Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2014.901193

54 (2015) 1393–1400
April

Prediction of water quality in piping system of bank filtrate

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Received 14 December 2013; Accepted 28 February 2014

ABSTRACT

During the operation of a pilot plant from July 2010 to January 2011 for the development of bank filtration along the Nakdong River, iron and manganese were detected on average as high as 23.99 and 3.45 mg/L, respectively. These levels are dozens of times higher than those found in standard quality Korean drinking water (less than 0.3 and 0.05 mg/L for iron and manganese, respectively). If the Nakdong River were to be used as a water resource, it would not only produce color or scale in the piping system but also result in an increase in water treatment costs. Therefore, this study used by EPANET-MSX modeling to investigate the behaviors of iron and manganese in a piping system. Additionally, it assessed the possibility of color or scale formation when the bank filtrate was passed through a pipe with 38 km length and 2,600–2,800 mm diameter. The modeling result predicted that if the transport was done without reducing iron to a certain level, approximately 5300 ton/year of ferric oxide and 324 NTU of turbidity would be produced in the piping system, whereas manganese would have no effect owing to insufficient oxidants. If the iron was reduced up to 3.0 mg/L by aeration pretreatment, the ferric oxide and turbidity were predicted to be approximately 746 ton/year and 57 NTU, respectively. Furthermore, in the case of a reduction up to 0.3 mg/L by the pretreatment, the levels were predicted to be about 75 ton/year and 5.9 NTU, respectively.

Keywords: Bank filtrate; Iron; Manganese; Piping system; EPANET-MSX; Ferric oxide; Turbidity

1. Introduction

The downstream areas of Korea's Nakdong River, including Busan and Gyeongsangnam-do, use the river as a water resource. However, there is a significant problem of water quality deterioration caused by wastewater from cities and industries located up- and mid-stream of the river. Accidental inflow of toxic substances including phenol, benzene, and toluene into the river resulted in the suspension of water supply for a period of time and an enormous distrust of

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Presented at the 6th International Conference on the "Challenges in Environmental Science and Engineering" (CESE-2013), 29 October—2 November 2013, Daegu, Korea

tap water [1,2]. To address this problem, the government is currently trying to develop and supply bank filtration as an alternative water resource in the area.

With bank filtration, relatively high quality water free of suspended materials can be obtained as a result of the physical, chemical, and biological purification of water as it passes through an aquifer [3,4]. However, the quality is significantly affected by the soil and geological feature of the aquifer. In general, the bank filtrate is reported to contain a small amount of minerals and a high concentration of silica materials [5]. It also includes significant amount of CO_2 that originates from organic decomposition. Unlike river water, bank filtration generally does not have the problem of eutrophication, but it does suffer from the problem of infiltration of pollutants such as fertilizers and pesticides through groundwater [6]. In particular, bank filtrate can sometimes contain high concentrations of iron and manganese due to the dissolution from underground under anoxic condition, which make it significantly more difficult to treat the water [3,4].

The Korean guidelines for drinking water quality have recently been revised to less than 0.05 and 0.3 mg/L for manganese and iron, respectively. Manganese concentration of greater than 0.02 mg/L is reported to produce taste and odor in water owing to iron bacteria (*clonothrix, crenothrix*) as well as a decrease in discharge capacity resulting from a pipe-coating of hydroxide or oxidated manganese [7]. A number of studies on pipeline corrosion have reported that the scale formation in a pipe is normally initiated by the formation of hydroferrous material due to the oxidation of iron [8]. Therefore, it is necessary to assess the impact of the bank filtrate on the piping system.

A pilot plant of the Nakdong River's bank filtration was operated from July 2010 to January 2011 to improve water quality. The operational result showed that iron and manganese were detected at 1.0 and 0.8 mg/L, respectively, from the Nakdong River. However, the levels were significantly increased in the bank filtrate (up to 23.99 mg/L for iron and 3.45 mg/L for manganese). These concentrations were dozens of times higher than those specified in the Korean drinking water guidelines. If this water were used as a water resource, it would not only produce color or scale in the piping system, but it would also result in a significant increase in water treatment cost. The US EPA has recently developed EPANET-MSX (Multi-Species Extension), which is capable of modeling the water quality behavior of water distribution systems [9]. In this study, we used EPANET-MSX modeling to investigate the behaviors of iron and manganese during the transport of bank filtrate through a piping system with 38 km length and 2,600–2,800 mm diameter. The effect of DO on the behavior was also studied, and *in situ* aeration was suggested as a pretreatment. The possibility of color or scale formation as a result of iron oxidation in the piping system was assessed by the modeling in terms of the production of ferric oxide and turbidity. The assessment was conducted in cases of various initial conditions to prove the need for the *in situ* aeration.

2. Methodology

2.1. Model

EPANET is a widely used program for modeling the hydraulic and water quality behavior of drinking water distribution systems. However, its water quality component is limited to tracking the transport and fate of just a single chemical species, such as fluoride used in a tracer study or free chlorine used in a disinfectant decay study. Different chemical species soluble or suspended such as iron and manganese are transported in the pipe and ultimately affect the water quality, as they react with the water body and the pipe wall. From a water quality modeling perspective, two significant physical phases exist within a water transportation system, namely a mobile bulk water phase and a fixed pipe surface phase. Bulk phase species are chemical or biological components that exist within the bulk water phase and are transported through the system with the average water velocity. Surface phase species are components that are attached or incorporated into the pipe wall and are thus rendered immobile. Bulk phase chlorine or oxygen can oxidize ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}) in the fixed surface phase at the pipe wall.

A water transportation system consists of pipes, pumps, valves, fittings, and storage facilities that convey water from source points to consumers. This physical system is modeled as a network of links connected at nodes in some particular branches or a looped arrangement. Links represent pipes, pumps, and valves; nodes serve as source points, consumption points and storage facilities. All the phenomena—including advective transport in pipes, mixing at pipe junctions and mixing in storage nodes—influence the water quality contained in the system and can be modeled using principles of conservation of mass coupled with reaction kinetics.

2.2. Input data

EPANET-MAX has two different kinds of input files: inp file and msx file. The inp file includes altitude, demand, length, diameter and roughness of the piping system. The msx file consists of modeling compounds, their reactions, kinetics, and initial water quality.

For the inp file, all the data of the piping system including altitude, demand, length, diameter, and roughness were collected and rearranged for the modeling. Fig. 1 shows the investigated piping system used to transport bank filtrate of 683,300 m^3/day abstracted from the *C* area of Gyeongsangnam-do in Korea. The piping system had two suction-type pumps that had 20 min retention time. The bank filtrate was pressurized by the 1st pump to transport 22.6 km, and then 15.4 km by the 2nd pump. The total length of the piping system was 38.0 km, and the diameter of the pipe was 2,600–2,800 mm.

For the msx file, the water quality of the bank filtrate obtained from the pilot plant was analyzed according to protocols described in *Standard Methods for Water and Wastewater* and is presented in Table 1. The proportions of soluble iron and manganese to the total amounts were as high as 79.3 and 64.3%, respectively. Previous research works were reviewed for the mechanisms of the oxidation of iron and manganese, and kinetic coefficients k and k_2 [10–12]. The units were transported into mg, L and h. According to the EPANET-MSX input method, k and k_2 were changed to 3.76×10^5 and 1.61×10^{-11} mg/L h, respectively.

3. Results and discussion

3.1. Behaviors of iron and manganese

The behaviors of iron and manganese in piping system were modeled by EPANET-MSX and the result is shown in Fig. 2. The model predicted nearly complete conversion of soluble iron into ferric oxide, whereas no change was predicted for manganese. The initial 19.02 mg/L of soluble iron was readily converted into ferric oxide as soon as the bank filtrate passed through the pipe, so that 21.43 mg/L of ferric oxide was produced, whereas 0.45 mg/L of soluble iron remained at the end of the 38 km pipe. On the other hand, 2.22 mg/L of soluble manganese did not change at all during the transport.

Iron occurs in two states of oxidation in nature, namely, divalent (ferrous, Fe^{2+}) and trivalent (ferric, Fe^{3+}). One state can be converted into the other by an exchange of electrons. The following equation represents a common type of reaction for the conversion of iron in water [13].

$$3H_2O + Fe^{2+} \leftrightarrow Fe^{3+} + 3OH^- + e^- + 3H^+ \quad (1)$$

The ferrous state is usually soluble, whereas the ferric state is insoluble. The iron of the ferric state ($Fe^{3+} + 3OH^-$) is precipitated as $Fe(OH)_3$. The equilibrium in the above equation is influenced by the concentration of electrons (designated Eh) as well as the concentration of hydrogen ions (designated pH). Several studies have reported the transition between the oxidized and reduced states of Fe and Mn as shown in Fig. 3 [13,14]. The lower of the two sloping lines shows the balance between ferrous and ferric iron. The upper sloping line shows the relation between divalent manganese (soluble) and tetravalent manganese (insoluble form).

Only a negligible variation in pH can be expected in the piping system of the bank filtrate, so that a soluble or insoluble state of iron and manganese depends significantly on the Eh, which is normally affected by DO. In general, the bank filtrate under the groundwater has very low DO so that the states of iron and manganese are all soluble according to the theory shown in Fig. 3. However, when it pumps up and passes through the piping system, the bank filtrate will have enough DO for the conversion into insoluble states. The DO will be initially consumed for the oxidation of soluble iron and then, it will oxidize the soluble manganese. However, the oxidation of manganese needs almost ten times the energy required for iron oxidation; hence, the DO in the piping system would be not enough for the oxidation of manganese. That might be the reason that no change was predicted for manganese.

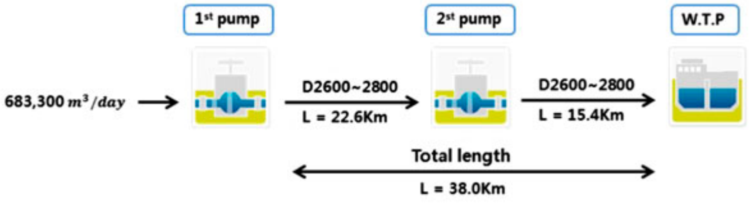

Fig. 1. Diagram of piping system.

Table 1
Analysis of water quality in bankfiltrate for modeling

Item	Daily max.	Daily min.	Daily average
Temperature (℃)	24.6	12.4	17.7
pH	7.1	6.2	6.7
Turbidity (NTU)	165.0	0.0	5.2
DO (mg/L)	6.1	0.1	2.37
Total Fe (mg/L)	29.5	6.2	23.99
Soluble Fe (mg/L)	28.1	2.7	19.02
Total Mn (mg/L)	14.6	0.02	3.45
Soluble Mn (mg/L)	3.9	0.0	2.22

The conversion of soluble iron into ferric oxide would significantly affect the water quality and the piping system. Sarin et al. have suggested a conceptual model to describe the formation and growth of iron scale [15]. They explained in the model that ferrous ion is the primary iron source for the formation and the growth of scale, which comes from the conversion of iron metal on the pipe wall. However, in this study the ferrous ions already existed sufficiently in the bank filtrate, which would cause significant formation of scale on the pipe wall. Cook and Husband have reported in their recent field research that iron scale has grown at a rate of 0.0057 mm/month with a 95% confidence level for 30 months in a piping system containing an average of 20–80 μg/L of soluble iron [16,17]. Based on their observation, the piping system in this study would be scaled at the rate of 36 mm/year, which means that the pipe would be clogged with scale at approximately 1.3% every year.

3.2. Effect of DO on iron oxidation

From the study on the behaviors of iron and manganese in the piping system, DO was found to be the only factor to govern the oxidation of iron (converting soluble iron into ferric oxide). DO in the piping system is significantly varied owing to seasonal temperature changes, turbulence, or air-contact in facilities. The effect of DO on the oxidation of iron was modeled by EPANET-MSX with initial soluble iron of 19.02 mg/L. The modeling result is shown in Fig. 4. As shown in Fig. 4, DO of 1.0 mg/L produced 15.60 mg/L ferric oxide by oxidation, whereas 8.39 mg/L of iron remained as a soluble state. When DO was 2.0 mg/L, the ferric oxide was produced at 20.28 mg/L and the soluble iron remained at 3.71 mg/L. More than 6.0 mg/L of DO was predicted to lead to almost complete oxidation of the soluble iron into the insoluble state of ferric oxide. The produced ferric oxide would precipitate to make a color, and the remaining soluble iron would be used in the formation and the growth of scale on the pipe wall. The ferric oxide was reported not to precipitate at the conventional piping velocity of more than 1.5 m/s because of tractive force or self-cleaning theory [18]. However, it would eventually inflow into the water treatment plant (WTP), causing serious problems and increasing treatment cost.

Therefore, the iron in the bank filtrate should be removed effectively before causing problems in the piping system. *In situ* pretreatment has been widely used in European countries to treat iron and manganese in the bank filtrate, which is normally called the Vyredox method [19,20]. This method uses direct precipitation of iron and manganese in the aquifer by

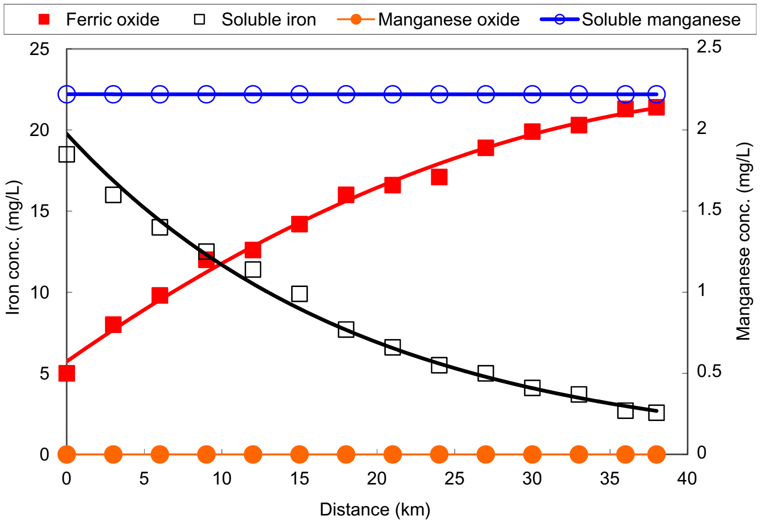

Fig. 2. Behaviors of iron and manganese with transport distance through pipe (modeled by EPANET-MSX).

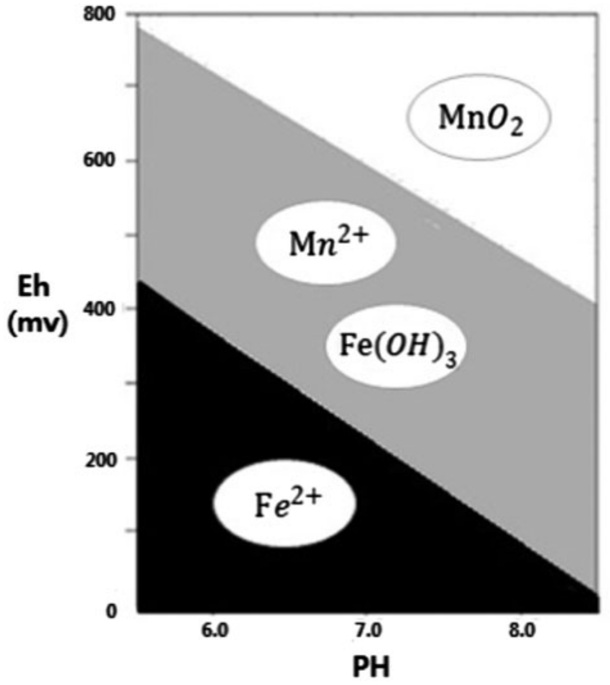

Fig. 3. States of iron and manganese with different Eh and pH (adapted from Hallberg et al. [13]).

oxygenation. For this purpose, air-saturated water is injected into the aquifer. This study applied *in situ* aeration as a pretreatment to treat the high concentration of iron. Fig. 5 shows the variation in DO and soluble iron with and without the aeration pretreatment. The average DO with aeration was 6.7 mg/L, whereas it was 2.3 mg/L without aeration. The average soluble iron with aeration was 4.5 mg/L, whereas it was 19.02 mg/L without aeration. The iron was fairly well controlled by DO. It was found that the iron could be reduced up to 0.3 mg/L with more than 9.0 mg/L of DO.

3.3. Effect of pretreatment on water quality

From theoretical and experimental research on a drinking water distribution system, Refait proved that the ferrous ions made from a pipe wall can be released into the bulk water, where they undergo conversion to particulate ferric iron, which is the cause of colored water [21]. Therefore, the variation in water quality in a piping system was modeled in terms of the production of ferric oxide and turbidity during the 38 km transportation of the bank filtrate. The initial values of soluble iron applied to the model were 19.02, 3.0, and 0.3 mg/L. Soluble iron of 19.02 mg/L was the value observed from the pilot plant without the pretreatment, and 3.0 and 0.3 mg/L were obtainable values with the pretreatment. Fig. 6 shows the result predicted by the model.

When the initial soluble iron was 19.02 mg/L, 4,422 ton/year of ferric oxide was predicted during the bank filtrate's transport until the 2nd pump. Another 878 ton/year of ferric oxide was modeled between the 2nd pump and WTP. This means that a total of 5,300 ton/year of ferric oxide would be produced during the bank filtrate transports through a 38 km piping system if its soluble iron was not removed by pretreatment. This product of ferric oxide would cause significant trouble in piping systems, pumping

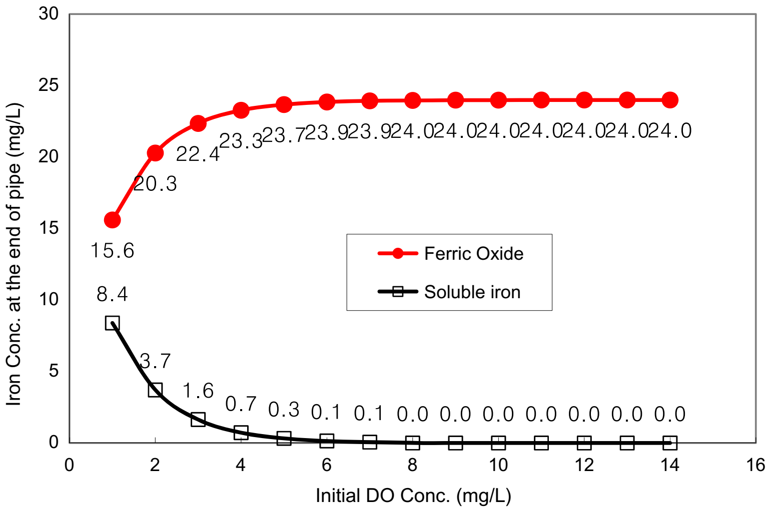

Fig. 4. Effect of DO on iron oxidation.

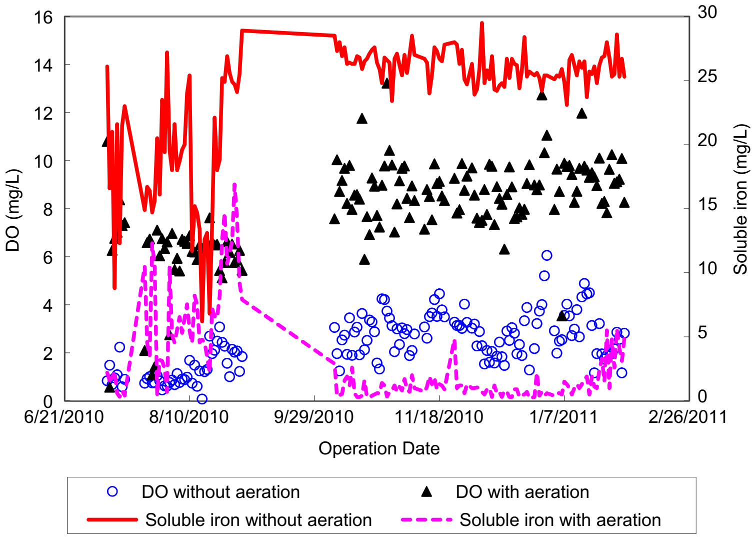

Fig. 5. DO and soluble iron concentrations with and without pretreatment (observed from pilot plant).

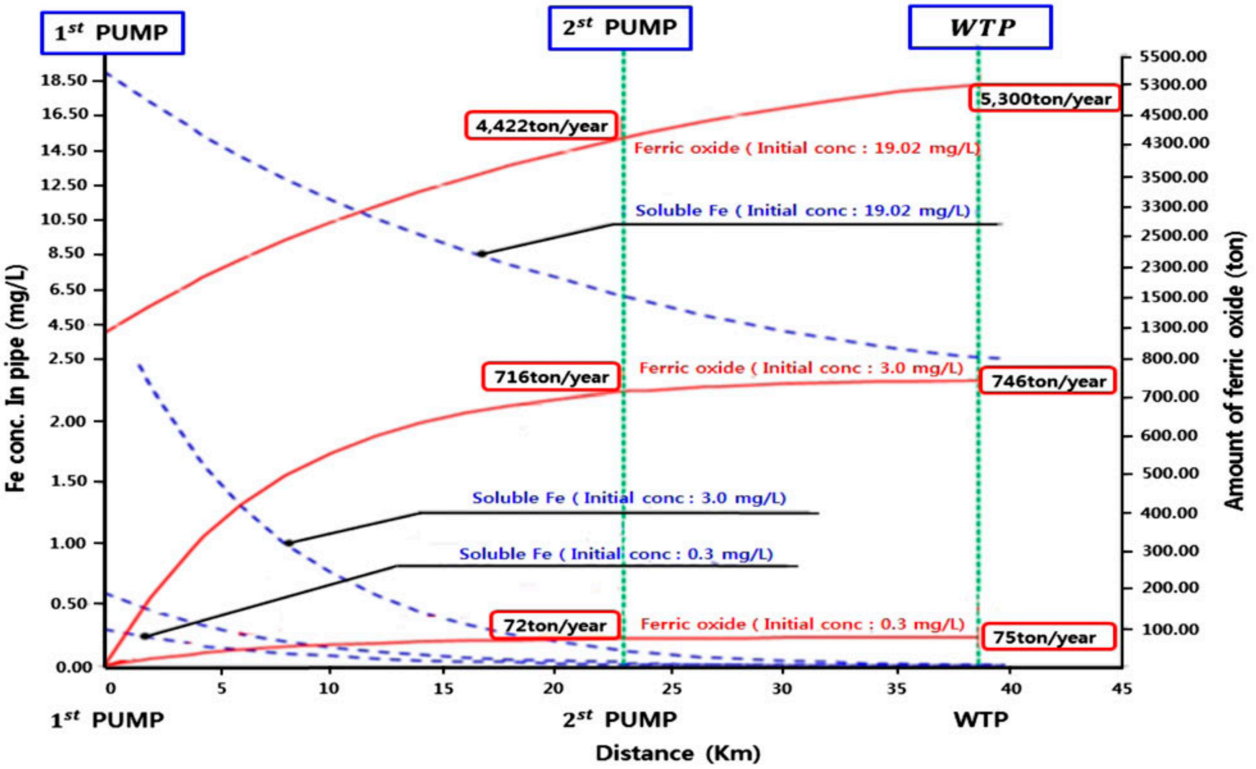

Fig. 6. Product of ferrous oxide depending on different initial soluble Fe.

facilities, or WTP. On the other hand, in the case of 3.0 mg/L of soluble iron reduced by the pretreatment, the amount of oxidation was predicted to be 716 ton/year until the 2nd pump and another 30 ton/year until the WTP. When the soluble iron was reduced to 0.3 mg/L, the model predicted 72 ton/year of ferric oxide production until the 2nd pump and 2 ton/year more until the WTP.

Table 2
Production of ferric oxide and turbidity

Before 2nd pump			Before WTP		
Initial Fe (mg/L)	Ferric oxide (ton/year)	Turbidity (NTU)	Fe after 2nd pump (mg/L)	Ferric oxide (ton/year)	Turbidity (NTU)
19.02	4,422	253.7	6.26	878	69.97
3.0	716	57.1	0.13	30	0.12
0.3	72	5.8	0.01	2	0.20

The result of the EPANET-MSX modeling is rearranged in Table 2 with calculated turbidity. The calculation of water turbidity was based on recent field research [17,22]. From the water quality data obtained from the pilot plant, a turbidity of 5.2 NTU was observed at 19.02 mg/L of the soluble iron. The turbidity increased to 103 NTU when the soluble iron decreased to 14.1 mg/L by aeration pretreatment. On the basis of this proportion, the oxidation of 1 mg/L of soluble iron was assumed to increase the turbidity to 19.88 NTU. The ferric oxide would precipitate at the area before the 2nd pump because the piping velocity is sufficiently slow. If the precipitated ferric oxide is removed before the 2nd pump, the water quality would be enhanced, and its effect on scale formation, color, and WTP would also be reduced. Table 2 indicates the effect of the installation of a removal facility before the 2nd pump.

Without the pretreatment, 19.02 mg/L of soluble iron would produce 253.7 NTU of turbidity before the 2nd pump, and 70.0 NTU of turbidity would still be produced between the 2nd pump and WTP. This result implies that the operation of the bank filtrate without pretreatment would cause significant problems in the piping system or WTP. When the pretreatment was applied to reduce the soluble iron and the removal facility was installed to remove the precipitated particles of ferric oxide, the water quality was predicted by the model to become satisfactory. The reduction in soluble iron to 3 mg/L would produce 57.1 NTU before the 2nd pump, whereas the turbidity remained at 0.12 NTU before WTP. In the case of the reduction up to 0.3 mg/L (which is the drinking water guideline), the turbidity was 5.8 NTU before the 2nd pump and 0.2 NTU before WTP.

4. Conclusions

In this study, the following conclusions could be drawn based on the modeling results;

- When the bank filtrate (initial soluble iron, manganese, and DO were 19.02, 2.22, and 2.37 mg/L, respectively) transported through a piping system with 38 km length and 2,600–2,800 mm diameter, EPANET-MSX predicted that ferric oxide would increase up to 21.43 mg/L at the end of the pipe, whereas oxidation of manganese was not predicted to occur. Based on previous research, the piping system would be scaled at the rate of 36 mm/year, which means that the pipe would be clogged with scale at approximately 1.3% every year.
- From the modeling with different initial concentrations of DO, soluble iron was predicted to be less than 0.14 mg/L at the end of the pipe if there was more than 6.0 mg/L of DO. This implied that almost all the soluble iron would be converted into an insoluble state of ferric oxide to produce color or scale in the piping system. Pretreatment of *in situ* aeration was suggested as an alternative and showed the ability to reduce the soluble iron up to 0. 3 mg/L.
- 19.02 mg/L of soluble iron would produce approximately 5,300 ton/year of ferric oxide and 324 NTU of turbidity. In the case of a reduction in soluble iron to 3.0 mg/L by pretreatment and installation of a removal facility before the 2nd pump, the produced ferric oxide and turbidity would be 716 ton/year and 57 NTU, respectively. When a reduction up to 0.3 mg/L and the removal of ferric oxide before the 2nd pump were applied, 75 ton/year of ferric oxide and 5.9 NTU of turbidity would occur.

Acknowledgment

This work was supported by a 2012 Inje University research grant.

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