

Assessment of chloramination control strategy based on free-ammonia concentration

Skadi Motzko, Rolando Fabris, Alexander Badalyan, Ralph Henderson, Christopher W. K. Chow and Dammika Vitanage

ABSTRACT

A new approach of using free-ammonia measurements as the basis of a control strategy to optimise a chloraminated water distribution system was tested in a laboratory evaluation. A test rig with a newly developed low level on-line free-ammonia analyser was constructed to investigate two different control configurations, the currently used feedback and the proposed feedforward. The results of this trial showed that only using the free-ammonia analyser for feedback control is not ideal due to its inability to detect chlorine overdosing situations. Better results regarding the maximum yield of disinfectant residuals when using the feedforward configuration were observed, and free-ammonia concentrations below 0.065 mg/L were consistently achieved.

Key words | ammonia monitoring, chloramination control, control strategy, disinfection

Skadi Motzko
Rolando Fabris
Alexander Badalyan
Christopher W. K. Chow (corresponding author)
Dammika Vitanage
Cooperative Research Centre for Water Quality and Treatment,
Private Mail Bag 3, Salisbury, SA 5108,
Australia

Skadi Motzko
Rolando Fabris
Christopher W. K. Chow (corresponding author)
Australian Water Quality Centre, PMB 3,
Salisbury, South Australia 5110,
Australia
E-mail: Chris.Chow@sawater.com.au

Skadi Motzko
Department of Process Engineering,
Georg-Simon-Ohm-Fachhochschule Nürnberg,
Wassertorstraße 10, D-90489 Nurnberg,
Germany

Alexander Badalyan
Sansom Institute, University of South Australia,
City East Campus, Adelaide,
South Australia 5095,
Australia

Ralph Henderson
Water Corporation, 629 Newcastle Street,
Leederville, Western Australia 6007,
Australia

Dammika Vitanage
Sydney Water Corporation,
115-123 Bathurst Street, Sydney, NSW 2000,
Australia

INTRODUCTION

Public health is an essential consideration for water utilities as a duty of care for consumers. The primary task of drinking water quality managers is to ensure supply of safe and high quality potable water to all customers. Maintaining disinfectant residuals within suitable ranges throughout a distribution system is one of the key parameters to achieve this goal.

In several countries, two of the most commonly used disinfection methods are chlorination and chloramination.

Chlorine has traditionally been a more popular choice but, in recent years, many water utilities have chosen chloramination as their disinfection regime. This is a practical solution to maintain residuals in longer distribution systems as the disinfectant residuals are reported to be more stable in comparison to disinfection by chlorine. In addition, since monochloramine is a less powerful oxidant than chlorine, chloramination can produce less disinfection by-products

doi: 10.2166/aqua.2009.068

and less taste and odour issues in water. However, chloramination requires significantly more careful control of water chemistry to maintain residuals and ensure pathogen inactivation throughout the distribution system (Miller *et al.* 1995; McMorran & Moriarty 1997; Powell 2004; Regan *et al.* 2004). This presents a challenge, particularly to operators, who control secondary disinfection via feedback control loops (Fitzgerald *et al.* 2006). Applied doses that are either too high or too low are often identified too late for an operator to react and to take corrective action (Hua *et al.* 1999; Rodrigues & Serodes 1999).

On-line water quality sensors have been used in drinking water utilities for a number of purposes including feedback control of the disinfection process and rapid detection of various chemical or biological contaminants (Hall *et al.* 2007). The interest in using ammonia measurements in chloraminated system (Yasue & Kitaoku 2000; Wilczak *et al.* 2003) is to minimise the risk of over- or under-dosing of ammonia, which adversely affects residual decay and the nitrification potential (rapid decay) in the distribution system. Optimising chlorine-to-ammonia feed ratio at water treatment plants and re-dosing stations will minimise available ammonia in the distribution system, thus reducing the occurrence of nitrification.

In current practice, free-ammonia monitoring (free ammonia is the portion of ammonia that has not combined with chlorine in chloraminated water) is only used to alert operators when the ammonia concentration after chloramination is too high (Brokenshire & Cumming 1995; Hall *et al.* 2007). In this paper, a custom-built on-line free-ammonia analyser was used in a laboratory control system to simulate a chlorine re-dosing station within a drinking water distribution network. Control configurations using free-ammonia measurements (feedback and feedforward control) and their effect on the effectiveness of chloramination were examined.

ANALYSIS OF THE MODELLED WATER DISTRIBUTION SYSTEM

For the present study, a distribution system in Western Australia was selected for modelling the chloramination control of a re-dosing station. The Goldfields & Agricultural

Water Supply (GAWS) system is located east of Perth, Western Australia (Figure 1). It starts in the Perth Hills at the Mundaring Reservoir (ca. 40 km from Perth). The main conduit transfers water from there to the goldfields of Western Australia over a distance of approximately 560 km. The system is split into several extension areas, where branches from the main pipe supply water to farmlands and smaller towns.

Primary disinfection takes place at Mundaring pump station. First, chlorine is added to achieve a total chlorine residual of 3.6 mg/L. Chlorine gas is fed straight into the main pipe via a diffuser. Ammonia solution (20% w/v) is dosed downstream, directly into the pipe to form chloramines. The time gap between the chlorine and ammonia dosing is a few seconds. The targeted free-ammonia residual is lower than 0.2 mg/L.

The laboratory control experiment simulated the re-dosing station in York. The town of York is located on the BG extension to the south of the main conduit. The extension is about 65 km long and is fed by the West Northam Tanks with chloraminated water coming from Mundaring. Water in York is supplied from two tanks (2 ML and 2.25 ML), where the east tank supplies Beverley, a town at the end of the extension. The east tank in York is located approximately 33 km from the offtake. After the tank, a chlorine booster station is installed to maintain a certain disinfectant residual until Beverley and, therefore, to top-up any remaining residual in the water after the tank. The mobile chlorinator is placed next to the water-conveying pipe coming from the tank and consists of a dosing pump which pumps a sodium hypochlorite solution from a small tank into the water pipe via a diffuser. Chlorine dosing is automatically adjusted by measuring the flowrate of the water in the pipe (flow-paced).

The control of secondary disinfection in York is carried out manually once a week in a feedback control configuration. The total available chlorine residual is measured approximately 50 m after the dosing point with a portable test kit (Method 8167—HACH GmbH, Germany). Taking into account disinfection experiences along the BG extension, the chlorinator is manually adjusted, targeting a total available chlorine residual of 3.0–3.2 mg/L.

Additional samples for monitoring are taken twice per week and analysed in the field for chloramine and ammonia

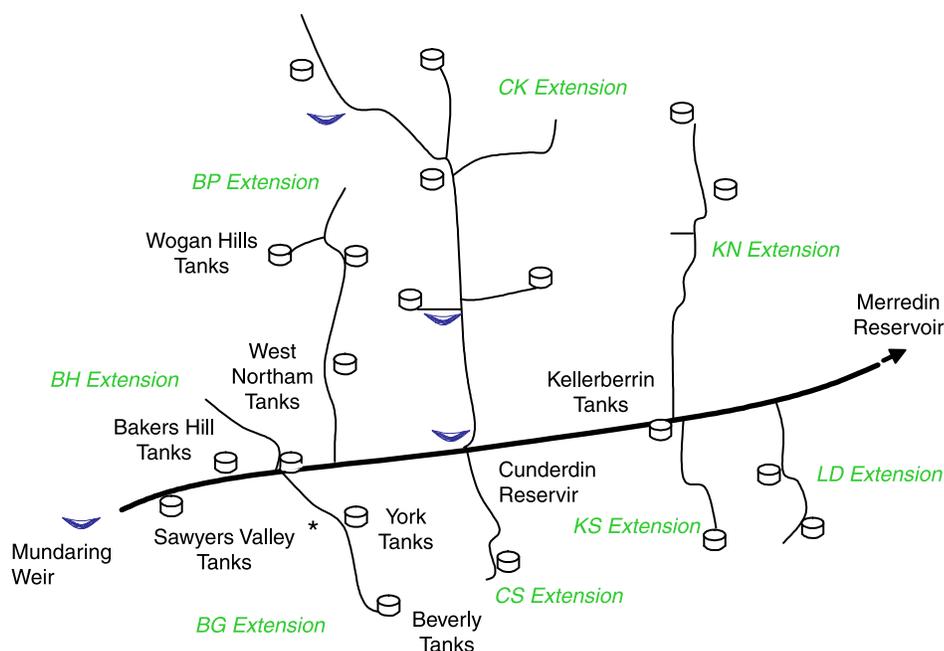


Figure 1 | Schematic diagram of the first part of the GAWS system. * York re-dosing station.

residuals in the water using a portable test kit (Method 10045–HACH GmbH, Germany) for nitrogen as monochloramine and free ammonia.

EXPERIMENTAL

Experimental apparatus

To simulate the re-dosing procedure at the dosing point in York, the applied detention time was required as a starting point. The detention time (t) is defined as the time taken by a fixed volume of water to travel from the dosing point to the sample point. The detention time (t) is determined by the internal diameter and length of the pipe and changes with a variable flow rate. It can be expressed as

$$t = \frac{V}{\dot{V}} \quad (1)$$

where \dot{V} stands for a certain flow rate and V represents the volume of the considered pipe section. The evaluated detention time of the selected system was 16.4 min. As the chlorine re-dosing operation in York is flow-paced, the water flow rate (\dot{V}) in the laboratory simulation was constant.

Figure 2 shows the layout of the constructed experimental test rig including feedback and feedforward control configurations (Figure 3). Water flow from the 50 L reservoir tank was regulated by a peristaltic pump through a polybutene tube coil (tube internal diameter, $D_{in} = 12 \times 10^{-3}$ m and tube length, $L = 6$ m) providing the system detention time. The flow rate was monitored with an in-line flowmeter (rotameter). For the laboratory simulation, a water flow rate of 2.5 L/h was chosen to provide the on-line ammonia analyser with the necessary sample volume and additionally for the periodic grab samples for other analyses.

For feedback control configuration, the on-line free-ammonia analyser was connected with the main tube 6 m after the dosing point. A sample point was set up after the analyser connection for confirming results by other analyses.

The required chlorine flow rate was given by a second peristaltic pump where the flow rate through tubing with internal diameter, $D_{in}^{Cl_2} = 1.83 \times 10^{-3}$ m, was adjusted according to the measured ammonia concentration. Pumps and the universal flowmeter were calibrated to ensure accurate flow rates. For the chlorine dosing procedure a sodium hypochlorite solution (NaOCl) with a concentration of 50 mg/L (as chlorine) was prepared. The following subsection shows the calculation for the required chlorine flow rate.

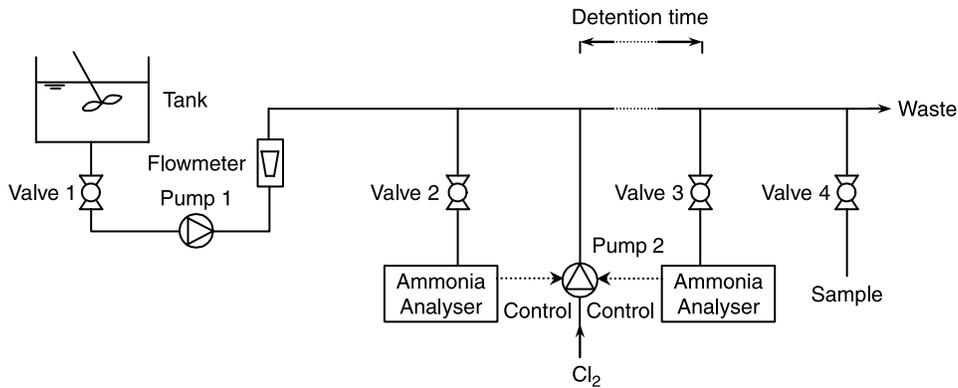


Figure 2 | General layout of the experimental test rig.

Calculation of chlorine dosing

For control purposes, the following considerations with respect to chlorine flow rate were made. The chlorine flow rate required to convert a certain ammonia concentration into monochloramine was calculated using the following mass balance:

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \quad (2)$$

or

$$\dot{V}_w \cdot \rho_w + \dot{V}_{Cl_2} \cdot \rho_{Cl_2} = \dot{V}_3 \cdot \rho_3 \quad (3)$$

where \dot{m}_1 and \dot{m}_2 are mass flow rates of streams entering the system (inlet stream and chlorine dosing mass flow rates, respectively) and \dot{m}_3 is the mass flow rate of the combined stream leaving the system. \dot{V}_w is the water flow rate, \dot{V}_{Cl_2} is the chlorine dosing flow rate and \dot{V}_3 represents the flow rate resulting from the sum of \dot{V}_w and \dot{V}_{Cl_2} . ρ_w and ρ_{Cl_2} are the densities of incoming fluids, water and chlorine solution. ρ_3 is the density of the stream leaving the system. Neglecting the differences in densities of all liquid streams, and because $\dot{V}_{Cl_2} \ll \dot{V}_w$, the dosing stream flow rate \dot{V}_{Cl_2} can be neglected. Thus, the inlet and outlet water flow rates are regarded as equal.

The mass balance for the component free ammonia (NH_3 -N) can then be described as follows:

$$\dot{m}_{1NH_3} + \dot{m}_{2NH_3} = \dot{m}_{3NH_3} \quad (4)$$

or

$$\dot{V}_w \cdot c_{aNH_3} - \dot{V}_{Cl_2} \cdot c_{NH_3} = \dot{V}_3 \cdot c_{eNH_3} \quad (5)$$

where c_{aNH_3} is the free-ammonia concentration in the water stream entering the system, c_{eNH_3} is the free-ammonia concentration in the water stream leaving the system and c_{NH_3} is the free-ammonia concentration which is reacted with free chlorine dosing.

As described previously, monochloramine is formed using a chlorine-to-ammonia weight ratio of 4:1 (according to data from the re-dosing station in York). That means 1 mg/L free ammonia (as NH_3 -N) is used to react with 4 mg/L free chlorine (as Cl_2), which can be expressed as follows:

$$c_{NH_3} = \frac{c_{Cl_2}}{4} \quad (6)$$

or

$$\dot{V}_{Cl_2} = \frac{\dot{V}_w \cdot 4 \cdot (c_{aNH_3} - c_{eNH_3})}{c_{Cl_2}} \quad (7)$$

where c_{Cl_2} is the free-chlorine concentration in the dosing solution (50 mg/L). The calculated required chlorine dosing flow rate derived through this equation was converted into the peristaltic pump speed (revolutions per minute) using a previously determined calibration equation.

ANALYTICAL METHODS

Ammonia measurement

An in-house developed analytical system based on a previously reported system (Lane *et al.* 1997, 1999) for the determination of low ammonia concentrations in drinking water was used. The expected benefit of including an on-line free ammonia monitoring system to control/optimize the chloramination process would be to ensure the formation of the desired chloramine species through accurate chlorine to ammonia ratio control, minimizing ammonia in the system and thus reducing the risk of nitrification. In addition, this system has the potential to prevent unwanted breakpoint chlorination.

The analyser measures ammonia in a working range of 0 to 4.0 mg/L with 5 min intervals. The performance of the analyser was evaluated via the limit of detection (LOD) and the limit of quantification (LOQ), which, according to the ISO Standard 8466-1 (1990), are as follows: LOD = 0.0115 mg/L and LOQ = 0.038 mg/L. The latter value is used as the lowest value of ammonia concentration which can be detected with a certain degree of accuracy.

Determination of free chlorine, chloramines and total chlorine

Free chlorine, chloramines and total chlorine in water were determined using the N,N-diethyl-p-phenylene diamine (DPD) ferrous ammonium sulfate (FAS) titrimetric method according to Standard Method 4500-Cl F (APHA, AWWA & WEF 2005). The LOD and LOQ of the analytical technique (free chlorine, chloramines and total chlorine) are 0.01 and 0.05 mg/L, respectively.

Simulation experiments

A laboratory simulation of the chlorine re-dosing station in York (Western Australia) was set up to investigate the feasibility of using ammonia measurements for chlorine dosing control. The idea was to simulate a feedback control system as it is applied in the temporary re-dosing station in York. Instead of measuring total chlorine residuals (common feedback control), the ammonia analyser was used as the control tool to manage the re-chlorination process. The

aim of this configuration was to achieve chloramine residuals similar to those in the real system which would indicate a successful demonstration of this new disinfection control system. To advance the current procedures, the re-dosing was additionally performed using a proposed feedforward control arrangement. This configuration was expected to be more appropriate for achieving accurate chlorine to ammonia ratios and a stable disinfectant residual.

The control configuration of both feedback (Figure 3(a)) and the proposed feedforward (Figure 3(b)) control systems is shown.

Feedback control configuration

The feedback control configuration of a blending system shown in Figure 3(a) (Seborg *et al.* 2004) was used in this study. A measuring device/transmitter (ammonia analyser) (position 1-1) measured the process variable

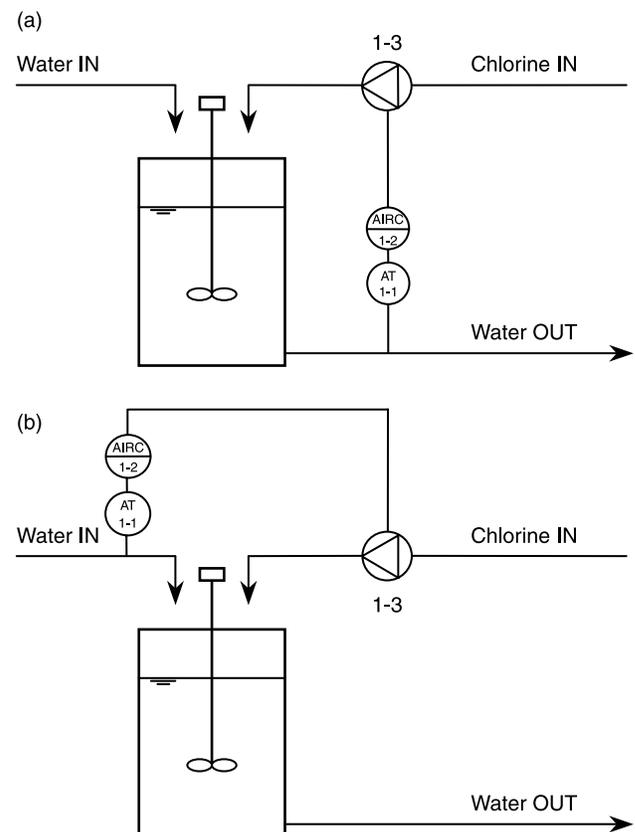


Figure 3 | The diagrams of (a) a feedback and (b) a feedforward control system for free ammonia.

(free-ammonia concentration in the water stream) and sent a signal to a controller (a personal computer) (position 1–2). This controller sent a control signal to a final control element (peristaltic pump) (position 1–3) and the latter was used to adjust the flow rate of the chlorine solution to bring the process variable to the desired value.

Feedforward control configuration

In a feedforward control configuration (Figure 3(b)), there is no need to measure the process variable. Instead, the disturbance parameter was continuously measured by the ammonia analyser as shown in Figure 3(b) (position 1–1). The controller (position 1–2) anticipated the effect on the process and the manipulated variable was adjusted using the final control element by such an amount as to completely eliminate, or, more realistically, to reduce within a tolerance, the effect of the disturbance parameter.

RESULTS AND DISCUSSION

Feedback control configuration

In this control configuration, chlorine flow rate is a manipulated variable and the process variable is directly measured, and the value of the manipulated variable was adjusted as required to keep the blending composition at the desired level (chlorine to ammonia weight ratio 4:1). Since the free-ammonia concentration in the inlet water stream varies continuously, this parameter is considered as a *disturbance parameter*. However, the *disturbance parameter* need not be measured, which is regarded as an advantage of this feedback configuration (Smith & Corripio 1997). Another advantage is that this control configuration is insensitive to possible modelling errors and parameter changes (Seborg et al. 2004).

Initial experiment—decreasing ammonia concentration

Primary trials were conducted with tap water to survey the simulation of chlorine dosing and its control by measuring ammonia residuals and to validate the experimental design and operation. An initial experiment using the feedback control configuration was accomplished to investigate the

possibility of using the improved monitoring capability of the ammonia analyser to enable a decrease of the target ammonia concentration to zero. After the ammonia analyser was calibrated, the reservoir tank with tap water was primed with an ammonia concentration of 0.3 mg/L. On-line readings were taken by the analyser, and the chlorine dosing pump was adjusted according to the readings. The results are presented in Figure 4, where measured values and calculated ammonia concentrations are displayed.

Measured free-ammonia concentrations in Figure 4 show an achieved averaged ammonia concentration of 0.034 mg/L, where reading fluctuations at 122 and 137 min are outliers and can be traced to an air bubble which interfered with the analytical system. The bold line represents theoretical ammonia concentrations calculated from the applied pump speed. After stable ammonia readings were achieved, the chlorine pump speed was re-adjusted. Figure 4 shows the change in readings 16 min after the pump adjustment due to the flow detention time. An averaged ammonia concentration of -0.004 mg/L was calculated, which in measurement terms, corresponded to an ammonia concentration of zero. The negative values are due to the standard deviation for the ammonia analyser at very low ammonia concentrations.

Proof that no breakpoint chlorination occurred is given in Table 1. Samples after the re-dosing point were taken and manually titrated to determine the concentration of free chlorine, monochloramine, dichloramine and trichloramine, respectively. No free chlorine was measured in any samples. Furthermore, almost all combined chlorine was

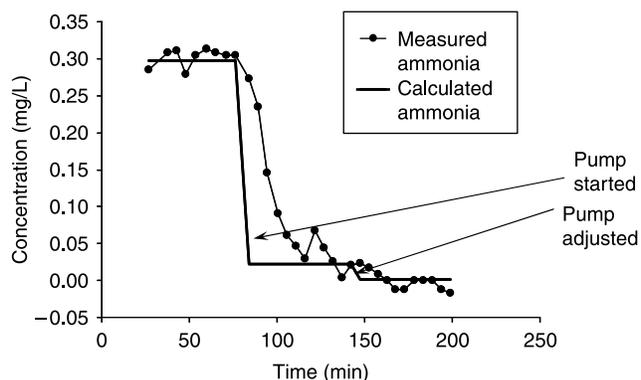


Figure 4 | Measured and calculated ammonia concentrations during trial with decreasing ammonia concentrations.

Table 1 | Titration results during trial to decrease ammonia concentration

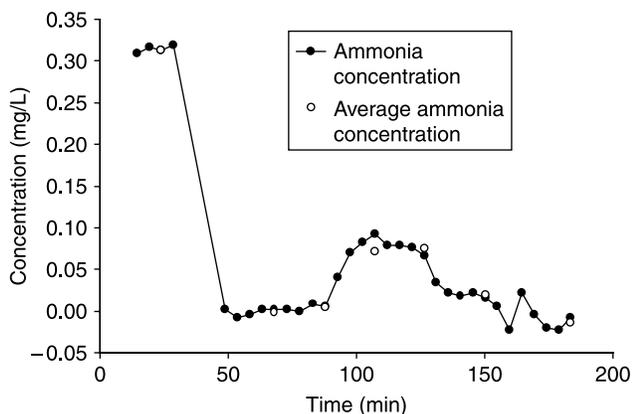
Parameter	Titration 1	Titration 2	Titration 3
Time of titration (min)	137	178	194
Concentration (free Cl ₂) (mg/L)	0.00	0.00	0.00
Concentration (NH ₂ Cl) (mg/L)	1.08	1.17	1.18
Concentration (NHCl ₂ /NCl ₃) (mg/L)	0.03	0.02	0.02
Concentration (total titrated Cl ₂) (mg/L)	1.11	1.19	1.20
Concentration (total calculated dosed Cl ₂) (mg/L)	1.11	1.19	1.19

present as monochloramine. Table 1 also shows the dosed total chlorine concentration calculated by the applied pump speed. Comparison with the concentration determined by titration demonstrates that accurate dosing has been achieved.

Trial–feedback control of chlorine dosing using Mundaring Reservoir water

This trial was conducted as a feedback control configuration, where ammonia concentrations were continuously determined during the experiment (Figure 5). Dosing pump adjustments were accomplished approximately every 30 min. During this time, up to six measurements were taken. The average of only the last three reproducible readings were used, because the system detention time (16 min) meant that any changes were not detected until after this time had passed.

A disinfectant residual in the tank was prepared, aiming at 2.0 mg/L monochloramine and 0.3 mg/L free ammonia,

**Figure 5** | Ammonia analyser readings with feedback control (Mundaring Reservoir water).

according to residuals previously measured before the chlorinator in the actual York system (WA).

As demonstrated in Figure 5, an initial averaged ammonia concentration was measured to be 0.32 mg/L. The difference between the measured ammonia concentration and the desired 0.30 mg/L can be traced back to the initial ammonia concentration in the raw water and to the chloramine demand of the water, leading to the release of ammonia through the chloramine decay. This is confirmed in Table 2, where the titration results show an initial monochloramine residual of only 1.92 mg/L. In accordance with the amount of ammonia in the water, the chlorine dosing pump was started and, after the detention time has passed, no free ammonia could be detected. Table 2 shows results of the titrations accomplished for monitoring chloramine residuals during the trial. No free chlorine was found after the dosing was started and almost all chlorine was successfully converted into monochloramine after 75 min.

To simulate a change in residuals leaving the tank, 3 L of water with a monochloramine residual of 0.27 mg/L and an ammonia concentration of 0.65 mg/L was added to the 50 L reservoir tank at 78 min, to aim for a monochloramine residual of 1.6 mg/L and an ammonia concentration of 0.38 mg/L in the tank. As shown in Figure 5, the ammonia residual after the dosing point increased to approximately 0.08 mg/L and, after the pump adjustment, it dropped down to 0.02 mg/L, which is acceptable within the margin of error of the analyser (± 0.04 mg/L). For the simulation of breakpoint chlorination (ammonia concentration $c(\text{NH}_3) = 0$ mg/L), 4 L of water with a free-chlorine concentration of 3.5 mg/L was added at 140 min. After the dosing point the ammonia concentration was determined to be -0.02 mg/L, i.e. no free ammonia. A free-chlorine concentration of 2.29 mg/L was determined by titration confirming the breakpoint chlorination (Table 2).

Table 2 | Titration results with feedback control (Mundaring Reservoir water)

Time of titration (min)	0	75	100	145	175
Free-chlorine concentration (mg/L)	0.00	0.00	0.00	0.00	2.29
NH ₂ Cl concentration (mg/L)	1.92	2.95	2.74	2.97	0.00
NHCl ₂ concentration (mg/L)	0.03	0.06	0.03	0.04	0.08
Total available chlorine (mg/L)	1.95	3.01	2.77	3.01	2.37

Due to the fact that the ammonia analyser cannot detect breakpoint chlorination in the feedback configuration, the controller would not response to reduce chlorine dose. As a result, an undesired free-chlorine residual would persist in the distribution system. For this reason, it can be concluded, that a feedback control configuration for chlorine dosing using ammonia measurements is not recommended due to the inability to detect ammonia in a chlorine overdosing situation, which results in free chlorine in the system. However, this control configuration is appropriate for monitoring and alerting since the detection limit of the analyser is suitably low.

In addition, as detection is conducted approximately 16 min downstream of dosing control, reaction to process changes is not accounted for within this significant time period. This control strategy might be considered a disadvantage of a feedback configuration. The controller receives information about the process variable in the form of an error signal only after all changes in the process have occurred. If the aim is to use ammonia measurements for chlorine dosing control to achieve the most efficient yield of monochloramine residual based upon the ammonia concentration in the system, a feedforward control configuration might be more beneficial.

Feedforward control configuration

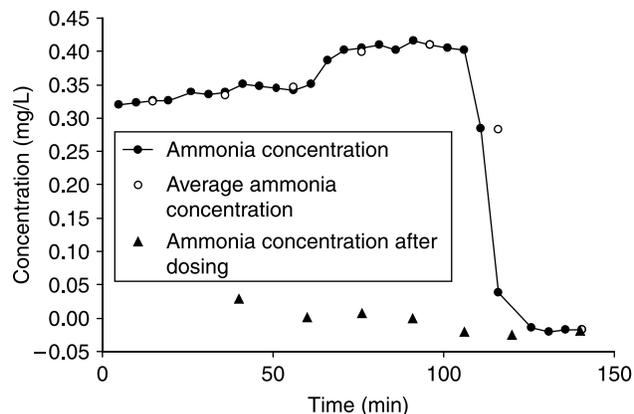
This control configuration is “good for slow systems or with significant dead times” (Stephanopoulos 1984) and in particular for the present system. The control action takes place well before changes occur to the process. Since the simulation of the re-dosing system is dealing with only one disturbance, a feedforward configuration was deemed most appropriate for the control task. However, in order to be able to accurately anticipate the impact of the measured

disturbance on the process output, a very good model of the process is required.

Trial–feedforward control of chlorine dosing using Mundaring Reservoir water

For the trial with a feedforward control configuration, the tank was prepared with a monochloramine residual of 2.0 mg/L plus an ammonia concentration of 0.3 mg/L. An outlet ammonia concentration of zero was targeted. The pump was adjusted every four measurements according to the averaged value given by the open circle data points in Figure 6.

Standard deviations of averaged values are also displayed, where the standard deviation from the value at 116 min is a result of the rapidly decreasing ammonia concentration during the reading period. To confirm the accuracy of chlorine dosing, samples were taken after the dosing point and analysed following the trial for free-ammonia residuals. The results are also shown in Figure 6 (triangle data points). Additionally, the samples were

**Figure 6** | Ammonia analyser readings with feedforward control (Mundaring Reservoir water).

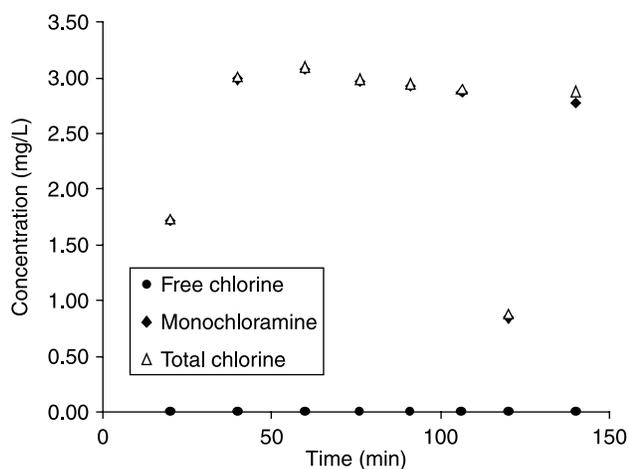


Figure 7 | Titration results after feedforward control (Mundaring Reservoir water).

titrated to determine chloramine residuals. The results are presented in Figure 7.

As observed in the previous feedback control configuration trial, the initial ammonia concentration measured by the analyser was higher than 0.3 mg/L due to the existing ammonia in the raw water and the ammonia released due to the chloramine demand of the water (Figure 6).

The chlorine dosing pump was started to account for 0.32 mg/L ammonia in the water. As shown in the data presented, the ammonia concentration increased during the first 60 min of the experiment to approximately 0.34 mg/L, which can be explained by the chloramine decay. At 62 min, 3 L of water ($c(\text{NH}_2\text{Cl}) = 0.16 \text{ mg/L}$; $c(\text{NH}_3) = 0.58 \text{ mg/L}$) were added to aim for a lower monochloramine residual of 1.60 mg/L and a higher ammonia concentration of 0.40 mg/L in the tank, and the pump was adjusted accordingly. To simulate a decreased ammonia concentration in the tank, another 4 L of water was added at 106 min, with a free-chlorine

concentration of 4.73 mg/L to aim for an ammonia residual of zero and a chloramine residual of 2.80 mg/L.

Importantly, despite a reduction of the ammonia concentration in the tank to zero, no free chlorine was found in water samples after dosing (Figure 7). The decrease in monochloramine due to an excessive chlorine-to-ammonia ratio was observed only over a short period of time. The drop of ammonia concentration was quickly detected by the analyser and an appropriate response could take place through pump adjustments (in this case, by stopping the dosing of chlorine). As shown in Figure 7, the monochloramine residual increased after stopping the pump and was determined to be 2.87 mg/L.

The results of all analysed samples show ammonia concentrations almost zero were consistently achieved, with some negative concentrations in the data presented being caused by the calibration function. However, the “negative readings” are still within the margin of error of the analyser.

The findings in this trial confirm that on-line ammonia measurement can be successfully applied for chloramination control using a feedforward control configuration. As the ammonia analyser performs measurements of ammonia before dosing, it can respond quickly to a decreasing initial ammonia concentration, in contrast to the feedback control configuration. Furthermore, a more stable chlorine-to-ammonia ratio can be achieved, resulting in an optimal yield of monochloramine, the desired predominant disinfectant species.

Significance of trial results

It was proved that using ammonia measurements for disinfection control applied in a feedforward control

Table 3 | Residual concentrations after the chlorinator in York

	Date, Time	Monochloramine concentration (mg/L)	Free-ammonia concentration (mg/L)
After chlorinator (York)	08/11/2006, n/d	3.17	0.07
After chlorinator (York)	16/11/2006, n/d	2.74	0.09
After chlorinator (York)	22/11/2006, 13:40	2.80	0.06
After chlorinator (York)	03/01/2007, 08:45	2.08	0.17
After chlorinator (York)	18/01/2007, 08:35	3.59	0.09
After chlorinator (York)	24/01/2007, 13:45	3.17	0.09

configuration could improve the current situation in the real distribution system. Occasional samples analysed (2–3 times per week) in the field do not give enough information for satisfactorily controlling the chlorine dosing, which is demonstrated by the highly variable monochloramine residual after the dosing point presented in Table 3. Disturbances, failures of re-dosing control equipment or inefficiency of the disinfection process can occur, but they may not be detected within an acceptable timeframe to respond to the changes. For this reason, to improve the overall disinfectant stability, on-line measurements are strongly recommended.

Additionally, controlling the chlorine re-dosing process without consideration of ammonia concentrations can lead to inappropriate dosing, resulting in an undesirably high free-ammonia concentration after the dosing point. This is clearly shown by residual data from York, where a reasonably high free ammonia residual of 0.17 mg/L persisted after the dosing point on 03/01/2007.

Using an ammonia analyser in a feedforward control configuration, results obtained in the laboratory simulation indicate a more efficient control system in comparison to the current system which uses chlorine residual measurements applied in feedback control. This is evident due to stable low ammonia concentrations (below 0.05 mg/L) and stable monochloramine concentrations achieved during the feedforward control trial using a natural water source.

CONCLUSIONS

From the conducted trials, it can be concluded that the conditions at the re-dosing station in York (WA) were successfully simulated in the laboratory. Chlorine dosing was successfully controlled by measuring ammonia residuals on-line in a feedforward control configuration. Furthermore, a more stable chlorine-to-ammonia ratio was achieved, resulting in an optimal yield of monochloramine and an ammonia concentration close to zero.

Current periodic sampling and analysis of samples for monitoring and disinfection control does not accurately capture the behaviour of a disinfection system. On-line measurements are strongly recommended to obtain more

frequent information to ensure consistent residuals in the distribution system.

A feedback control using ammonia measurements for disinfection management was found to perform inadequately. However, an ammonia analyser in this control configuration can be used effectively for monitoring and/or alerting purposes.

The simulated dosing system could be used to test the control strategy for a real system without the risk of affecting the drinking water quality. The control strategy using ammonia measurements for managing chloramination could be used in future for achieving more stable disinfection residuals and hence improve drinking water quality.

ACKNOWLEDGEMENTS

The authors acknowledge the valuable support of Associate Prof. David Davey and Dr. Stan Macleod from the University of South Australia.

REFERENCES

- APHA, AWWA & WEF 2005 Chlorine residual by DPD ferrous titration 4500-Cl F. In: Eaton, A. D., Clesceri, L. S., Rice, E. W. & Greenberg, A. E. (eds) *Standard Methods for the Examination of Water and Wastewater*. American Public Health Association, Water Environment Federation and American Water Works Association, Washington, DC, USA, p. 168.
- Brokenshire, J. L. & Cumming, C. A. 1995 An ammonia monitor for the water industry. In: *Proc. Third International Workshop on Ion Mobility Spectrometry, 1994*. NASA Conference Publication, 3301, pp 214–220.
- Fitzgerald, F., Chow, C. W. K. & Holmes, M. 2006 Disinfectant demand prediction using surrogate parameters—a tool to improve disinfection control. *J. Water Supply Res. Technol.—AQUA* 55(6), 391–400.
- Hall, J., Zaffiro, A. D., Marx, R. B., Kefauver, P. C., Krishnan, E. R., Haught, R. C. & Herrmann, J. G. 2007 On-line water quality parameters as indicators of distribution system contamination. *J. AWWA* 99(1), 66–77.
- Hua, F., West, J. R., Barker, R. A. & Forster, C. F. 1999 Modelling of chlorine decay in municipal water supplies. *Water Res.* 33(12), 2735–2746.
- ISO Standard 8466-1 1990 *Water Quality—Calibration and Evaluation of Analytical Methods and Estimation of*

- Performance Characteristics. Part 1: Statistical Evaluation of the Linear Calibration Function.* ISO, Geneva.
- Lane, R., Chow, C. W. K., Davey, D. E., Mulcahy, D. E., Lane, R. & McLeod, S. 1997 Online microdistillation-based preconcentration technique for ammonia measurement. *Analyst (UK)* **122**(12), 1549–1552.
- Lane, R., Chow, C. W. K., Davey, D. E., Mulcahy, D. E. & McLeod, S. 1999 An integrated microdistillation flow injection system for nitrite measurement. *Anal. Chim. Acta* **395**(1–2), 225–234.
- McMorran, C. & Moriarty, K. 1997 Observations of reconditioning a chlorinated water distribution system to chloramines. In: *Proc. Annual Conference, American Water Works Association (Engineering and Operations)*, pp 239–247.
- Miller, K. L., Grabow, L., Castle, R. S. & Price, M. L. 1995 Anticipating conversion to monochloramine: development of predictive indicators for distribution system water quality monitoring. In: *Proc. Water Quality Technology Conference (Pt. 2)*, pp 1215–1235.
- Powell, R. M. 2004 Implementation of chloramination by a Florida utility: the good, the bad, and the ugly. In: *Proc. Water Quality Technology Conference and Exhibition*, pp tue5 1/1–tue5 1/16.
- Regan, J. M., Cho, A. -Y., Kim, S. & Smith, C. D. 2004 Monitoring nitrification in chloraminated systems using molecular detection strategies. In: *Proc. Water Quality Technology Conference and Exhibition*, pp mon12 14/11–mon12 14/19.
- Rodrigues, M. J. & Serodes, J. -B. 1999 Assessing empirical linear and non-linear modelling of residual chlorine in urban drinking water systems. *Environ. Modell. Softw* **14**, 93–102.
- Seborg, D. E., Edgar, T. F. & Mellichamp, D. A. 2004 *Process Dynamics and Control*. John Wiley & Sons, Brisbane.
- Smith, C. A. & Corripio, A. B. 1997 *Principle and Practice of Automatic Process Control*. John Wiley & Sons, Brisbane.
- Stephanopoulos, G. 1984 *Chemical Process Control: An Introduction to Theory and Practice*. Prentice Hall, Englewood Cliffs, NJ.
- Wilczak, A., Smith, C. D., Cohen, Y. K., Martin, P. B. 2003 Strategies for combining free ammonia and boosting chloramines in distribution systems—survey of utility practice. In: *Proc. Water Quality Technology Conference* pp 1123–1141.
- Yasue, T. & Kitaoku, K. 2000 *Water Treatment Equipment*. Yokogawa Electric Corp. Application: JP.

First received 2 August 2007; accepted in revised form 5 February 2008. Available online December 2008