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Contaminant intrusion through leaks in water distribution system: experimental analysis

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Abstract

This paper presents the results of experimental tests on the intrusion of contaminant through pipe cracks in water distribution network resulting from low/negative pressures. The tests were carried out on a looped distribution network at the University of Enna and were performed first producing a pressure transient that causes negative pressures then reproducing intermittent supply. A soluble contaminant was added to the water volume in the network through a pipe crack. Sampling of water volume was carried out in two nodes of the network and the contaminant concentrations were measured. It was showed that: the contaminant was drawn in and transported, in the first set of tests; the contaminant was carried through the network to the point-of-use when the pipes become completely full and the distribution system was in steady state conditions, in the second, and that the concentrations was higher than in the first set of tests.

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Keywords: Health risks; intermittent distribution; pollutant intrusion; transient analysis; water distribution system

1. Introduction

Drinking water distribution systems are vulnerable to external contaminant entry if there is a loss of physical integrity, e.g. a crack in a pipe. The main driver for an intrusion event to occur is the failure to maintain an adequate pressure in the distribution system. Low and negative pressure events have the potential to result in intrusion of

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pollutants: negative pressures create a suction effect inside the pipe and the contaminant intrusion through pipe leaks [1]. These adverse pressure conditions may take place as consequence of pressure transients and/or interruption of water supply and depressurisation of the system. Pressure transients (or water hammer) are caused by abrupt changes in the velocity of water; these are short duration events (typically last from a few milliseconds to a few minutes) and may be caused by sudden pump shutdowns, power outages, and rapid changes in demand. Distribution systems most vulnerable to intrusion events are those with intermittent water supply. Water distribution systems are often operated on an intermittent basis during water shortage period. This approach is widely adopted not only in developing countries that suffer from chronic water shortage and lack of funds to invest in water supply [2], but also in developed ones for solving short-term scarcity conditions, which can be caused by drought periods [3,4]. Although intermittent distribution has some advantages in that it requires little financial efforts and reduces background water losses, it leads to network operating conditions that are very far from the usual ones [5,6]. The network is subjected to cyclical filling phase and emptying period during which the distribution system is unpressurised and it may occur that pollutants enter the pipes often characterised by integrity problems. In this period of stagnation the microbial re-growth can be promoted, further compromising water quality [7]. During distribution periods, these pollutants are carried through the network to the point-of-use when the pipes become completely full and the distribution system is in steady state conditions. For this reason, water is usually heavily chlorinated in order to maintain it potable.

Lindley and Buchberger [8] introduced three requirements to be met for stating risk conditions to human health due to contaminant intrusion: adverse pressure conditions (the driving force), a pathway (leakage points, badly fitted joints, air valves, cross connections), and contaminant source. Previous researches found out that: transient pressure waves and depressurisation period are the driving force of the intrusion process [9,10,11,12] and the existence of contaminant in the environment surrounding the water distribution network [12,13,14]. Low/negative pressure drives the contaminant in water distribution system through the most common pathway: pipe cracks. The existence of the three requirements is not sufficient to quantify the risk of contaminant intrusion: the interaction between them needs to be understood. In previous studies, the pathway has been considered a circular orifice, open to atmosphere, and the interaction (the contaminant intrusion flow rate) has been simply modelled using the well-known orifice equation [12,14,15]. The intrusion occurs as soon as network water head drops below external head. This model results very simple but not exhaustive because it does not take into account the effects of the surrounding soil conditions and of pressure changes on the orifice size; the transient nature of the flow through the orifice, the coupling of the intrusion flow and the driving pressure, the re-intrusion of water that was lost during the leak process [16]. Collins and Boxall [16] and Collins et al. [17] modelled the intrusion of fluids into a pipe system through a circular orifice under steady-state conditions using Computational Fluid Dynamics (CFD). The pipe is buried in a homogeneous isotropic saturated porous media and the intrusion has been considered from both water and soil surrounding the pipe. The modelling and experimental results showed an excellent agreement with the orifice equation for water surrounding the pipe, giving confidence in the CFD approach and that the presence of a surrounding porous media decreases the intrusion flow rate from that predicted by the standard orifice equation. The steady-state intrusion rate remained proportional to the square root of the driving pressure but the results also suggested a greater dependency on the size of the orifice and that a more complicated function than a single discharge coefficient is required in the orifice equation.

The brief literature review above reported denotes that intrusion of contaminant in water distribution system resulting from low/negative pressures is a complex phenomenon that has been theorised and it is an active area of research still now. The main difficulty is the lack of understanding regarding the interaction between the pipe, the crack and the surrounding water and soil.

To improve understanding of the intrusion process, this paper presents the results of tests carried out on a high-density polyethylene looped distribution network at the Environmental Hydraulic Laboratory of the University of Enna. The tests, aiming at appraising how and how much a contaminant entering the network through a pipe crack spreads out until the point-of-use, were performed producing network operating conditions that aid a contaminant enters the system (negative pressure due to a water hammer and atmospheric pressure due to network emptying in intermittent service). Samples of water volumes were taken at points-of-use after the contamination and the temporal pattern of the concentration of the contaminant used was obtained. The paper is organised as follows: in section 2, the laboratory network and the tests performed are described; in section 3, the experimental evidences are presented and discussed; and in section 4, the study conclusions are presented.

2. Materials and Methods

2.1. Experimental setup: the laboratory network

The tests were carried out on a high-density polyethylene (HDPE 100 PN16) looped distribution network (Fig. 1) at the Environmental Hydraulic Laboratory of the University of Enna. This laboratory network has three loops, nine nodes and eleven pipes DN 63 mm, and it is fed by three water tanks that can store up to 6 m^3 overall. Each pipe is about 45 m long and is arranged in almost horizontal concentric circles, with bends having a radius of 2.0 m, thus ensuring that the form-resistance losses due to pipe bend can be neglected. Four pumps (P in Fig. 1) supply the needed discharge from the recycling reservoir to the upstream air vessel (AV in Fig. 1), which behaves as a constant head tank, keeping the pressure constant and equal to a value set by varying the speed of the pumps (total water head ranging from 10 to 60 m). The system is monitored by: 7 electromagnetic flow meters (M in Fig. 1); pressure cells and multi-jet water meters that are at each node position where demands are assumed to occur. Four hand operated sphere valves are installed in pipe 1-2, 4-3, 6-7, and 10-9 to control the flow of each loop. Node water demand is set by a regulation system by Bürkert (electropneumatic positioner controller, pneumatically actuated control valve, and water flow rate transmitter) installed at each network node.

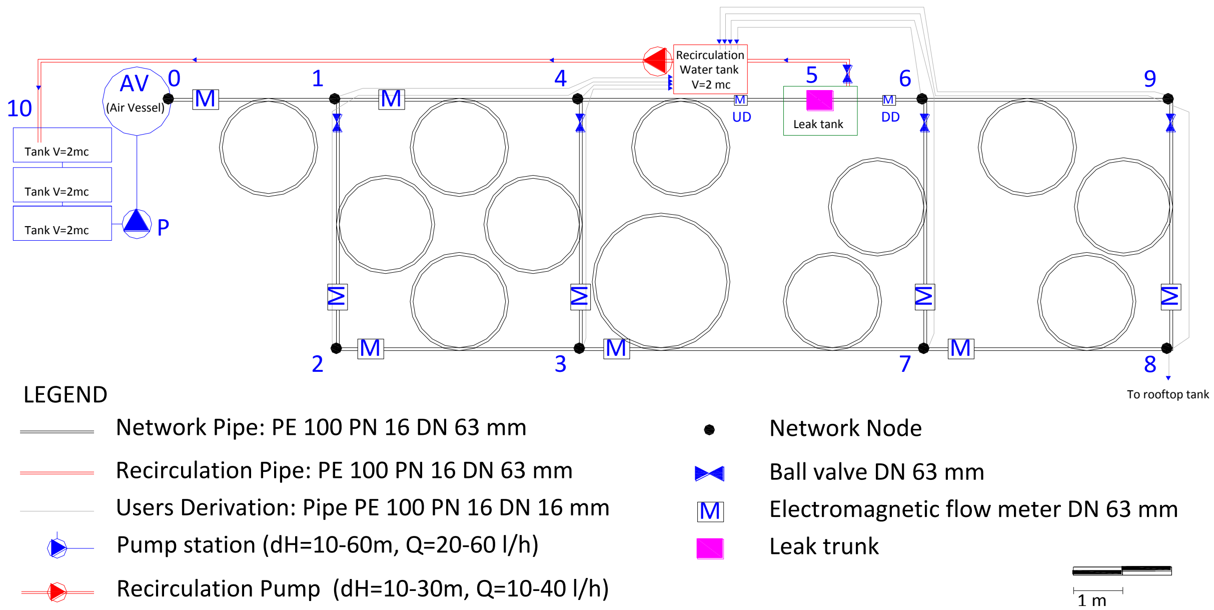

Fig. 1. Layout of the network.

In the scope of distribution network pollution analysis, the effect of a leak discharge into the atmosphere in pressurised pipe systems was obtained by substituting a small portion of the pipe 4-6 with a trunk, about 70 cm long, sliced with longitudinal rectangular-shaped incision 20 mm x 1.5 mm. The pipe where the cracked trunk is installed is horizontal. The leak discharges into a free surface tank. Thanks to a recirculation system the leak discharges are pumped to supply water tanks. To evaluate the water volume lost, two electromagnetic flow meters are placed 1 m upstream and downstream the leak trunk (UD and DD in Fig. 1). Pressure is measured by means of a piezoresistive pressure transducer, located about 1 m upstream the leak. Pressure data was used to evaluate the time history of water head values. At the same position of the piezoresistive pressure transducer, another pressure cell is installed to exclude measurement errors. The correct calibration of the instruments was checked before each test. The pressure and discharge were acquired simultaneously for all the tests.

2.2. Contamination tests

Two sets of tests were carried out to analyse the intrusion of contaminant through a pipe leak in water distribution system resulting from low/negative pressures. In the first set (experiment 1), the intrusion of the contaminant chosen (a solution of water and NaCl with concentration equal to 105 g/l) occurred as a result of a pressure transient (water hammer) that caused negative pressures. In the second (experiment 2), the intrusion took place as a consequence of intermittent supply.

The water hammer was produced closing very quickly the valve installed in the pumps outlet pipe and then turning off the pumping system beginning from network steady state condition. Two values of pressure at the network inlet node were set to performed the test twice: 2.0 and 4.5 atm (experiment 1a and 1b).

As above-mentioned, water supply may be periodically interrupted and the water resources rationed to cope with chronic water shortage, lack of capital to invest in water service or for solving short-term scarcity conditions. These distribution systems with intermittent supply (commonly found both in developing countries and in developed one) are most vulnerable to intrusion events: the system is subjected to cyclical filling phase and emptying period during which it is unpressurised and it may occur that pollutants enter the pipes. This condition was performed turning off the pumping system that supplies the network in steady state condition at the beginning of the test and users' connection closed for 24 hours. The pressure at the inlet node was set equal to 2.0 bar. The network emptied during the interruption of the supply and when the pressure became lower than the water head in the free surface tank the contaminated water volume inside the tank, a solution of water and NaCl having a constant concentration of 105 g/l, enters the pipe through the leak. After 24 hours, the pumping station was turned on, the pipes became completely full, the network reached the steady state conditions, and the contaminant was carried through the network to the point-of-use.

During the tests, the network was sectioned to get a linear path about 400 m long. Sampling of water volume at different temporal intervals was carried out in two different nodes (point-of-use) of the network and the contaminant concentrations were measured: the node 9 and 3, about 50 and 250 m from the leak tank, respectively. The solution of water and NaCl was dosed in two different way. In the first sets of tests, a gradual release gear was adopted: it was made up of a vessel, that held the solution, connected with a flexible pipe and a valve controlling which the solution was dosed close to the rectangular crack. In the second sets of tests, the solution was put in the leak tank.

The pipe flow ranged from 7.5 to 8.5 m^3/h as a function of the pressure during the tests. The node water demand was set equal to 0.72 m^3/h. The sampling at the nodes was discontinuous: 73 and 76 samples were picked up in 40 minutes in the first and second sets of tests, respectively. During the first 14 minutes the sampling was carried out at node 9, then, during the last 26 minutes, the sampling was performed at node 3. These temporal ranges that characterised the total and partial duration of the sampling are a result of the study of the traveler time of a water particle from the leak tank to the nodes 9 and 3. Sampling was performed with different time step: the time step was shorter (1 sample/15 sec) when the concentration peak was expected; the time step was longer, ranging from 30 seconds to 2 minutes, otherwise.

The contaminant concentration of each sample was derived by the direct measure of the conductivity. A sampling of water volume before the contamination was carried out to get "the white" as reference. After the contamination, the electric conductivity of the water volumes sampled was measured by means of a multi-parametric bench meter. The concentration of the solution of NaCl was taken from the calibration line that expresses the concentration-conductivity relationship. This curve was experimentally obtained measuring the conductivity of solutions of concentration known.

3. Results analysis

The results of the experimental campaign described above are here presented. In the experiment 1, pressure at the pumping station mains was set up to 2.0 atm (experiment 1a) and an instantaneous pump block was simulated (the valve installed in the pumps outlet pipe was closed very quickly and then the pumping system was turned off). In a similar experiment (experiment 1b), pressure was set at 4.5 atm and, similarly, an instantaneous pump block was simulated. In both cases, negative pressure transients were experienced. Figure 2 shows the water head recorded in node 4 and node 6, upstream and downstream of the cracked pipe, and node 7 on the other side of the network at a distance of more than 300 m considering the length of enveloped pipes. In the first case, the transient had an higher peak and shorter temporal evolution; in the second case, the transient was longer with a lower peak.

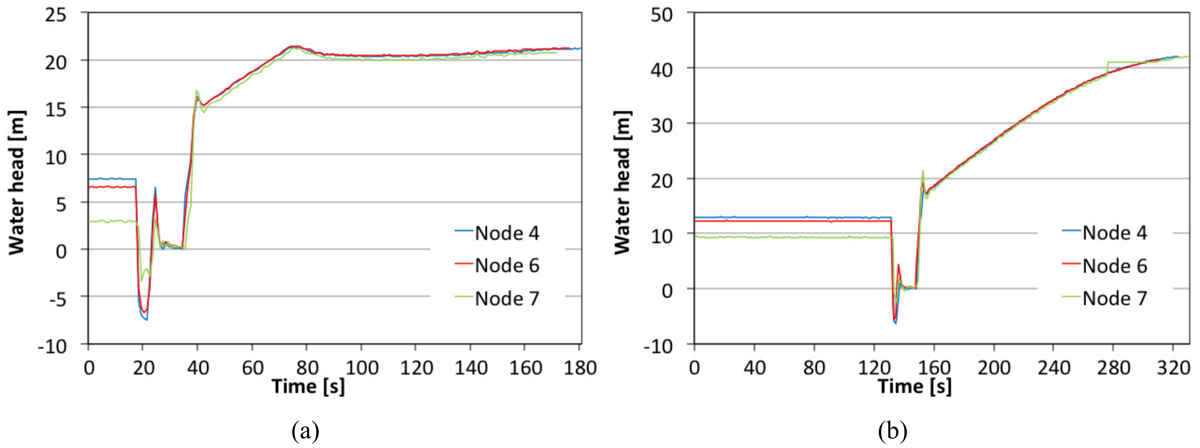

Fig. 2. Pressure transients in nodes 4, 6 and 7 during experiment 1a (a) and 1b (b).

Figures 3 and 4 show the conductivity and the correlated salt concentration in the two nodes during the experiments. The transient process took part in a few seconds after the instantaneous stop of the pumps; the contamination process started immediately with the suction of contaminants from the groundwater and the following propagation to the users node. Node 9 is only about 50 m downstream of the cracked pipe and the contamination reached the node only 5 minutes after the beginning of the experiment. The concentration graph is characterised by a sharp peak with concentration equal to 600 mg/l. After 200 seconds, node 9 is no more interested by contamination. After 28 minutes, contamination reached the node 3 (on the other side of the network) with much lower concentrations even if the contaminants reside at the node for more than 8 minutes.

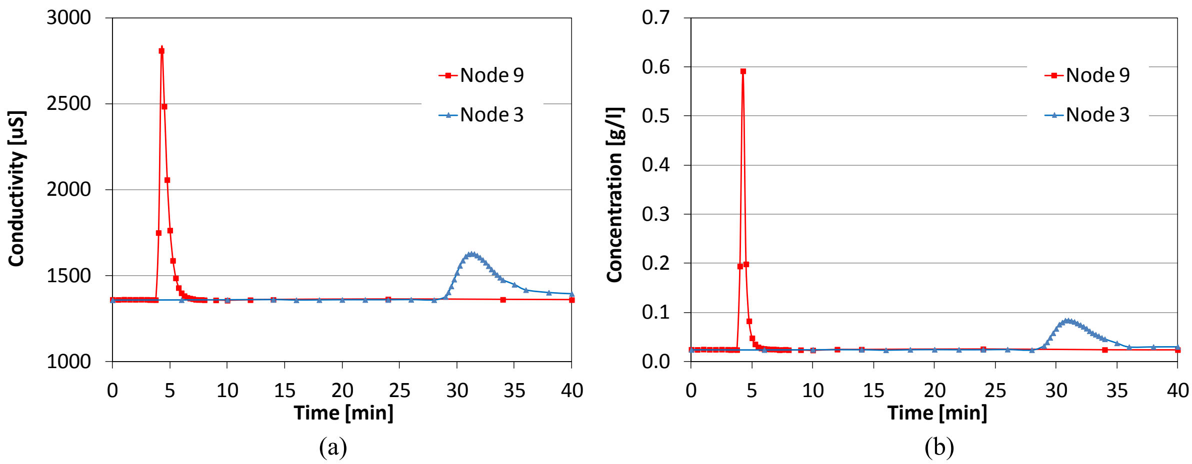

Fig. 3. Water conductivity (a) and contaminant concentration (b) in nodes 3 and 9 during experiment 1a.

During experiment 1b, contamination at node 9 presented characteristics similar to experiment 1a even if with lower peak due to the smaller mass of contaminant that entered the network during the transient. The longer transient and the high pressure oscillation produced more intense mixing of the contaminants inside the pipes. As a consequence, contaminants reached node 3 after only 13 minutes residing at the node for more than 20 minutes.

The analysis of transient episodes demonstrated that contaminants can enter the water system through pipe cracks. The magnitude of contamination events is strictly related to the characteristics of the pressure transient especially in the parts of the network that are far from the contaminant inlet.

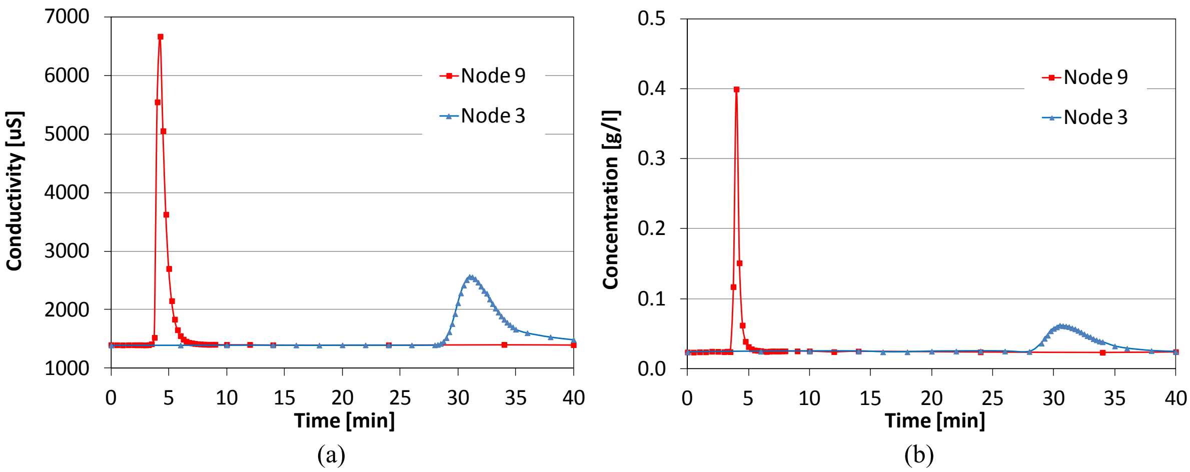

Fig. 4. Water conductivity (a) and contaminant concentration (b) in nodes 3 and 9 during experiment 1b.

A following analysis was carried out considering intermittent network supply. As mentioned above, such practice is adopted by water managers in water scarcity and water distribution networks are operated intermittently in order to reduce leakages. Usually intermittent supply is operated on daily basis so leaving pipes empty at atmospheric pressure for 24 hours. Experiment 2 was designed to simulate such condition: after normal operation, the pumps were shut off and users' connection closed for 24 hours; during such period, the tank containing the cracked pipe was filled with water, having a NaCl concentration of 105 g/l, in order to keep the water level constantly 10 cm higher than the pipe. After 24 hours, the system was started again and users reconnected collecting data about contaminant concentration. Figure 5 shows the contaminant concentrations in the same two nodes considered in experiments 1a and 1b:

- concentrations peaks are higher due to the larger mass of contaminants that entered the network in 24 hours;
- the contamination process is similar to experiment 1a with the contaminant reaching node 3 after 28 minutes and lasting for 12 minutes;
- the mixing process inside the pipe is not relevant due to the slow inflow process of contaminated waters into the pipes.

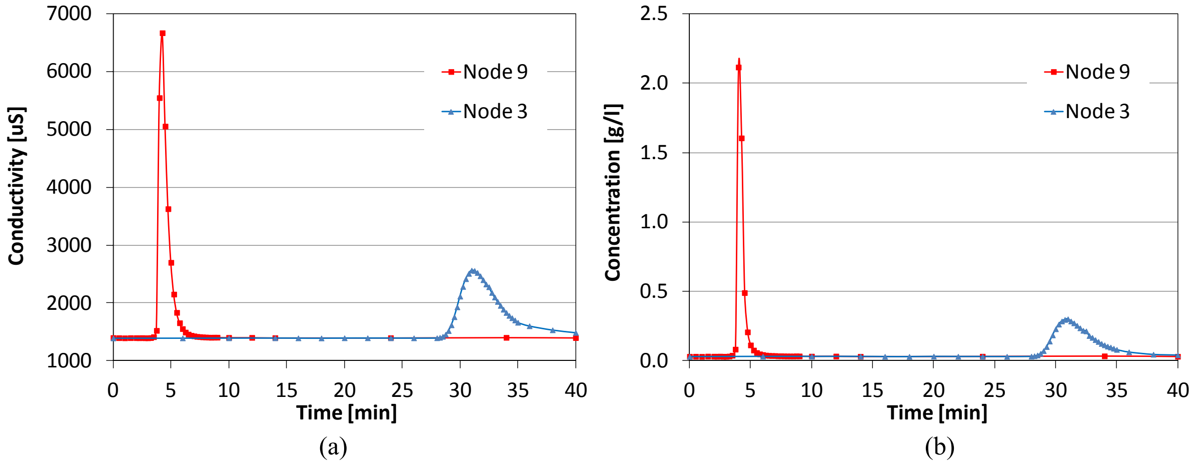

Fig. 5. Water conductivity (a) and contaminant concentration (b) in nodes 3 and 9 during experiment 2.

4. Conclusions

The present paper shows the results of an experimental campaign aimed to the evaluation of potable water contamination in water distribution network due to the presence of leakages. Contaminants, coming from the soil, can be introduced in the pipe during transients with negative pressures or during periods in which pipes are not supplied and partially empty (for maintenance or intermittent distribution). Two series of experiments were carried out considering the two possible phenomena.

Experimental results showed that intermittent distribution can allow a large amount of contaminants inside the pipes. Contaminants got into the pipe by means of infiltration when the pipe was partially empty and the service was discontinuous. The pressurisation of pipes ejected part of the contaminants from the pipe but a large amount remained in the pipe and it was supplied to the users. The physical process was similar in the case of transients involving negative pressures but the temporal scale of the process was much smaller and the amount of contaminants flowing into the pipe was smaller. The contamination was still present and it could produce risks for the users but it was strictly related with the extension and the magnitude of the negative pressure transient.

Intermittent supply is surely the most relevant cause of distribution network contamination because of the longer time in which contaminants can enter the pipes and mix with potable ones: peak contaminant concentrations and masses was much higher than those obtained during transients. On the other side, transient contamination may be mitigated by positive pressure oscillation that may eject contaminants through the pipe cracks. The effects of the surrounding soil conditions is not considered during these tests.

In the present experimental campaign, a soluble contaminant was used but further analyses have to be carried out including non soluble contaminants and suspended contaminants in order to evaluate the possible impact on population. Moreover, the fate of contaminants in the looped network will be investigated by testing several demand patterns at the point-of-use.

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