Comparative analysis of air scouring and unidirectional flushing of water distribution systems

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ABSTRACT

Unidirectional flushing is a widely used method to remove sedimented particles from water distribution systems and prevent water discolouration events. However, it shows low efficiency in cases of high pressure losses, usually requires large volumes of water, and does not remove incrustations. Air scouring is known for being very effective in particle removal with minimal impacts from pressure loss, requiring little water and improving hydraulic capacities by removing soft incrustations. Flushing sequences of unidirectional flushing and air scouring were performed in similar conditions on 18 pipe sections from four water distribution networks located in the province of Quebec, Canada; unidirectional flushing was also performed on 14 additional pipe sections located in three other water distribution networks. Total suspended solid concentration, water flow and pressure of flushed water were recorded to estimate the amount of flushed particles, the required water volume and the evolution of hydraulic capacities. Within the studied networks, the water requirements for air scouring were approximately 8-fold less than for unidirectional flushing and did not significantly improve the hydraulic capacity of the cleaned pipes.

Key words | hydraulic capacity, particles removal, pipe roughness, total suspended solids, turbidity, water consumption

HIGHLIGHTS

- Unidirectional flushing and air scouring sequences were performed on 32 pipe sections (diameters 100–150 mm) from four water distribution networks in Canada.
- For air scouring sequences, water and air velocities were selected to obtain slug flow conditions.
- Air scouring required about 8-fold less water than unidirectional flushing to flush the same amount of particles.
- Air scouring removed larger particles than unidirectional flushing, some of them being pieces of tubercles.
- Air scouring did not reduce the roughness coefficient of the pipes.

INTRODUCTION

Despite its previous treatment and filtration, potable water in water distribution systems (WDSs) accumulates particles due to various mechanisms, such as corrosion of iron-based pipes and equipment, precipitation of dissolved compounds or introduction of exogenous material (Gauthier 1998; Vreeburg & Boxall 2007). Sedimented particles offer a protection against disinfectants, which favour bacterial proliferation and thus may aggravate corrosion, generate taste and flavour or allow the development of pathogenic species. Particles also accumulate toxic compounds such as heavy metals and organic contaminants (De Rosa 1993; Gauthier 1998). Changes in water flow may resuspend sedimented

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particles and generate water discolouration events, which are the main cause of customer complaints, and could also expose customers to released contaminants (Hasit 2004). Additionally, WDSs commonly develop incrustations which are a problematic source of energy loss. As an example, iron tubercles are prevalent in the province of Quebec (Canada) where water pipes are commonly composed of cast iron (36% grey cat iron and 32% ductile iron; CERIU 2017). Tubercles can grow to several centimetres in thickness and thus induce very significant pressure losses, generating complaints from customers and firefighters due to low water pressure (Ellison 2003; Sarin *et al.* 2004).

Several cleaning methods have been developed to fight particle accumulation and incrustation growth, such as unidirectional flushing (UDF), air scouring (AS), swabbing, pigging or chemical methods. The most appropriate cleaning method to apply is generally selected based on the objective of the cleaning, e.g. preventing discolouration events, removing tubercles before rehabilitation or dislocating the biofilm. UDF and AS, which restore clean water (Ellison 2003; Vitanage *et al.* 2004) and thus prevent discolouration events, are less invasive methods than swabbing, pigging and chemical methods. They are similar in their set-up, where a hydrant (this could be several for UDF) is opened to accelerate the water within the pipe section desired for cleaning. Over time, incrustations and sedimented particles are flushed away due to the increased shear stress resulting from these higher water velocities. For sections in looped areas of WDSs, some valves are closed to direct water to an opened hydrant from a single direction. For AS sequences, water flow is reduced by partially closing an upstream valve, then compressed and filtered air is injected through an upstream hydrant. Also, a downstream valve is closed to prevent further the penetration of air within the WDS. With correct air and water flows, these fluids will automatically generate a diphasic flow known as slug flow (Elvidge 1982; Kitney *et al.* 2001; Ellison 2003; Vitanage *et al.* 2004). In this type of flow, alternating pockets of gas and liquid slugs propagate at high speed through the pipeline, as can be seen in Supplementary Video S1 and Supplementary Figure S1.

UDF is the main method used in Canada for water pipe cleaning due its low cost/efficiency ratio. Its main limitations are related to the water velocity that can be attained, which is constrained by head losses along the pipe section to be flushed, and to the amount of water required. Many studies suggest that these limitations can be overcome by AS, where the presence of air considerably lowers the mixed fluid (air + water) viscosity within the pipe, decreasing head losses while increasing velocity. During AS sequences, the water slugs can move much faster than water alone during UDF sequences. A higher velocity means a higher shear stress and thus better particle and incrustation removal (Ellison 2003; Le Hir 2008). Indeed, water velocities varying from 0.7 to 3 m/s are reported in the literature for UDF (Ellison 2003; Carrière *et al.* 2005; Ahn *et al.* 2011; Besner *et al.* 2012; Lewis 2015), whereas slug velocities above 6 m/s were reported for AS (Grob 2004). Moreover, Kitney *et al.* (2001) and Vitanage *et al.* (2004) observed that AS requires usually about 40% less water than UDF. Concerning the removal of sedimented particles and incrustations, it was quantified to be 3-fold higher for AS than for water flushing by Kitney *et al.* (2001). Elvidge (1982) identified iron and manganese removal to be 100- and 1,000-fold higher, respectively, for AS than for water flushing. Finally, as it is not known if UDF provides any significant positive impacts on hydraulic performance of WDSs (Ellison 2003), both Ellison (2003) and Grob (2004) observed improvements in the Hazen–Williams friction factor of pipes cleaned with AS. Conversely, according to Shore & Lythell (1992), AS would not be able to remove a significant amount of tubercles or incrustation.

Stated briefly, many studies suggest that AS is superior to UDF in terms of water consumption, particle elimination and improvement of hydraulic conditions (due to incrustation removal), although no consensus has been reached regarding the later. Additionally, the scientific literature supporting these assumptions is scarce, as most of the publications about AS are technical reports produced either by the managers of the WDSs where the method has been used (Shore & Lythell 1992; Ellison 2003), or by companies offering the AS services (Kitney *et al.* 2001; Grob 2004; Exotec 2008). To the authors' knowledge, no publication relates recent results about the performance of AS as evaluated by a reproducible protocol.

To this end, the main objective of this paper is to quantify the performance of AS when compared with UDF in terms of the required volume of water and amount of flushed particles, from tests performed on WDSs located in the province of Quebec, Canada. The possibility to improve the hydraulic performance of WDSs pipes with AS is also evaluated.

MATERIALS AND METHODS

UDF and AS flushing tests were conducted on 32 sections of WDSs located in seven different cities within the province of Quebec, Canada. For 18 of the 32 test sections, the flushing test begun with an UDF sequence, immediately followed by an AS sequence, in order to measure the differences in the amount of flushed particles, hydraulic performance and volume of water required. The other 14 tests consisted of an UDF sequence alone. The characteristics of the tested WDSs sections are summarized in Table 1. More detailed information is given in Supplementary Tables S1 and S2.

Table 2 summarizes the main steps of the tests. UDF was performed following the procedures described, among others, by Friedman *et al.* (2002) and Kammareck & Reisinger (2016). Stated briefly, first, some upstream fire hydrants were successively opened to ensure a clear water front (<5 NTU) in the studied pipe. Second, the downstream fire hydrant of the studied piped was fully open until the turbidity of the flushed water became below 5 NTU. AS sequences were performed following the procedures described by Elvidge (1982), Stephenson (1989), Ellison (2003), and Scottish Water (2013). To summarize, first, water flow was reduced by partially closing the upstream valve of the studied pipe, and, second, air was injected in the pipe from the compressor at a constant flow until turbidity of flushed water got stable over 15 min. Some adaptations were made to the standard UDF and AS procedures to allow for recording of flow and pressure, and to sample water in good conditions. Figure 1 illustrates the global configuration of UDF and AS tests, while Figure 2 shows how the measuring equipment was installed during those tests, and Figure 3

Table 1 | Summary of flushing tests

City	Pipe material	Number of sequences	Length of flushed sections (m)	Diameter of flushed sections (mm)	Water velocity UDF[c] (m/s)	Air pressure AS[c,d] (kPa)	Superficial water velocity AS[c] (m/s)	Superficial air velocity AS[c] (m/s)	Mean slugs velocity AS[c] (m/s)
UDF alone									
Québec	Cast iron	4	230–830	150	1.4 ± 0.5	–	–	–	–
Sainte-Thérèse	Cast iron	4	180–516	150	1.8 ± 0.4	–	–	–	–
L'Assomption	Cast iron	6	365–750	150	2.0 ± 0.2	–	–	–	–
UDF + AS									
Saint-Charles-Borromée	Cast iron	2	122 and 291	150	1.3 ± 0.1	172 ± 10	0.4 ± 0.1	2.1 ± 0.2	3.2 ± 0.1
Saint-Édouard-de-Maskinongé	Cast iron	3[a]	305–350	100 and 150	1.1 ± 0.1	172 ± 30	0.4 ± 0.1	4.3 ± 3.4	5.8 ± 4.0
	PVC	2[a]	250 and 415	100 and 150	1.2 ± 0.2	94 ± 21	0.5 ± 0.0	3.2 ± 0.7	4.5 ± 0.9
Rivière-du-Loup	Cast iron	3	195–225	150	1.7 ± 0.6	188 ± 36	0.4 ± 0.0	2.3 ± 0.8	3.6 ± 0.9
	PVC	1	350	150	2.3	141	0.4	1.6	2.8
Salaberry-de-Valleyfield	Cast iron	4	618–690	150	1.1 ± 0.1	210 ± 20	0.5 ± 0.0	1.4 ± 0.1	2.6 ± 0.2
Salaberry-de-Valleyfield bis	Cast iron	3[b]	618–681	150	1.2 ± 0.1	223 ± 6	0.6 ± 0.1	3.1 ± 0.1	4.5 ± 0.2

[a] One sequence for each material was performed on a section with a diameter of 100 mm.

[b] A second series of tests was performed on the same sections (except for one section, for which work was underway) 1 month later with increased AS velocities.

[c] Mean ± standard deviation.

[d] Measured in the hydrant, after having left the compressor.

Table 2 | Summary of sequences main steps

Step	Measured parameters	Water samples	Stopping criteria
1. UDF sequence, following a standard procedure (e.g., Friedman *et al.* (2002); Kammareck and Reisinger (2016))	• Water flow • Upstream and downstream pressure	• One sample every 2 min for 10 samples • One sample every 5 min until the end of the sequence	UDF sequences stop when turbidity, measured every 2 min, gets below 5 NTU[a]
Next steps concern only tests with UDF followed by AS			
2. Water flow is reduced by partially closing the upstream valve[b]	• Water flow (considered stable after air injection as observed on a bench test)	• None	
3. Air injection (AS sequence)[b]	• Air flow • Upstream and downstream pressure	• One sample every 2 min for 15 samples • One sample every 5 min for five samples • One sample every 15 min for three samples • One sample every 30 min until the end of the sequence (may vary due to the irregularity of slug flow)	AS sequences stop when turbidity readings get stable over 15 min
4. Air flow is stopped	• None	• None	Air flow is stopped until water fills the pipes entirely
5. Upstream valve is fully opened and another UDF sequence is performed	• Water flow • Upstream and downstream pressure	• One sample every 2 min for 10 samples • One sample every 5 min until the end of the sequence	UDF sequences stop when turbidity, measured every 2 min, gets below 5 NTU[a]

[a] 5 NTU is the maximal turbidity allowed to deliver drinking water in Quebec province (Légis Québec 2019).

[b] Water and air flows were controlled and varied from one test to the other.

provides some pictures of this equipment. For AS, velocities of water and air were selected in order to get slug flows in the pipes with constant air flow from the compressor (for reference about these velocities, see the flow map developed by Mandhane *et al.* (1974), shown in Supplementary Figure S2). In all cases, air pressure remained much lower than water pressure in the pipes.

During each flushing sequence, pressure, water flow and air flow (for AS) were measured continuously, while flushed water samples were collected at the jet regulator at various time (cf. Table 2). Water flow was measured using a Proline Promag 50 W flowmeter (error ±0.5%; precision ±0.05 l/s) installed on the downstream hydrant. The jet regulator helped with stabilizing the flowmeter. Pressure was measured on both upstream and downstream hydrants by Basco 0–100 psi glycerine manometers (error ±2%; precision ±5 psi). During AS sequences, air flow was measured just before its injection in the upstream hydrant by a Cole-Parmer Valved Acrylic Flowmeter 400–3400 LPM (error ±2%; precision 100 l/min). To convert the results to standard conditions, air pressure was measured with a Pitanco glycerin manometer 0–160 psi (error ±2%; precision ±2 psi). Turbidity of water samples was measured on-site with a

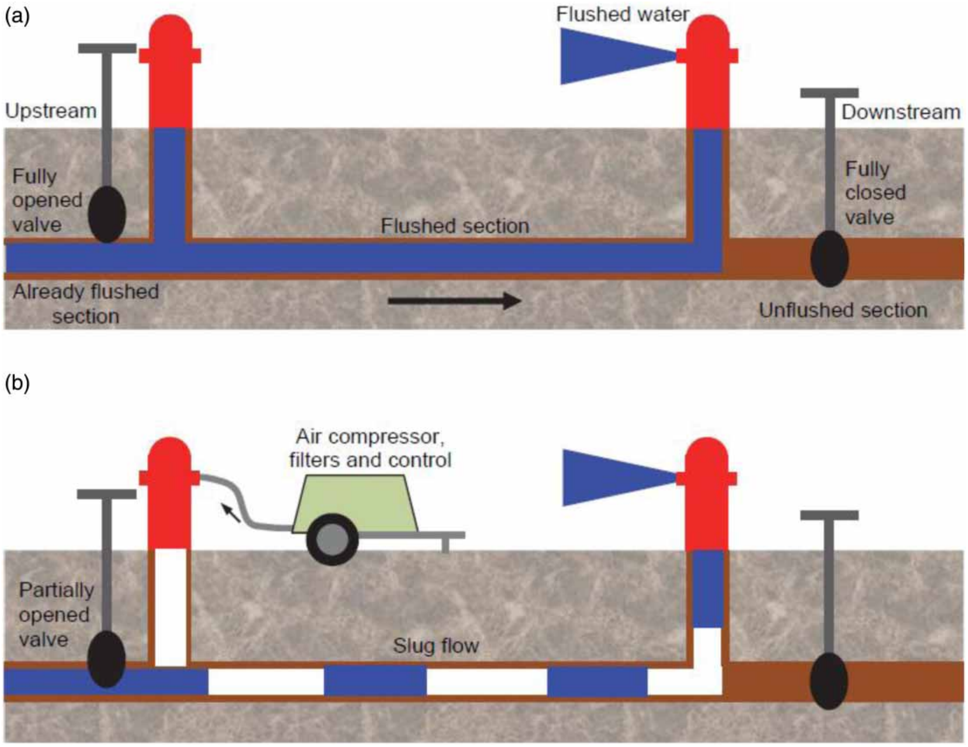

Figure 1 | Global configuration of tests for (a) UDF and (b) AS.

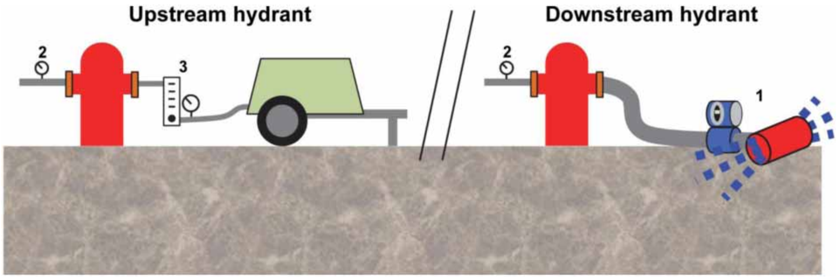

Figure 2 | Installation of measurement equipment (1: water flowmeter and jet regulator; 2: hydrant manometers; 3: air rotameter and manometer).

Hack 2100Q turbidimeter (error ±2%; precision 1 NTU if turbidity $\geq$ 100 NTU, 0.1 NTU if $100 \leq$ turbidity < 10 and 0.01 NTU if turbidity $\leq$10 NTU). Total suspended solid concentration (TSSC) of collected samples was measured afterwards in the laboratory, following the AFNOR (2005) protocol. Granulometry of the collected water samples was analysed using a Partica LA-950 laser diffraction particle size distribution analyzer.

Water velocity during UDF sequences was calculated by dividing water flow by the pipe's internal area. For AS sequences, slugs mean that velocity was estimated from the Bendiksen's equation (Bendiksen 1984):

$$u_{\mathrm{slug}} = \max\left[1.2(u_{\mathrm{w}} + u_{\mathrm{a}});\ 1.05(u_{\mathrm{w}} + u_{\mathrm{a}}) + 0.542\sqrt{gD}\right]$$

where u_{slug} defines the slug mean velocity (m/s); u_{a} the air superficial velocity (m/s); u_{w} the water superficial velocity (m/s); g the gravitational acceleration (m/s^2) and D the pipe diameter (m).

Superficial velocities were obtained by dividing the respective fluid's (water or air) flow by the pipe's internal area, without

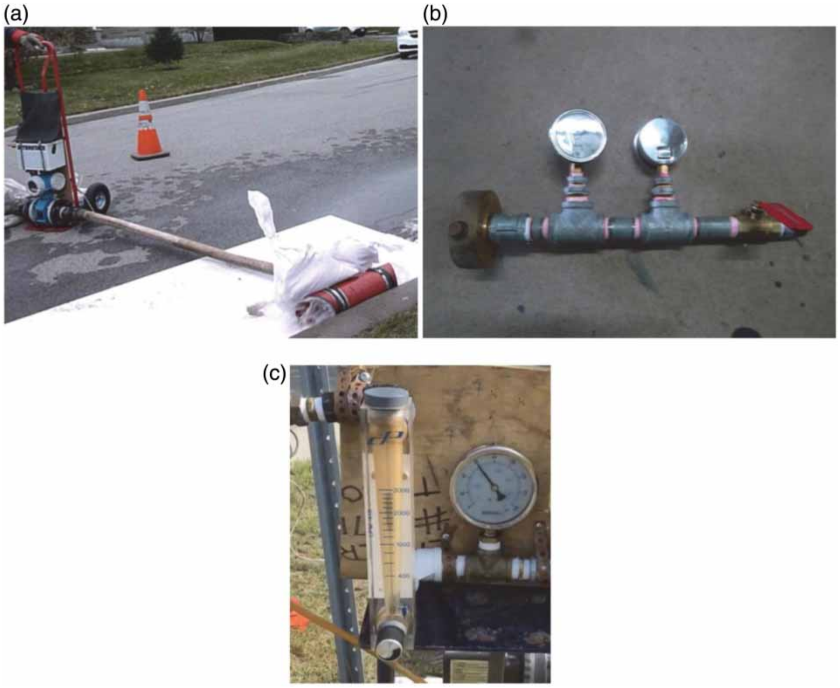

Figure 3 | Measurement equipment: (a) water flowmeter and jet regulator; (b) hydrant manometers; and (c) air flowmeter and manometer.

taking the other fluid into consideration. As water flowmeters cannot work properly during diphasic flow, water flow was measured before air injection during AS sequences.

For UDF sequences, shear stress was calculated with the following equation:

$$\tau_{\mathrm{UDF}} = \frac{1}{8} f_{\mathrm{D}} \rho_{\mathrm{w}} u_{\mathrm{w}}^2$$

where τ_{UDF} represents the shear stress during UDF sequences (N/m^2); f_{D} the Darcy friction factor (–); ρ_{w} the water density (kg/m^3); and u_{w} the water velocity (m/s).

Shear stress during slug flow can be calculated by the same equation as for UDF (Maley 1997), but two phenomena have to be taken into consideration: the incorporation of air bubbles, which lowers the density (Woods 1998), and additional turbulences within the slug front, which increase the shear stress (Kaul 1996). The equation then becomes:

$$\tau_{\mathrm{AS}} = \frac{1.35}{8} f_{\mathrm{D}} \left(\frac{1}{1 + \left(\frac{u_{\mathrm{w}} + u_{\mathrm{a}}}{8.66} \right)^{1.39}} \right) \rho_{\mathrm{w}} u_{\mathrm{s}}^2$$

where τ_{AS} is the shear stress during AS sequences (N/m^2).

The amount of flushed particles was calculated from TSSC using the following equation:

$$\mathrm{Part} = \frac{\Sigma_i((V_i - V_{i-1})\mathrm{TSSC}_i)}{L}$$

where Part is the amount of flushed particles during the whole sequence (g/m); TSSC$_i$ the TSS concentration in sample i (g/m^3); V_i the volume of flushed water before sample i (m^3); and L the section length (m).

The hydraulic performance was estimated by calculating the Hazen–Williams C-factor, which was computed from water flow, upstream and downstream pressure, and pipe length and diameter, using the Hazen–Williams' equation:

$$C = \frac{Q_{\mathrm{w}}}{0.279\, D^{2.63} \left(\frac{\Delta_{\mathrm{p}} + \Delta_{\mathrm{z}}}{L} \right)^{0.54}}$$

where C is the Hazen–Williams C-factor; Q_{w} the water flow (m^3/s); D the pipe diameter (m); Δ_{p} the pressure difference between the upstream and downstream hydrants; Δ_{z} the elevation difference between the upstream and downstream hydrants and L the section length (m).

The AS and UDF tests were performed on WDSs of municipalities carrying out UDF on a regular basis. Since the duration between the last UDF and each test day greatly varies and could impact the test results, all results were reported to the same time unit using the accumulation rate of particles (as proposed by Carrière *et al.* (2005)):

$$\mathrm{Acc} = \frac{\mathrm{Part_{UDF}}}{\Delta t_{\mathrm{flushing}}} 365$$

where Acc is the accumulation rate of particles that can be removed by UDF $(\mathrm{g/m/yr})^{-}$; $\mathrm{Part_{UDF}}$ the amount of flushed particles during the UDF sequence (g/m); and $\Delta t_{\mathrm{flushing}}$ the duration between the day the test was performed and the previous UDF performed by the municipality (d).

The efficiency of AS was computed using the following equation:

$$\mathrm{ASEC} = \frac{\mathrm{Part_{AS}}}{\mathrm{Acc}}$$

where ASEC is the AS efficiency coefficient (yr) and $\mathrm{Part_{AS}}$ the amount of flushed particles during the AS sequence (g/m).

This parameter expresses the amount of flushed particles by AS relative to the yearly accumulation of particles that can be removed by UDF in the cleaned pipe.

RESULTS AND DISCUSSION

A typical profile for turbidity and particle removal obtained during the UDF + AS test is presented in Figure 1. The horizontal axis presents the flushed water volume expressed in SVE (section volume equivalent), i.e. the flushed water volume divided by the volume of the flushed pipe section.

As shown in Figure 4, turbidity often increases at the beginning of the first UDF sequence and decreases afterwards, first quickly and then slowly, until reaching 5 NTU (criteria to stop the UDF). TSSC usually follows a similar profile, but the concentration is often not measurable soon after the peak, as particles are too thin to be caught by the filters. During the AS sequences, the turbidity peak is usually observed within the first water sample of the sequence. Turbidity then decreases, first quickly and then slowly. Due to field constraints, AS sequences were stopped when turbidity values were similar over 15 min intervals. The TSSC profile was usually similar to the turbidity profile for AS sequences as well. During the final UDF, performed to clean the pipe before putting it back in service, turbidity usually falls

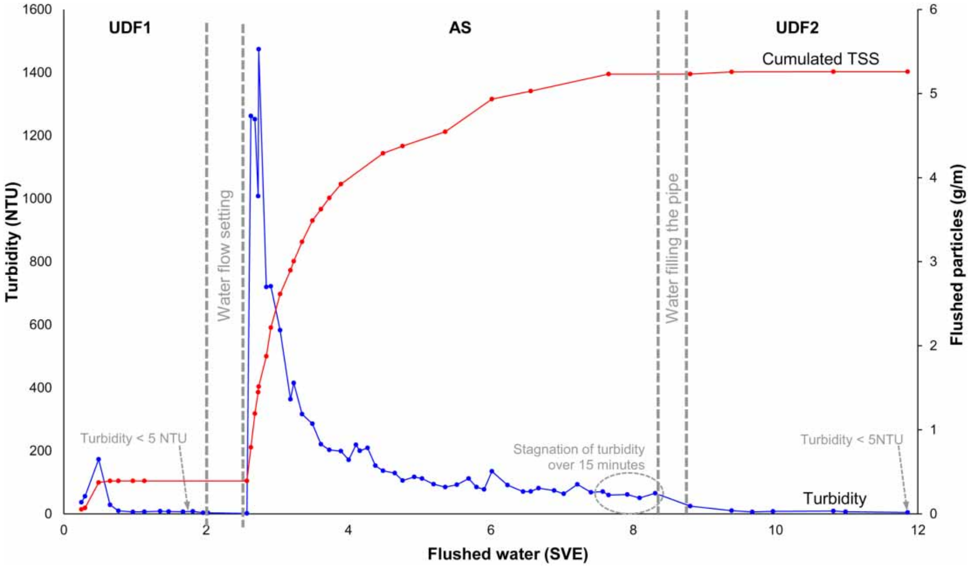

Figure 4 | Typical turbidity (blue) and cumulated TSS (red) profiles (test performed on Charles-Auguste-Majeau Street, Saint-Charles-Borromée).

quickly, sometimes almost below 5 NTU with a TSSC lower than the detection limit for the first water sample taken. Results are synthetized in Table 3. For AS, results for water volume and flushed particles are the sum of those for the AS sequence and the following UDF sequence, as it is assumed that the particles flushed during the second UDF sequence were resuspended during AS.

The UDF mean velocity is 1.53 m/s, which matches the literature (Carrière *et al.* 2005; Ahn *et al.* 2011), with a standard deviation of 0.45 m/s and no significant difference between cast iron and PVC. AS slug velocities varied over a wide range, as air and water flows were intentionally varied to study the impact of their variations on AS efficiency. Slug velocities ranged from 2.81 to 5.08 m/s, if only considering 150 mm pipes, and went up to 10.3 m/s when considering the test performed with the compressor at its maximal capacity on a 100 mm cast iron pipe. As shear stress is a function of the square of velocity, variations for shear stress are higher than for velocity. UDF mean shear stress was 16.8 Pa with a standard deviation of 15.4 Pa. The difference between PVC and cast iron is important with UDF, as the mean values for PVC (smooth material) and cast iron (rough material, especially if tubercles are present) are 5.0 and 19.7 Pa, respectively. For AS, the mean shear stress is 175.1 Pa with a very high standard deviation (238.3 Pa) as the test performed with the compressor at its maximum capacity on the 100 mm cast iron pipe induced a shear stress as high as 1,176 Pa. The difference between PVC and cast iron is once again important, as it is 57.2 and 193.7 Pa for PVC and cast iron, respectively.

The mean water volume required to obtain turbidity below 5 NTU for UDF is 2.76 SVE, with a standard deviation of 1.94 SVE, which matches the literature (Stephenson 1989; Ellison 2003). Surprisingly, PVC pipes required more water, but only for three pipes, with a mean of 4.19, and 2.60 SVE for cast iron pipes. Some authors report that AS requires 40% less water than UDF to obtain clear water (Kitney *et al.* 2001; Vitanage *et al.* 2004). In the tests presented here, the mean volume of water required for AS to obtain turbidity values below 5 NTU is 8.92 SVE, with a standard deviation of 7.93 SVE. There is little difference in the required volume of water for AS between PVC and cast iron (mean of 6.70 and 9.32 SVE, respectively).

Table 3 | UDF and AS sequences results

		Water velocity (m/s)	**Shear stress (N/m^2)**	**Water volume (SVE)**	**Hazen–Williams *C*-factor evolution**	**Flushed particles (g/m)**	**Acc (g/m/yr)**	**Mean particle size (μm)**
UDF	Global mean	1.53	16.8	2.76	–	0.49	0.60	14.29
	Global standard deviation	0.45	15.4	1.94		0.38	0.54	6.03
	Cast iron mean	1.52	19.7	2.60	–	0.51	0.61	14.94
	Cast iron standard deviation	0.44	15.9	1.77		0.39	0.56	5.92
	PVC mean	1.59	5.0	4.19	–	0.32	0.45	8.47
	PVC standard deviation	0.62	1.4	3.13		0.26	0.14	2.72
		Slug mean velocity (m/s)	**Shear stress (N/m^2)**	**Water volume (SVE)**	**Hazen–Williams *C*-factor evolution**	**Flushed particles (g/m)**	**ASEC (yr)**	
AS	Global mean	3.77	175.1	8.92	– 2%	5.29	10.23	22.45
	Global standard deviation	1.66	238.3	7.93	9%	15.22	13.46	10.88
	Cast iron mean	3.75	193.7	9.32	– 2%	5.99	11.84	22.82
	Cast iron standard deviation	1.75	251.3	8.42	8%	16.32	14.22	11.55
	PVC mean	3.91	57.2	6.70	– 4%	0.86	2.18	19.69
	PVC standard deviation	1.14	61.5	4.60	15%	1.22	3.02	2.71

However, the required volume to obtain clear water (e.g. turbidity values lower than 5) is not an appropriate measure to compare the performance of AS and UDF. Indeed, since AS leads to higher shear stress values, it should remove more particles and tubercles than UDF and, consequently, bring higher turbidity values at the downstream end of the cleaned pipes for a longer period of time. Therefore, two other comparison criteria were computed.

The first criterion is the required water volume to flush the same number of particles with AS and UDF. Not all the test results could be used for this comparison, since (i) for the second series of tests performed in Salaberry-de-Valleyfield (three tests), the first UDF sequences did not produce measurable quantities of flushed particles; and (ii) for one sequence in Rivière-du-Loup, on a PVC pipe which was installed 1 year before the test, less particles were removed during the AS sequence than during the UDF sequence. For all the other 14 tests combining UDF and AS, the required water volume and the amount of flushed particles are given for UDF in Table 4, along with the required volume to remove the same amount of particles with AS. Results in this table show that the mean water volume required for UDF is 8-fold higher than the mean water volume required with AS to flush the same amount of particles. It has to be taken into consideration that, for five of the tests, the first sample of the AS sequence showed an amount of particles that was already higher than the amount of flushed particles with the UDF sequence. Thus, for these five tests, the required water volume to remove the same amount of particles with AS than UDF is, in fact, lower than the one presented in Table 4, but could not be estimated.

The second additional criterion that was computed to compare the performance of AS and UDF was the amount of particles removed with a water volume of 1 SVE: for the 28 UDF tests performed (UDF alone and UDF + AS), the mean value of removed particles is 0.32 g/m (standard deviation = 0.24 g/m), while it is 1.62 g/m for the 14 AS tests (standard deviation = 1.80 g/m).

To summarize, the above results show that: (i) to remove the same amount of particles as UDF (when this one is

Table 4 | Water volume required for UDF and AS to remove the same amount of particles

			Required water volume		
Test	**Pipe material**	**Particles removed with UDF (g/m)**	**UDF for 5 NTU (SVE)**	**AS for same amount of particles as UDF (SVE)**	**Ratio AS/UDF**
Saint-Charles #1	Cast iron	0.96	6.30	0.40	0.06
Saint-Charles #2	Cast iron	0.38	2.66	0.25	0.09
Saint-Édouard #1	Cast iron	0.39	1.96	0.05	0.03
Saint-Édouard #2	PVC	0.25	2.15	0.14	0.07
Saint-Édouard #3	PVC	0.10	2.62	0.33	0.13
Saint-Édouard #4	Cast iron	0.03	1.03	0.22	0.21
Saint-Édouard #5	Cast iron	0.63	3.38	1.13	0.33
Rivière-du-Loup #1	Cast iron	0.57	4.14	1.72	0.42
Rivière-du-Loup #2	Cast iron	1.03	9.34	0.25	0.03
Rivière-du-Loup #3	Cast iron	0.25	14.03	0.39	0.03
Valleyfield #1	Cast iron	0.12	1.24	0.38	0.31
Valleyfield #2	Cast iron	0.13	1.18	0.38	0.32
Valleyfield #3	Cast iron	0.06	0.95	0.48	0.51
Valleyfield #4	Cast iron	0.17	1.22	0.14	0.11
Mean		0.36	3.73	0.45	0.19
Standard deviation		0.32	3.79	0.45	0.16

stopped after obtaining a turbidity value lower than 5), AS requires, on average, 8.33-fold less water than UDF, and (ii) with a water volume equal to 1 SVE, AS removes, on average, 4.67-fold more particles than UDF.

As it can be seen in Figure 4, AS usually generates a high turbidity peak at the beginning of the sequence, then requires a long time to reduce turbidity to a low value. It can be assumed that due to a higher shear stress, AS removes, layer after layer, particles that adhered to the pipe walls as a result of electrostatic forces (Tomas 2004) and, for cast iron pipes, breaks some tubercle shells, releasing the core material. Results in Table 3 show that AS removes particles that are in average 57% larger than UDF and that pipe material impacts the size of removed particles with UDF, but less with AS, with larger particles removed from cast iron pipes than from PVC pipes. With AS, the high standard deviation value for the size of particles removed from cast iron pipes suggests that some large particles, such as pieces of tubercles, are dislodged. Indeed, huge metallic particles were found in the flushed water during AS sequences as presented in Supplementary Figure S3. Those particles were not observed during UDF sequences.

One could think that finding pieces of tubercles in the flushed water during AS sequences might mean that the pipes have been smoothed and that, consequently, the hydraulic performance has been improved. However, the results show the opposite. Indeed, the mean evolution of the Hazen–Williams *C*-factor is −2%, with no significant difference between PVC and cast iron. An explanation could be that once the sedimented particles were removed, the mean thickness of the incrustation becomes higher, leading to higher head losses (for PVC sections, incrustations may come from the cast iron equipment such as valves or upstream pipes). A camera inspection was performed within a 150 mm cast iron section and showed no significant removal of tubercles after an AS sequence, even though all sedimented particles were removed, leaving tubercles with an appearance of a metallic shell, as shown in Figure 5. The section illustrated in Figure 5 is not included in the results presented in Table 3 as the camera movements damaged the tubercles.

Concerning the amount of flushed particles, the mean accumulation rate measured with UDF sequences is 0.60 g/m/yr, with a standard deviation of 0.54 g/m/yr. The observed mean accumulation rate is qualified as low according to the scale proposed by Carrière *et al.* (2005). Two sections have a moderate accumulation, according to this scale, with a maximum at 2.09 g/m/yr. Cast iron sections show a slightly higher accumulation rate than PVC, as the mean accumulation rates are 0.61 and 0.45 g/m/yr for those two materials, respectively. This could be explained by the corrosion of cast iron pipes, which may generate particles. The accumulation within PVC pipes could be due to the migration of particles from cast iron pipes, the corrosion of cast iron equipment within PVC sections, water born particles or existing particles at the entrance of the WDS. Mean ASEC for AS is 10.23 yr, with a standard deviation of 13.46 yr. The difference between the ASEC for cast iron and PVC is important (mean of 11.84 and 3.18 yr, respectively). These results show that AS is more efficient in removing particles than UDF, especially with cast iron pipes, which matches previous results from the literature (Elvidge 1982; Kitney *et al.* 2001). Higher shear stress during AS sequences could help remove particles sedimented between tubercles, where the water could remain steady during UDF sequences.

CONCLUSION

The results presented herein, obtained from various tests on Quebec WDSs, showed that, for the tested WDSs:

- AS requires about 8-fold less water than UDF to flush the same amount of particles.
- AS requires much more water than UDF to obtain low turbidity values.
- AS removes larger particles than UDF, some of them being pieces of tubercles.
- AS has no impact on the hydraulic performance (roughness coefficient).

The obtained results show that, in general, AS is suitable to fight water discolouration events when UDF is limited by pressure losses due to high tuberculation. However, AS cannot replace more aggressive cleaning methods such as jetting or pigging to remove tubercles.

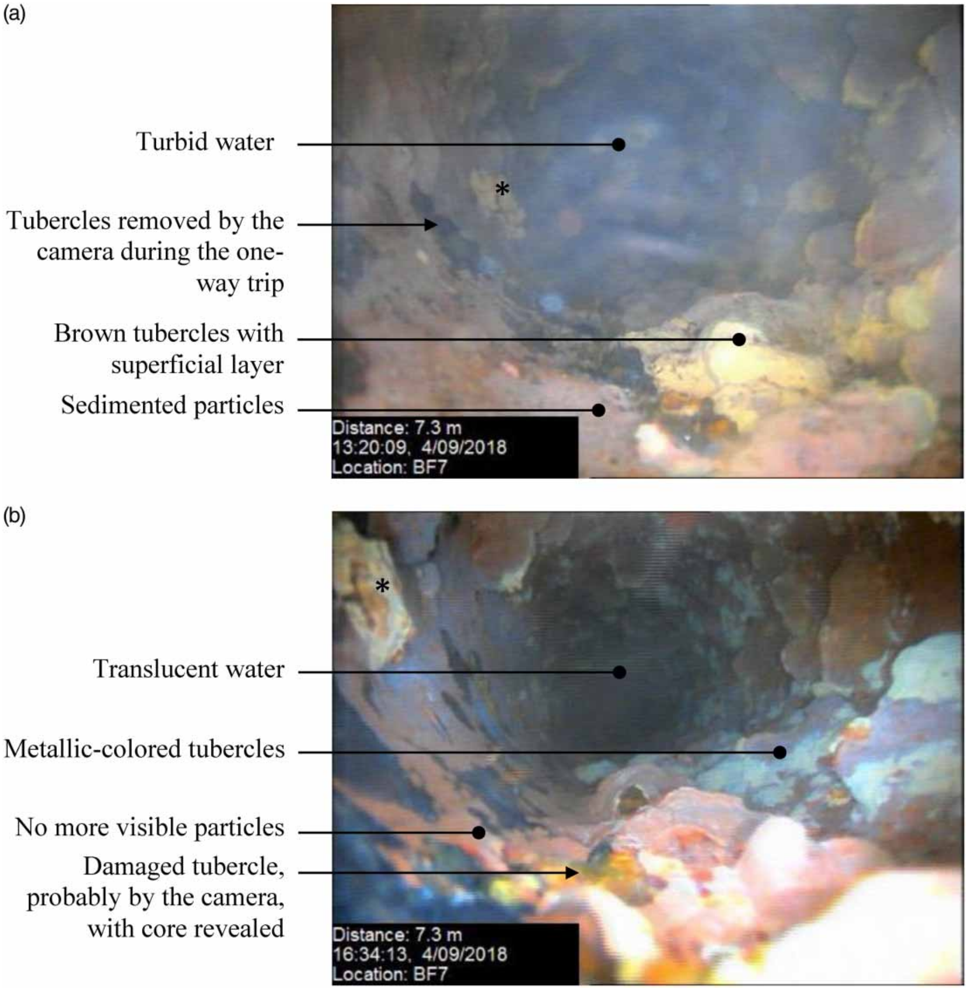

Figure 5 | Comparison of the inner view of a 150 mm cast iron pipe (a) before and (b) after UDF and AS sequences. Identified by a star is the same tubercle for a visual reference, as the camera did not stop at the same position for both pictures.

The conclusions of this study are valid for pipe diameters of about 100–150 mm and most particularly for highly tuberculated pipes. They could be different in countries or regions where aggressive anti-corrosion policies result in lowest corrosion and sediment accumulation rates, and in regions where water has different characteristics and treatments, such as for calcareous water. Also, since pipe diameter controls the velocity, and thus the shear stress, that can be reached during flushing sequences, conclusions could have been different for larger pipes. Finally, further studies, performed over many years, should evaluate if AS could be required at a lower frequency than UDF to reduce customer complaints for red water, which could help reduce water consumption for pipe cleaning over time.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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