RESILIENCE INDEX FOR CHLORINE ANALYSIS IN WATER DISTRIBUTION NETWORKS

Suparak Kaewsang, Adichai Pornprommin and
Surachai Lipiwattanakarn
Department of Water Resources Engineering
Faculty of Engineering, Kasetsart University
Bangkok, Thailand
kaewsang_s@yahoo.com,fengacp@ku.ac.thandfengsuli@ku.ac.th

Thunchanit Wongwiset
Bang Bua Thong Branch Office
Metropolitan Waterworks Authority
Bangkok, Thailand
thunchanit.w@mwa.co.th

***Abstract*—Reducing water losses in water distribution systems can benefit in many ways varying from a reduction of water production and distribution to energy efficiency and hydraulic reliability. In this study, we investigated an impact of water losses on chlorine distribution in a district metering area (DMA) of the Metropolitan Waterworks Authority (MWA) network. The major factor that causes the decay of chlorine is water age (time used to be transported). The longer water age isthe more reactions of chlorine in bulk water and at pipe walls, and, consequently, the more decay. Using the EPANET 2.0 software, we simulated the DMA network for two cases, the present situation with water losses and the situation without water losses. A measure of the reliability of chlorine distribution was proposed by modifying the resilience index that has been used for hydraulic reliability [1]. We found that as water losses decrease the total amount of input chlorine mass to the DMA reduces. Surprisingly, however, the reliability of chlorine distribution decreases as well. It implies that without water losses, velocities in pipes decrease and cause an increase in water age in the network. Subsequently, customers receive lower free residual chlorine concentrations. The result contrasts with what we found in the investigation of hydraulic reliability.**

Keywords—Chlorine; Water distribution; Water losses; Reliability

I. INTRODUCTION

Free chlorine is the most common disinfectant used around the world. Chlorination has been used to meet primary disinfection requirements and provide a residual disinfectant in distribution system. According to the World Health Organization [2], free chlorine should be present in drinking-water distribution networks at a minimum concentrations of 0.2 mg/liter. Since chlorine can decay in networks by the reactions in bulk water and at pipe walls, the travel time from DMA inlet points to customer points(water age)is one of the most important factors causing the losses of chlorine in distribution networks.

The residual chlorine concentration is reduced by the flow in water pipes mainly due to the water's reaction in terms of the water's natural organic matter (NOM) (bulk decay) and with the pipe walls (wall decay) [3]-[4]. Overall water quality did not change following DMA implementation. However,water quality (chlorine residuals, turbidity, and metals) was degraded at locations with elevated water residence times such as created dead ends[5].

Recently, the analysis of water age has become more important especially for the design of water distribution systems. As the traditional way, the design was based on a hydraulic capacity-based approach to meet future demand and fire and emergency demands. Under this consideration alone, sometimes systems are oversized and cause low velocities in pipes, longer water age and, finally, negative impacts on water quality [6]. With this awareness of water quality degradation in water distribution systems, the design has been shifted toward a new approach that balances hydraulic capacity and water age.

It has been known that water lossesnot only cause an increase in water production, but also they lead to lower pressure and more energy consumption [7]-[8]. Although leakage as a major factor of water losses can result in backflow through leaks and water-borne contamination, it also causes an increase in flow velocity and, thus, water age becomes shorter.Decreasing water age is good for chlorine concentration. However, to the best of the authors' knowledge, there is no study on the impact of water losses on chlorine distribution in pipe networks. Thus, this study aims to investigate the relationship between water losses and chlorine distribution as a key parameter to evaluate water quality by modifying the resilience index usedin hydraulic reliability.

II. RELIABILITY OF CHLORINE DISTRIBUTION

Hydraulic reliability in water distribution systems generally means the capability of the systems to satisfy water demands and pressure in both normal and critical situations such as pipe burst, fire and emergency demands, etc. A measure of hydraulic reliability often used in water distribution systems is a resilience index (I_r) [1]. Many studies are useI_r for investigation and optimization [9]-[12]. According to Todini's approach [1], resilience implies the intrinsic hydraulic capacity of a system to overcome failures in relation to pressure head surplus in normal operating conditions. This surplus allows a network to overcome critical operating conditions. The higher I_r value can show the higher hydraulic reliability in a system.

In terms of water quality, a concept of resilience index was implemented to investigate the reliability of chlorine distribution in this study. First, the mass of total free residual chlorine at inlet points (Cl_{tot}) can be computed by

$$Cl_{tot} = \sum_{i_t=1}^{n_t} Q_{inlet,i_t} C_{inlet,i_t} \Delta t \qquad (1)$$

wherei_t is an time index, n_t is total time step, Q_{inlet,i_t} and C_{inlet,i_t} is inflow and free residual chlorine concentration, respectively, and Δt is time interval.

Then, the mass of free residual chlorine received by water users (Cl_{ext}) can be estimated by

$$Cl_{ext} = \sum_{i_t=1}^{n_t} \sum_{i=1}^{n} q_{i,i_t} C_{i,i_t} \Delta t \qquad (2)$$

where$i$ is a user index, n is the total number of users, and q_{i,i_t} and C_{i,i_t} are water demand and concentration at a user, respectively.

In this study, the minimum free residual chlorine mass for users ($Cl_{ext,min}$) used the minimum concentration according to the WHO standard ($C_{i,\min}$ = 0.2 mg/liter). Thus, $Cl_{ext,min}$ can be written as follows:

$$Cl_{ext,min} = \sum_{i_t=1}^{n_t} \sum_{i=1}^{n} q_{i,i_t} C_{i,\min} \Delta t \qquad (3)$$

Therefore, we can estimate the real free residual chlorine lost in water distribution system (Cl_{int}) can be expressed as

$$Cl_{int} = Cl_{tot} - Cl_{ext} \qquad (4)$$

And, the maximum free residual chlorine lost in the system that still satisfies the constraints regarding demand and concentration at users ($Cl_{int,\max}$) is

$$Cl_{int,\max} = Cl_{tot} - Cl_{ext,\min} \qquad (5)$$

Finally, the resilience index for chlorine ($I_{r,Cl}$) can be computed as follows:

$$I_{r,Cl} = 1 - (Cl_{int} / Cl_{int,\max}) \qquad (6)$$

Similar to the original resilience index (I_r) by [1], $I_{r,Cl}$ implies the intrinsic water quality capacity of a system to overcome failures in relation to chlorine mass surplus in normal operating conditions. This surplus allows a network to overcome critical operating conditions. For example, the critical operating conditions regarding to water quality are an increase in water age or chlorine decay or microbial waterborne pathogens in a network.

In this study, the distribution of free residual chlorine concentration in a water distribution network was modeled using the first order decay model of the EPANET 2.0 software. Thus, the reaction rate (R) can be written as:

$$R = K_b C + \frac{A}{V} K_w C \qquad (7)$$

where$C$ is free residual chlorine concentration, A/V is the surface area per unit volume within the pipe, K_b and K_w are the bulk and wall reaction coefficients, respectively.

III. STUDY AREA

Our study area is DMA 54-09-03 in the Bang Bua Thong branch office (BBT) service area, the Metropolitan Waterworks Authority (MWA) as shown in Fig. 1. The BBT has a service area of around 340.23 square kilometers with 124,324 of water users. The area is divided into 123,191 small water users, 636 large users and 497 government users. The water distribution system consists of 80.3-km trunk mains and 2,059-km distribution pipes. The daily water demand is around 150,000 to 170,000 cubic meters per day, and the average pressure is approximately 6.8 meter. The BBT area is separatedinto 41 District Metering Areas (DMAs) for pressure and water loss management.

Table Ishows the hydraulic and pipe network information of our study area (DMA 54-09-03). It is a residential area with very low pressure but a high percentage of water losses.We installed three pressure loggers (P1-P3) on fire hydrants in the DMA during the period of our investigation and measured free residual chlorine concentration at three locations (C1-C3) as shown in Fig.2. At the inlet, there was a district meter where pressure and flow were automatically recorded, but we had to measure chlorine by ourselves manually (C1).

TABLE I. DETAIL OF STUDY AREA (DMA 54-09-03)

Data	Detail
Service area	2.10 square kilometers
Number of customer meters	2,457
Total pipe length	26.13 kilometers
Average pressure head	6.8 meters
Water loss	35.01%
Type of distribution pipe	PVC (80%), AC (20%)

IV. METHODOLOGY

The methodology in this study can be described as follows.

A. The necessary data were collected for model simulation and calibration such as data at observation point (DM), field data of water demand and pressure head. The model uses free residual chlorine data for the calibration.

B. Hydraulic model (EPANET 2.0) was performed the water distribution system in DMA 54-09-03

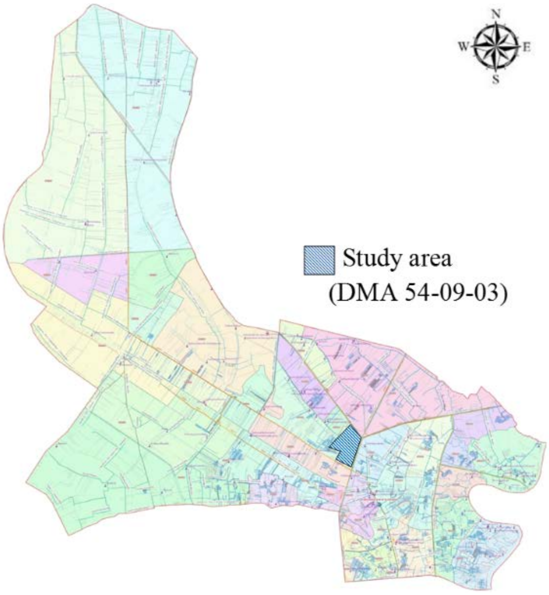


Fig. 1. DMA 54-09-03 in the Bang Bua Thong branch office service area

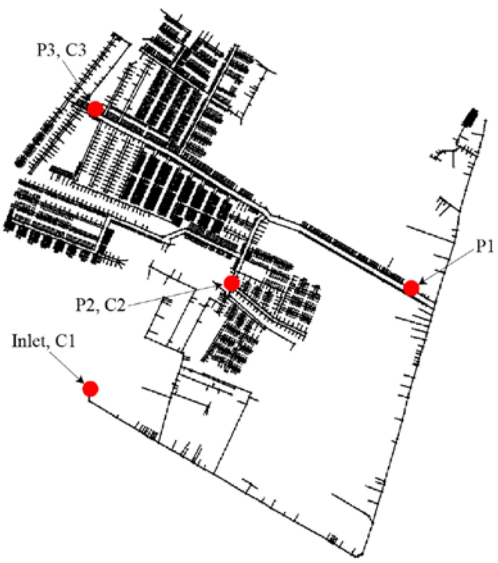


Fig. 2. Locations of the inlet, the pressure loggers (P1-P3) and the chlorine measurements (C1-C3) in DMA 54-09-03

C. The model calibration was performed by using base demand andloss in the study area. Base demand input into the model to be the observed data, and water loss data input into the model using Emitter function

$$Q_{leak} = CP^N \tag{8}$$

whereQ_{leak} is a leakage rate, C is an emitter coefficient, P is pressure at any junction and N is an emitter exponent. In this study, water loss that occurs in the system was assumed to be pressure-dependent flow because pipe leakage should be a main portion of water losses [6].We used pressure variation at $N = 1$ and then varied C value to calibrate the water discharge at DM between the model and actual data.

D. The model calibration was executed by adjusting demand pattern for the real pattern and Hazen-Williams pipe roughness coefficient (C_{HW}) to achieve pressure in the model conform to observed pressure at 3 loggers in the field (P1-P3).

E.K_b equals -3.384 day^{-1} taken from the MWA bulk FRC test report, and $K_w$was used as our calibration parameter for chlorine distribution at C2 and C3.

*F.*Our water quality model after calibration was implemented.The reliability measurement of the chlorine distribution was proposed by modifying the resilience index used for hydraulic reliability and simulate2cases, the situation with water losses and the situation without water losses.

V. MODEL CALIBRATION AND VALIDATION

A. Hydraulic model

1) Water inlet calibration

The result of the calibration shows that 0.1211 meter^2/day of the C value reflects flow inlet with best correlation at DM point between simulated and observed data. The data that used for the calibration is on November 11st 2017, and the case without water lossesuses the parameters and coefficients as same as the case with water losses.Only water losses dropped, so the emitter coefficient (C) is set to be zero.

2) Pressure validation

Use three loggers in the study area were used to be the observed data for model validation in November 11st 2017. The result of the validation is that the roughness coefficient (CHW) equals 138. Moreover, a comparison between observed data and simulated data indicate a good result of model validation, the consistency of the pressure data.

B. Water quality model

This research uses free residual chlorine data from MahaSawat water treatment plant to be the missing data representative of field measurement since the pattern of free residual chlorine between the water treatment plant and the inlet point of the study area (logger C1) have been related. Thus, the pattern of free residual chlorine was expanded by substituting the missing observed data with the water treatment plant's data, but the average of free residual chlorine is smaller than the treatment plant 0.05 mg/liter as shown in Fig. 3.

From the model calibration, thevalue of $K_b$was defined as -3.384 day^{-1} and used $K_w$equal 0.00 and -0.02 meters/day. From the result, after modified K_w to -0.02 meters/day,the modelcalibration expresses a correlation better than K_w 0.00 meters/day.

It is found that the average the concentration of free residual chlorine at the inlet point is 0.85 mg/liter results the average concentration of free residual chlorine as 0.60 mg/liter (0.25 mg/liter dropped) at the farthest point from the inlet (logger C3) on the case of unconcern global wall reaction (K_w = 0.00 meters/day) and the case of concern global wall reaction (Kw = -0.02 meters/day) results the average concentration of free residual chlorine equals 0.41 mg/liter (0.44 mg/liter dropped) at the farthest point from the inlet.

It shows that the wall reaction affects chlorine decay in a similar scale as a mass reaction in water. Likewise, using the first-order reaction for K_b and K_w as equation (7) leads the equation to be the linear first-order differential equation which makes the decay rate of free residual chlorine rely on the concentration at that time.

Fig. 4showthe temporal variations of water age and free residual chlorine.From ourresult, the inverse relationship between water age and free residual chlorine can be seen. During minimum nightflow (01:00am), the water age increased, and it reached the maximum at 4:00 am while the chlorine concentration was minimum.Themeasurement point (C3) is a maximum of 53 hours,and the amount of chlorine at the measurement point (C3) in the range of 0.30-0.55 mg/L, higher than the minimum recommendation of 0.20 mg/L by WHO [1].

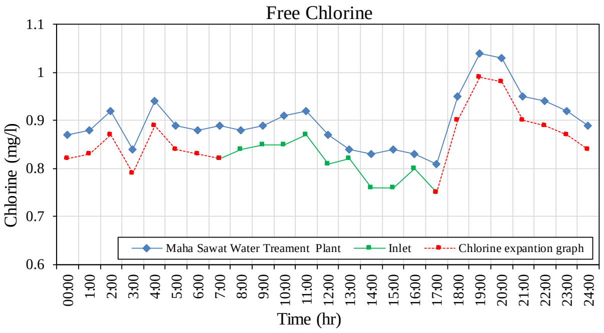


Fig. 3. The relationship of free residual chlorine between Maha Sawat water treatment plant and the inlet of DMA 54-09-03

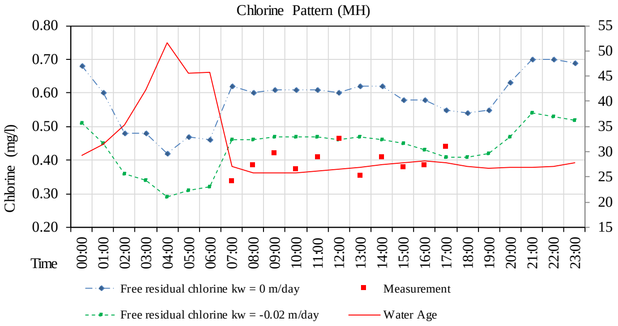


Fig. 4. Temporal variation of water age and simulated and measured free residual chlorine at point C3 in DMA 54-09-03

VI. RESULT AND DISCUSSION

Fig. 5 shows the contour of free residual chlorine at the shortest water age (8:00 am) and the longest water age (04:00 am) for the situations with water losses and without water losses. It was found that the chlorine concentration in DMA 54-09-03 was always higher than 0.20 mg/L (the minimum recommended value) with the average around 0.5 mg/L. From our results, the chlorine distribution at the time of the shortest and longest water ages showed a similar pattern. This is due to that the chlorine concentration at the inlet was not uniform (Fig. 3). The highest concentration at the inlet was at 19:00 pm, and it helps to increase the concentration during night time. Comparing the situationswith and without water losses, the chlorine concentration in the case without water losses is lower than that with water losses both at the time of the shortest and longest water ages.

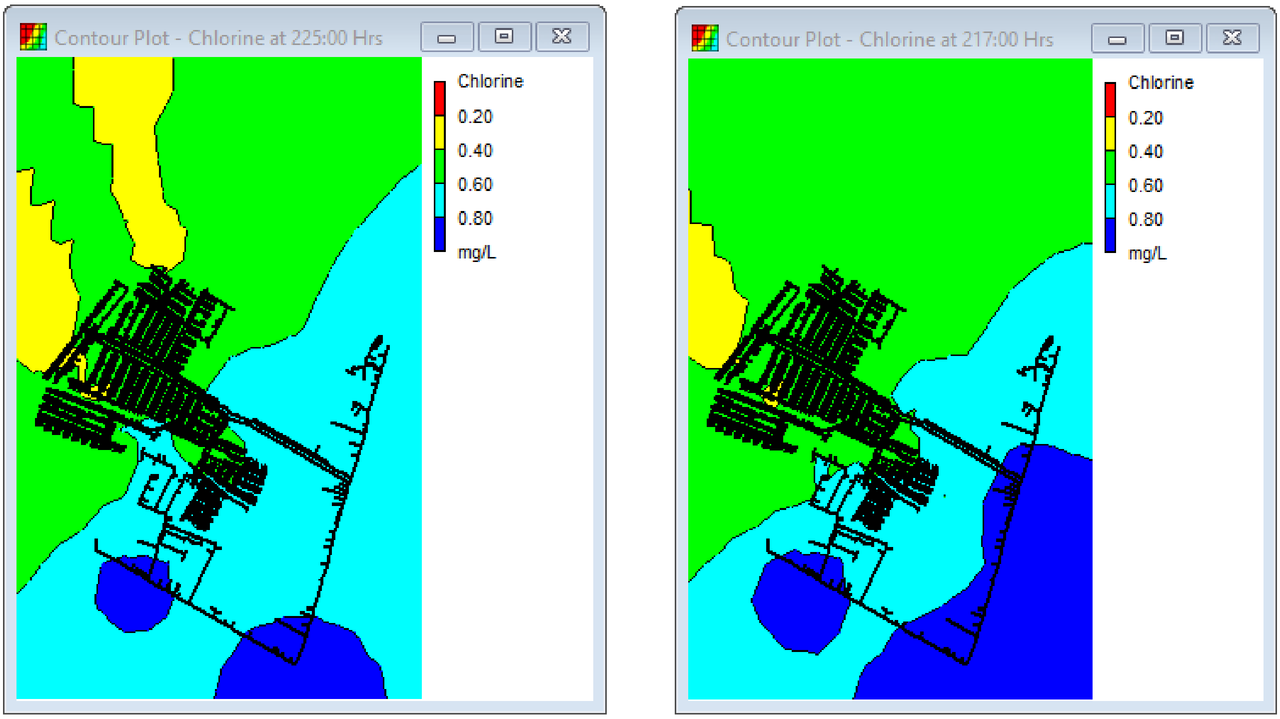
After calculating chlorine mass for 24 hours in the cases with and without water losses, we summarized our results in Table II. The total free residual chlorine mass (Cl_{tot}) in the system reduced by -28.15% when water losseswere not considered.This means that reducing water losses can reduce the chlorine input. The chlorine concentration at the inlet was assumed to be unchanged in this study. It showedthat both free residual chlorine at customer point (Cl_{ext}) and chlorine losses in the system (Cl_{int}) reducedat almost the same rate (-28%).A smaller value of Cl_{int} implies that the losses and decay in the system reduces. This is good for the system. But a smaller value of Cl_{ext}means that users are receiving less chlorine concentration. This is due to a decreaseof flow velocity in the system when there was no water loss. It leads to an increasing of water age in the system. So, the users will receive less free residual chlorine, and finally, it drops from 0.559 to 0.515.Thisresult indicatedthat the reliability in the area became lower.

TABLE II. RESULTS OF FREE RESIDUAL CHLORINE FOR 24 HOURS IN CASES WITH AND WITHOUT WATER LOSSES

Free Residual Chlorine	**%WL = 25% Grams (%)**	**%WL = 0% Grams (%)**	**Change (%)**
Cl_{tot} Cl_{ext} Cl_{int}	2,996 (100%) 1,887 (63%) 1109 (37%)	2,153 (100%) 1,342 (62%) 811 (38%)	-28 -29 -27
$Cl_{ext,min}$ $Cl_{int,max}$	482 2,514	482 1,671	0 -34
I_r	0.559	0.515	-7.9

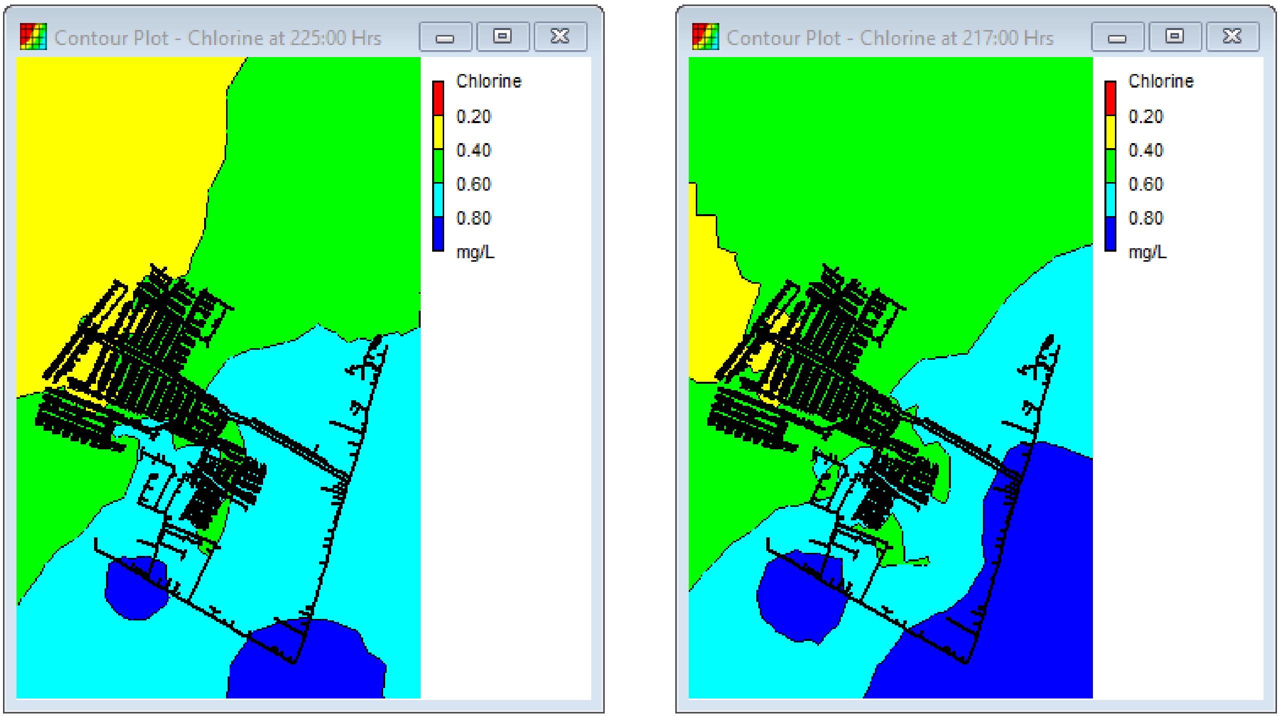
VII. CONCLUSION

We have performed a pipe network model to investigate the reliability of chlorine distribution in a water distribution system of the Metropolitan Waterworks Authority (MWA), Thailand. We proposed a new indicator, the resilience index for chlorine ($I_{r,Cl}$), to assess how the system overcome the critical condition related to water quality. $I_{r,Cl}$ implies the intrinsic water quality capacity of a system to overcome failures in relation to chlorine mass surplus in normal operating conditions. This surplus allows the network to overcome critical operating conditions regarding to water quality, for example, an increase in water age or a higher chlorine decay rate or microbial waterborne pathogens in a network. It is found that the model can represent the actual hydraulic and chlorine situation of our study area very well. The inverse relationship between water age and chlorine concentration havebe found.



Time8:00 am. Time 04:00 am.

Contour of free residual chlorine of the situation with water losses



Time8:00 am. Time 04:00 am.

Contour of free residual chlorine of the situation without water losses

Fig. 5. Countour of free residual chlorine in DMA 54-09-03.

The result shows that reducing water losses can help to decrease the input chlorine mass into the system. However, when flows and velocities in pipes decrease due to no water losses, water age increases, and, consequently, chlorine concentration decreases. Thus, unlike the energy concept that reducing water losses, users may receive higher pressure and energy, in the case of chlorine, users receive less chlorine, and this may lead to poorer water quality if the chlorine concentration becomes lower than the recommended value of 0.2 mg/L. This discussion is clearly shown in the form of $I_{r,Cl}$ that it was lower in the case of no water losses.

In conclusion, when water losses in the system decrease significantly, the reliability of chlorine distribution can be smaller. We recommend that water companies should reanalyze their chlorine distribution and may increase chlorine concentration at inlets or feeders to maintain chlorine concentration at users and the reliability similar to the situation before reducing water losses.

ACKNOWLEDGMENT

The researchers would like to express the sincere thanks to Bang Bua Thong waterworks office of Metropolis Waterworks Authority for the data of this research.

REFERENCE

[1] Todini E. Looped water distribution networks design using a resilience index based heuristic approach. Urban water. 2000 Jun 1;2(2):115-122.

[2] World Health Organization (WHO) 2011 Guidelines for Drinking-water Quality, 4th Edition.

[3] Konstantinos Gonelas, Apostolos Chondronasios, Vasilis Kanakoudis, Menelaos Patelis, Panagiota Korkana. "Forming DMAs in a water distribution network considering the operating pressure and the chlorine residual concentration as the design parameters." Journal of Hydroinformatics. 2017.

[4] Yingying Zhao, Y. Jeffrey Yang, Yu Shao, Jill Neal, Tuqiao Zhang. "The dependence of chlorine decay and DBP formation kinetics on pipe flow properties in drinking water distribution." Water Research 141 (2018): 32-45.

[5] Vanessa C.F. Dias, Marie-Claude Besner, Michèle Prévost, Predicting "Water Quality Impact After District Metered Area Implementation in a Full-Scale Drinking Water Distribution System." Journal-American Water Works Association 109, no. 9 (2017): E363-E380.

[6] American Water Works Association (AWWA). Water Quality in Distribution Systems: M68. American Water Works Association, 2017.

[7] Lapprasert, Sutthisak, Adichai Pornprommin, Surachai Lipiwattanakarn, and Suwatana Chittaladakorn. "Energy balance of a trunk main network in Bangkok, Thailand." Journal-American Water Works Association 110, no. 7 (2018): E18-E27.

[8] Gómez E, del Teso R, Cabrera E, Soriano J. Labeling Water Transport Efficiencies. Water. 2018 Jul 13;10(7):935.

[9] Prasad TD, Park NS. Multiobjective genetic algorithms for design of water distribution networks. Journal of Water Resources Planning and Management. 2004 Jan;130(1):73-82.

[10] Di Nardo A, Di Natale M, Giudicianni C, Greco R, Santonastaso GF. Complex network and fractal theory for the assessment of water distribution network resilience to pipe failures. Water Science and Technology: Water Supply. 2018 Jun 1;18(3):767-77.

[11] Maiolo M, Pantusa D, Carini M, Capano G, Chiaravalloti F, Procopio A. A New Vulnerability Measure for Water Distribution Network. Water. 2018 Jul 30;10(8):1005.

[12] Di Nardo A, Di Natale M, Gargano R, Giudicianni C, Greco R, Santonastaso GF. Performance of partitioned water distribution networks under spatial-temporal variability of water demand. Environmental Modelling & Software. 2018 Mar 31;101:128-36.