CHAPTER 5

FULL-SCALE INVESTIGATIONS

RESULTS AND DISCUSSIONS

5.1 INTRODUCTION

Full-scale investigations were conducted to demonstrate the validity of jar test results. The constantly changing raw water quality however does not allow sufficient time for the researcher to confirm laboratory findings under the exact same full-scale conditions.

Investigations were structured to determine the effect of the point of chlorine dosing, pH and coagulant type and dosing on the removal of different algal species and chlorophyll-*a* and on the formation of THMs.

5.2 THE REMOVAL OF DIFFERENT ALGAL GROUPS AND SPECIES

Algal cell counts and chlorophyll-*a* concentrations measured in the raw water during full-scale investigations are shown in Table 6.

Table 6: Cell counts and chlorophyll-*a* levels in the raw water during full-scale investigations.

Date		**97-09-12**	**97-09-27**	**97-10-11**	**98-02-21**	**98-02-22**
Total algae cells	Cells/ml	8850	8090	6875	955	650
Bacillariophyceae	Cells/ml	2860	3740	3150	840	300
Chlorophyceae	Cells/ml	5205	4020	3610	90	200
Chlorophyll-*a*	µg/l	145,21	44,42	28,66	18,34	8,96

Increasing light and water temperature during Spring is probably the dominant factor contributing to the increase in cell numbers observed during September. Raw water cell counts obtained during laboratory investigations as well as the numbers shown in Table 6, indicate that the spring maximum was followed by a period of low algal numbers and biomass, which extended throughout the summer. This correlates with the pattern of occurrence of algae as described by Wetzel (1983) and Visser (1997).

5.2.1 THE REMOVAL OF *Cyclotella* (BACILLARIOPHYCEAE)

Cell counts obtained by laboratory investigations indicated that *Cyclotella* was the dominant Bacillariophyceae species. High removal rates obtained for this species (> 90%) will consequently mean that similar removals can be obtained for Bacillariophyceae.

The effect of chlorination

Figure 40 shows that, even when *Cyclotella* cell numbers were high, reductions of > 90% could be obtained by coagulation and sedimentation without pre-chlorination. This is in confirmation with laboratory results which indicated that removals in excess of the average rate of 10 –70% as mentioned by Mouchet and Bonnélye (1998), can be obtained.

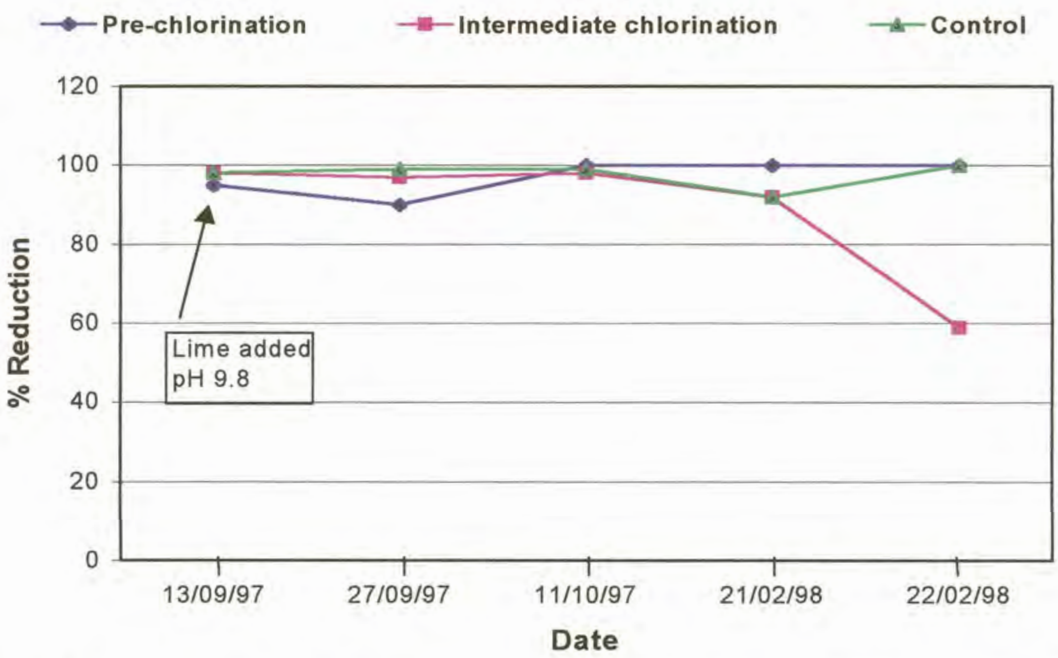

Figure 40: The effect of chlorination on the removal of *Cyclotella* cells by coagulation and sedimentation during a full-scale operation.

The poor removal of cells with intermediate chlorination during the last investigation could be due to the low cell numbers present in the raw water at the time of the investigation (the low detection causing low precision).

The effect of pH

The role of pH in the removal of *Cyclotella* cells from pre-chlorinated raw water was not significant, as illustrated in Figure 40, on 13/09/97. This is in confirmation with observations made during the laboratory investigations.

The effect of coagulants

Full-scale results are in confirmation with laboratory investigations which indicated that the removal of algal cells is enhanced by increased coagulant dosages and by the use of a poly-electrolyte as secondary coagulant. The results illustrating the effect of coagulants on the removal of *Cyclotella* cells are shown in Table 7.

Table 7: The effect of increased coagulant concentration and the addition of a poly-electrolyte on the removal of *Cyclotella* cells by coagulation and sedimentation.

Coagulants used (+ pre-chlorination: 4 mg/l)	**% Removal**
No lime added	***Cyclotella***
$FeCl_3$ 35 mg/l	88,03
$FeCl_3$ 55 mg/l	96,32
$FeCl_3$ 35 mg/l	88,71
$FeCl_3$ 35 mg/l + Poly-electrolyte (1mg/l)	97,02

As in excess of 85% of *Cyclotella* cells were already removed by 35 mg/l of $FeCl_3$, the role of coagulants appeared to be less significant.

5.2.2 THE REMOVAL OF *Chlorella* (CHLOROPHYCEAE)

The effect of chlorination and pH

The poor removal of *Chlorella* cells obtained with bench scale experiments are confirmed by the full-scale investigations. Laboratory results showed that the removal rates of some Chlorophyceae species were adversely affected when pre-chlorination was applied at increased pH-values.

Figure 41 illustrates the removal of *Chlorella* cells obtained during full-scale investigations. Proper full-scale comparisons were not possible due to operational limitations. The better results obtained with intermediate chlorination on 13/09/97 could probably be due to the effect of pH on the efficiency of chlorine as oxidant (White, 1992 and Steynberg *et al*, 1996).

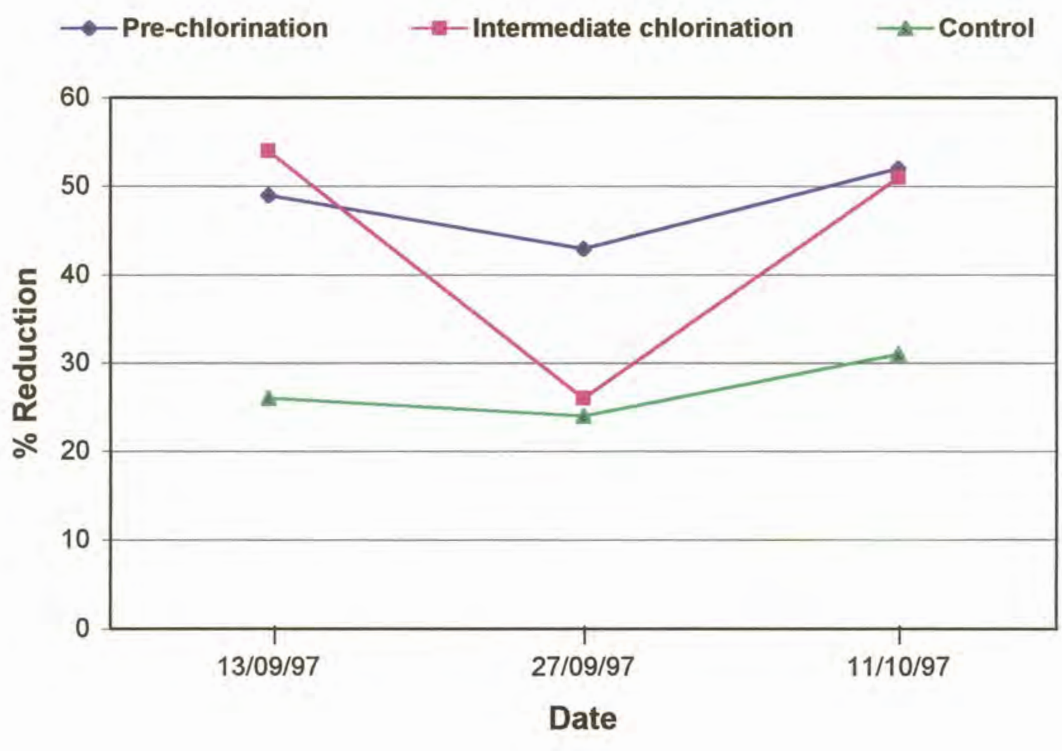

Figure 41: The effect of chlorination on the removal of *Chlorella* cells by coagulation and sedimentation.

The effect of coagulants

Table 8 shows the role of coagulants in the removal of *Chlorella* cells. As laboratory investigations proved that chlorination was necessary for the effective removal of *Chlorella* cells, pre-chlorination was incorporated.

Increasing the $FeCl_3$ dosage from 35 to 55 mg/l resulted in a 25% increase in the reduction of cells. An improvement of approximately 14% in cell removal rate was obtained by the addition of 1 mg/l poly-electrolyte as secondary coagulant, but at approximately 50% of the cost of increasing the $FeCl_3$ dosage from 35 mg/l and 55 mg/l.

Table 8: The effect of increased coagulant concentration and the addition of a poly-electrolyte on the removal of *Chlorella* cells by coagulation and sedimentation.

Coagulants used (+ pre-chlorination: 4 mg/l)	**% Removal**
No lime added	***Chlorella***
$FeCl_3$ 35 mg/l	60,04
$FeCl_3$ 55 mg/l	85,11
$FeCl_3$ 35 mg/l	61,13
$FeCl_3$ 35 mg/l + Poly-electrolyte (1mg/l)	75,08

Discussion

The removal rate of *Chlorella* cells obtained in this study corresponds with the removal rate of 10-50% mentioned by Mouchet and Bonnélye (1998). The best removals were obtained with chlorination (pre-chlorination or intermediate chlorination).

Pre-chlorination was traditionally incorporated in the treatment line at Balkfontein for the removal of *Chlorella* and *Monoraphidium* cells. Poor reductions by settling results in an increased load on the filters, shorter filter runs and frequent filter blocking and increased filter backwash. This ultimately results in increased costs and correlates with the problems experienced in the Netherlands where seasonal blooms of cyanobacteria were responsible for similar problems at treatment works (Vlaski *et al.*, 1996). During normal plant operation at the Balkfontein plant when no raw water quality problems with respect to algae are experienced, filter runs usually reach the 70-hour pre-set run time. Filter runs, however, could decrease to as low as 20–30 hours when Chlorophyceae cells are in abundance.

These full-scale results, obtained during this study, however show that intermediate chlorination can be used instead of pre-chlorination. Further full-scale investigations into the effect of intermediate chlorination on filter run time indicated that in order to obtain adequate removal of *Chlorella* and *Monoraphidium* cells, the intermediate chlorine dosage should be increased to 4 mg/l. In this way the operator can ensure extended filter run time. Although conclusions cannot readily be drawn from one set of results per investigation. The results obtained, correlates with the results obtained from a large number of laboratory experiments. It is therefore possible to conclude that the removal of algal cells can be improved during a full-scale operation by increasing the coagulant dosages or by adding a poly-electrolyte.

5.2.3 TURBIDITY

Turbidity levels in the final water were measured to investigate the correlation of turbidity with the presence of algal cells. As filtered turbidities are dependent on the run time within the cycle of the filter, turbidities were also measured directly after backwash, during filter ripening and during the normal run cycle of the filter. With intermediate chlorination filter ripening took approximately 25 minutes, whereas in the other two lines the same ripening period was approximately 90 minutes.

The results as shown in Table 9 indicate that better filtered turbidities could at times be obtained in the line where intermediate chlorination was applied.

Table 9: Turbidity levels and algal cell numbers present in the final water. (PC = Pre-chlorination; IC = Intermediate chlorination; C = Control)

Date	Total algal cells (numbers/ml)			Turbidity (NTU)		
	PC	IC	C	PC	IC	C
13/09/1997	2780	1090	1985	0,62	0,32	0,52
27/09/1997	1680	2030	1460	0,28	0,32	1,37
11/10/1997	2245	1930	2040	0,65	0,40	0,49
21/02/1999	1605	3045	2490	0,64	0,82	0,89
22/02/1999	3100	2565	2770	0,49	0,30	0,33

This shorter ripening time, in the case of intermediate chlorination, could probably be the reason for the better turbidity levels measured in this line during the full-scale investigations. The impact of intermediate oxidation on minimising the filter ripening period and significantly lowering the filtered water particle counts, was discussed in a paper presented at the IAWQ international conference in France during April, 1999 (Becker and O'Melia, 1999).

5.2.4 MICROBIAL GROWTH

The researchers Reeds, (1983) and El-Dib and Ali, (1994) emphasised the benefit of pre-chlorination with respect to the control of bacterial and algal growth in treatment units.

The long-term effect of omitting the pre-chlorination step, with respect to microbial growth, could not be evaluated during the full-scale investigation due to the specific operating procedures the operator had to adhere to. Observations made during normal day to day operation indicated that growths only became visible on the sedimentation units after approximately ten days when pre-chlorination was excluded. This was also related to algal counts and chlorophyll-*a* concentrations in the raw water. The operating procedures did not allow for a comparison to be made between the different treatment lines as all three lines werenot continuously in operation for a period longer than 72 hours. The increase in THMFP due to bacterial and algal growth could thus not be investigated.

Full-scale experience indicates that the problem with microbial growth can successfully be eliminated by intermittent chlorination. This practice, whereby pre-chlorination is introduced for 6-7 hours weekly or periodically for shorter times, ensures the control of growth in the intake and sedimentation basins.

5.2.5 CONCLUSIONS

- The laboratory findings with regard to the removal of *Cyclotella* and *Chlorella* cells are confirmed by full-scale investigations:
  - (i) Adequate removal of *Cyclotella* cells can be obtained without chlorination.
  - (i) Chlorination, other than for disinfection, should be incorporated in the treatment line for the removal of *Chlorella* cells.
  - (ii) Experimental results provide sufficient evidence for the use of intermediate chlorination instead of pre-chlorination, although probably at increased concentrations when Chlorophyceae are present in large numbers. The increased dosages contribute to increased filter run times when *Chlorella* and *Monoraphidium* cells are in abundance.
- Microbial growth in the treatment units can be controlled by intermittent chlorination when pre-chlorination is excluded.
- Whether the turbidity results are significant enough with respect to a further advantage of intermediate chlorination is not possible to conclude. Further investigations should be carried out.

5.3 REMOVAL OF CHLOROPHYLL-*a*

The effect of chlorination and pH

Laboratory experiments demonstrated the adverse effect of increased pH on the efficiency of chlorine as oxidant and the consequent poor removal of certain algal species when chlorinating at increased pH-values. Results from full-scale investigations were analysed to determine the effect of chlorination and pH on the removal of chlorophyll-*a*.

The removal of chlorophyll-*a* during a full-scale operation is illustrated in Figure 42.

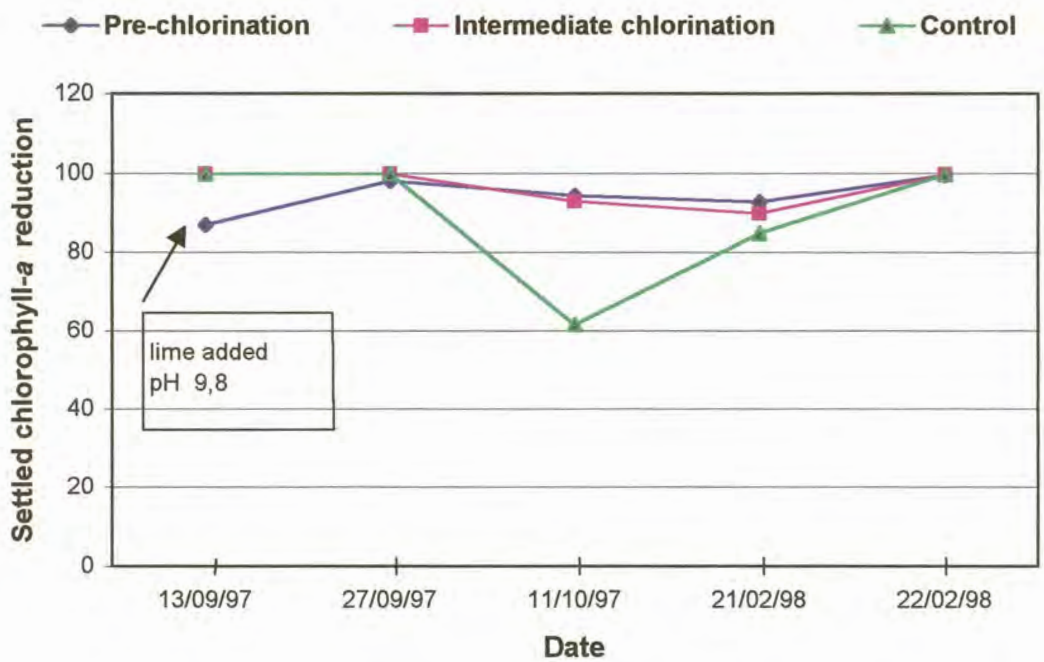

Figure 42: The removal of chlorophyll-*a* during full-scale operation.

Laboratory investigations indicated that the removal of chlorophyll-*a* was adversely affected by applying pre-chlorination at increased pH-values. The poor removal of chlorophyll-*a* obtained with pre-chlorination (as indicated in Figure 42) is in confirmation with the laboratory findings.

Despite algal cell counts of 8090 and 6875 cells/ml present in the raw water, chlorophyll-*a* concentrations could be reduced to < 1 μg/l in the final water. Although mainly Chlorophyceae contributes to chlorophyll-*a* concentrations (Visser, 1997 and laboratory investigations) the presence of chlorophyll-*a* does however not only depend on the specific algal group, species and cell numbers present but also on the size of the cells. Increases in algal cell counts therefore do not necessarily correlate with increases in chlorophyll-*a* concentrations (Mouchet and Bonnélye, 1998).

The chlorophyll-*a* concentration in the final water exceeded the 1 μg/l limit once during the full-scale investigations; this occurred when the raw water chlorophyll-*a* concentration was in excess of 100 μg/l. This is in contradiction with the research of Steynberg (1994), stating that pre-chlorination should be implemented when raw water chlorophyll-*a* concentrations are in excess of 30 μg/l. Increased coagulant dosage or optimum filter performance could probably be the reasons for the better results achieved. Results obtained during full-scale investigations furthermore indicate that intermediate chlorination can produce results which are comparable with those obtained by pre-chlorination.

Raw water chlorophyll-*a* concentrations of 8 and 16 μg/l respectively, were measured during February. At these low concentrations and low turbidities a slight algal growth in the sedimentation basins could have been responsible for as significant percentage increase in chlorophyll-*a* concentration. This could have negatively affected chlorophyll-*a* removals.

The effect of coagulants

Laboratory results showed that the type of coagulant and coagulant dosages play an important role in the removal of algae and algal related substances. It was however not possible to investigate and compare all laboratory findings on full-scale, due to the operational limitations.

The role of coagulant and coagulant dosage concentration on the removal of chlorophyll-*a*, is illustrated in Table 10. These results indicate that improvements in the reduction of chlorophyll-*a* can be obtained by increased coagulant dosage and by the addition of a poly-electrolyte.

Table 10: The effect of increased coagulant concentration and the addition of a poly-electrolyte on the removal of chlorophyll-*a* by coagulation and sedimentation.

Coagulants used (+ pre-chlorination: 4 mg/l)	**% Removal**	**Raw water Chlorophyll-*a* (µg/l)**
No lime added		
$FeCl_3$ 35 mg/l	94,06	64
$FeCl_3$ 55 mg/l	99,13	
$FeCl_3$ 35 mg/l	94,54	76
$FeCl_3$ 35 mg/l + Poly-electrolyte (1mg/l)	97,05	

Conclusions

The effect of pH, chlorination and coagulants on the removal of chlorophyll-*a*, can be summarised as follows:

1. pH and chlorination

   The full-scale investigations confirm the findings from laboratory experiments, which were conducted over a wide range of different conditions and indicates that;

   (i) the efficiency of chlorine in removing chlorophyll-*a* was adversely affected by increasing the pH

   (ii) chlorophyll-*a* could be removed effectively by intermediate chlorination even when raw water concentrations exceeded 30 µg/l.

2. Coagulants

   As only one set of analyses per investigation is available it cannot be concluded without any doubt that coagulant and coagulant dosage are positively affecting the removal of chlorophyll-*a* in a full scale operation. The results obtained are however in confirmation with bench-scale experimental results which indicated that chlorophyll–*a* removal is enhanced by increased coagulant dosage and by the addition of a poly-electrolyte as secondary coagulant.

These findings provide sufficient proof for the researcher to conclude that intermediate chlorination can be used as an economic substitute for pre-chlorination for the removal of chlorophyll-*a* at the Balkfontein plant.

5.4 THE FORMATION OF THMs

Pre-chlorination traditionally formed part of the treatment process at the Balkfontein plant mainly to address water quality problems related to the presence of algae in the raw water and to provide some degree of taste and odour control. In recent years it is also used as an oxidant for iron and manganese removal (Benefield *et al.*, 1982).

From experimental work at the Balkfontein plant and from literature it is known that pre-chlorination results in the formation of THMs. In order to produce safe water of an acceptable aesthetic quality and at the same time minimise the formation of THMs, it became necessary to verify laboratory findings by means of full-scale investigations.

The effect of chlorination

The concentrations of THMs measured in the final water after disinfection, are shown in Figure 43. The analyses were done by the CSIR and as the facility was not available for analysing all the samples, only three sets of results are used.

Figure 43 shows that the highest THM levels were measured in the line where pre-chlorination was applied and when the coagulation pH was increased to 9,8 (13/09/97). These results correlate with laboratory findings, which showed that the exclusion of pre-chlorination results in a decrease in the formation of THMs.

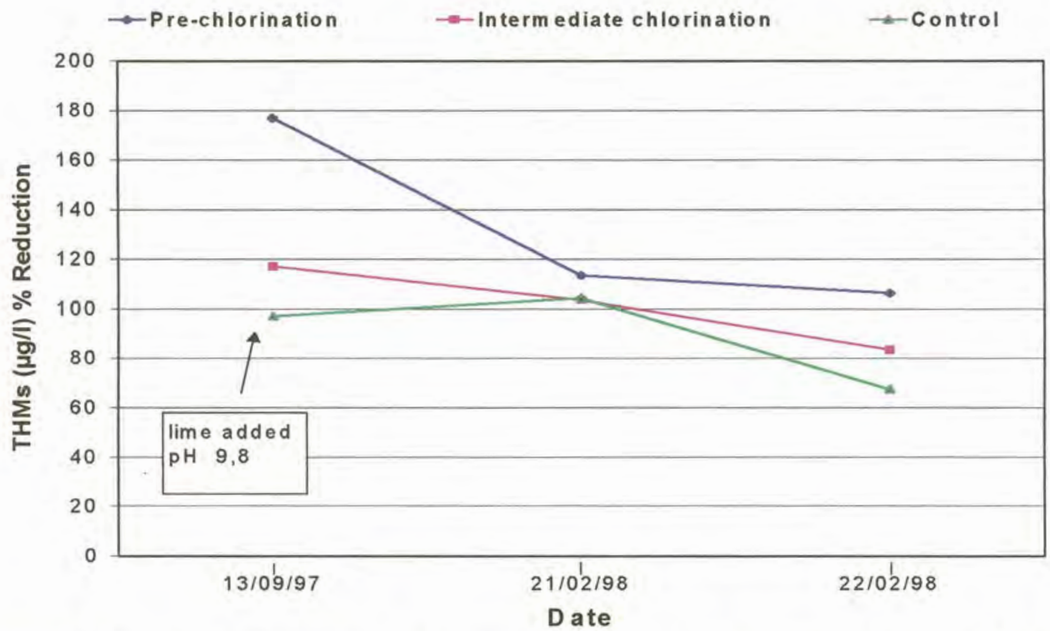

Figure 43: The formation of THMs, after disinfection, during full-scale investigations.

Chlorine reacts with the organic substances present in the water to form chlorine substituted compounds or chlorinated organics. By removing such organic substances which can act as precursors for the formation of THMs, the potential for THM formation is reduced (Wnorowski, 1992 and White *et al.*, 1997).

The effect of coagulants

Laboratory investigations showed that increased coagulant concentration and the use of a poly-electrolyte enhances the removal of DOC and therefore decreases the potential for THM formation. Full-scale results are shown in Table 11.

The introduction of pre-chlorination results in the formation of an increased concentration of THM precursors and chlorine substituted compounds. This consequently will result in poorer DOC removals and an increased THMFP. A slight improvement is however obtained by increasing the coagulant dosages or by adding a cationic poly-electrolyte. Laboratory investigations however showed that coagulant and coagulant dosage only contribute to significant enhancement of THMFP removal when pre-chlorination is excluded.

Table 11: The effects of increased coagulant concentration and poly-electrolyte on the formation of THM during full-scale operation.

Coagulants used (+ pre-chlorination 4 mg/l)	**THMs (μg/l)**
$FeCl_3$ 35 mg/l	101,7
$FeCl_3$ 55 mg/l	89,8
$FeCl_3$ 35 mg/l	106,3
$FeCl_3$ 35 mg/l + Poly-electrolyte (1mg/l)	95,7

It was reported by Steynberg *et al.*, (1996) that chlorination impairs the capability of cationic poly-electrolytes to flocculate algae. This could possibly also affect the removal of algal related products.

Conclusions

The full-scale results are in confirmation with laboratory findings and can be summarised as follows:

1. Chlorination

   It can be concluded from the full-scale investigations that the application of pre-chlorination prior to the removal of organic substances will result in an increased potential for the formation of THMs.

2. Coagulants

   Full-scale investigations into the removal of THMFP by increased coagulant dosages and the use of a poly-electrolyte, could not be investigated for different treatment options, due to operational constrictions. Sufficient proof for laboratory findings could therefore not be obtained.

5.5 SUMMARY OF CONCLUSIONS

The results obtained by bench scale experimental work are confirmed by the full-scale investigations.

Sufficient proof is provided to conclude that intermediate chlorination, increased coagulant dosages and the use of a cationic poly-electrolyte can be applied successfully for the full-scale removal of algal cells and chlorophyll-*a*. Intermediate chlorination also contributes to the removal of THM precursors and consequently the formation of less THMs in the final drinking water.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Laboratory investigations were in most cases confirmed by the full-scale investigations. The findings of this investigation can be summarised as follows:

6.1.1 THE EFFECT OF CHLORINATION ON:

The removal of algal cells

- Bacillariophyceae can be removed by the existing treatment processes without pre-chlorination.
- Chlorination has to be applied for the removal of Chlorophyceae. Intermediate chlorination, however, proves to be an economic substitute for pre-chlorination.
- The removal of algal cells by filtration is enhanced by intermediate chlorination.

The removal of organic substance and the formation of THMs

- A strong relationship exists between the presence of certain algal species and the formation of THMs. A positive correlation exists between the presence of *Cyclotella* and *Scenedesmus* and the potential for the formation of THMs.
- Pre-chlorination adversely affects the removal of organic substances and consequently increases the THMFP.
- The concentration of THMs in the final water can be lowered by removing organic material prior to chlorination. Investigations for this study demonstrate that the use of intermediate chlorination after the removal of some organic substances results in a reduction in THM formation.

The removal of chlorophyll-*a*

- Chlorophyll-*a* can be removed sufficiently by incorporating intermediate chlorination instead of pre-chlorination.

6.1.2 THE EFFECT OF pH

- Increasing the coagulation pH adversely affects the removal of some algal species.
- Increasing the pH, when pre-chlorination is excluded enhances the removal of chlorophyll-*a*. Pre-chlorination, applied for the removal of algal cells and chlorophyll-*a*, is less effective at increased pH-values.
- Increasing the coagulation pH negatively affects the removal of organic substances. At pH values > 10,4 the coagulation mechanism, however, favours the removal of DOC.
- The potential for the formation of THM increases as pH increases.

6.1.3 THE EFFECT OF COAGULANTS AND COAGULANT CONCENTRATION

- Increased coagulant dosages and the addition of a cationic poly-electrolyte as secondary coagulant enhance the removal of algal cells and chlorophyll-*a*.
- Increased coagulant dosages improve the removal of organic substances and therefore decrease the THMFP.
- The efficiency of a poly-electrolyte in removing algae is negatively affected by pre-chlorination.

6.1.4 ADDITIONAL OBSERVATIONS

- Filter ripening time appears to be shortened by incorporating intermediate chlorination.

- The application of intermediate chlorination at increased dosages positively affects the removal of algal cells (Chlorophyceae) by secondary sedimentation in this way and therefore contributes to increased filter running times.
- Intake lines and basins can be kept free of algae and slime by intermittent chlorination.

6.2 RECOMMENDATIONS

The following process choice for the Balkfontein Water Purification Works is recommended:

- Coagulation pH of 9,8 for manganese removal (when necessary).
- The addition of a cationic poly-electrolyte as secondary coagulant or the use of a metal coagulant at a dosing concentration in excess of the optimum for turbidity removal.
- The use of CO_2 after primary sedimentation, for lowering the pH.
- Intermediate chlorination (before secondary sedimentation).

6.3 FUTURE PROJECTS

- Further research is needed to optimise for the removal of iron.
- The establishment of a relationship between the presence of certain algal species and the formation of THMs.
- *Enhanced coagulation* for eutrophied waters.
- The interrelationship between all factors (raw water quality, process choice, design of works, etc.) should be taken into account and a comprehensive study is required in order to develop a process, optimising for all aspects.