Study of hydraulics and mixing in roof tanks used in intermittent water supply

R. D. Hernandez-Lopez, V. G. Tzatchkov, A. Martin-Dominguez and V. H. Alcocer-Yamanaka

ABSTRACT

Roof tanks are common in low and middle income countries, due to the intermittent water supply. Their hydraulic and water mixing behaviour has not been studied. This paper presents the results of a study on mixing and water demand in roof tanks, based on physical and numerical models. Tracer tests were carried out on a real scale transparent wall laboratory model of a roof tank, and a three-parameter residence time distribution model was applied, showing that the model that best describes mixing in roof water tanks is the one with a completely stirred flow reactor with a small portion of bypassing. This result was confirmed by computational fluid dynamic simulations and visual observation. The instantaneous water flow derived from activating typical home water-using fixtures was measured at the pipe feeding the tank, the pipe exiting the tank, and without a roof tank. Stochastic water demand patterns were generated with the measured data and used in the numerical model of a small distribution network. Based on this model it was found that water demand and pipe flow behave differently in continuous and intermittent water supply networks. The instantaneous flow rate withdrawn from the water distribution network pipes is lower in systems with roof tanks.

Key words | computational fluid dynamic (CFD) models, instantaneous water demand, intermittent water supply, residence time distribution, roof tanks

R. D. Hernandez-Lopez
Universidad Nacional Autónoma de México,
Morelos Campus, Paseo Cuauhnahuac 8532,
Jiutepec, Mor.,
Mexico,
CP 62550

V. G. Tzatchkov (corresponding author)
A. Martin-Dominguez
Instituto Mexicano de Tecnología del Agua,
Paseo Cuauhnahuac 8532, Jiutepec, Mor,
Mexico,
CP 62550
E-mail: *velitchk@tlaloc.imta.mx*

V. H. Alcocer-Yamanaka
Comisión Nacional del Agua,
Insurgentes Sur 2416, Coyoacan, Ciudad de
Mexico,
Mexico,
CP 04340

INTRODUCTION

Intermittent water supply is prevalent in many low and middle income countries around the globe, more out of necessity than by design. Rapid and unplanned urbanization, where the water supply infrastructure lags behind city growth, and water scarcity, are frequent reasons for intermittent water supply. To overcome the inconveniences of being without continuous tap water, consumers secure their water supply through the use of ground or roof tanks inside their homes. Inequitable water distribution, possible water contamination, wasting water, the coping costs for consumers and water providers (Lee & Schwab 2005) as well as meter malfunctioning (Criminisi *et al.* 2009) are some of its negative consequences. Although a transfer to a 24-hour supply by reducing water losses and/or adding new supply sources would be in principle the best solution, it may take a long time to achieve, or may require financial resources that are not available. It has been observed that even when the transfer to a 24-hour supply is achieved, many consumers prefer to keep their roof tanks (Burt & Ray 2014). Although undesirable, intermittent water supply and roof tanks are likely to remain for many years to come, so appropriate design and operation methods that can minimize their negative impacts need to be developed. Hydraulic and water quality distribution network models can be useful tools in developing such methods (Coelho *et al.* 2003; Cabrera-Bejar & Tzatchkov 2009). Such models

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originated from developed countries however, where water service is continuous and water demand is satisfied all the time. This is very different from the intermittent supply networks, where the amount of water each user is able to collect depends on the available pressure and the duration of the service, and user demand is not always fully satisfied (Vairavamoorthy *et al.* 2007). Existing studies on the impact of intermittent water supply on water quality (Evison & Sunna 2001; Tokajian & Hashwa 2003; Ayoub & Malaeb 2006; Kumpel & Nelson 2013) have been centred on collecting and testing samples of water for contamination in the network or at in-home storage, without modelling the networks.

Modelling of intermittent supply distribution networks requires special considerations, based on a clear understanding of the local hydraulic and water quality processes that occur inside the roof tanks. Conceived for continuous supply networks, known network models consider that water demand is withdrawn directly from the network pipes and thus consumed with the same quality it has in the pipes. The situation is very different in intermittent supply networks, and also in networks where the water supply is continuous but the users still use their roof tanks. Water is consumed from the roof tanks in these cases and may reside for a long period of time in them before being consumed, affecting its quality. It is therefore important to model the roof tanks along with the pipes in the water distribution network. Known water distribution network analysis programs, such as Epanet (Rossman 2000) and others, do consider tanks, based on some idealized reactor models, such as the completely stirred reactor, the plug flow reactor and a two compartment mixing model. Several researchers have studied the applicability of such reactor models for large distribution storage tanks in continuous supply networks. Grayman & Clark (1993) conducted a series of studies demonstrating that water quality in distribution networks is degraded as a result of long residence times in storage tanks and proposed a model for mixing in those tanks. Grayman *et al.* (2004), Mahmood *et al.* (2005), and Crowther & Dandy (2010) have applied computational fluid dynamics (CFD) models to study the mixing in distribution storage tanks. All those studies were focused on large tanks, and may not be applicable to roof tanks, which are much smaller. This paper presents a study of water demand, residence time and disinfectant mixing in roof tanks, based on physical, numerical (CFD) and theoretical models.

MATERIAL AND METHODS

A real scale acrylic transparent wall model of a 1,100 L roof tank was constructed at the Hydraulics Laboratory of the National Autonomous University of Mexico, Morelos Campus (Figure 1). Tracer tests were carried out on the model to determine the type of mixing inside the tank and the percentage of eventual dead-space and bypassing. Tracer tests, widely used in chemical reactor engineering (Levenspiel 1998) to detect the type of non-ideal flow and mixing through a vessel, consist of introducing a tracer at the vessel entrance, observing its concentration at the vessel exit under steady water flow through the vessel, and processing the observed data by a theoretical model. Steady water flow through the tank is a necessary condition for tracer tests. In order to maintain such steady flow, water was taken from a lower tank (cistern) and pumped to two smaller, additional roof tanks needed to achieve a constant level and thus constant flow through the modelled roof tank.

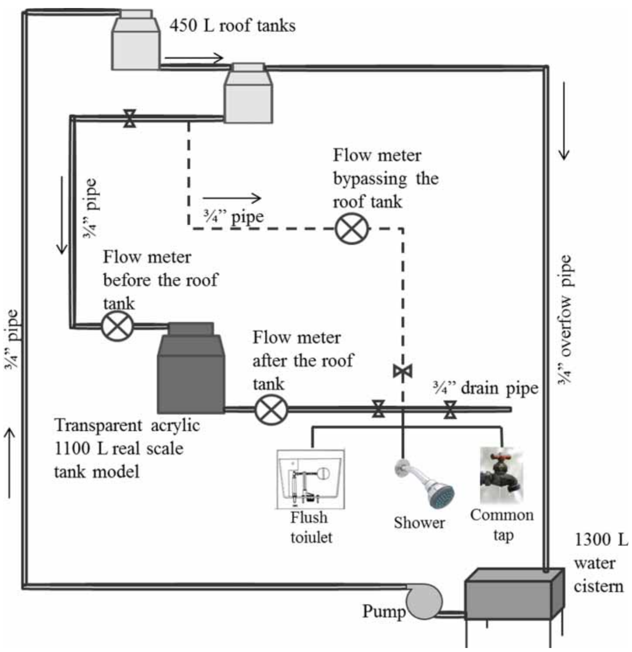

Figure 1 | The experimental setup of the roof tank model.

The model was equipped with high resolution water flow meters capable of registering water demand up to every second; instruments for measuring conductivity (a HANNA multi-parameter instrument to continuously register the total dissolved solids), the colour (a Hach colorimeter), and other accessories for tracer tests. The model was also intended to be used for studying the instantaneous residential water demand in homes with private water tanks. For this reason, three typical home water-using fixtures (a common tap, a shower and a flush toilet) were connected to the tank exit to simulate and measure typical instantaneous home water demand.

The experiments on this model were not intended to replicate the filling and emptying process that take place in a roof tank in a home. Water flow through real roof tanks is never steady. In intermittent supply, roof tanks are normally filled up when the piped water supply is on, and they then drain as households use the water from the tanks, before refilling. There are many forms of intermittency: some intermittent systems may provide water for most hours every day, while others may provide only a few hours once per week (in which cases the tanks would be nearly empty most of the time or even may be emptied). All these situations can be readily modelled by a water distribution network analysis software, such as Epanet (Rossman 2000) or similar (except for the distribution system filling which requires different treatment) (Cabrera-Bejar & Tzatchkov 2009; De Marchis et al. 2010), if supplied with a proper model for the mixing inside the roof tanks and proper water demand, which are the focus of this paper.

Two conservative tracers (common salt and methylene blue) were used. For each tracer, the tests were performed for different flow and water volumes values in the tank. The three-parameter-residence-time-distribution model for several reactors in series with stagnation space and bypassing, developed by Martín-Dominguez et al. (2005) and Tzatchkov et al. (2009), was applied to analyse the hydraulic behaviour of the water tank. Particularly, the fractions of stagnation space and bypassing, as well as the theoretical number of reactors in series, were obtained by using an optimization procedure that minimizes the error between tracer test data and the model's residence-time-distribution function. The flow through the tank is theoretically represented as flow through a series of N equal size continuous flow stirred tank reactors (CFSTRs), allowing for stagnation space and bypassing at each CFSTR. The residence time distribution function for this model, for an instantaneous tracer addition at the tank's inlet, is given by Equation (1):

$$E(\theta) = \frac{Nn}{M} \sum_{i=1}^{N} \frac{N!\, e^{-N\theta_{eff}} N^{i-1} \theta_{eff}^{i-1} (1-n)^{N-i} n^{i}}{(N-i)!\; i!\; (i-1)!} + (1-n)\,\delta(\theta_{eff}) \tag{1}$$

where $\theta = t/\tau$ = dimensionless residence time; $E(\theta)$ = residence time distribution function; t = time; $\tau = V/Q$ = global mean residence time; Q = volumetric flow rate; V = volume of water in the tank; N = theoretical number of reactors in series; n = fraction of the flow rate effectively used; M = fraction of the tank's volume that is effectively used in the process (with no stagnation space); $\theta_{eff} = n\theta/M$ = effective dimensionless residence time; $\delta(.)$ = Dirac function, a mathematical abstraction, with zero width and an infinite height.

A computational fluid dynamics (CFD) model of the roof tank was implemented using the PHOENICS numerical modelling software (CHAM 2005), providing a detailed flow velocity distribution inside the tank.

Residential water demand, an important component of distribution network modelling, is difficult to precisely determine. It is most frequently represented by a smooth curve, generally on an hourly basis. At the residential service level, this curve does not reflect reality. Real residential water demand is inherently stochastic, sporadic, and very different from that representation. Special stochastic methods have been developed in the last few years to properly represent the residential water demand (Alvisi et al. 2003; Buchberger et al. 2003) where it is characterized by sudden demand pulses. The authors further developed such a technique by employing the Neyman–Scott Rectangular Pulse method, based on the solution of a non-linear optimization problem that involves the observed moments (from field measurements) and theoretical moments for the synthetic demand series, and validated it on a real distribution network (Alcocer-Yamanaka et al. 2012). Statistically equivalent synthetic demand series can be generated for use in distribution network modelling by using the obtained pulse parameters.

In order to extend such a stochastic technique to an intermittent supply network, the instantaneous water

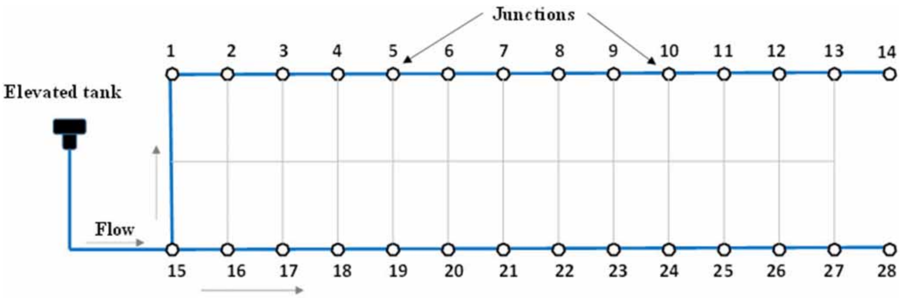

Figure 2 | The distribution network model used for comparing the continuous and intermittent pipe flow.

demand evolution of the three typical home water-using fixtures was measured. Water meters measuring the flow rate once per second were placed in three locations: in the pipe out-flowing from tank (after the tank), in the pipe feeding the tank (before the tank), and on a line that bypasses the tank (the last case emulates a home without a roof tank, as in continuous water supply systems). The instantaneous flow rate evolution on activating each of the three typical home water-using fixtures was then recorded, with 1 s time resolution. The objective of this series of experiments was to compare the instantaneous water demand in three scenarios: as drawn from the roof tank, as drawn from the distribution network pipe with a roof tank, and drawn directly from the distribution network. The tank was maintained full in these experiments, and the water level constant, by mean of a float valve. These experiments were repeated 10 times. This situation (for the flow rate observed before and after the tank) would correspond to modelling the case where the tank is full up during delivery time, although the real objective of maintaining it full was to have the same pressure at the water-using fixtures for all the experiments.

The Epanet program (Rossman 2002) was then used to simulate the flow in a small network supplying 28 homes from an elevated storage tank (Figure 2), in three scenarios: (a) without private tanks, as in continuous water supply systems; (b) with ground level private tanks (cisterns); and (c) with roof private tanks. A special procedure for generating the water demand series was used, providing a different demand pattern for each of the network nodes (homes) using the observed demand. Details about the network model and the water demand generation procedure are presented in a separate paper (Tzatchkov et al. 2015).

RESULTS AND DISCUSSION

The tracer tests were carried out for five combinations of three different flow rates ($Q = 0.05$, 0.075 and 0.10 L/s) and three water volumes in the tank ($V = 290$, 580 and 870 L), in two trials for each combination, as shown in Table 1 along with the results. $N = 1$ was obtained for all tests. Figure 3

Table 1 | Results from the tracer tests

		Mean residence time (min)		1–*M* (%)		1–*n* (%)	
Q (L/s)	*V* (L)	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
0.05	870	162.57	155.03	25	26	0	0
0.1	870	101.28	112.68	18	19	2.6	1.2
0.075	580	93.4	95.4	21	21	1.4	1.8
0.05	290	87.36	84.87	0	0	1.8	1.7
0.1	290	51.98	60.27	0	0	2.1	1.9

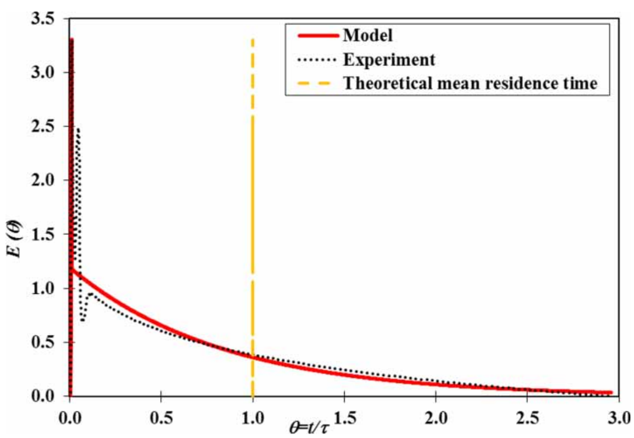

Figure 3 | The result of a tracer test for $Q = 0.10$ L/s and $V = 870$ L, and its three parameter model fitting.

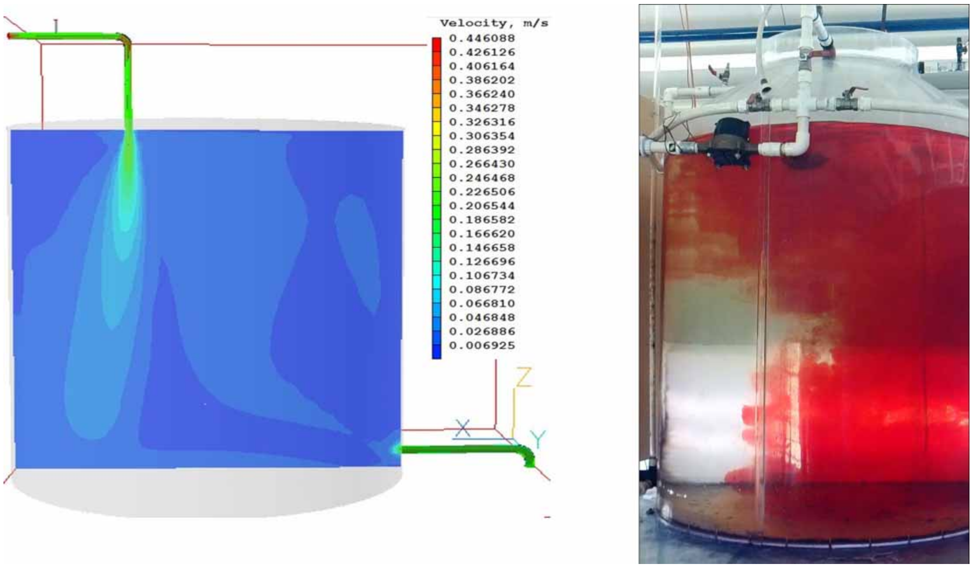

Figure 4 | The velocity distribution inside the tank obtained by CFD for $Q = 0.10$ L/s and $V = 870$ L (left) and the instantaneous colour tracer distribution at time 30 s after the tracer injection (right).

shows the results for one of the tracer tests, corresponding to $Q = 0.10$ L/s and $V = 870$ L, fitted to the three parameter model. For this test, the model obtained 1–$M = 18\%$ stagnation space and 1–$n = 2.60\%$ bypassing. Figure 4 shows the velocity distribution obtained by the CFD model for the same test conditions and a photograph of the instantaneous colour tracer distribution at the very beginning of the test (30 s after the tracer injection). Figures 5 and 6 show the same results for another test with $Q = 0.10$ L/s and $V = 290$ L, where the model obtained 1–$M = 0$ and 1–$n = 2.10\%$.

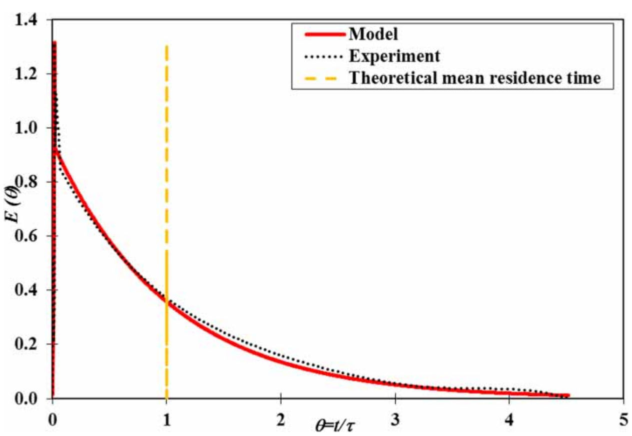

Figure 5 | The result of the tracer test for $Q = 0.10$ L/s and $V = 290$ L, and its three parameter model fitting.

These results show that the mixing model corresponds to one completely stirred flow reactor with a small portion of bypassing and a stagnation zone for larger tank volumes. The visual observation of the colour tracer and the output of the CFD model, partially shown in Figure 4, confirmed these results.

For $N = 1$, as obtained from the tracer tests, Equation (1) simplifies to:

$$E(\theta) = \frac{n^2 e^{-\frac{n}{M}\theta}}{M} + (1-n)\,\delta\left(\frac{n}{M}\theta\right) \quad (2)$$

Equation (2), which expresses the residence time distribution for a CFSTR with stagnation zone and bypassing, was first obtained by Cholette & Cloutier (1959) using material balance principles. It can be also deduced from probability considerations as shown by Tzatchkov *et al.* (2009). For $M = 1$, as obtained from the tracer tests for a small volume of water in the tank, it further reduces to:

$$E(\theta) = n^2 e^{-n\theta} + (1-n)\,\delta(n\theta) \quad (3)$$

Given the results of the tracer test obtained in this study ($N = 1$, $M > 0$ for larger water volumes, and 1–$n \approx 2.50\%$), Equations (2) and (3) are recommended for modelling the

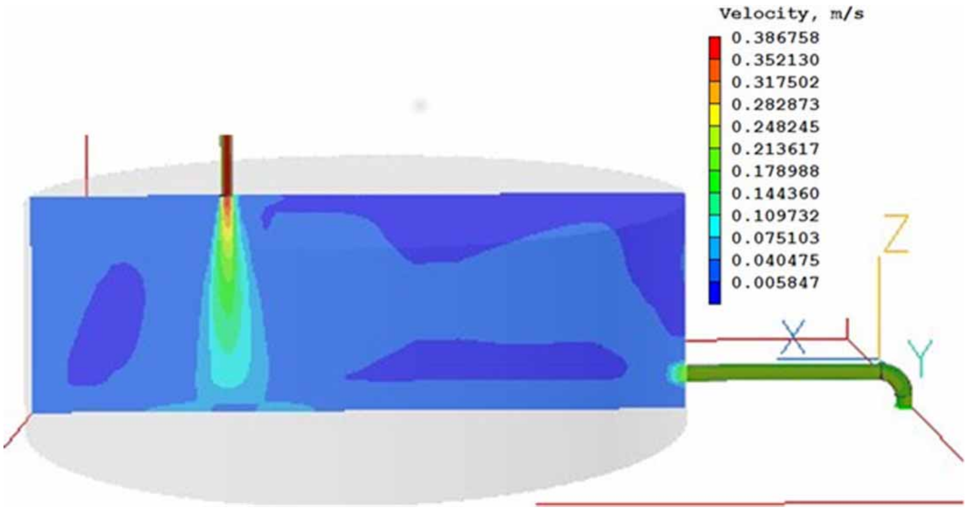

Figure 6 | The velocity distribution inside the tank obtained by CFD for $Q = 0.10$ L/s and $V = 290$ L.

mixing behaviour of roof tanks, where the value of n should be about 97.5%. For practical work, the Dirac function $\delta(n\theta)$ can be approximated by a very sharp Gauss function, as done in Figures 3 and 5, or by another suitable function.

Figures 7–9 compare the observed flow rate variation upon activating the flush toilet, shower and tap, respectively. For single short time water uses, as in the cases of the flush toilet and common tap, the maximum flow without a tank was much higher than the flow before the tank. This result shows that, when water is used while a supply is being delivered by the distribution system, the instantaneous flow rate withdrawn from the water distribution network pipes by

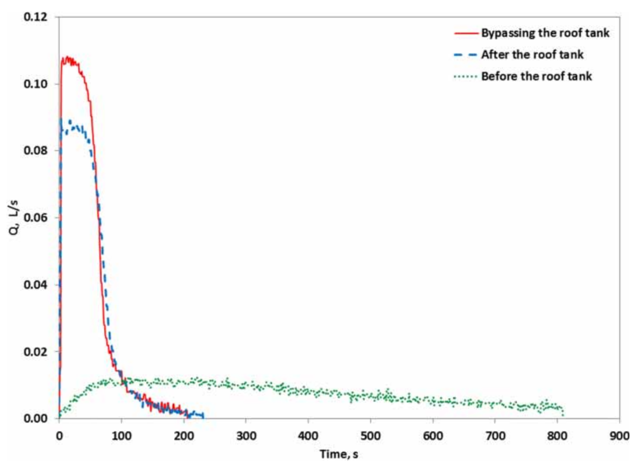

Figure 7 | The observed flow variation upon activating a flush toilet, for the three positions of the water meter.

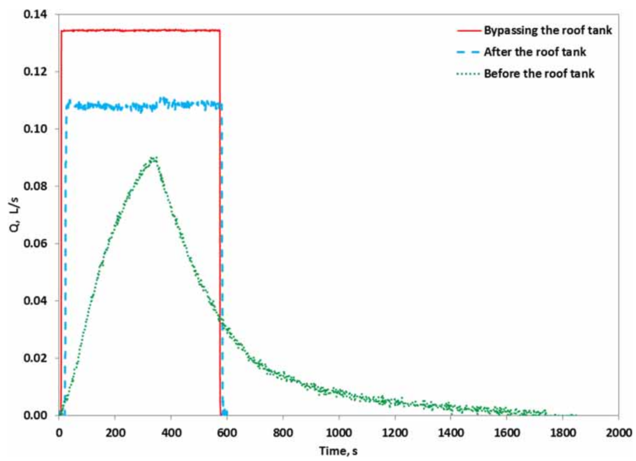

Figure 8 | The observed flow variation upon activating a shower, for the three positions of the water meter.

home water-using fixtures is lower in systems with roof tanks, i.e. roof tanks dampen instantaneous water demand. This effect is less pronounced for longer time water uses, such as for the shower (Figure 8), because the flow before the tank has more time to react to the sudden demand pulse. The flow rate during the filling of the roof tank, which depends on the duration of delivery and the volume of the tank, is much higher, however.

Based on the Epanet model of a small network supplying 28 homes from an elevated storage tank (Figure 2) in three scenarios, it was found that the instantaneous water demand and the pipe flow behave differently in the

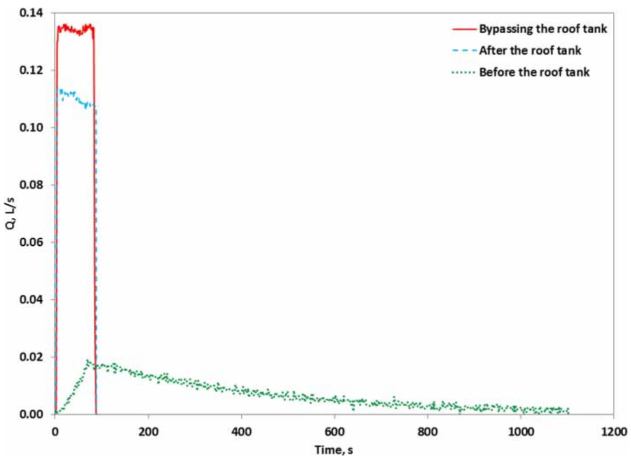

Figure 9 | The observed flow variation upon activating a common tap, for the three positions of the water meter.

continuous and the intermittent water supply networks. The instantaneous flow rate withdrawn from the water distribution network pipes by the home water-using fixtures is lower in systems with roof tanks. The peak pipe flow coefficients are higher in the intermittent water supply networks, however, compared to the continuous supply networks, because of the shorter duration of supply (see also De Marchis *et al.* 2010). More information about these results and the corresponding analysis are presented in a separate paper (Tzatchkov *et al.* 2015).

CONCLUSIONS

Hydraulic and water quality modelling of the intermittent supply distribution networks requires special treatment of demand and mixing at in-home water storage tanks that are not considered in the known water distribution network analysis programs. By applying a three-parameter (number of reactors in series, stagnation space and bypassing) residence time distribution model to the tracer tests on a real scale laboratory model, it is shown in this paper that the model that best describes the mixing in roof water tanks is the continuous flow stirred reactor with a small portion of bypassing and stagnation space. This result was confirmed by CFD simulations and visual observation. The instantaneous water demand and the pipe flow behave differently in the continuous and the intermittent water supply networks. The instantaneous flow rate withdrawn from the water distribution network pipes by the home water-using fixtures is lower in the systems with roof tanks. Based on a numerical model of a small distribution network, it is shown that the peak pipe flow coefficients are higher in the intermittent water supply networks than in the continuous supply networks.

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