Application of EPANET for the determination of chlorine dose and prediction of THMs in a water distribution system

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ABSTRACT

The purpose of this study is to predict the level of chlorine residual and trihalomethanes (THMs) in a drinking water distribution system and to help operators to determine chlorine dose in a drinking water treatment plant (WTP) using EPANET 2.0. Water quality modelling was conducted by chlorine bulk decay and THM formation from bottle tests. Chlorine decay tests for the finished water of the WTP were performed on a monthly basis for one year. As the result, a simple equation for the target chlorine concentration in the finished water was derived by a multiple regression method in relation to initial chlorine concentrations, temperatures, total organic carbon and chlorine decay coefficients. The chlorine concentration after it leaves a WTP, before entering its distribution networks, is critical in maintaining chlorine residual levels throughout the system. It is apparent that the chlorine concentration of the finished water be maintained to be flexible to keep it at over 0.1 mg L⁻¹ throughout the system because chlorine consumption is different according to the season, flow and pipe networks. These chlorine values of the finished water are the target chlorine concentrations for determining the chlorine dosage to the filtered water in a WTP. As the results of this study using a multiple regression model for chlorine decay and EPANET, the target chlorine concentrations of the finished water were set to 0.5 mg L⁻¹ in spring and fall, 0.55 mg L⁻¹ in summer and 0.45 mg L⁻¹ in winter. These values are slightly lower than the existing target values.

INTRODUCTION

Water treatment has contributed to the prevention of waterborne disease and to safeguard human health in drinking water. Chlorine disinfection is one of the key factors in drinking water treatment processes. However chlorine disinfection may cause unpleasant tastes and odours due to the chlorine residual, corrosion of pipes, the formation of disinfection by-products such as trihalomethanes (THMs), among others. Therefore, management of the chlorine residual from finished water in a water treatment plant (WTP) to consumers’ taps is critical to balance customer satisfaction and protection from pathogens. Understanding the factors contributing to the loss of chlorine and the formation of disinfection by-products is a requisite to maintain chlorine residual levels in distribution systems.

Chlorine residual levels with a range of 0.1 to 0.4 mg L⁻¹ set by Seoul city as the government guideline in distribution systems are to meet the minimum level of chlorine residual levels throughout the entire water distribution systems and to alleviate customer complaints related to the odour of the disinfectant.

Flow in distribution system affects water quality in general and chlorine residual in particular. The concept of water quality modelling in distribution system networks was based on steady-state formulations in the early 1980s, and then dynamic water quality models were developed in the mid-1980s. There are now many modelling software packages available for hydraulic and water quality network analyses: EPANET, AQUIS, H2ONET, InfoWorks WS, MikeNet, Pipe2000, WaterGEM/WaterCAD and so on [1].

EPANET was developed in 1993 with the functions of modelling chlorine decay and THM formation [2]. Hydraulic modelling should be first developed for predicting chlorine residual levels within a water
distribution system using EPANET. The water quality model then predicts the chlorine residual in a distribution system by inputting chlorine $k_v$ and $k_w$ in EPANET. The chlorine concentration after the WTP decreases gradually due to many factors as the finished water goes through the pipe networks. This phase of chlorine consumption could be mainly divided by chlorine bulk decay and wall decay. The bulk decay is due to chlorine consumption with organic and inorganic matters, and the wall decay is due to reactions with pipe materials, biofilms on inner pipe walls and so on. The chlorine bulk decay rate can be obtained by experiments and the wall decay rate can be also estimated by comparing the results from a simulated network model with the results measured in a distribution system. Kinetic models describing the decay of chlorine in EPANET have been developed, tested and evaluated using data collected in field sampling studies [3-6].

Chlorine disinfectant reacts with natural organic matter present in raw waters, and generates by-products including THMs. As THMs are potentially carcinogenic, there has been the establishment of maximum admissible levels [7]. Several studies developing predictive models of THM formation have been performed for a better understanding of THM formation and to help manage different strategies in distribution systems. The formation of THMs is affected by various water quality parameters: organic matter, chlorine dose, pH, temperature, reaction time, bromide levels and so on. Multiple regression analysis and artificial neural networks approaches have been used to develop the THM formation model with water quality parameters [8-12].

It is important to understand hydraulic behaviour to investigate water quality variations in a distribution system. Clark et al. [13] predicted THMs by using a network model in a distribution system. THMs were assumed to be conservative tracers for studying the effects of hydraulic behaviour on water quality. Vasconcelos et al. [14] developed a kinetic model of THM formation by using nonlinear least squares regression. It was a first order growth model with a limiting concentration to be applied to EPANET.

The purpose of this study is to predict chlorine residual and THM formation in a drinking water distribution system and to help operators to determine the chlorine dose in a drinking WTP using EPANET 2.0.

**MATERIALS AND METHODS**

Water quality modeling was conducted by chlorine bulk decay and THM formation from the bottle tests under controlled conditions [15]. Chlorine decay tests for the finished water were performed monthly for one year. Samples for the chlorine bulk decay tests were taken from the storage tank just before entering its distribution system. The 250 mL amber bottles screwed-capped with PTFE-lined septa were used for the tests. The THM formation tests were simultaneously performed for the same sample when the chlorine bulk tests were conducted.

Chlorine concentrations were measured by a pocket colorimeter (Pocket Colorimeter™ II, Hach, Loveland, CO). As the result, a simple equation for the target chlorine concentration in finished water was derived by a multiple regression method in relation to initial chlorine concentrations, temperatures, the total organic carbon (TOC) level and the bulk decay rate. THM concentrations were also predicted by EPANET in the distribution system. The THM concentrations were measured by a purge and trap concentrator, a GC/MS, and TOC concentrations by a TOC analyzer (Sievers 820, GE Analytical Instruments, Boulder, CO).

**RESULTS AND DISCUSSION**

1. **Hydraulic Modelling**

A WTP with a flow of $0.22 \times 10^6 \text{ m}^3 \text{ d}^{-1}$ was used for this study. The WTP treats source water by conventional processes including prechlorination, coagulation/flocculation, sedimentation, rapid sand filtration and post chlorination. The distribution system has two service reservoirs and five pumping stations. The distribution system consists of two zones: a UM zone and a CD zone. The finished water is supplied to the UM zone by gravity, but to the CD zone, it is supplied half by gravity and half by pumping because it is partially in a hilly area.

Customers’ water usage, pipe diameters, the elevation and other related data were input to perform hydraulic network modelling with EPANET 2.0. The network model consisted of 6,573 pipes and 4,522 junctions. The network model was simulated with a 24 h demand pattern for an extended period simulation (EPS). The EPS is a tool for the simulation of distribution system behaviour under time-varying demand and operational conditions [1].

There was the smallest demand at 4 a.m., and the largest demand was at 10 a.m. in the CD zone (Fig. 1). Pressure measurement has been used as one of the hydraulic calibration methods [1]. Figure 2 shows the measured and the predicted values of the pressures at twenty sampling locations throughout the study area. The average error value of the two was 33 kPa with a similar pattern. Vasconcelos et al. [14] conducted hydraulic calibration by comparing the observed and the predicted pressure by the EPANET model in a study area. As the average error of the six sampling locations was 25 kPa, it was smaller than that in this study.

2. **Modelling of Chlorine Residual**

There have been several studies describing bulk
decay in drinking water. Wable et al. [16] and Zhang et al. [17] found that chlorine consumption in treated water followed the equation of a first order reaction. Vasconcelos et al. [14] implemented bottle tests for 11 different waters and evaluated the performance of four kinetic models: a first order model, an $n^{th}$ order model, a limited first order model and a parallel first order model that Hass and Karra [18] applied to wastewater effluents as follows:

\[ C = C_0 \exp(-k_n t) \]  

(1)

ii) $n^{th}$ order model

\[ C = [k_n t(n - 1) + C_0(\exp(n t))^{-1/(n - 1)}] \]  

(2)

iii) limited first order model

\[ C = C^* + (C_0 - C^*) \exp(-k_n t) \]  

(3)

iv) parallel first order model

\[ C = C_0 n^z \exp(-k_{n,wall} t) + C_0 (1 - n) \exp(-k_{n,wall} t) \]  

(4)

where $k_n$ is the chlorine bulk decay coefficient (d$^{-1}$), $t$ is the residence time in the pipe (d), $C_0$ is the initial chlorine residual (mg L$^{-1}$), $C$ is the chlorine residual at time $t$, $n$ is the $n^{th}$ order bulk decay constant (d$^{-1}$ mg$^{-1}$ L$^{-2n}$), $C^*$ is the limiting chlorine concentration (mg L$^{-1}$), $k_{n,wall}$ is the bulk decay constant for slow reactions (d$^{-1}$), $k_{n,fast}$ is the bulk decay constant for fast reactions (d$^{-1}$), and $z$ is the ratio of fast to slow reactions (dimensionless).

The kinetic models were compared with the residual sum of squared errors between the predicted and observed values, and the adjusted coefficient of determination ($R^2$). The $n^{th}$ order model was the best fit for half of the cases while the parallel first order model was the best fit for the other half. Although the first order model was not best for these waters, the differences between the model fits were very small. Vasconcelos et al. [6] applied the first order model to study water quality behaviour in water distribution systems using EPANET. Powell et al. [19] examined the performance of six different kinetic models: a first order model, a second order model with respect to chlorine only, a second order model with respect to chlorine and another reactant, an $n^{th}$ order model, a limited first order model, and a parallel first order model. The kinetic models were compared regarding the $R^2$ values and average errors between the modelled results and the observed results. The authors concluded that it is generally reasonable to assume a first order model for network modelling purposes.

Rossman et al. [4] and Vasconcelos et al. [6] suggested Eqs. 5 and 6 for a first order reaction for modelling chlorine residuals in distribution systems. The reactions of chlorine consumption are divided by the bulk decay and wall decay for application to water quality modelling in distribution systems. While the $k_n$ values were determined by bottle tests based on a laboratory, the $k_n$ values were adjusted over a range of values, and the simulated EPANET results were compared to the observed data at the sampling locations of the study area. The first order wall decay was characterized by a rate coefficient with units of length divided by time, which was equivalent to a ratio of the mass per unit volume to the mass per unit wall surface area per unit time. The relevant equations are

\[ C = C_0 \exp(-kt) \]  

(5)

\[ k = k_n + \frac{k_{n,wall}}{R_H (k_{n,wall} + k_f)} \]  

(6)

where $k$ is the overall chlorine decay coefficient (d$^{-1}$), $k_n$ is the chlorine wall decay coefficient (m d$^{-1}$), $k_f$ is the mass transfer coefficient between the bulk flow and pipe wall (m d$^{-1}$), and $R_H$ is the hydraulic radius of the pipeline (m).

Chlorine bulk decay is affected by the initial chlorine concentration, TOC, and temperature in treated water [14,20-24]. $k_n$ values are inversely proportional to the initial chlorine concentration if the other water quality parameters are fixed. However, it increased with the TOC and temperature. Vasconcelos et al. [14] reported Eq. 7 as a function of the TOC and temperature.
Powell et al. [21] added a term for the initial chlorine concentration to Eq. 7, and extended it to Eq. 8. Al-Omari et al. [22] showed a logarithmic relationship between the chlorine k and each water quality parameter of the initial chlorine concentrations, TOC and temperature through a study based on laboratory experiments. The authors modified Eqs. 7 and 8, and suggested Eq. 9 with an R² value of 0.99, obtaining the constants by multiple regression analysis. The equations are:

\[ k_b = 1.8 \times 10^6 \text{TOC exp} \left[ -\frac{6050}{T + 273} \right] \] (7)

\[ k_b = p \left( \frac{1}{C_0} \right) \text{TOC - } f \exp \left[ -\frac{E}{R(T + 273)} \right] \] (8)

\[ k_b = 41233C_o^{0.76} \exp(1.3887 \text{TOC}) \exp\left( -\frac{4590.5}{T} \right) \] (9)

where the constants p and f are derived by optimisation to minimise the sum of the squared errors between the predicted and observed kₜ values. T is the temperature (°C), E is the activation energy (J mol⁻¹), and R is the ideal gas constant (8.31 J mol⁻¹ °C⁻¹).

In this study, experiments were carried out to obtain the kₜ at the water temperatures when the samples were taken from the effluent just before entering into the distribution system. Thirteen bulk tests were conducted on a monthly basis. As the effluent from the WTP took about 2 d to reach the entire supply area, the bulk tests lasted over 50 h. The first order decay reaction model was applied to this study because the curve for the bulk tests was good fit, and it is easy to handle the first order model in EPANET [19]. The kₜ values ranged from 0.18 to 0.41 d⁻¹ with an average R² value of 0.95, as shown in Fig. 3 and Table 1.

Vasconcelos et al. [6] reported that the kₜ values ranged from a low of 0.082 d⁻¹ with an R² of 0.85 to a high of 17.7 d⁻¹ with an R² of 0.99. Powell et al. [19] observed a wide range of values for kₜ with an average R² of 0.95.

Water quality varies with temperature, rainfall, contaminants and so on, and it is also natural that the chlorine kₜ depends on the water quality parameters. It needs to consider the variations of water quality parameters for modelling chlorine residuals in distribution systems.

Multiple regression analysis was performed to develop a mathematical model of chlorine bulk decay. The dependent variables were the initial chlorine concentration, temperature and TOC (Eq. 10). The independent and dependent variables were first formed into natural logarithms, and then the coefficients of the dependent variables were identified by multiple regression analysis. Figure 4 showed a good agreement for kₜ between the predicted and the observed values with an R² of 0.92.

\[ k_b = 0.0488 T^{-0.368} C_o^{3.268} \text{TOC}^{-0.5979} \] (10)

![Fig. 3. An example of chlorine bulk decay tests.](image)

![Fig. 4. Predicted and observed values of kₜ.](image)

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Water Temp. (°C)</th>
<th>Initial chloride, C₀ (mg L⁻¹)</th>
<th>TOC (mg L⁻¹)</th>
<th>pH</th>
<th>Conductivity (µS cm⁻¹)</th>
<th>Chlorine bulk decay, kₜ (d⁻¹)</th>
<th>R²</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>Jun.</td>
<td>20</td>
<td>0.64</td>
<td>1.1</td>
<td>7</td>
<td>147</td>
<td>0.3</td>
<td>0.98</td>
<td>effluent to UM zone</td>
</tr>
<tr>
<td></td>
<td>Jul.</td>
<td>20</td>
<td>0.77</td>
<td>0.9</td>
<td>6.7</td>
<td>146</td>
<td>0.2</td>
<td>0.94</td>
<td>to CD zone</td>
</tr>
<tr>
<td></td>
<td>Aug.</td>
<td>23</td>
<td>0.7</td>
<td>0.9</td>
<td>6.8</td>
<td>120</td>
<td>0.23</td>
<td>0.96</td>
<td>to UM zone</td>
</tr>
<tr>
<td></td>
<td>Sep.</td>
<td>21</td>
<td>0.69</td>
<td>1</td>
<td>7.1</td>
<td>142</td>
<td>0.25</td>
<td>0.96</td>
<td>to UM zone</td>
</tr>
<tr>
<td></td>
<td>Oct.</td>
<td>17</td>
<td>0.67</td>
<td>0.9</td>
<td>7</td>
<td>153</td>
<td>0.19</td>
<td>0.95</td>
<td>to UM zone</td>
</tr>
<tr>
<td></td>
<td>Dec.</td>
<td>8</td>
<td>0.63</td>
<td>1</td>
<td>7.1</td>
<td>164</td>
<td>0.19</td>
<td>0.95</td>
<td>to UM zone</td>
</tr>
<tr>
<td>2007</td>
<td>Jan.</td>
<td>4</td>
<td>0.58</td>
<td>0.9</td>
<td>7.2</td>
<td>143</td>
<td>0.18</td>
<td>0.92</td>
<td>to UM zone</td>
</tr>
<tr>
<td></td>
<td>Feb.</td>
<td>5</td>
<td>0.49</td>
<td>1.2</td>
<td>7.3</td>
<td>168</td>
<td>0.24</td>
<td>0.94</td>
<td>to CD zone</td>
</tr>
<tr>
<td>May</td>
<td>12</td>
<td>0.52</td>
<td>1.1</td>
<td>7.3</td>
<td>159</td>
<td>0.28</td>
<td>0.87</td>
<td>0.96</td>
<td>to UM zone</td>
</tr>
<tr>
<td>Jun.</td>
<td>23</td>
<td>0.6</td>
<td>0.8</td>
<td>7.1</td>
<td>159</td>
<td>0.27</td>
<td>0.98</td>
<td>0.95</td>
<td>to UM zone</td>
</tr>
</tbody>
</table>
Vasconcelos et al. [6] tested and evaluated the kinetic rate equations of chlorine decay through field sampling studies using EPANET. The authors performed a study to find out the chlorine kinetics of bulk and wall decay in five water distribution systems with sampling locations from 8 to 31. The results of the study indicated that chlorine kinetics can be effectively characterized as a combination of first order decay in the bulk liquid and first order or zero order decay reactions at the pipe wall.

The \( k_w \) values were input and the \( k_c \) values were then estimated through chlorine calibration that minimises the difference between the observed and the predictive values. The \( k_c \) values ranged from 0.0 to 1.5 m \( \text{d}^{-1} \) according to chlorine demand by the pipe wall.

Ahn et al. [24] conducted a study on the identification of \( k_w \) and \( k_c \) for chlorine residual management in a distribution system using a network model. The parallel first order model was applied to the field study: fast reaction for the WTP to large service reservoirs, and slow reaction for the large service reservoirs to the dead-end area. The \( k_c \) values by the first order model were obtained on a bimonthly basis by chlorine calibration. The wall decay of ductile cast iron pipes (DCIP) lined with cement mortar was small at 0.02 and 0.05 m \( \text{d}^{-1} \) in March, but was larger at 0.2 m \( \text{d}^{-1} \) in July. The wall decay of unlined gray cast iron in the study area varied from 0.1 to 0.4 m \( \text{d}^{-1} \) in November, and from 0.2 to 0.7 m \( \text{d}^{-1} \) in July.

Table 2 shows the input values for the simulation of chlorine using EPANET throughout the distribution networks. The “initial chlorine” is the chlorine concentration in the effluent of the WTP. When the initial chlorine residuals were 0.63 mg L\(^{-1}\) in the effluent for the UM zone and 0.65 mg L\(^{-1}\) for the CD zone with a water temperature of 23 °C and a TOC of 1.0 mg L\(^{-1}\), the chlorine \( k_w \) values calculated by Eq. 10 were 0.29 d\(^{-1}\) for the UM zone, and 0.27 d\(^{-1}\) for the CD zone. The chlorine \( k_c \) values were introduced from the previous study by Ahn et al. [24] and were adjusted as shown in Table 3.

The water quality model was calibrated by comparing the predicted values with the values of the chlorine residual measured at the nineteen sampling locations in the field. As shown in Fig. 2, the absolute error was 0.04 mg L\(^{-1}\). In the study of Vasconcelos et al. [6], the models showed the absolute errors in the range of 0.05 to 0.15 mg L\(^{-1}\) compared with the predicted and the observed chlorine concentrations.

Figure 5a showed the distribution of chlorine concentrations at all junctions in the distribution system. When the chlorine concentration in the effluent of the WTP was 0.63 mg L\(^{-1}\), junctions with 0.5 mg L\(^{-1}\) or more were 31% of the total, and those with more than 0.4 mg L\(^{-1}\) were 91% of the total. However, more than 90% of the junctions in this study did not meet the range of 0.1 to 0.4 mg L\(^{-1}\) in chlorine residual levels. The range of chlorine concentration from 0.1 to 0.4 mg L\(^{-1}\) has been set by Seoul city as the guideline for chlorine residual levels in distribution systems to reduce customer complaints about the odour of the disinfectant.

Fig. 5. Percentage of junctions according to chlorine and THMs concentrations.

3. Modelling of THMs

THM formation is usually affected by the source water quality, water temperature, TOC, residence time and so on. It is high in summer according to the increase of chlorine consumption and temperature although other water quality parameters have no changes [8]. Ahn et al. [24] showed that THMs formed in lab tests were similar to those in a distribution system. THM formation was observed for the effluent of the WTP when chlorine bulk test was simultaneously conducted in August for the prediction of the level of THMs in the distribution system. THMs concentration in the effluent of the WTP was 42 \( \mu \text{g L}^{-1} \) at a water
temperature of 23 °C.
A first-order growth reaction for THM formation was developed by a nonlinear least squares regression method in Eq. 11 [14], and the THM formation coefficient was applied to EPANET for the prediction of THMs in this study. The equation is

$$THMs = C_0 + C_{\text{max}} (1 - \exp(-k't)) \quad (11)$$

where $k'$ is the THM formation coefficient (d$^{-1}$), $t$ is the residence time in the pipe (d), $C_0$ is the initial THMs concentration ($\mu$g L$^{-1}$), and $C_{\text{max}}$ is the ultimate formation potential ($\mu$g L$^{-1}$).

The first-order growth coefficient and the ultimate formation potential obtained by nonlinear least squares regression were 0.18 d$^{-1}$ and 43.5 $\mu$g L$^{-1}$, respectively (Fig. 6). These values were applied to EPANET for the prediction of THMs in the distribution networks.

Fig. 6. Comparison of predicted and observed THMs concentration.

The result of the simulation with EPANET showed that the concentration of 42 $\mu$g L$^{-1}$ of THMs in the effluent was increased to 52 $\mu$g L$^{-1}$ at the location with the longest residence time. The 10 $\mu$g L$^{-1}$ of difference in the THM concentration was due to the residence time in the distribution system. Figures 5b and 7 described THM concentrations at junctions in the distribution system. The THM concentration at 27% of junctions was 45 $\mu$g L$^{-1}$ or less, and 99% below 50 $\mu$g L$^{-1}$.

Most THMs were formed within the WTP before being pumped to the distribution system, for the treated water had a long residence time for about 13 h in the clear well. On the other hand, its formation was not much in the distribution system with the short travel time of about 2 d or less.

4. Target Chlorine Concentration of the Effluent According to Season

Chlorine concentration of the effluent of a WTP before entering to its distribution networks is a critical point to maintain chlorine residual levels throughout the distribution system. It is natural that chlorine concentration of the effluent be changed to keep over 0.1 mg L$^{-1}$ of chlorine residual throughout the system, because chlorine consumption is different according to the season in bulk flow and pipe networks. These values of the effluent are the target chlorine concentrations to determine the chlorine dosage to the filtered water in a WTP.

As shown in Fig. 5a, it was necessary to reduce the chlorine concentration in the distribution system by lowering the effluent’s target chlorine concentration. The target concentrations of chlorine residual were set on a seasonal basis using EPANET.

The water demands in spring and fall, summer and winter in the network model were 220,440, 234,860 and 206,020 m$^3$ d$^{-1}$, respectively. Chlorine $k_w$ and $k_e$ values were calculated by Eq. 10 with the effluent’s chlorine concentration, water temperature and TOC. The TOC concentration was assumed to 1 mg L$^{-1}$ at this time. Chlorine $k_w$ values were introduced from the previous study by Ahn et al. [24].

As the results of simulations with a decrease in the effluent’s chlorine concentration little by little, the effluent’s chlorine concentrations were set at 0.45 mg L$^{-1}$ in the spring and fall, 0.50 mg L$^{-1}$ in the summer and 0.40 mg L$^{-1}$ in the winter (Table 3). However with regard to the range of fluctuation in the chlorine dosing system, the target chlorine concentrations of the effluent were set to 0.5 mg L$^{-1}$ in the spring and fall, 0.55 mg L$^{-1}$ in the summer and 0.45 mg L$^{-1}$ in the winter (Table 4, Fig. 8). This study found that the 0.05-0.15 mg L$^{-1}$ concentration of chlorine can be reduced compared with the existing target values using the multiple regression model for chlorine decay and the network model simulations.

Table 4. Target chlorine concentrations of the effluent on a seasonal basis

<table>
<thead>
<tr>
<th></th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>(15 °C)</td>
<td>(15 °C)</td>
<td>(15 °C)</td>
<td>(5 °C)</td>
<td>(5 °C)</td>
</tr>
<tr>
<td>Effluent chlorine conc. (mg L$^{-1}$)</td>
<td>0.60 ± 0.05</td>
<td>0.70 ± 0.05</td>
<td>0.60 ± 0.05</td>
<td>0.50 ± 0.05</td>
</tr>
<tr>
<td>Existing target values</td>
<td>0.60 ± 0.05</td>
<td>0.70 ± 0.05</td>
<td>0.60 ± 0.05</td>
<td>0.50 ± 0.05</td>
</tr>
<tr>
<td>Result of this study</td>
<td>0.50 ± 0.05</td>
<td>0.55 ± 0.05</td>
<td>0.50 ± 0.05</td>
<td>0.45 ± 0.05</td>
</tr>
</tbody>
</table>

Fig. 7. Contour plot of THMs in the distribution.
CONCLUSIONS

Water quality modelling was conducted by chlorine bulk decay and THM formation from the bottle tests. As the result, a simple equation for chlorine dose was derived by the multiple regression method in relation to the initial chlorine concentrations, temperatures, TOC and $k_o$.

The chlorine concentration of the effluent in a WTP before entering into its distribution networks is a critical point to maintain the chlorine residual levels throughout the system. It is natural that chlorine concentration of the effluent be changed to keep over 0.1 mg L$^{-1}$ of chlorine residual concentration throughout the system, because chlorine consumption is different according to the season in bulk flow and pipe networks. These effluent values are the target chlorine concentrations for determining the chlorine dosage to the filtered water in a WTP. As the results of the study using the multiple regression model for chlorine decay and EPANET, the target effluent chlorine concentrations were set at 0.5 mg L$^{-1}$ in the spring and fall, 0.55 mg L$^{-1}$ in the summer and 0.45 mg L$^{-1}$ in the winter. This study found that the 0.05-0.15 mg L$^{-1}$ concentration of chlorine can be reduced compared with the existing target values using the multiple regression model for chlorine decay and the network model simulations.

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