Practical Paper

Disinfectant efficacy in distribution systems: a pilot-scale assessment

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ABSTRACT

Disinfection efficacy was evaluated in four pilot-scale systems that were operated at four water utilities across North America. Through this approach, factors which are difficult to simulate in a laboratory environment (such as water properties, process conditions, climatic conditions) were assessed, in order to determine their influence on disinfectant effectiveness. The results from this study show that a critical level of disinfectant residual (C_{crit}) was necessary for inhibiting heterotrophic bacterial growth to less than $500\,CFU\,ml^{-1}$ in the effluent of these pilot-scale systems. When free chlorine was the disinfectant, this critical residual concentration was found to be approximately $0.6\,mg\,L^{-1}$. A total chlorine concentration of $1\,mg\,L^{-1}$ resulted in low bacterial counts with chloramine disinfectants, though approximately 10–20% of this residual was found to be comprised of slowly degradable organic chloramines which are less effective as disinfectants. A higher ductile iron pipe corrosion rate was observed with a free chlorine disinfectant as compared with chloramines. The results from this study are likely to be of interest to water utilities responsible for the operation and optimization of drinking water distribution systems.

Key words | chlorine, corrosion, disinfection, monochloramine, organic chloramines, pilot-scale

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INTRODUCTION

Final disinfection is the process of applying a disinfectant which provides a residual concentration in the distribution system and the primary mitigation step used by utilities for controlling microbiological growth in distribution systems. Not surprisingly, most North American treatment plants strive to ensure that a disinfectant residual is maintained throughout the distribution system. In the US, The Total Coliform Rule (TCR) promulgated in 1989 is associated with the SWTR and established a maximum contaminant level goal (MCLG) of zero coliforms. The TCR requires that a

minimum disinfectant residual of $0.2\,mg\,L^{-1}$ for free chlorine and $0.5\,mg\,L^{-1}$ for chloramines be present throughout the distribution system continually. In Canada, disinfectant concentration requirements vary by province from ensuring "detectable" levels to ensuring a minimum concentration value in a manner similar to the TCR. For example, in the province of Ontario free chlorine must be maintained at a concentration of at least $0.2\,mg\,L^{-1}$ and at most $4\,mg\,L^{-1}$ at all locations in the distribution system, while utilities applying chloramines must maintain at least $1\,mg\,L^{-1}$ and

at most $3\,mg\,L^{-1}$ of chloramines at all locations (Ontario Ministry of Environment 2001). In Europe, emphasis has been placed on removal of biodegradable organic matter (BOM) and other nutrients which may cause microbial growth in the distribution system (van der Kooij *et al.* 1999). However, North American practice has identified disinfectant residuals as a critical component of the total quality management of distribution systems. In particular, Haas (1999) raised three arguments which support the maintenance of a disinfectant residual and are presented herein:

- a residual minimizes the propensity for regrowth or reinoculation (from the biofilm) of indicator or pathogenic vegetative microorganisms;
- a residual reduces the risk of general contamination from exogenous intrusions into the distribution system; and,
- a residual serves as a sentinel of any breach in system integrity and can detect intrusion more rapidly than microbial monitoring.

In order to meet these goals, understanding the factors which affect the loss of disinfection efficacy in distribution systems remains a significant challenge for the water industry. Disinfectant residuals can also lead to the degradation of water quality and distribution system materials by causing pipe corrosion (AWWA 1999; McNeill & Edwards 2001; Eisnor & Gagnon 2004). In particular, understanding the effects of secondary disinfection factors on copper corrosion has become an important issue for the water industry because of information concerning chloramines and lead corrosion (Renner 2004). The objective of this study was to evaluate the effect of free chlorine and chloramine residuals on water quality in pipe loop systems constructed of PVC, ductile iron or cast iron pipe.

In North America, free chlorine is the most widely used disinfectant for treating drinking water (Clark *et al.* 1994; AWWA Disinfection Committee 2000). Chloramines are also frequently used in distribution systems, as they have been found particularly effective in reducing the formation of disinfection by-products (DBPs), and controlling the growth of biofilms in distribution systems (LeChevallier *et al.* 1990; Kirmeyer *et al.* 1993; Norton & LeChevallier 1997). However, organic chloramines, are known to be ineffective disinfectants (Feng 1966; Stringer *et al.* 1977; Wolfe *et al.* 1984; Donnermair & Blatchley 2003), and may even inhibit the bactericidal properties of inorganic chloramines (Wolfe *et al.* 1985). Organic chloramines can be produced from the chlorination of certain organic nitrogen compounds (e.g. amino acids and nitrogen heterocyclic aromatics). The presence of organic chloramine species may obstruct the measurement of total chloramine residuals, resulting in deceptively high estimates of inorganic chloramine levels. The formation of organic chloramines in water distribution systems is clearly undesirable, and their prevalence in the pilot-scale systems examined in this study is addressed.

Numerous factors affect disinfectant efficacy and water quality in distribution systems, such as hardness, alkalinity, pH, hydraulic retention time (HRT), organic carbon content, water temperature, among others. Hardness, alkalinity and pH have also been shown to have an impact on the corrosivity of water in distribution systems (Droste 1997). Waters with high levels of hardness and alkalinity tend to precipitate $CaCO_3$, which forms a protective layer on pipes and inhibits corrosion. Studies have shown that soft waters with low alkalinity enhance corrosion on cast iron (Maddison *et al.* 2001) and ductile iron (Facey & Smith 1995) pipes. In general, low pH values cause higher corrosion rates, whereas high pH can decrease the solubility of pipe materials, lowering corrosion rates (Schock 1999). In this work, the impact of pipe corrosion on water quality was investigated in each pilot-scale system.

In this study, four full-scale water treatment plants were selected to provide a variety of water properties, operational conditions and final disinfectants for testing the effects of disinfectant residuals on water quality. Two of the plants used free chlorine as distribution system disinfectant residual, whereas the other two plants used chloramines as final disinfectant. Two of the plants treated soft waters with low alkalinity, while the other two plants treated hard, alkaline waters. The effect of water quality on the distribution systems was examined using a specially designed pipe loop system. At each of the four treatment plants, pilot-scale pipe loop systems were operated to perform tests at various hydraulic retention times (HRTs), with the final disinfectant used at each location.

MATERIALS AND METHODS

Experimental setup

Pilot-scale testing was conducted using a pipe loop system at four water treatment utilities. Descriptions of the utilities and the specific treatment plants providing water for the study are provided in the following subsection. Each utility operated and maintained four pipe loops which received treated and disinfected water from the plant without any further chemical additions. A schematic of the pipe loop is shown in Figure 1. The pipe loops consisted of seven main components: the test section (composed of 100 mm diameter pipe), the recirculation pump, the support frame, the return section, the transition section, the feed pump and the influent/effluent sample ports.

A recirculating pipe loop configuration was used as opposed to a once through flow regime because a previous study using the same pipe and once through configuration found no observable changes in water quality between the influent and effluent (Maddison *et al.* 2001). Further, the recirculating system is consistent with the design for previous pipe loop designs which were intended to study disinfection / bioiflm characteristics in distribution systems (Eisnor & Gagnon 2003). As well, the recirculating system allows retention times of up to 24 hours to be simulated with a pipe velocity representative of a real distribution system. With a once through system the retention would be under 30 seconds with a similar velocity.

Each pipe loop consisted of a pipe section, a recirculation pump, influent and effluent water ports and on-line corrosion probe will be provided for selected pipe loops. The test pipe for each loop is a 1.8 m (6′) length of 100 mm (4″) unlined cast iron pipe, as manufactured according to ANSI/AWWA standard C104/A21.4-95.
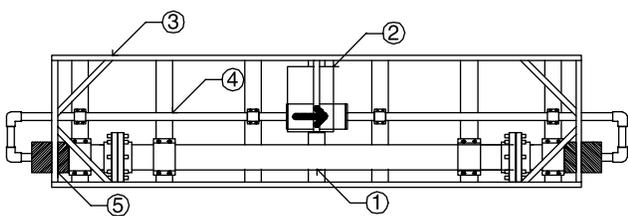
Figure 1 | Schematic of the recirculating flow pipe loop. (1) test section, (2) recirculation pump, (3) support frame, (4) return section, (5) transition section. The feed pump and influent/effluent sample ports are not shown.

Water was recirculated using a centrifugal pump rated at 146 L min^{-1} (38.5 gpm (US)) at 2.1 m (7.0′) of head through 25 mm (1″) PVC pipe (Schedule 40) and pipe fittings. The pump was sized based on a desired velocity of approximately 0.30 m s^{-1} (1 fps) in the cast-iron section, which was typical of actual velocities in a distribution system (McAnally & Kumarawamy 1994; MacKoul *et al.* 1995; Camper 1996). The corrosivity of the water in each of the loops was measured using linear polarization probes (Corrator®, Corrpro Canada Inc.). The linearization probe was mounted in line prior to the influent feed port.

The influent feed port and effluent drain port consisted of 6.4 mm (1/4)′ PVC gate valves. The influent feed port was located on the suction side of the centrifugal pump. The effluent drain port is located on the top of the 100 mm (4″) PVC header. The effluent drain port remained open during the experiment (approximately 8–9 months).

Description of water treatment plants

The influent water properties at each location are presented in Table 1. The four locations tested exhibited variability in the source water quality and treatment processes. The raw water at Waterloo and JVWTP contained high hardness and alkalinity, while Halifax and East Bay Municipal Utility District (EBMUD) exhibited very low hardness and alkalinity. The pH at EBMUD was substantially higher than the other plants. Halifax and Jordan Valley Water Treatment Plant (JVWTP) used free chlorine as final disinfectant, while Waterloo and EBMUD used chloramines. Descriptions of the four water treatment plants which fed the pipe loops over the course of the study are provided below:

Halifax Regional Water Commission (Halifax, Nova Scotia)

The J. Douglas Kline Water Supply Plant (JDKWSP) is a direct filtration plant with free chlorine as its primary and final disinfectant. The water source for the JDKWSP is Pockwock Lake, which is in a protected watershed and is characterized by its low alkalinity (< 5 mg L^{-1} as CaCO$_3$) and turbidity (< 0.5 NTU). Treatment begins with the addition of lime and potassium permanganate for the oxidation of iron and manganese. pH is then lowered

Table 1 | Average and standard deviation of influent conditions at each site

	Halifax	Waterloo	JVWTP	EBMUD
Alkalinity (mg $CaCO_3 L^{-1}$)	15 ± 13	177 ± 27	108 ± 30	22 ± 11
Hardness (mg $CaCO_3 L^{-1}$)	8 ± 1	144 ± 22	87 ± 7	12 ± 2
Temperature (°C)	7.1 ± 3.9	12.0 ± 2.4	10.0 ± 2.1	14.8 ± 1.2
pH	7.4 ± 0.2	7.4 ± 0.04	6.7 ± 0.2	9.2 ± 0.3
TOC (mg L^{-1})	2.0 ± 0.3	2.4 ± 0.4	1.9 ± 0.3	1.5 ± 0.2

using carbon dioxide, and the water is coagulated using alum. During the cold weather months from December to June, polymer is added. Free chlorine is added prior to filtration and the water was stored in a clearwell prior to distribution. Free chlorine and fluoride are added as the water leaves the clearwell for distribution, along with sodium hydroxide and polyphosphate for pH adjustment and corrosion control.

Regional Municipality of Waterloo (Waterloo, Ontario)

The Mannheim Water Treatment Plant (MWTP) is a conventional filtration plant with free chlorine as primary disinfectant and monochloramine as the final disinfectant. Water from Grand River is stored in a 145,000 m³ (38MG) reservoir for several days prior to being pumped into the treatment plant. This reduces the turbidity and provides consistent water quality to the plant. Treatment consists of two parallel streams, each consisting of coagulation with alum, flocculation, sedimentation, ozonation, filtration and chlorination. Four filters containing GAC and sand were operated in biological mode. In the plant effluent, the water was blended with ground water from the wells, chloraminated and distributed.

Jordan Valley Water Conservancy District (Bluffdale, Utah)

Two plants provided water to the pipe loops over the course of the project: Jordan Valley Water Treatment Plant (JVWTP) and Southeast Regional Water Treatment Plant (SERWTP). The pipe loops were set up at the JVWTP and received water from that plant for the majority of the study. For a three-month period, JVWTP was shut down for modifications and SERWTP provided water to the pipe loops. Both plants use the same primary water source, which is the Deer Creek Reservoir and is fed from the Provo River. Accordingly, both plants have similar raw water quality and treatment processes. The main difference is that JVWTP uses a conventional clarification process, whereas SERWTP uses a high-rate up-flow clarifier. At each plant, treatment consists of coagulation with alum and cationic polymer, flocculation, sedimentation and filtration. Taste and odors are controlled as needed with the addition of potassium permanganate and/or PAC. Free chlorine is added for primary disinfection prior to filtration. Filtered water then enters a reservoir and free chlorine is added as the final disinfectant prior to distribution.

East Bay Municipal Utility District (Oakland, California)

During most of the study, the pipe loops were operated with water from EBMUD's largest plant, the Orinda Water Treatment Plant which is supplied surface water from the Pardee Reservoir. The Orinda plant treatment sequence consists of chemical pre-treatment, in-line filtration, and chemical post treatment. Coagulation is done with poly-aluminum chloride and cationic polymer addition, and filtration is performed on dual-media, anthracite and sand filters. After filtration, monochloramine, fluoride, sodium hydroxide and ammonia are added to the water.

Analytical methods

Heterotrophic plate counts (HPCs) were enumerated using the spread plate method with incubation on R2A agar as described in APHA *et al.* (1998). Plates were incubated at 20°C for 7 days. All microbial enumeration was performed in duplicate. Alkalinity, hardness and TOC were analysed according to standard methods (APHA *et al.* 1998).

Analysis of total chlorine incorporated free chlorine, inorganic chloramines (monochloramine, dichloramine and nitrogen trichloride) and organic chloramines. At all

locations free and total chlorine were measured using DPD spectrophotometric method (*Standard Method for the Examination of Water and Wastewater, 19th edition*–4500 D). The reported method detection limit in this study was $0.05\,mg\,L^{-1}$. At Waterloo, additional analytical methods were employed to characterize organochloramines. In particular the amperometric titration method (APHA *et al.* 1998) was used in this study to measure free and total chlorine in all samples, using a Wallace & Tiernan amperometric titrator Series A-790 (USFilter/Wallace & Tiernan Canada, Inc., Markham, Ontario). Phenylarsene oxide (PAO) was the reducing agent used in the titrating solution, at a concentration of 0.000564 N. The detection limit was $0.01\,mg\,L^{-1}$ of residual chlorine.

Inorganic chloramines (i.e. monochloramine and dichloramine) were determined using high performance liquid chromatography (HPLC) for samples collected at Waterloo, through a post column reaction with potassium iodide and electrochemical detection. A Dionex DX-500 ion chromatograph (Dionex Canada Ltd., Oakville, Ontario) was used, which consisted of an AS-40 automated sampler, LC-25 chromatography oven, GP-40 gradient pump, ED-40 electrochemical detector and a PC-10 pneumatic controller (reagent delivery method). The eluent solutions used were as follows (both at a pH of 6.2): mobile phase A was a 10:90 CH_3-CN/phosphate solution, while mobile phase B was a 70:30 CH_3CN/phosphate solution. The flow rate was one $ml\,min^{-1}$, with a linear gradient of 4:1–1:4 (A:B ratio) in 20 minutes. The samples were subjected to a post column reaction with 0.09 M KI in 0.294 M sodium acetate at a flow rate of $0.5\,ml\,min^{-1}$. The ED40 electrochemical detector measured current resulting from the application of 0.1 V across the electrodes in flowthrough cells. Andrews & El-Farra (2000) reported the detection limit to be $0.01\,mg\,L^{-1}$ in a similar system. The organic chloramine concentrations were determined through subtracting the monochloramine and dichloramine concentrations, obtained through HPLC, from the total chlorine concentration measured through amperometric titration (Andrews & Cheng 2000).

Corrosion rate

Corrosion rates were measured using two-electrode linear polarization Corrator® probes, Model 6112 (Rohrback Cosasco Systems, Santa Fe Springs, CA). The two Corrator® probes were composed of carbon steel. The electrode Corrator® probes provide a direct measure of corrosion rate and a qualitative pitting tendency of metals in electrolytes. Measurement is based on linear polarization techniques, which rely on the nearly linear relationship between current and voltage when the surface potential offset is in close proximity to the freely corroding surface potential measures (Reiber *et al.* 1996). Linear polarization probes and instruments interact with the electrochemical corrosion mechanism in order to determine the rate at which the metal is corroding.

RESULTS AND DISCUSSION

Disinfection in the pipe loops

Table 2 shows the average free and total chlorine residual concentrations, as well as the bacterial counts (HPCs) in the pipe loops at each location. The only location which was able to maintain a minimum disinfectant residual of $0.2\,mg\,L^{-1}$ for free chlorine or $0.5\,mg\,L^{-1}$ for total chlorine in the effluent of all pipe loop conditions was EBMUD. None of the other locations were able to maintain these levels beyond the 6 hour HRT loops. At the other sites low chlorine residuals were often observed in pipe loops with longer retentions times. Weekly variations in the free and total chlorine residuals were observed at all of the sites. Not surprisingly, the consistent trend between plants was that the chlorine residual in the pipe loop influent increased during warmer months, as is shown in Figure 2 for the case of Jordan Valley. Nevertheless, the effluent chlorine concentration did not increase in the effluent during these warmer months, as chlorine decay in the pipe loops increased during the warmer months (Figure 2).

The average bacterial count in the EBMUD pipe loops was lower than at the other three facilities (Table 2), correlating well with the observed residual concentrations. Longer HRTs were also correlated with higher numbers of heterotrophic bacteria in the effluent of each system. Interestingly, the DOC concentration was not affected by water age, as the DOC concentration was not significantly different between the influent water and the effluent water

Table 2 | Average and standard deviation of free and total chlorine residuals, and HPC concentrations in each pipe loop

		Free Cl_2 (mgL^{-1})	Total Cl_2 (mgL^{-1})	HPC (CFUml^{-1})
Halifax	Influent	0.6 ± 0.1	0.7 ± 0.1	$5.8 \times 10^{-1} \pm 2.1 \times 10^{-2}$
	6-h	0.3 ± 0.1	0.4 ± 0.1	$1.8 \times 10^{-3} \pm 4.4 \times 10^{-3}$
	24-h	0.1 ± 0.0	0.1 ± 0.0	$4.7 \times 10^{-3} \pm 5.7 \times 10^{-3}$
Waterloo	Influent	0.1 ± 0.0	1.3 ± 0.1	$2.3 \times 10 \pm 6.1 \times 10$
	6-h	0.1 ± 0.0	1.1 ± 0.1	$5.1 \times 10^{-2} \pm 2.0 \times 10^{-3}$
	24-h	0.0 ± 0.0	0.3 ± 0.0	$4.1 \times 10^{-4} \pm 9.8 \times 10^{-4}$
JVWTP	Influent	0.9 ± 0.5	1.0 ± 0.5	$8.2 \times 10^{-1} \pm 3.8 \times 10^{-2}$
	6-h	0.5 ± 0.3	0.6 ± 0.3	$1.8 \times 10^{-3} \pm 3.9 \times 10^{-3}$
	24-h	0.1 ± 0.1	0.1 ± 0.1	$1.6 \times 10^{-4} \pm 2.4 \times 10^{-4}$
EBMUD	Influent	0.0 ± 0.0	2.1 ± 0.3	$6.0 \times 10^{-2} \pm 2.8 \times 10^{-3}$
	6-h	0.1 ± 0.0	2.0 ± 0.2	$9.1 \times 10^{-1} \pm 3.9 \times 10^{-2}$
	24-h	0.0 ± 0.0	1.7 ± 0.2	$3.1 \times 10^{-2} \pm 1.3 \times 10^{-3}$
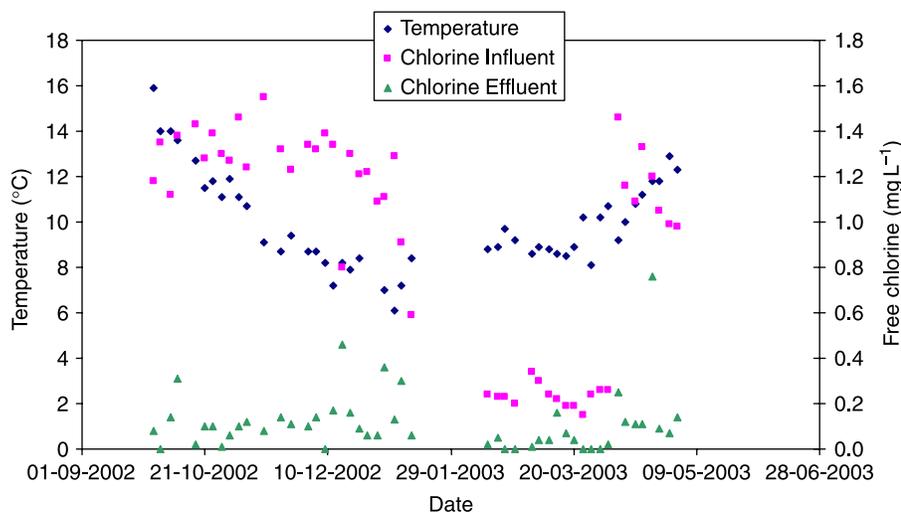
Figure 2 | Seasonal variation of free chlorine in the influent and effluent of the Jordan Valley pipe loop.

for any pipe condition at all locations. Consistent with full-scale studies (e.g. LeChevallier et al. 1987; Volk et al. 2002) water age plays an important role in increasing bacterial concentrations in distribution systems. At a mechanistic level, DiGiano & Zhang (2004) found that the extent of bacterial regrowth was affected mainly by the rate constants for chlorine decay reactions in bulk water and on the pipe wall and by the maximum growth rate constant of attached bacteria. Thus the impact water residence time is a reflection of the rate kinetics of the disinfectant residual and bacteria growth.

Disinfectant levels necessary to prevent bacterial growth

As discussed by Huck & Gagnon (2004), for most distribution systems there is a very specific critical growth region for heterotrophic bacteria. The critical growth region is bounded by a disinfectant residual concentration of 0 mg L^{-1} and C_{Crit}, the critical disinfectant residual concentration. For disinfectant concentrations greater than C_{Crit}, the effect of water quality conditions on enabling growth conditions is minimized. However for residual concentrations less than C_{Crit},

water quality will have a significant effect on microbial growth in the distribution system. Although the C_{Crit} concept can be applied to any distribution system, it is limited to chronic symptoms (such as changes in pH, turbidity, corrosion) in a distribution system which may impact microbial growth rather than acute changes such as microbial breaches in distribution system integrity.

Figure 3 shows the bacterial growth in the pipe loops as a function of free chlorine residual, for the Halifax and JVWCD plants where free chlorine was the final disinfectant. In general, a higher free chlorine residual corresponded to lower numbers of heterotrophic bacteria. The USEPA (1989) recommends an HPC concentration less than 500 CFUml^{-1} in drinking water systems. Figure 4 shows the percentage of occasions where this limit was exceeded, at different disinfectant levels. In each pipe loop, the HPCs exceeded 500 CFUml^{-1} less than 15% of the time at free chlorine concentrations greater than 0.6 mg L^{-1}, while bacterial growth was undetectable at free chlorine concentrations greater than 1 mg L^{-1}. However, the recommended free chlorine residual concentration for preventing bacterial growth in distribution systems is generally 0.2 mg L^{-1}. In this study, the HPC limit was frequently exceeded (>50% of the time in both loops) when the free chlorine residuals were between 0.2 and 0.6 mg L^{-1}, suggesting that a 0.2 mg L^{-1} residual was insufficient for preventing bacterial regrowth. Frequent breaches (>70% of the time) in the HPC limit were observed in both plants at free chlorine concentrations less than 0.2 mg L^{-1}. Clearly, a sufficient disinfectant residual concentration is necessary for preventing bacterial growth. Results from this study based on the characteristics of both plants suggest that a C_{Crit} closer to 0.6 mg L^{-1} would be more appropriate than 0.2 mg L^{-1} for controlling heterotrophic bacteria in distribution systems. Similarly, Besner *et al.* (2001) found in a full-scale sampling campaign that 10–15% of the samples which contained less than 0.2 mg L^{-1} of free chlorine had heterotrophic bacteria concentrations greater than 10 CFUml^{-1}. However Besner *et al.* (2001) also found at free chlorine concentrations greater 0.65 mg L^{-1} samples never had HPCs greater than 10 CFUml^{-1}. In a full-scale
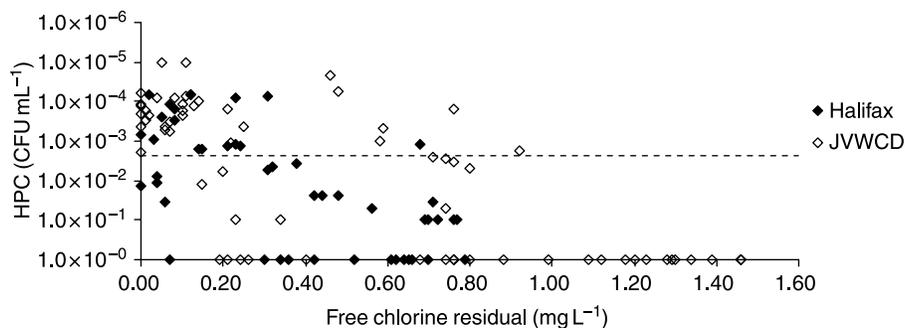

Figure 3 │ Bacterial growth as a function of free chlorine residual in the plants where chlorine was the final disinfectant. The dashed line represents an HPC count of 500 CFU ml^{-1}.
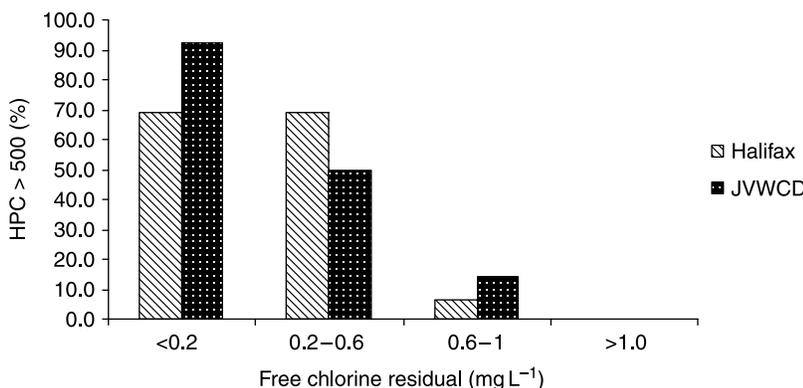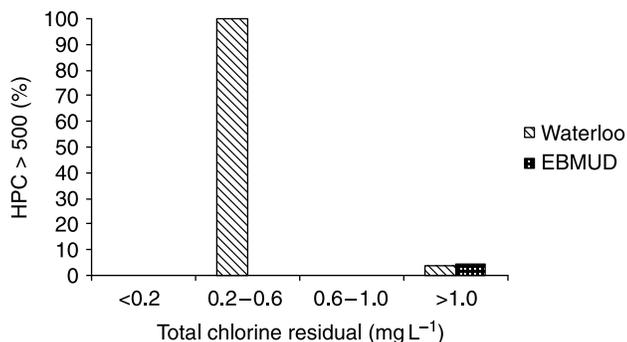

Figure 4 │ Occurrence of excessive HPC concentration (greater than 500 CFU ml^{-1}) as a function of residual in the free chlorine plants.

assessment of coliform occurrence LeChevallier et al. (1996) reported that the lowest level of coliform occurrence was achieved by maintaining 0.5 mg of free chlorine per litre or 1 mg chloramines per litre.

In the Netherlands and many European countries biological stability in distribution systems is achieved by minimizing nutrient availability and thus little or no disinfectant residual is provided during distribution (van der Kooij et al. 1999). This is largely a result of concerns related to the formation of harmful disinfection by-products or consumer perceptions of chlorinated water (van der Kooij et al. 1999). Although the turbidity of drinking water in the Netherlands is kept to levels below 0.04 NTU in the distribution system in the absence of chlorine, the particle volume concentration (for particles greater than 1 μm) has been observed to increase by a factor forty from the treatment plant to the extremities of the system (Verberk et al. 2007). Furthermore, Lehtola et al. (2004) reported that heterotrophic bacteria exceeded 1000 CFUml^{-1} in the distribution system for two European cities (Riga, Latvia and Kuopio, Finland) in which the free chlorine concentration was below 0.1 mg L^{-1}. Similarly, a Belgium study found that for drinking water with low concentration of biodegradable dissolved organic carbon (BDOC), less than 0.25 mg L^{-1} of BDOC, required a minimum of 0.07 mg of free chlorine per litre to suppress biomass in the distribution system (Niquette et al. 2001). Thus, the literature suggests there is a need to define a C_{crit} value, which may range for free chlorine from as low as 0.05 mg L^{-1} (or detectable) to as high as 0.6 mg L^{-1}. The interaction between available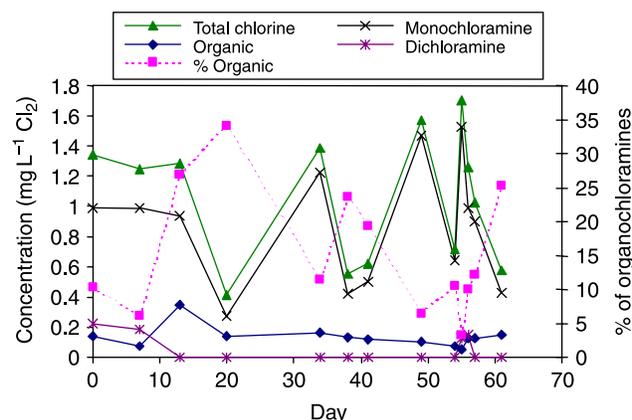 nutrients (LeChevallier et al. 1996), pipe material (Camper et al. 2003), system hydraulics (Batte et al. 2003) and other factors such as temperature would need to play a role in defining C_{crit} for a specific system.

Figure 5 shows the frequency of bacterial growth greater than 500 CFUml^{-1} in the chloraminated pipe loops. At EBMUD, the total chlorine residual was always maintained above 1 mg L^{-1} in each pipe loop, and thus the total number of heterotrophic bacteria observed at this location were generally below the 500 CFUml^{-1} limit. At Waterloo, the total chlorine residual was maintained above 1 mg L^{-1} in the pipe loop with a 6 hour HRT, which resulted in very low bacterial counts. However, the residual was only maintained between 0.2 and 0.4 mg L^{-1} in the loop with a 24 hour HRT, thus resulting in HPC levels which were consistently higher than 500 CFUml^{-1} (Table 2). The results from this study suggest that a total chlorine concentration greater than 1 mg L^{-1} is sufficient for preventing bacterial growth in distribution systems with a chloramine disinfectant.

Organic chloramines

In the Waterloo plant, where chloramines were used as the final disinfectant, the prevalence of undesirable organic chloramines was assessed, in order to determine its effect on the disinfection capacity of the system. The influent total chlorine and composition of inorganic and organic chloramines are shown in Figure 6. Free chlorine and nitrogen trichloride were not detected throughout the study. The vast majority of the inorganic chloramine was in the form of
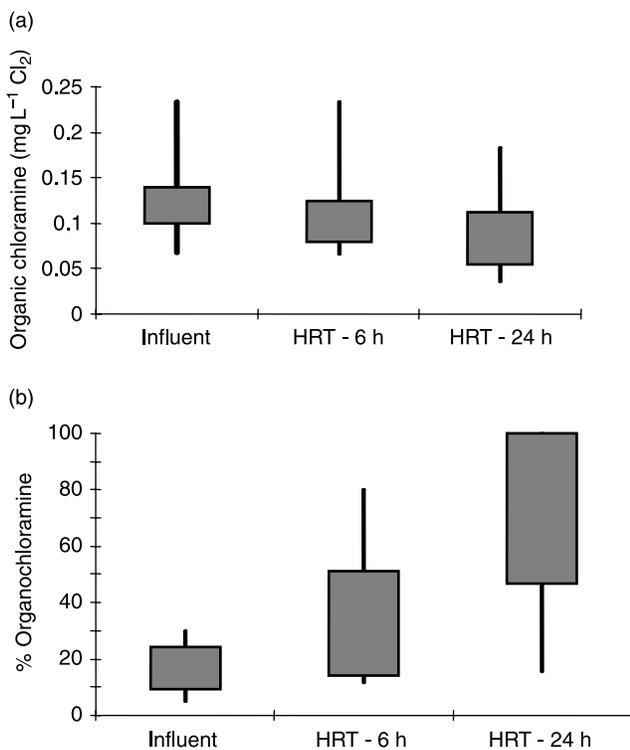
Figure 5 | Occurrence of excessive HPC concentration (greater than 500 CFU ml^{-1}) as a function of residual in the chloraminated plants.

Figure 6 | Chlorine composition in the influent to the Waterloo pipe loops.

monochloramine, while dichloramine was present only in low concentration, often below the method detection limit. The organic chloramine content remained reasonably stable throughout the study with an average concentration of 0.13 mg $Cl_2 L^{-1}$ (± 0.07). Therefore, organic chloramines often comprised approximately 10–20% of the total chlorine residual in the Waterloo drinking water treatment plant.

Figure 7 shows the organic chloramine concentration (Figure 7(a)) and the percentage of organic chloramines per total chlorine (Figure 7(b)), in the Waterloo pipe loops. The concentration of organic chloramine remained relatively stable throughout the pipe loops, little organic chloramine appeared to be produced or consumed. However, a 24 h HRT resulted in a much lower chlorine residual than the 6 h HRT (see Table 2), thus the fraction of organic chloramine rose due to the reduction in total chlorine concentration. In particular, the data presented Table 2 show that the total chlorine residual was less than 0.5 mg L^{-1} in the 24 h pipe loop. Furthermore, in Figure 5 it is clear that the number of

heterotrophic bacteria was greater than 500 $CFUml^{-1}$ for this samples less than 0.5 mg L^{-1} of total chlorine in the Waterloo pipe loops. From the data presented, it is not possible to determine inactivation kinetics of organochloramine, however given the preponderance of heterotrophic bacteria detected at low total chlorine levels it is expected that their biocidal capabilities are low relative to other chemical disinfectants, such as free chlorine. Similarly, under more controlled laboratory conditions, Donnermair & Blatchley (2003) found that the organic chloramines examined in this research had little or no effect on the viability of *E. coli*.

The increased proportion of organic chloramines appeared to be largely due to their slower degradation rate as compared to inorganic chloramines. This suggests that organic chloramines decay at a slower rate than inorganic chloramines, which is in agreement with literature evidence that they are less effective as disinfectants. This also suggest that at remote areas of the distribution system, the chloramine residual measured consists most likely of organochloramines only, as organochloramines interfere with field methods for chlorine residual analysis. This is a concern to water suppliers, considering that organochloramines are less effective disinfectants than inorganic chloramines.

Corrosion of pipe loops

The rate of corrosion measured in each pipe loop is shown in Figure 8. HRT had only a limited influence on the

(a)

(b)

Figure 7 | Organic chloramine content in the Waterloo pipe loops, as concentration (a) and percentage of total chlorine content (b). The top and bottom of the box represent the 75th and 25th percentile, respectively, while the whiskers represent the 95th and 5th percentile, respectively.
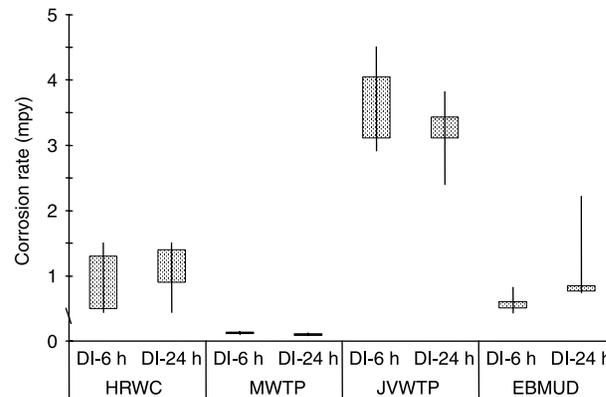
Figure 8 | Corrosion rates in mils per year (mpy) measured at all sampling sites. The top and bottom of the box represent the 75th and 25th percentile, respectively, while the whiskers represent the 95th and 5th percentile, respectively.

corrosion rate at each plant. The corrosion rates were significantly greater at the free chlorinated sites than at the chloraminated sites. This result is in contrast with the study performed by Eisnor & Gagnon (2004), who observed chloramines to be more corrosive than free chlorine. However, the study of Eisnor & Gagnon (2004) was conducted using cast-iron pipe with water from Halifax only, suggesting that these opposing observations may have been due to different pipe material (i.e., ductile iron) used between these two projects. The results from this study suggest that the corrosivity of free chlorine was greater than monochloramine on ductile iron pipes, in both hard and soft waters.

There were also differences observed in the corrosion rates between the two free chlorinated sites, Halifax and JVWCD. The lower corrosion rate observed at Halifax is likely explained by the use of corrosion inhibitors, lime and polyphosphate, by that utility. The other water utilities were not using any corrosion inhibitors, although the high alkalinity and hardness of the JVWCD water should have provided some corrosion protection in their pipe loops, through the formation of a $CaCO_3$ passivation layer. The high corrosion rate observed at JVWCD may have also been partially influenced by the lower pH (Schock 1999), which tends to increase corrosivity, or by the higher residual concentrations in the pipe loop influent (Table 2).

The corrosion rates observed in the free chlorinated pipe loops are shown in Figure 8 as a function of residual concentration for the Halifax (Figure 9(a)) and JVWCD (Figure 9(b)) systems. In the Halifax pipe loops, a general decrease in corrosion rate was observed at residual concentrations above $0.4 \, mg \, L^{-1}$. This effect may have been related to the lower bacterial counts at the higher residual concentrations, resulting in lower bacterial
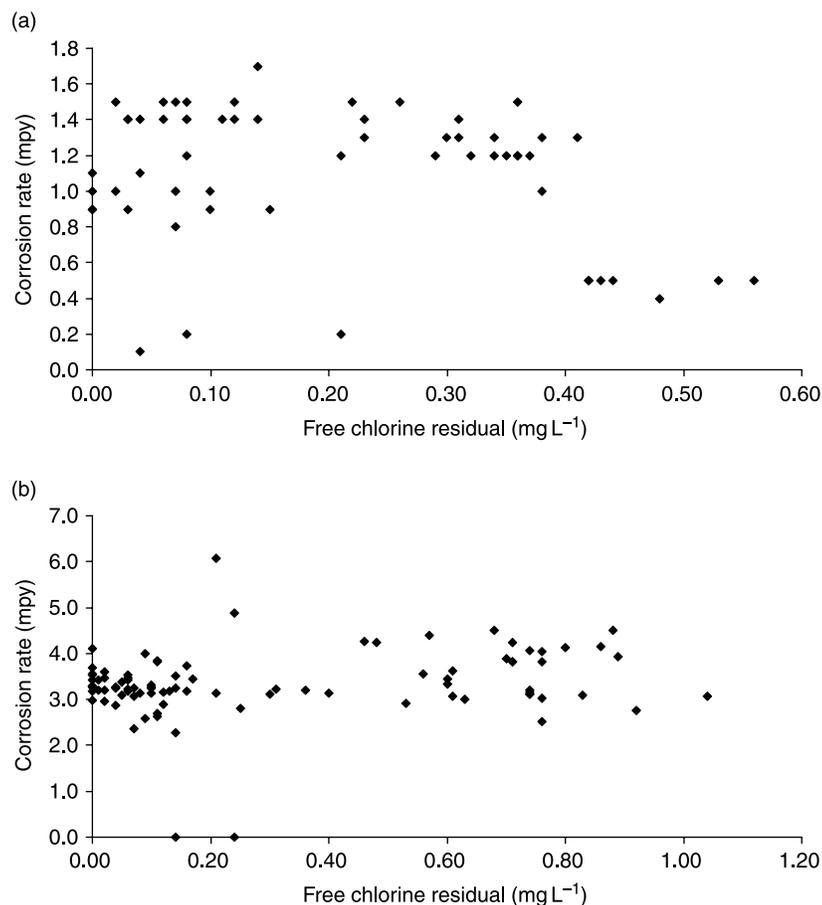
(a)

(b)

Figure 9 | Corrosion rate in mils per year (mpy) as a function of free chlorine residual in the Halifax (a) and JVWCD (b) pipe loops.

corrosion in the system. However, this effect was not observed in the Jordan Valley pipe loops, where corrosion rate did not seem to be affected by residual concentration. It is possible that the higher corrosion rates observed in the JVWCD pipe loops led to higher bacterial counts relative to the Halifax loops, as shown in Table 2.

CONCLUSIONS

The results from this study show that maintaining a sufficient disinfectant residual was necessary for inhibiting bacterial growth in pilot-scale systems. With a free chlorine disinfectant, a critical residual concentration for preventing microbial contamination was found to be $0.6\,\mathrm{mg\,L^{-1}}$ for the conditions studied, which is not intended to be a threshold value for drinking water disinfection. Rather this paper demonstrates a strategy to determine C_{crit} for a specific water quality, pipe condition and water age. A total chlorine concentration of $1\,\mathrm{mg\,L^{-1}}$ resulted in low bacterial count with chloramine disinfectants, though approximately 10–20% of this residual was found to comprise slowly degradable organic chloramines which are less effective as disinfectants. A higher ductile iron pipe corrosion rate was observed with a free chlorine disinfectant as compared with chloramines. Overall, the results from this study are likely to be of interest to those responsible for the operation and optimization of drinking water distribution systems.

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