Optimisation of coagulation and chlorination in drinking water treatment: laboratory and full-scale studies

N.D. Basson* and C.F. Schutte
Department of Chemical Engineering, Water Utilisation Division, University of Pretoria, South Africa
* Business address: Sedibeng Water, Private Bag X5, Bothaville, South Africa

Abstract The paper deals with laboratory and full-scale studies aimed at optimising treatment processes at the Balkfontein plant of Sedibeng Water in South Africa. The raw water is highly eutrophic and contains a large fraction of treated effluent from domestic and industrial sources as well as agricultural runoff. The eutrophic nature and changing raw water quality give rise to many operational difficulties and high treatment costs as well as problems with the final water quality. Optimisation of the coagulation and chlorination processes was seen as a cheaper solution to these problems than to install advanced processes such as ozonation and activated carbon adsorption that would add greatly to treatment costs. The laboratory studies indicated that through optimisation of coagulation-flocculation and by replacement of pre-chlorination by intermediate chlorination (after primary sedimentation) most of the treatment problems could be solved and final water of the required quality produced without a large increase in treatment costs.

Keywords Chlorination; drinking water treatment; iron and manganese removal; THM formation

Introduction
The water treatment plant of Sedibeng Water near Bothaville in South Africa with a capacity of 360 Ml/day produces potable water abstracted from the middle Vaal River. The raw water from this part of the river is highly eutrophic and contains a large fraction of treated effluent from upstream domestic and industrial sources in the Johannesburg and Vaal Triangle industrial and mining areas. The raw water quality is also subject to seasonal variations with algae blooms during spring and autumn, high turbidity during the summer rainfall months, and high organic loading during the dry winter months when most of the flow in the river is from treated return flows.

The main problems that gave rise to the project on which this paper is based, include:
• Problems related to effective removal of algae during periods of algae blooms in the raw water. This requires pre-chlorination (about 4–6 mg/l), which in turn results in taste and odour problems and in relatively high THM (trihalomethane) levels in the final water.
• Problems related to the removal of relatively high levels of iron and manganese in the raw water at times, resulting from pollution from industrial and mining activities in the catchment. Iron and manganese occur as organic complexes in the raw water, making them difficult to remove. Removal of iron and manganese also requires pre-chlorination but at elevated pH levels of about 9.6. Incomplete removal of manganese and iron results in post oxidation and coloured water in the distribution system and in staining of clothes and household equipment.
• Problems related to the removal of natural organic matter and organic matter resulting from algae lysis which act as precursors for THM formation upon chlorination.
• Operational problems of short filter runs and occurrence of biological growth in the sedimentation tanks and sand filters.

One alternative to deal with the problems of taste and odour, of excessive THM formation and of incomplete iron and manganese removal would be the implementation of advanced processes such as ozonation and activated carbon adsorption. These processes
would require a very large capital investment and would add to the operating complexity of the treatment processes. It was therefore decided to rather try and solve the problems by optimising the coagulation-flocculation and chlorination processes, which would require very little additional capital investment.

The project involved a series of laboratory studies with the objective to optimise the coagulation-flocculation and chlorination processes and to identify an optimal process configuration that would solve the treatment problems. The second phase of the project involved the implementation on full-scale of the optimal configuration in one of the three parallel modules of the treatment plant in order to verify the findings of the laboratory studies.

Historical developments

Historically, the high-lime coagulation-flocculation process at a pH of 11.2 or higher was used. At the time very few treatment problems were experienced. However, treatment costs were high and substantial sludge disposal problems were experienced. The available sludge disposal lagoons were filling up and high capital costs were needed to expand the sludge disposal facilities. This was one of the main reasons why it was decided to replace high-lime treatment with ferric chloride as primary coagulant. The new coagulation-flocculation system performed well at a much lower cost than the high-lime process and with much less sludge production.

Difficulties were however experienced during periods of algae blooms in the raw water in removing the algae effectively. Early filter breakthroughs occurred and the final water turbidity on occasions exceeded the target value of less than 1 NTU. Pre-chlorination at levels of between 4 and 6 mg/l was introduced to deal with this problem. This achieved effective removal of most algae species, but resulted in THM levels that exceeded the recommended maximum level of 100 µg/l during most of the periods when algae blooms occurred. A further problem became evident when consumer complaints were received about tastes and odours in the drinking water. These problems were caused by pre-chlorination of the raw water containing high algae counts.

At this point the water still contains dissolved and particulate contaminants, specifically organic matter which:

- Contribute to an increased chlorine demand (Van Steenderen et al., 1991);
- Upon chlorination result in the release of organic substances by algae (Bernhardt et al., 1986)
- Result in an increased potential for trihalomethane (THM) formation (Basson and Pieterse, 1993)
- Also negatively impact on tastes and odours associated with certain algae as was experienced at the Balkfontein plant.

At the time problems were also experienced with ineffective removal of iron and manganese from the raw water. Complaints were received of red water in the distribution system during certain periods and of staining of laundry. The pre-chlorination level had to be increased to 6 mg/l on occasions and the pH had to be raised to a level of about 9.6 to improve oxidation and removal of manganese. This in turn, resulted in lower removal efficiencies of the organic matter in the water that acts as a THM precursor, and therefore higher levels of THMs in the treated water. These problems prompted the search for solutions along the lines of improving coagulation-flocculation and changes to the approach to chlorination.

An alternative treatment approach which formed the basis of this project, would be to move the point of chlorine application to a position after coagulation and sedimentation where a large fraction of organic matter has been removed (Jiang and Graham, 1992). The
objective was to retain the benefits of pre-chlorination while minimising the negative effects.

Table 1 gives an indication of the relatively poor quality of the raw water during 1998 when the studies were conducted. The final water quality as well as the South African target water quality for certain parameters in drinking water is also given.

**Treatment plant layout**

The treatment plant layout is shown in Figure 1. It consists of three modules operated in parallel, each with a capacity of 120 megalitre per module.

Pre-chlorination is applied ahead of coagulation, followed by lime to increase the pH to about 9.6. The pH is reduced by addition of carbon dioxide after primary sedimentation to around 8. Modules 2 and 3 of the plant were used for the full-scale experimental work. Module 3 consists of four similar sections. Chlorine-dosing points were installed in two sections of Module 3, after primary sedimentation, to investigate the effect of intermediate chlorination. The other two sections of this module were used for control purposes. Module 2 was used to investigate the role of pre-chlorination.

**Laboratory studies**

The laboratory studies involved different series of jar tests conducted on a microprocessor-controlled apparatus. The procedure was aimed at simulating the coagulation-flocculation process in the treatment plant.

**Table 1** Quality of raw and treated water at the Balkfontein plant

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Raw water: Average</th>
<th>Raw water: Maximum</th>
<th>Treated water: Average</th>
<th>Treated water: Maximum</th>
<th>Target water quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>48</td>
<td>265</td>
<td>0.6</td>
<td>2.9</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>TDS</td>
<td>mg/l</td>
<td>372</td>
<td>698</td>
<td>363</td>
<td>572</td>
<td>&lt;450</td>
</tr>
<tr>
<td>pH</td>
<td>8.7</td>
<td>9.8</td>
<td>8.2</td>
<td>11.0</td>
<td>6–9</td>
<td></td>
</tr>
<tr>
<td>DOC</td>
<td>mg/l</td>
<td>8.1</td>
<td>10.3</td>
<td>7.1</td>
<td>8.4</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Manganese</td>
<td>µg/l</td>
<td>122</td>
<td>858</td>
<td>27</td>
<td>156</td>
<td>&lt;50</td>
</tr>
<tr>
<td>Iron</td>
<td>µg/l</td>
<td>468</td>
<td>13111</td>
<td>118</td>
<td>560</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Chlorophyl-a</td>
<td>µg/l</td>
<td>47</td>
<td>290</td>
<td>0.8</td>
<td>4.2</td>
<td>&lt;1</td>
</tr>
<tr>
<td>THM</td>
<td>µg/l</td>
<td>–</td>
<td>–</td>
<td>102</td>
<td>131</td>
<td>&lt;100</td>
</tr>
</tbody>
</table>
and sedimentation full-scale processes. Comprehensive testing by means of jar tests was done to establish and compare the effect of chlorination, coagulants and coagulant dosages at different pH levels on the removal of algae, organic matter, iron and manganese and on the formation of THMs. The procedure was aimed at simulating the treatment process of coagulation and settling, retaining the advantages of chlorination in the removal of algae and at the same time reducing the THM formation potential (THMFP).

The tests were conducted in sets of six samples (one litre each) in square beakers according to the procedure described in Table 2. Ferric chloride supplied as a 43% FeCl₃ solution, was used as primary coagulant. Dosing concentrations are expressed as mg FeCl₃ per litre raw water. A cationic organic polymeric coagulant was used as secondary coagulant. A chlorine stock solution was made by bubbling chlorine gas through deionised water (Steynberg et al., 1996).

In the case of pre-chlorination, the samples were stirred for one minute at 250 revolutions per minute (rpm) after the addition of the chlorine solution. The addition of the primary coagulant was followed by rapid stirring at 250 rpm for two minutes. The stirring time was however changed to one minute when a secondary coagulant was used. After adding the secondary coagulant, further stirring for one minute, at 200 rpm, followed. Flocculation was simulated by stirring at 40 rpm for eight minutes. The sample was stirred for one minute at 25 rpm after intermediate chlorination.

The supernatant of each sample was drawn off after the prescribed settling times. To compare jar test results with sand filtered water, the supernatant in each case, was filtered through a Whatman No. 1 filter paper. Samples were analysed for pH, turbidity, THMs, iron and manganese as well as algae identification.

**Results**

Due to length restrictions, only the results for chlorophyll-a removal are given in detail while results on removal of other parameters are given in summarised form. Detailed results are reported elsewhere (Basson, 2000).

**Chlorophyll-a removal**

Chlorophyll-a concentrations in the raw water varied between 14 and 158 µg/l during the test period. Peak values were measured during August and September. During this period, between 60 and 95% of the total algae population was from the Chlorophyceae group. The effect of chlorination on the removal of chlorophyll-a is shown in Figure 2.

*The effect of chlorination.* A comparison between the chlorophyll-a reductions obtained when applying chlorine at different dosing points is illustrated in Figure 2 (no lime was added). These results indicate that there was almost no difference in the removals obtained by pre-chlorination and intermediate chlorination. The benefits of pre-chlorination can

<table>
<thead>
<tr>
<th>Table 2</th>
<th>The procedure for conducting jar tests (+ indicates the procedure was included, – not included)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control (C)</td>
</tr>
<tr>
<td>Pre-chlorination 4 mg/l</td>
<td>–</td>
</tr>
<tr>
<td>Primary Coagulant FeCl₃ (various concentrations)</td>
<td>+</td>
</tr>
<tr>
<td>Secondary Coagulant (cationic poly-electrolyte: 1 mg/l)</td>
<td>+</td>
</tr>
<tr>
<td>Flocculation</td>
<td>+</td>
</tr>
<tr>
<td>Sedimentation</td>
<td>20 min</td>
</tr>
<tr>
<td>Chlorination of supernatant 2 mg/l</td>
<td>–</td>
</tr>
<tr>
<td>Sedimentation</td>
<td>–</td>
</tr>
</tbody>
</table>

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therefore be obtained at a decreased cost and with fewer water quality problems when pre-chlorination is replaced by intermediate chlorination.

**The effect of coagulants.** Chlorophyll-a removal was enhanced by the addition of 1 mg/l of a poly-electrolyte as a secondary coagulant. The improvement obtained was more significant when pre-chlorination was excluded and at the lower FeCl₃ dosage concentrations. These results also indicate that poly-electrolyte could be used for the removal of chlorophyll-a concentrations exceeding 30 µg/l instead of applying pre-chlorination. Improved removal at the higher coagulant concentrations could be related to the higher coagulant demand due to organic substances present in the water (Edzwald, 1993). The effect of pre-chlorination on the removal of chlorophyll-a was more significant at lower coagulant dosages than at the higher dosages, probably due to the fact that the coagulant demand was not satisfied at the lower dosages and that pre-chlorination, under these circumstances, could add positively to the removal of chlorophyll-a. Chlorination however, adversely affects the role of poly-electrolytes (Steynberg, 1994) and therefore the smaller impact on chlorophyll-a removal in the pre-chlorinated samples.

**THM formation**

Results on the formation of THMs upon post chlorination for different treatment options are given in Table 3.

The results in Table 3 show that less DOC removal was achieved at the higher pH values and when pre-chlorination was applied. This consequently resulted in higher THM formation at higher pH values. Increasing the pH to 11.4 however enhanced the removal of organic substances due to precipitation of Mg(OH)₂.

**Full-scale studies**

Based on the laboratory studies it was concluded that the operational and water quality problems could to a large extent be eliminated by replacing pre-chlorination with intermediate chlorination (after primary sedimentation) and by improving coagulation-flocculation (with higher dosages and addition of a secondary coagulant). One of the 120 megalitre modules was operated with this configuration while the other two modules were operated according to the old configuration with pre-chlorination. The performance of the modules

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![Figure 2](https://iwaponline.com/ws/article-pdf/2/2/131/408103/131.pdf)  
**Figure 2** The effect of moving the point of chlorine dosing on chlorophyll-a removal
was monitored over a period of a week for four different test runs in an attempt to investigate different raw water qualities.

**Chlorophyll-a**

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

**pH and chlorination.** The full-scale investigations confirmed the findings in laboratory experiments, which were conducted over a wide range of different conditions:

- the efficiency of chlorine in removing chlorophyll-a was adversely affected by increasing the pH
- chlorophyll-a could be removed effectively by intermediate chlorination even when raw water concentrations exceeded 30 µg/l

From these findings it can be concluded that intermediate chlorination can be used as an economic substitute for pre-chlorination for the removal of chlorophyll-a at the Balkfontein plant.

**Coagulants.** As only one set of analyses per test run is available it cannot be concluded without any doubt that coagulant and coagulant dosage are positively related to the removal of chlorophyll-a in the 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.

**THM Formation during full-scale runs**

The concentration of THMs measured in the final water after disinfection is shown in Figure 3. The highest THM levels were measured in the line where pre-chlorination was applied and when the coagulation pH was 9.8. These results correlate with laboratory findings, which showed that the replacement of pre- by intermediate chlorination results in a decrease in THM formation.

**Removal of iron and manganese**

The removal of these metals presents problems during certain periods, even at relatively high pH levels and with high chlorine dosages. The factors that affect removal form the basis of further studies. At this stage the only conclusion that could be made is that the metals occur as organic complexes that are stable and difficult to break down and therefore difficult to remove to low levels.

**Conclusions**

The problems with final water quality and with certain aspects of the operation of the
Balkfontein plant could to a large extent be solved by replacement of pre-chlorination with intermediate chlorination and by improvement of the coagulation-flocculation process. Maximum removal of algae and organic matter by enhanced coagulation-flocculation before intermediate chlorination results in lower THM formation and fewer problems with taste and odour in the final water. Operating experience has shown that occasional pre-chlorination (a few hours per week) is still necessary to prevent biological growth in intake lines and primary sedimentation, but this does not affect the final water quality.

References


Figure 3 The formation of THMs after disinfection during full-scale operation