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# Experimental study of the impact of Reynolds number and chlorine concentration on manganese concentration in pilot-scaled water distribution system

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**ABSTRACT**

Discoloration of the water is one of the major customer complaints in drinking-water-distribution systems (DWDSs). Manganese is one of the main sources of discoloration because once it oxidizes and accumulates on the pipe wall of distribution systems, the aesthetic water quality of DWDSs is affected. Therefore, understanding the potential conditions for manganese issues in DWDSs is important for proper management of drinking water. We performed an experiment to explore the effect of the Reynolds number and residual-chlorine concentration on the manganese concentration. A pilot-scaled water-distribution system was designed and fabricated, and 12 different system conditions having various residual-chlorine concentrations and the Reynolds numbers were analyzed. The result demonstrated that the decay rate of the total manganese concentration was increased with the increase both in the Reynolds number and the residual-chlorine concentration. However, the total manganese concentration did not exhaust under the condition of $Cl_2/Mn(II) < 1$.

*Keywords:* Manganese; Water distribution system; Hydraulic; Chlorine concentration

## 1. Introduction

Providing reliable quality and quantity of drinking water is the primary goal of water-distribution systems (WDSs). In a water-treatment plant, while the water quality after performing the water-treatment process is mainly evaluated from the perspective of microbiological and chemical safety, the major complaint regarding the water quality of the distribution system is an aesthetic issue. The discoloration of drinking water is the most frequent cause of customer complaints in WDSs [1–5].

Discoloration of drinking water is caused by the presence of suspended particles alongside various other components in the water [6]. Metals such as manganese and iron are the main source of discoloration-causing particles [7,8]. Manganese tends to be oxidized by the aeration process even in neutral pH conditions. Furthermore, the low concentration of manganese in WDSs can result in the accumulation of manganese oxide on the pipe wall, thereby resulting in the deterioration of discoloration of drinking water and undesirable hydraulic loss [9]. Therefore, most water authorities control the concentration of manganese in WDSs between 0.1 and 0.05 mg/L [10,11]. Therefore, it must be removed using cleaning or replacement processes.

The oxidation characteristics of Mn(II) were analyzed in several studies. Sly et al. [12] investigated manganese-deposition rates in relation to the concentration of Mn(II), which penetrates the filters of treatment plants. The chemical and

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biological processes of manganese depositions were monitored at four different points along with the WDS. They suggested new guidelines regarding the concentration of manganese and chlorine to eliminate the discoloration problem. Hao et al. [13] evaluated the kinetics of Mn(II) oxidation on using chlorine. They observed that the oxidation of Mn(II) by using chlorine depends upon the concentration of chlorine and that the presence of $MnO_2$ can accelerate the oxidation of homogeneous Mn(II).

The discoloration-causing particulate materials are affected by the hydraulic conditions of WDSs. The prediction of discoloration in the distribution systems (PODDS) model was proposed by Boxall et al. [14]; this model is based on the cohesive transport theory instead of the traditional gravity-driven sediment-transport theory [15,16]. The PODDS turbidity model demonstrated good performance in simulating the temporal turbidity response within the pipes for various properties of the systems. Gerke et al. [17] investigated the physicochemical characteristics of manganese deposition on brass and lead components of WDSs and observed that the differences in alloy compounds in the components of WDSs did not affect the manganese deposition.

Previous studies have demonstrated that the characteristic of manganese deposition in WDSs was expected to be influenced by system conditions. However, most case studies did not simultaneously consider both chemical and hydraulic conditions. Furthermore, the impact of hydraulic conditions for Mn(II) reduction in WDSs had not been studied. In this regard, this study aims to investigate the decay rate of Mn(II) concentration under various chemical and hydraulic conditions. A pilot-scale experimental WDS was designed and fabricated for this study. The concentration of manganese was monitored under 12 system conditions of varying residual chlorine and the Reynolds number.

## 2. Material and methods

### 2.1. Pilot-scaled water distribution system

A pilot-scaled WDS was designed and fabricated to perform experiments. As shown in Fig. 1, the system consists of pipeline, three reservoir tanks, and two pumps. The stainless pipeline was 300 m long with 0.03 m of internal diameter. Two of the reservoir tanks were installed at the ends of the pipeline, and the storage volumes of the reservoir tanks were 660 and 1,000 L, respectively. A centrifugal pump was installed between the two reservoirs, which can generate the minimum and maximum flow rate between 1.8 and 5.1 $m^3/h$, respectively. The minimum and maximum Reynolds number ranged between 20,000 and 60,000. Water-quality-sensor units were installed in the middle of the pipeline system to collect the time series of turbidity, electronic conductivity, temperature, chlorine concentration, and pH. The sampling valve was located at 250 m along the pipe length from reservoir tank #1 for obtaining a water sample from the system. We used a portable spectrophotometer of DR 2800 (Hach Inc., USA) for measuring the total manganese concentration of the samples. To supply the accurate concentration of manganese and residual chlorine for the experimental system, a mixing tank was used. The mixing tank was connected with reservoir tank #1, and a centrifugal pump was installed between the reservoir tank #1 and the mixing tank.

### 2.2. Experimental setup and data acquisition

To measure the variation in the manganese concentration under various hydraulic and chemical conditions, 12 experimental conditions were introduced. Table 1 presents the experimental conditions used in this study. Three different flow conditions of 1.81, 2.55, and 5.07 $m^3/h$ were considered for this study with the corresponding Reynolds numbers as 21,251.42; 29,939.85; and 59,527.46, respectively.

We used manganese(II) sulfate monohydrate ($MnSO_4{\cdot}H_2O$) as a source of Mn(II) and maintained the total manganese concentration to be 0.37 ppm for the initial condition of the 12 experimental conditions. As the stoichiometric ratio between ($Cl_2$) and (Mn(II)) is 1:1 (molar ratio), we used four different initial chlorine concentrations of 0.125, 0.25, 0.5, and 1.0 ppm; the concentrations of the corresponding $Cl_2$/Mn(II) were 0.26, 0.52, 1.05, and 2.09 ppm, respectively. The sampling frequency was 0.25 h at the beginning and was

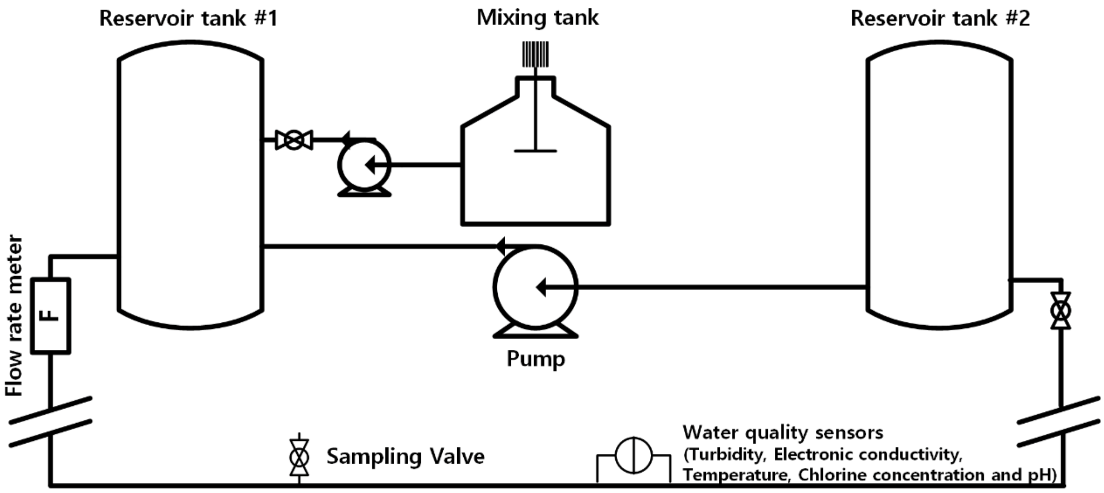



Fig. 1. Pilot-scaled experimental WDS.

Table 1
Summary of experimental condition

| Condition | Mn concentration (ppm) | Cl concentration (ppm) | $Cl_2$/Mn(II) | Reynolds number |
|---|---|---|---|---|
| A | 0.37 | 1.000 | 2.09 | 21,251.42 |
| B | 0.37 | 1.000 | 2.09 | 29,939.85 |
| C | 0.37 | 1.000 | 2.09 | 59,527.46 |
| D | 0.37 | 0.500 | 1.05 | 21,251.42 |
| E | 0.37 | 0.500 | 1.05 | 29,939.85 |
| F | 0.37 | 0.500 | 1.05 | 59,527.46 |
| G | 0.37 | 0.250 | 0.52 | 21,251.42 |
| H | 0.37 | 0.250 | 0.52 | 29,939.85 |
| I | 0.37 | 0.250 | 0.52 | 59,527.46 |
| J | 0.37 | 0.125 | 0.26 | 21,251.42 |
| K | 0.37 | 0.125 | 0.26 | 29,939.85 |
| L | 0.37 | 0.125 | 0.26 | 59,527.46 |

gradually decreased over time to 1 hour between the first hour and eighth hour. The sampling frequency was adjusted such that the difference between any two consecutive concentrations was approximately 0.01 mg/L.

The experimental pipeline was cleaned after each experimental setup. A 2,000-ppm sodium hypochlorite solution was circulated throughout the pipeline system to oxidize the residual Mn(II) in the system. Furthermore, pigs were inserted several times into the pipeline to remove the manganese oxide attached to the pipe wall. Finally, the pipeline was filled with tap water, and the water was circulated throughout the pipes for 4 h to remove the remaining Mn(II) oxide particles. Furthermore, a duplicate test was conducted to check the reproducibility of the entire observational data. The results demonstrated that the standard deviation of the errors in multiple tests was ±0.0012 mg/L.

## 3. Results and discussion

The time series of manganese concentration under 12 different conditions were collected. Fig. 2 depicts the time series of the total manganese concentration under various residual-chlorine concentrations with the Reynolds numbers equal to (a) 21,261.42; (b) 29,939.85; and (c) 59,527.46.

While the residual-chlorine concentration increased from 0.5 to 1.0 ppm, the lag period was significantly reduced for every hydraulic condition, and it is analogous to the result of the previous study of Hao et al. [13]. In the case of a stoichiometric ratio of less than 1.0 ($Cl_2$/Mn(II) = 0.26 and 0.52), the decay rate of the total manganese concentration also decreased upon increasing the residual-chlorine concentration; however, the total manganese concentration was not exhausted even after 5 days. This can be explained by the stoichiometric relation between Mn(II) and $Cl_2$. Chemically, when the molar ratio $Cl_2$/Mn(II) is less than 1; therefore, $Cl_2$ acts as a limiting reagent of manganese oxidation and, thereby, regulates the total amount of oxidation.

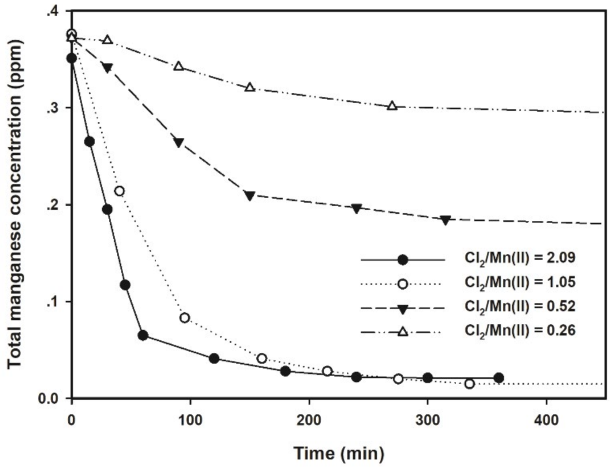
Fig. 3 depicts the time series of the total manganese concentration for various Reynolds numbers with an identical residual-chlorine concentration. The increase in the Reynolds number accelerates the manganese decay. Similar results were reported by several previously conducted studies regarding the acceleration of chlorine decay by the increase in the Reynolds number [18–22]. This means that the increase in turbulence intensity due to the increase in the Reynolds number can explain the acceleration of manganese reduction in this study.

The first-order decay model provides one of the most widely used regression equations for predicting water-quality parameters. In this study, as we can observe, the stable concentration of the total manganese, which is limited by the first-order decay model, is used. The model can be written as follows:

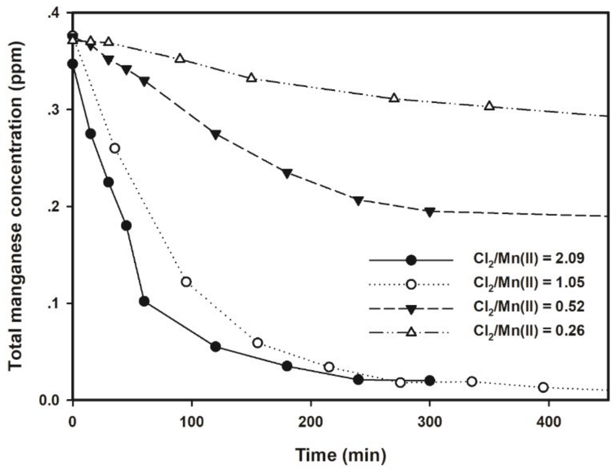
$$C_{\mathrm{Mn}} = C^{*}_{\mathrm{Mn}} + \left(C^{0}_{\mathrm{Mn}} - C^{*}_{\mathrm{Mn}}\right) \times \exp\left(-kt\right) \tag{1}$$

where $C_{\mathrm{Mn}}$ denotes the concentration of the total manganese, $C^{*}_{\mathrm{Mn}}$ the stable concentration of the total manganese, $C^{0}_{\mathrm{Mn}}$ the initial concentration of the total manganese, and $k$ the decay coefficient. Table 2 presents the calibration results and root-mean-squared error (RMSE) values obtained using the least-squares method.

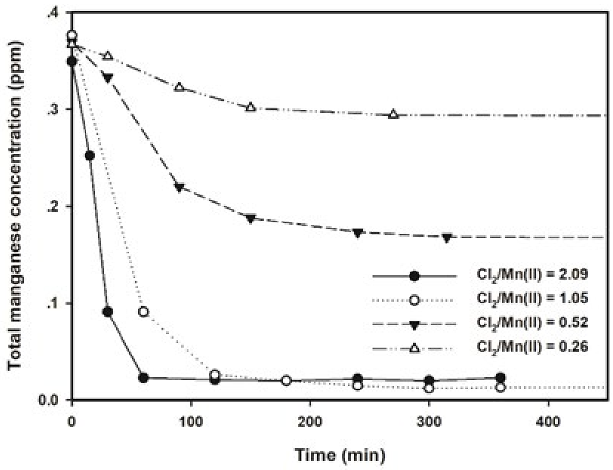
The first-order decay equation showed good agreements with every experimental condition with an average RMSE of 0.007458 ± 0.0054 mg/L. The average value of the initial concentration of the total manganese in the entire system condition was 0.374 ± 0.0096 mg/L. In the cases, wherein $Cl_2$/Mn(II) = 2.09 and 1.05, the stable concentration of the total manganese reached the measurement limit of the device, that is, 0.01 mg/L. However, in the cases, wherein $Cl_2$/Mn(II) = 0.52 and 0.26, the result exhibited the average value of $C^{*}_{\mathrm{Mn}}$ to be 0.167 and 0.288 mg/L, respectively. As mentioned previously, this result suggests that the residual chlorine can play an important role as the oxidation inhibitor of Mn(II) in WDSs. Furthermore, the decay coefficient $k$ was increased as the Reynolds number and the ratio of $Cl_2$/Mn(II) were increased.




(a) Reynolds number = 21261.42




(b) Reynolds number = 29939.85




(c)Reynolds number = 59527.46

Fig. 2. Time series of total manganese concentration under various chlorine concentration and same Reynolds number.

Table 2
Calibrated parameters for manganese decay models with various conditions

| Condition | $Cl_2$/Mn(II) | Reynolds number | $C^*_{Mn}$ (mg/L) | $C^0_{Mn}$ (mg/L) | $k$ (min$^{-1}$) | RMSE |
|---|---|---|---|---|---|---|
| A | 2.09 | 21,251.42 | 0.018 | 0.354 | 0.018 | 0.01174 |
| B | 2.09 | 29,939.85 | 0.021 | 0.362 | 0.026 | 0.01224 |
| C | 2.09 | 59,527.46 | 0.016 | 0.363 | 0.041 | 0.02070 |
| D | 1.05 | 21,251.42 | 0.009 | 0.381 | 0.012 | 0.00439 |
| E | 1.05 | 29,939.85 | 0.014 | 0.379 | 0.016 | 0.00498 |
| F | 1.05 | 59,527.46 | 0.014 | 0.376 | 0.026 | 0.00205 |
| G | 0.52 | 21,251.42 | 0.168 | 0.387 | 0.006 | 0.00719 |
| H | 0.52 | 29,939.85 | 0.170 | 0.380 | 0.009 | 0.00671 |
| I | 0.52 | 59,527.46 | 0.161 | 0.379 | 0.013 | 0.00991 |
| J | 0.26 | 21,251.42 | 0.291 | 0.378 | 0.005 | 0.00368 |
| K | 0.26 | 29,939.85 | 0.281 | 0.377 | 0.006 | 0.00295 |
| L | 0.26 | 59,527.46 | 0.291 | 0.370 | 0.011 | 0.00296 |

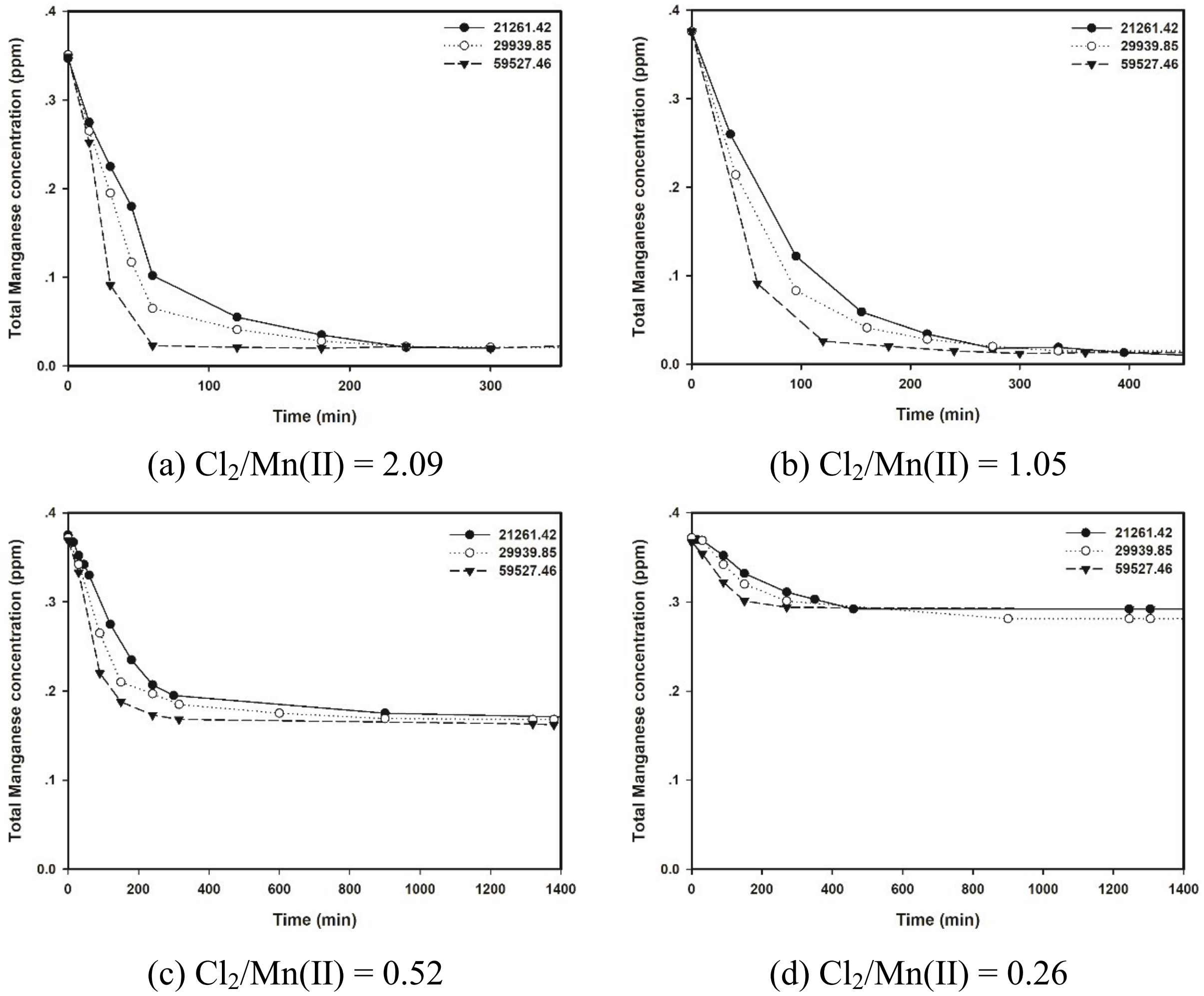



Fig. 3. Time series of total manganese concentration under various Reynolds number with an identical residual concentration of chlorine.

## 4. Conclusions

In this study, we explored the effect of the Reynolds number and the residual-chlorine concentration on manganese decay. A pilot-scale WDS was designed and fabricated. A total of 12 different system conditions were introduced including three different Reynolds numbers and four different residual-chlorine concentrations. The result demonstrated that the decay rate of the total Mn(II) concentration increased for both higher Reynolds numbers and higher residual-chlorine concentrations. In addition, we observed that the stoichiometric ratio between ($Cl_2$) and (Mn(II)) played an important role in determining the decay rate of the total manganese concentration.

The above-mentioned discussions regarding the effect of hydraulic conditions and chemical conditions on Mn(II) decay indicate that both high Reynolds number and high residual-chlorine concentration can increase the decay rate of the total manganese concentration in pipeline systems. However, further studies are warranted, particularly considering the types of manganese in WDSs, such as soluble, particulate, and total manganese. Furthermore, experiments in unsteady-state hydraulic conditions, which occur frequently in real water pipe networks, are required to understand the effect of turbulence intensity on the behavior of manganese concentrations.

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## Symbols

| | | |
|---|---|---|
| $C_{\mathrm{Mn}}$ | — | Concentration of total manganese |
| $C^*_{\mathrm{Mn}}$ | — | Stable concentration of total manganese |
| $C^0_{\mathrm{Mn}}$ | — | Initial concentration of total manganese |
| $k$ | — | Decay coefficient |

## References


[1] V. Gauthier, C. Rosin, L. Mathieu, J.M. Portal, J.C. Block, P. Chaix, D. Gatel, Characterization of the Deposits in Drinking Water Distribution Systems, American Water Works Association, Boston, MA, 1996, pp. 1–14.

[2] J.B. Boxall, P.J. Skipworth, A.J. Saul, A Novel Approach to Modelling Sediment Movement in Distribution Mains Based on Particle Characteristics, Proc. Computing and Control in the Water Industry Conference, Water Software Systems: Theory and Applications, De Monfort University, UK, 2001, pp. 263–273.

[3] N. Slaats, Processes Involved in Generation of Discolored Water, American Water Works Association Research Foundation, Kiwa, The Netherlands, 2004.

[4] R.A. Prince, I. Goulter, G. Ryan, What causes customer complaints about discoloured drinking water?, Water, J. Austral. Water Assoc., 30 (2003) 62–67.

[5] D. Ellison, Investigation of Pipe Cleaning Methods, AWWA Research Foundation and American Water Works Association, Denver, USA, 2003.

[6] J.H.G. Vreeburg, Discolouration in Drinking Water Systems: A Particular Approach, Civil Engineer, Delft, Ph.D., 2007, pp. 183.

[7] C.Y. Peng, G.V. Korshin, Speciation of trace inorganic contaminants in corrosion scales and deposits formed in drinking water distribution systems. Water Res., 45 (2011) 5553–5563.

[8] C.Y. Peng, G.V. Korshin, R. Valentine, A. Hill, H. Friedman, S. Reiber, Characterization of elemental and structural composition of corrosion scales and deposits formed in drinking water distribution systems, Water Res., 44 (2010) 4570–4580.

[9] C. Alvarez-Bastida, V. Martínez-Miranda, G. Vázquez-Mejía, M. Solache-Ríos, G. Fonseca-Montes de Oca, E. Trujillo-Flores, The corrosive nature of manganese in drinking water, Sci. Total Environ., 447 (2013) 10–16.

[10] WHO, Guidelines for Drinking-water Quality, Vol. 2, World Health Organization, Geneva, 2004.

[11] United States Environmental Protection Agency, Office of Water (4304J) Health and Ecological Criteria Division Washington D.C. 20460 Drinking Water Health Advisory for Manganese, EPA-822-R-04-003, 2004.

[12] L.I. Sly, M.C. Hodgkinson, V. Arunpairojana, Deposition of manganese in a drinking water distribution system, Appl. Environ. Microbiol., 56 (1990) 628–639.

[13] O.J. Hao, A.P. Davis, P.H. Chang, Kinetics of manganese(II) oxidation with chlorine, J. Environ. Eng., 117 (1991) 358–374.

[14] J.B. Boxall, A.J. Saul, P.J. Skipworth, A novel approach to modelling sediment movement in distribution mains based on particle characteristics, Water Software Syst., 1 (2001) 263–273.

[15] J.B. Boxall, A.J. Saul, Modeling discoloration in potable water distribution systems, J. Environ. Eng., 131 (2005) 716–725.

[16] J.B. Boxall, R.A. Prince, Modelling discolouration in a Melbourne (Australia) potable water distribution system, J. Water Supply Res. Technol. AQUA, 55 (2006) 207–219.

[17] T.L. Gerke, B.J. Little, J.B. Maynard, Manganese deposition in drinking water distribution systems, Sci. Total Environ., 541 (2016) 184–193.

[18] H. Ramos, D. Loureiro, A. Lopes, C. Fernandes, D. Covas, L.F. Reis, M.C. Cunha, Evaluation of chlorine decay in drinking water systems for different flow conditions: from theory to practice, Water Resour. Manage., 24 (2010) 815–834.

[19] G. Mutoti, J.D. Dietz, J. Arevalo, J.S. Tayor, Combined chlorine dissipation: pipe material, water quality and hydraulic effects, J. Austral. Water Assoc., 99 (2007) 96–106.

[20] H. Kim, J. Koo, S. Kim, A general framework of chlorine decay modeling at a pilot-scale water distribution system, J. Water Supply Res. Technol. AQUA, 64 (2015) 543–557.

[21] H. Kim, S. Kim, Evaluation of chlorine decay models under transient conditions in a water distribution system, J. Hydroinf., 19 (2017) 522–537.

[22] H. Kim, D. Baek, S. Kim, Exploring integrated impact of temperature and flow velocity on chlorine decay for a pilot-scaled water distribution system, Desal. Wat. Treat., 138 (2019) 265–269.