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Development of iron release, turbidity, and dissolved silica integrated models for desalinated water in drinking water distribution systems

Huiyan Tong[a], Peng Zhao[a,*], Chunkai Huang[b], Hongwei Zhang[a], Yimei Tian[a], Zhengkun Li[c]

[a]*Department of Environmental Engineering, School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China, Tel./Fax: +86 22 27408298; emails: anqierthy@tju.edu.cn (H. Tong), zhpeng@tju.edu.cn (P. Zhao), hwzhang@tju.edu.cn (H. Zhang), ymtian_2000@126.com (Y. Tian)*

[b]*Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta T6G 2W2, Canada, Tel. +1 780 863 2630; email: khuang@ualberta.ca*

[c]*China Petroleum Pipeline Research Institute, Langfang, Hebei 065000, China, Tel. +86 22 27408298; email: left8236237@126.com*

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ABSTRACT

To meet the growing demand for potable water, desalinated water is becoming a significant component of the overall water supply. As a result, there is an increased need to understand how the addition of desalinated water within aging water distribution systems impacts water quality and the ability to deliver safe drinking water when unlined cast iron pipes and cement mortar-lined cast iron pipes are both present in the distribution systems. In this paper, we studied the relationship of turbidity, total iron content, and the effects of pH, alkalinity, and hardness on the dissolved silica. Then, we presented the mathematical and pilot-scale empirical development and quantification of three nonlinear regression models and used pH, alkalinity, total hardness, temperature, and hydraulic retention time as water quality variables. The dependent variables were the total iron concentration, the increase in turbidity, and the concentration of dissolved silica. Based on the three models, which use a genetic algorithm, an integrated solution for simultaneously minimizing the release of iron, the increase of turbidity, and the dissolved silica content was presented. This solution provides an economical and efficient method for water plants to identify specific water quality parameters that require adjustment to maintain an acceptable water quality.

Keywords: Desalinated water; Drinking water distribution systems; Iron release; Turbidity; Dissolved silica; Statistical models

1. Introduction

Water scarcity is one of the most important political and economic problems in the world, despite the huge amount of water covering the earth's surface. To meet the growing demand, large investments are being made, such as desalination of seawater and brackish groundwater, wastewater renovation and reclamation, the reduction of water loss from the water distribution systems, the control and reuse of runoff water and cloud seeding [1–6]. Today, in many

*Corresponding author.

countries, desalinated water is becoming a significant component of the overall water supply [7–10]. It has become the most important sources of drinking water in some arid countries of the Middle East to close the gap between water supply and demand. Many industrialized and developing regions and some tropical and subtropical islands have been increasingly dependent on desalination to satisfy their water supply [7]. This trend is expected to continue and even increase in the future [8–10]. Water scarcity is also a serious problem in China. It is reported that more than half of the 667 cities in China are facing water shortage [11], and 27% of China's surface water quality is much lower than the lowest class of the national water standard, which is usable only for agricultural irrigation [12]. Seawater desalination is a viable method for China to provide fresh water to these water-shortage areas [13]. By the end of 2013, China's desalination capacity had reached more than 1,000,000 m^3/d.

Although there are apparent benefits of using desalination to produce a reliable potable water source, its deficiencies in chemical stability, water buffering capacity, and nutrients required for both humans and agricultural plants are causes for concern and should generate further research. The alkalinity and hardness of desalinated water are very low. Water with such quality cannot be supplied directly for either the existing drinking water distribution systems (DWDS) and/or irrigation, for a variety of reasons [8,14]. Delivery of unconditioned desalinated water to the consumers may lead to unfavorable results, e.g. "red water". Many regions encountered corrosion and other water quality related problems (e.g., Boston, Massachusetts [15], Cyprus [16], and Tucson, Arizona [17]). For these reasons, post-treatment should be applied to improve the water quality. There are various post-treatment options to stabilize aggressive water, which could be classified into three treatment processes: (1) chemical addition, (2) carbon dioxide addition, and (3) blending with water containing high mineral content [18–24].

Many studies have been conducted to ensure the safe distribution of desalinated water in DWDS. Alid and Al-Faraj developed a goal-programming model to determine the daily production of seawater desalination plant and the optimal allocation of desalinated water to various blending stations [25]. Imran et al. evaluated the impact of blends of three different source waters (groundwater, surface water, and desalinated water) on the water quality of the distribution system and on the release control of lead, copper, iron, and monochloramine [26]. Lahav et al. simulated the calcium carbonate precipitation potential (CCPP) values that would develop in a schematic distribution system fed by three water sources (desalinated, surface and groundwater) under a simulative water consumption pattern and studied the effects of temperature, TDS, alkalinity, pH, and calcium ion concentration on the corrosion of pipelines [10]. Haizhou Liu et al. examined the effect of desalinated water on the corrosion and metal release from copper- and lead-containing materials [27]. Liang et al. examined the effect of various remineralization options on the stabilities of pipeline materials (ductile iron, cast iron, and cement-lined ductile iron) under tropical conditions [28]. Husband et al. investigated the processes of discoloration within a water distribution system and built a model based on the hypothesis that discoloration was caused by the erosion and transport of fine particles and used turbidity as an indicator of water quality issues [29].

The main cause of discoloration for corroded metal pipes may be the release of iron. For the new cement mortar-lined cast iron pipes, the main problematic issue is the leaching of hydrated cement paste [30]. The consequences of leaching are increase in pH, $CaCO_3$ content, and dissolved silica content [30]. Turbidity is a direct manifestation of the deterioration of water quality. However, little attention has been paid to the control of the release of iron, turbidity, and dissolved silica of blending water sources simultaneously when unlined cast iron pipes and cement mortar-lined cast iron pipes both exist in the distribution systems. Therefore, this work was conducted to study the composition of suspended particulate in the water, the relationship of turbidity and total iron content, and the effects of pH, alkalinity, and hardness on the dissolved silica content. Based on three models, we developed an integrated solution to simultaneously minimize iron release, turbidity, and dissolved silica content, which provides an economical and efficient method for water plants to identify water quality parameters to adjust and maintain water quality.

2. Materials and methods

Effects of pH, alkalinity, and hardness in desalinated water blends on iron release, turbidity, and dissolved silica were studied based on two recirculation devices. Water sources were tap water and desalinated water, which were obtained from the Hangu District in Tianjin. Tap water had relatively high alkalinity and hardness, and had pH values between 7 and 8.5. All of the water quality indexes of the desalinated water were superior to that of the tap water. The values of alkalinity, hardness, and concentrations of all types of ions (such as chloride and sulfate) were extremely low, and the pH value was approximately 6.4. Properties of tap water and desalinated water are summarized in Table 1.

Table 1
Properties of tap water and desalinated water

Items	Tap water	Desalinated water
pH	8.22	7.23
Conductivity (μS/cm)	572	7.3
Total salt content (mg/L)	286	4
Alkalinity (mg/L as $CaCO_3$)	130.9	13.08
Hardness (mg/L as $CaCO_3$)	120	13.01
Total iron (mg/L)	0.044	–

2.1. Iron release and turbidity studies

A pilot-scale pipe loop was constructed to examine the effects of pH, hardness, and alkalinity on the iron release and turbidity. Gray cast iron pipes (20 m length, 100 mm diameter) were used in this study. The gray cast iron pipes were obtained from the Hangu District, Tianjin City, which have been used for approximately 30 years in DWDS. The pipes were externally cleaned, wetted, binned, and transported to the pilot site. Before conducting iron release and turbidity experiments, the pipes were reconditioned for 1 month. U-PVC pipes were used to connect the pipe loop. The recirculation device was composed of water tanks, the rotameter, the water pump, the plate heat exchanger, and the pipes. The schematic diagram is shown in Fig. 1. The plate heat exchanger mainly adjusted the water temperature rose by the pump operation. The rotameter controlled the flow rate as 5 L/s. To simulate the actual pipe network, the work tank was sealed. For each experiment, turbidity and concentrations of iron content were observed during 12 h of continuous recirculation studies in the pipe loop. The starting point was set as 0 h for each experiment. Five hundred mL samples were taken every 2 h for analysis.

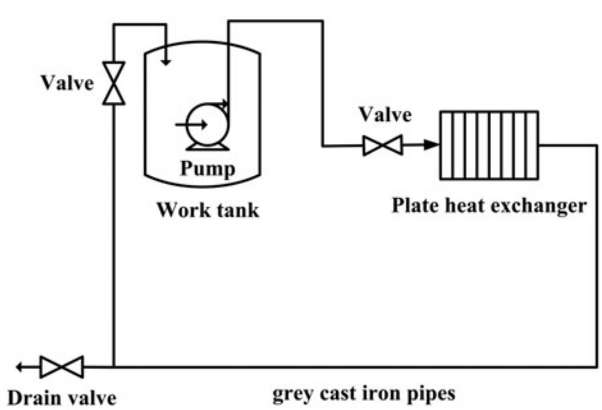

Fig. 1. The schematic diagram of iron release and turbidity studies.

2.2. The dissolved silica studies

This recirculation device was similar to the device of iron release experiment. However, the test section used new cement mortar-lined ductile iron pipes (200 mm diameter). Cement mortar-lined iron pipe is an iron pipe with cement lining on the inside surface that has prominent anti-corrosive properties and provides a barrier between the water and the iron pipe. It is used to replace the old or damaged pipes in DWDS in China. Whereas, the use of cement mortar lining prevents the corrosion of the ferrous metal pipe, the reaction between the hydrated cement and water leads to another type of corrosion [30]. When cement mortar linings are subjected to soft water, calcium silicate hydrates will be attacked by these waters. Soft waters can progressively hydrolyze calcium silicate hydrates into dissolved silica. Thus, the effect of pH, alkalinity, and hardness on the dissolved silica was studied using desalinated water. For each experiment, the dissolved silica was observed during 24 h of continuous recirculation studies in the pipe loop. The starting point was set as 0 h for each experiment. Five hundred mL samples were taken every 3 h and filtered with 0.45 μm membrane for analysis.

2.3. Analytical methods

The main analysis items of water quality indexes include turbidity, pH, alkalinity, total iron, and dissolved silica content. Turbidity was determined on a HACH 2100P portable turbidimeter. The total iron concentration was determined by flame atomic absorption spectrometry (Beijing Rayleigh WFX 130). The concentration of dissolved silica was measured by employing silicon molybdenum blue spectrophotometry. A detailed list of analysis items and methods is shown in Table 2.

2.4. The composition of particles studies

The composition of the particles studies were conducted in the recirculation device using the gray cast iron pipe with tap water. Before collecting the particles, the water was recirculated for 2 d, and then, 2 L samples were taken every 6 h and were filtered immediately with 0.45 μm microporous membrane. Then, the particles were dried approximately 8 h in the oven at 103℃ and cooled approximately 6 h in the desiccator. Finally, the samples were sealed and stored. The elemental composition of the particles was analyzed by energy dispersive X-ray spectroscopy (EDX) [31].

Table 2
Analysis items and methods

Analysis items	Analysis methods	Method number
Turbidity	HACH 2100P portable turbidimeter (HACH, America)	EPA 180.1
pH	HACH HQ30d flexi portable meter (HACH, America)	EPA 151.1
Alkalinity	Acid–base indicator titration	Standard Methods 2320
Hardness	EDTA titration	Standard Methods 2340
Total iron	Flame atomic absorption spectrometry (Beijing Rayleigh WFX 130, China, Beijing)	Standard Methods 3111
Dissolved silica	Silicon-molybdenum blue spectrophotometry	EPA 370.1

3. Results and discussion

3.1. The composition of particles in the water

Discoloration is one of the main reasons for customers to complain about water quality. In general, the presence of dissolved colloidal or suspended substances in the drinking water plays an important and potentially dominant role in the generation of a discoloration risk [32–34]. Discoloration can be measured as turbidity. However, different particles can have significantly different effects on detected turbidity due to varying size, shape, number, composition, color, etc. Particles in the water are mostly composed of metal oxides and hydroxides. However, they differ in composition because of different sources and reactions in the pipes. To investigate the composition of particles in this test device, we analyzed constituent elements of five water samples using EDX. The results were shown in Table 3.

Table 3 shows that the microporous membrane was mainly composed of C and O, 45.17 and 54.83%, respectively. C and O present a large proportion in the five samples. This is because the samples were measured on the microporous membrane, and should be deducted when analyzing the composition of particles. Thus, suspended particles in water were mainly composed of iron, calcium, and silicon. As seen from Table 3, the Fe element content in particles increased with time. Two reasons can be taken into consideration. One is that iron release occurred in the drinking water pipelines. Iron ions released into the water formed suspended particles due to the adsorption. The other is that iron corrosion products on the pipe wall came into the water due to hydraulic action. The deviation in calcium concentration may be because the pipes did not reach equilibrium. In sample 1, the Si element content was at first almost undetectable and increased gradually. This was because of the formation of small flocs. These flocs adsorbed pipe scale particles that combined into large-sized suspended particles.

Table 3
Elemental composition of samples in the water (%)

Sample	C	O	Fe	Ca	Si
Blank	45.17	54.83	–	–	–
1	34.24	50.43	14.78	0.55	–
2	31.96	48.12	15.59	1.12	3.21
3	38.75	40.46	18.05	0.69	2.04
4	31.73	43.41	21.54	0.98	2.34
5	27.75	35.62	32.61	1.23	2.79

3.2. The relationship between turbidity and total iron content

In most studies, corrosion of cast iron pipes and ancillaries within distribution systems is often seen as the major cause of discoloration. Sarin et al. stated that iron corrosion played important roles in water quality degradation [35]. The scale structure and scale reactions permitted the release of ferrous iron into the bulk water, where it had undergone conversion into particulate ferric iron, which led to colored water [35]. Imran et al. highlighted red water in distribution systems, as measured by the increase in apparent color, was caused by the release of corrosion products from unlined and galvanized iron pipes [36]. Thus, a number of studies assessed the water quality by the measurement of total iron. And some researchers tried to develop an iron concentration prediction model for DWDS that could help us to understand the occurrence of red water and ways to mitigate those phenomena [36,37]. Imran et al. used apparent color as a surrogate for total iron concentrations and developed an empirical statistical model that identified the effects of water chemistry on apparent color [36]. However, some studies found that turbidity is more likely to be the reason of discoloration than apparent color [38–42]. Mutoti et al. found the relationship between total iron concentration and turbidity as follows [37]:

$$\Delta\text{Fe}(\mu\text{g/L}) = 7.3 \times 10^{-3} \times \Delta\text{Turbitity (NTU)} \quad (1)$$

Gaffney and Boult found that the relationship between metal (Al, Fe, and Mn) concentration and turbidity was positive and had an r^2 value of 0.9633 [43]. From the results above, particles in this test device contain a small amount of calcium, silicon, and other elements except iron. Therefore, the relationship between turbidity and total iron content was investigated in the recirculation device. From our study, the relationship between total iron concentration and turbidity was better to fit log-linear than linear (Fig. 2). The relationship between total iron concentration and turbidity was shown as follows:

$$\text{Turbidity} = 4.478 \times [\text{Fe}]^{0.319} (R^2 = 0.811) \quad (2)$$

where [Fe] is the total iron content in mg/L, turbidity is the turbidity in NTU.

As seen from Fig. 2, the turbidity increased more rapidly with the increasing total iron concentration below a concentration of 0.3 mg/L than above. Thus, while adjusting water quality parameters, iron release and turbidity should be assessed simultaneously.

3.3. The dissolved silica study

Cement mortar lining is the most common coating used in drinking water pipes. It has prominent anti-corrosive properties and provides a barrier between the water and the iron pipe. However, it is not perfect, as the corrosion and softening of cement mortar lining could do harm to water quality. Cement mortar lining material is composed of cement, sand, and water. Portland cement clinker is mainly composed of CaO (62–67%), SiO_2 (20–24%), Al_2O_3 (4–7%), and Fe_2O_3 (2.5–6.0%), accounting for more than 95%, in addition to small amounts of other oxides. When cement mortar linings are subjected to soft water, these waters will attack calcium silicate hydrates and progressively hydrolyze calcium silicate hydrates into dissolved silica. Therefore, the dissolved silica calls for further research.

3.3.1. The effect of pH on the dissolved silica

The tests of four initial pH levels (6.10, 7.04, 8.10, and 9.07) were carried out to investigate the different effects of pH on the dissolved silica. The initial pH value of desalinated water was adjusted with sodium hydroxide and hydrochloric acid. Each test continued for 24 h, and the results are shown in Fig. 3.

Fig. 3 shows that irrespective of the starting pH, dissolved silica concentration increased with time. It was observed that there was a significant decrease in dissolved silica concentration due to an increase in the initial pH from 7.04 to 8.10. However, the change in the initial pH from 8.10 to 9.07 slightly increased the dissolved silica concentration. When the pH was 6.10, the dissolved silica concentration reached the lowest point. However, the components of the cement mortar lining also include CaO and Al_2O_3 in the anti-corrosive coating, which is easy to dissolve under acidic conditions. Under the condition of weak alkalinity, the chemical stability of water quality was much better, and the cement mortar lining did not experience serious corrosion. Inspection of the results from Fig. 3 demonstrates that pH should be controlled at approxi-

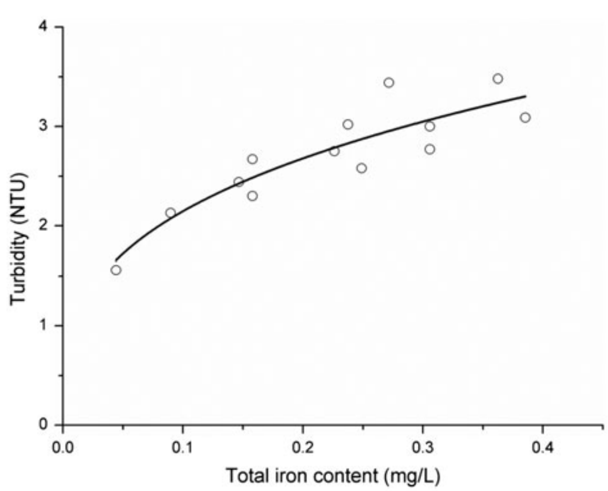

Fig. 2. The relationship between total iron concentration and turbidity.

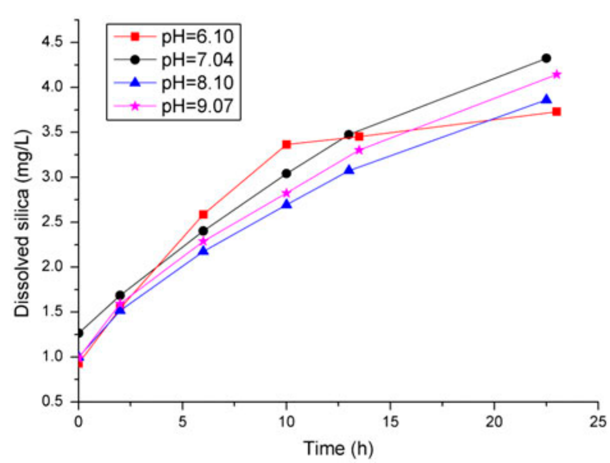

Fig. 3. The change trend of dissolved silica concentrations in different pH values.

mately 8.00 when desalinated water is delivered in the cement mortar-lined ductile iron pipes.

3.3.2. The effect of alkalinity on the dissolved silica

The tests of three initial alkalinity levels (53.94, 112.58, and 170.04 mg/L) were carried out to investigate the different effects of alkalinity on the dissolved silica. The initial alkalinity of desalinated water was adjusted with sodium carbonate. Each test continued 24 h and the results are shown in Fig. 4.

Fig. 4 shows that irrespective of the starting alkalinity concentration, dissolved silica concentration increased with time. When the total alkalinity was 170.04 mg/L, the change in trend of dissolved silica concentration was most gradual. The possible explanation may be that the total alkalinity and pH have certain correlations; pH will increase when the total alkalinity increases, so that the chemical stability of desalinated water will be improved. This greatly reduces the possibilities of corrosiveness due to the desalinated water and alleviates the dissolution of anti-corrosive coating of cement mortar. In conclusion, the total alkalinity should be adjusted appropriately when desalinated water is delivered in the cement mortar-lined ductile iron pipes.

3.3.3. The effect of hardness on the dissolved silica

The tests of three initial hardness levels (107.64, 210.56, and 309.81 mg/L) were carried out to investigate the different effects of hardness on the dissolved silica. The initial hardness of desalinated water was adjusted with $CaCl_2$ and $MgSO_4$. Each test continued 24 h and the results are shown in Fig. 5.

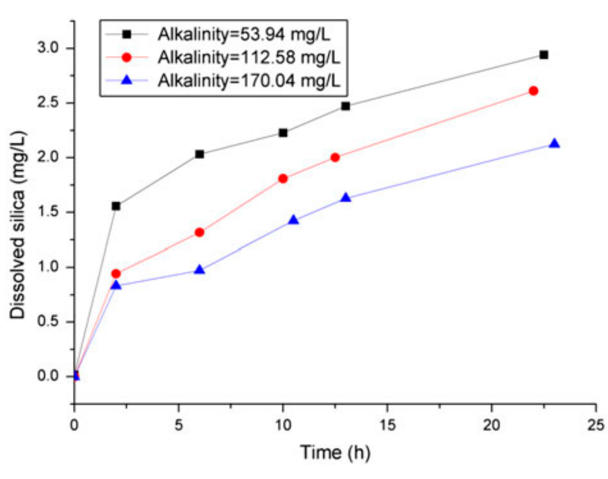

Fig. 4. The change trend of dissolved silica concentrations in different alkalinity.

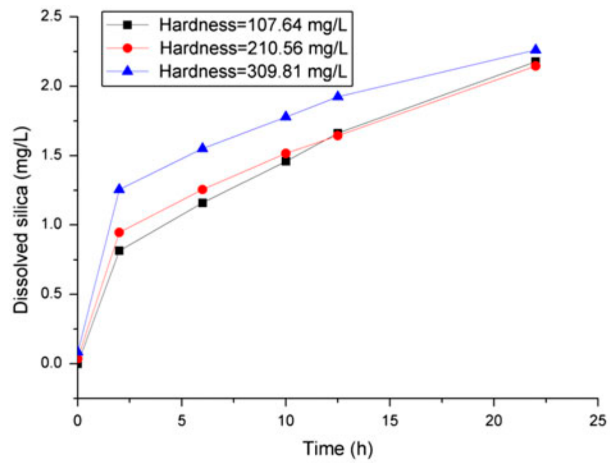

Fig. 5. The change trend of dissolved silica concentrations in different hardness.

Fig. 5 shows that with the increase in time, dissolved silica concentration increased significantly in the first two hours and then increased slightly. Dissolved silica concentration increased with the increasing initial total hardness marginally. The hardness should be adjusted appropriately when desalinated water was delivered in the cement mortar-lined ductile iron pipes.

3.4. Development of statistical models

Traditional optimization involves optimizing water quality sources and costs of water treatment and supply. In terms of water quality, a number of researchers are interested in the minimization of water quality deterioration within the distribution systems. Many studies considered the release of iron using unlined cast iron pipes. From the results obtained in this paper, when cement mortar linings were present, dissolved silica should be considered to extend the service life of cement mortar-lined cast iron pipes and aids in maintaining water quality. Additionally, the release of iron, turbidity, and dissolved silica were evaluated at the same time to optimize water quality of blending water sources in unlined cast iron pipes and cement mortar-lined cast iron pipes in distribution systems. Water quality deterioration results from a complex interrelation of physical, chemical, and biological effects. This paper presents a mathematical and pilot-scale empirical development and quantification of three nonlinear regression models.

For the nonlinear models, water quality parameters analyzed in the two recirculation studies were put into consideration. We used pH, alkalinity, total hardness, temperature, and hydraulic retention time as the water quality variables. The dependent variables were the total iron concentration, the increase in turbidity, and the concentration of dissolved silica, respectively. The results are shown in Eqs. (3–5). It should be noted that the models described here were developed to correspond to the specific operating conditions and pipes:

$$[\text{Fe}] = 4.14 \times \frac{\text{HR}T^{0.442}\text{Hardness}^{2.964}T^{2.133}}{\text{pH}^{6.788}\text{Alk}^{2.248}} \quad (R^2 = 0.886) \tag{3}$$

$$\Delta\text{Turbidity} = 3.04 \times 10^{-5} \times \frac{\text{HRT}^{1.026}\text{Hardness}^{4.281}\text{pH}^{5.537}}{T^{1.726}\text{Alk}^{3.799}} \quad (R^2 = 0.862) \tag{4}$$

$$[\text{Dissolved silica}] = 1.923 \times \frac{\text{HRT}^{0.359}\text{Hardness}^{0.02}T^{0.168}}{\text{pH}^{0.379}\text{Alk}^{0.029}} \quad (R^2 = 0.934) \tag{5}$$

where [Fe] is the total iron concentration in mg/L, Δturbidity is the increase in turbidity (NTU), [Dissolved silica] is the concentration of dissolved silica in mg/L, alk is the alkalinity measured in mg/L as CaCO3, hardness is the total hardness measured in mg/L as CaCO3, T is the temperature in ℃, and HRT is the hydraulic retention time in hours. Each model is statistically significant ($\alpha = 0.01$).

From the models, it can be seen that increasing alkalinity can reduce iron release, the increase in turbidity and dissolved silica content, while increasing

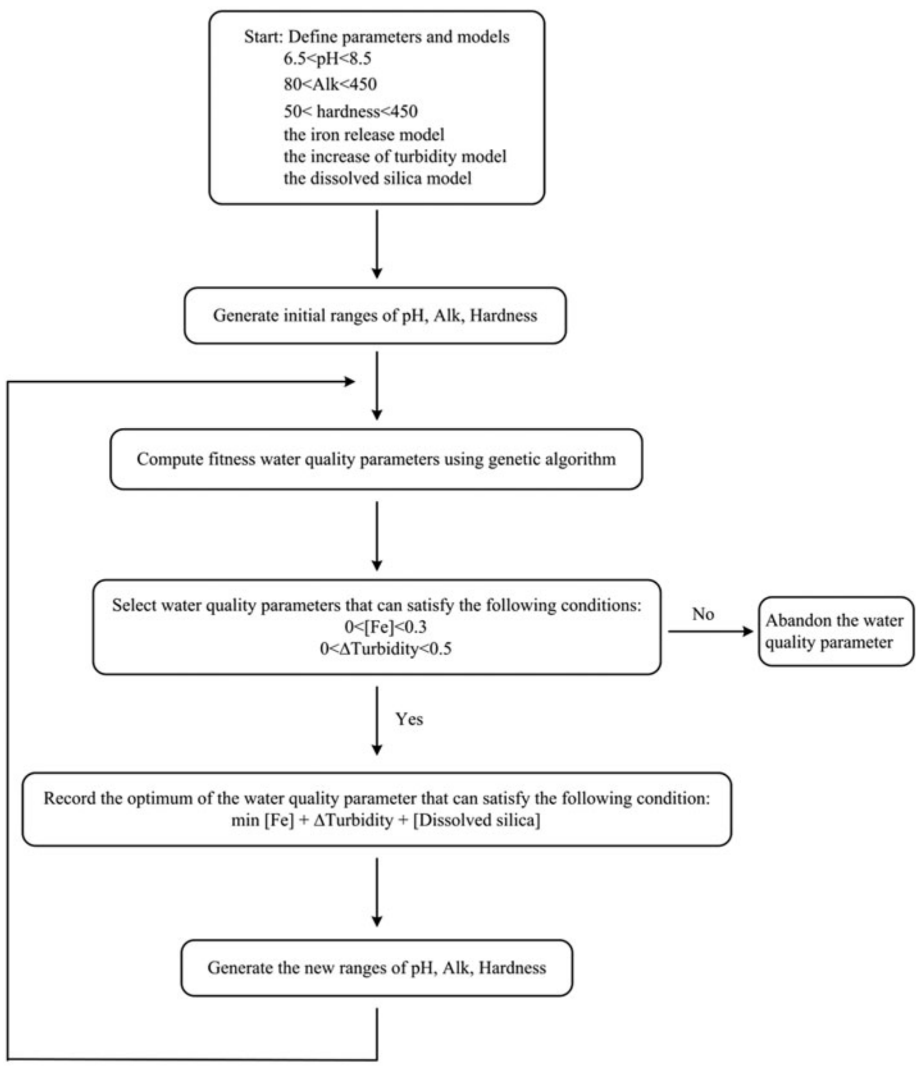

Fig. 6. Flow chart of a genetic algorithm for the optimization.

the hydraulic retention time or hardness sees the reverse. In Eq. (5), the index of hardness is extremely small. This is most likely because calcium and magnesium ions have very little impact on the dissolved silica in the range of hardness in the test. The models also found some conflicting aspects of water quality goals. For example, iron release and dissolved silica were reduced by increasing pH, whereas increasing pH was beneficial in reducing the increase of turbidity. Additionally, increasing temperature was found to reduce the increase of turbidity while increasing iron release and dissolved silica content. Thus, water quality parameters should be controlled in a certain range to minimize the release of iron, the increase in turbidity and the dissolved silica content simultaneously.

Therefore, the goal should be to find water quality that minimizes the release of iron, the increase in turbidity and the dissolved silica simultaneously. We need to know the level for which each parameter can minimize the three dependent variables simultaneously. This can be proposed as an optimization problem, which involves release of iron, turbidity, and the dissolved silica content together. According to the water quality standard, iron concentration should be below 0.3 mg/L, and the turbidity of drinking water should be below 1 NTU. Generally, water plants control the turbidity of water coming out below 0.5 NTU or even smaller. So this study set the maximum of the increase in turbidity as 0.5 NTU. Considering the condition of the real DWDS, the temperature and the hydraulic retention time were set as constants. Therefore, the optimization problem can be shown as follows:

$$\min\ [\text{Fe}] + \Delta\text{Turbidity} + [\text{Dissolved silica}]$$

s.t.

$$0 < [\text{Fe}] < 0.3$$

$$0 < \Delta\text{Turbidity} < 0.5$$

$$6.5 < \text{pH} < 8.5$$

$$80 < \text{Alk} < 450$$

$$50 < \text{Hardness} < 450$$

In this paper, a genetic algorithm was used for the optimization. A flow chart describing the individual steps of the water quality parameters search is shown in Fig. 6. Different levels of pH, alkalinity, and hardness at some specific temperature and hydraulic retention time that satisfied the optimization problem can be calculated. Thus, through monitoring pH, alkalinity, and hardness at some specific temperature, it can provide an economical and efficient method for water plants to identify if any of the three parameters require adjustment to control corrosion of unlined cast iron pipes and cement mortar-lined cast iron pipes, thus maintaining water quality.

4. Conclusions

This study showed that the relationship between total iron concentration and turbidity was fit better to log-linear than linear. The effects of pH, alkalinity, and hardness on the dissolved silica were studied in this paper. The results further our understanding of drinking water quality with cement mortar-lined cast iron pipes. Three nonlinear regression models for the release of iron (Eq. (3)), the increase in turbidity (Eq. (4)), and the dissolved silica (Eq. (5)) were developed based on the data from the test. The effects of pH, alkalinity, total hardness, temperature, and hydraulic retention time were incorporated into the models. Based on the three models, an optimization solution was presented. The structure for the optimization using a genetic algorithm was built here to assist water plants in adjusting the water quality parameters. Therefore, through monitoring pH, alkalinity, and hardness at some specific temperature, it can provide an economical and efficient method for water plants to identify water quality parameters that may require adjustment to control iron release, the increase in turbidity and the dissolved silica simultaneously with different pipes in aging water distribution systems.

Further research is needed to include more water quality parameters in the three models.

Acknowledgments

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