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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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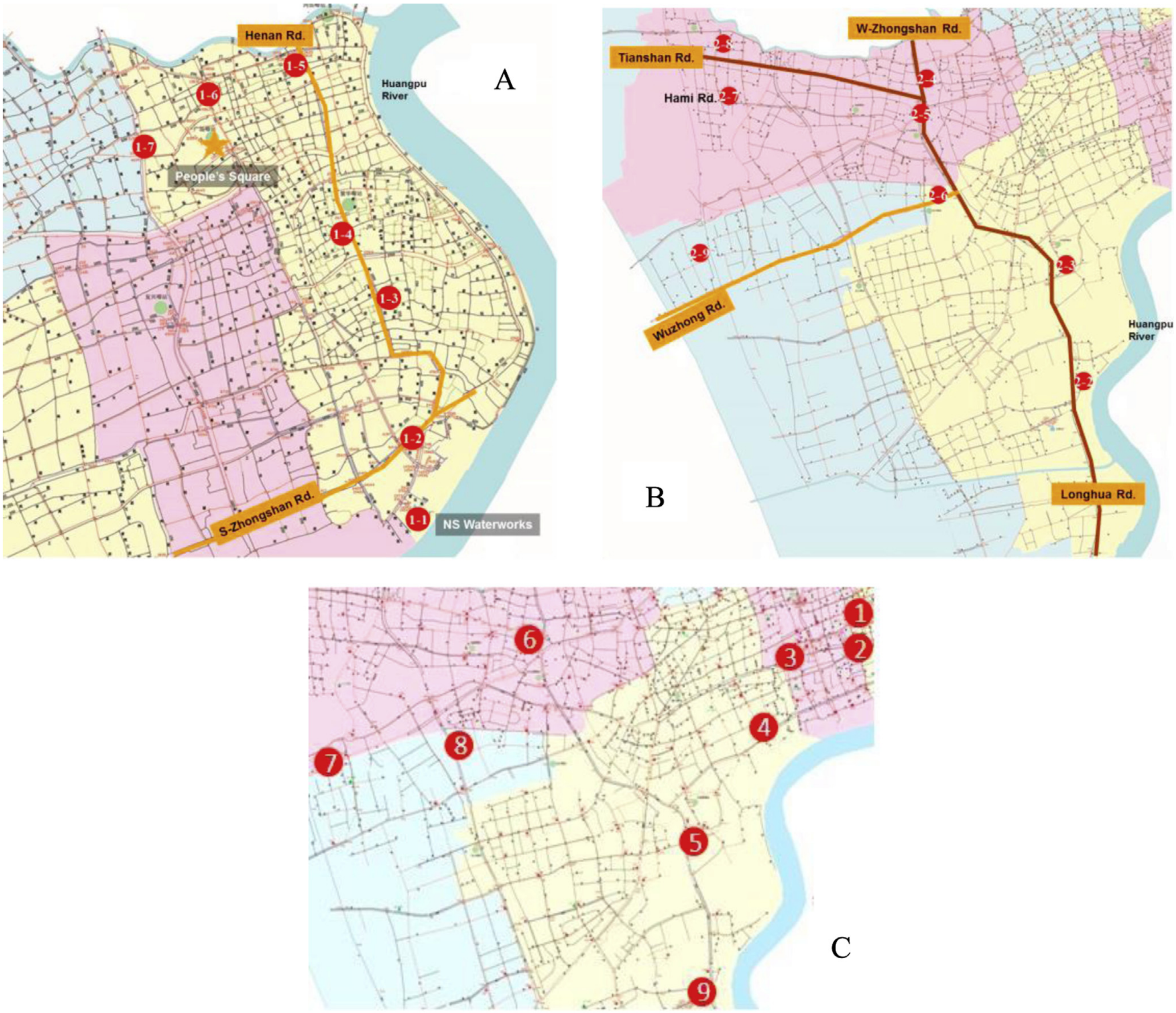


Fig. 1 – Sampling spots in Shanghai pipe system from two water works (A and B) and the communities (C).

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 (Francisque et al., 2009).

This study focuses on the relationships between the HPC and chloramine residual and the development of a method to rapidly show the results of changing level of chloramine residual set at the treatment plant to ensure that the changed chloramine residual is capable of inhibiting the HPC levels in the Shanghai DWDS. The models describe the control of disinfectant decay without using any precise hydraulic data. The model can be used to forecast the disinfectant level required by the system.

2. Methods

2.1. Sampling and analytical methods

This study investigated the water distribution system in Shanghai, China, which serves nearly 12,000,000 people. Shanghai is located in a region that experiences major seasonal climate variations, and air temperatures range from 0 °C to 37 °C. The waterworks use water from the Qingcaosha reservoir or Huangpu River and chloramine is both the primary disinfectant at the treatment plant and the secondary disinfectant in the distribution system.

As shown in Fig. 1, 16 sampling sites in two pipelines from two waterworks and 9 sampling sites from related community taps were selected to establish the chloramine control models. The microbiological and physico–chemical parameters of 384 pipe water samples and 204 tap water samples were collected and measured for over 2 years (2009–2010). All samples were taken once a week during the sampling period. Two cars were sent to take the samples. As Shanghai is a large city, a whole day was needed for all samples to be taken. We always started at 7 am in the early morning and ended at around 5 pm in the afternoon. The residence time of the tap water in the distribution system ranged from a few hours to three days.

All sampling facilities and vessels were sterilized before sampling. The water temperature, pH, turbidity, and chloramine residuals were measured while sampling. Other parameters, such as dissolved organic carbon (DOC), were measured within 24 h. Samples were stored below 4 °C. Turbidity was determined by a turbidity meter (Hach 2100Q, USA). Chloramine residual was measured by using an HACH Pocket Colorimeter II (Model 46700-001, USA; DPD Method 8167 (0.02–2.00 mg/L Cl_2)) and the real-time monitoring system. The pH was measured by a pH meter (Mettler-Toledo FE20K), and DOC was determined by a TOC analyzer (Shimadzu TOC-V CPH).

The HPC was selected as the primary microbial indicator in this study. It has also been used as the primary parameter for assessing the general microbial quality of drinking water (Allen et al., 2004; Sartory, 2004). Furthermore, HPC measurement has been used to indicate the effectiveness of water treatment processes and as a measure of microbial regrowth numbers in water (WHO, 2002). HPC determination in this study followed the Standard Methods (American Public Health Association, 1998) spread plate count method (9215C). R2A agar was used for HPC determination and the plates were incubated at 28 °C for 7 days.

Both Chinese Standards for drinking water quality (GB 5749-2006) and National Primary Drinking Water Regulations (NPDWRs) (USEPA, 2009) have total bacteria (TB) and total coliform (TC) requirements, therefore they were compared with the HPCs when monitoring the tap water samples. TB was incubated using plate count agar (PCA) at 37 °C for 2 days, according to GB 5749-2006. TC was incubated using the membrane filter method and Fuchsin Basic Sodium Sulfite Agar.

Chloroform and carbon tetrachloride are typical DBPs in the Shanghai DSDW. They were measured using a gas chromatography (GC) electron capture detector (ECD). The following analytical conditions were used: GC, Angilent 6890-N; ECD, μECD; and capillary chromatogram pillar, HPC-5, 5%, and PhenylMethylSiloxane, 30 m*320 μm*0.25 μm.

2.2. Data analysis

2.2.1. Geographic information system and ArcGIS analysis

A geographic information system (GIS) is a type of application that includes a set of facilities to capture, store, retrieve, maintain, and display geographic data and information. A GIS is created by combining maps, databases, and computer graphics (Bai et al., 2011). Spatial analysis is the core function of GIS. GISs can be used to resolve many statistical problems associated with spatial information.

ArcGIS is an integrated collection of GIS software products for building a complete GIS. ArcGIS enables users to deploy GIS functionality wherever it is required on desktops, servers, or custom applications over the Web or in the field. ArcGIS is a platform for designing and managing solutions through applying geographic knowledge (Zafar and Cutright., 2014; Roberts et al., 2010).

In this research, real-time and in situ chloramine residual concentrations were captured from 152 real-time water quality monitoring spots in the Shanghai water distribution network. Visible maps of the chloramine residual distribution were produced using Arcmap (an ArcGIS product). The detailed parameters of the spatial analysis are described as follows: interpolation method, Kriging method; semivariogram model, exponential; number of points, 5; maximal distance, null (auto); and output cell size, 0.91.

2.2.2. Statistical analysis and regression approach for the control models

The monthly average water temperature during 2009 and 2010, as well as the minimal and maximal residual chloramine levels were selected in the system after integrating the residual chloramine values. The maximal chloramine value was always determined from the initial chloramine value as water left the waterworks because effluent water from waterworks generally contains higher concentrations of disinfectant than water from any other location in the system. A regression analysis on the effect of temperature and maximal disinfectant values on minimal chloramine values was developed. As stated in other studies (Francisque et al., 2009; Hallam et al., 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:

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

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.

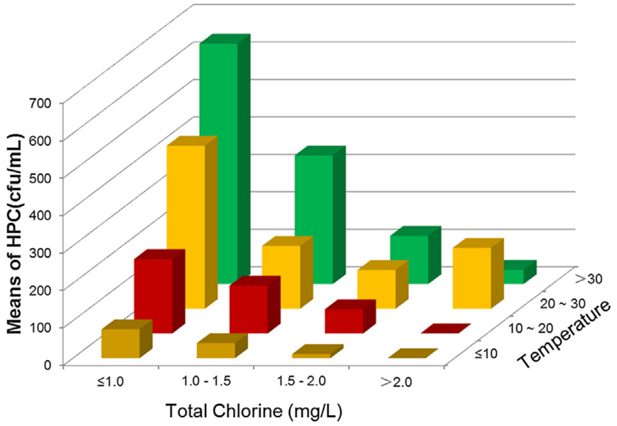


Fig. 2 – Relations between HPC, total chlorine and temperature in Shanghai water distribution system.

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. Compared with the small fluctuation of TB and TC (see in Table 1), the HPC index is more appropriate to indicate the microbial levels in the Shanghai drinking water supply system.

Although it was not as serious as in certain countries, such as Finland (Lipponen et al., 2002), some microbial risk was reflected in the Shanghai drinking water system when its HPC levels were compared with HPC levels reported by other studies (Francisque et al., 2009). Microbial risk management should be seriously focused on diminishing and inhibiting the HPC in water distribution systems, especially in tap water.

3.2. *Relationship between the heterotrophic plate count and chloramine residual*

The effects of some parameters on HPC levels in the Shanghai DWDS are negligible. Organic matter is one of these parameters. The effect of turbidity is also negligible because of the narrow range of turbidity in drinking water (standard deviation: 0.16 nephelometric turbidity units [NTUs] in pipe water and 0.3 NTU in tap water, see Table 1), although several studies (Weinberg, 1999) have investigated the effect of turbidity on disinfection.

3.2.1. *Exponential decay model*

The exponential decay curve to describe the relationship between the HPC and disinfectant residual in pipe water above 25 °C was fitted and is shown in Fig. 3. The curve equation is:

$$\begin{aligned} y =& 367.59 - 3891.60^{*}\exp[-(x - 0.08)/0.047] \\ &+ 18193.14^{*}\exp[-(x - 0.08)/0.26] \quad R^2 = 0.31, \end{aligned} \tag{1}$$

where y represents the HPC (CFU/mL) and x represents the total chloramine residual concentration (mg/L).

Fig. 4 shows the inhibition effect of chloramine residual on the HPC in tap water above 25 °C. The equation representing this effect is described as follows:

Table 1 – Water quality in the main pipe water and tap water.

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

$$y = 305.19 + 125575.98*\exp(-x/0.11) \quad R^2 = 0.44, \tag{2}$$

where y represents the HPC (CFU/ml) and x represents the total chloramine residual concentration (mg/L).

The correlation coefficient reflected a low degree of fit. This may have occurred because of the inhibition inefficiency of chloramination. In this study, the residual regression analysis focuses on exponential decay models, which are shown in Fig. 3(b) and Fig. 4(b). The models fit the measured data with high chloramine residual values, but a sudden invalidation occurred when the chloramine value dropped below a 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.

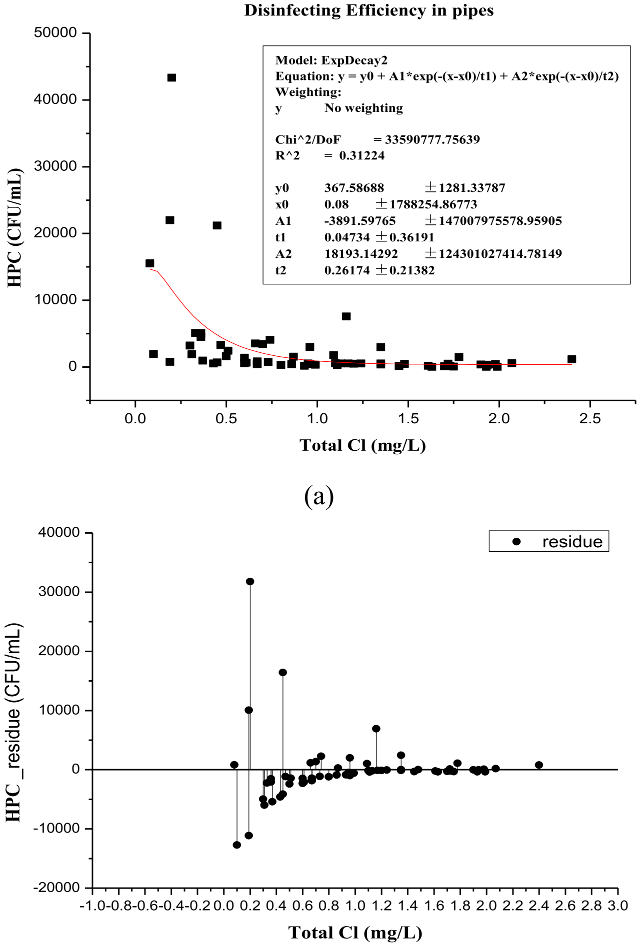


Fig. 3 – Regression curve of the inhibition effect of chloramine residual on HPC in pipe water (a) Exponential decay curve. (b) Residuals regression analysis.

New decay curves were generated using the measured data with chloramine levels above the threshold values. The results are described as follows.

$$y = 609.55 + 615849450.78*\exp(-x/0.042) \quad R^2 = 0.71 \tag{3}$$

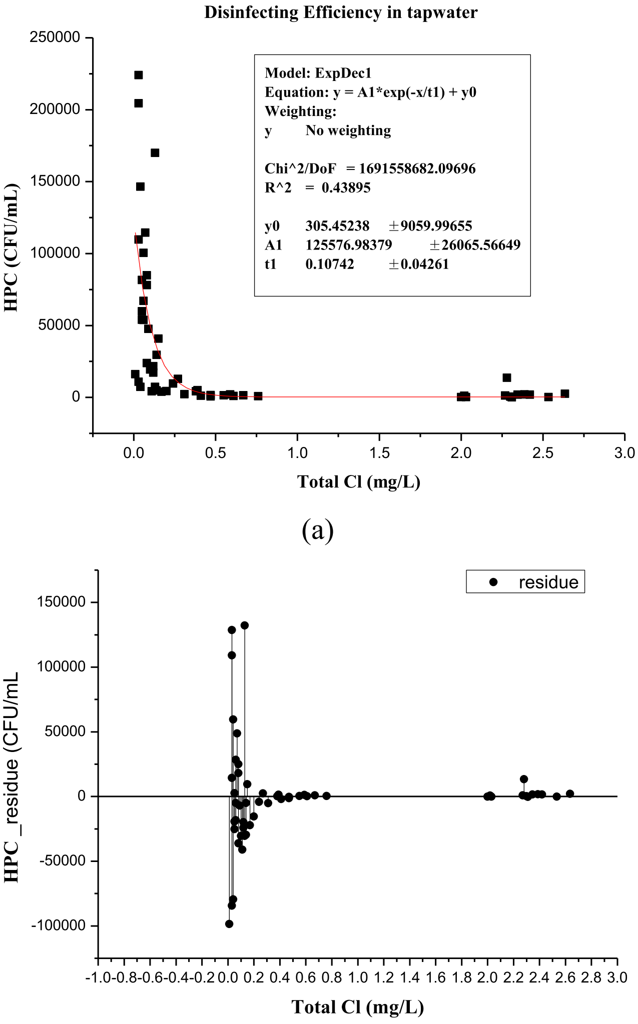
$$y = 1013.81 + 138584.00*\exp(-x/0.092) \quad R^2 = 0.74 \tag{4}$$

Equation (3) was developed based on the data from 147 pipe water samples, with chloramine residuals higher than 0.45 mg/L. Equation (4) was developed based on the data from 124 tap water samples, with chloramine concentrations higher than 0.2 mg/L. According to the correlation coefficient statistics table, the fitting curve reflected a 99.9% confidence value if the coefficient as higher than 0.597 in a set of 25 data points, therefore the R^2 values of these two equations were acceptable. Comparing the R^2 values from Equations (3) and (4) with those from Equations (1) and (2) demonstrated that the predicted HPC results did not fit the measured data when the disinfectant residuals in the Shanghai DWDS were less than the threshold values. A chloramine residual in water that is less than the threshold value is a potential microbiological risk for HPCs in water that is above 25 °C.

3.2.2. *Prediction of chloramine residual requirements*

Predictions of the chloramine concentration required to inhibit HPC growth in pipe systems above 25 °C were made according to US Environmental Protection Agency standards (HPC < 500 CFU/mL) and certain EU countries' drinking water quality standards (HPC level < 1000 CFU/mL). The results simulated using Equations (3) and (4) reflected high chloramine concentrations in pipe water and tap water. In pipe water, a chloramine concentration of above 1.37 mg/L is required to maintain HPC levels below 500 CFU/mL in summer. The chloramine concentration should be above 0.96 mg/L if the HPC standard is 1000 CFU/mL in pipe water. The required chloramine concentrations in tap water are 0.7 mg/L (500 CFU/mL) and 0.56 mg/L (1000 CFU/mL).

The results demonstrated the inefficiency and inadequacy of chloramine disinfection, which was caused by the low



(a)

(b)

Fig. 4 – Regression curve of the inhibition effect of chloramine residual on HPC in tap water (a) Exponential decay. (b) Residuals regression analysis.

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 environmental parameters, such as biofilms and pipe materials, in DWDSs. But these parameters are difficult to quantify and their effects are difficult to define. Therefore, parameter selection was required while developing the decay model, as stated by earlier studies. For instance, Powell et al. (2000) reported on the negative effect of pH on chlorine decay in bulk water. They concluded that the narrow range of pH fluctuation (6.9–7.3 or more) would not cause any obvious decay of chlorine. The pH fluctuation detected in this study was also low (standard deviation: 0.13 in pipe water and 0.12 in tap water), as shown in Table 1. Thus, it was excluded from this discussion.

Regression models on chloramine decay in the Shanghai DSDW were developed. Two variables that were considered were the water temperature and maximal chloramine concentration.

The first model was developed using 24 months of pipe system data (2009 and 2010).

$$\mathrm{TClmin(fit)} = 0.6161 + 0.2379*\mathrm{TClmax} - 0.0159*T*\mathrm{TClmax} \tag{5}$$

The standard deviation between the fitted and measured values of minimal residual chloramine in the DWDS was 0.26 mg/L. Data with a mean water temperature lower than 25 °C were selected and the second model was developed.

$$\mathrm{TClmin(fit)} = 0.2168 + 0.4344*\mathrm{TClmax} - 0.0142*T*\mathrm{TClmax} \tag{6}$$

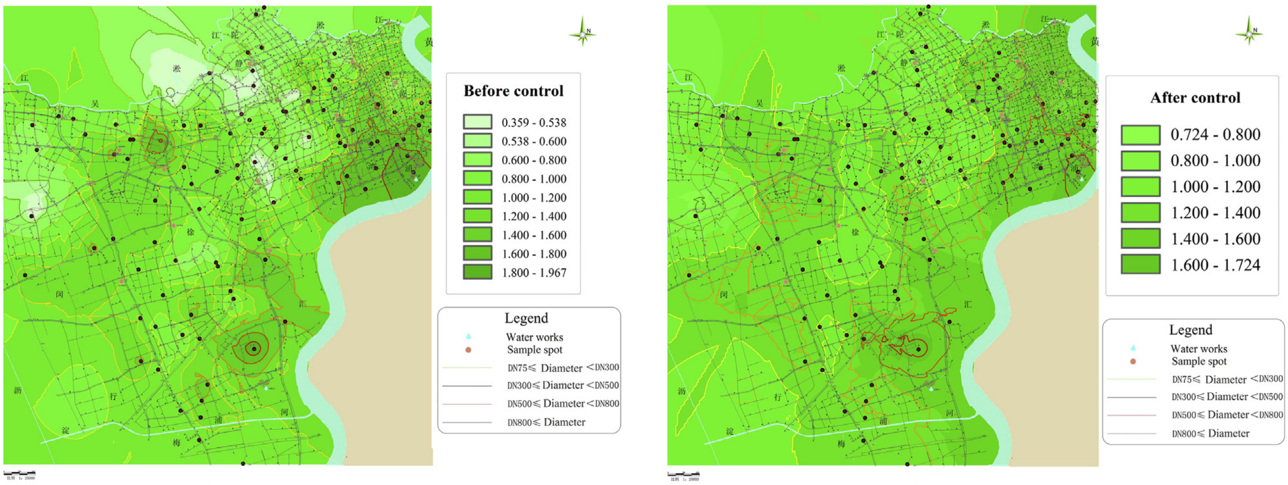
The standard deviation between the fitted and measured values was 0.15 mg/L, which is a more practically acceptable value.

This model can be used to regulate the initial chloramine concentration of the water exiting waterworks at certain temperatures, and the required minimal residual chloramine value in the pipe system can be derived using Equation (3) or 4. For instance, if the water temperature is 15 °C and the required minimal residual chloramine in the system is 0.6 mg/L, the calculated maximal residual chloramine concentration is 1.74 mg/L (fitted by Equation (6)), meaning that the effluent chloramine concentration leaving the waterworks should be maintained above 1.74 mg/L.

By contrast, the model did not fit well at high temperatures (>25 °C). The reason for this result is unknown. Increasing effects of pipe materials over a long distribution distance and higher activities in biofilms may be relevant to the result.

3.4. *Real-time ArcGIS-based chloramine residual control*

As shown in Fig. 5, we cooperated with Shanghai Municipal Waterworks South Co. Ltd and the Shanghai Municipal Water Supply Control and Monitoring Centre to set and modulate the chloramine residual concentration in the research area by using the described prediction models and real-time ArcGIS in 2011. In Fig. 5(a), the distribution of the chloramine residual concentration before control was uneven in the researched areas – some of the concentrations were inadequate and some were below the recommended range of a chloramine residual from 0.45 to 0.5 mg/L Fig. 5(b) shows the controlled distribution of chloramine residual in the researched area. The chloramine residual in Fig. 5(b) is more uniform than in Fig. 5(a) and all of the residuals were above the recommended range of 0.45–0.5 mg/L Fig. 5 also shows that control helps to



(a) (b)

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

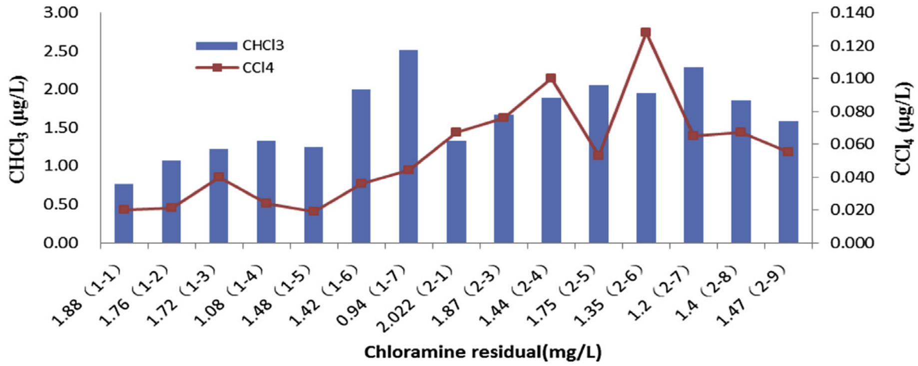


Fig. 6 – DBPs in the researched water distribution system (X axis stands for the chloramine residual concentration at different sampling points in pipes.)

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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