Dead-end flushing of a distribution system: Short and long-term effects on water quality

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ABSTRACT

The effectiveness of routine spot flushing in two dead-end locations of the Montreal distribution system (DS) was assessed. The two 203 mm (8 in) pipes were roughly 500 m long. Two successive annual spot flushings, 25 minutes each, were performed and the impact on water quality was assessed during the first 24 hours, 2 weeks later, and the following year. The flushing water was also analysed in order to evaluate the quantity and nature of loose deposits that were drained. High numbers of atypical coliforms were removed during the first annual flushing procedure. No atypical coliforms were recovered from the flushing water during the second annual procedure, suggesting that the first procedure was effective in eliminating these organisms. During the first 24 h after flushing, chlorine decreased rapidly at both dead-end locations while heterotrophic plate counts (HPC) counts increased during the same period. Therefore, only minor improvements in water quality (mainly turbidity and total iron) were measured during the two weeks after the flushing procedure. With respect to spot flushing dead-end locations on a routine basis, the principal benefits observed in this specific DS were related to short-term improvements in the aesthetic characteristics of the distributed water.

Key words | dead-ends, distribution system, drinking water, loose deposits, unidirectional flushing

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INTRODUCTION

Distribution system dead-ends are well known problematic locations for water quality. High residence times, absence of residual disinfectants, and favourable corrosion conditions may interact to create an adequate environment for bacterial regrowth (Carter 1997). The hydraulic conditions (i.e. laminar flow) favour the accumulation of sediments (loose deposits). The latter, if resuspended, may play an important role in water quality degradation by increasing mineral content, but also organic matter, bacterial biomass, and even macroorganisms (LeChevallier *et al.* 1987; Van Lieverloo *et al.* 1997; Gauthier *et al.* 1999; Zacheus *et al.* 2001). The biological activity in loose deposits may create anaerobic conditions favourable to taste and odour problems and even enhance corrosion by creating regions with different oxygen, pH and iron concentrations (Snoeyink & Wagner 1996). The high disinfectant demand of these loose deposits (Gauthier *et al.* 1999) makes it difficult to control the biological activity by using disinfectants.

The use of unidirectional flushing (UDF) has often been proposed as good management practice for controlling biofilms and sediment accumulation (Chadderton *et al.* 1992; Rodgers *et al.* 1998; Friedman *et al.* 1998; Antoun *et al.* 1999). However, unidirectional flushing involves various costs, such as the labour and water used during the procedure. Time must also be allocated to manage the procedure and compile the data acquired during flushing. Finally, in some regions, appropriate measures must be taken in order to limit the environmental impact of chlorinated/chloraminated water released during flushing events. Due to these constraints, many utilities rely solely on spot flushing

(opening one fire hydrant at a time without closing valves in order to canalize the flow in one direction) to address problems located in certain portions of their system.

Considering the wide differences in distribution system environments, only a limited number of studies have investigated the nature of loose deposits, their quantity and associated bacterial activity (LeChevallier *et al.* 1987; Emde *et al.* 1995; Antoun *et al.* 1999; Gauthier *et al.*, 1999; Rompré *et al.* 2000; Zacheus *et al.* 2001; Carrière *et al.* 2002). Such information is essential in order to assess the potential impacts of flushing on water quality in the short term (just after the hydrants are closed and the distribution system (DS) is put back in service) and in the long term (weeks or months after the procedure). Even if the flushing is performed according to standards, the short-term disturbances caused by the flushing could indeed be the cause of adverse water quality during the 24 hours following the procedure.

OBJECTIVES

The general objective of this study was to document the benefits of periodically spot flushing dead-end locations in a distribution system. More specifically, its aims were to:

(1) Evaluate the short-term variations (24 h, 7 days) and long-term impacts (1 yr) on water quality of a periodical dead-end flushing.
(2) Characterize the loose deposits, and the associated biomass, accumulated in these dead-end locations.
(3) Assess whether or not spot flushing dead-end locations was an efficient procedure in improving water quality in these problem areas.
(4) Compare the loose deposit characteristics recovered for two successive annual flushings.

MATERIALS AND METHODS

General water characteristics in the distribution system

The City of Montreal (Canada) is supplied by the Atwater (250 MGD) and the DesBaillets (300 MGD) Water Treatment Plants. Both plants use filtration without coagulation, and post-chlorination. DesBaillets also injects ozone before the final chlorine disinfection. The Montreal distribution system is divided into six pressure zones. This partitioning is done by closing valves on the distribution system, therefore creating dead-end conditions on each side of the valve. The total number of dead-ends is estimated to be over a thousand.

The water quality in this distribution system is not cause for serious concerns (Desjardins *et al.* 1997). The microbiological quality is very good with less than 0.5% of samples positive for total coliforms and 57% of heterotrophic plate counts (HPC) samples showing less than 1 CFU ml^{-1}. The distributed water is well mineralized (alkalinity = 90 mg $CaCO_3$ l^{-1}, pH 7.8, total hardness 126 mg $CaCO_3$ l^{-1}) and not very aggressive (aggressivity index = 11.9), which prevents the corrosion of iron, since ductile iron pipes make up the vast majority of the DS. Consequently, complaints about red water events are scarce and water quality degradations are mostly localized in dead-end locations.

Description of the study site

Two adjacent sampling sites were chosen on parallel streets in the pressure zone no. 4 of the Montreal DS (Figure 1). The first site (CLDI) is located on a cement-lined ductile iron pipe laid in 1978, while the second (GCI) is located on a grey cast iron pipe laid in the early 1920 s (Table 1). During the winter, chlorine residuals at the entry of the sector vary from approximately 0.2 to 0.5 mg Cl_2 l^{-1}. During the summer, chlorine is supplemented at the high-pressure pump discharge (located at the outlet of the storage tank) using hypochlorites in order to maintain a target level of 0.6–0.9 mg Cl_2 l^{-1} at the storage tank outlet. A mean residence time of 7 to 10 hours was calculated between the outlet of the tank and the inlet of the dead-end locations according to hydraulic modelling.

Experimental design

Water quality was sampled on a weekly basis over a 3-month period (summer of year 1) at the outlet of the tank (sector entry) and at sampling ports installed directly

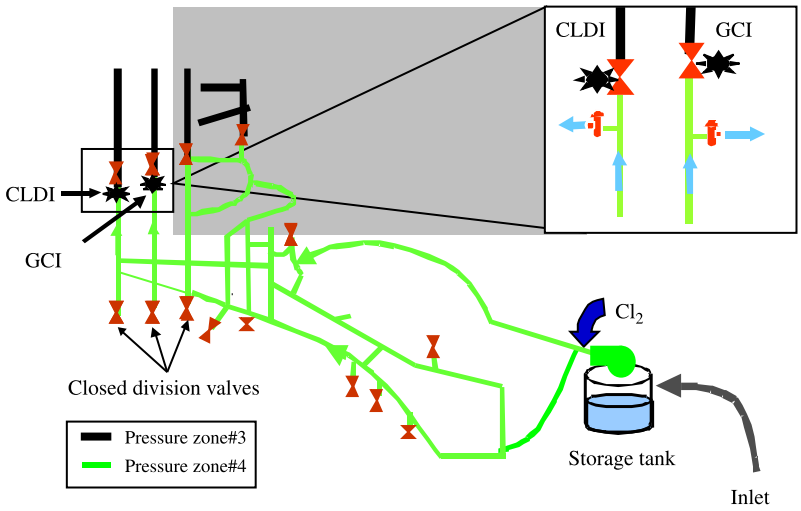

Figure 1 | Location of study site and sampling location (CLI: cement-line ductile iron, GCI: grey-cast iron).

on the pipes at both dead-end locations (sites CLDI and GCI). Table 2 summarizes the analytical methods employed.

At the end of the summer, both dead-ends were flushed one week apart using the fire hydrants located within a range of 10 m (30 ft) of the pipe's dead-end. Prior to the flushing procedure, the water quality in the dead-end was sampled. The 203 mm (8 in) mains were flushed for a total duration of 25 min at a velocity of $1.8 +/- 0.2$ m s^{-1} (6 ft s^{-1}).

Samples were collected at the fire hydrant outlets at fixed intervals during the procedure (t = 1, 4, 7, 10, 15 and 20 minutes) using a sampling tap, as described in Figure 2. These samples were tested for water quality parameters described in Table 2.

Taking repeated samples at the dead-end locations after 3 h, 6 h, 9 h and 24 h helped to assess short-term water quality variations after flushing. Long-term impacts were evaluated by comparing the summer water quality data of year 1 with the data set collected during the summer of year 2.

Finally, both sampling sites were then flushed a second time at the end of year 2. This additional procedure allows a direct comparison to be made between the loose deposits recovered from two consecutive annual flushing procedures.

Table 1 | Dead-end characteristics

Characteristics	CLDI	GCI
Pipe materials	Cement-lined ductile iron	Unlined grey cast iron
Length	470 m (1,542 ft)	535 m (1,755 ft)
Diameter	202 mm (8 in)	202 mm (8 in)
Age	1978	1920–1930

Analytical methods

Table 2 provides the references for the analytical methods used during the course of this study. Chlorine residuals were measured using the standard DPD method (*Standard Methods* 1995 4500F). Total iron was measured using the phenantroline colorimetric method. Turbidity was measured using a ratio turbidimeter (Hach, model 2100A). Results are expressed as nephelometric turbidity units (NTU).

Heterotrophic plate counts were measured on R2A agar following incubation at 20 °C during a 7-day period. Results are expressed as CFU ml^{-1}. Total coliforms were analysed on m-Endo media after 24 h at 35 °C. Atypical coliforms (background colonies not exhibiting a green metallic sheen after 24 h at 35 °C) were also recorded. Results are expressed as CFU 100 ml^{-1}. The direct total bacterial counts were determined by epifluorescence microscopy after acridine orange staining, following the Hobbie *et al.* (1977) procedure. Enumerations are based on estimates

Table 2 | Description of analytical methods

Parameters	References	Comments
Turbidity (NTU)	APHA, 2130B	Hach (model 2100A)
Total iron (mg Fe l^{-1})	APHA, 3500D	Phenantroline method
pH	APHA, 4500-H +, B	FisherMeter-119
Suspended solids – TSS (mg l^{-1})	APHA, 2540 D	
Volatile suspended solids – VSS (mg l^{-1})	APHA, 2540 E	
Mineral characterization	APHA, 3500	Atomic absorption spectrometric method
Free chlorine (mg Cl_2 l^{-1})	APHA, 4500-Cl, F	DPD ferrous titrimetric method
Heterotrophic plate counts – HPC (CFU ml^{-1})	APHA, 9215 D	R2A, 7 days at 20 °C
Total direct counts -TDC (log of bacterial counts ml^{-1})	APHA, 9216 B	0.22 μm filters stained with acridine orange (0.01%) during 2 min, observation at 1000X
Total coliforms (CFU 100 ml^{-1})	APHA, 9222 B	M-Endo media, membrane filtration

from 10 microscopic fields per slide. We consider this method to be semi-quantitative due to the interference of particles that are present in flushing waters. It was possible to observe some of these particles being colonized by an abundant biomass without being able to precisely count each bacterium.

Total suspended solids (TSS) were measured on flushing waters using precombusted fibreglass filters (Watman, 934-AH, ∅ 47 mm) and were calculated based on filter mass differences after 103 °C drying and the measured volume of filtered water (2 to 5 l). The mass difference between the burnt filters (505 °C) and the dried filters (103 °C) was used to calculate the volatile solids fraction (in order to estimate organic matter content). Mineral analysis was performed by mineralizing filters (cellulose acetate, MF5 type) in a Teflon pot containing 1 ml HCl, 0.5 ml HNO_3 and 0.5 ml HF. The concentrate was then diluted and analysed for Al, Ca, Na, K, Fe, Mn, Zn, Cu and Pb by flame atomic absorption spectrometry. Results are expressed as μg l^{-1} or as percentages of the TSS.

Figure 2 | Sampling device installed on the fire hydrants.

RESULTS

Water quality prior to flushing procedure

Water samples were collected at the tank outlet (after rechlorination) and also at the CLDI and GCI sites during a 3-month period before the beginning of the first annual flushing procedure. Figure 3 represents the average water quality measured during this period. The general water quality at both sites was similar and typical of dead-end locations: absence of residual chlorine, increased turbidity, and elevated culturable bacteria (HPC). The total iron concentrations in

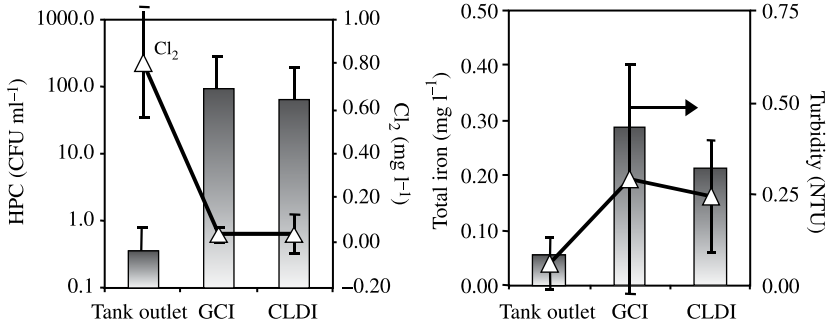

Figure 3 | Average year 1 summer water quality conditions (N = 6–8) at tank outlet and at both dead-end locations prior to flushing procedure.

dead-end water samples (0.2–0.3 mg l^{-1}) also indicated corrosion and probably explain the increased turbidity. However, no coliforms (<0.25 CFU 100 ml^{-1}) were detected during the weekly sampling campaigns ($n = 6–8$).

Water quality during flushing procedure

Water samples were collected in increasing intervals in order to characterize the initial peak of loose deposits and, ultimately, to estimate the time required to flush out all deposits. Figure 4 represents the total iron profile, total suspended solids (TSS) and total direct bacterial counts (TC) eliminated from both sites during the two consecutive annual flushing procedures.

During each flushing procedure, TSS peaked sharply during the first 5 minutes, then decreased steadily during the next 15 minutes, and finally reached a plateau of around 1–2 mg l^{-1}. The peak TSS recorded during each flushing varied from 6.9 to 12.3 mg l^{-1}, which are very low values compared with our personal experience with other distribution systems (TSS > 200 mg l^{-1}, typically).

Total iron concentrations generally took longer to decrease and flushing for at least 15 minutes was necessary

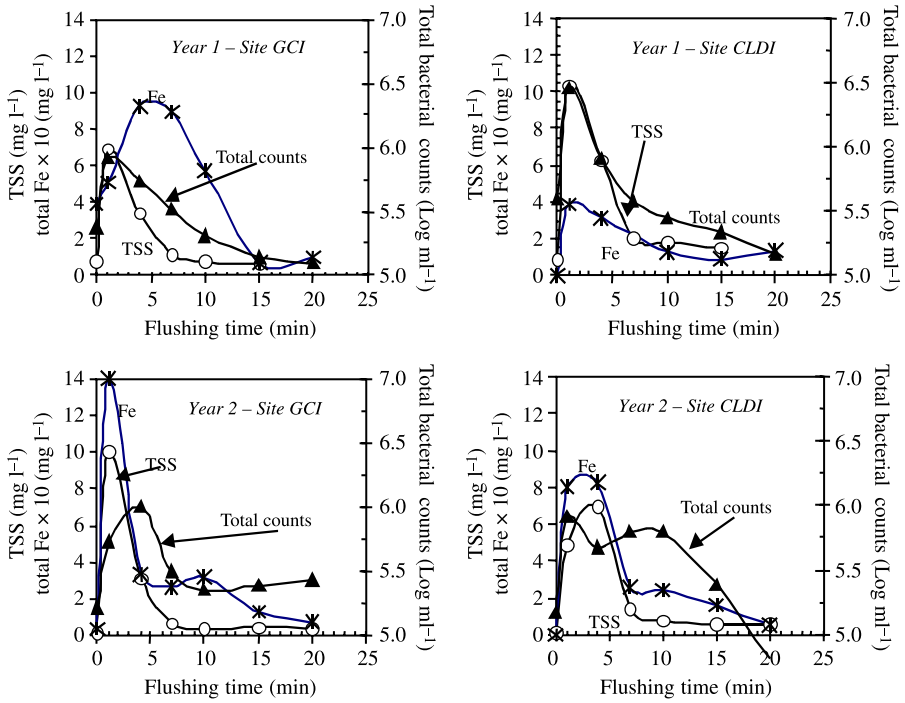

Figure 4 | Total suspended solids (TSS), total bacterial counts (total counts) and total iron measured during 20-min flushing procedures at the CLDI and GCI sites. Top: Year 1 procedure. Bottom: Year 2 procedure.

to reduce total iron concentrations to less than 0.10 mg l^{-1} (Figure 4). Significant differences were observed between the two sampling sites; the GCI site exhibited higher iron concentrations for a longer duration compared with the CLDI site. Such observation confirms routine monitoring data, which had showed higher average (Figure 3) and maximum (data not shown) iron concentrations at the grey cast iron sampling location.

A comparison of total iron analysis with suspended solids data (Figure 5a) indicates that these two parameters, although significantly correlated, were not as closely associated as would have been expected if deposits were essentially composed of corrosion by-products. For example, in year 1, a much higher linear density of iron (in g Fe m^{-1}) was removed during flushing at the GCI site compared with the CLDI site (0.069 g m^{-1} vs. 0.019 g m^{-1}, respectively), yet this finding did not translate into higher suspended solids (0.26 vs. 0.40 g m^{-1}, respectively). In Year 2, the linear iron density was equal at both locations (0.044 and 0.046 g m^{-1}, respectively), even though TSS was still twice as high at the CLDI site than at the GCI site (Table 3).

Analyses of the flushing water were used to obtain information on loose deposits. The characteristics of the drained deposits are explained in the following sections.

Quantity of loose deposits

By performing a numerical integration of the TSS concentration vs. time curve (Figure 4), it is possible to calculate the total amount of loose deposits drained during the first 20 minutes of the flushing procedure (using the actual flowrates measured on site) (Table 3). Considering experimental error (+/− 10%), we calculated that, for a given site, an identical mass of loose deposits was removed during year 1 and year 2. A total mass of 122 g and 221 g were removed at the GCI and CLDI sites respectively during the first annual campaign (year 1), while 121 g and 202 g were removed during the second one (year 2). Such values are equivalent to a loose deposit linear accumulation of approximately 0.26 g m^{-1} and 0.40 g m^{-1} for the GCI and CLDI sites, respectively.

Loose deposit composition

The mineral and organic characteristics of loose deposits were evaluated during each annual flushing procedure. Results, presented in Table 4, indicate that the TSS collected were mainly made of (i) iron (27–71%), (ii) a relatively high, but constant, abundance of volatile suspended solids (19–22%), (iii) calcium (2.8–3.1%), (iv) manganese (0.35–6.2%), and (v) other marginal components (Pb, Cu, etc.). Moreover, a relatively high percentage of unknown material (5.7–45%) was observed. For both years, the CLDI site had a particularly higher amount of unknown material than the GCI site. This unknown amount would most likely be composed of silica and aluminium, two components not analysed during this research, but that can be found in cement or sand, silt and clay particles detected in Montreal treated water suspended solids (Gauthier *et al.* 2001). A follow-up study in the area indicated that 1.7 to 6.4% of TSS was composed of aluminium while silicates accounted for 5 to 24% of the mass of deposits (Carrière 2002). It is also suggested that the amount of iron measured at the CLDI site in year 1 (27%) might have been underestimated, as it is quite low compared with the typical iron values in this zone (53–71%). Finally, it is noteworthy that the TSS level of manganese was greatly reduced during

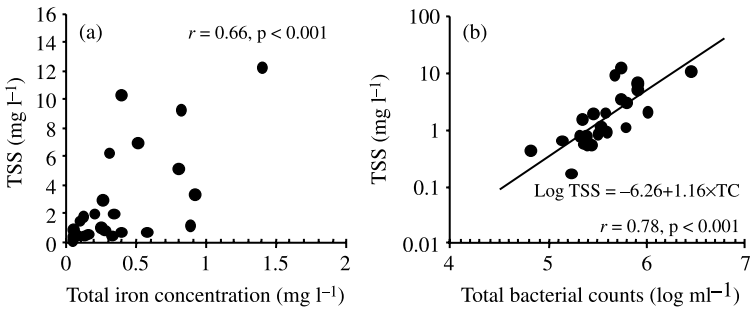

Figure 5 | Correlation between total suspended solids and iron concentration (Figure 5a) or total bacterial counts (Figure 5b), as measured on samples collected during flushing procedures (Year 1 and Year 2).

Table 3 | Comparison of contaminants drained for two consecutive annual flushings

	Grey cast iron			Cement-lined ductile iron		
Parameters	**Year 1**	**Year 2**	**Variation**	**Year 1**	**Year 2**	**Variation**
Microbiological						
Total bacterial counts (bacteria m^{-3})*	3.0×10^5	3.8×10^5	+0.1 log	5.2×10^5	4.1×10^5	−0.1 log
Atypical coliforms (CFU 100 ml^{-1})*	211	<0.12	>-3.2 log	425	2.4	−2.2 log
Physico-chemical						
Total iron (g m^{-1})	0.069	0.044		0.019	0.046	
TSS (g m^{-1})	0.26	0.26		0.38	0.41	
Total mass (g)	122	121	1%	221.	202	9%

*Total numbers of organisms divided by the total volume of flushed waters

the second annual flushing. Loose deposits were, on average, made of 5.9% manganese in year 1. This value declined to 0.41% during the second annual flushing and stayed quite low at an average of 0.35%, which was measured at these sites in 2000 and 2001 (Carrière 2002).

Microbiological content of loose deposits

Microscopic observations confirmed that bacteria heavily colonized flushed deposits. Except for a few particles that were too densely colonized, it was generally possible to adequately enumerate bacteria in the samples (Table 3).

Table 4 | Loose deposit composition drained during flushing

	GCI		CLDI	
	Year 1	**Year 2**	**Year 1**	**Year 2**
Iron (as FeOOH)	53%	71%	27%*	55%
Volatile suspended solids	21%	22%	19%	21%
Calcium (as $CaCO_3$)	2.8%	NA	3.1%	NA
Manganese (as MnO_2)	6.2%	0.35%	5.6%	0.46%
Lead (as Pb)	0.14%	0.86%	0.13%	0.15%
Copper (as Cu)	0.13%	0.08%	0.09%	0.11%
Unknown (including Si and Al compounds)	17%	5.7%	45%*	24%
Total	100%	100%	100%	100%

NA: not available, *suspect results

Total bacterial counts during flushing were significantly ($p < 0.01$) correlated with log-transformed values of turbidities ($r = 0.69$), total suspend solids ($r = 0.78$) and total iron concentrations ($r = 0.55$). Figure 5b displays the relationship between TSS and total bacterial counts, which was the most significant observed. The measured bacterial colonizations were around $1.5-1.9 \times 10^{11}$ bacteria g^{-1} of suspended solids for both sampling sites. When subtracting the number of bacteria naturally present in the bulk phase (approx. 1.3×10^5 bacteria ml^{-1}), the bacterial colonization attributed to deposits is reduced by approximately 0.5 log to values of around $1.0-1.4 \times 10^{11}$ bacteria g^{-1}. The number of bacteria in deposits was similar from one year to the next. Therefore, no significant effect was attributed to flushing in regard to reducing the total number of bacteria in deposits.

No attempt was made to correlate HPC with other water quality parameters. The HPC profiles during flushing were very different from the total bacterial counts (data not shown). No HPC bacterial peaks were observed during the flushing. The presence of large particles in the sample can account, in part, for such findings. These particles were colonized by an abundant biomass, as evidenced by microscopic counts. HPC analysis underestimates bacterial density by counting a bacterial aggregate as a single colony. Moreover, the flushing procedure increased the free chlorine concentration up to 0.60 mg Cl_2 l^{-1} by allowing fresh water into the sector. As for many other cultivation methods, free chlorine interferes with HPC measurements by decreasing culturability.

Finally, no total coliforms were detected during any of the four flushing procedures (<1 CFU 100 ml^{-1}). However, 75% of the samples ($n = 12$) were too numerous to count (>250 CFU 100 ml^{-1}) for atypical coliforms during the first annual procedure. The large number of colonies may have interfered with the detection of total coliforms. By contrast, atypical coliforms were almost completely absent during the second annual flushing campaign for both sites. Only three samples out of 12 were exhibiting atypical coliforms, and even so, only at low densities (1–22 CFU 100 ml^{-1}). Thus, flushing apparently had a positive effect on reducing the presence of atypical coliform in deposits.

Short-term (24 h) and mid-term (14 days) water quality evolution after flushing procedure

Figure 6 represents the short-term (24 h) water quality variations measured at both sites following the flushing procedure. HPC bacteria (Figure 6a) were low during the first 8 hours after flushing. However, one day later, the concentrations had returned to typical pre-flushing values. Interestingly, this increase was inversely related to the free chlorine residual concentration in both dead-ends (Figure 6b), which disappeared rapidly. The GCI site exhibited a lower final chlorine residual after 24 h (0.05 mg l^{-1}). Turbidity at the CLDI site slowly decreased during the first 24 h as opposed to the GCI site where it remained fairly stable (Figure 6c).

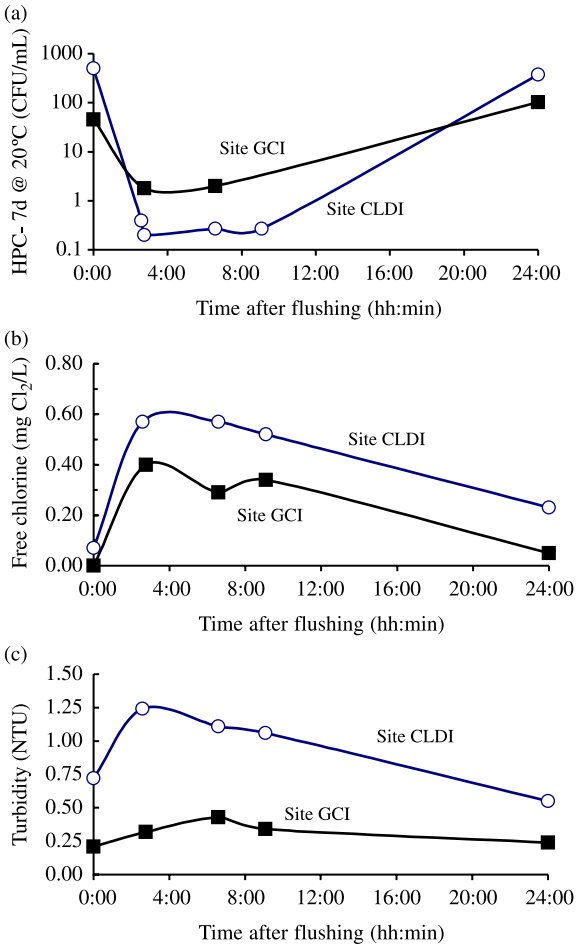

Figure 6 | Short-term (24 h) water quality variations after flushing for 20 min: dead-end sites A and B. (a) Heterotrophic plate counts, (b) free chlorine residual and (c) turbidity (time 0:00 represents the conditions prior to flushing).

Water quality was also monitored at both dead-end locations for two weeks following the flushing and compared with the data acquired during the three weeks preceding the flushing procedure. Figure 7 shows the impact of flushing on turbidity, HPC bacteria, total iron concentrations, and free chlorine residuals. Turbidities (Figure 7a) were generally lower and more stable following the flushing procedure. For one of the four assays (year 1 at the CLDI site), turbidity decreased slowly over the next two weeks to finally reach the 0.1–0.3 NTU range observed for the other assays. With regard to HPC bacteria (Figure 7b), the flushing did not produce a measurable impact. HPC levels remained relatively high (100–1,000 CFU ml^{-1}) during the following two weeks, while coliforms remained undetected in 400 ml samples (data not shown). As with free chlorine (Figure 7c), a significant impact was only observed for the cement line ductile iron site. For this site, the flushing procedure helped to increase the free chlorine residual up to approximately 0.2 mg l^{-1} while it remained at undetectable levels at the GCI pipe location. Finally, the flushing procedure was beneficial for the reduction of total iron levels, which always remained below 0.15 mg l^{-1} at both locations during the following two weeks.

Long-term impacts of the flushing procedure on water quality

By comparing the weekly monitoring data prior to flushing for the two consecutive annual summers, it was possible to assess the long-term impacts of the procedure on water quality. This approach assumed that the dead-end water quality measured during the summer of year 2 was causally linked with the flushing procedure of year 1. Obviously, several confounding factors may interfere with this analysis. For one, the impact of seasonal water quality variations is difficult to ascertain. For example, water temperatures were approximately 0.7 to 1.0 °C higher in year 2 compared with year 1. Routine distribution system operations (pipe repairs, valve maintenance, fire) also represent potential confounding events that may have been accidentally monitored during our weekly sampling. Keeping these limits in mind, we compared in Table 5 the average microbiological water quality before (summer of year 1) and after (summer of year 2) the first flushing procedure. Comparisons were based on geometrical means (microbiological) or arithmetic means (physico-chemical) calculated using pre-flushing summer data ($n = 4–6$).

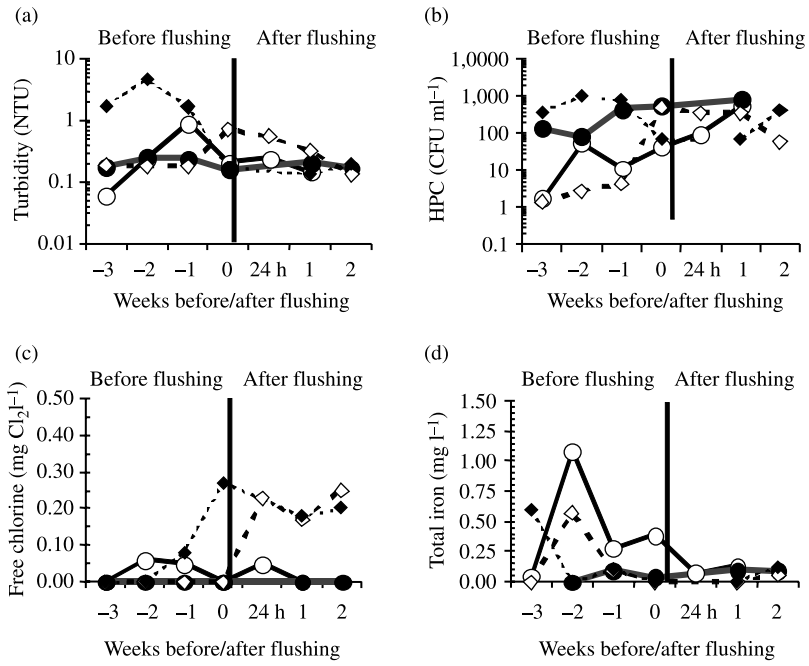

Figure 7 | Mid-term (two weeks) water quality variations after flushing for dead-end sites A and B. (a) Turbidity, (b) heterotrophic plate counts, (c) free chlorine, (d) total iron. GCI: Year 1 = ○, Year 2 = ●, CLDI: Year 1 = ◇, Year 2 = ◆(time 0:00 represents the conditions just before flushing).

Table 5 | Average weekly water quality at both sites two months prior to flushing procedures (performed at the end of the summer of each year)

	GCI		CLDI	
Parameters	**Year 1**	**Year 2**	**Year 1**	**Year 2**
Microbiological				
Total counts (log ml^{-1})	4.81	5.33	5.42	5.44
Atypical coliforms (CFU $100\,ml^{-1}$)	10 (0.25–200)	<0.13	6 (0.75–137)	<0.13
HPC (CFU ml^{-1})	15 (1.8–560)	235 (35–840)	10 (0.8–373)	383 (71–1,020)
Physico-chemical				
Temperature (°C)	21.4 (19.5–22.5)	22.4 (21–24)	20.5 (19–21.5)	21.2 (20–22)
Total organic carbon (mg l^{-1})	1.98	1.75	2.12	1.71
Turbidity (NTU)	0.16 (0.06–0.21)	0.19 (0.15–0.25)	0.18 (0.18–0.19)	2.7 (1.7–4.6)
Total iron (mg l^{-1})	0.29	0.10	0.19	0.23
Free chlorine (mg l^{-1})	0.03 (0.00–0.06)	0.00 (0.00–0.00)	0.07 (0.00–0.19)	0.03 (0.00–0.20)

From a water utility perspective, the most interesting result was the dramatic reduction in the atypical coliforms enumerated on m-Endo media (Table 5). Concentrations were lowered from an average of 6–10 (CFU ml^{-1}) before the first flushing to below the detection limit (0.25 CFU $100\,ml^{-1}$). This reduction can probably be attributable to flushing, since large concentrations of atypical coliforms were drained during the year 1 spot flushing.

In contrast to m-Endo counts, HPC bacteria (Table 5) increased significantly during the summer of year 2 (about 1.6 log and 1.2 log at the CLDI site and the GCI site, respectively). This result might not be directly attributable to flushing, since water temperatures were 1 °C warmer and free chlorine residuals lower in year 2 (0.00–0.03 vs. 0.03–0.07 mg $Cl_2\,l^{-1}$). In fact, no favourable long-term impact on chlorine residual persistence was observed at either location.

Finally, similar yearly comparisons were attempted for both turbidity and total iron concentrations (Table 5). Turbidity stayed relatively constant and total iron concentration went down for the GCI site. However, both parameters deteriorated at the CLDI site. Turbidity was especially high at this location even though total iron concentrations were only slightly higher. This would suggest a turbidity increase unrelated to corrosion phenomenon, although such a phenomenon was not identified.

DISCUSSION

The quantities of deposits found in the two pipes studied (0.26 to 0.40 g m^{-1}) were small compared with published values in the literature. Carrière *et al.* (2002) measured between 0.3 and 24 g m^{-1} of deposits in four Canadian networks. On cast iron pipes in France, Harmant *et al.* (2000) measured up to 12 g m^{-1} of loose deposits. These results highlight the fact that deposit accumulation is highly site specific and will vary to a large extent in different networks.

Many authors studied the microbial colonization of loose deposits and published data on the topic. In general, HPC measurements range between 1.8×10^6 and 2.0×10^8 CFU g^{-1} (LeChevallier *et al.* 1987; De Rosa 1993; Gauthier *et al.* 1996; Carrière *et al.* 2002). The enumeration of total bacteria resulted in values from 2.6×10^{10} to 9.4×10^{10} (bacteria g^{-1}) in Montreal

(Carrière 2002) and averaged 10^{10} in another study (Zacheus *et al.* 2001). The results obtained in this study ($1.5–1.9 \times 10^{11}$ bacteria g^{-1}) are slightly higher than other total counts mentioned previously, but are still within the same range. The hydraulic conditions (dead-end locations) may explain this higher result. Site-specific conditions (corrosion, water quality, organic matter content of deposits, etc.) may also explain the variations in bacterial densities of deposits from one DS to another. However, each study is in agreement in their conclusions that loose deposits are colonized by an abundant biomass.

The mid-term impact (in terms of weeks) of flushing on water quality has also been studied by Cossins *et al.* (1999). They obtained similar results: a decrease in turbidity and total iron over a six-week period. Recently, Lehtola *et al.* (2004) observed a decrease in microbial growth after cleaning pipes with air and high velocity flushing. While we observed an increase in chlorine residuals in one of the two sites, Cossins *et al.* (1999) did not measure an increase in chlorine residuals due to flushing. Regarding the short-term (24 hours) impact of flushing, none was noticed by Carrière (2002) in Jonquiere (Canada) and only reduced iron levels were observed by Lehtola *et al.* (2004). In this study, only reduced turbidities and iron levels were obtained through spot flushing. Therefore, only very short-term impacts of flushing are observed in dead-end locations (within the first 24 hours), after which time, the effects disappeared.

Long-term impacts (1 year) of flushing are hard to evaluate, primarily because of the numerous potential confounding factors (chlorine level, local hydraulic condition, breaks and repairs, intrusion, etc.). Among the analyses performed 1 year after flushing, one result was particularly interesting: the elimination of atypical coliforms in water samples. Reduction of total coliforms has also been observed by other researchers (Oliver and Pimentel 1998; Antoun *et al.* 1999). However, when other practices to reduce coliform occurrence are implemented (Oliver and Pimentel 1998) or when there is a change in disinfectant (Antoun *et al.* 1999), the true effect of flushing is hard to dissociate. The results obtained here support the hypothesis that flushing was responsible for the reduction of atypical coliform occurrence in these two dead-end locations. Although there is no clear evidence of the impact of atypical coliforms on public health, many distribution system managers exploit this information as an indicator of potential positive coliform events and, therefore, use them as a guideline to trigger spot flushing. Non-coliform bacteria, such as *Aeromonas hydrophila* (a candidate on the USEPA contaminant list), are known to grow on m-Endo media (Rompré *et al.* 2002). This emerging health issue supports the good management practice of minimizing the total counts of atypical coliforms.

CONCLUSIONS

This research project aimed at increasing the understanding of the benefits of spot flushing dead-end locations. The following conclusions can be drawn:

- Even if they appear identical (same source water, pipe diameter, hydraulic configuration, etc.), variability exists from one dead-end location to another.
- The usefulness of HPC analysis for characterizing microbiological quality of flushed waters is inadequate due to the interference of chlorine residual and colonized particles.

Regarding the spot flushing procedure and the short-term impacts:

- High numbers of atypical coliforms were drained during the first annual flushing procedure.
- During the first 24 h after flushing, chlorine decreased rapidly at both dead-end locations, while HPC counts increased during the same period.
- Minor improvements in water quality (mainly turbidity and total iron) were measured during the two weeks following the flushing procedure.

Regarding the second annual flushing:

- No reductions in the turbidity, suspended solids and microscopic bacterial counts were observed when comparing flushing profiles from both years.
- No atypical coliforms were recovered from the flushing waters during the second annual campaign.

Generally, water utilities will implement flushing procedures at a frequency based on good management

practices, past experiences, or cost constraints. With respect to spot flushing dead-end locations on a routine basis, the principal benefits observed in this specific DS were related to short-term improvements in water aesthetic characteristics. The reduction of atypical coliforms is also an interesting benefit to mention, although its health significance remains unclear at this time. Therefore, the routine spot flushing of dead-end locations will be triggered by consumer complaints or as a preventive measure for specific problem locations. The fact that the DS under investigation is unfavourable to iron corrosion is a key variable to take into account for explaining these conclusions.

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