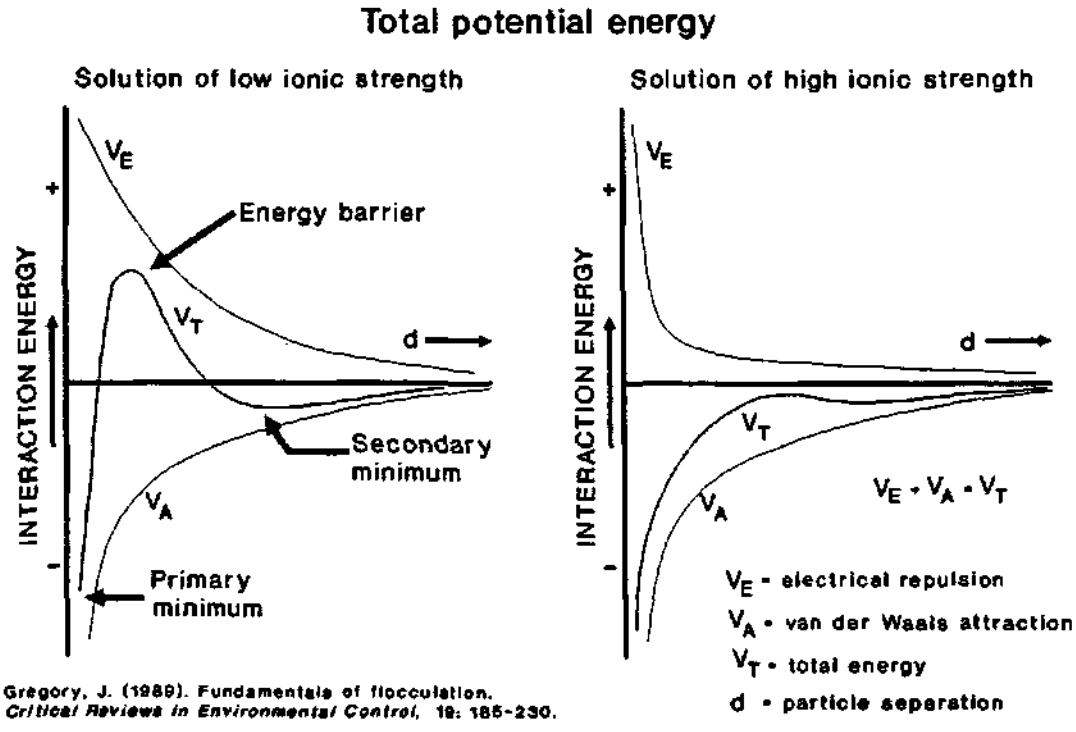

Figure 1: Energy diagrams for the interaction of colloidal particles (modified from Gregory, 1989).

FLOCCULATION OF ALGAL CELLS

Mathematical models based on the mechanisms stated above to simulate the performance of settling tanks in a water purification plant are available from the literature (Lawler *et al.*, 1983; Lawler & Wilkes, 1984; Valioulis & List, 1984b). The models usually provide computational results that are in agreement with small-scale experiments as long as the sedimentation of colloidal particles is involved. However, because of the increasing levels of eutrophication of many rivers such as the Vaal River, coupled with the occurrence of algal blooms, the problems of water purification are not only restricted to the removal of unwanted inorganic elements from the water, but also has to deal with the additional problem of sedimenting organic material, such as algal cells, present in the water.

Superficially the flocculation of algal cells in a sedimentation tank can be considered to be identical to the flocculation of colloidal particles (see Ives, 1954). It is true that the different interactions mentioned above are not valid only for colloidal particles; they should also play a role in the removal of algae. However, algae show specific properties that are not shared by colloidal particles. These specific properties might be important in the understanding of the flocculation process involving algal cells. Algal cells may be elongated in shape or may be arranged in filaments or colonies, or the cells may have long spines that could affect the efficiency of flocculation (Fig. 1). Others have flagella with which the cells could avoid flocculation or with which they could swim out of flocs.

In the following paragraphs, however, reference will only be made to the possible effects of cell size and the exchange of molecular material between the cell and its environment.

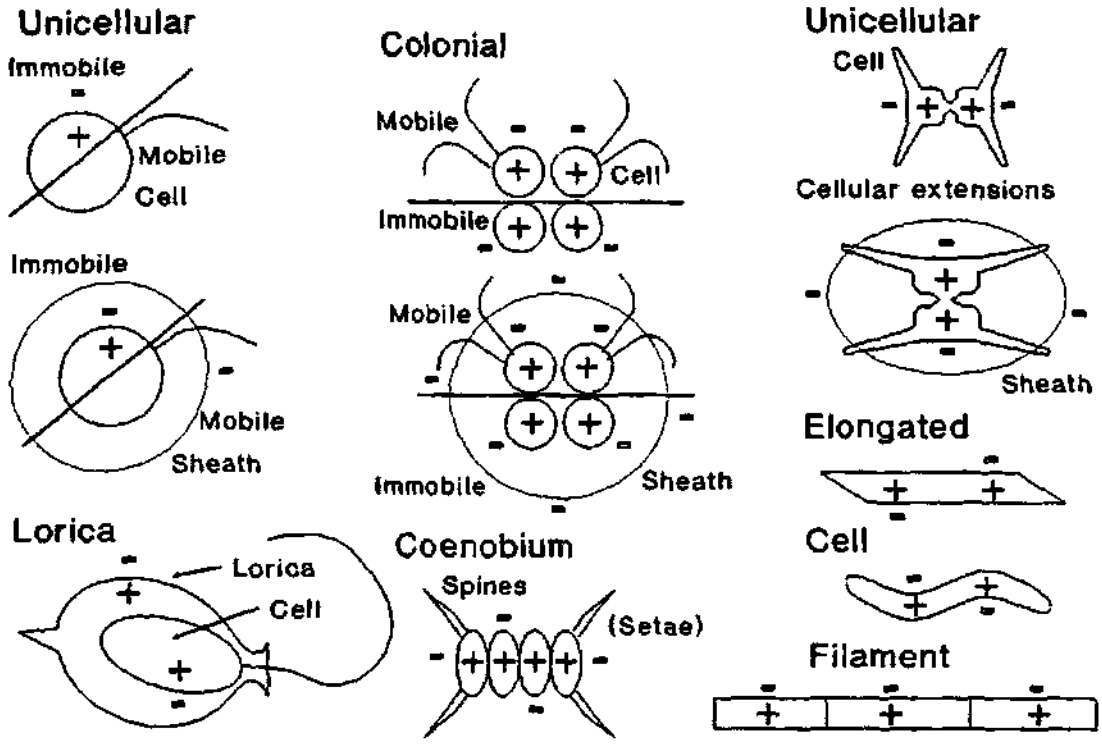

Figure 2: Different shapes, sizes and combinations of algal cell considered to affect flocculation.

Usually colloids are sized in the nanometer range, while algal cells are generally characterised by diameters in multiples of 10 micrometers, resulting in a typical size ratio of 10^3 to 10^4. One of the main implications of the difference in size may be the presence of significant mutual attraction force (universal gravitation), as an additional short-range interaction force between the larger algal cells. This assertion can easily be illustrated by considering the interactions between two identical spheres of radius a and distant from each other of a distance *r* (see Fig. 3).

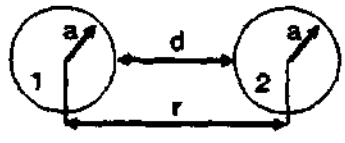

Figure 3: Schematic representation of two particles at close approach.

For the above configuration (in Fig. 3), the expressions of Van der Waals and gravitational forces can be given in an explicit form.

Van der Waals (London) interaction:

$$F_{vdw} = \frac{32}{3}\frac{Aa^6}{r^3(r^2-4a^2)^2} \quad (1)$$

Gravitational interaction:

$$F_g = \frac{\gamma m_1 m_2}{r^2} \quad (2)$$

where A, γ are the Hamaker and the gravitational constants respectively. The quantities $m_i; i=1,2$ represent the mass of each particle which, in this case, are taken to be equal.

In order to compare the relative magnitude of these forces, we considered their ratio:

$$\left|\frac{F_{vdw}}{F_g}\right| = \frac{6A}{\pi^2\rho^2\gamma}\frac{1}{r(r^2-4a^2)^2} \quad (3)$$

where ρ represents particle density.

If we take a density of 3 g cm^{-3} and sizes in the nanometer range (e.g. 0.015 μm) into account (these values may be regarded as being within the framework of colloidal particles), it can be shown from equation 3 that gravitational forces will be of the same order as that of the Van der Waals forces when the distance between the colloids equals approximately 8 000 times the diameter of the particles. If we take into account that Van der Waals interactions are considered to be effective wherever the surface-to-surface distance between the particles is of the order of the size of the particle, it is clear that the effect of gravitational forces may be neglected when describing the flocculation of colloidal particles. If, however, algal cells are considered, then a density of 1 g cm^{-3} and diameter sizes of the order of 10 μm are more appropriate values to be taken into account. If we repeat the computations done for the colloidal particles, but using diameters of 15 and 30 μm, we can demonstrate that the interaction due to the gravitational effect is of the same order of magnitude as the one developed by the Van der Waals forces when the surface-to-surface distance between the 15 and 30 μm sized cells is more or less respectively 7 and 3 times the cell diameter. In other words, both effects are of the same magnitude in a region where the effectiveness of Van der Waals forces is usually inferred when the flocculation process is described. Thus, within the framework of the flocculation of algal cells, it appears that the mathematical modelling of the flocculation process should not, as in the case of colloidal particles, be based on the Van der Waals interactions alone. Modelling of the flocculation of algal cells should also

include the effect of the gravitational force. In that case we have an additional unconditional attractive force which favours the coagulation process.

Another fundamental difference between colloidal and algal particles is the physiological ability of the cells to respond to conditions in their immediate environment. This physiological activity can affect the overall efficiency of the flocculation process in different ways. For example, when assimilating CO_2 and other nutrients, when producing O_2, or when substances like organic molecules are excreted, an algal entity (cell, filament, colony) affects its immediate environment by acting as a sink (during uptake) or a source (during excretion) of material. Tables 1 and 2 give some morphological characteristics and photosynthetic exchange rates in three representative algal species isolated from the Vaal River into uni-algal cultures.

Table 1: Morphological characteristics of three Vaal River algae.

Cell	Radius (μm)	Volume (μm^3)	Surface area (μm^2)	μg Chla $cell^{-1}$ x 10^{-7}
Microcystis aeruginosa	2.16	42	58	1.8
Chlamydomonas species	2.91	103	106	9.6
Cyclotella meneghiniana	6.53	1164	535	12.0

As shown in Table 2, the photosynthetic activity of the algae results in a net mass uptake which most probably perturbs the dynamics of the approach of two particles when they are close to each other, by creating an additional hydrodynamical force (interaction) which is favourable to the efficiency of the flocculation process. In a general context, a simple but exact formula for the quantification of this photosynthetic pulling force, F_{ph}, is tedious to obtain, but it can be demonstrated that in first approximation, and for two identical algae, the following relation holds:

$$F_{ph} \sim \frac{3}{2} \frac{\pi \mu U a^4}{d^3} \qquad (4)$$

In this relation U represents the mass uptake speed, μ the viscosity of the fluid, while a en d define the radius of the algae and the surface-to-surface distance between the

particles, respectively. The effectiveness of this additional interaction during the flocculation process, can once again be demonstrated by comparing the magnitude of the pulling force with Van der Waals interactions. In this case we consider the ratio

$$\left|\frac{F_{vdw}}{F_{ph}}\right| \sim \frac{64 A a^2}{9\pi\mu U} \frac{r - 2a}{r^3 (r + 2a)^2} \tag{5}$$

Table 2: Photosynthetic exchange rates of three Vaal River algae.

Cell	Rates mass exchange 10^{-8} µg cell^{-1} sec^{-1}	Net photosynthetic mass uptake speed 10^{-10} µg cell^{-1} sec^{-1}	Net photosynthetic 10^{-2} µm sec^{-1}
Microcystis aeruginosa	CO_2: 0.10 O_2: 0.0944	0.56	0.33
Chlamydomonas species	CO_2: 0.8026 O_2: 0.755	4.76	1.53
Cyclotella meneghiniana	CO_2: 1.0032 O_2: 0.9438	5.94	0.38

Table 3: Comparison between the photosynthetic pulling force and Van der Waals forces.

Cell	Net photosynthetic pulling force x 10^{-15} g cm sec^{-2}	Distance where $F_{vdw}/F_{ph} \sim 1$ *ø algae
Microcystis aeruginosa	0.002	4.75
Chlamydomonas species	0.16	2.00
Cyclotella meneghiniana	0.14	1.75

Using data in Tables 1 and 2 together with equation 5, it can be shown (Table 3) that the magnitude of these two interactions are similar when the algae are close to each other. Thus, it can be concluded that, as in the case of the gravitational force, the

hydrodynamical interactions resulting from the photosynthetic activity developed by the algae, should be taken into account when attempts are being made to model the flocculation of algal cells.

In addition, it has been shown in algal cultures that, under certain conditions, added $FeCl_3$ may stimulate carbon assimilation rates, and, consequently, also the O_2 production rates. Should the flux of substances in and out of cells affect flocculation, the type of flocculant used could become very important.

Another consequence of the uptake and/or excretion process is the possible modification of the fluid viscosity in the immediate vicinity of the colliding algal entities which, once again, can affect the efficiency of collisions.

Table 4: Comparison between algal and colloidal entities.

Algal Entity		Colloidal Entity
cell	BASIC UNIT	colloid
10 to 10^3 μm	SIZE	10^{-3} to 10^{-1} μm
1.02 g cm^{-3}	DENSITY	3 g cm^{-3}
complex	MORPHOLOGICAL FEATURES	simple
various	COVERING	none
yes	APPENDAGES	no
unicells, colonies filaments	TYPE	single to agglomerates
spherical to elongated	SHAPE	spherical to subspherical
yes	CHANGE SHAPE	no
yes	ADSORPTION	yes
yes	METABOLIC PROCESSES	no
yes	ABSORPTION	no
yes	EXCRETION	no
flagella, gliding creeping	LOCOMOTION	no

Apart from effects caused by their photosynthetic activities, algal cells are also known to be able to react to perturbations caused by changes in the environment. The

physiological ability of algae may allow the cells to counterbalance electrical charge neutralisation as a result of the addition of a coagulant for flocculation.

If the assumption is made that an algal cell is globally in equilibrium with itself, it is possible that neutralisation of the negative electrical charge present on the outer covering of the cell will be followed by a reaction of the cell to re-establish the initial negative charge. Should this happen, it would affect the adherence ability of the algae after collision.

If the time of the restoration of the surface charge is shorter than the sedimentation time, a natural break-up of the aggregates could occur in the sedimentation tank. The breaking-up is then not the result of any condition in the environment of the floc, but it is the result of conditions within the floc.

CONCLUSIONS

As indicated in the above paragraphs, there most probably exists many significant differences between colloidal and algal suspensions. Table 4 provides a list of these differences. Using approximation theory, it has been shown, by means of comparisons with classical theory of flocculation for colloidal particles, that at least some of these differences may significantly affect the coagulation and flocculation processes when algal cells are involved. Therefore, more intensive investigations must be done on how these additional features specific for algal cells, affect the flocculation process. In addition, intensive investigations should be done on how the negative effects posed by the cells can be overcome.

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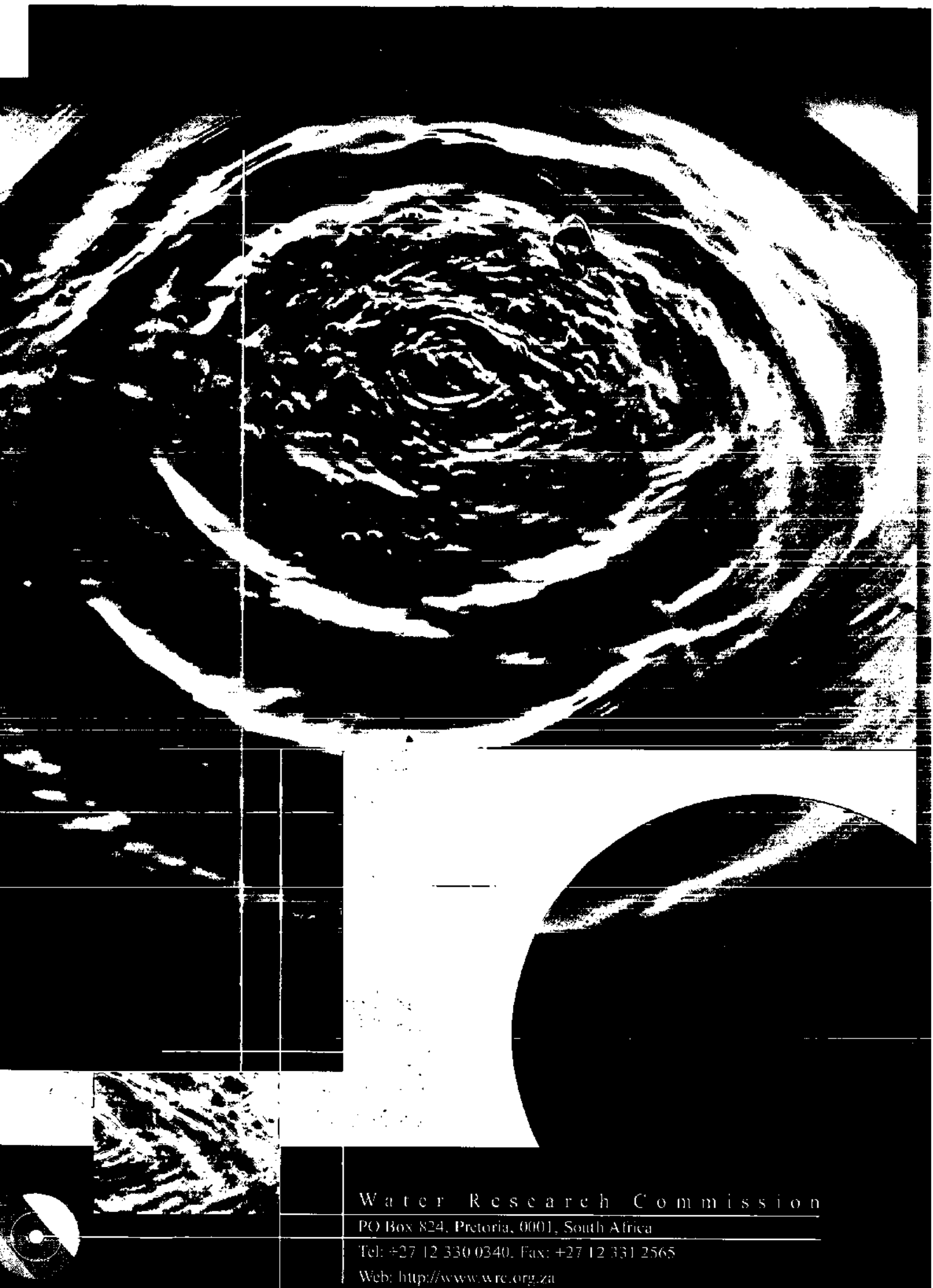

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