# Impact of incomplete mixing in the prediction of chlorine residuals in municipal water distribution systems

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## ABSTRACT

This paper investigates the mixing phenomena in pipe junctions in water distribution systems. Network simulation models frequently assume that mixing at pipe junctions is complete and instantaneous. In the present study, a series of experiments using tee and cross junctions with varying inflows and free chlorine concentrations were carried out in the Hydraulic Laboratory of the Institute of Engineering at the National Autonomous University of Mexico. Numerical simulations of these experiments were also performed using EPANET-BAM. Experimental results from this study showed that mixing is not complete in most of the cases; intersecting flows tend to bifurcate rather than mix completely. Numerical simulations indicated good agreement between calculated and measured values. The model was also tested using data from the water distribution system of Duberger-Les Saules, in Quebec City, Canada. A larger vulnerability zone was identified due to the impact of the incomplete mixing at the cross junction in the prediction of chlorine residual in a water distribution network.

**Key words** | chlorine residual, cross junction, EPANET-BAM, mixing, mixing parameter, water distribution systems

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## INTRODUCTION

The goal of a water distribution network is to provide safe, odorless and colorless water to consumers. Water quality within a drinking water distribution network is strongly influenced by many factors, the most important ones being residence time in the network (water age), biochemical reactions in the bulk flow and with the pipe walls, and mixing at junctions. In order to understand how water quality parameters evolve in time and space in the drinking water distribution network, a good understanding of the hydraulics is necessary. A pressurized flow simulation model is useful to analyze hydraulic paths and flow velocities under various water demand conditions. Furthermore, in recent years, there has been an increased interest in integrating water quality processes such as the chlorine decay into the modeling of water distribution systems. Maintaining minimum chlorine residual throughout the distributions system at all times reduces the risk of microbial regrowth in the network and thus reduces health risks for consumers. The most commonly used simulator, EPANET (Rossman 2000), has demonstrated profusely its ability to simulate real-life hydraulics and chlorine degradation, but has a limitation in that it assumes mixing at pipe junctions as complete and instantaneous. Then, Mays (2004) stated that complete and instantaneous mixing of incoming water occurs at all intersections, such as cross and tee junctions. Currently, nearly all water network models assume complete and instantaneous mixing at pipe junctions.

Fowler & Jones (1991) first questioned the assumption that complete mixing occurred at various intersections in water distribution systems. Recent experimental and computational studies have shown that mixing at cross junctions is incomplete. Chávez *et al.* (2005) studied the mixing at cross

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junctions that showed incomplete mixing. Their experiments included a cross junction supplied by two inlet pipes that has a clean inlet and a contaminated (e.g. tracer) inlet. Experimental tests were performed with various flow rates ranging from 0.32 to 1.5 L/s. However they did not perform numerical studies.

Mompremier & Fuentes Mariles (2012) also studied similar mixing effect phenomena in pipe junctions. They used two adjacent incoming flows (one with NaCl as tracer and the other with clean water) having the same Reynolds numbers in turbulent regime ($Re > 10,000$) for the inflow and outflow sections. It was observed that the NaCl concentration in the two outflow sections were different with more than 85% of the NOCl concentration observed in the outlet adjacent to where the tracer was introduced. Simulations for this flow configuration indicated a very good correlation between experimental and numerical findings and showed that complete mixing did not occur.

Ho *et al.* (2007) investigated various junction configurations such as cross and double tee junctions. Results showed that mixing in confined cross junctions is incomplete and depends on the transient instabilities at the impinging interface and the relative flow rates entering and leaving the junction. Following that study, a new bulk advective mixing (BAM) model that was implemented in EPANET which can simulate incomplete mixing in cross junctions.

Austin *et al.* (2008) studied mixing phenomenon at cross junctions with flow rates of 7.6 L $min^{-1}$ or higher and a wide range of Reynolds numbers in the turbulent regime. Two conventions were chosen to present the level of mixing: dimensionless concentration and mass split. Results indicated that the average dimensionless concentration and mass split through the outlets were 85% and 15%, respectively. These findings indicated that mixing at cross junction was incomplete unlike in perfect mixing where 50% would be expected.

Thus, experimental results from multiple researchers have revealed that mixing at cross junctions is incomplete. However, most of the previous research studied mixing phenomena in turbulent regime ($Re > 10,000$) with an experimental setup using clean water and a tracer at inlets. This research investigates the mixing phenomena at cross and tee junctions (to evaluate its impact in the prediction of the chlorine decay in water distribution system) under various flow rate and tracer concentration combinations. Experiments were conducted in laminar, transitional and turbulent regimes using sodium hypochlorite (NaOCl) as a soluble tracer.

## MATERIALS AND METHODS

### Experimental setup and preparation

In real water distribution network there are often four configurations of cross junction that include: one inlet with two outlets; two inlets with one outlet (tee junction: Figure 1(a)); two inlets with two outlets (depending on the direction of flow, this can be divided into two categories – two inflows at 90° (Figure 1(b)) and two inflows at 180° (Figure 1(c))); and one inlet with three outlets (Figure 1(d)).

These configurations were constructed in the Hydraulic Laboratory of the Institute of Engineering at the National Autonomous University of Mexico, as shown in Figure 1.

The experimental setup consisted of a cross-junction pipe system, a water reservoir (2.12 $m^3$ capacity) and two storage tanks at elevated position for gravity flow. The network system included two flow control valves, four flow meters and four free chlorine controllers. Pipes were of the following diameters: 12.7, 19, 25.4, 32 and 38 mm. An upstream pipe length of 7.55 m was used to allow a better mixing of NaOCl and for turbulent flow to fully develop before entering the cross junction. Detailed dimensions of the cross junctions and PVC pipes are presented in Figure 2.

### Materials and equipment

In order to control the concentration released from the storage tanks, a NaOCl dosing pump (BL3-12 model, Hanna Instruments) was installed. An advanced system for chlorine measurement (CL7635 model, B&C Electronics) was installed at each inlet and outlet of the cross junction. The controllers are designed for direct reading of chlorine dioxide, ozone and free chlorine. The concentration range is from 0 to 20 mg/L. A data logger (El-USB-4 model, Lascar Electronics) was connected to each controller to record measurements at a rate of a data point per second. Data were then downloaded to a PC where they could be analyzed.

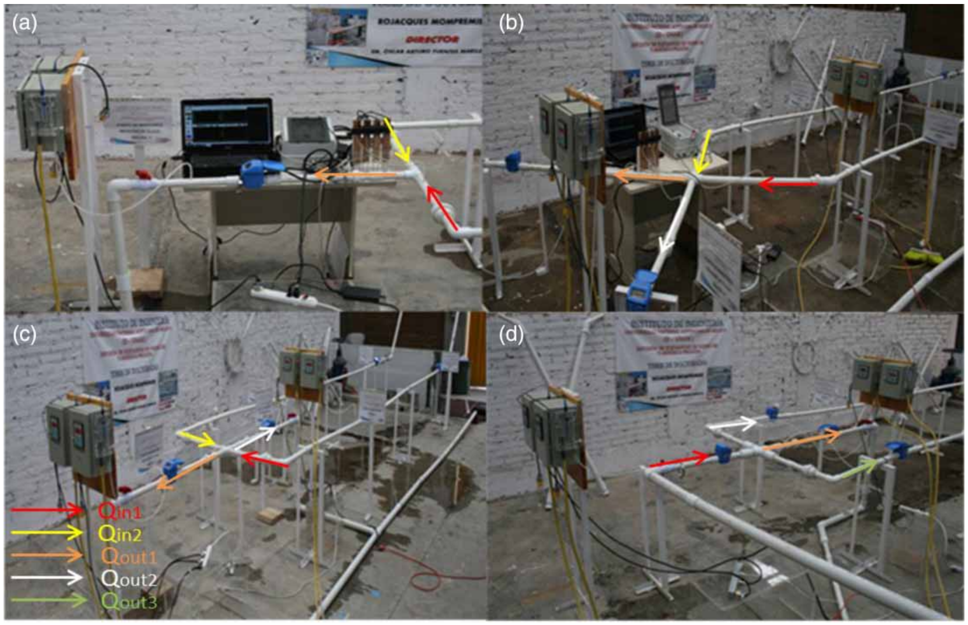

**Figure 1** | Configurations of the experimental setup: (a) two inlets with one outlet; (b) two inlets at 90° with two outlets; (c) two inlets at 180° and two outlets; d) one inlet and three outlets.

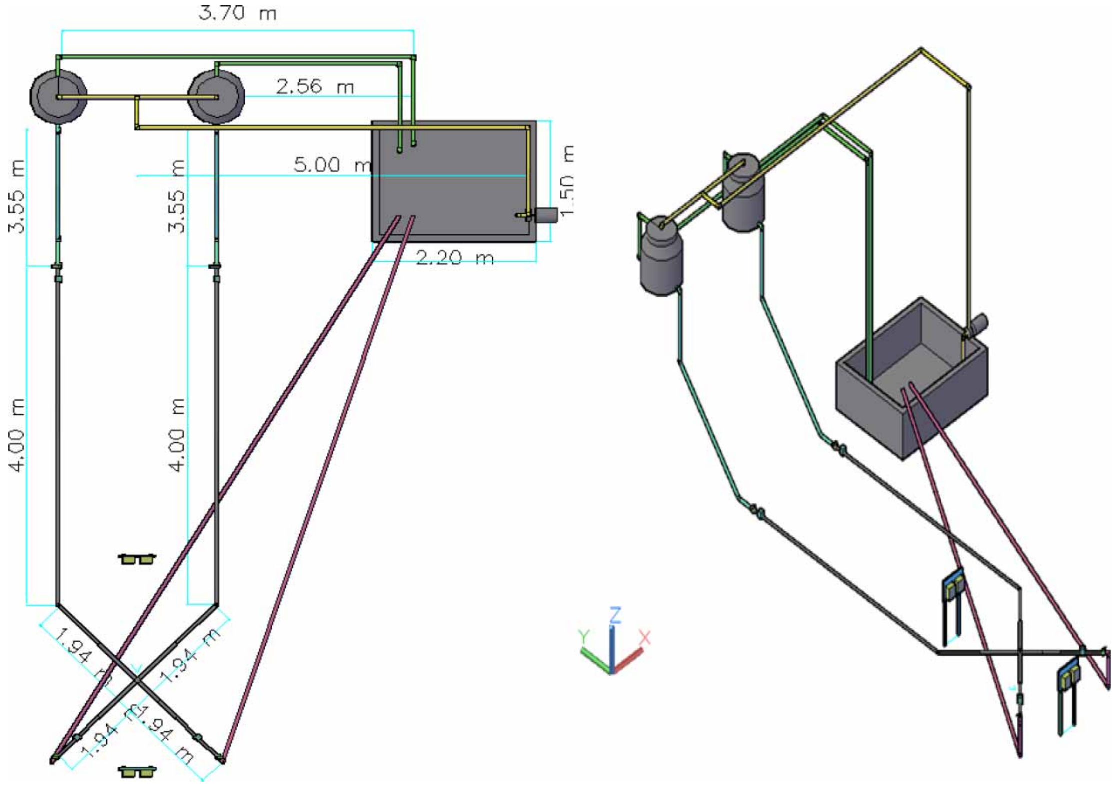

**Figure 2** | Details of the experimental setup: plan view and 3D view.

The system also included four flow meters (CZ3000s model, Contazara SA) located at each inlet and outlet of the cross junction to measure instantaneous flow rate in the system. To ensure the precision of the measurement, a relative error was calculated for each test, a margin of error of 5% is acceptable. A data acquisition system was used to collect flow rate and tracer concentration data at inlets and outlets.

## Estimating concentration ratios of the scenarios

Different combinations of flows, concentrations and configurations were investigated to assess mixing phenomena at cross junctions. In total seven scenarios were designed as shown in Tables 1 and 2, and described below.

Scenario A provides equal inflows from inlet 1 ($Q_{in1}$) and inlet 2 ($Q_{in2}$) having the same free chlorine concentration in both inlets ($C_{in1} = C_{in2}$). All the other scenarios have varying inflows from their two or three inlets. Like scenario A and scenario B, free chlorine concentrations in both inlets are equal. All other scenarios have varying concentrations for their two or three inlets, scenario C is a special case of a tee junction with two inlets and one outlet, scenario D is the only one with three inlets. Scenario E has the same configuration as scenario F but the free chlorine concentration for inlet 1 is higher than for inlet 2. Finally, scenario G has 2 inlets at 180° instead of 90°. As flows tend to bifurcate at adjacent outlets, a concentration ratio R was then defined for each scenario to provide a means to determine the outlet concentrations based on inlet concentration. For scenarios A and B, as $C_{in1} = C_{in2}$, R is calculated as:

**Table 1** | Description of the scenarios in terms of cross-junction configurations, inflows and inlet concentrations

| | **Cross-junction configurations** | | | |
|---|---|---|---|---|
| **Scenarios** | **Inlets** | **Outlets** | **Inflows** | **Concentrations** |
| A | 2 | 2 | $Q_{in1} = Q_{in2}$ | $C_{in1} = C_{in2}$ |
| B | 2 | 2 | $Q_{in1} \neq Q_{in2}$ | $C_{in1} = C_{in2}$ |
| C | 2 | 1 (tee) | $Q_{in1} \neq Q_{in2}$ | $C_{in1} \neq C_{in2}$ |
| D | 3 | 1 | $Q_{in1} \neq Q_{in2} \neq Q_{in3}$ | $C_{in1} \neq C_{in2} \neq C_{in3}$ |
| E | 2 at 90° | 2 | $Q_{in1} > Q_{in2}$ | $C_{in1} > C_{in2}$ |
| F | 2 at 90° | 2 | $Q_{in1} > Q_{in2}$ | $C_{in1} < C_{in2}$ |
| G | 2 at 180° | 2 | $Q_{in1} > Q_{in2}$ | $C_{in1} > C_{in2}$ |

**Table 2** | Flow rates and concentrations for the tested scenarios

| **Scenarios** | **Flow rates [L/s]** | **Free chlorine concentration [mg/L]** |
|---|---|---|
| A & B | 0.16–0.90 | 0.29–0.85 |
| C & D | 0.17–0.42 | 1.25–1.75 |
| E | 0.09–0.90 | 0.13–1.80 |
| F | 0.10–0.90 | 0.06–1.65 |
| G | 0.14–0.24 | 0.59–1.68 |

$$R_{Sc1-2} = \frac{C_{out2}}{C_{in}} \tag{1}$$

For scenarios C and D, since there is only one outlet, mixing will be complete. For scenarios E and G, as $C_{in1} > C_{in2}$, R is defined as:

$$R_{Sc5\,\mathrm{or}\,7} = \frac{C_{out2}}{C_{in1}} \tag{2}$$

Finally, for scenario F, as $C_{in1} < C_{in2}$, R is defined as:

$$R_{Sc6} = \frac{C_{out1}}{C_{in2}} \tag{3}$$

Once the concentration ratio R is estimated for each scenario, $C_{out1}$ or $C_{out2}$ can be estimated from Equation (1), (2) or (3). Then, a solute mass balance is performed within the cross junction to obtain the concentration at the other outlet, as follows:

$$C_{out1} = \frac{(Q_{in1}C_{in1} + Q_{in2}C_{in2}) - RC_{in1}Q_{out2}}{Q_{out1}} \tag{4}$$

## RESULTS AND DISCUSSION

Scenarios A and B are the simplest cases studied in this investigation. Table 3 shows inlet and outlet concentrations [free chlorine] and volumetric flow rates for the two scenarios. As observed during the experiments, for inflows with equal chlorine concentration there was no difference between the inlet and outlet concentrations [$C_{in1} = C_{in2} = C_{out1} = C_{out2}$] in all the tests. It is important to mention that when two or three incoming flows meet in a junction, turbulent and transient instability along the impinging

**Table 3** | Experimental results for scenarios A and B

| Scenario | Tests | $Q_{in1}$ [L/s] | $Q_{in2}$ [L/s] | $Q_{out1}$ [L/s] | $Q_{out2}$ [L/s] | ΔQ [L/s] | ΔQ/(Qin) [%] | $C_{in1}$ [mg/L] | $C_{in2}$ [mg/L] | $C_{out1}$ [mg/L] | $C_{out2}$ [mg/L] | $M_{inlet}$ [mg/s] | $M_{outlet}$ [mg/s] | R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 1 | 0.17 | 0.17 | 0.16 | 0.18 | 0.00 | 0.0 | 0.40 | 0.40 | 0.40 | 0.40 | 0.136 | 0.136 | 1.00 |
| | 2 | 0.18 | 0.18 | 0.17 | 0.19 | 0.00 | 0.0 | 0.33 | 0.33 | 0.33 | 0.33 | 0.119 | 0.119 | 1.00 |
| | 3 | 0.22 | 0.22 | 0.21 | 0.23 | 0.00 | 0.0 | 0.45 | 0.45 | 0.45 | 0.45 | 0.198 | 0.198 | 1.00 |
| | 4 | 0.25 | 0.25 | 0.24 | 0.26 | 0.00 | 0.0 | 0.40 | 0.40 | 0.40 | 0.40 | 0.200 | 0.200 | 1.00 |
| B | 1 | 0.32 | 0.17 | 0.18 | 0.31 | 0.00 | 0.0 | 0.35 | 0.35 | 0.35 | 0.35 | 0.172 | 0.172 | 1.00 |
| | 2 | 0.34 | 0.21 | 0.26 | 0.29 | 0.00 | 0.0 | 0.60 | 0.60 | 0.60 | 0.60 | 0.330 | 0.330 | 1.00 |
| | 3 | 0.34 | 0.20 | 0.22 | 0.32 | 0.00 | 0.0 | 0.29 | 0.29 | 0.29 | 0.29 | 0.157 | 0.157 | 1.00 |
| | 4 | 0.36 | 0.22 | 0.27 | 0.31 | 0.00 | 0.0 | 0.30 | 0.30 | 0.30 | 0.30 | 0.174 | 0.174 | 1.00 |
| | 5 | 0.38 | 0.16 | 0.24 | 0.29 | 0.01 | 1.9 | 0.45 | 0.45 | 0.45 | 0.45 | 0.243 | 0.239 | 1.00 |
| | 6 | 0.38 | 0.16 | 0.24 | 0.29 | 0.01 | 1.9 | 0.85 | 0.85 | 0.85 | 0.85 | 0.459 | 0.451 | 1.00 |
| | 7 | 0.45 | 0.24 | 0.34 | 0.34 | 0.01 | 1.4 | 0.33 | 0.33 | 0.33 | 0.33 | 0.228 | 0.224 | 1.00 |
| | 8 | 0.90 | 0.48 | 0.70 | 0.68 | 0.00 | 0.0 | 0.33 | 0.33 | 0.33 | 0.33 | 0.455 | 0.455 | 1.00 |
| Max | | 0.90 | 0.48 | 0.70 | 0.68 | | 1.9 | 0.85 | 0.85 | 0.85 | 0.85 | 0.460 | 0.460 | 1.00 |
| Min | | 0.17 | 0.16 | 0.16 | 0.18 | | 0.0 | 0.29 | 0.29 | 0.29 | 0.29 | 0.120 | 0.120 | 1.00 |
| Average | | 0.36 | 0.22 | 0.27 | 0.31 | | 0.4 | 0.42 | 0.42 | 0.42 | 0.42 | 0.240 | 0.240 | 1.00 |
| Inlet or outlet average | | 0.29 | | 0.29 | | | | | | | | | | |

interface is observed. This instability causes the fluid to mix (Webb & van Bloemen Wanders 2006). In the case of equal inflows (scenario A), no turbulence was observed and flow streams bounced one another and exit through adjacent pipe without mixing. However, in scenario B, although inflow rates were different and turbulent instability was observed, results showed no difference between the inlet and outlet concentrations since inflow concentrations were equal (Mompremier *et al.* 2012).

Tests 5, 6 and 7 of scenario B showed a difference between inflows and outflows, resulting in a relative error of 1.9% for tests 5 and 6, 1.4% for test 7. Overall, an average error of 0.4% was observed in the flow balance for all the tests due to equipment calibration and precision. For scenarios A and B, the concentration ratio R was 1.0.

In scenarios C and D (2 and 3 inlets, respectively, and 1 outlet), six separate tests were conducted with varying inflows and varying initial concentrations. Concentration data were collected at the outlet and an average of inlet concentrations was observed in Tests 1, 2, 3, 4 and 6, while in test 5 an absolute error of 0.05 was observed. Since flows enter the cross or tee junction and leave through a single outlet, regardless of whether inflow rates are similar or not, turbulent and transient instability occur along the interface resulting in perfect mixing, Rossman (2000). Results for scenario C are presented in Table 4.

**Table 4** | Experimental results for scenario C

**Varying inflows; Varying concentrations (Tee junction)**

| Scenario C | $Q_{in1}$ [L/s] | $Q_{in2}$ [L/s] | Q out1 [L/s] | ΔQ | $C_{in1}$ [mg/L] | $Ci_{n2}$ [mg/L] | $C_{out1}$ [mg/L] | $M_{inlet}$ [mg/s] | $M_{outlet}$ [mg/s] | Average $C_{in1}$,$C_{in2}$ [mg/L] | Absolute error [mg/L] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test 1 | 0.220 | 0.400 | 0.610 | 0.010 | 1.26 | 1.08 | 1.17 | 0.7092 | 0.7107 | 1.17 | 0.00 |
| Test 2 | 0.110 | 0.200 | 0.300 | 0.010 | 1.60 | 0.96 | 1.28 | 0.3700 | 0.3840 | 1.28 | 0.00 |
| Test 3 | 0.150 | 0.200 | 0.350 | 0.000 | 0.96 | 1.36 | 1.16 | 0.4160 | 0.4060 | 1.16 | 0.00 |
| Test 4 | 0.180 | 0.300 | 0.480 | 0.000 | 1.00 | 1.80 | 1.40 | 0.7200 | 0.6720 | 1.40 | 0.00 |
| Test 5 | 0.360 | 0.600 | 0.950 | 0.010 | 0.90 | 1.30 | 1.15 | 1.1040 | 1.0925 | 1.10 | 0.05 |
| Test 6 | 0.240 | 0.170 | 0.410 | 0.000 | 1.60 | 1.24 | 1.42 | 0.5965 | 0.5863 | 1.42 | 0.00 |

Experimental results for scenario E are presented in Table 5. An average relative error of 1.2% was observed on the flow balance for all the tests, with a maximum relative error of 2.9% for test 3. In the case of this scenario, it is observed that the largest momentum caused some of the flow to crossover the junction into the opposite outlet and turbulent as well as transient instability occurred along the interface. Figure 3 compares experimental results for Scenario E with the ones that assumed complete mixing. Experimental results showed a significant difference (>15%) between the two outlet concentrations when the chlorine concentration in the higher inflow was approximately 1.47 to 2.5 times more than the other. For Tests 4, 5 and 7 where the chlorine concentration in the higher inflow was approximately 1.27 to 1.46 times greater than the other, the difference was around 6%. These findings indicate that mixing is not perfect. Impinging flow within the cross junction tend to bifurcate rather than mix completely (Austin *et al.* 2008; Romero-Gomez *et al.* 2008; Ho & O'Rear 2009). The concentration ratio (calculated from Equation (2)) for this scenario ranged from 0.89 to 0.97, with an average R of 0.93.

Experimental results for scenario F are presented in Table 6. An average relative error of 0.6% was observed on the flow balance for all the tests, with a maximum relative error of 3.4% for Test 7. This scenario showed similar effect presented in scenario E, but now a crossover effect from higher momentum of the lower free chlorine inflow was observed. However, the bifurcation of $Q_{in1}$ into $Q_{out2}$ is clearly observed. A significant difference (>20%) between the two outlet concentrations was also observed. It is important to mention that this difference depends on the concentrations at inlets. The higher the difference between the inlets concentrations, the higher the difference in the outlets. As shown in Test 5 where concentration at inlet 2 was approximately 8 times bigger than inlet 1, a difference of 82.5% was observed in outlet concentrations. For Test 4 where concentration at inlet 2 was 1.5 more than inlet 1, only a difference of 3.7% was observed between outlets. The concentration ratio (calculated from Equation (3)) ranged from 0.78 to 0.83, with an average value of 0.80. Figure 4 compares results obtained in the laboratory for scenario F with the ones obtained with the assumption of complete mixing. Ho & O'Rear (2009) studied mixing behavior at pipe junctions, using clean and contaminated water at inlets. The study reported that when the clean water inlet flow rate is greater than the tracer inlet flow rate, the greater momentum causes the flow to push across the junction, blocking the incoming flow in the other inlet (for example the case of unequal pipe sizes). Thus, one outlet was

**Table 5** | Experimental results for scenario E

| **Scenario E** | **$Q_{in1}$ [L/s]** | **$Q_{in2}$ [L/s]** | **$Q_{out1}$ [L/s]** | **$Q_{out2}$ [L/s]** | **$\Delta Q$** | **$\Delta Q/Qn$ [%]** | **$C_{in1}$ [mg/L]** | **$C_{in2}$ [mg/L]** | **$C_{out1}$ [mg/L]** | **$C_{out2}$ [mg/L]** | **$\Delta C_{out}$ [%]** | **$M_{in}$ [mg/s]** | **$M_{out}$ [mg/s]** | **R** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test 1 | 0.180 | 0.090 | 0.140 | 0.125 | 0.005 | 1.9 | 1.75 | 0.70 | 1.24 | 1.63 | 31.5 | 0.378 | 0.377 | 0.93 |
| Test 2 | 0.194 | 0.120 | 0.150 | 0.160 | 0.004 | 1.3 | 1.65 | 0.70 | 1.06 | 1.53 | 44.3 | 0.404 | 0.404 | 0.93 |
| Test 3 | 0.210 | 0.105 | 0.156 | 0.150 | 0.009 | 2.9 | 1.75 | 0.75 | 1.27 | 1.63 | 28.3 | 0.446 | 0.443 | 0.93 |
| Test 4 | 0.250 | 0.160 | 0.260 | 0.140 | 0.010 | 2.4 | 1.25 | 0.87 | 1.10 | 1.17 | 6.4 | 0.452 | 0.450 | 0.94 |
| Test 5 | 0.350 | 0.180 | 0.300 | 0.220 | 0.010 | 1.9 | 1.80 | 1.42 | 1.65 | 1.75 | 6.1 | 0.886 | 0.880 | 0.97 |
| Test 6 | 0.360 | 0.180 | 0.290 | 0.250 | 0.000 | 0.0 | 1.65 | 0.80 | 1.16 | 1.53 | 31.9 | 0.738 | 0.719 | 0.93 |
| Test 7 | 0.380 | 0.230 | 0.310 | 0.300 | 0.000 | 0.0 | 0.19 | 0.13 | 0.16 | 0.17 | 6.3 | 0.102 | 0.101 | 0.89 |
| Test 8 | 0.400 | 0.240 | 0.310 | 0.325 | 0.005 | 0.8 | 1.25 | 0.85 | 1.00 | 1.16 | 16.0 | 0.704 | 0.687 | 0.93 |
| Test 9 | 0.430 | 0.210 | 0.330 | 0.300 | 0.010 | 1.6 | 1.75 | 0.75 | 1.25 | 1.63 | 30.4 | 0.910 | 0.902 | 0.93 |
| Test 10 | 0.390 | 0.280 | 0.350 | 0.320 | 0.000 | 0.0 | 1.55 | 0.80 | 1.04 | 1.44 | 38.5 | 0.829 | 0.825 | 0.93 |
| Test 11 | 0.900 | 0.440 | 0.630 | 0.710 | 0.000 | 0.0 | 1.39 | 0.50 | 0.88 | 1.29 | 46.6 | 1.471 | 1.470 | 0.93 |
| Max | 0.900 | 0.440 | 0.630 | 0.710 | | 2.9 | 1.80 | 1.42 | 1.65 | 1.75 | | | | 0.97 |
| Min | 0.180 | 0.090 | 0.140 | 0.125 | | 0.0 | 0.19 | 0.13 | 0.16 | 0.17 | | | | 0.89 |
| Average | 0.368 | 0.203 | 0.293 | 0.273 | | 1.2 | 1.45 | 0.75 | 1.07 | 1.35 | | | | 0.93 |

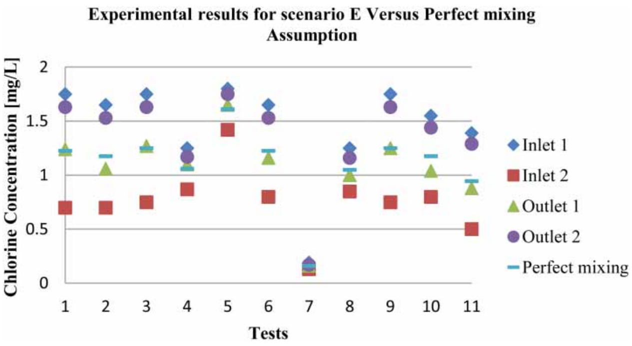

**Figure 3** | Free chlorine concentration from the experimental setup and assuming perfect mixing for all tests of scenario E.

composed of clean water, which was not mixed with the tracer while the other outlet had a mixture of both inflows. The results indicate that mixing was not perfect.

Scenarios A, B, C, E and F have focused on two inflows at 90°, except scenario D that has three inflows. Scenario G, however, studied flows entering the junction at 180°. Experimental results for this scenario are presented in Table 7 where different combinations of flow rates with different free chlorine concentrations in each of the inlet were investigated. During the experiments, it is observed that the incoming flows collide in the junction; provoke turbulence along the impinging interface then exited through the outlet pipes. Free chlorine concentrations in both outlets were equal. Similar configurations have been studied by Ho & O'Rear (2009), where junctions consisting of two opposing inlets with equal and unequal pipe sizes; different combination of flow rates were investigated and yielded results equivalent to perfect mixing. The concentration ratio (calculated from Equation (2)) ranged from 0.58 to 0.61, with an average of 0.60.

## Numerical simulation

In this study, numerical simulations of flows at cross and tee junctions were performed using open-source software EPANET-BAM, a bulk advective model developed by Ho & Khalsa (2007). This software allows users to select a mixing parameter 's' (between 0 and 1) for each junction in the network.

The model was calibrated by comparing the predicted values with experimental data. Finally, to ensure that the mathematical model adequately represented the measured physical phenomena, the root mean square error (RMSE) was calculated as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_1)} \qquad (5)$$

where RMSE is the root mean square error, $x_i$ is calculated data, $y_i$ is the measured data and $n$ is the number of data. The optimal value of this parameter is zero, which ensures

**Table 6** | Experimental results for scenario F

| Scenario F | $Q_{in1}$ (L/s) | $Q_{in2}$ (L/s) | $Q_{out1}$ (L/s) | $Q_{out2}$ (L/s) | ΔQ | ΔQ/ (Qin) | $C_{in1}$ (mg/L) | $C_{in2}$ (mg/L) | $C_{out1}$ (mg/L) | $C_{out2}$ (mg/L) | $\Delta C_{out}$ | $M_{in}$ (mg/s) | $M_{out}$ (mg/s) | R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test 1 | 0.200 | 0.170 | 0.170 | 0.200 | 0.000 | 0.0% | 0.64 | 1.90 | 1.62 | 0.74 | 54.3% | 0.451 | 0.423 | 0.85 |
| Test 2 | 0.250 | 0.150 | 0.170 | 0.230 | 0.000 | 0.0% | 0.60 | 1.00 | 0.78 | 0.73 | 6.7% | 0.300 | 0.300 | 0.78 |
| Test 3 | 0.320 | 0.170 | 0.180 | 0.310 | 0.000 | 0.0% | 0.61 | 1.25 | 1.00 | 0.73 | 27.0% | 0.408 | 0.406 | 0.80 |
| Test 4 | 0.340 | 0.200 | 0.220 | 0.320 | 0.000 | 0.0% | 0.90 | 1.35 | 1.08 | 1.04 | 3.7% | 0.576 | 0.570 | 0.80 |
| Test 5 | 0.340 | 0.210 | 0.260 | 0.290 | 0.000 | 0.0% | 0.06 | 0.50 | 0.40 | 0.07 | 82.5% | 0.125 | 0.124 | 0.80 |
| Test 6 | 0.360 | 0.220 | 0.270 | 0.310 | 0.000 | 0.0% | 0.15 | 0.51 | 0.41 | 0.18 | 55.9% | 0.166 | 0.166 | 0.80 |
| Test 7 | 0.380 | 0.200 | 0.250 | 0.310 | 0.020 | 3.4% | 0.21 | 0.81 | 0.65 | 0.21 | 67.6% | 0.242 | 0.227 | 0.80 |
| Test 8 | 0.400 | 0.300 | 0.350 | 0.340 | 0.010 | 1.4% | 0.71 | 1.39 | 1.15 | 0.87 | 24.2% | 0.701 | 0.701 | 0.83 |
| Test 9 | 0.450 | 0.240 | 0.340 | 0.340 | 0.010 | 1.4% | 0.50 | 1.40 | 1.12 | 0.52 | 53.6% | 0.561 | 0.558 | 0.80 |
| Test 10 | 0.680 | 0.400 | 0.440 | 0.640 | 0.000 | 0.0% | 0.30 | 0.70 | 0.58 | 0.36 | 38.6% | 0.484 | 0.484 | 0.83 |
| Test 11 | 0.900 | 0.480 | 0.700 | 0.680 | 0.000 | 0.0% | 0.90 | 1.65 | 1.32 | 0.99 | 25.0% | 1.602 | 1.597 | 0.80 |
| Max | 0.900 | 0.480 | 0.700 | 0.680 |  | 3.4% | 0.900 | 1.900 | 1.620 | 1.04 |  |  |  | 0.85 |
| Min | 0.200 | 0.150 | 0.170 | 0.200 |  | 0.0% | 0.060 | 0.500 | 0.400 | 0.07 |  |  |  | 0.78 |
| Average | 0.420 | 0.249 | 0.305 | 0.361 |  | 0.6% | 0.507 | 1.133 | 0.919 | 0.58 |  |  |  | 0.80 |

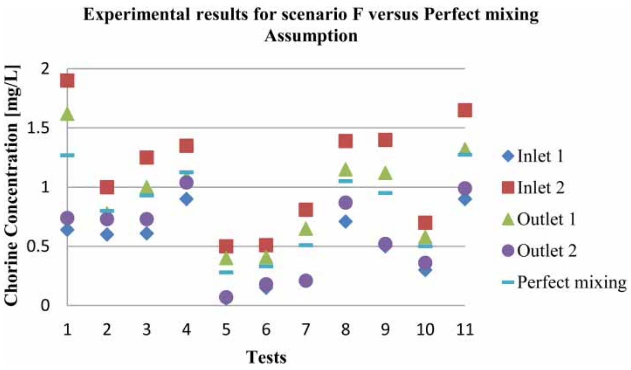

**Figure 4** | Free chlorine concentration from the experimental setup and assuming perfect mixing for all tests of scenario F.

that the calculated data is identical to the measured value. In this study, for each scenario, simulations were performed using the mixing parameter ranging from 0 to 1; the RMSE was calculated for each case. The mixing parameter that yielded the lowest value for the RMSE was assigned to each scenario. Table 8 shows the calibration process for scenario F and the RMSE value for five simulations. As the optimal values were observed starting the second simulation, only five simulations have been performed.

As shown in the calibration process, a mixing parameter of 0.2 was assigned to scenario F because it yielded the lowest value for RMSE. Simulations were performed for each scenario using the same method. Table 9 shows values of mixing parameter assigned to each scenario. For scenarios C and D with only one outlet, the mixing parameter was equal to 1.

## Application of the numerical simulation on real water distribution system

Finally, in order to compare model results that assume complete and incomplete mixing at a cross junction, the model was tested using the data of the water distribution system of Duberger – Les Saules, in Quebec, Canada. This real

**Table 7** | Experimental results for scenario G

| Tests | $Q_{in1}$ [L/s] | $Q_{in2}$ [L/s] | $Q_{out1}$ [L/s] | $Q_{out2}$ [L/s] | ΔQ [L/s] | ΔQ/ ($Q_{in}$) | $C_{in1}$ [mg/L] | $C_{in2}$ [mg/L] | $C_{out1}$ [mg/L] | $C_{out2}$ [mg/L] | ΔCout | $M_{in}$ [mg/s] | $M_{out}$ [mg/s] | R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test 1 | 0.14 | 0.24 | 0.25 | 0.13 | 0.000 | 0.0% | 1.47 | 0.59 | 0.88 | 0.88 | 0.0% | 0.347 | 0.334 | 0.60 |
| Test 2 | 0.13 | 0.23 | 0.24 | 0.12 | 0.000 | 0.0% | 1.67 | 0.59 | 0.97 | 0.97 | 0.0% | 0.353 | 0.349 | 0.58 |
| Test 3 | 0.14 | 0.22 | 0.24 | 0.12 | 0.000 | 0.0% | 1.37 | 0.61 | 0.82 | 0.84 | 2.4% | 0.326 | 0.298 | 0.61 |
| Max | 0.140 | 0.240 | 0.250 | 0.130 | | 0.0% | 1.670 | 0.610 | 0.970 | 0.97 | | | | 0.61 |
| Min | 0.130 | 0.220 | 0.240 | 0.120 | | 0.0% | 1.370 | 0.590 | 0.820 | 0.84 | | | | 0.58 |
| Average | 0.137 | 0.230 | 0.243 | 0.123 | | 0.0% | 1.503 | 0.597 | 0.890 | 0.90 | | | | 0.60 |

**Table 8** | Calibration process for scenario F

| Position | Experimental data [mg/L] | Simulations | Mixing parameter | Estimated data [mg/L] | RMSE [mg/L] |
|---|---|---|---|---|---|
| Outlet 1 | 1.62 | 1st | 0.1 | 1.67 | 0.05 |
| Outlet 2 | 0.74 | | | 0.70 | 0.04 |
| **Outlet 1** | **1.62** | **2nd** | **0.2** | **1.62** | **0.00** |
| **Outlet 2** | **0.74** | | | **0.76** | **0.02** |
| Outlet 1 | 1.62 | 3rd | 0.3 | 1.57 | 0.05 |
| Outlet 2 | 0.74 | | | 0.82 | 0.08 |
| Outlet 1 | 1.62 | 4th | 0.4 | 1.52 | 0.10 |
| Outlet 2 | 0.74 | | | 0.87 | 0.13 |
| Outlet 1 | 1.62 | 5th | 0.5 | 1.48 | 0.14 |
| Outlet 2 | 0.74 | | | 0.93 | 0.19 |

**Table 9** | Mixing parameter assigned to each scenario

| **Scenarios** | **Mixing** | **Intersection Cross** | **Mixing parameter s [Numerical]** | **Concentration ratio R [Experimental]** |
|---|---|---|---|---|
| A | Complete | X | 1 | 1.00 |
| B | Complete | X | 1 | 1.00 |
| E | Incomplete | X | 0.3 | 0.93 |
| F | Incomplete | X | 0.2 | 0.80 |
| G | Complete | X | 1 | 0.60 |

network (Figure 5(a)) is supplied by two valve chambers represented by two water reservoirs: sources A and B with initial chlorine concentrations of 1.5 mg/L. For simulation purposes, we assumed chlorine concentration of 0.1 and 1.5 mg/L in sources A and B, respectively (concentration at source A was not the real value but was used to show how the common assumption of complete mixing could lead to potentially inaccurate transport predictions). The distribution system consists of a flow control valve and a pressure-reducing valve, along with 169 nodes and 216 pipes with a diameter ranging from 75 to 300 mm. Water demand was associated with each node of the model according to the population, depending on the land use. Characteristics of the network were calculated by EPANET, and the water quality model produced results for the perfect mixing case. The same hydraulic conditions were used for the incomplete mixing model. Global bulk coefficient (−0.053 per day) and global wall coefficients (0.080 m/day) were also incorporated in the new model (to study chorine decay). Then, an adjustment of mixing parameter has been incorporated for each node, according to experimental study. In order to assign mixing parameter

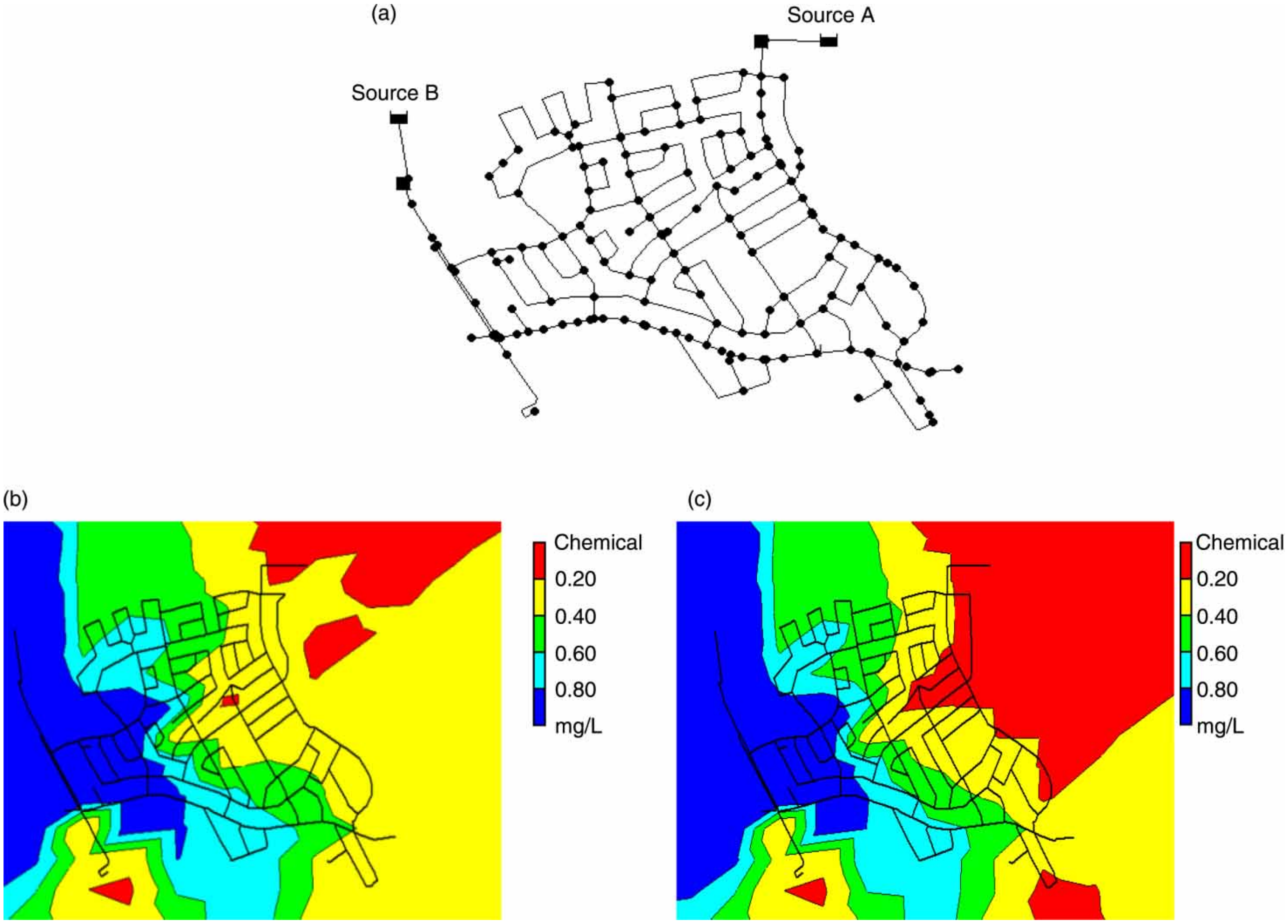

**Figure 5** | (a) EPANET model for the case study; (b) prediction of chlorine concentrations using the complete mixing model; and (c) prediction of chlorine concentrations using the incomplete mixing model developed in this study.

for each type of junction, simulations were performed using EPANET. Flow, Velocity, and Chlorine concentration rates were obtained in the links of each node. The EPANET 2. NET files were exported as an .INP input file, then a mixing parameter column to the exported .INP file has been added. Finally a mixing parameter was assigned to each junction according to results obtained in Table 9. The modified .INP file has been opened in the EPANET-BAM. Then, new simulations were performed using EPANET-BAM to predict the chlorine residual concentrations within the network. Contour maps of chlorine concentrations are shown in Figure 5(b) and Figure 5(c) for the complete mixing and incomplete mixing model, respectively.

Transport of contaminant through a water distribution system depends on mixing at pipe junctions along the network where different flow rates with varying chlorine concentrations can exist. This example shows significant difference between models that assume complete versus incomplete mixing. A perfect mixing model can lead to erroneous representation of the actual mixing behavior. In Figure 5(b) it is clearly observed that chlorine concentrations were maintained between 0.10 and 1.50 mg/L, except in a small low-consumption zone where concentrations were less than 0.10 mg/L; while in the incomplete model (Figure 5(c)), chlorine concentrations were under 0.10 mg/L in much larger areas because of the bifurcation and reflection of incoming fluid streams. With a perfect mixing model, chlorine concentration in various regions is over predicted while the actual chlorine residual concentration is very low and the quality of water can be seriously affected. Such a complete mixing assumption may result in public health risk. To assess risk and detect sources of contaminants, it is strongly recommended to use the model that assumes incomplete mixing pipe junctions.

## CONCLUSION

This study has deepened our understanding of the mixing phenomenon in cross and tee junctions and its impact on the distribution of chlorine residuals in the different pipes at junctions in municipal water distribution systems. This study shows how modeling on the assumption of perfect mixing can create error in water quality in particular when the network is supplied by more than one source. A series of experiments with varying inflows and free chlorine concentrations were carried out. For two equal or varying incoming flows with equal free chlorine concentration, results showed no difference between the inlet and outlet concentrations. For two or three varying incoming flow (cross and tee junction), solute mixing has shown to be complete due to the turbulence of the fluid stream. For two varying incoming flows with varying free chlorine concentration solute mixing was shown to be incomplete, flows tend to bifurcate and reflect off rather than mix completely. For two varying opposing inflows, solute mixing has shown to be perfect due to the collision of the fluid stream. Concentration ratio R was calculated for each case and can be useful to modify water quality modeling in relation to the mixing at cross junction. Finally, numerical simulations were performed using EPANET-BAM and the model was calibrated based on experimental results. A mixing parameter was assigned to each scenario. In addition, simulations were performed using data from a real network. By comparing the results with those obtained with EPANET, this finding showed how modeling on the assumption of perfect mixing can create error in water quality predictions in particular when the network is supplied by more than one source.

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