Tracer study to verify hydraulic limits and determine water residence times in a distribution system: Part I

François-Julien Delisle, Simon Rochette, Geneviève Pelletier and Manuel J. Rodriguez

ABSTRACT

This study introduces a methodology for assessing the residence times of drinking water in distribution systems using a tracer. The injection of a tracer followed by an intensive sampling campaign was used to evaluate the residence times of water in Quebec City's main system, which is supplied by the St Charles River. Samples were also analysed to determine the hardness and conductivity of the water in order to identify interconnections with a neighbouring system supplied by the St Lawrence River, a source with different properties. To validate the assumptions of interconnectivity, a complementary conductivity campaign was carried out. The tracer campaign allowed us to obtain the mean residence times (MRTs) within the study area and to target areas with low and high MRTs between 6 and 33 h. The mixing zones between water from the various sources and with longer MRTs following a stay in a reservoir were also identified. Results of this study were used to develop strategies to minimise MRT in order to improve water quality. These strategies are presented in the 'companion paper' (Part II) in this issue.

Key words | conductivity, hardness, tracer study, water distribution systems, water quality, water residence time

François-Julien Delisle
Roche Ltd Consulting Group,
Quebec City, Quebec,
Canada

Simon Rochette
Department of Civil and Water Engineering,
Université Laval,
Quebec City, Quebec,
Canada

Geneviève Pelletier (corresponding author)
Department of Civil and Water Engineering,
Faculty of Science and Engineering, Université Laval, Pavillon Adrien Pouliot, 1065, avenue de la Médicine,
Quebec City, Quebec G1V 0A6,
Canada
E-mail: *genevieve.pelletier@gci.ulaval.ca*

Manuel J. Rodriguez
ESAD, Université Laval,
Quebec City, Quebec,
Canada

ABBREVIATIONS

DS	water distribution system
DBP	disinfection by-product
LT	Lower Town
MRT	mean residence time
S1	Sillery
S2	Saint-Sacrement
UL	Université Laval
UT	Upper Town
WTP	water treatment plant

INTRODUCTION

It is important for operators, managers and especially consumers that drinking water quality is excellent, safe, and exempt from unwanted taste and odour. A physicochemical treatment suited to the characteristics of the water source is typically used to reduce the various microbiological contaminants liable for its colour, taste and odour and to inactivate or remove pathogenic organisms responsible for waterborne diseases. A secondary disinfectant is usually injected into the water at the entrance of the water distribution system (DS) to prevent the growth of pathogenic organisms throughout the residence-life of water in the pipes (Prévost *et al.* 1998).

For over a century, chlorine has been the most commonly used secondary disinfectant because of its effectiveness and low cost (Crittenden *et al.* 2005; Gopal *et al.* 2007). Injected at the end of the treatment process, it acts as a chemical barrier to prevent microbiological growth in the DS. However, this disinfectant reacts with the organic matter naturally found in water to produce disinfection by-products (DBPs) (Gallard & von Gunten 2002; Rodriguez *et al.* 2007). Chlorine's response to organic and

doi: 10.2166/aqua.2014.050

inorganic substances in the water leads to a decrease in the concentration of free residual chlorine, thus weakening the barrier preventing the regrowth of microorganisms in the DS. For Quebec City's DS, located in a northern climate, strong seasonal variations and significant spatial variations in residual chlorine concentrations, DBP concentrations and microbiological quality were observed by Rodriguez *et al.* (2004) and Francisque (2009).

Since it is widely accepted that water quality decreases over time (e.g., Zhang & DiGiano 2002; Hallam *et al.* 2002; Al-Jasser 2007), it is useful for system operators to know the mean residence time (MRT) at different locations in the DS in order to consider various strategies to reduce it. This study aims to develop a methodology to determine the hydraulic limits of the system and to evaluate the MRT in the DS in order to improve the quality of the water distributed to consumers. A better understanding of these factors would help identify strategies to ensure greater residual chlorine concentrations in vulnerable areas and reduce the formation of DBPs. This methodology is developed and tested on the main DS of Quebec City, supplied by its main drinking water treatment plant (WTP). To achieve this objective, experimental MRTs were evaluated using a tracer study. Verification of the actual limits of the studied DS was also performed, as they may vary due to possible interconnections with adjacent DS.

EVALUATION OF MEAN RESIDENCE TIMES

Tracer studies

Tracers can be of great use for a better understanding of the behaviour of a real DS. They can be used to estimate MRT (DiGiano *et al.* 2005), to identify the limits of differently supplied areas (Simard *et al.* 2009) and to estimate unknown water demands (Al-Omari & Abdulla 2009), among other things. DiGiano *et al.* (2005) proposed an interesting technique to assess MRT using a tracer. Their method takes into account the mixing between the 'old' water that is already in the pipes and the 'new' water introduced during a tracer study. It involves following the decrease of tracer concentration in the pipe after the injection is completed at the WTP. The MRT is expressed as follows:

$$\mathrm{MRT} = \sum_{i=0}^{n} t_i \Delta F_i(t) \tag{1}$$

where i is the ith sample of water, t_i is the time elapsed since the tracer injection was stopped, $\Delta F_i(t)$ is the change in the fractional concentration F_i of the tracer over time which is defined as follows:

$$F_i(t) = \frac{C_{\mathrm{before}} - C_{t_i}}{C_{\mathrm{before}} - C_{\mathrm{after}}} \tag{2}$$

where C_{before} and C_{after} refer to the tracer concentration before and after the tracer injection was stopped. C_{after} is, in fact, the natural concentration of the tracer in the water.

DiGiano *et al.* (2005) compared the MRT calculated from the tracer concentrations observed in the field ($\mathrm{MRT_{field}}$) with MRT calculated from the tracer concentrations simulated using an EPANET model ($\mathrm{MRT_{model}}$). These MRT values were also compared with the average age of water ($\mathrm{AA_{EPANET}}$) predicted by the EPANET model (Rossman 2000). The $\mathrm{MRT_{model}}$ obtained in the study fitted well with the $\mathrm{AA_{EPANET}}$, with nine out of the twelve sampling stations having less than a 3-h difference between the two. However, major differences in simulated and measured tracer concentrations were observed, resulting in large gaps between $\mathrm{MRT_{field}}$ and $\mathrm{MRT_{model}}$. $\mathrm{MRT_{field}}$ ranged from 21 to 75 h and $\mathrm{MRT_{model}}$ ranged from 8 to 28 h, resulting in a mean absolute error of approximately 28 h between observations and simulations. These differences were explained by the insufficient number of pipes in the model (less than 35% of the real system, since only 12-inch diameter pipes or more were included in the model), an inadequate model calibration and an inaccuracy regarding water demands.

Furthermore, it is essential to consider the chemical behaviour regarding its degradation and its potential to react with other substances found in water in order to properly conduct a tracer campaign. In some cases, the type of material used for the pipes (walls) seems to play a role in the various tracer behaviours (Tamminen *et al.* 2008). A tracer must therefore be chosen carefully. Fluorides, for example, do not degrade or react easily with other substances with which they come into contact in the DS (Tzatchkov *et al.* 2002).

Advection, diffusion and dispersion are the most likely means of transportation for a tracer in water pipes (Tzatchkov *et al.* 2002). Advection is the transport of a solute (tracer) following the movement of a solvent (water). Diffusion is better defined as the tendency of the solute to travel in the solvent under the influence of a concentration gradient. Dispersion is due to the lack of uniformity of the velocity field, resulting in a random dispersion of the solute in the solvent (Tzatchkov *et al.* 2002). When the flow is laminar, dispersion appears to be the predominant mode of transport (Axworthy & Karney 1996; Tzatchkov *et al.* 2002). Low velocities associated with laminar flows are only observed during times of low consumption (at night) and in hydraulic dead-ends, namely the extremities of the system. In the transitional flow regime, which is the most common in DS, transport by advection largely dominates. Diffusion, being slower than dispersion, can be neglected.

Simard *et al.* (2009) used calcium chloride ($CaCl_2$) as a tracer to determine the supply patterns for a Quebec City neighbourhood. This neighbourhood has the particularity of being supplied by water coming directly from the WTP and by water from the same WTP but that had spent up to 3–5 days in a reservoir. The tracer study allowed the identification of those areas of the neighbourhood directly supplied by the plant, those supplied by the reservoir and those in the mixing zones.

Uncertainties about water demands

Uncertainties about water consumption (and its variation over time), as well as the lack of knowledge regarding the state of the pipes (real roughness, effective diameter, etc.), are the main sources of error associated with measured and simulated data (pressure, flow, tracer concentration, etc.) (Ormsbee 1989; Ormsbee & Lingireddy 1997; Al-Omari & Abdulla 2009). To these must be added communication problems between different city departments about specific events that can affect water demand and hydraulics (e.g., open/close state of the valves, water main leakage, fire-related site specific water demand, seasonal street cleaning, etc.).

A method for determining the water consumption using tracers was suggested by Al-Omari & Abdulla (2009). These authors believe that the lack of knowledge on water demand is the largest source of error between observations and simulations. Their technique is to identify unknown flows based on fluoride concentrations. When tested with EPANET models, they obtained good results when the number of observation sites is greater than the number of junctions where the demands are unknown. In this case, the percentage error between the actual flows and those determined by their technique varied between 0% and 2%. In the case where the number of observations is lower than the number of junctions, the percentage error was overall much larger; varying between 1% and 26%. This situation is by far the most common. In addition, to obtain good results, the authors suggest selecting junctions that are more sensitive to changes in flows for data collection. Since the sensitivity of the junctions is not necessarily known when a sampling campaign is planned, it would not be surprising to find percentage errors greater than 26% on real DS.

METHODOLOGY

Case study

The current methodology tests one DS from Quebec City (Canada). Although the various sub-systems that supply the city are usually independent, interconnections increase during periods of high demand in order to better balance hydraulic requirements. The study area (Figure 1) corresponds to several sectors of the main DS of Quebec City: the Lower Town (LT), the Upper Town (UT), Sillery (S1) and Saint-Sacrement (S2). Université Laval (UL) manages its own system. Drinking water comes from the WTP of Quebec, located north of the city. It is supplied by the St Charles River, a few kilometres downstream of St Charles Lake, which is used as a raw water reservoir. Once the water is treated, it is transported by three water mains of 750, 1,015 and 1,070 mm in diameter. The natural drop between the WTP and study area enables supply by gravity. Along the way, water is withdrawn from the mains, via valve chambers, to supply the different neighbourhoods on both sides of the primary and secondary pipe systems. Within this DS, there is also the Plains of Abraham reservoir, which can hold up to 130,000 m^3 of water and is supplied directly by the WTP. The water,

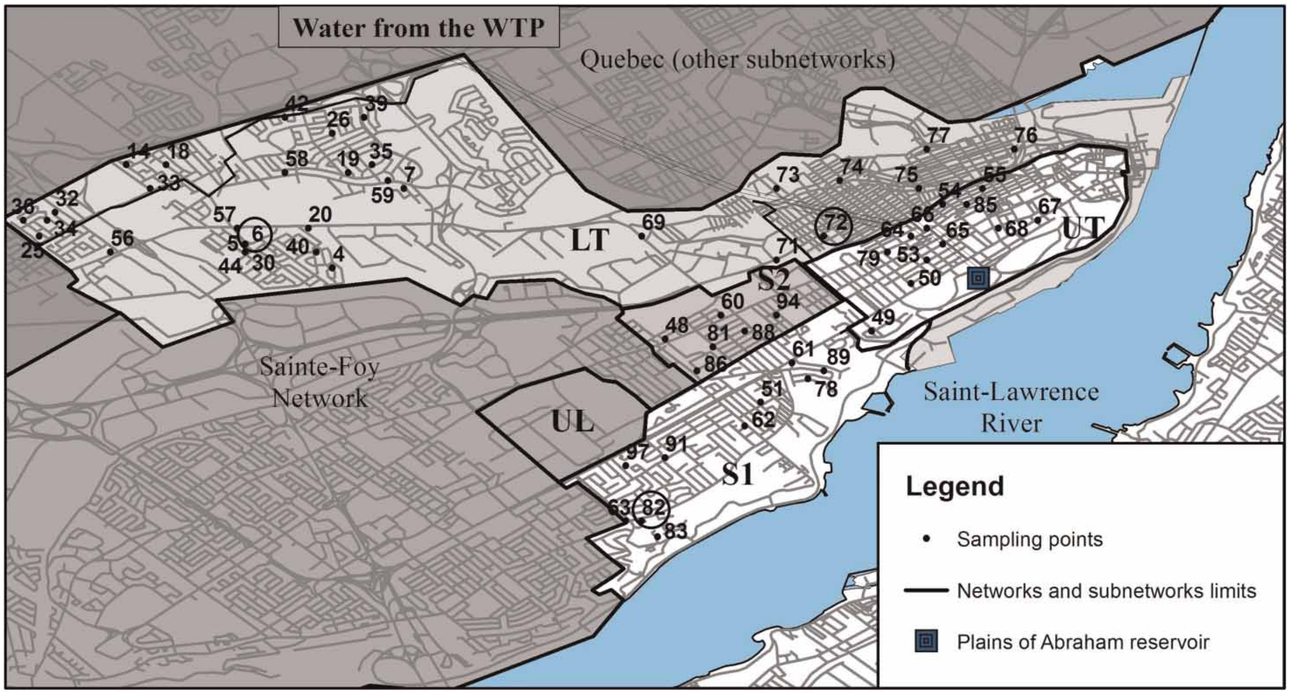

Figure 1 | Fluoride sampling sites.

which stays there for 3–5 days, supplies most of sub-sector LT (Figure 1) (see also Simard *et al*. 2009).

These sub-sectors have been selected to develop the methodology for evaluating MRT because they are located relatively far from the WTP and the probability of observing high MRTs is important. Moreover, challenges in maintaining adequate concentrations of free residual chlorine are known in sector S1 (Figure 1). Finally, population density is higher compared to other areas of Quebec City, which is an important factor in the prioritisation of monitoring water quality in DS.

Sampling campaigns

Two intensive sampling campaigns were conducted: the first to assess MRT and identify the origin of the water and the second to confirm the limits of DS. As part of the first campaign, a fluorosilicic acid solution (25% w/w) was injected (~0.5 mg/L) at the WTP as a tracer. This molecule instantly dissociates into tetrafluorosilane (SiF_4) and hydrogen fluoride. After a full review of long-term series of flow rates at the valve chambers at the entrance of the sector, it was found that the flow rates did not vary much between the week days and the weekend. For logistical reasons, weekend dates were chosen. The injection started at 3:00 a.m. on Saturday, 24 May 2008, and stopped at 5:00 a.m. on Sunday, 25 May 2008, lasting a total of 26 h. Water samples were collected in 60 sampling sites (865 total samples) across the entire study area. These samples, collected between 9:00 a.m. and 11:00 p.m. on 24 May and from 9:00 a.m. to 5:00 p.m. on 25 May, at a rate of one sample every 2 h, were analysed for fluoride concentration colorimetrically using an Astoria auto-analyser. It should be noted that the beginning and end times of sampling, and frequency, varied from one site to another.

Water samples were also collected at the Venturi building (122 samples), located approximately 2 km downstream of the WTP. These samples were used to draw the fluoride concentration curves for water coming out of the WTP, given that there is no water consumption between the WTP and Venturi site on any of the three main pipes from the WTP. The sampling there was carried out between 4:00 a.m. and 9:00 p.m. on 24 May and between 7:00 a.m. and 5:00 p.m. on 25 May. The frequency of sampling varied from one sample every 15 min up to one sample every 2 h. The higher sampling frequency better monitors the initial progression of fluoride from the WTP. Sampling times were evaluated taking into account the preliminary results of MRT obtained from the hydraulic model, using the daily average demands for the year.

Fluoride concentration curves were used to evaluate MRT but also to formulate a hypothesis about the origin of the water. A curve whose fluoride concentration evolves slowly may be characteristic of an area where MRT is high, but could also mean that it was mixed with water that does not contain a tracer (e.g., from a neighbouring DS or a reservoir with high MRT). This is why it is important to validate the origin of the water using a parameter that differs from one DS to another.

Isolating valves that link two DS are normally closed. This physical barrier prevents water from flowing from one DS to another, which simplifies monitoring. A theoretical limit between two DS can be drawn according to the location of the closed valves. Given the extent of the system, the hardness of the water at each sampling site was measured to identify possible interconnections between the Quebec DS and the neighbouring DS of Sainte-Foy. The hardness is determined by measuring the divalent cations found in water (mainly Ca^{+2} and Mg^{+2}) in terms of $CaCO_3$ (Crittenden *et al.* 2005). The characteristic hardness of the water in Quebec, supplied by the St Charles River, varies between 30 and 50 mg/L of $CaCO_3$, while the characteristic hardness of the water in Sainte-Foy, supplied by the St Lawrence River, varies between 70 and 90 mg/L of $CaCO_3$. $CaCO_3$ can build up a protection layer on the pipe walls creating a barrier against corrosion in metallic pipes but also changing the effective hydraulic diameters of the pipes. Difference in hardness between the waters of Sainte-Foy and Quebec may lead to different levels of protection from corrosion and different impacts on the effective hydraulic diameters, but these impacts have not been explored in this study.

The second sampling campaign was conducted during the months of June, July and August of 2008. The conductivity measurement was used to validate the hypotheses based on the results of the first campaign regarding interconnections, but also to pinpoint the limits between the two DS, as samples were taken from both sides of the theoretical limit, which had not been done during the first campaign. The water conductivity is defined as a measurement of the ionic activity in terms of capacity to transmit electric current (Crittenden *et al.* 2005). The water conductivity of Quebec varies between 130 and 160 μS/cm and that of Sainte-Foy varies between 225 and 240 μS/cm.

Evaluation of mean residence times

MRT was estimated at different locations in the study area based on the tracer evolution in time. A tracer injection can be either started (the tracer concentration will increase, e.g., calcium chloride) or stopped (an existing tracer injection is stopped, e.g., fluorides), depending on the case study. MRT can be measured using the MRT technique developed by DiGiano *et al.* (2005), as defined previously. To properly assess MRT using this method, sampling must be done long enough before and after stopping the tracer injection to obtain good initial and final concentrations. In addition, it is more difficult to properly control the tracer concentration by injecting than by stopping an injection. For these reasons, it is harder to apply DiGiano *et al.*'s (2005) method by injecting a tracer than by ceasing the injection (e.g., when there are fluorides at all times).

A simpler and more common technique, used when a tracer is injected (Liem *et al.* 1999; Mainville *et al.* 2002; Rodriguez *et al.* 2004), is to determine the amount of time it takes for the tracer to reach each sampling site at a concentration level equal to 50% of the maximum concentration measured at the WTP. It is important not to neglect the natural tracer concentration in water. If the natural concentration is high, 50% of the difference between the source and the natural concentrations should be considered. Although this method does not adequately take into account the mixing of 'old' and 'new' water, it still allows the proper characterisation of the MRT between different areas. Because of the difficulties mentioned above regarding the MRT method developed by DiGiano *et al.* (2005), only the method based on 50% of the maximum concentration was used to assess MRTs across all sample sites.

RESULTS AND DISCUSSION

Identification of MRT: injection and detection of fluorides

Fluoride concentration curves drawn from samples collected at the 60 sites (as seen in Figure 1, not numbered

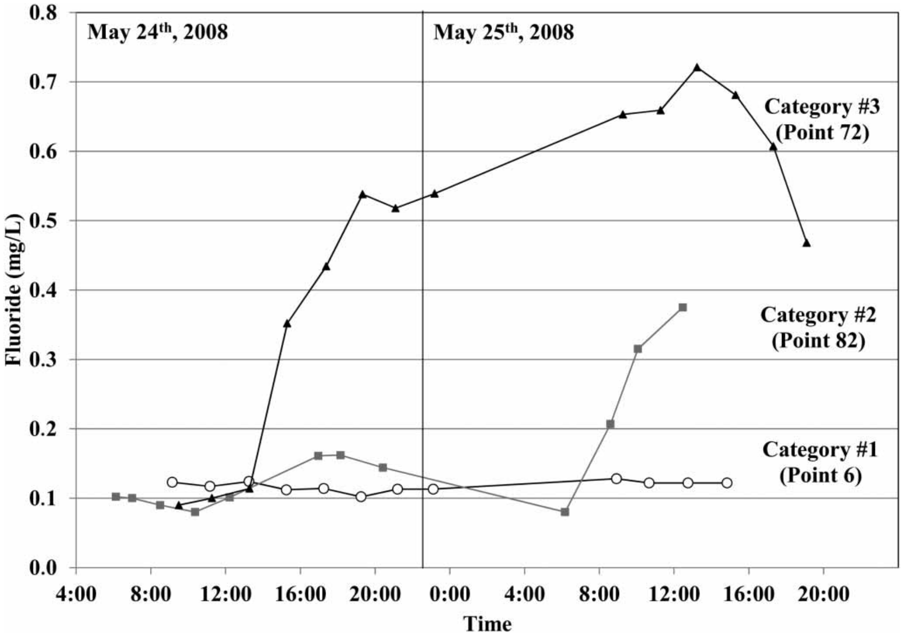

Figure 2 | Examples of fluoride curves for the three categories of fluoride progression.

consecutively) can be used to identify the origin of the water sample and also to evaluate the MRT when water comes directly and strictly from Quebec's WTP. Curves were divided into three categories according to variations in fluoride concentrations. Examples of curves are shown in Figure 2 and are described below:

- In Category 1 are those curves whose progression of fluoride concentration is zero for the whole sampling period, such as at Site 6, located in the west part of LT in Figure 1. Sites associated with Category 1 may be supplied by the Sainte-Foy WTP, the reservoir (MRT in the reservoir is estimated at between 3 and 5 days) or the Quebec WTP, but their MRT would be much higher than the duration of the sampling period (from 36 to 40 h).
- In Category 2 are the curves whose progression of fluoride concentration is rather slow, such as at Site 82, located to the west in S1. This category may be associated with low water consumption in the area where the sampling site is located or may be the result of a mixing with water containing no tracer, either from the reservoir or from the Sainte-Foy DS.
- Category 3 curves are those in which the fluoride concentration increased rapidly to reach the maximum level of concentration during sampling, such as at Site 72, located in LT, close to the water mains. Sites associated with this type of curve have the characteristic of being strictly and directly fed by water from the Quebec WTP, without any mixing with water from the reservoir or the Sainte-Foy DS.

The curve categories associated with each of the sampling sites are shown in Figure 3. Sectors S1 and S2 are likely to have high MRT associated with Category 2, particularly in the west part of these areas, further away from the water mains. Curves associated with Sites 62, 91, 63 and 82 are, indeed, a Category 2 in the western sector of S1, with the exception being Site 97, listed as Category 3. This site is not located directly on a water main, but it is still located near a water main, which may explain the rapid increase of fluorides.

Sites in the western part of sector S2 (Sites 48, 60, 81 and 86), however, seem to be supplied by the WTP of Sainte-Foy, as demonstrated by the zero progression of fluoride concentrations associated with Category 1. The slow progression of fluoride concentrations moving eastward (Site 88) suggests that an interconnection is open, allowing a water intrusion from the Sainte-Foy DS, where pressure

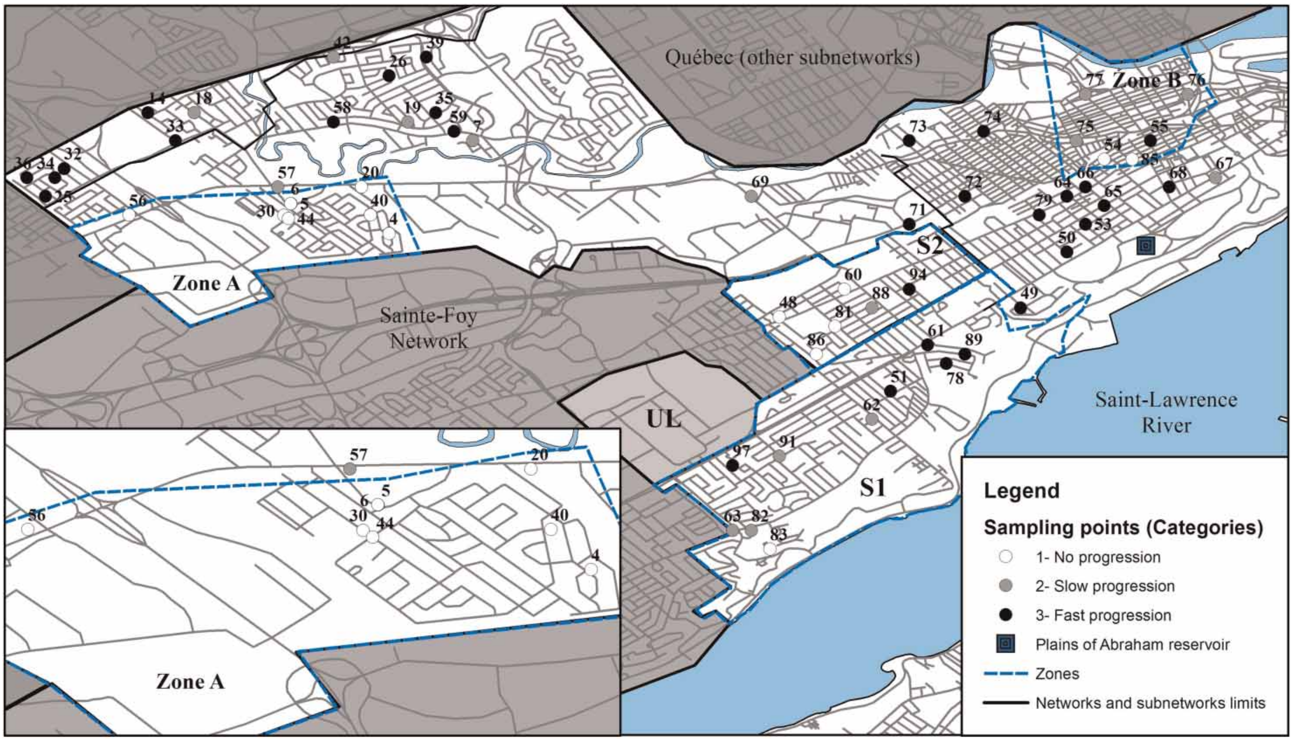

Figure 3 | Fluoride curve categories for all sampling sites.

levels are higher than in Quebec. This was later confirmed after a verification by the Department of Public Works.

Two areas also have unusual behaviours. Area A (Figure 3) is usually supplied by Quebec's WTP, as suggested by the systems' limits. However, the zero progression of fluoride concentrations in all the sampled sites of this area (Sites 4, 5, 6, 20, 30, 40, 44 and 56) shows that it is, at this time, strictly supplied by the WTP of Sainte-Foy. Upon verification, it was determined that work took place in this area during the period of sampling: a change in the opening and closing of the valves allowed this area to be supplied by the Sainte-Foy DS during this period.

Normally, sites in area B of LT, to the east of the water mains, are supplied by a mixture of water directly from the WTP and the reservoir, while the sites in UT are fed directly by the WTP and without mixing. Sites 75, 76 and 77 showed an increase in fluoride concentration (very slightly for Sites 76 and 77 at the end of the campaign), revealing that water from the WTP reached these sites, taking much longer to reach Sites 76 and 77. However, surprisingly, a few sites in UT (54 and 85) could also be supplied by the reservoir, whereas, according to the system configuration, the reservoir should only feed sites that are located in LT.

Finally, all other sites seem, at first sight, to be supplied by the WTP of Quebec without any kind of mixing with water from the reservoir or from the Sainte-Foy DS. From our knowledge of the City's land use and DS, we noticed that most sites associated with Category 2 are located in low water consumption areas, which would explain the higher MRT.

Determination of the hydraulic limits: water hardness

Total hardness (mg/L of $CaCO_3$) was measured at every sampling site for fluorides during the campaign on 24 and 25 May 2008. This analysis was performed to verify the presence of interconnections between the DS of Quebec and Sainte-Foy. Given that the hardness of the water of Quebec varies between 30 and 50 mg/L of $CaCO_3$ and that Sainte-Foy's water varies between 70 and 90 mg/L of $CaCO_3$, it is easy to figure out the origin of the drinking water at that sampled site. Results presented in Figure 4 help to identify two zones (A and S2) of the system of

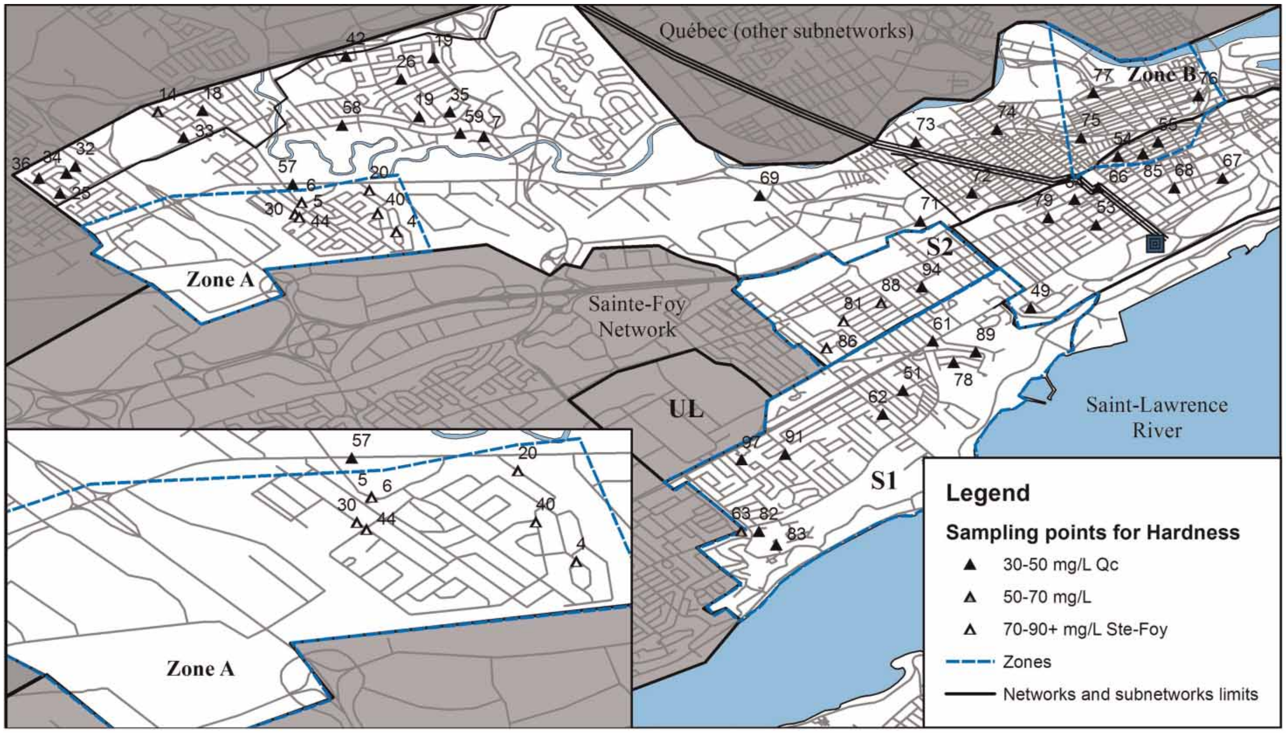

Figure 4 | Water hardness at different sampling sites.

Quebec that are partially or totally supplied by water from the Sainte-Foy system and to confirm the original hypotheses about the origins of water from the analysis of the curves of fluoride concentrations.

Hardness measured in zone A (Sites 4, 5, 20, 30, 40 and 44) is indeed characteristic of the water of Sainte-Foy, as is the one measured in the western part of area S2 (Sites 81 and 86). Hardness measured in the eastern part of area S2 (Site 94) is characteristic of the usual hardness of the water from the Quebec WTP, while the hardness measured in the middle of area S2 (Site 88) suggests a mix between the two waters.

Evaluation of the spatiotemporal variation of the hydraulic limits: water conductivity

This sampling campaign, carried out as part of a complementary study, was conducted from June to August of 2008, at a rate of one sampling per month on 27 sites located on both sides of the theoretical limit between the Quebec and Sainte-Foy DS (Figure 5(a), 5(b) and 5(c)). Results were used to verify the spatiotemporal variability of this limit, knowing that the conductivity of the water of Quebec varies between 130 and 160 μS/cm and that Sainte-Foy's water varies between 225 and 240 μS/cm.

A first analysis was performed on samples collected on 19 June 2008, at sites on both sides of the theoretical limit between the systems in sectors S1 and S2. Results presented in Figure 5(a) allow us to conclude, without any doubt, that there was indeed an open interconnection between Sainte-Foy and Quebec at the time of this sampling. Sites located on either side of this limit respect the characteristic conductivity of their DS, with the exception of seven sites (9, 11, 18, 21, 22, 23 and 24). Six of these sites, one located in the far western part of sector S1 (9), another east of UL (18) and four in the western part of sector S2 (21, 22, 23 and 24) have a conductivity that is characteristic of Sainte-Foy even though they are theoretically located in the DS of Quebec. In addition, a site (11) located in the south-eastern part of Sainte-Foy has a conductivity that is characteristic of the DS of Quebec. This finding is somewhat surprising and suggests a shifting of the limit rather than the opening of an interconnection, since all the other sites have a conductivity

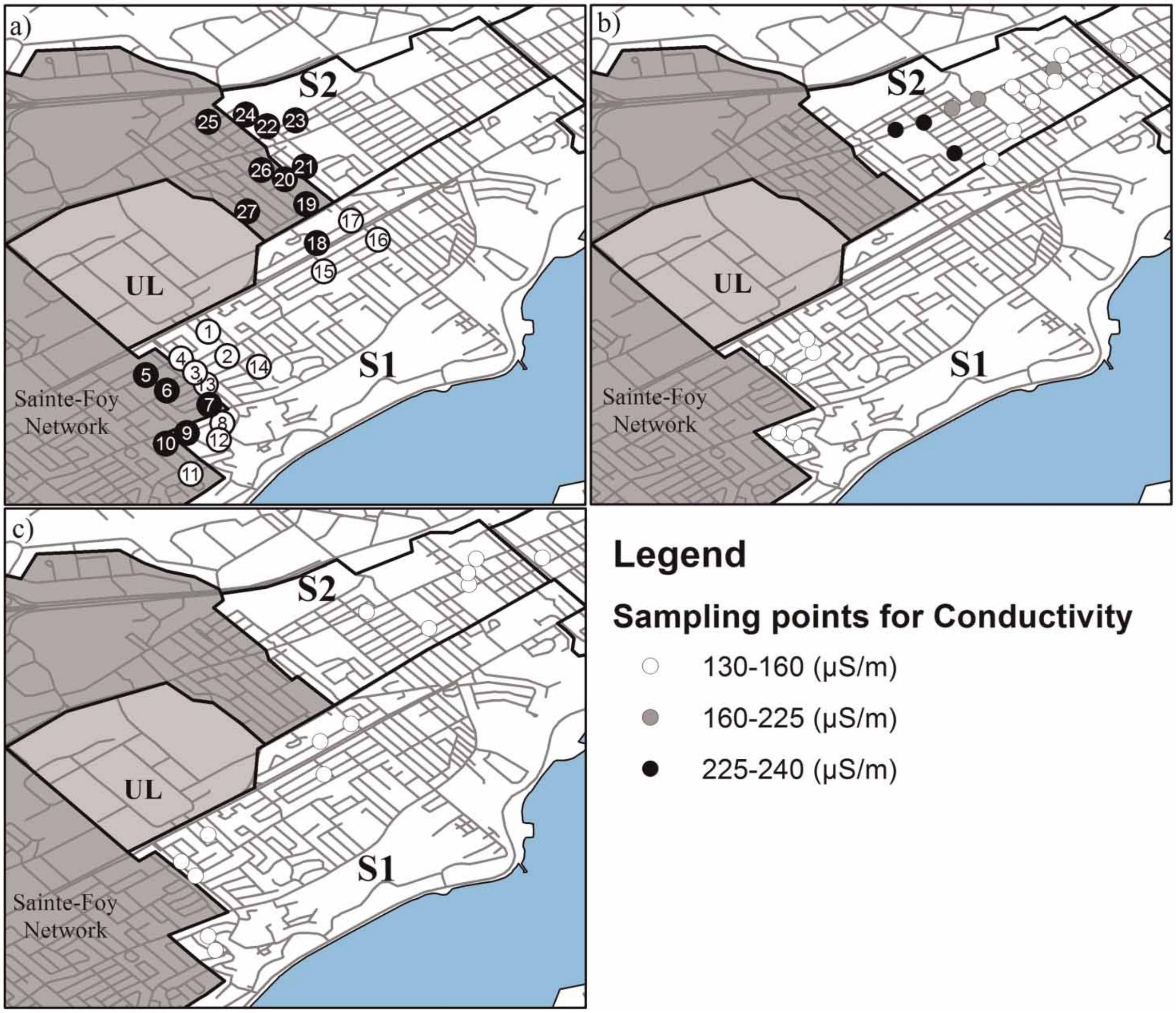

Figure 5 | Water conductivity: (a) 19 June 2008; (b) 16 July 2008; and (c) 11 August 2008.

that is characteristic of their respective DS with no sign of mixing.

It is therefore possible that the real limit is somewhat different from the theoretical limit, but without necessarily implying any kind of interconnections open between the two DS. In light of these results, it seemed interesting to check how far the waterfront from Sainte-Foy progressed within the sector S2 around 16 July (Figure 5(b)) and 11 August (Figure 5(c)). Figure 5(b) allows us to visually evaluate the progress of the waterfront from the Sainte-Foy DS as well from the mixing zone between Quebec and Sainte-Foy. The water conductivity measured at sites in the western part of sector S2 (33, 34 and 28) is characteristic of the Sainte-Foy WTP, while the water conductivity measured at sites in the eastern part of sector S2 (32, 35, 36, 37, 38, 39, 40, 41 and 42) is characteristic of the Quebec WTP. Between these two areas is a mixing zone: a site in the eastern part of sector S2 (31) has the characteristic conductivity of a mixture between the two DS. This observation is not surprising and can be explained by the location of the sampling site (water main vs. local pipe), by open or closed valves, by different head losses in each pipe, etc. Results presented in

Figure 5(c) lead us to believe that the interconnections between Quebec and Sainte-Foy's DS were closed during that sampling period (11 August 2008), highlighting the spatiotemporal variability of the theoretical limit.

Real hydraulic limits of the study area

From the curves of fluoride concentrations, hardness and conductivity (Figures 3, 4, 5(a), 5(b) and 5(c)), it was possible to identify the supply patterns and the limits of the DS. These supply patterns and limits are shown in Figure 6. LT is divided into three areas: (1) zone LT1 is supplied strictly by the WTP of Sainte-Foy; (2) zone LT2 is, as expected, supplied strictly and directly by the WTP of Quebec; and (3) zone LT3 is supplied by the reservoir, with or without mixing with water from the WTP of Quebec. UT is divided into two areas: (1) zone UT1, where the water seems to come entirely from the WTP of Quebec; and (2) zone UT2, where there is mixing between water from the reservoir and water directly from the WTP of Quebec.

Moreover, we found a mixture in sector S2. An open interconnection let in a significant amount of water from the Sainte-Foy DS. The western part of sector S2 is supplied entirely by the WTP of Sainte-Foy, the eastern part is supplied entirely by the WTP of Quebec while a mixing zone is located halfway. The sampling campaign on conductivity revealed that the interconnection was closed between 17 July and 12 August 2008.

In sector S1, we see two areas where there is a possible mixing between water from the WTP of Quebec and Sainte-Foy. These areas do not appear to extend very far into S1. It could be a movement of the limit between the DS rather than the presence of an open interconnection.

Mean residence times

In order to evaluate MRT, the tracer must be at least 50% of the maximum concentration measured at the exit of the WTP, at the sampling site during the sampling period. In addition, mixing with water from the reservoir or the neighbouring DS has the effect of diluting the fluoride concentrations from the Quebec WTP. It has therefore been possible to assess the MRT only from the fluoride concentrations of samples collected at sites strictly and directly

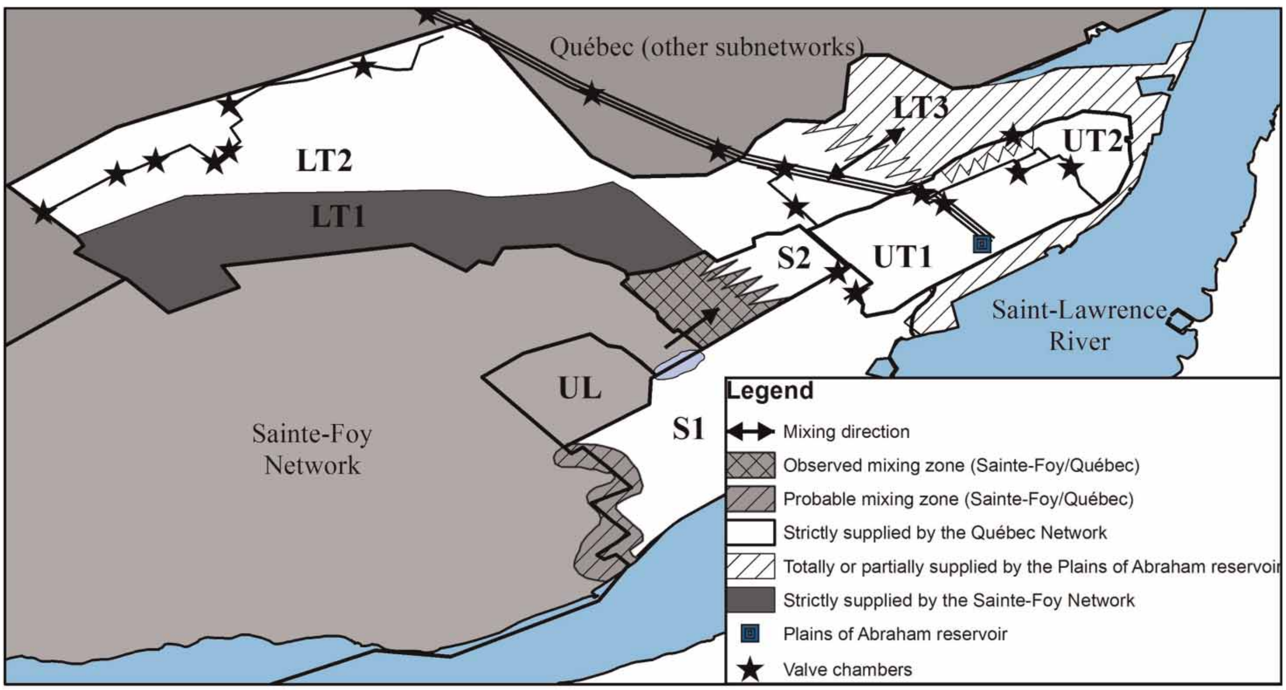

Figure 6 | Water DS limits.

supplied by the Quebec WTP (see Figure 6). These residence times are shown in Figure 7 and range from 6 to 33 h from the exit of the WTP (Table 1). As expected, the sites associated with Category 2 generally exhibit higher MRT. Water travels quickly in the water mains but once in the neighbourhoods, it flows much more slowly, especially in residential areas where there is less demand. MRTs are thus higher at the extremities of the system, but also in some central neighbourhoods where there are no large consumers. It can therefore be difficult to predict MRT solely by the distance travelled from the WTP. A hydraulic model is thus very useful once calibrated with a measurement campaign.

CONCLUSION

This study presents a methodology to determine the residence times of drinking water in DS in order to improve water managers' knowledge on the quality of water delivered to consumers. The selected area is part of the DS supplied by Quebec City's main WTP. A tracer sampling campaign was conducted to estimate MRT in different sampling sites. In addition, sampling campaigns to evaluate the conductivity and hardness were carried out to determine the origin of the water. This verification is necessary because some interconnections may allow water intrusion from a neighbouring DS. Fluoride concentrations obtained from the tracer campaign were used to assess MRT and to identify areas with high and low residence times. These sampling campaigns have helped to clearly identify the different areas where there is a mixing of water between the nearby DS and water from the reservoir, as well as areas supplied strictly by Quebec's DS or Sainte-Foy's and to highlight the temporal variation of the limits of these areas. Besides improving knowledge about the hydraulic system for operational purposes, the identification of the limits ensures that the sampling sites used for regulatory monitoring effectively represent water from the system whose standards' compliance is evaluated. Results were used to calibrate and validate a hydraulic model used to design strategies to minimise MRT in order to enhance water quality in the studied

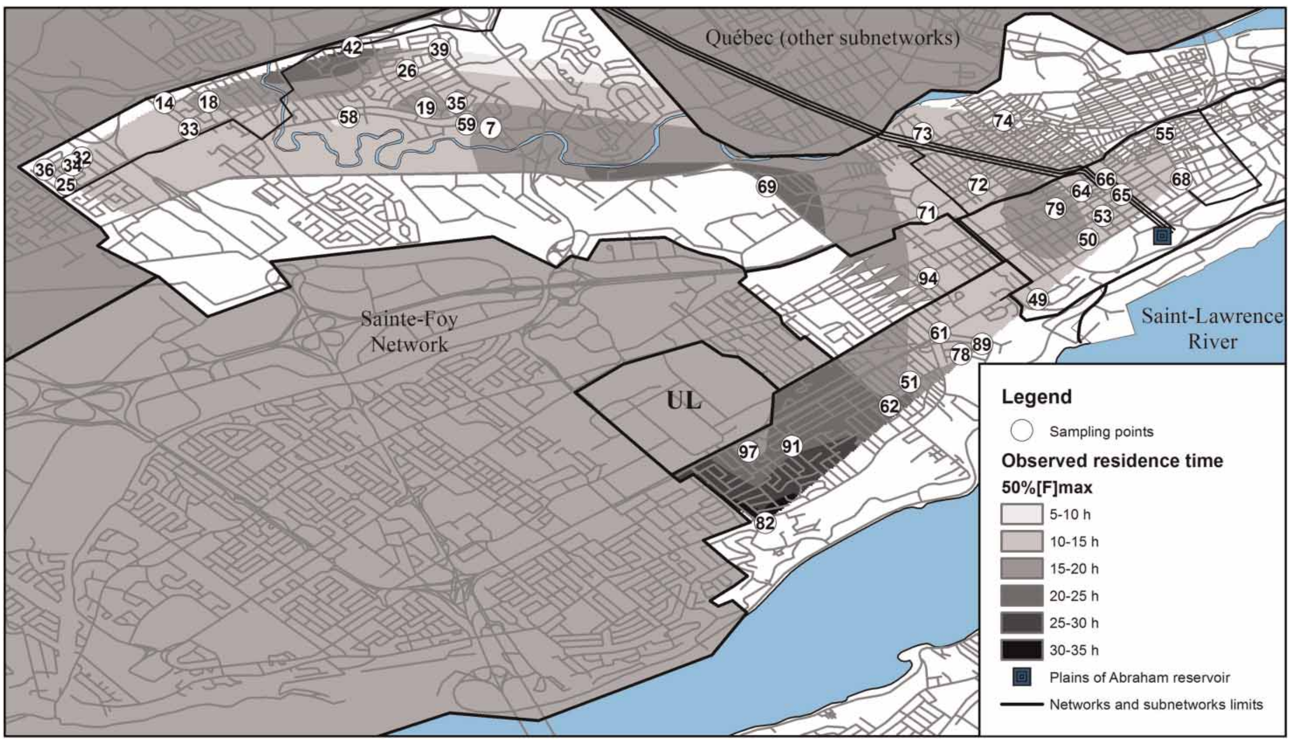

Figure 7 | Observed MRTs.

Table 1 | Category of fluoride curve, water hardness and observed MRTs at the sampling sites

Sampling site	Category of fluoride curve	Water hardness (mg/L $CaCO_3$)	Observed MRT (h)
39	3	44	6.8
100	3	39	7.0
26	3	36	8.6
58	3	44	9.5
32	3	38	9.9
33	3	34	10.8
66	3	32	10.9
25	3	42	11.1
73	3	34	11.1
35	3	38	11.2
59	3	38	11.2
61	3	42	11.4
64	3	34	11.4
34	3	40	11.9
74	3	48	12.0
49	3	40	12.2
72	3	32	12.3
78	3	42	12.5
14	3	54	12.7
51	3	42	12.7
53	3	48	12.7
71	3	40	13.1
68	3	36	13.2
36	3	42	13.4
89	3	46	14.1
94	3	48	14.1
55	3	46	14.9
50	3	N/A	15.0
65	3	36	15.3
18	2	42	17.7
97	3	38	18.1
7	2	38	19.7
79	3	48	20.9
19	2	48	21.5
62	2	43	22.8
69	2	35	23.5
91	2	46	23.9
42	2	38	26.9
82	2	42	32.7

neighbourhoods. The model and hydraulic strategies are found in the 'companion paper' (Part II) in this issue (Delisle *et al.* 2015).

REFERENCES

Al-Jasser, A. O. 2007 Chlorine decay in drinking-water transmission and distribution systems: pipe service age effect. *Water Res.* **41** (2), 387–396.

Al-Omari, A. S. & Abdulla, F. A. 2009 A model for the determination of residential water demand by the use of tracers. *Adv. Eng. Software* **40** (2), 85–94.

Axworthy, D. H. & Karney, B. W. 1996 Modeling low velocity/high dispersion flow in water distribution systems. *J. Water Resour. Plann. Manage.* **122** (3), 218–221.

Crittenden, J. C., Trussel, R. R., Hand, D. W., Howe, K. J. & Tchobanoglous, G. 2005 *Water Treatment Principles and Design*. John Wiley & Sons, Hoboken, NJ.

Delisle, F.-J., Rochette, S., Pelletier, G., Asadzadeh, M., Tolson, B. A. & Rodriguez, M. J. 2015 Minimizing water residence time in Quebec City's main distribution network using hybrid discrete dynamically dimensioned search (HD-DDS): Part II. *J. Water Supply Res. Technol.-AQUA* **64** (3), 378–390.

DiGiano, F. A., Zhang, W. & Travaglia, A. 2005 Calculation of the mean residence time in distribution systems from tracer studies and models. *J. Water Supply Res. Technol.-AQUA* **54** (1), 1–14.

Francisque, A. 2009 Modeling of heterotrophic bacteria counts in a water distribution system. *Water Res.* **43** (4), 1075–1087.

Gallard, H. & von Gunten, U. 2002 Chlorination of natural organic matter: kinetics of chlorination and of THM formation. *Water Res.* **36** (1), 65–74.

Gopal, K., Tripathy, S. S., Bersillon, J. L. & Dubey, S. P. 2007 Chlorination byproducts, their toxicodynamics and removal from drinking water. *J. Hazard. Mater.* **140** (1–2), 1–6.

Hallam, N. B., West, J. R., Forster, C. F., Powell, J. C. & Spencer, I. 2002 The decay of chlorine associated with the pipe wall in water distribution systems. *Water Res.* **36** (14), 3479–3488.

Liem, L. E., Stanley, S. J. & Smith, D. W. 1999 Residence time distribution analysis as related to the effective contact time. *Can. J. Civil Eng.* **26** (2), 135–144.

Mainville, É., Gauthier, V., Lavallée, D. & Marche, C. 2002 Nouvelle approche pour déterminer la distribution des temps de séjour dans les réservoirs d'eau potable en régime non permanent (New approach to determine the distribution of drinking water residence time in tanks under unsteady flow conditions). *Can. J. Civil Eng.* **29** (4), 612–621.

Ormsbee, L. E. 1989 Implicit network calibration. *J. Water Resour. Plann. Manage.* **115** (2), 243–257.

Ormsbee, L. E. & Lingireddy, S. 1997 Calibrating hydraulic network models. *J. Am. Water Works Assoc.* **89** (2), 42–50.

Prévost, M., Rompré, A., Coallier, J., Servais, P., Laurent, P., Clément, B. & Lafrance, P. 1998 Suspended bacterial biomass and activity in full-scale drinking water distribution systems: impact of water treatment. *Water Res.* **32** (5), 1393–1406.

Rodriguez, M. J., Serodes, J.-B. & Levallois, P. 2004 Behavior of trihalomethanes and haloacetic acids in a drinking water distribution system. *Water Res.* **38** (20), 4367–4382.

Rodriguez, M. J., Serodes, J.-B., Levallois, P. & Proulx, F. 2007 Chlorinated disinfection by-products in drinking water according to source, treatment, season and distribution location. *J. Environ. Eng. Sci.* **6**, 355–365.

Rossman, L. A. 2000 *EPANET 2 User Manual*. Environmental Protection Agency, Cincinnati, Ohio.

Simard, A., Pelletier, G. & Rodriguez, M. J. 2009 Using a tracer to identify water supply zones in a distribution network. *J. Water Supply Res. Technol.-AQUA* **58** (6), 433–442.

Tamminen, S., Ramos, H. & Covas, D. 2008 Water supply system performance for different pipe materials part I: water quality analysis. *Water Resour. Manage.* **22** (11), 1579–1607.

Tzatchkov, V. G., Aldama, A. A. & Arreguin, F. I. 2002 Advection-dispersion-reaction modeling in water distribution networks. *J. Water Resour. Plann. Manage.* **128** (5), 334–342.

Zhang, W. & DiGiano, F. A. 2002 Comparison of bacterial regrowth in distribution systems using free chlorine and chloramine: a statistical study of causative factors. *Water Res.* **36** (6), 1469–1482.

First received 16 April 2014; accepted in revised form 17 November 2014. Available online 30 December 2014