Application of unidirectional flushing in water distribution pipes

Jae Chan Ahn, Su Won Lee, Kevin Y. Choi, Ja Yong Koo and Hyun Jeong Jang

ABSTRACT

In this study unidirectional flushing (UDF) was conducted to improve the effectiveness of deposit removal from internal pipe walls and to provide information on pipe networks to enable operators to implement flushing in field. Four ductile cast iron pipes with epoxy-lined and cement-lined were selected for the practice of UDF. Water pressure was measured using a data logger equipped with a pressure gauge. The normal flow velocities of the networks were found to be 0.12 m/sec or below in the study area. Flushing velocities ranged from 1.07 m/sec to 2.78 m/sec by using a blow-off valve for discharge. The discharged water was taken in five-minute intervals to measure water quality parameters: turbidity, residual chlorine, pH, temperature and conductivity in the field; metals, inorganic ions, total suspended solids and heterotrophic plate count bacteria in the laboratory. The practice of periodic UDF as preventive maintenance is expected to contribute to enhancement of safety and stability of the water supply. It was indicated that part of the biofilm could be removed with the sediments in the pipe by UDF since the removal of HPC bacteria was correlated with total suspended solids (TSS) ($R^2 = 0.90$). The coefficient of determination (R^2) between turbidity and TSS is 0.90 except for one outlier. Sediment removal could be estimated from the turbidity data of flushed water in the field using the equation of the relationship between turbidity and TSS.

Key words | discoloured water, distribution system, hydrant, loose deposits, TSS, unidirectional flushing

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INTRODUCTION

There are two basic types of red water. The first is oxidized red water, which is the product of the oxidation reaction of water and oxygen on the raw surface of steel, cast iron or ductile iron pipe. The second basic type is mineralized red water. This is the mineral, which has been dissolved in water and the change of pressure, flow and addition of treating chemicals, primarily chlorine, has allowed this iron to coagulate and drop out (Gray 1988). Sediments accumulate within all water mains and storage facilities at varying rates depending on the level of treatment; where the coagulation process at a water treatment plant has not been optimized, alum can precipitate from treated surface waters (CNRC 2003). A gelatinous deposit on the walls of the pipe is aluminium hydroxide. The deposit is triggered by the pH reduction caused by the booster chlorination (Emery 1987). Although water quality complies with the most stringent regulations, water distribution systems can never be free of particles (Carriere *et al.* 2005). If the red water is due to oxidization or rust, using a plastic or cement-lined pipe will prevent the problem. But if the red water is mineralized,

doi: 10.2166/aqua.2011.013

a plastic or cement-lined pipe will not solve the problem (Gray 1988). Hydraulic entrainment involves the physical suspension of loose deposits induced by flow changes, which affect the deposit–water interface. Entrainment is the result of a force imbalance on the deposit. Once the particle is in suspension, transport is determined by buoyancy, weight, drag in the flow direction and drag in the vertical direction (Friedman *et al.* 2003).

Water utilities have long implemented flushing programs in one form or another, and to varying extents with the distribution systems. Generally, these programs have been established as corrective measures in response to customer complaints or to expel contaminants inadvertently introduced into the system due to backflow problems (Kirmeyer 2000) and as preventative maintenance measures to solve water quality problems by adequately removing sediments and other materials from the drinking water distribution system (Chadderton *et al.* 1992; Boomen *et al.* 2004).

There are several flushing techniques that can be applied to distribution systems. Continuous blow-off may be conducted to force a low velocity flow in a small area for utilities that have many dead ends and severe water circulation problems. Conventional flushing is usually implemented for restoring disinfectant residual and removing containments in specified areas of the system. Flushing velocities are not maximized because water to the hydrant and the blow-off valve flow from several mains. Unidirectional flushing (UDF) consists of isolating a particular pipe section appropriately through a closing valve and creating a single direction flow. The term 'unidirectional' is often associated with a velocity of 1.5 m/sec (Friedman *et al.* 2002).

Discoloured water caused by valve operation, water failure and pipe works and water with loss of residual chlorine at some dead ends has been flushed through hydrants and blow-off valves as a conventional flushing in Seoul city, Korea, though systematic flushing of water mains by methods such as UDF has not yet been conducted. In this study UDF was performed as an active measure to prevent water quality deterioration in distribution systems and as an efficient tool to provide information for management of pipe networks.

In this study UDF was conducted to improve the effectiveness of sediment removal from internal pipe walls and to provide information on pipe networks to enable operators to implement flushing in field.

METHODS

System overview

The total length of distribution mains installed in the city is approximately 8,700 km. Main pipes consist of 80% ductile cast iron (DCIP) lined with cement mortar, 12% grey cast iron (CIP), 7% steel and 1% PVC and PE. The 761 km of CIP was rehabilitated with epoxy resin in place (Ahn *et al.* 2005).

The study area is fed by the Amsa water treatment plant (WTP) and located at a distance of 5 km from the WTP. Typical raw and treated water quality of the Amsa WTP are presented in Table 1. The Amsa WTP, located in eastern Seoul, with a daily production capacity of 1.6 million m^3, supplies 1.05 million m^3 of tap water per day to its distribution system and serves water to 2.7 million people. The Amsa WTP treats source water by conventional processes including prechlorination, coagulation (poly aluminium hydroxide chloride silicate)/flocculation, sedimentation, rapid sand filtration and post chlorination. Powdered activated carbon is added to reduce the taste and odour due to algae in source water.

There are 42 households and 1 elementary school in the study area. The network consists of φ 200 mm × L 261 m, φ 150 mm × L 1,539 m, φ 100 mm × L 180 m and φ 80 mm × L 129 m. Three epoxy-lined and one cement mortar- lined ductile cast iron pipes larger than 150 mm in diameter, installed between 1982 and 1992, were selected for a practice of UDF. The description of flushed pipelines is shown in Table 2. The flushed pipes #1, 2 and 3 were laid in 1982, and then rehabilitated with epoxy resin in 1992. The lengths of the pipes are 261 m, 393 m and 484 m, respectively. The cement mortar-lined DCIP #4 was laid in 1991 and is 218 m in length. Pipe #1 was 200 mm in diameter and the remainder were 150 mm. UDF was implemented from March to July 2004 to consider the application of flushing and to establish a maintenance plan for the networks in Seoul city.

Flushing and sampling for water analysis

The angle valves of the water meters were closed to prevent intrusion of discoloured water into household-plumbing systems. Flushing using fire hydrants and blow-off valves was conducted and the objective pipe was equipped with a

Table 1 | Typical raw and treated water quality of Amsa water treatment plant (Apr. 2004) (unit: mg/L)

Parameters	Raw water quality standards	Drinking water quality standards	Water quality	
			Raw water	Finished water
pH	6.5–8.5	5.8 ~ 8.5	9.2	7.4
Total coliforms	1,000/100 mL	0/100 mL	310	0
Turbidity (NTU)	–	0.5	2.1	0.08
Total solids	–	500	–	116
NO_3-N	–	10	1.732	1.7
Zinc	–	1.0	ND	ND
Iron	–	0.3	0.13	ND
Manganese	–	0.3	0.009	ND
Copper	–	1.0	ND	ND
Aluminium	–	0.2	0.23	0.08
Hardness	–	300	65	65
Chloride	–	250	–	15
Sulfate	–	200	–	15

ND: not detected

blow-off valve whose internal diameter is 100 mm at both ends. The flushing source water was supplied from a larger pipe to a smaller one in one direction and discharged to a hydrant or blow-off valve. The additional operation was conducted to enhance removal efficiency of deposits in the pipe: turbulence was given to the water in the pipe by turning valves on/off during the flushing and the flushing procedure was repeated in the opposite direction. Flushing velocity and duration were observed to determine parameters for the implementation of flushing in field.

Pipe effluents discharged from internal pipes by UDF were taken every five minutes and characterized by physical and chemical analysis to provide information on the change in water quality during the implementation. The criterion of <1 NTU in turbidity was usually used to finish the flushing procedure in previous studies. The criterion is the absence of visible particles, generally corresponding to a turbidity of <1 NTU. According to the National Primary Drinking Water Standard of US EPA, turbidity cannot go any higher than 1 NTU (Antoun *et al.* 1997; Kuehn *et al.* 2001; Carriere *et al.* 2005; US EPA 2009). Water samples were tested for turbidity, residual chlorine, conductivity, temperature, pH and water pressure in the field. Residual chlorine was measured using a portable colorimeter (Pocket Colorimeter, Hach). Conductivity was measured using a conductivity cell (SENSION 5, Hach). Water temperature and pH of the effluent were measured using a pH meter (704, Metrohm) with a combined electrode.

Water pressure gauges (Primelog 2i, Primayer) and data loggers were used for recording water pressure. Flow rates were estimated using a Pitot tube attached to a diffuser

Table 2 | Description of pipelines selected for unidirectional flushing

Pipe #	Pipe and inner lining materials	Diameter (mm)	Length (m)	Year		Remarks
				Installation	Rehabilitation	
1	Epoxy-lined DCIP	200	261	1982	1992	Rehabilitated
2	Epoxy-lined DCIP	150	393	1982	1992	Rehabilitated
3	Epoxy-lined DCIP	150	484	1982	1992	Rehabilitated
4	Cement-lined DCIP	150	218	1991	–	–

installed in a hydrant during the hydrant flushing procedure. Water pressure was measured at two points of the pipe before and during the flushing. Water pressure data were inputted to network software (WaterGEM, Haestad Method) to estimate the velocities and volumes during flushing. The software was used for performance of hydraulic network modelling.

Water quality parameters, Fe, Cu, Mn, Pb, Zn, Al, sulfate (SO_4^{2-}), chloride (Cl^-), total suspended solids (TSS), heterotrophic plate count (HPC) and particle count were measured in a laboratory. Metals and inorganic ions were measured to understand the characterization of the flushed water quality and to identify whether the concentrations would exceed the water quality standards or not, for evaluation of the suitability of the criterion of <1 NTU to finish flushing as mentioned above. Metals were acidified, microwave-digested and analysed by an inductively coupled plasma-atomic emission spectrophotometer (Ultra, Jovin Yvon). An ion chromatograph (Dionex 500, Dionex) equipped with a conductivity detector was used to analyse sulfate and chloride ion. Total suspended solids are the portion of total solids retained by a filter. A well-mixed sample is filtered through a weighed standard glass-fibre filter and the residue retained on the filter is dried to a constant weight at 103 to 105°C. The increase in weight of the filter represents the total suspended solids. If the suspended material clogs the filter and prolongs filtration, the difference between the total solids and the total dissolved solids may provide an estimate of the total suspended solids (APHA, AWWA, WEF 1998). HPC was experimented using R2A agar plate count and incubated at room temperature 21 ± 1.0°C for 72 ± 3 hr. The particle counter used was PC2400PS (Chemtrac System, Inc.).

RESULTS AND DISCUSSION

Flushing velocities are estimated by a Pitot pressure gauge when flushed water is discharged to a hydrant. But if a blow-off valve is used for discharge in flushing, it is difficult to identify flushing velocities and volumes. Water pressure before and during flushing was measured at two positions of the pipe. The results of hydraulic network modelling are presented in Table 3. The normal flow velocities of the networks were found to be 0.12 m/sec or below in the study area. Particle deposition is possible in mains with routine flow velocities in the range of 0–0.6 m/sec, regardless of the pipe condition, according to the computational fluid dynamics (CFD) modelling (Friedman *et al.* 2003). Therefore, it was expected that loose deposits were accumulated on the inner pipe wall in the study area. Flushing velocities ranged from 1.07 to 2.78 m/sec when a blow-off valve was used for discharge. The flow velocity of flushing by a hydrant was 1.79 m/sec in pipe #2 (Table 3).

Flushing in pipe #1

When the UDF procedure (B→A direction) was attempted, water did not run into the pipe because of the difference in the altitude of positions A and B in pipe #1. The altitudes of position A and B are 32.7 m and 27.7 m above sea level. When the flushing was implemented in the opposite direction, flow velocity in the pipe was 2 m/sec (Table 3). Flushing velocity might be affected by the difference in the altitude between the two ends of the objective pipe in the grid system.

As the temperature of the sampled water was 10.0°C, pH was in the range of 7.2 to 7.6 and conductivity was in the range of 160 to 174 μS/cm, the water quality did not present much variation during flushing. Turbidity increased to 65 NTU rapidly in the first 5 minutes of flushing, and then in the 5 minute consecutive intervals decreased to 25 NTU and 14 NTU. Finally turbidity was 1.1 NTU after 30 minutes of flushing (Figure 1).

Total suspended solids are considered as the loose deposits discharged from the internal pipe wall by the flushing operation since TSS were not retained in tap water in this study area. TSS reached to 80.8 mg/L when turbidity was 65 NTU, and reduced to 30.4 mg/L and 12.0 mg/L, respectively, in consecutive 5 minute intervals. Cumulative TSS discharged from the blow-off valve in pipe #1 was 2.89 kg for 55 minutes of flushing.

Water samples collected during the flushing in pipe #1 were analysed to characterize the effluent water. Cl^-, SO_4^{2-}, Pb, Cu and Zn concentrations in flushed water met water quality regulations during the flushing, but Fe, Mn and Al did not. Cl^- and SO_4^{2-} showed the range of 15 to 18 and 13 to 14 mg/L, respectively, with no variation. The level of Pb was not detected, and Cu and Zn were in the range of 0.011 to 0.399 mg/L and 0.003 to 0.092 mg/L, respectively, with far below maximum admissible concentration. The highest levels

Table 3 | Flushing parameters estimation by pipe network analysis

			Recorded pressure (kg/cm^2)		Calibrated pressure (kg/cm^2)				
Pipe #	**Flushing direction**	**Pressure gauge**	**Before flushing**	**During flushing**	**Before flushing**	**During flushing**	**Flushing velocity (m/sec)**	**Flow-rate during flushing (m^3/hr)**	**Flushing facilities**
1	A→B	Gauge 1	2.4	1.3	2.5	1.3	2.02	229	Blow-off valve
		Gauge 2	2.5	1.2	2.6	1.2			
2	A→B	Gauge 1	2.9	2.4	2.9	2.4	1.79	114	Hydrant
		Gauge 2	3.8	2.3	3.4	2.3			
	A→B	Gauge 1	2.9	1.5	2.9	1.5	2.78	177	Blow-off valve
		Gauge 2	3.8	0.7	3.4	0.7			
	B→A	Gauge 2	3.8	2.5	3.4	2.5	1.93	123	
3	A→B	Gauge 1	3.4	0.7	3.2	0.7	1.07	68	Blow-off valve
		Gauge 2	3.4	0.9	3.2	0.8			
	B→A	Gauge 1	3.4	2.8	3.2	2.8	1.19	76	
4	A→B	Gauge 1	2.9	1.8	3.1	1.9	1.04	62	Blow-off valve
		Gauge 2	3.0	2.6	3.2	2.6			
	B→A	Gauge 1	2.9	2.3	3.1	2.6	2.14	136	
		Gauge 2	3.0	2.0	3.2	2.1			

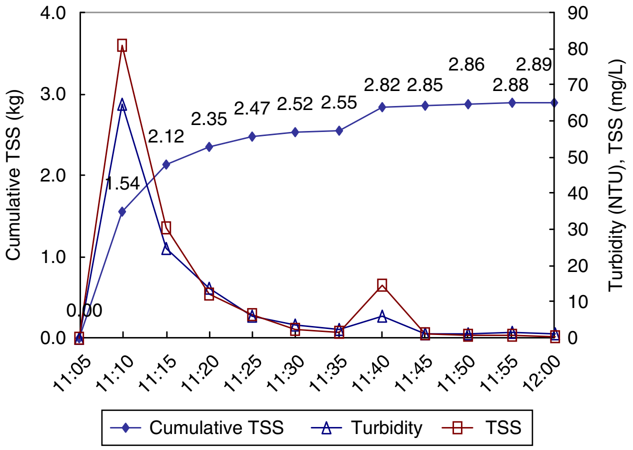

Figure 1 | Variations of turbidity and TSS in pipe #1.

of Fe, Mn and Al were 5.8 mg/L, 5.8 mg/L and 28.1 mg/L, respectively (Figure 2). However, after 40 minutes of flushing the levels of Fe, Mn and Al met the water quality standards of <0.3 mg/L, <0.3 mg/L and 0.2 mg/L, respectively. Fe and Mn could be accumulated by imperfect treatment or corrosion within pipes. It is considered that the aluminium from the coagulation process at a water treatment plant would contribute to the increase in aluminium concentration on a pipe wall in the distribution system (CNRC 2003).

Flushing in pipe #2

At first UDF was conducted in the direction of A to B (A→B direction), and then in the opposite direction (B→A direction) in pipe #2. The inlet valves were operated to the on and off position to enhance removal efficiency of deposits from the inner pipe during flushing.

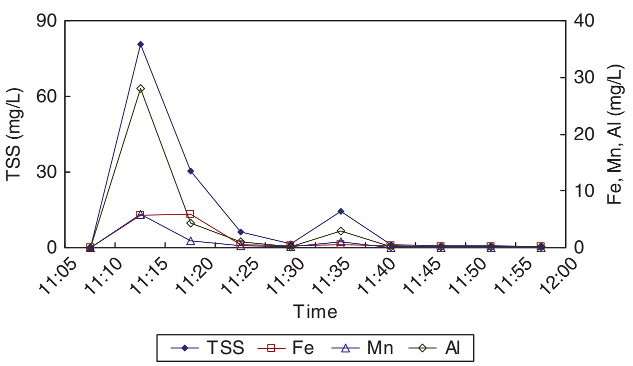

Figure 2 | Analytical results of water samples collected during flushing in pipe #1 (TSS, Fe, Mn, Al).

Flushed water was discharged for 15 minutes to a hydrant near position B, and to a blow-off valve 100 mm in diameter, attached to position B (A→B direction), and then after a lapse of 1 hour to a blow-off valve at position A (B→A direction). Stagnated water in the hydrant was released before sampling flushed water at the hydrant.

Flushing velocity, measured using a Pitot tube, to the hydrant was 1.79 m/sec. The velocity of 2.78 m/sec during discharge to a blow-off valve at position B was higher than that of 1.93 m/sec at position A (Table 3). This could be attributed to the difference in the altitude of the two positions; the altitudes of positions A and B are 27.7 m and 21.6 m, respectively, above sea level. Cumulative TSS discharged to a blow-off valve in pipe #2 were 0.57 kg for 66 minutes of the flushing. The highest levels of turbidity and TSS for the hydrant effluent were 22 NTU and 48.4 mg/L, respectively (Figure 3). Turbidity of the flushed water by blow-off valve at the flushing of B→A direction was 8.3 NTU and was decreased 62% with respect to that of the hydrant effluent in the opposite direction. When the inlet valve of position A at the flushing of A→B direction was operated to on and then off, the turbidity change of the effluent was 0.9 to 1.4 NTU with little variation. Turbidity rose to 3.1 NTU during the flushing in the opposite direction (B→A direction).

pH, temperature and conductivity of the effluent water were 7.5, 15.0°C and 175 μS/cm, respectively, and the water quality showed little variation during flushing. Cl^-, SO_4^{2-}, Pb, Cu and Zn concentrations in flushed water met water quality regulations during the flushing, but Fe, Mn and Al did not. The highest level of metals was found in aesthetic parameters, Fe 8.3 mg/L, Mn 0.4 mg/L and Al 1.3 mg/L in

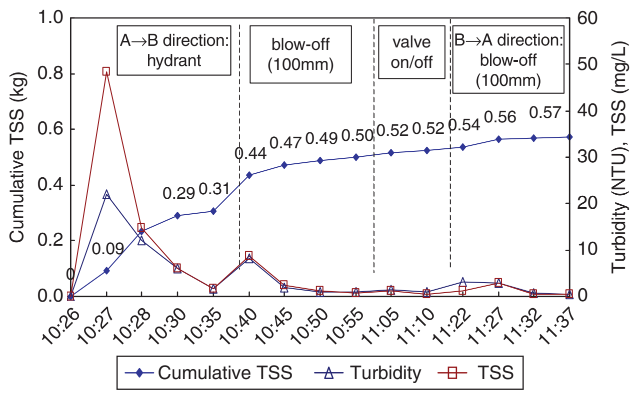

Figure 3 | Variations of turbidity and TSS in pipe #2.

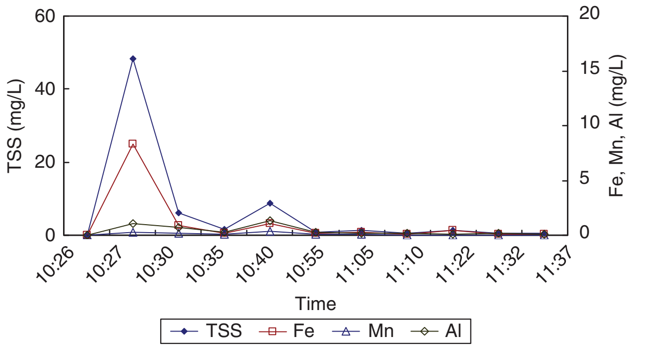

Figure 4 | Analytical results of water samples collected during flushing in pipe #2 (TSS, Fe, Mn, Al).

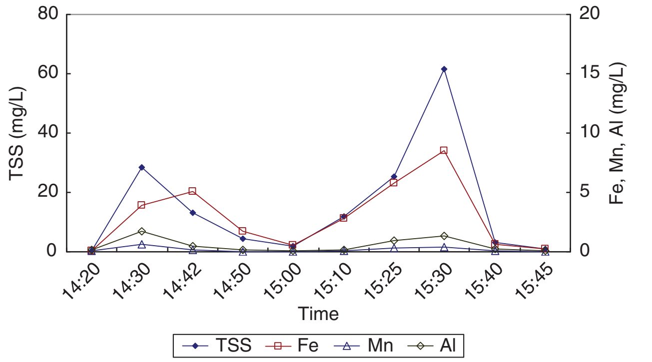

Figure 6 | Analytical results of water samples collected during flushing in pipe #3 (TSS, Fe, Mn, Al).

flushed water (Figure 4). Fe that gave rise to the red colour in the water was higher than any other constituents, though Al was the highest value in pipe #1.

Flushing in pipe #3

UDF was implemented in the same direction as in pipe #2, the difference being that a hydrant was used. During the overall procedure turbidity ranged between 0.1 and 51 NTU, TSS 0.4 and 61.6 mg/L (Figure 5) and residual chlorine 0.05 and 0.73 mg/L. Turbidity in discharged water presented 18 NTU for the A→B direction, reduced to 11 NTU and rose to 24 NTU when the inlet valve of flushing water at A was turned off and immediately on. Flushing in the opposite direction (B→A direction) gave rise to high numbers of loose deposits; 51 NTU of turbidity and 61.6 mg/L of TSS. Cumulative TSS discharged to a blow-off valve in pipe #3 were estimated at 2.81 kg for 90 minutes of the flushing. Higher turbidity and TSS in this direction could be attributed to the large difference in the altitudes of the two positions; the altitudes of positions A and B at pipe #3 are 21.6 m and 32.7 m, respectively, above sea level.

pH, temperature and conductivity of the effluent water were 7.5, 19.0°C and 161 μS/cm, respectively, and the water quality showed little variation during flushing. Both Cl^- and SO_4^{2-} concentrations in flushed water were about 13 mg/L with no variation. The highest levels of metals were found in aesthetic parameters, Fe 8.5 mg/L, Mn 0.6 mg/L and Al 1.7 mg/L, in flushed water in pipe #3 (Figure 6).

Flushing in pipe #4

UDF was implemented according to the same procedure conducted in pipe #3. Turbidity ranged from 0.1 to 142 NTU and TSS from 0 to 59.2 mg/L during the entire process of flushing (Figure 7). Turbidity in discharged water reached 12 NTU and reduced during A→B direction and rose to 9.8 NTU during valve operation, and reached its peak of 142 NTU during B→A direction. Cumulative TSS discharged to a blow-off valve in pipe #4 was estimated at 0.93 kg for

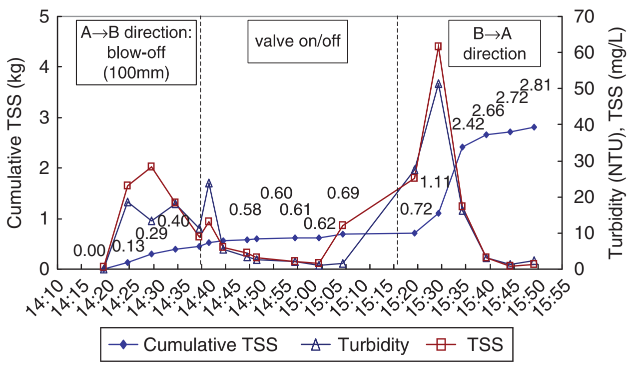

Figure 5 | Variations of turbidity and TSS in pipe #3.

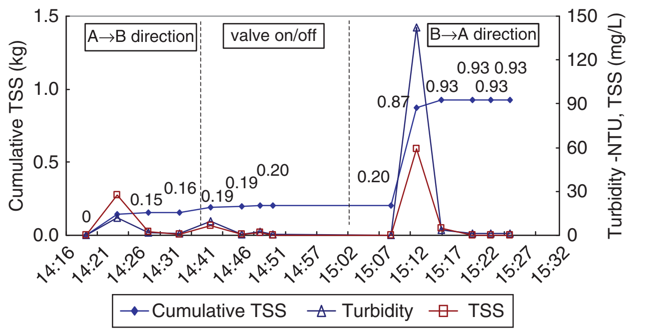

Figure 7 | Variations of turbidity and TSS in pipe #4.

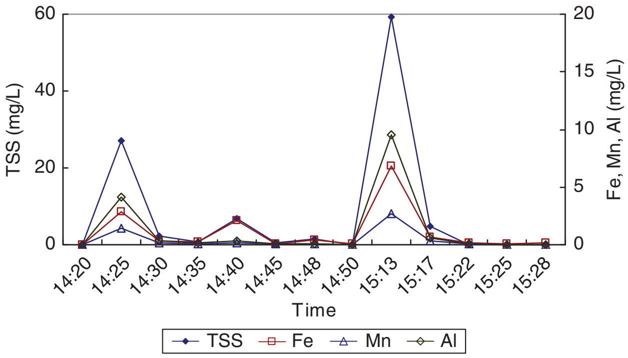

Figure 8 | Analytical results of water samples collected during flushing in pipe #4 (TSS, Fe, Mn, Al).

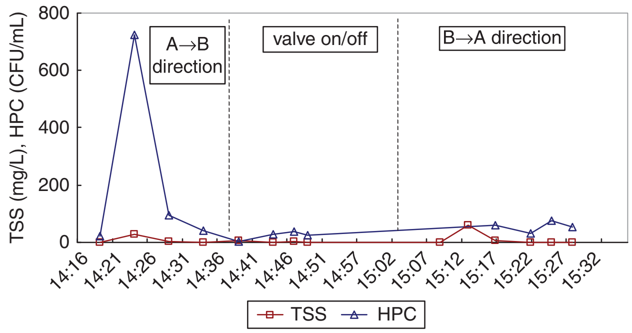

Figure 9 | Variations of HPC and TSS in pipe #4.

70 minutes of the flushing. Flow velocity of flushing in the A→B direction was 1.04 m/s, and in the B→A direction 2.14 m/s (Table 3). 0.2 kg of the cumulative TSS was allocated to the process in the A→B direction and 0.73 kg in the B→A direction. The higher the flushing velocities are, the greater the effectiveness of flushing is, and the less flushing time is needed, since a higher velocity discharges more deposits out of pipes.

Average residual chlorine was 0.74 mg/L and decreased to 0.53 mg/L during flushing of the B→A direction. pH, temperature and conductivity of the effluent water were 7.4, 18.0°C and 132 μS/cm, respectively, and the water quality showed little variation during flushing in pipe #4. Cl^- and SO_4^{2-} content in flushed water were about 17 mg/L and 9 mg/L, respectively, with no variation. The highest levels of metals were found in aesthetic parameters, Fe 6.8 mg/L, Mn 2.7 mg/L and Al 9.6 mg/L, in flushed water (Figure 8). Fe, Mn and Al concentrations showed a tendency to follow the rise or fall of TSS during flushing.

Heterotrophic plate count (HPC) bacteria removal

Bacterial species involved with biofilm formation are important to the water industry for quality concerns. Biofilms will grow on cast or ductile iron, cement or polyvinyl chloride and may include chlorine-sensitive bacteria because the diffusion of chlorine to the walls of the pipes is impeded by the film (Reilly & Kippin 1983; Chadderton *et al.* 1992).

Water samples were taken before and during the flushing of pipes #3 and #4, cultured at 21 ± 1.0°C for HPC bacteria tests to estimate biofilm removal by UDF.

Four samples of the total 18 samples in pipe #3 with epoxy-lining were tested to identify HPC levels. There was 0 CFU/mL in the sample before flushing. During flushing, HPC levels were 1 CFU/mL in 6.0 mg/L of TSS, 0 CFU/mL in 0.0 mg/L and 33 CFU/mL in 12.0 mg/L.

On the other hand, in pipe #4 with cemented-lining, HPC was 22 CFU/mL in the sample before flushing. HPC levels were in the range of 4 to 725 CFU/mL during flushing although HPC bacterial counts were 22 CFU/ml in tap water before flushing. When TSS was 27.2 mg/L, HPC bacteria were 725 CFU/mL in the highest value (Figure 9 and Figure 10). It showed that the cement-lined pipe might have more biofilm than the epoxy-lined pipe on the surface of the inner pipe. This could be because the internal pipe roughness of cement-lined pipes is generally higher than that of epoxy-lined pipes.

The removal of HPC bacteria from pipe #4 was correlated with TSS (1). The coefficients of determination (R^2)

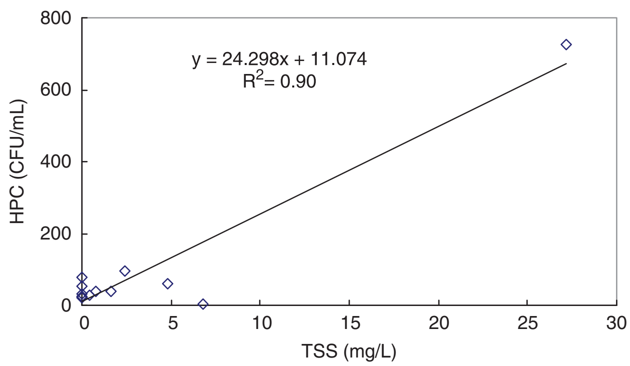

Figure 10 | Relationship between HPC and TSS in pipe #4.

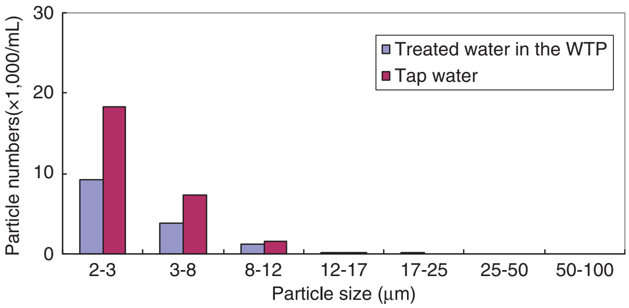

Figure 11 | Particle distributions of the treated water in the WTP and the tap water.

were 0.90 with TSS and 0.50 with turbidity. It was concluded that the biofilm was closely related to TSS consisting of loose deposits. It was also indicated that a part of the biofilm could be removed with the sediments in the pipe by UDF.

$$Y_{HPC} = 24.298 \times X_{TSS} + 11.074 (R^2 = 0.90) \quad (1)$$

Particle distributions in flushed water

Figure 11 shows a particle size distribution in the treated and tap water sampled in the study area before flushing. The number of particles that were 2–3 μm in size was 9 counts/mL in the treated water. The number of particles of 3–8 μm was 4 counts/mL, 8–12 μm 1 count/mL. In the tap water, the number of particles that were 2–3 μm size was also 18 counts/mL, 3–8 μm was 7 counts/mL, 8–12 μm 2 counts/mL. There was a similar pattern in the distribution of particle size, but the number of particles in the tap water increased to more than twice as many as those in the treated water. Figure 12 shows a particle distribution of the flushed water from pipe #2.

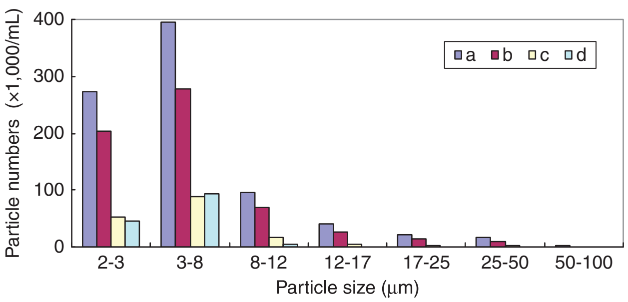

Figure 12 | Particle distributions of the flushed water. a: the first sample of the flushed water, 22 NTU, b: the second after 1 minute of flushing, 12 NTU, c: the third after 3 minutes of flushing, 6 NTU, d: the fourth after 8 minutes of flushing, 2 NTU.

When the turbidity of the flushed water was 22 NTU, the number of particles was 8.5×10^5 counts/mL at its highest. The number of particles whose sizes were 2–3 μm and 3–8 μm occupied 80% of the total numbers. 2–3 μm particles were dominant in the treated and the tap water sampled in the study area whereas 3–8 μm particles were dominant in flushed water.

UDF mainly removes loose deposits attached on the surface of internal pipes. The fact that the particles of 3–8 μm in size occupy a large portion of the particle distribution means that they are dominant in the loose deposits whereas the particles of 2–3 μm are dominant in tap water.

Information on implementation of flushing

An examination was performed to find out whether metals in flushed water samples would exceed the water quality regulations or not, when turbidity in flushed water was <1.0 NTU. The turbidity was compared with the metal that exceeded the water quality regulations in Figure 13. Figure 13 shows the levels of Fe, Mn and Al with <10 NTU of turbidity in flushed water.

Both the levels of Fe and Mn corresponding to <0.5 NTU and <1.0 NTU met the water quality regulations of 0.3 mg/L or less. The level of Al with <0.5 NTU also met the water quality regulation of 0.2 mg/L, but one of nine samples with <1.0 NTU exceeded the regulation. It is estimated from these results that the levels of metals will meet the water quality regulations if flushing is finished in <1.0 NTU in turbidity.

The relationship between turbidity and TSS was observed for the estimation of the amount of the removed deposits from the flushing process by measuring the turbidity of flushed water in the field (Figure 14). The coefficient of determination (R^2) between turbidity and TSS is 0.66 (2). R^2 rose to 0.90 except for when dealing with the value (λ) of 142 NTU in pipe #4 as an outlier (3). Sediment removal could be estimated from the turbidity data of flushed water in the field if (3) were used.

$$Y_{TSS} = 0.6405 \times X_{turbidity} + 3.6166 (R^2 = 0.66) \quad (2)$$

$$Y_{TSS} = 1.226 \times X_{turbidity} - 0.1707 (R^2 = 0.90) \quad (3)$$

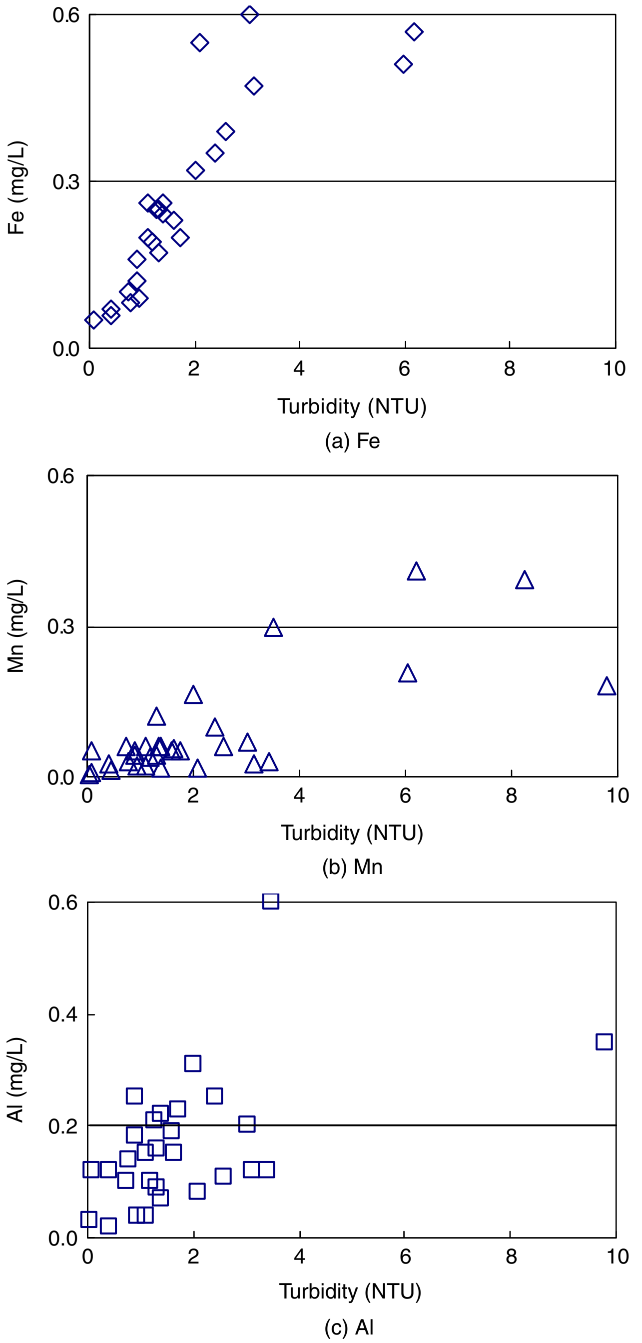

Figure 13 | Relationship between turbidity and metals (Fe, Mn and Al) in the flushed water.

Table 4 shows the dimension of the pipes, the volume of the flushed water to pipe volume, the flushing duration and flushing facilities used. The volume ratio of the flushed water to the pipe was 25.6 for 55 minutes of flushing in pipe #1. The volume ratio ranged from 3.9 to 14.8 in pipes #2, 3 and 4. The

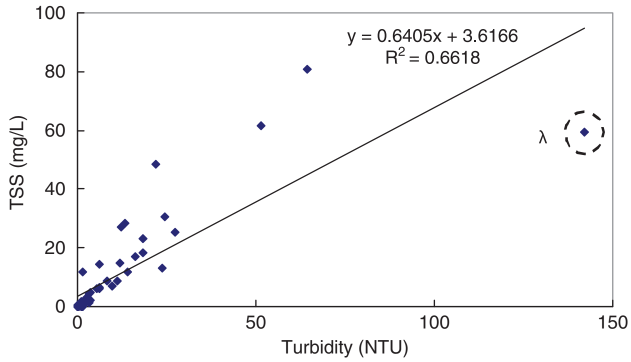

Figure 14 | Relationship between turbidity and TSS.

flushing duration until water meets the target turbidity of 1 NTU was about 1 hour.

The practice of a periodic UDF is expected to reduce customer complaints on water quality deterioration, and to contribute to the enhancement of the safety and stability of the water supply and to the effectiveness of network management by setting the preventive maintenance plan in the distribution systems.

CONCLUSIONS

In this study UDF was modified to improve the effectiveness of sediment removal from internal pipe walls and the information on pipe networks was provided for the operators to implement flushing in the field.

Four ductile cast iron pipes with epoxy-lining and cement-lining were selected for a practice of the UDF. The additional valve operation was conducted to modify the procedure of UDF: turbulence was given to the water in the pipe by turning valves on/off during the flushing; and the flushing procedure was repeated in the opposite direction.

The normal flow velocities of the networks were found to be 0.12 m/sec or below in the study area. Flushing velocities ranged from 1.07 to 2.78 m/sec using a blow-off valve for discharge of effluent while the velocity in pipe #2 using a hydrant was 1.79 m/sec. According to Table 4, the flushing duration until water meets the target turbidity is from 55 to 86 minutes. It seems to depend on the flushing velocity and the conditions of inner pipes.

Water samples collected during flushing were analysed to characterize the flushed water. Cl^-, SO_4^{2-}, Pb, Cu and Zn in

Table 4 | Flushed water volume and flushing duration

Pipe #	Flushing direction	Pipe diameter (mm)	Length (m)	Pipe volume (m^3)	Flushed water volume (m^3)	Flushed water to pipe volume (times)	Flushing duration (min)	Flushing facilities
1	A→B	200	261	8.2	210	25.6	55	Blow-off valve
2	A→B	150	393	6.9	30	4.3	16	Hydrant
	A→B			6.9	89	12.8	30	blow-off valve
	B→A			6.9	41	5.9	20	
3	A→B	150	484	8.6	68	8.0	60	Blow-off valve
	B→A			8.6	33	3.9	26	
4	A→B	150	218	3.9	41	10.6	40	Blow-off valve
	B→A			3.9	57	14.8	25	

flushed water met the Korean drinking water quality regulations except for some aesthetic parameters such as Fe, Mn and Al. Cumulative TSS discharged from pipes #1, 2, 3 and 4 were 2.89 kg, 0.57 kg, 2.81 kg and 0.93 kg, respectively. This indicated that a part of the biofilm could be removed with the sediments in the pipe by UDF since the removal of HPC bacteria was correlated with TSS ($R^2 = 0.90$).

The coefficient of determination (R^2) between turbidity and TSS is 0.90 except for one outlier. Sediment removal could be estimated from the turbidity data of flushed water in the field using the equation of the relationship between turbidity and TSS.

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First received 23 February 2009; accepted in revised form 25 August 2010