Investigation into the implementation of chloramination at Sedibeng Water

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Abstract The Balkfontein and Virginia plants of Sedibeng Water, situated in the Free State Province of South Africa, treat water for potable purposes. Chlorine is used as disinfectant at both plants. Low levels of free chlorine measured in the water supplied from some reservoirs, logistics and costs, related to the application of chlorination at various points in the distribution system, were the main thrusts for an investigation into the use of chloramination as an alternative means of disinfection.

The so-called contact time (CT)-approach from the United States Environmental Protection Agency was applied for the evaluation of disinfection efficiency. The distribution system was modelled by using a hydraulic computer system. Decay rates for both chlorine and monochloramine – a vital parameter for eventual determination of the amount of chlorine and ammonia to be dosed – were determined. The levels of disinfectant in the water at a specific location could be predicted by using the decay values.

The main findings of this investigation are that chloramination is an attractive and cost-effective alternative for conventional chlorination for providing quality assurance to all. It is estimated that the capital layout will be recovered within one year of operation of the ammoniation system.

Keywords Chloramination; decay rate; disinfection; Sedibeng; South Africa

Introduction

The Balkfontein and Virginia plants of Sedibeng Water, situated in the Free State province of South Africa, treat water for potable purposes. Chlorine is used as disinfectant at both treatment plants. The disinfection of water after treatment is a vital prerequisite before it can be distributed to consumers. Switching from chlorine to chloramines is not simply exchanging two equivalent methodologies. Each method has its own benefits and pitfalls that have to be thoroughly evaluated before implementation.

Chlorine reacts with water to form hypochlorous acid, chloride ions and protons as indicated in equation 1 and typically reaches completion in 100 ms.

$$Cl_2 + H_2O \leftrightarrow H^+ + HOCl + Cl^- \qquad (1)$$

The hypochlorous acid is a relatively weak acid, which undergoes slight dissociation.

$$HOCl \leftrightarrow H^+ + OCl^- \qquad (2)$$

At a pH of 7.5, the activities of HOCl and OCl^- are equal and when the pH drops below 7.5, HOCl predominates while OCl^- is the dominant species at pH above 7.5. HOCl is a more effective disinfectant than the OCl^- ion and at pH 4, practically all the available chlorine is present as active HOCl. As the pH increases, the concentration of OCl^- ions increases and at pH 10, only OCl^- ions are present. pH control is therefore a critical factor in determining the degree of disinfection achieved by a certain level of chlorine. Chlorine is also a strong

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oxidant and reacts with normal organic matter (NOM) in the water to from disinfection byproducts (DBPs) such as trihalomethanes (THMs). Apart from organic matter, chlorine also reacts with nitrogen to form chloramines. The concentration of interfering substances will therefore have a marked effect on the effectiveness of chlorine as disinfectant.

Chloramines, on the other hand, are formed from the reaction between chlorine and ammonia. The mixture that results may contain monochloramines (NH_2Cl), dichloramine ($NhCl_2$) or trichloramine (NCl_3). The simplified stoichiometry of chlorine–ammonia reactions is as follows:

$$NH_3 + HOCl \rightarrow NH_2Cl + H_2O \quad \text{(monochloramine)} \quad (5)$$

$$NH_2Cl + HOCl \rightarrow NHCl_2 + H_2O \quad \text{(dichloramine)} \quad (6)$$

$$NHCl_2 + HOCl \rightarrow NCl_3 + H_2O \quad \text{(trichloramine)} \quad (7)$$

$$2NH_2Cl + HOCl \rightarrow N_2 + H_2O + 3HCl \quad \text{(monochloramine)} \quad (8)$$

$$NH_2Cl + 3OCl^- \rightarrow NO_3^- + 4Cl^- + 2H^+ \quad \text{(nitrate)} \quad (9)$$

These competing reactions are primarily dependent on pH and controlled to a large extent by the chlorine:ammonia nitrogen (Cl_2:N) ratio. Monochloramine is predominantly formed when the applied Cl_2:N ratio is less than 5:1 by weight. As the applied Cl_2:N ratio increases from 5:1 to 7.6:1, the so-called breakpoint reaction occurs, reducing the residual chlorine level to a minimum. Breakpoint chlorination results in the formation of nitrogen gas, nitrate and nitrogen chloride. At Cl_2:N ratios above 7.6:1, free chlorine and trichloramines are present.

The sum of the concentrations of the three chloramines species is typically referred to as combined chlorine while the sum of the free and combined chlorine concentrations is referred to as total chlorine.

Situation in South Africa

Chloramination is practiced at the following known facilities in South Africa:

- the 180 Mℓ/d Vaalkop water treatment plant of Magalies Water;
- the 120 Mℓ/d Umzoniana water treatment plant in East London;
- the Rand Water water treatment plant where ammonia is added at the Swartkoppies pumping station;
- the Umgeni Water treatment plants at Hazelmere, Umlaas, DV Harris and Midmar.

A common denominator of the above plants is the retention times in the distribution network, which at times can be in excess of two weeks. Practical information on the implementation of chloramination could thus be obtained from these facilities.

Contact time requirements for disinfectants

The effectiveness of disinfectants is determined by using the product of the final residual concentration of disinfectant (in mg/l) and the contact time (CT) (in minutes) that the residual disinfectant is in contact with the water. The Environmental Protection Agency of the United States (USEPA) has developed CT values for inactivation of *Giardia* cysts and viruses using several disinfectants under specified conditions.

The surface water treatment rule (SWTR) in the USA requires that filtration and disinfection must be provided to ensure that the total treatment of the system achieves at least a 3-log removal/inactivation of *Giardia* cysts and a 4-log removal/inactivation of viruses. In addition to this, the disinfection process must demonstrate, by continuous monitoring, that the disinfectant residual in the water entering the distribution system is never less than 0.2 mg/ℓ for more than 4 hours.

For the implementation of chloramination at Sedibeng Water, the aim will therefore be to provide for sufficient CT and to ensure that a residual of 0.2 mg/l can be maintained. The results of field tests performed on the filtered water will enable the determination of the decay rate of the disinfectants. This can in turn be used for the determination of the CT values.

Field tests

Decay rates were determined on water samples from both the Virginia and Balkfontein plants. The results were used to enhance the application of the decay rate models in the determination of rate constants. The following equation was applied to calculate decay rates for chlorine and chloramines:

$C(t) = C_o e^{-kt}$

where:

$C(t)$ = calculated disinfectant concentration after time t (mg/l);

C_o = initial disinfectant concentration (mg/l);

k = decay rate (1/h);

t = time (h).

In general, the demand for disinfectants is lower for the Virginia water than for the Balkfontein water.

Figure 1 indicates the decay of chlorine and monochloramine in filtered water from Balfontein and Virginia over a 3-day period. The initial concentration was chosen as 1.5 mg/l, which is typical for the final water leaving the clear water well after 2 hours. It can be seen that, after 3 days, the concentration of the chlorine has declined to approximately 0.2 mg/l, which is the minimum level proposed by the SWTR. In contrast with this, the chloramines levels in the water were in excess of 1.2 mg/l.

Having obtained the decay rates for the disinfectants, the next step was to determine the

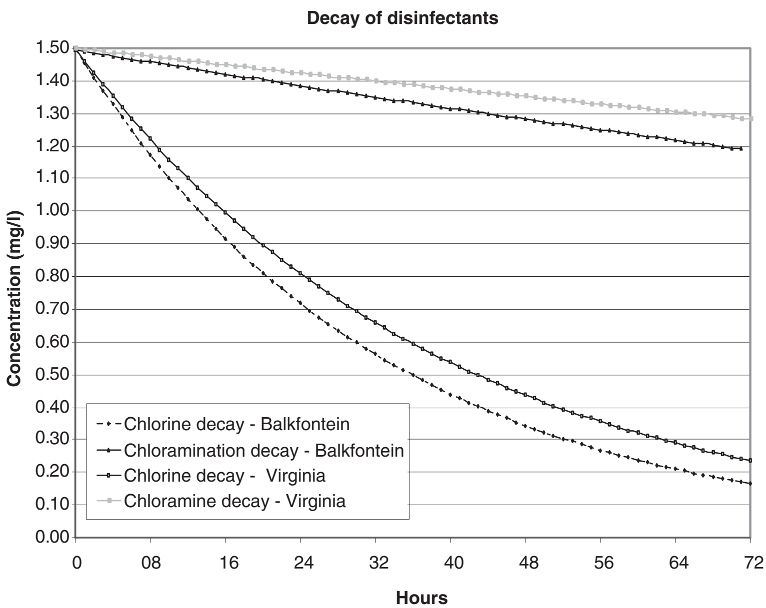

Figure 1 Decay of chlorine and monochloramine

retention time in the distribution system. With the retention time and the decay rates known, it was now possible to calculate the concentration of the disinfectant at the beginning of the distribution system by means of a method of back calculating, using a final concentration of say 0.4–0.6 mg/l at the furthest point.

Retention time in the distribution system

EPANET, a simple hydraulic computer programme that models the distribution system (pipes, pumps and reservoirs), was used to determine the retention times in the distribution system. The programme has the ability to determine eventual age of the water at any given point as well as concentrations of chemicals. The decay rate of the disinfectant is an input value to the model and provides an easy method of back calculating the initial concentration required at the starting point of the system. This model can also be controlled by means of a set of rules whereby the levels in the reservoirs and the time of pumping can be controlled. At the Balkfontein plant, where pumping is mainly done during the night, this rule-based method will be used to override a case where, for instance, a reservoir "requests" water but is prohibited due to the operational procedure.

Figure 2 shows the system between Balkfontein and Bothaville. From the age analysis it is indicated that the age of the water, as it leaves the reservoir at Bothaville, could vary between 140 and 160 hours. The maximum retention time in the system was 400 hours.

The concentration of chlorine and monochloramine for the above system is shown in Figures 3 and 4. The superior resistance of monochloramine with regard to decay, is clearly illustrated.

Discussion

As chlorine is currently used as disinfectant at both these plants, it is ideal to make use of the superior disinfection properties of free chlorine in the clear water reservoir on site whilst benefiting from the advantages of the much slower decay rate of monochloramine in the distribution system. Results on decay rate analyses indicate that the immediate chlorine demand of filtered water at the Balkfontein plant is about 1.4 to 1.9 mg/l. Figure 1 indicates chlorine decay after this immediate demand was satisfied. Chlorine is currently dosed at a dosage concentration of 5 mg/l at the clear water reservoir. With an immediate demand of say 2 mg/l, a chlorine residual of 3 mg/l could be present in the clear water reservoir at the

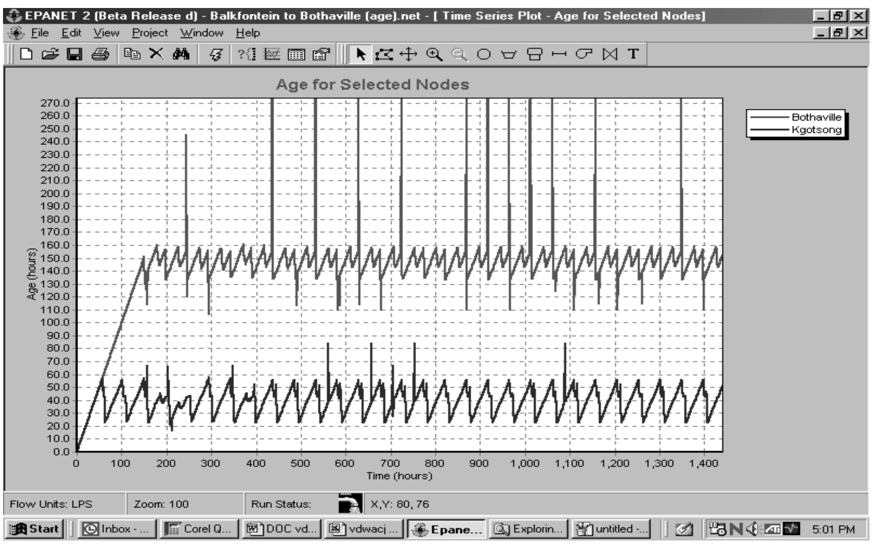

Figure 2 Age of the water in the distribution system to Bothaville and Kgotsong reservoirs

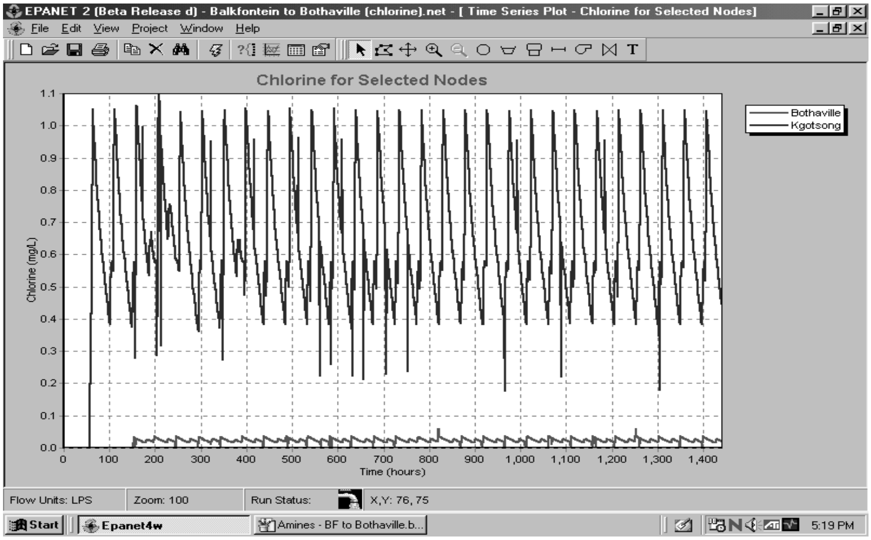

Figure 3 Chlorine levels in the reservoirs of Bothaville and Kgotsong

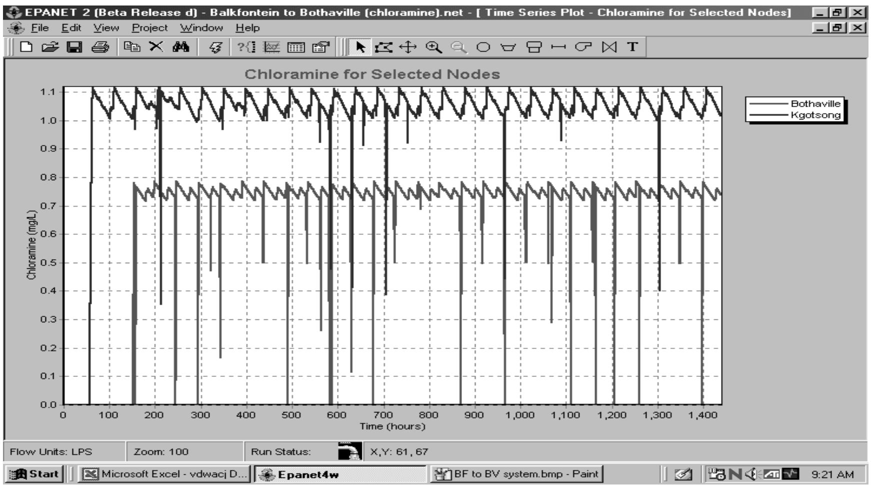

Figure 4 Monochloramine levels in the reservoirs of Bothaville and Kgotsong

start of the 2-hour period. The CT value achieved in this way will be 350 mg/l.min which is three times more than the 104 mg/l.min required for inactivation of *Giardia* with chlorine. However, the use of chloramines at this point will result in a CT value of 359 mg/l.min, which is not sufficient (1,850 mg/l.min is required using chloramines). Should the dosage at the beginning of the clear water reservoir be reduced to 3.5 mg/l, the immediate chlorine demand will reduce chlorine levels at the start of the clear water reservoir to 1.5 mg/l. It can be indicated that, by using the determined decay rates, free chlorine levels in the water will be 1.4 mg/l after two hours. At these levels, the CT values achieved in the clear water reservoir can be calculated as 174.5 mg/l.min – still above the recommended levels of 104 mg/l.min.

The decay rates calculated indicate that it is possible to achieve a CT value of 1,850 mg/l.min with monochloramines after about 27 hours with a concentration of 1.2 mg/l after the clear water reservoir. The EPANET model indicates a situation where most of the reservoirs will have the added benefit of not only maintaining disinfectant levels above 0.2 mg/l but also providing a second barrier for the inactivation of *Giardia* by reaching the CT value where 99.9% of *Giardia* present in the water will be inactivated.

The advantage of using chloramination is not only related to water quality but chloramination is also a cost effective alternative for chlorination. The unit cost of adding ammonia at Balkfontein was estimated at 0.4 c/m^3 and at Virginia at 0.76 c/m^3. It is foreseen that the chlorine cost will be reduced by about 30% (dosing 3.5 mg/l instead of the current 5 mg/l) bringing the cost of chlorination down from 4 c/m^3 to about 3 c/m^3. A further cost saving will be brought about by the termination of chlorination at booster pump stations in the network once chloramination has been implemented. This additional dosing of chlorine currently amounts to about Rand 1 million per annum and was implemented to obtain the required free chlorine residual in the distribution system.

Conclusions

The findings of this investigation can be summarised as follows.

It is possible to obtain a CT value of 1,850 mg/l.min with chloramines after about 27 hours by providing sufficient contact time after chlorination and before the addition of ammonia.

Disinfectant levels in excess of 0.2 mg/l can be maintained in the distribution system.

The inactivation of Giardia cysts will be enhanced due to the fact that it is possible to obtain CT values required for a 99.9% removal of the cysts.

A cost saving will be obtained as result of lower chlorine dosing concentrations on site and the termination of chlorination in the distribution system.

It can be concluded that chloramination proofed to be a cost-effective alternative for conventional chlorination in the supply of potable water.

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