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The effect of fluctuation in flow rate on the performance of conventional and membrane water treatment for a smart water grid

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ABSTRACT

A smart water grid can save water and energy by delivering the water to consumers according to the time-dependent demands. One of the key water treatment technologies for a smart water grid is to control the water supply rate as per the consumers' demand. However, a conventional water treatment plant is designed for a constant production rate operation, which is not appropriate for a smart water grid. The present study focuses on the effect of fluctuation on the production rate of three water treatment technologies: i.e. (1) sedimentation followed by ozonation and coagulation/flocculation, (2) sand filtration followed by coagulation/flocculation and sedimentation, and (3) membrane process (microfiltration [MF]). For sedimentation and sand filtration processes, the pilot- and real-scale plant data were analyzed to investigate the fluctuation patterns of the flow rate and water quality. For the membrane process, an MF operation was simulated to investigate the effect of fluctuation flux on the membrane fouling rate. Two key findings emerged from the pilot and field data analyses and simulation results in the present study. First, there exists a time delay between the input and output flow fluctuations for sedimentation and sand filtration processes, and the water quality is changed during and after the time delay for the flow rate fluctuation. Second, in the MF process, the flow rate fluctuation does not have any significant effect either on the permeate water quality or on the fouling behavior.

Keywords: Smart water grid; Fluctuation in the flow rate; Conventional water treatment; Membrane water treatment

1. Introduction

Smart water grid is a new concept for total water management with the help of information technology. It originated from the smart grid for electricity. Smart grid is defined as an electricity network that can cost-efficiently integrate the behaviors and actions of all users connected to it—generators, consumers, and those that do both—to ensure an economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety [1]. The definition of a smart water grid can be easily obtained by substituting water-related keywords for electricity-related ones as follows:

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> Smart Water Grid is a water network that can cost efficiently integrate the behavior and actions of all users connected to it—water supplier, consumers and those that do both—in order to ensure an economically efficient, sustainable water system with low losses and high levels of quality and security of supply and safety.

Smart water grid will be a good substitute for the current water management systems as water and energy sources will be limited sooner or later. Smart water grid can be achieved by an effective communication between each node, for example, water source, water treatment plant (WTP), pipe network, wastewater treatment plant, customers, and environment as seen in Fig. 1, which is a simple concept of smart water grid. The information for intercommunications are the amount of source water, water flow rate, water quality, demand patterns, water price, environmental regulation, system availability and failure, and so forth.

With the help of intercommunication, water suppliers set an optimal supply strategy to fit a real-time water demand without excess in water production rate like the case of current water supply system and customers easily know the information of the water usage pattern coupled with variable water prices according to peak and ordinary time, which finally results in saving water and energy. The most important technologies for smart water grid are smart sensors, real-time water demand prediction, optimization, and so on.

In addition to the technologies discussed above, water treatment should be evolved to achieve a smart water grid. The water treatment plants for a smart water grid need to control the water supply rate in accordance with the consumers' demand. In a conventional centralized water distribution system, the best way to control the water supply rate is to change the water level of the water distribution tank, while the production rate of WTP remains constant. In a smart water grid, the decentralized water distribution system with the smaller WTPs and water distribution tanks is more efficient than the centralized system. Owing to a limitation in the smaller sizes of water distribution tanks, controlling the production rate of WTP is inevitable for a smart water grid.

The first tank, which forms the water level or head for the intake water from water source within an arbitrary water treatment plant, is generally called the "equalization basin". The water flow between the equalization basin and the latter processes, i.e. rapid mixing, distribution channel, flocculation, sedimentation, filtration, and so on, is connected through a weir, orifice, open channel, and closed pipes. Even though might be attributed to a certain particularity each water treatment plant, the water level within the equalization tank could be affected by the fluctuation in the inlet flow rate and the recycled flow rate with time. Several previous researches have reported that this change in water level within the equalization basin can make a serious impact on the performance of each successive unit process as well as the efficiency of the total system [2,3]. For example, in the case of a rapid mixing step, the flow rate fluctuation makes it difficult to optimize the chemical dose and mixing intensity. This flow rate fluctuation tends to confuse the fixed optimal velocity gradient value (*G* value) in the flocculation step, and changes the water level and hydraulic behavior within the sedimentation basin. The change in shear rate on the surface of media resulted from the variation of the water level above the filter media in the filtration tank can detach the attached particles accumulated inside media. Table 1 lists the details in the effect of the flow rate fluctuation on the output water quality according to the unit process to consist of WTP.

According to the phenomena discussed in Table 1, there are three main reasons for the water quality change in due to the variation in water flow rate; (1) change of chemical concentration or UV light intensity,

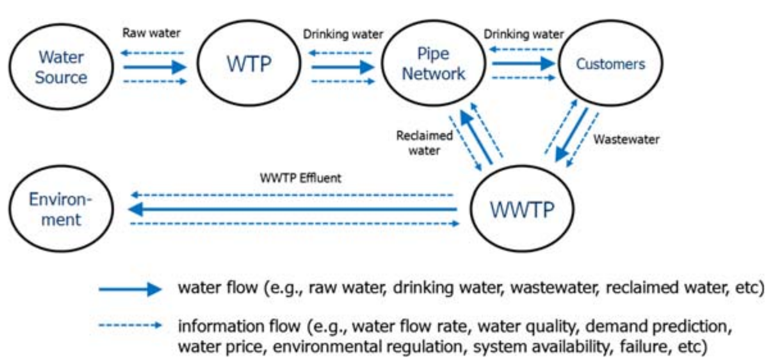

Fig. 1. The water and information flow diagram in a smart water grid.

Table 1
The effect of the water flow rate fluctuation on the product water quality of each unit process

Unit process	Q_p[a] > Q_d[b]	$Q_p < Q_d$
Coagulation/ flocculaton	Coagulant underdosing, and non-optimized mixing condition → Lowering water quality	Coagulant overdosing, and non-optimized mixing condition → Lowering water quality
Sedimentation	Increased surface loading rate → Lowering water quality	Decreased surface loading rate → Raising water quality
Media filtration	Increased hydraulic loading rate → Lowering water quality	Decreased hydraulic loading rate → Raising water quality
PAC[c]	PAC underdosing and decreased contact time → Lowering water quality	PAC overdosing and increased contact time → Raising water quality
GAC[d]	Decreased EBCT,[e] and increased hydraulic loading rate → Lowering water quality	Increased EBCT,[e] and decreased hydraulic loading rate → Raising water quality
Ozone	Ozone underdosing and decreased contact time → Lowering water quality	Ozone overdosing and increased contact time → Raising water quality
UV radiation	Decreased radiation efficiency and contact time → Lowering water quality	Increased radiation efficiency and contact time → Raising water quality
Membrane (MF[f]/ UF[g])	Increased permeate flux → Negligible effect on water quality	Decreased permeate flux → Negligible effect on water quality

[a]Actual water production rate.
[b]Designed water production rate.
[c]Powdered activated carbon.
[d]Granular activated carbon.
[e]Empty bed contact time.
[f]Microfiltration.
[g]Ultrafiltration.

(2) change of contact time, and (3) change of hydraulic loading rate. A well-designed chemical concentration or UV light intensity for a certain design flow rate is altered by the flow rate change without changing the dosing rate, which results in an underdosing or overdosing. The contact time is inversely proportional to the flow rate and affects the efficiency of activated carbon adsorption, ozonation, coagulation, and UV radiation. The higher contact time assures the higher efficiency in removing the pollutants. The hydraulic loading rate (i.e. surface loading rate in the case of sedimentation process) is directly proportional to the flow rate. The higher loading rate increases the turbidity of product water in sedimentation and sand filtration.

The product water quality of membrane water treatment (i.e. microfiltration [MF] or ultrafiltration [UF]) is not affected by the flow rate fluctuations in the case of particle removal. The particle size of interest for water treatment is in a range of one to several microns, which is much larger than the pore sizes (i.e. 0.01–0.1 μm) of MF and UF membranes [4–6]. Therefore, the flow rate fluctuation has a negligible effect on the turbidity of product water of MF or UF processes.

The present study focuses on the effect of the water flow rate fluctuation of three water treatment technologies for particle removal: sedimentation, sand filtration and MF. Pilot- and real-scale plant data were analyzed to investigate the fluctuation patterns of the flow rate and water quality in the sedimentation and the sand filtration processes. In addition, an MF operation was simulated to investigate the effect of fluctuation in permeate flux upon the membrane fouling rate.

2. Methods

2.1. Pilot and field data analysis for conventional water treatment processes

Two representative processes in conventional water treatment technologies, sedimentation and sand filtration, were selected for this study. The pilot data were obtained from the pilot-scale system at the K-water institute and the field data were obtained from the Chungju Water Treatment Plant operated by the Korea Water Resources Corporation, South Korea. The pilot-scale system consists of ozonation, coagulation/

flocculation, and sedimentation in order, while the Chungju Water Treatment Plant has coagulation/flocculation, sedimentation, and sand filtration processes in order, as described in Fig. 2. The input flow rate and raw water turbidity were observed to be in the range from 12 to 24 m^3/h and 2.3 ± 0.5 NTU respectively, during the time period for the data analysis in the case of the pilot-scale system, while a range of 1,800–3,600 m^3/h of input flow rate and 18.1 ± 1.3 NTU of raw water turbidity were observed in the case of the real-scale system.

The input and out flow rate data were analyzed for both pilot- and real-scale systems so as to investigate the pattern of fluctuation in the flow rate. The input flow rate data were measured at the entrance of intake facility for each system, and the output flow rate data were obtained from the supernatant water in the sedimentation process for the pilot-scale system and the filtrate water from the sand filtration for the real-scale system. The turbidity of the output water from the both pilot- and real-scale systems was analyzed to check the effect of flow rate fluctuation on the product water quality of each conventional process.

2.2. Simulation for membrane water treatment process

As discussed earlier, the product turbidity of membrane water treatment is not supposed to be affected by the flow rate fluctuations. There are tons of research papers and textbooks discussing the excellence of MF and UF in turbidity removal and we do not need to verify this fact. However, the fluctuation may or may not affect the membrane fouling, which is of utmost concern in the operation and maintenance of membrane water treatment. To clarify this issue, a simulation of MF operation was carried out. Two different operation types, (1) constant and (2) variable flux operation, were simulated for 100 days. For both simulation cases, an average permeate flux of 1.0 m/d was selected to maintain the same production rate of 1,000 m^3/d with the total membrane area of 1,000 m^2. In the case of variable flux operation, two permeate fluxes of 1.6 m/d and 0.8 m/d were selected to fit the peak time and the ordinary demand, respectively. The details in the simulation condition are discussed in Table 2.

3. Results and discussion

3.1. Conventional water treatment: sedimentation and sand filtration

The input flow rate of a process is the same as the output flow rate because of mass balance in the steady state. However in a dynamic state when the input flow rate is being changed immediately for example, those two flow rates do not become identical but instead follow different patterns of variation as shown in Fig. 3.

During the time period from 50 to 1,500 s in Fig. 3, the output flow starts to increase after a time delay of 50 s from the beginning of the input flow increase and is stabilized after another time delay of 450 s from the end point of the input flow increase. Since the duration to increase the input flow is 10 s, the total time delay between the input and output flow fluctuations is 460 s (i.e. from the beginning of the input flow increase to the end point of the output flow increase). The reason for the time delay is the water-level fluctuation of the open-channel flow and it can be quantified by using the concept of surface wave adopted from the Froud Number as discussed elsewhere [10,11].

While the output flow rate increases from 12 to 24 m^3/h for about 410 s (i.e. the duration of the dynamic state to increase output flow rate; 460 s—50 s; from the beginning of the output flow increase to the end point of the output flow increase), there was a sharp increase in turbidity of the output water (i.e. the supernatant water in the sedimentation process) up to 0.92 NTU as shown in Fig. 3. The reason for the sharp

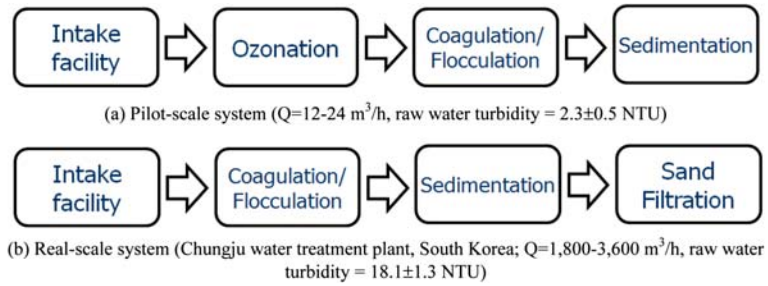

Fig. 2. The flow diagrams of two conventional water treatment systems for this study.

Table 2
Simulation conditions for MF operation

Simulation conditions for MF operation		
Flux model[a]		$J = \frac{\Delta p}{\mu R}$
Fouling model[b]		$\frac{d(\Delta p_i)}{dt} = k(\Delta p_i)^n$
Irreversible fouling[c]		$R_{i+1,0} = R_{i,0} + (R_{i,f} - R_{i,0}) * \text{RIF}$
Operation mode		29 min for filtration and 1 min for backwash per each cycle
Simulation time		2,400 h (100 days)
Boundary condition[d]		$Q = 1{,}000\ \text{m}^3/\text{d}$, $\mu = 0.00089$ Pa.s at 25℃, $R_{1,0} = 5.0 \times 10^{11}\ \text{m}^{-1}$, $n = 1.5$ (pore constriction), $k = 2.40 \times 10^{-7}\ \text{Pa}^{-0.5}\ \text{s}^{-1}$ RIF = 0.01
Specific condition[e]	Case 1	$J = 1.0$ m/d, $A = 1{,}000\ \text{m}^2$
	Case 2	$J = 0.8$ m/d for 18 h a day, 1.6 m/d for 6 h a day, $A = 1{,}000\ \text{m}^2$

[a]Darcy's Law; J: permeate flux (m/s), Δp: trans-membrane pressure (Pa), μ: the dynamic viscosity of water (Pa.s), and R: total resistance of membrane (m^{-1}).
[b]A generalized equation for the constant flux MF operation [7–9]; Δp_i: trans-membrane pressure (Pa) at the ith cycle, t: time (s), k: equation parameter (Pa^{1-n}/s), n: fouling characteristic parameter ($n = 0$ for the cake filtration, $n = 1.5$ for the pore constriction, and $n = 2$ for a complete blockage process).
[c]Irreversible fouling can be calculated by the increment of resistance which is not cleaned by the backwash process; $R_{i,0}$: total resistance of the membrane at the beginning of the ith cycle, $R_{i,f}$: total resistance of membrane at the end of ith cycle, and RIF: ratio of irreversible fouling (=0.01 for this study).
[d]Common simulation conditions for all the cases; Q: average water production rate (m^3/d).
[e]Specific simulation conditions for each case; A: total area of the installed membranes (m^2).

increase in turbidity is possibly attributed to the detachment of particles attached onto orifices or weirs in the sedimentation basin by the increased shear rate from the increased output flow rate.

The increased turbidity during the dynamic state is then decreased with time to reach a stabilized value of 0.25 NTU, which is slightly higher than the turbidity (=0.22 NTU) at the flow rate of 12 m^3/h, which can be called the permanent water quality change due to the changed hydraulic loading rate. The increased flow rate means the increased surface loading rate. As discussed in the introduction of this paper, the turbidity of supernatant water in the sedimentation process increases as the surface loading rate becomes higher. However, the difference of 0.03 NTU (i.e. 0.25 NTU—0.22 NTU) might be rather insignificant to be considered.

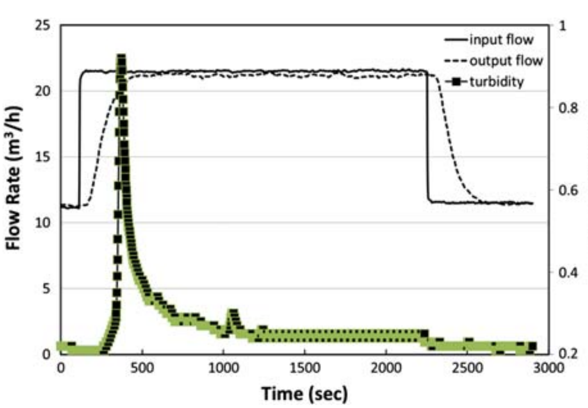

Fig. 3. The turbidity of the supernatant water (output) in the sedimentation process in the pilot-scale system according to the flow rate fluctuation.

The time delay between the input and output flow rate fluctuations is also observed in the case of decreasing flow rate ($t = 2{,}200$–$2{,}800$ s in Fig. 3). However, the turbidity remains unchanged during the dynamic state since the particles on the orifices or weirs do not get detached owing to the shear rate becoming smaller as the flow rate decreases.

The same trends in the flow rate fluctuation patterns are observed in the case of sand filtration as shown in Fig. 4. The time delay between the input and output flow rate fluctuations is about 50 min, which is higher than the observed time delay (i.e. 460 s) discussed in Fig. 3. The time delay is the function of system size (i.e. 1,800–3,600 m^3/h vs. 12–24 m^3/h) and will increase as the size of the open channel increases.

The trend of turbidity change is almost the same as that observed in the case of a sedimentation pilot system. A sharp increase in turbidity is also observed during the dynamic state for the output flow increase ($t = 50$–100 min in Fig. 4) and the stabilized turbidity at the higher flow rate is also higher than that at the lower flow rate. The difference in stabilized turbidity between the higher and the lower flow rate conditions is 0.11 NTU, which is high enough to be considered, higher hydraulic loading rate induces more detachment of particles from the surfaces of sands. Therefore, the filtrate water at a higher flow rate (3,600 m^3/h) exhibits a higher permanent turbidity (i.e. 0.14 NTU) than the product water at the lower flow rate (0.03 NTU at 1,800 m^3/h).

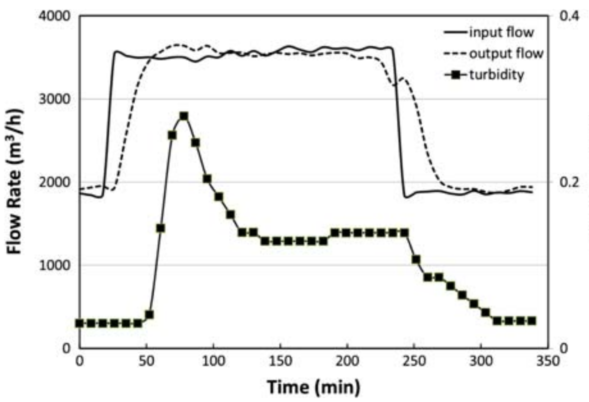

Fig. 4. Turbidity of filtrate (output) from the sand filtration in the real-scale system according to the flow rate fluctuation.

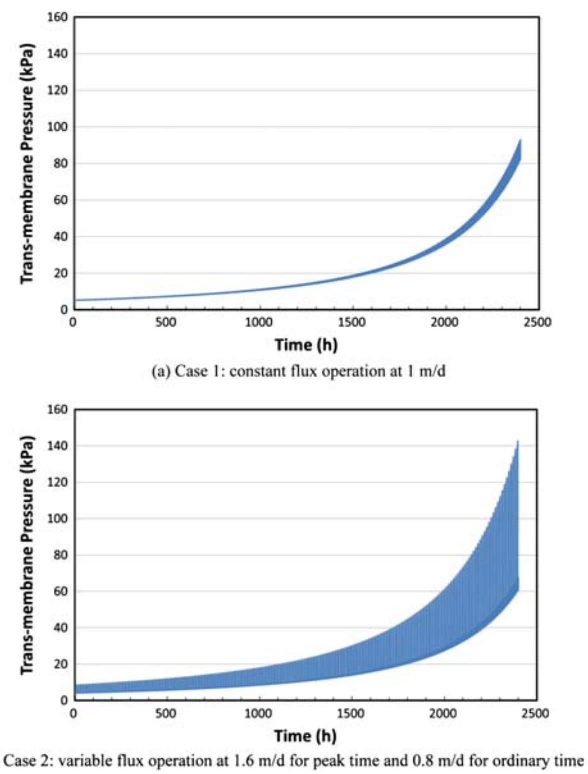

Fig. 5. Changes of trans-membrane pressure for 100 days of the MF simulation.

3.2. Membrane water treatment

The MF operation was simulated to investigate the effect of the flow rate fluctuation on membrane fouling. The details in the simulation conditions were already discussed in Section 2. Figs. 5 and 6 depict the simulated trans-membrane pressure (TMP) increase with time for both cases of constant flux

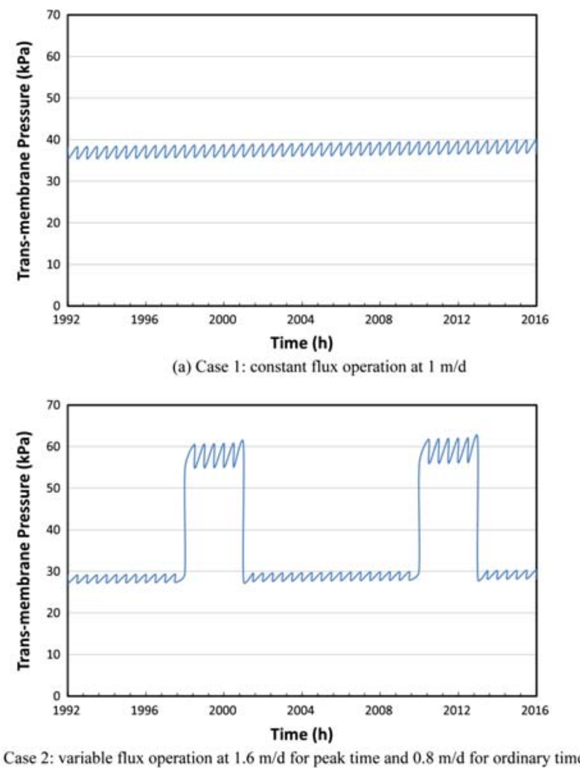

Fig. 6. Changes of trans-membrane pressure for a specific day in the MF simulation.

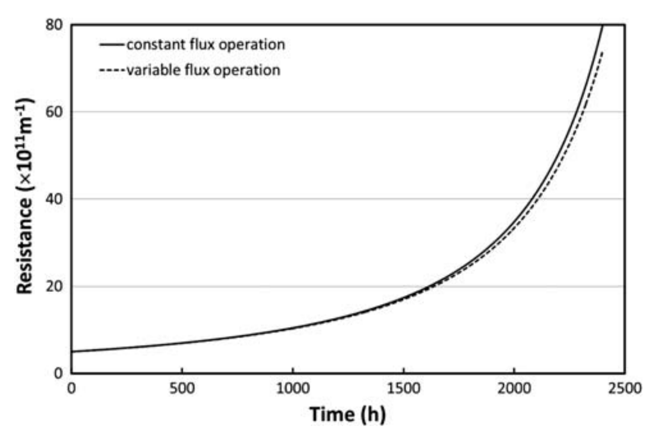

Fig. 7. Changes of total membrane resistance for 100 days of the MF simulation.

and variable flux operation, respectively. TMP increases gradually with time and the increasing rate will be faster as the TMP becomes higher according to the fouling model in Table 2 used for this study. If we assume that the critical TMP for chemical cleaning is 100 kPa, Case 1 (i.e. constant flux operation) does not need any chemical cleaning during the simulation period of 100 days, while Case 2 (i.e. variable flux operation) should undergo the cleaning at the time close to 2,250 operation hours as shown in Fig. 5. Therefore, more frequent chemical cleaning for variable flux operation is needed, which is because there are TMP jumps in this case as described in Fig. 6.

In the simulation of Case 2, there are two jumps per day in the TMP according to two peak time demands (i.e. 6–9 am, and 6–9 pm) as shown in Fig. 6. The TMP at peak times in Case 2 is about 1.6 times larger than the TMP in Case 1, while the TMP at ordinary times in Case 2 is about 0.8 times smaller than the TMP in Case 1. These ratios of the TMP values are similar to those of flux values. This fact means that there are no significant differences in the fouling behaviors between the constant and variable flux operation.

To more specifically quantify the fouling rate by the flux fluctuation, the total membrane resistance is calculated from the trans-membrane pressure, water viscosity, and permeate flux as discussed in Method section. Resistance given in Fig. 7 means the total membrane resistance, which is the sum of the intrinsic membrane resistance and the fouling resistance. The resistance in variable flux operation is slightly lower than that in constant flux operation as shown in Fig. 7.

The flux fluctuation has a negligible effect on fouling as presented in Fig. 7. However, this does not mean that the MF is absolutely free from the risk of the flux fluctuation because the simulation conditions used in this study are rather ideal and simple. For example, the fouling model used in this study is the simple pore constriction model and RIF (ratio of irreversible fouling) is assumed to be constant in our simulation. Therefore, a more realistic simulation methodology based on the field operation data should be developed to clarify the fouling concerns of the flow rate fluctuation.

4. Conclusions

A smart water grid can efficiently manage water and will be a potent future water system owing to the limited resources of water and energy. The water treatment technology in accordance with variable demand will play an important role in the effective management of the waste grid. As discussed using the experimental and simulation results presented in this paper, conventional water treatment technologies are affected by varying input flow rates. When a time delay between the input and output flow rate fluctuations for sedimentation and sand filtration is noticed, the water quality (i.e. turbidity) gets changed during and after the time delay for the flow rate fluctuation. However, the membrane water treatment is not considered to have any significant effect of the flow rate fluctuation not only on the permeate water quality but also on the fouling rate. Although the simulation condition is rather simple to clarify the fouling concerns of a flux fluctuation, the membrane process could be a good option to design an appropriate water treatment process for a smart water grid.

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