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Practical Paper

Using a tracer to identify water supply zones in a distribution network

Andréanne Simard, Geneviève Pelletier and Manuel J. Rodriguez

ABSTRACT

This paper presents a methodology that can effectively identify contributions of water sources to end-use water consumption in distribution network locations. The sector selected for the study is a residential sector of Quebec City supplied with drinking water directly from the main supply pipes from the water treatment plant and by re-chlorinated water from a reservoir. The proposed methodology relies on three strategies: a hydraulic characterization of the distribution network, a tracer study and a water quality characterization study. A tracer study was conducted by injecting $CaCl_2$ brine at the reservoir outlet in order to increase calcium concentrations in water from that source. It was then possible to associate sampling points at which calcium concentrations showed an increase during the test as being supplied by the reservoir. A water quality characterization study was conducted simultaneously with the tracer study, making it possible to validate the distribution zones identified. This validation was made possible by analysing the difference between residual chlorine values from the two sources; in fact, water from the reservoir had distinctively higher levels due to re-chlorination. With this fact, it was possible to identify distribution zones at points where the calcium concentration had remained constant during the tracer test.

Key words | tracer study, water distribution system, water quality, water supply zones

Andréanne Simard
BPR, 4655 boulevard Wilfrid-Hamel,
Quebec City, Quebec G1P 2J7,
Canada

Geneviève Pelletier (corresponding author)
Department of Civil Engineering,
Université Laval, Pavillon Adrien-Pouliot,
local 2986, 1065 avenue de la Médecine,
Quebec City, Quebec G1V 0A6,
Canada
Tel.: +1 418 656 2647
Fax: +1 418 656 2928
E-mail: *genevieve.pelletier@gci.ulaval.ca*

Manuel J. Rodriguez
École supérieure d'aménagement du territoire et développement régional (ESAD),
Université Laval, Pavillon Félix-Antoine-Savard,
local 1624, 2325 rue des Bibliothèques,
Quebec City, Quebec G1V 0A6,
Canada

INTRODUCTION

Context

Chlorine is the most commonly used disinfectant in the world, but it decays over time within the distribution network due to reactions with organic and inorganic materials in water as it is transported. In major distribution networks in particular, residual chlorine concentrations may be very low or even undetectable at the dead-ends of the network (Powell *et al.* 2000; Rodriguez & Sérodes 2001). An effective method for reducing the risk of microbiological contamination in distribution systems is to maintain sufficiently high levels of residual chlorine. In Quebec (Canada), a minimum level of free residual chlorine of 0.3 mg/L is required in water leaving the treatment plant (DWP) according to regulations. This criterion is not applied to re-chlorination stations within the distribution network.

A compromise needs to be found regarding chlorine dosage at the DWP or at re-chlorination stations throughout the distribution network, because chlorine, an oxidant, reacts with natural organic matter and generates disinfection by-products (DBPs) such as trihalomethanes (THMs) and haloacetic acids (HAAs). In fact, some of these products are believed to be carcinogenic and have recently been associated with reproductive health problems in humans (Xie 2003). Re-chlorination of water within the distribution network is the most commonly used strategy to maintain sufficient residual chlorine at dead-ends. It has been

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demonstrated, however, that re-chlorination followed by several hours of residence in a reservoir can result in the formation of additional DBPs (Rodriguez *et al.* 2004).

Residual chlorine concentrations vary both spatially and temporally, making it difficult to guarantee adequate concentrations everywhere at all times. A hydraulic model used with a chlorine degradation model can provide good knowledge of residual chlorine concentrations anywhere at any time, as long as adequate observations are available to calibrate both the hydraulic and degradation models in various water consumption conditions. To obtain such observations, a measurement campaign must be designed and carried out. After calibration, the hydraulic model can be used to identify the best hydraulic strategies to improve the quality of drinking water in the distribution network. For example, valve closings on certain pipes can increase the velocity in adjacent pipes, which can lead to reductions in residence times, which, in turn, can lead to better residual chlorine concentrations and less DPB production.

Study objective

The purpose of this study is to describe a methodology for identifying drinking water supply patterns within a distribution network using $CaCl_2$ as a tracer. The tracer study provides the necessary information to calibrate a hydraulic model that can be used to identify the best hydraulic strategies to improve the quality of drinking water in a distribution network. The originality of the study resides in the fact that it combines three different strategies: the hydraulic characterization of a distribution network, a tracer study and a water quality characterization study.

The methodology could be adapted to multiple water sources if there were significant differences in water quality parameters (e.g. conductivity, hardness) from each source or if multiple tracers were used. Furthermore, contaminant source identification and tracking is certainly another possible application of this methodology.

METHODS

Case study

The case under study concerns a section of the main distribution network in Quebec City. The water distribution network is supplied by the St. Charles River and provides water to about 40% of the city's population, or some 230,000 people. The specific sector under study is the network serving the sector of Limoilou (Figure 1). Water from the St Charles River intake is first routed to the DWP and then conveyed by gravity along two mains to a reservoir located under the Plains of Abraham. The 50 m drop between the plant and the reservoir is sufficient to allow gravity flow. The Plains of Abraham reservoir contains two compartments, providing a total storage capacity of 130,000 m^3. The average flow through the reservoir is about 40,000 m^3/d. Water reaching the reservoir first passes through a re-chlorination station, then remains in the reservoir for a period estimated at about two to three days. Water passes through a second re-chlorination station at the reservoir outlet before being conveyed to one of two pressure-reducing valve chambers (PRV). About 90% of the water passes through the PRV located north of the reservoir, responsible for feeding part of the adjoining network, including Limoilou. The second PRV located south of the reservoir serves a very small consumption sector.

Drinking water enters Limoilou through three main inlet pipes and a secondary inlet. One of the inlet pipes is supplied with water directly from the mains from the DWP (inlet 1 in Figure 1); therefore, the age of this water is relatively low. The other two inlet pipes are supplied with

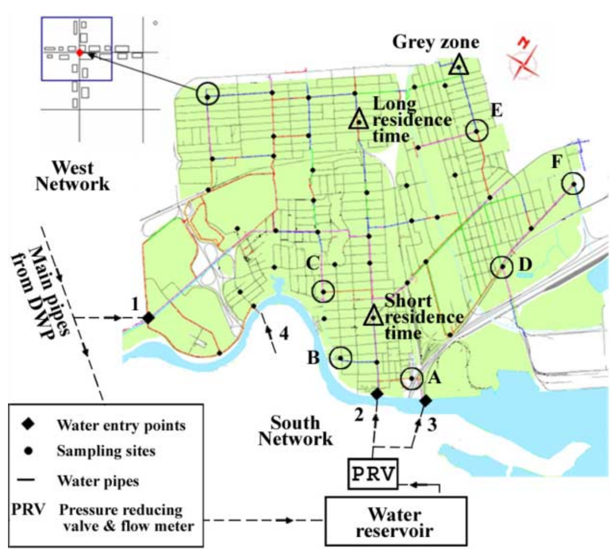

Figure 1 | Location of inlets to the sector of interest (numbers), sampling sites (dots), sites with particular local hydraulic conditions (letters) and examples of sites with different residence times (triangles).

re-chlorinated water from the Plains of Abraham reservoir (inlets 2 and 3 in Figure 1); the age of this water is relatively high, considering the residence time in the reservoir. The secondary inlet (inlet 4 in Figure 1) contributes very little flow and probably carries mixed waters from both the DWP and reservoir.

Limoilou's water distribution network is characterized by several dead-ends due to the absence of interconnections with the bordering water distribution networks to the north and east. Limoilou is also the furthest sector to be supplied on the eastern side of the DWP service area. Unfortunately, water consumption is relatively low, resulting in a long residence time in the water pipes. These conditions lead to the degradation of water quality.

Hydraulic characterization of the water distribution network

Building on an existing hydraulic model of the main pipes, a detailed hydraulic characterization was carried out: local pipes (all diameters) with Hazen–Williams coefficients (C_{HW}) based on pipe age were added to the model. C_{HW} of new pipes depends on the material: PVC, cast iron, ductile iron, etc. Thereafter, C_{HW} decreases with age, especially for iron pipes. Hydrant tests conducted by the city were used to adjust the C_{HW} values and consider the current deteriorated state of the pipes. These tests were conducted in four sections and *severe* corrosion levels were identified. Given that Limoilou pipes have similar average ages (60–100 yrs) and that more detailed information was not available, the same level of deterioration was assigned to all pipes. Elevations were also included in the model: the difference in elevation throughout Limoilou is 11 m, a very flat topography.

As with most Quebec municipalities, Limoilou is not equipped with residential water meters. In order to distribute water demand realistically, a methodology was developed to account for the several types of housing in the Limoilou sector (including several apartment buildings) and institutional, commercial and industrial (ICI) water consumption. This methodology consisted of three stages: allocation of ICI water flows to the nearest modelled nodes, spatial distribution of the population based on consumption nodes and determination of the average daily consumption per person (per capita flow).

The population corresponding to each of the modelled network nodes (located mainly at intersections) was evaluated using Quebec City's *Rôles d'évaluation foncière* (municipal tax assessments), as well as a database on major water users in the Limoilou sector (taken from industrial water meters). Using a geographic information system, the Euclidean distance of each building to the nearest consumption node was calculated. The assessment information contained in the *Rôles d'évaluation foncière* database was used to provide the number of housing units per apartment building. This information was then used to assess the number of people per apartment building, based on the assumption that each apartment is occupied by 1.84 individuals. This factor was calculated based on the area's total population of 46,556 persons. Even though the per capita flow is known to vary from 225–445 L/person/d in Quebec (Réseau Environnement 2000; Brandes & Ferguson 2003), the exact value for the study area remained unknown, because the total flow entering Limoilou could not be determined precisely. Thus, the next step was to determine a per capita flow, based on the information provided by the City's flowmeters.

The two flowmeters used for this study are at inlet 1 and in the pressure-reducing valve chamber located upstream of inlets 2 and 3. However, both flowmeters include the water consumption of their bordering network, to the west of Limoilou for inlet 1 and to the south for inlets 2 and 3. Given that the west and south neighbouring sectors are similar in terms of land use and socio-economic characteristics of the population, water consumption habits are assumed to be the same.

The value of the total flow (Q_{total}) is 57,060 m^3/d. The ICI flow (Q_{ICI}) for Limoilou is 10,859 m^3/d and the population is 46,556. The ICI flow (Q_{ICI}) for the south network is 5,220 m^3/d and the population is 24,605. From this data, a per capita flow of 576 L/person/d was obtained. This higher-than-expected water consumption for a residential area led us to believe that the network had significant leakage, due to the deterioration of the pipes. An assessment of water leakage through the network was not done; therefore the consumption was distributed across the territory by multiplying this flow by the population assigned to the model's various nodes. Variations in daily consumption were obtained from the flowmeters.

The distribution of the population among the model's nodes and the identification of Limoilou's flow per capita were used to apportion water consumption across Limoilou's distribution network. Although this information is sufficient to run a hydraulic simulation and determine flow paths within the network, it is not possible to know if the simulated distribution patterns from the DWP and reservoir are realistic. A measurement campaign was designed and carried out using a tracer to determine the distribution patterns in the field.

Tracer study and water quality

In order to do so, a tracer study was carried out. Most tracer studies are conducted by switching off the fluoride injection and observing the decrease in fluoride concentrations downstream, as it is the case in the first case study presented in DiGiano *et al.* (2005), for example. The tracer used was a 47% solution (w/v) of food grade calcium chloride ($CaCl_2$) injected at the reservoir outlet. A similar tracer has been used by Panguluri *et al.* (2005). The injection resulted in an increase in the water's calcium concentration at inlets 2 and 3 supplied by the reservoir. Although Ca^{2+} can be a reactive species, the water here is aggressive and, in the studied sector of the distribution network, it is at equilibrium in solution. Ca^{2+} was used because the laboratory measurement technique (ICP method) provided a very low relative error ($<5\%$) compared with the technique used for chlorine (Mercuric Thiocyanate Flow Segmented Analysis) for which the relative error can be quite high ($\approx 10\%$). Following this injection, an intensive sampling operation was carried out to follow the evolution of calcium concentrations at several sampling points distributed throughout the Limoilou network.

Tracer injection

The injection took place using a rotameter to pump $CaCl_2$ brine from a reservoir booster. The injection rate had to meet three main criteria. First, although the accuracy of the automatic analyzer was about 0.2%, increased calcium concentrations in water coming from the reservoir should be sufficient to cause a noticeable difference between the reservoir's and the DWP's water. Second, to avoid excessive water hardness, the maximum water hardness in the network could not exceed 50 mg/L of calcium. Finally, injection was to take place over a long enough period to allow the water to reach the sampling points at both dead-ends of the network, estimated at about eight hours. The tracer injection took place between 7:00 and 15:00 at an average flow of about 3 L/min. The injection rate increased total reservoir water hardness to an average of 35 mg/L of calcium, more than twice the DWP water hardness which is usually around 16 mg/L. During the campaign, the average DWP water hardness was 13.2 mg/L.

Tracer monitoring

A tracer monitoring operation was conducted throughout the entire Limoilou sector at 47 sampling points, located at the intersection of major diameter pipes. Figure 1 also presents the location of these sampling points. An enlargement of one consumption node in the model illustrates examples of buildings associated with this node. Sampling points included inlets 1, 2 and 3, and the valve chamber.

This operation served to pinpoint when and where calcium concentrations increased in each of the sampling points fed by the reservoir. Likewise, this operation served to identify water routes and residence times associated with these sampling points. The operation was carried out during the first very hot day of Spring 2007, May 25. Air temperature reached 30°C, while water temperature was between 9–18°C, depending on the location and time of day, with an average of 11°C overall. Due to this hot temperature, water demands were higher during the sampling periods (due to outdoor water use) and there were relatively few variations in water consumption.

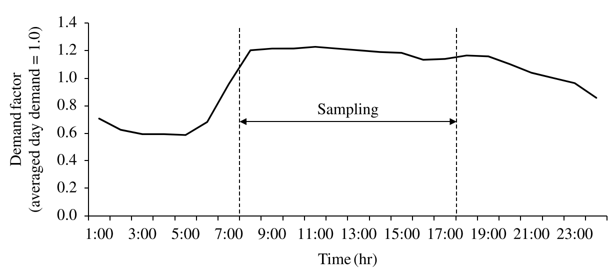

Figure 2 | Consumption pattern observed during the sampling day.

Figure 2 shows the consumption pattern observed during the sampling day in relation to the average consumption, for which the demand factor is equal to 1. During the measurement campaign, the demand factor remained constant at about 1.2 times the average water consumption for that day.

In order to ensure monitoring of spatio-temporal concentrations of calcium in water, a water sampling operation was carried out by a team of twelve workers over an eight-hour period (from 8:00 to 16:00) throughout the entire Limoilou sector. Each person was responsible for three to five points and had to repeat the sampling in a "loop", visiting each point over 90 min intervals. All samples were then taken to the laboratory for calcium concentration analysis.

Such a high number of points monitored intensively in a relatively small area (47 points over 140 km of pipes over an 8-hour period) sets this field campaign apart from other studies. For example, both case studies in DiGiano *et al.* (2005) covered over 1,700 km of pipes: in their first case study, monitoring was done at 20 stations over a 5-day period, and in the second, 9 stations were monitored over a 7-day period.

Water quality characterization

Drinking water characterization was carried out simultaneously to validate tracer study results. The water quality monitoring strategy was identical to that used in the tracer study. As such, water samples were taken at each point in each loop in order to analyze free residual chlorine and measure *in situ* temperatures. During the last loop, additional samples were collected to measure THMs and HAAs. The purpose of the sampling protocol developed in this study was to minimize contamination risks and ensure sample integrity. Before tap water samples were taken, the water was allowed to run for at least five minutes so that the water collected would be from the network and not water that has been standing in the pipes of the houses or buildings. Sampling and analysis for residual chlorine, THMs and HAAs were carried out based on standard methods (APHA, AWWA & WEF 1998).

RESULTS AND DISCUSSION

In the characterization of the distribution network, a hydraulic model was developed to represent the main and the local pipes. Water consumption was apportioned across the nodes of the distribution network model. The tracer injection rate was first designed to be constant throughout the campaign and last a much longer period. Since the maximum residence time of water in the sector served by the reservoir had never been estimated before the field study, the uncalibrated hydraulic model was used to evaluate the duration for the tracer injection and sampling campaign. But an incident occurred two days before the campaign: one-third of the volume of the tracer solution was lost due to a valve malfunction of its holding reservoir. Simulations were carried out after the incident to determine if there was sufficient volume remaining and to estimate the impact of decreasing the concentration to be injected, although this was difficult with the equipment at hand. The decision was taken to carry out the tracer injection and sampling.

Afterwards, a "virtual tracer" was simulated in the hydraulic model by entering a time series of the real input tracer concentrations at the inlet node and simulating the evolution of the concentrations in time and space. Simulated distribution zones for this tracer were then compared to those obtained from the field data. Minimal manual calibration of the hydraulic model was needed to reproduce in simulation the observed distribution zones. Figure 3 presents a comparison of water ages obtained from field measurements (time of occurrence of the tracer) with those obtained from the hydraulic model. Considering the hypotheses made, the agreement between field and simulated values is good. In general, water age is higher in the model than in the field, which could indicate that the effective diameter of the real pipes is smaller than in the model due to tuberculation. Only at points A and B in Figure 1 does water reach these points faster in the model than in the field, probably due to the fact that these two points are located on local pipes where the uncertainty in flows is higher compared to main pipes. As for the four points where the agreement is not good (points C, D, E and F in Figure 1), local conditions were identified that prevented the model to represent real-life conditions:

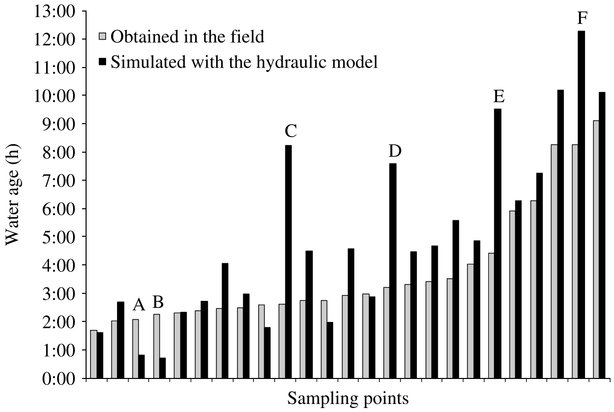

Figure 3 | Comparison of water ages obtained in the field with those obtained from the hydraulic model. Sampling points are presented in increasing field-obtained water ages.

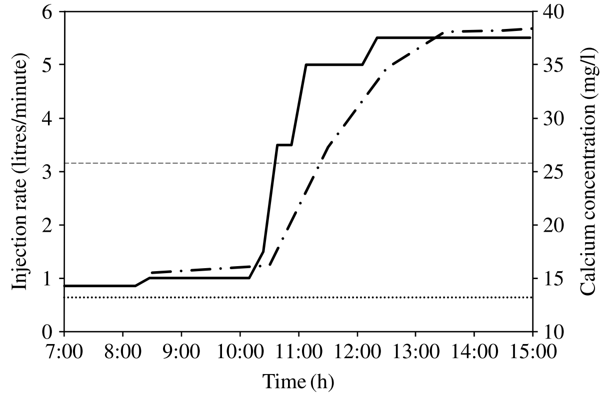

Figure 4 | Flow rate injection of $CaCl_2$ at the outlet of the reservoir (plain line). Broken line represents the $CaCl_2$ concentrations at PRV chamber, dotted line represents the average DWP $CaCl_2$ concentration and dashed line represents the mean injection rate.

point C is a dead-end in the model while this might not be the case in real life (a valve might be opened in the vicinity); there is higher uncertainty concerning water consumption in the sector of points D and F since they are located along a main boulevard with only a few buildings on one side of the street and there are many types of small commercial buildings that did not have a flowmeter; and we uncovered an interconnection with a neighbouring network in the vicinity of point E. In a following study, the hydraulic model will be finely tuned and used to test different hydraulic strategies to improve the residual chlorine concentrations in problematic sectors.

Tracer study

Adjusting the metering pump (rotameter) was more delicate than expected, since the tracer injection needed to be carried out at an average flow of 3 L/min. As shown in Figure 4, the tracer was in fact injected into the distribution network at three rates for a total period of eight hours: (1) from 7:00 to 10:15, the rate of injection was less than 1 L/m, (2) from 10:30 to 11:00, the rate was increased significantly from 1.5 to 3.5 L/m, (3) from 11:15 to 15:00 pm, the rate was further increased from 5 to 5.5 L/m. As such, total hardness obtained during the test for water from the reservoir varied from 12–39 mg/L of calcium. Starting at 11:00, four hours after injection had begun, water hardness had reached 36 mg/L of calcium in the network, equivalent to more than twice the concentration of DWP water. As shown in Figure 4, the tracer concentration surpassed the natural concentration of 13.2 mg/L early in the measurement campaign at the PRV chamber located 2.5 km from the reservoir outlet (there is no water consumption between these two sites). Changes in the rate of injection did not overly affect the results since the objective was to identify distribution zones from the reservoir and the DWP, not to determine the percent flow contribution from the sources of water.

For the points served by the DWP, a small increase in calcium concentration during the early hours of the test had no impact on the results. In fact, because the analysis was carried out using a very high precision instrument (ICP-OER: precision ≈ 0.2%), the tracer route was monitored from the beginning of the sampling at around 8:00.

Figure 5 shows the mean calcium values measured at sampling points during the tracer test at four different periods throughout the day. As mentioned previously, the average calcium concentration in water from the DWP was 13.2 mg/L, slightly lower than the usual average of around 16 mg/L. One hour after the test had started (Figure 5(a)), the calcium concentrations in water samples taken at the PRV chamber and just downstream from inlets 2 and 3 were already greater than the other sampling points. During subsequent hours, the tracer continued to evolve within the network right through to the end of the operation at around 16:00. The value of 15 mg/L chosen as the limit of the zone reached by the tracer represents an increase of about 15% compared to the average concentrations of calcium in the water network studied. Figures 5(b–d) show this

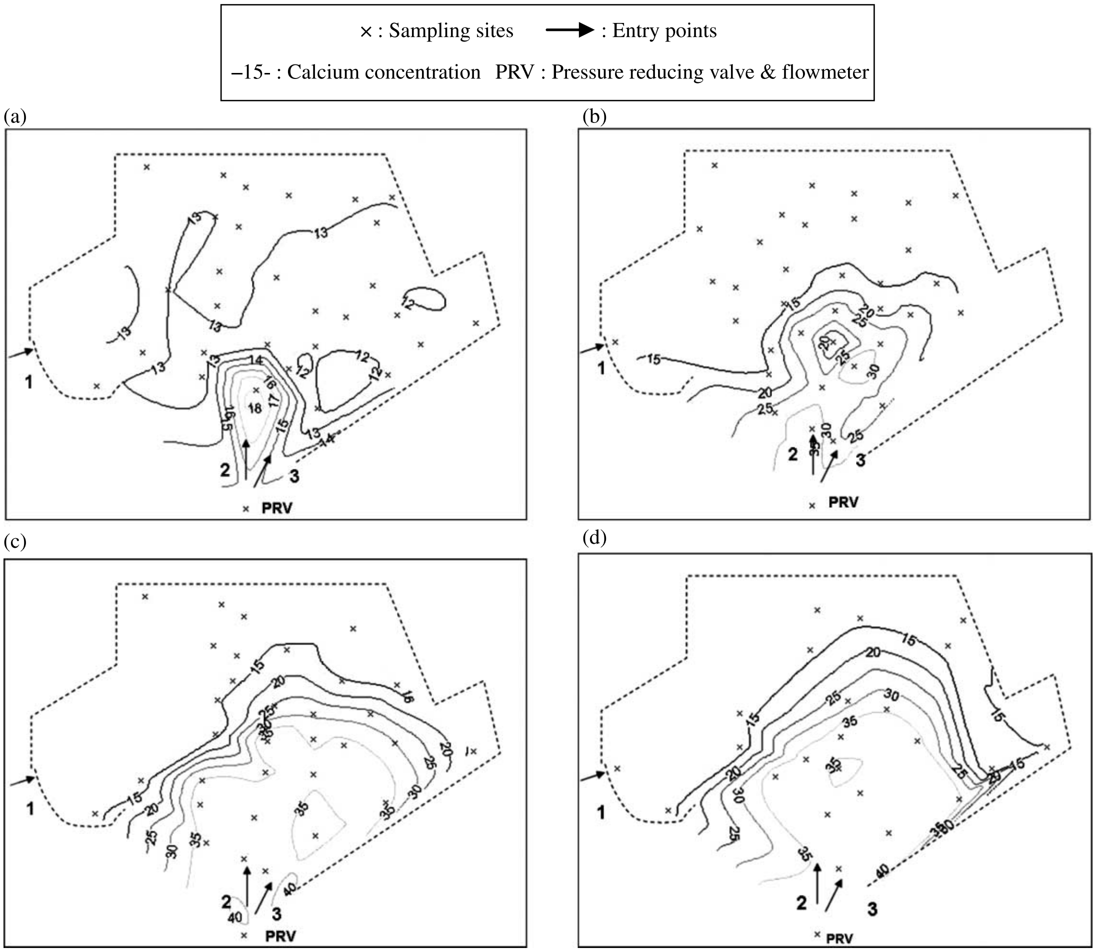

Figure 5 | Mean measured calcium concentrations (mg/L) at sampling sites for different periods of the tracer monitoring operation: (a) 8:00–9:00; (b) 12:00–13:00; (c) 14:00–15:00; (d) 15:00–16:00.

progression. It was evident that it continued to move northward. For logistical reasons, however, the tracer was not monitored after 16:00.

Sampling points where calcium concentration increased above the DWP average of 13.2 mg/L during tracer injection were identified as supplied by the reservoir. Elsewhere in the network, there are two possibilities for the small variations in calcium concentrations: either the points were fed by the DWP (from inlet 1), or they were entirely or mostly fed by the reservoir, but the water residence time associated with these points was greater than the duration of the tracer monitoring operation. The sampling points covered by the latter were generally located at the dead-ends of the network. These points were considered to be located within the so-called "grey zone", where there is uncertainty about the source of water. Figure 6 presents the changes in calcium concentration at three sampling points with different residence times shown in Figure 1. As expected, the sampling site with the shortest residence time showed the fastest increase in calcium concentration while the one with a high residence time showed an increase later during the day. The third point, showing no increase, is in the grey zone.

Water quality characterization study

Figure 7 shows free residual chlorine concentrations measured at sampling points at the inlets of the two distribution areas. The differences in residual chlorine values at these two points may be attributed to the fact

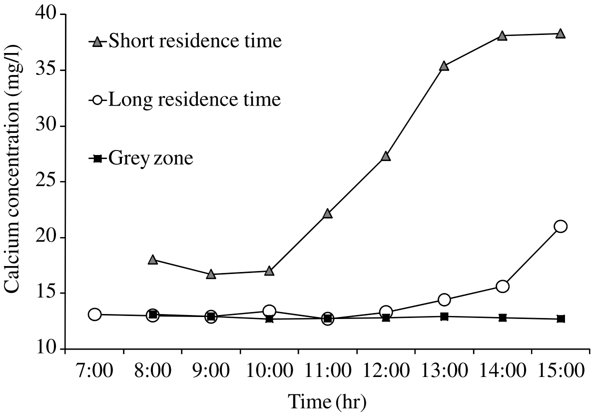

Figure 6 | Calcium concentrations at three sampling points with different residence times.

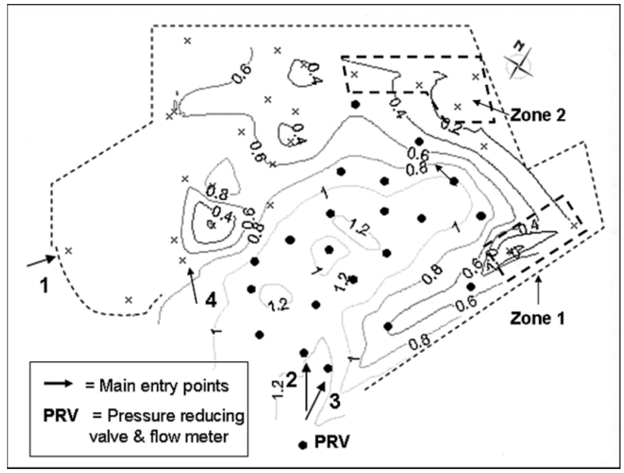

Figure 8 | Mean residual chlorine concentrations between 14:00 and 17:00 (contour lines). Black dots represent calcium concentrations at sampling sites associated with the reservoir.

that water from the reservoir was re-chlorinated at its outlet. Fortunately, the difference in residual chlorine was significant and, since the residence time is relatively short in the local distribution network (about 12 h), the chlorine does not degrade to a point that the difference becomes negligible. The chlorine concentrations for the reservoir and DWP are stable between 13:00 and 15:00. However, for comparison purposes, a period from 14:00 to 17:00 was considered to take into account the time it takes for water to reach the various points in the network.

Figure 8 shows the mean residual chlorine values obtained during the period when the reservoir and DWP chlorine concentrations were stable. Dots shown in this figure are water sampling points where calcium concentrations increased during the tracer test and where residual chlorine concentrations were also relatively high. The 0.8 mg/L contour line in this figure has a similar shape as the 15 mg/L contour line in Figure 5(d), showing a good agreement between the residual chlorine and calcium concentrations. There are two zones where the residual chlorine concentrations were relatively low and where the tracer was not routed during the test. Both zones are dead-end sectors: zone 1 is an industrial sector, while zone 2 is a low water consumption residential area. Although originally planned to cover a 12-hour period, the 8-hour tracer injection and 10-hour sampling was not sufficient to clearly identify the sources of water in these two zones.

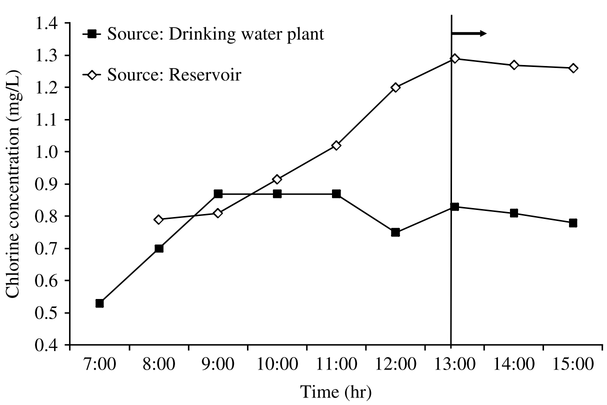

Figure 7 | Residual chlorine concentrations at the entry points of the two distribution zones.

Since the tracer did not reach zones 1 and 2 shown in Figure 8, a strategy based on decreasing chlorine concentrations was used. The flow paths obtained from the hydraulic simulation were validated with the measured chlorine concentrations, making sure they followed a decreasing concentration gradient. The larger diameter pipes, which make up the backbone of the distribution network, are less likely than the local pipes to have changes in flow direction with variations in water consumption throughout the day. Having verified the simulated flow paths with this strategy, we could conclude that zone 1 was fed exclusively by the reservoir and zone 2 by a mixture of both the DWP and the reservoir as shown in Figure 9: the upper edge of the sector is fed by the DWP (dashed paths), while the reservoir feeds the right part of the sector (dotted paths).

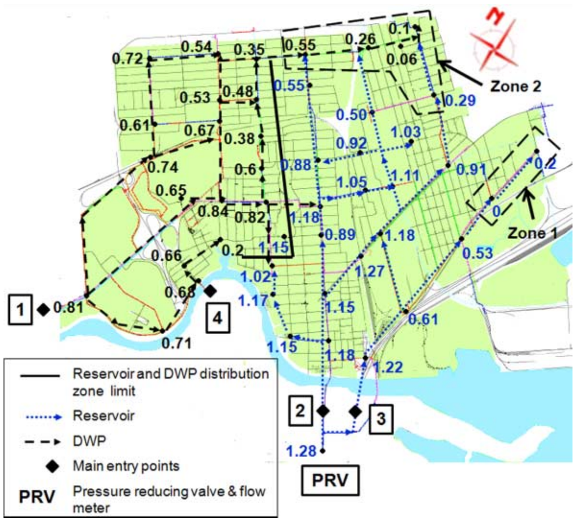

Figure 9 | Water paths in decreasing gradients of mean residual chlorine concentrations obtained between 14:00 and 17:00.

An analysis of other water quality parameters was used to validate these water flow path hypotheses. Figures 10(a) and 10(b) provide a portrait of THMs and HAAs at sampling points fed by the reservoir, the DWP and in the grey zone. These parameters were measured in the final loop of the sampling operation between 16:00 and 17:00. THM and HAA concentrations were significantly higher for sampling points fed by the reservoir than for those fed by DWP, while they were in-between for the ones in the grey zone. These results might be explained by the fact that re-chlorination at both the inlet and outlet of the reservoir, along with an increased residence time in the reservoir, significantly increased DBP concentrations.

Furthermore, as shown in Figure 11, levels of THMs and HAAs in the sector fed by the DWP are somewhat correlated, which is not the case in the sector fed by the reservoir. Weak correlations between these compounds in the latter sector might be explained by the fact that, as suggested by other studies, microbiological degradation of HAAs can occur within distribution systems (Chen & Weisel 1998; Rossman et al. 2001). HAA degradation may become greater in pipes with small diameters and when water residence time is higher (Williams et al. 1994), which is the case for several points supplied by the reservoir. This result suggests that the chemical characteristics of water that may influence the THM/HAA ratio are different in the two sectors (e.g. specific fractions of DBP precursors).

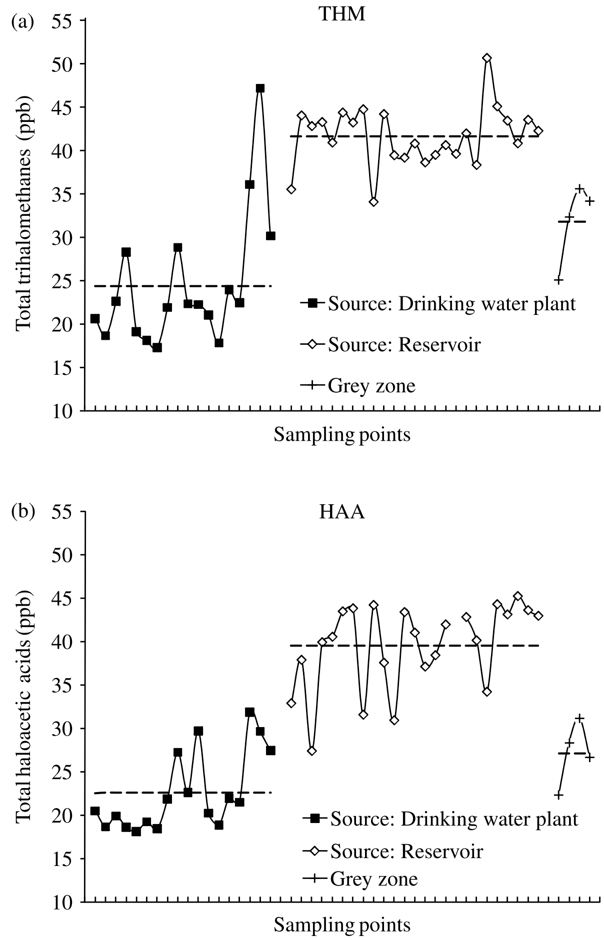

Figure 10 | THMs (four compounds) and HAAs (nine compounds) measured at the sampling sites.

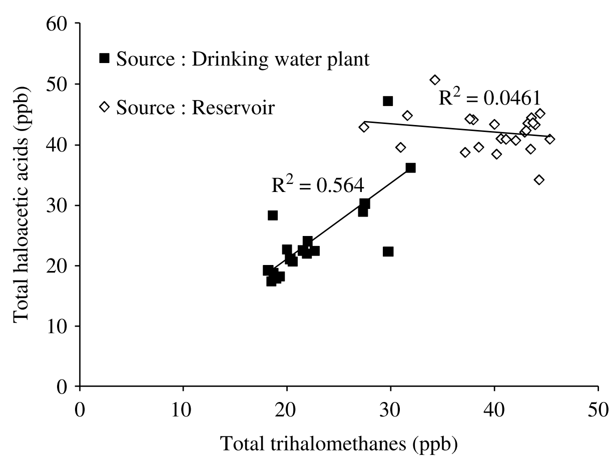

Figure 11 | Correlation between THM and HAA concentrations.

CONCLUSIONS

This study presents a methodology that can effectively identify distribution zones within a drinking water distribution network using $CaCl_2$ as a tracer. The proposed methodology is based on hydraulic modelling and tracer and water quality studies. The tracer study was conducted by injecting $CaCl_2$ at the reservoir outlet in order to increase calcium concentrations in water supplied by the reservoir. Following this injection, an intensive sampling campaign was carried out to monitor calcium concentrations at 47 locations. A water quality study was conducted simultaneously to measure residual chlorine, THM and HAA concentrations at all sampling sites.

The results of this research show that combining information from a hydraulic model, a tracer study and key water quality parameters is a good strategy to identify distribution system zones. The spatio-temporal monitoring of $CaCl_2$, as a tracer, allowed us to effectively identify contributions of water sources to end-use water consumption in distribution network locations. Sampling locations for which calcium concentrations increased during the campaign were associated with the reservoir distribution sector. In addition, results showed that water supplied by the reservoir had distinctively higher levels of residual chlorine (due to re-chlorination) than water supplied directly by the treatment plant. In fact, water quality data (residual chlorine, THMs and HAAs), along with the hydraulic model, allowed us to overcome the shortcomings associated with the insufficient duration of the tracer injection and sampling.

In future work, the calibrated hydraulic model will be used to test different hydraulic strategies to improve the residual chlorine concentrations in problematic sectors. This tool would be very useful in managing and improving the quality of drinking water in a distribution system.

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