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Real-time ArcGIS and heterotrophic plate count based chloramine disinfectant control in water distribution system

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ABSTRACT

This study investigates the effect of chloramine residual on bacteria growth and regrowth and the relationship between heterotrophic plate counts (HPCs) and the concentration of chloramine residual in the Shanghai drinking water distribution system (DWDS). In this study, models to control HPCs in the water distribution system and consumer taps are also developed. Real-time ArcGIS was applied to show the distribution and changed results of the chloramine residual concentration in the pipe system by using these models.

Residual regression analysis was used to get a reasonable range of the threshold values that allows the chloramine residual to efficiently inhibit bacteria growth in the Shanghai DWDS; the threshold values should be between 0.45 and 0.5 mg/L in pipe water and 0.2 and 0.25 mg/L in tap water.

The low residual chloramine value (0.05 mg/L) of the Chinese drinking water quality standard may pose a potential health risk for microorganisms that should be improved. Disinfection by-products (DBPs) were detected, but no health risk was identified.

1. Introduction

Microbial risk is a significant threat to drinking water safety all over the world, as the World Health Organization stated in their guidelines for drinking-water quality (WHO, 2011). The primary goal of drinking water quality management is to ensure the supply of safe and high quality potable water to all consumers. Rapidly locating an area with an inadequate disinfectant concentration and responding to maintain the concentration within a suitable range throughout the distribution system is a key task. Because of increased pollution of water resources and inefficient disinfection processes, potential microbial risk in drinking water distribution systems (DWDSs) is increasing.

Most waterworks in Shanghai use chloramine as their disinfection regimes. This is a practical solution to maintaining chloramine residual in a long distribution system, because it is more stable than free chlorine (Motzko et al., 2009). In

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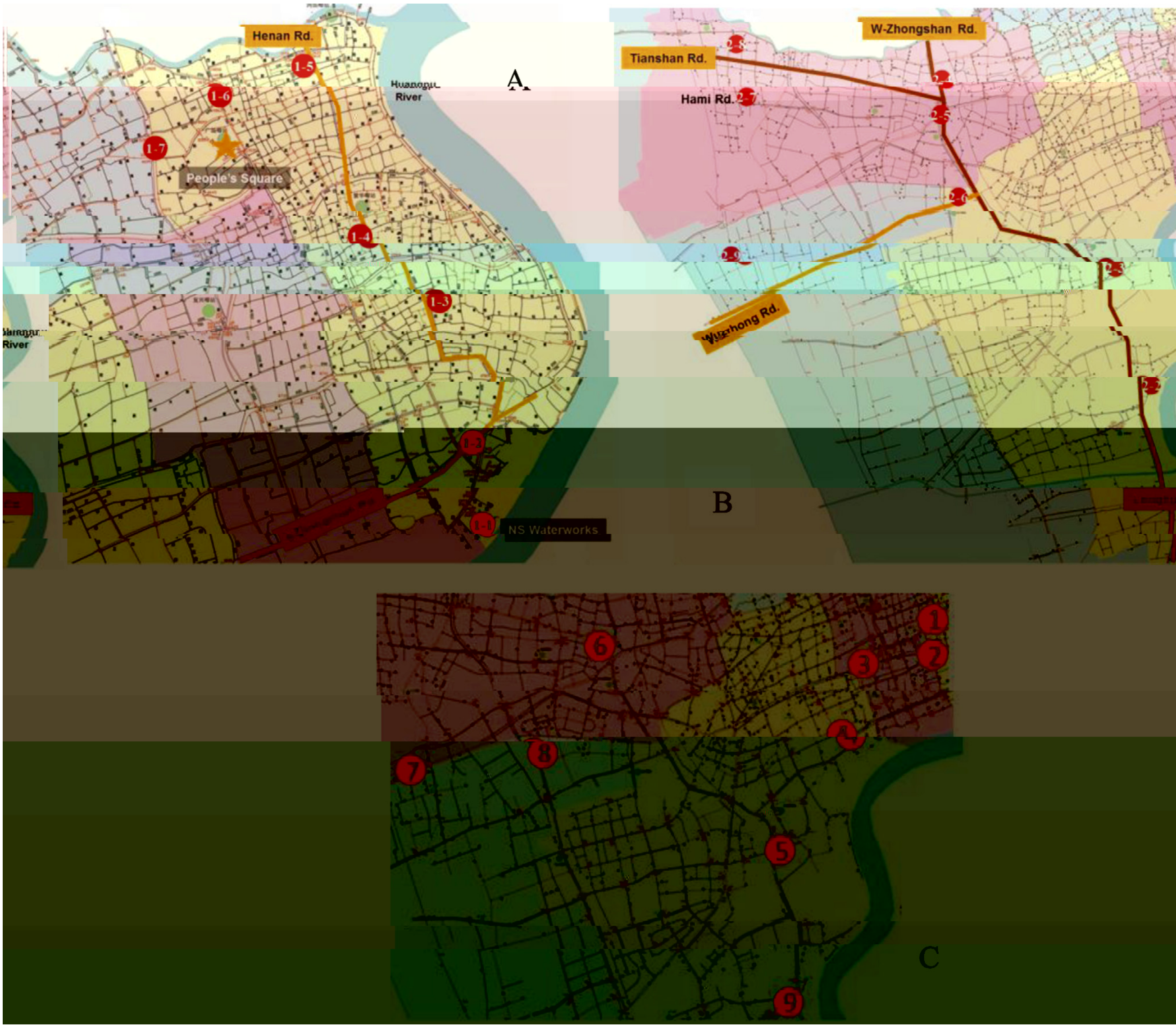

Fig. 1 – Sampling spots in Shanghai pipe system from two water works (A and B) and the communities (C).

addition, because monochloramine is a less powerful oxidant than chlorine, it may produce fewer disinfection by-products (DBPs) and fewer taste and odor issues in water. However, chloramine disinfection must be carefully controlled through the management of water chemistry to ensure pathogen inactivation throughout a distribution system (Miller et al., 1995). The application of either too high or too low a dose of chloramine disinfectant is often identified too late for an operator to respond and take corrective actions (Hua et al., 1999; Rodriguez and Serodes, 1998). Practitioners, particularly operators who control secondary disinfection via feedback control loops, should acquaint themselves with the regulation of chloramine decay in water distribution systems (Fitzgerald et al., 2006).

Many researchers (Francisque et al., 2009; Hallam et al., 2002; Vasconcelos et al., 1997) have indicated that the concentration of chlorine residual in pipe water is inversely related to the level of microbes and the water temperature, and positively related to the initial chlorine concentration in water. Some scientists (Hallam and Hua, 2003; Powell et al., 2000) have found that the Arrhenius equation can be used to describe the relationship between temperature and the bulk decay constant (k_b). However, these conclusions would be unusable without exact and complex hydraulic data from water distribution networks.

Many studies on the inhibition and regrowth of bacteria in drinking water have been conducted. The growth of bacteria in distribution systems depends on various physical, chemical, and operational conditions (Zhang and DiGiano, 2002), as well as seasonal fluctuations (Berry et al., 2006). Francisque et al. (2009) developed models based on multivariate regression analysis for predicting heterotrophic plate counts (HPCs) in the distribution systems of Quebec City. He applied the widely accepted concept that many other water quality parameters are associated with the HPC level (Spiegel and Stephens, 2007) and attempted to identify them by using one regression approach. The development of one-level and multi-level statistical models for HPC occurrence led to the simultaneous consideration of different factors that potentially govern HPC levels. But this method was associated with several disadvantages. The models were specific to the distribution system of Quebec City, and another limitation of the model was that it was more suited to describing and predicting the HPC in distribution systems where bacterial occurrence was relatively low (

2002), the chloramine residual in the water distribution system was negatively related to water temperature and positively related to the initial disinfectant concentration. Water temperature affected the chloramine residual concentration by changing the disinfectant decay rate. Thus, the equation should include a monomial to represent the initial disinfectant concentration and another monomial to represent the value of the initial disinfectant concentration multiplied by temperature. The Matlab sentences are described as follows:

$$X = [\text{ones}(\text{length}(x),\ 1) x\ tx];\ \ B = \text{regress}(y,\ X),$$

where x represents the maximal total chloramine residual (TClmax), t represents temperature (T), y represents the minimal total chloramine residual (TClmin), and $tx = t^{*}x$.

The relationship between chloramine and the HPC in pipe water and tap water were also considered and regression curves of chloramine residual decay were fitted.

3. Results and discussion

3.1. *Effect of chloramine residual on bacteria growth in water distribution systems*

Fig. 2 shows the relationships among the HPC, total chlorine level, and temperature in the researched Shanghai water distribution system reflected by the collected data. The HPC exhibited a negative relationship with chlorine residual and a positive relationship with temperature. The water temperature in summer is high (nearly 30 °C). Table 1 shows the quality of the water in the pipe system. The data indicated that the system exhibited a high organic matter level. Researchers (Gibbs et al., 1993; LeChevallier, 1990) have stated that organic matter is the main feature that limits microbial growth or regrowth in drinking water. But other studies (Srinivasan and Harrington, 2007; Chandy and Angles, 2001) have indicated that the growth of bacteria in water cannot be controlled by organic matter if carbon resources are abundant and above a threshold level, which was thought to be a low value. LeChevallier (1990) suggested that regrowth of coliform bacteria might be limited by assimilable organic carbon (AOC) levels less than 100 μg/L acetate-C. Srinivasan and Harrington (2007) also found that an AOC level significantly lower than 100 μg/L acetate-C was required to control HPC regrowth. Hem and Efrimsen (2001) proved that the major component of AOC was natural organic matter with molecular weights less than 1000 u, which accounted for 16%–38% of TOC in water. Because the average DOC level detected in the Shanghai drinking water system was higher than 5 mg/L (Table 1), AOC in the drinking water may be above 0.8 mg/L, which is much higher than the previously mentioned threshold value. The COD_{Mn} level even exceeded the Chinese standard (3 mg/L) for drinking water quality (GB5749-2006). Therefore, it is reasonable to treat the inhibition effect of organic matter on HPC levels as negligible and exclude the parameter while fitting the regression equations between the HPC and residual disinfectants.

Mean HPC levels in pipe water and tap water were both higher than the NPDWR requirements (500 colony forming units [CFUs]/mL, see Figs. 3 and 4). By contrast, TB and TC levels were unexpectedly low. No sample contained more TB than the Chinese standard requirement (100 CFU/mL), and only two or three TCs were found in several water samples. Data indicated that TB or TC was a less sensitive measure of variations of microbial levels in drinking water than the HPC.

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[redacted] 1 – Water quality in the main pipe water and tap water.

[redacted]	pH	Total chlorine (mg/l)	Turbidity (NTU)	DOC (mg/l)	COD_{Mn} (mg/l)	TB (CFU/ml)	Total coliforms (CFU/mL)
[redacted]	7.10	0.99	0.32	5.77	4.15	/	/
[redacted]	0.13	0.58	0.16	1.51	1.68	/	/
[redacted]	7.22	0.67	0.50	5.14	3.27	3.56	0.48
[redacted]	0.12	0.90	0.30	1.29	0.18	2.57	1.62

[redacted] $= 0.44$, (2)

[redacted] x represents the [redacted]

[redacted] of fit. This [redacted] ficiency of [redacted] analysis [redacted] in [redacted]

threshold, meaning that the growth and regrowth of the HPC in water would be out of control when the chloramine value decreased below that value. Fig. 3(b) and Fig. 4(b) show that the threshold value ranges required to avoid a loss of HPC control in pipe water and tap water were 0.45–0.5 mg/L and 0.2–0.25 mg/L, respectively. This result was confirmed in other studies. For instance, LeChevallier (1990) indicated that systems that maintained dead-end monochloramine levels of less than 0.5 mg/L exhibited substantially more coliform occurrences than systems with higher disinfectant residuals.

New decay curves were generated using the measured data [redacted] chloramine levels above the threshold values. The re- [redacted] are described as follows.

[redacted] 615849450.78*exp(−x/0.042) $R^2 = 0.71$ (3)

[redacted] 584.00*exp(−x/0.092) $R^2 = 0.74$ (4)

[redacted] developed based on the data from 147 pipe [redacted] chloramine residuals higher than [redacted] developed based on the data from [redacted] chloramine concentrations [redacted] the correlation coefficient [redacted] a 99.9% confidence [redacted] in a set of 25 data [redacted] equations were [redacted] (3) and (4) [redacted] that the [redacted] when the [redacted] oxidizing ability of chloramine compared with free chlorine. To diminish the health risk caused by microorganisms, a higher chloramine residual should be maintained in pipe systems. Therefore, the optimization of booster chloramination should be considered and calculated, and a study on the decay control of disinfectant in systems is essential.

3.3. *Disinfectant decay model in distribution networks*

Seasonal changes in chloramine residual decay reflect the obvious influence of temperature. Many studies (Francisque et al., 2009; Hallam et al., 2002; Liu et al., 2014; Vasconcelos et al., 1997) have described this phenomenon, as well as the effect of the initial chloramine concentration. However, many other factors also affect the process. Researchers (Lehtola et al., 2005; Al-Jasser, 2007) have examined many environ-

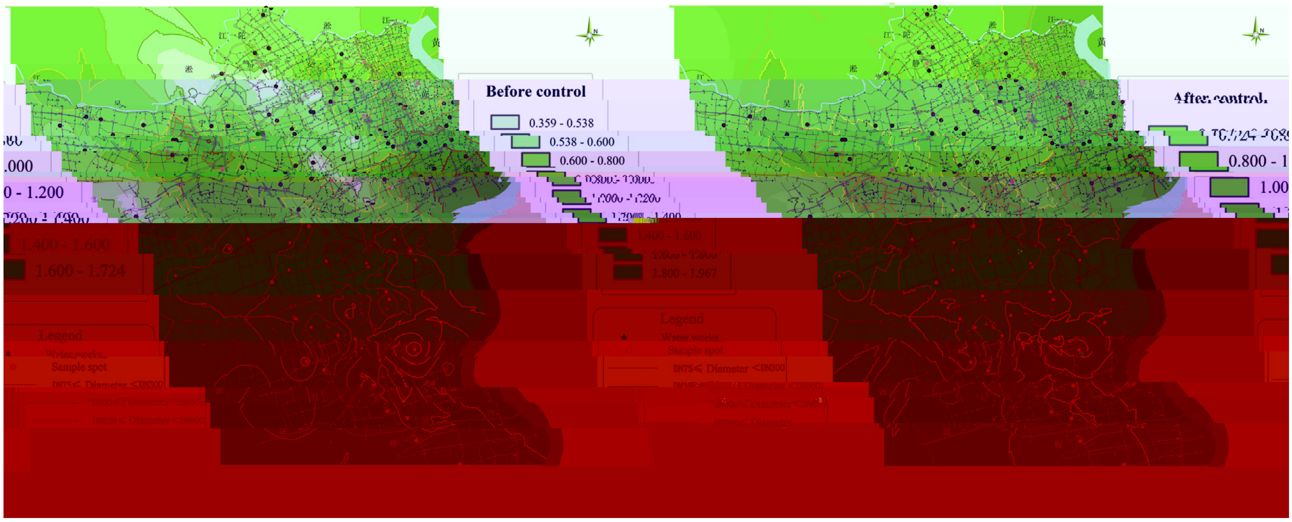

Fig. 5 – Control of chloramine residual in Shanghai DWDS (a) Before control (b) After control.

decrease the level of chloramine residual concentration in the water distribution system and correspondingly reduces the dosage of disinfectant in waterworks and decreases the risk from DBPs and flavor issues from chlorine.

Other authors (Fisher et al., 2011, 2012) have attempted a more complex analysis of the factors driving chloramine loss and disinfection by-product formation in distribution systems. However, we have found that in the two distribution systems that we studied a useful practical approach to controlling regrowth and disinfection by-products using relatively simple analysis. This approach was linked to an ArcGIS system to provide near-to-real-time representation of the effectiveness of the approach throughout the systems.

3.5. *Disinfection by-products in drinking water distribution systems*

The predicted chloramine threshold values required to control the HPC in the Shanghai DWDS were high, which prompted the authors to check the risk of DBPs in the Shanghai DWDS. Chloroform in pipe water was measured and are shown in Fig. 6.

Chloroform and carbon tetrachloride are suspected carcinogens or toxins and can exert adverse effects on health. The Chinese standard limits for the amounts of chloroform and carbon tetrachloride in drinking water are 60 μg/L and 2 μg/L, respectively. The concentrations of DBPs in all samples were less than the limits, indicating that DBPs in the Shanghai DWDS are not a health risk. Even with the high values of residual chloramine in the DWDS (see Fig. 5), a chloramine residual threshold of 0.5 mg/L did not cause an overproduction of DBPs.

4. Conclusion

This paper describes a rapid method for setting and modulating chloramine residuals by using a real-time ArcGIS and establishes two types of model to maintain the HPC at safe levels in pipe systems by changing the chloramine residual concentration at the effluent of waterworks. Shanghai Water

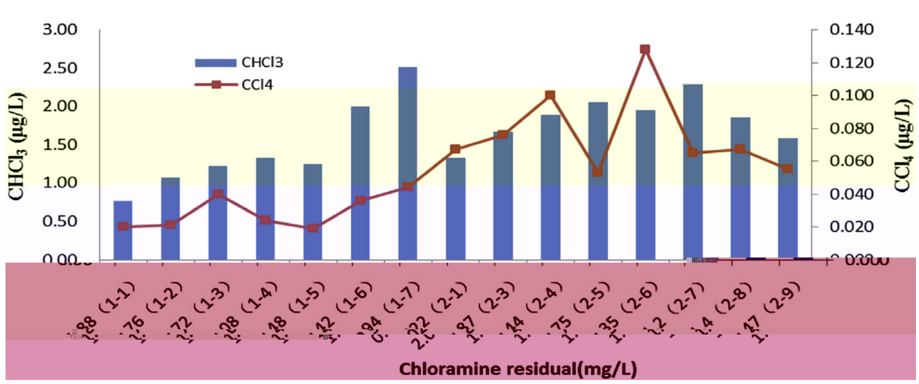

Fig. 6 – DBPs in the researched water distribution system (X axis stands for the chloramine residual concentration at different sampling points in pipes.)

Authority can improve the management of water quality to advance microbial safety in drinking water by using these tools.

Based on the calculations generated by the prediction models, the recommended initial chloramine residual concentration in the effluent from waterworks below 25 °C was also provided. The threshold values of residual chloramine to avoid loss of HPC control were 0.45–0.5 mg/L in pipe water and 0.2–0.25 mg/L in tap water. According to the Chinese standard for drinking water quality (GB5749-2006), the required chloramine residual maintained in distribution systems must be only 0.05 mg/L. The standard for microbial safety should be improved to avoid health risks from bacteria in drinking water. DBPs in the studied system were detected, but not at levels that pose a health risk. This result supports the proposal to increase the chloramine residual concentration in pipe systems. So other water suppliers in other cities can consider this method to check their pipe system for the chlorine residual modulation and control, and we will also do some works in the future to see if this approach works in other systems.

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