

Case Report

Water age in drinking water distribution systems: A case study comparing tracers and EPANET



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ABSTRACT

This study aimed to compare the water age in a drinking water distribution network (DWDN) using tracers and EPANET. The results indicate that all DWDN have residence times within the “short” time, established by the EPA and does not represent quality problems. These two techniques provided similar estimates of water age with small differences at points close to the treatment plant. This difference may be due to the fact that tracers can be retained in pipes, which overestimates the age of the water; meanwhile, EPANET could underestimate residence times due to the calibration or simplified representation of the network.

1. Introduction

The supply of drinking water is essential for public health and the well-being of society. However, as water distribution infrastructure ages and demands on water resources increase, it becomes crucial to evaluate the quality and age of the water reaching homes [1,2]. The water age refers to the time elapsed from when the water enters the distribution system until it reaches the consumer's tap, and its calculation can offer relevant information about the effectiveness of the system and the possible presence of contaminants [3]. Water age is a representative measure of drinking water quality, a lower water age indicates better water quality [4]. While drinking water travels in a distribution network, it goes through some aesthetic, physical, and chemical transformations that influence its quality [3,5]. These transformations will occur to a lesser or greater extent depending on certain characteristics such as water flow, final water quality, pipe materials and deposited materials [4]. All these problems increase as the age of the water increases [6].

Residence time, or water age, is an important performance indicator

for many drinking water utilities [7]; since, if the treated water remains in a network for a long time before reaching consumers, the concentration of disinfectant (chlorine) may not be adequate enough to control microorganisms that can cause health problems [8]. Chlorine residual concentrations decrease with increasing travel time (water age), which is typically followed by an increase in bacterial count and diversity [9]. Likewise, excessive water age can cause problems such as the generation of substances harmful to health, known as disinfection byproducts [10]. For this reason, it is necessary to evaluate the age of the water within the DWDN, this allows us to focus on areas with high values of residence time, since the age of the water and the physicochemical parameters of the water have a directly proportional relationship; that is, the older the water, the lower the quality with which it reaches the user [11].

Water age can vary from a few hours to several days, due to daily and seasonal variations in water demand [6]. At a given point in a DWDN, the age of the water cannot be directly measured and must be deduced from tracer testing or calculated using hydraulic software for the simulation of a water distribution network [3]. Studies carried out by the EPA [12] and Kourbasis [13] indicate that the average water

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retention time in a distribution network is 1.3 days and at most, 3.0 days, defining a “short” time as less than 3 days and a “long” time as more than 3 days.

The tracer technique can be used to experimentally estimate travel time and flow path in a drinking water distribution network [14]. The general principle is to track a dissolved non-reactive chemical as it is transported within the distribution network [15]. This chemical can be added just before scanning begins, and the concentration is measured using data loggers, or by taking random samples at chosen locations within the network. Therefore, the methodology for these follow-up studies is not very standardized [14]. These techniques may use tracers such as fluorine or sodium chloride. When choosing a tracer, the chemical stability of the tracer, ongoing regulatory compliance, and consumer perception must be considered [15].

A study applying tracers to verify hydraulic limits and determine the residence times of water in a distribution system was carried out by Delisle et al. [16] in Quebec City in Canada. In this study, a 25 % v/v fluorosilicic acid solution was injected as a tracer into the DWTP and samples were collected every 2 hours at 60 points in the distribution network for a total of 26 hours. The resulting concentration curves of the tracer were evaluated for the calculation of the MRT (Mean Residence Time), obtaining values between 6 and 33 hours. In a study carried out in Raleigh, North Carolina, two methods were used to calculate the residence time of water in the distribution network, with tracers and through a simulation in EPANET. Fluoride was chosen as a tracer and samples were taken at 20 points over a period of 5 days. From this they calculated the MRT, obtaining a maximum value of 75 hours and a minimum of 2 hours [15]. The study conducted in the city of Riga, Latvia used online measurements to predict the water age from tracer tests. 20 locations were established throughout the distribution network to measure conductivity change. From this, it was validated in 8 nodes, obtaining a water age between 3 and 60 hours [17].

Due to the aforementioned, it is very important to ensure the quality of the water that reaches homes through the RDAP, for which monitoring the residence time of the water in the distribution network plays a key role in maintaining its quality [18]. To address this challenge and better understand the water dynamics in the DWDN, the present study has been carried out. The main objective was to compare the age of drinking water obtained using the tracer technique and the EPANET simulation program in the DWDN of the Bayas parish, city of Azogues, Republic of Ecuador. The results obtained in this study have significant implications for the management and planning of the drinking water distribution system; Furthermore, the method of determining the water age by tracers can be useful in places with similar distribution systems, obtaining an additional tool for the control and monitoring of the quality of drinking water in supply networks.

2. Methodology

2.1. Study area

The “Bayas” parish is part of the peri-urban sector of the city of Azogues, Ecuador. The Bayas Drinking Water Administrative Board is in charge of supplying drinking water to approximately 6200 people, for which it has a conventional treatment plant. The purification process in the plant occurs in 4 levels of operation: raw water collection, clarification (includes coagulation, flocculation, sedimentation and filtration), disinfection and distribution. Raw water is collected from 5 surface sources, and then transported to the plant for treatment. For the coagulation-flocculation stage, Polyaluminum Chloride is added. Once the coagulant is added, the water passes to the vertical flow flocculator, to then move on to the sedimentation and rapid filtration phase. Once this is completed, it goes to the chlorination chamber, where chlorine gas is added. Finally, the purified water is stored in a tank for immediate distribution to the population.

2.2. Determination of the age of the water in the RDAP applying the tracer technique

2.2.1. Identification of monitoring and sampling points

This study implemented a stratified random sampling, which consisted of a methodology that allows the researcher to segment the population into subgroups that have some characteristic in common, with the aim of maintaining the same composition of the population (Wellen et al., 2020) [19]. This type of sampling allowed the identification of points that maintain conditions such as population, distance from the treatment plant, accessibility, among other variables to consider. In this case, 15 representative points of the network were chosen (Fig. 1).

The technique for sampling was based on the APHA technique, this technique establishes that conductivity can be modified by the absorption of carbon dioxide from the air, so the analysis was carried out in situ [20,21]. At each sampling point, the tap water was allowed to run for 2 min to eliminate the water stored in the pipe and in the tap, 500 ml of water was collected in a sterilized bottle. Next, the conductivity was measured using a HACH HQ40d multiparameter device, which gave us values in $\mu\text{S}/\text{cm}$. After this, the conductivity meter was washed with distilled water for the next measurement.

2.2.2. Application of the tracer technique

The age of the water was calculated as the time it takes for the tracer to arrive from the treatment plant to the monitoring point. The tracer used was sodium chloride, because it is safe for consumers, economical and easy to measure in real time as conductivity. The increase in the concentration of Na^+ and Cl^- because of the addition of the tracer becomes an increase in conductivity and total dissolved solids [22]. Initially, the conductivity and average temperature of the drinking water in the distribution tank of the treatment plant were measured and 130 $\mu\text{S}/\text{cm}$ and 14 °C were obtained, respectively. The methodology recommended by Rakstang [14] was followed to calculate the amount of salt necessary to increase the conductivity by 100 $\mu\text{S}/\text{cm}$, that is, increase the conductivity from 130 to 230 $\mu\text{S}/\text{cm}$, in such a way that it can be noticed an increase in conductivity. The results indicated that the concentration of tracer to be prepared should be 35 %. In the purification plant, a 35 % saturated brine solution was prepared in a 20L container. Using a valve, the brine was added to the treated water from 07:00 a.m. to 08:00 a.m., before it came into contact with the chlorine, in this way a complete mixture was ensured and the risk of contamination of the water with microorganisms that could be found in the brine was reduced.

Immediately after adding the tracer, at each monitoring point, drinking water samples were taken, then the electrical conductivity was measured. From 7:00 a.m., samples were taken every 15 minutes and the conductivity was measured, until it became the same as the initial conductivity that the drinking water had before adding the tracer. This process was carried out two days a week for each monitoring point, since duplicate tests were carried out, until completing the 15 points (15 weeks in total). Wednesday of each week was chosen for the first test and Fridays for the replication of each point.

2.2.3. Calculation of the water age

To calculate the age of the water or mean retention time (MRT), the method proposed by Delisle et al. was used. (2015) [16], residence time distribution function method $E(t)$ and the EPANET method.

2.2.3.1. A. method Delisle et al. (2015). This method is based on the concept that the water age or MRT corresponds to the moment in which the tracer has crossed 50 % of the maximum concentration measured in the treatment plant. Using the conductivity measurements, graphical representations or response curves were created that illustrate how the tracer concentration varies at each sampling point over time. These representations show the time it takes for the tracer to travel from the

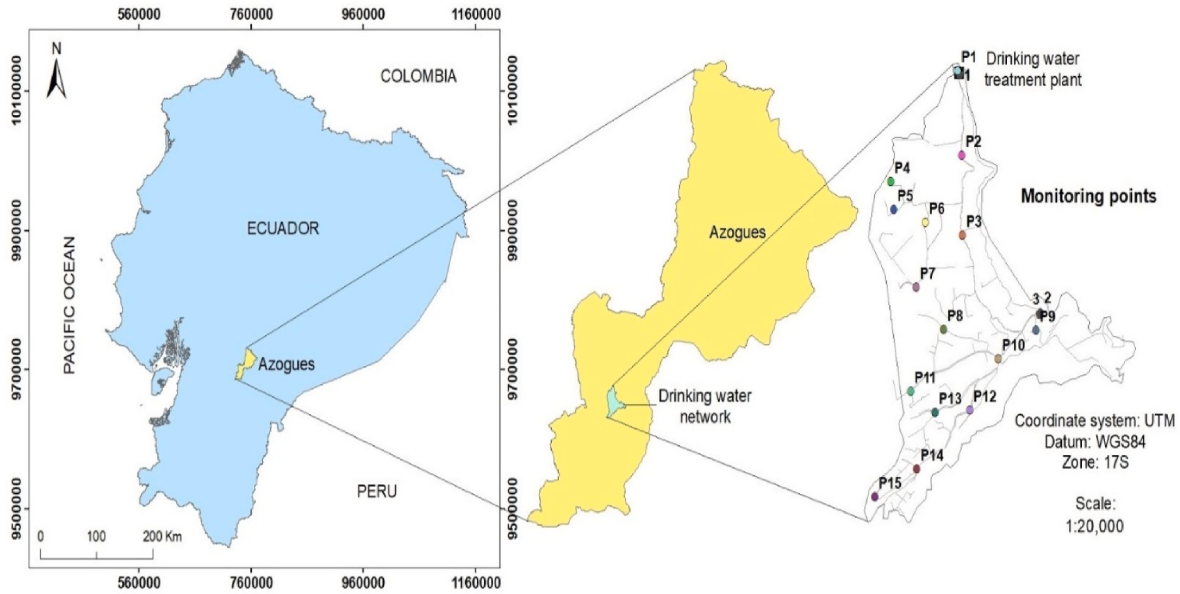


Fig. 1. Location of sampling stations in the distribution network.

treatment plant to each location in the network. In the response curves, the time in which the tracer concentration reaches 50 % of its maximum value is identified. This point represents the time in which 50 % of the introduced tracer has reached that location on the network. It is important to take into account the initial concentration of conductivity that is naturally found in drinking water; therefore, 50 % of the difference between the maximum concentration and the initial concentration must be considered [16].

Considering what was described by Delisle et al. [16], the water age or MRT is a function of the concentration of the conductivity $MRT = f(C)$. The procedure followed to determine the MRT was:

1. The initial concentration of conductivity naturally found in drinking water and the maximum conductivity of the tracer measured at the treatment plant are identified;
2. For each sampling point, the different conductivity concentrations measured on the monitoring day are graphed vs. the respective time;
3. The difference between the maximum measured concentration and the initial concentration (conductivity of drinking water before adding tracer) is calculated and 50 % of this difference is calculated;
4. Calculate $f(C)$ with Equation (1).

$$f(C) = \frac{\text{Max. Concentration} - \text{Initial Concentration}}{2 + \text{Initial Concentration}} \quad (1)$$

5. In the same figure of concentration vs time indicated in step 2, the time corresponding to $f(C)$ is located, which would be the age of the water or MRT.

The age of the water is considered from the moment the water leaves the plant to the monitoring point; That is, the time elapsed from the moment the tracer was added until it left the treatment plant must be discarded. In this study, the time from the tracer addition (before chlorination) to the exit of the storage tank was discounted. To know this discarded time, it was established as P0 at the exit of the treatment plant; In this way, the time in P0 was subtracted from the MRT determined at all points of the distribution network and thus the real residence time of the water at all sampling points could be obtained.

2.2.3.2. B. Residence time distribution function $E(t)$. In the context of a drinking water distribution network, $E(t)$ describes the probability that a water particle remains in the system for a time equal to or greater than t . In other words, it provides a representation of the distribution of water retention times in the network. This is important to understand water

quality and potential contamination or disinfection issues.

The residence time distribution function is represented by an exit age distribution, $E(t)$ (Equation (2)). The average residence time is calculated with a moment equation (Equation (3)) [23,24].

$$\bar{t} = \int_0^{\infty} t \cdot E(t) dt \quad (2)$$

For a variable volume system, the mean residence time is the mathematical expectation of the distribution function E :

$$\bar{t} = \frac{\int_0^{\infty} t \cdot E(t) dt}{\int_0^{\infty} E(t) dt} = \frac{\sum t_i E(t_i) \Delta t_i}{\sum E(t_i) \Delta t_i} \quad (3)$$

$E(t)$ is calculated by Equation (4)

$$E(t) = \frac{C_i}{\sum C_i \Delta t_i} \quad (4)$$

2.2.3.3. C. water age calculated by EPANET. A detailed model of the drinking water distribution network was built using EPANET. This involved defining nodes, pipes, tanks, valves and other relevant elements of the system. Specific data from the network were incorporated, such as pipe diameters, lengths, roughness coefficients, water demands in different nodes, operating conditions of the valves, location of storage tanks, among other hydraulic and operational parameters [25].

Calibration of the EPANET model was carried out to ensure that the simulated results matched the actual conditions of the water distribution system. This involved adjusting model parameters such as roughness coefficients, water demands, network geometry. Once calibrated, the EPANET model was validated using historical data and real flow and pressure measurements in the water distribution system to confirm its accuracy and reliability in system simulation [26]. With the network model prepared and validated, simulations were carried out in EPANET to calculate the average residence time of water in different parts of the distribution system, allowing these results to be compared with the residence times measured in the field using tracers [15].

2.3. Statistic analysis

To determine if there is a significant difference between the three methodologies used to measure the age of the water in the distribution network, the normality of the results of each methodology was verified

using the Shapiro-Wilk test [27]. As the data followed a normal distribution, ANOVA was applied to compare the means of the three methodologies. For a p-value obtained from ANOVA lower than the significance level (generally 0.05), it is concluded that there is a significant difference between at least one of the methodologies. Subsequently, the Tukey post-hoc test was applied to determine between which pairs of methodologies the difference is found [28].

3. Results and discussion

3.1. Distribution curve of the tracer in the distribution network

At point P0 (DWTP outlet), the conductivities observed throughout the monitoring day are presented in Fig. 2. It can be seen how the conductivity increases exponentially from 08:30 a.m. to 08:30 a.m. 09:30, where it reaches its maximum concentration, this conductivity remains constant for 30 minutes, then begins to decrease slowly, but with a more constant decay, unlike when it increased. This behavior could be observed at all monitoring points.

Fig. 3a shows the graphs of four sampling points close to the treatment plant (P1, P2, P3 and P4). Fig. 3b shows the graphs of five sampling points located at intermediate points with respect to the treatment plant and the most distant points (P5, P6, P7, P8 and P9). Fig. 3c shows the graphs of five sampling points far from the treatment plant (P10, P11, P12, P13 and P14). In these figures you can see the different conductivity peaks reached at the different monitoring points. At the points closest to the DWTP, a higher conductivity was reached, with a value of 210 $\mu\text{S}/\text{cm}$ in P1; meanwhile, at the intermediate points a maximum value of 200 $\mu\text{S}/\text{cm}$ was reached in P6. Starting from P9, at the points furthest from the DWTP the conductivity did not reach more than 190 $\mu\text{S}/\text{cm}$. This is because the concentration of the tracer is lost throughout its journey through the network, since it is dispersed when entering the secondary pipes. Reason why, all the curves present a similar behavior with respect to their variation in conductivity.

3.2. Water age calculation

3.2.1. Water age applying tracer method

Considering that the natural conductivity of the drinking water was 130 $\mu\text{S}/\text{cm}$ and the maximum conductivity measured after adding the tracer was 220 $\mu\text{S}/\text{cm}$ in the treatment plant. The difference between the maximum concentration and the initial concentration, which was 90 $\mu\text{S}/\text{cm}$, was calculated. 50 % of this difference was calculated, which was 45 $\mu\text{S}/\text{cm}$. The age of the water was then the time that elapsed from when the tracer was injected until the conductivity increased by 45 $\mu\text{S}/\text{cm}$, that is, until the water reaches a conductivity of 175 $\mu\text{S}/\text{cm}$. In Fig. 4, as an example for point 1, the figure of conductivity vs time is presented. It

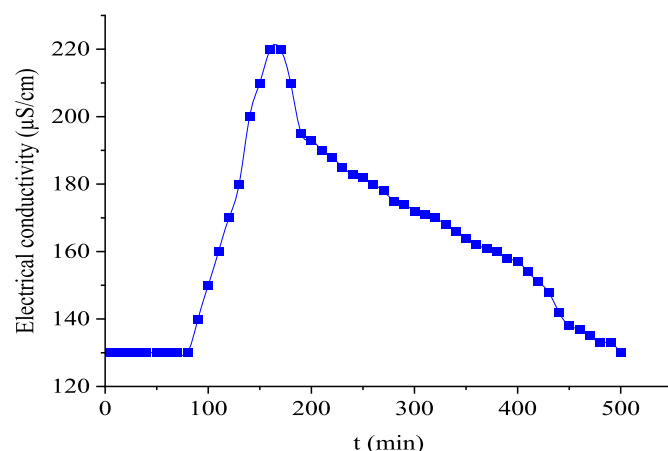


Fig. 2. Electrical conductivity vs time observed at P0.

is observed that the conductivity of 175 $\mu\text{S}/\text{cm}$ was reached at 390 minutes (6.5 hours). However, the age of the water is determined from the treatment plant to a specific point; For this reason, to determine the MRT in P1, the time determined in P0 must be discounted, which was determined to be 280 minutes (4.67 hours) according to the applied methodology. Therefore, the MRT at P1 was 110 minutes (1.83 hours).

Table 1 shows the actual age of the water, which was obtained by subtracting the residence time calculated for point P0 (reference point) from the residence times calculated for each of the DWDN points. This was done for both the age of the water calculated by the tracer technique and that obtained with EPANET.

In general, the results of the water ages obtained by the method of Delisle et al. (2015) varied between 1.83 and 12.31 hours, which are within a “short” time (less than 3 days) for a distribution network, according to the EPA. Even for point P14, which is the furthest point from the DWTP, a value of 10.50 hours was obtained, this value is within the “short” time.

From the calculated results, a map was made in ArcGIS 10.3 to identify the sectors with different age ranges throughout the network. Using the Kriging interpolation tool, a raster was created, where the different areas with age variations can be distinguished. It was classified into 8 ranges, as can be seen in the legend of Fig. 5 (a). The areas with bluish colors present the lowest ages recorded in the monitoring, varying between 0.01 and 4.63 hours; meanwhile, yellowish areas have ages between 4.64 and 7.70 hours; while the areas with reddish colors have the highest ages, between 7.71 and 12.31 hours.

The results obtained by applying the residence time distribution function method E(t) are also presented in Table 1. In this case the “real” water age at each point was calculated by subtracting the residence time determined at point P0 (4.21 hours) from the observed water age at each point. The results show a progressive increase in the age of the water as the points move away from the treatment plant, which is expected due to the longer travel time in the network. Points P7, P10, P11 and P12 have the highest ages of the water, which could indicate problems of stagnation and low renewal in those areas of the network. However, it meets the “short” time requirements (less than 3 days) for a distribution network, according to the EPA.

With the water ages calculated by the residence time distribution function method E(t), a map was also made in ArcGIS 10.3. It was also classified into 8 ranges, as can be seen in the legend of Fig. 5 (b). The areas with bluish colors present the lowest ages recorded in the monitoring, varying between 0.01 and 3.95 hours; meanwhile, yellowish areas have ages between 3.96 and 6.58 hours; while the areas with reddish colors have the highest ages, between 6.59 and 10.52 hours.

3.2.2. Water age applying EPANET

The results obtained through the simulation in EPANET show a considerable variation in the age of the water throughout the distribution network (Table 1). It is observed that there are points with a relatively low water age, while others have higher residence times. However, it meets the “short” time requirements (less than 3 days) for a distribution network, according to the EPA. At point P0, which is considered the reference (treatment plant), the age of the observed water is 4.98 hours. From this point, you can observe the evolution of the age of the water at different points in the network. At points P1 to P6, the observed water age ranges between 5.28 and 7.38 hours, with a gradual increase as we move away from the reference point. This indicates that, in this area of the network, the residence time of the water remains relatively low, evidencing good circulation and flow renewal. However, at points P7 to P12, higher water ages are recorded, reaching values between 12.02 and 14.66 hours. These points are characterized by having longer residence times, which may be due to factors such as lower demand, network geometry or areas with stagnant flow. Finally, at points P13 and P14, a decrease in the age of the water is observed, placing it in the range of 12.25–13.40 hours. This reduction may be related to the incorporation of new flows through connections or

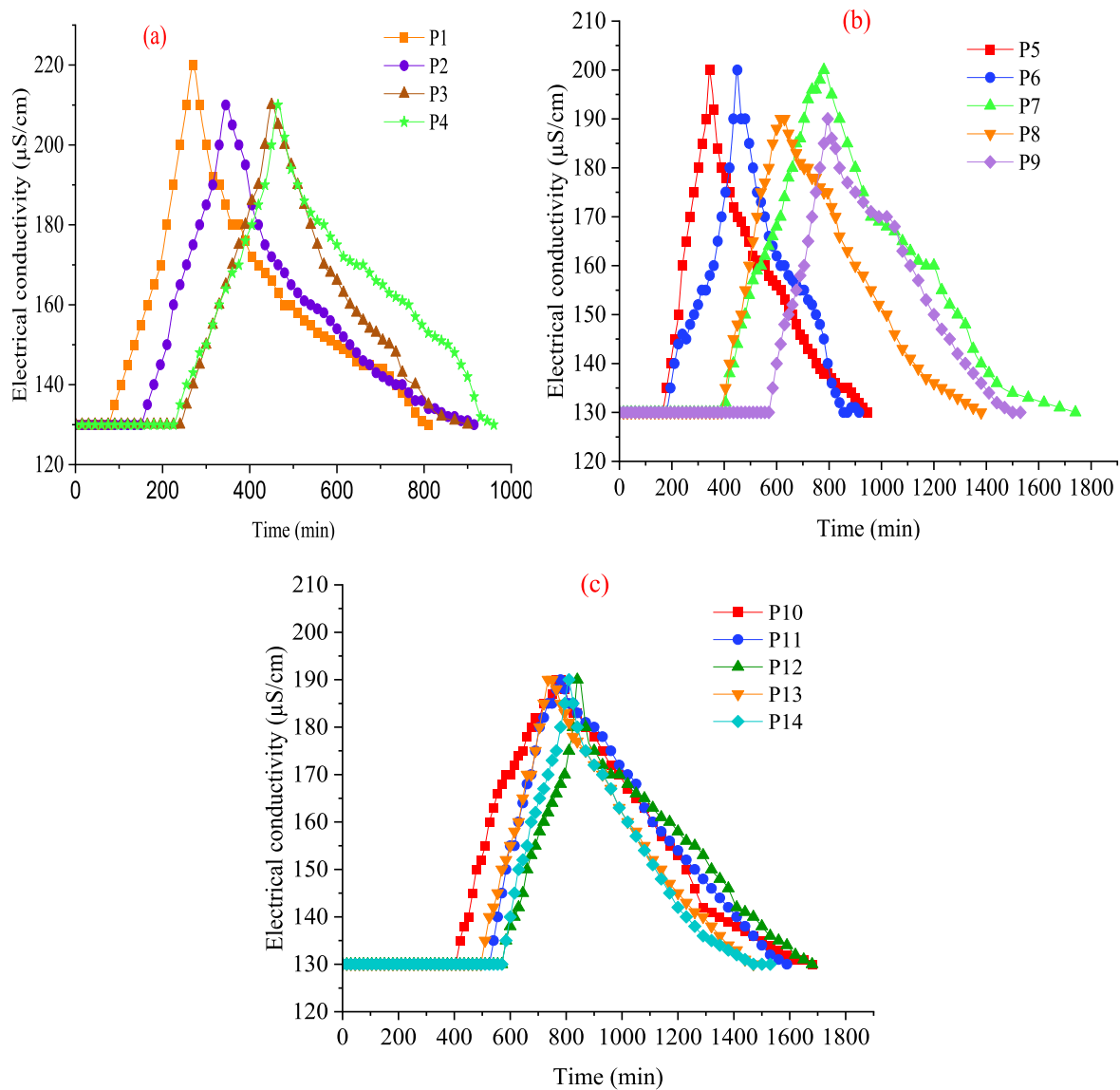


Fig. 3. Conductivities observed at different monitoring points. (a) Nearby points to the treatment plant (P1, P2, P3 and P4), (b) Intermediate points with respect to the treatment plant and the furthest points (P5, P6, P7, P8 and P9), (c) Far points to the treatment plant (P10, P11, P12, P13 and P14).

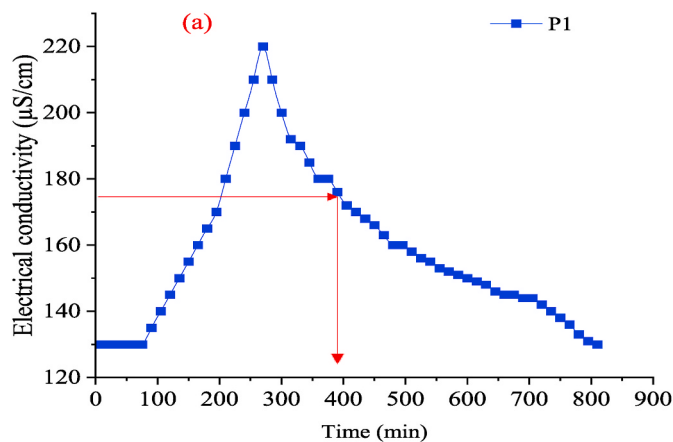


Fig. 4. Procedure for calculating the age of the water for Point 1.

branches that provide new flows of fresh water from other sections of the network. It is important to highlight that the age of the observed water was obtained from the simulation in EPANET, while the age of the real water corresponds to the transit time from the reference point (P0) to each of the analyzed points; That is, at each monitoring point, 4.98 h was subtracted, which was the time determined in P0. The results obtained highlight the importance of using modeling tools, such as EPANET, to evaluate the flow dynamics and water age in drinking water distribution networks.

In Fig. 6 it can be seen that the behavior of the water age in the distribution network shows a similar pattern throughout the day. During peak consumption hours, such as 7 a.m., 1 p.m. and 7 p.m., the water retention times at the different measurement points are relatively similar. Meanwhile, at 2 a.m., the time of lowest consumption, the age of the water tends to increase slightly, presenting points with longer retention times. This is mainly due to the fact that, during hours of lower consumption, the flow speed in the distribution network decreases, which leads to an increase in the residence time of water in certain sections of the network. Likewise, the behavior of users during the early morning hours, when consumption is lower, causes the water to remain in the network longer before being extracted, thus increasing its age.

Table 1

Water age per point monitored using the Delisle et al. method. (2015), the temporal distribution function approach for residence time $E(t)$ and EPANET software.

Sampling point	Delisle et al. (2015)		Distribution function $E(t)$		EPANET	
	Observed water age (h)	Real water age (h)	Observed water age (h)	Real water age (h)	Observed water age (h)	Real water age (h)
P0	4.67	0.00	4.21	0.00	4.98	0.00
P1	6.50	1.83	5.53	1.31	5.28	0.30
P2	7.25	2.58	5.08	0.87	5.62	0.64
P3	9.25	4.58	7.75	3.54	8.04	3.06
P4	10.00	5.33	8.31	4.10	7.59	2.61
P5	7.00	2.33	7.93	3.72	7.38	2.40
P6	8.75	4.08	7.52	3.30	7.29	2.31
P7	15.50	10.83	14.74	10.52	14.53	9.55
P8	13.25	8.58	11.77	7.56	12.02	7.04
P9	15.00	10.33	13.23	9.01	13.97	8.99
P10	15.50	10.83	14.24	10.03	14.66	9.68
P11	16.00	11.33	13.71	9.49	14.21	9.23
P12	17.00	12.31	14.48	10.27	14.60	9.62
P13	15.00	10.33	12.68	8.47	12.25	7.27
P14	14.50	9.83	12.91	8.69	13.40	8.42

3.3. Comparison of water age applying tracers and EPANET

The tracer technique allowed the direct measurement of the retention time at each of the monitored points (Table 1). This information is valuable in identifying critical areas of the distribution network where water quality may be compromised due to long retention times. This technique demonstrated that the age of the water is influenced by the topography and the length of the distribution network with higher values in areas other than the treatment plant [3,29]. The variation in the water age in the distribution network depends mainly on the demand for water by consumers, as the demand for water increases, the time it remains in the distribution system decreases [13]. In the case of the simulation of water age applying EPANET, it allowed us to compare the mean residence times calculated from real observations with the

simulated ones, identifying significant discrepancies and highlighting the importance of accurate modeling and careful selection of tracers in water age studies. water distribution systems.

The average age of the water reached values of 6.99 years applying the method proposed by Delisle et al. [16]; meanwhile, the average age of the water applying the $E(t)$ Distribution Function method was 6.06 years, on the other hand, the average age of the water using EPANET was 4.74 years. The integration of the different approaches, combining field measurements and simulation models, is essential to obtain a more accurate and reliable assessment of the water age in the distribution network. This will allow distribution network administrators to make appropriate decisions to optimize the quality and safety of the drinking water supplied to the population.

Comparing the results of the ages obtained using tracers through the methods Delisle et al. [16] and the Distribution Function $E(t)$, it can be observed that, at the close and intermediate points of the network, from P1 to P6, some differences are observed between the values obtained by these techniques. Thus, at point P2, Delisle et al. [16] reports an age of 2.58 years, while the Distribution Function $E(t)$ indicates 0.87 years. These differences may be due to the way each method represents and calculates the water age in the network. Meanwhile, at the furthest points of the network, from P7 to P14, the water age values obtained by both methods are more similar. For example, at point P10, Delisle et al. [16] reports 10.83 years and the Distribution Function $E(t)$ indicates 10.03 years. This greater agreement at the most distant points suggests that the two approaches converge in estimating the water age in the most distant areas of the network.

Starting from the premise that the age of the water at the outlet of the storage tank of the treatment plant, which represents the entry of the water into the distribution network, is zero hours, both for measurements with tracers (Delisle et al. [16] and the distribution function $E(t)$) as in the EPANET model, it can be observed that in the section between points P1 and P6 there are more significant differences between the water age values obtained through the use of tracers and those calculated through the EPANET model. In general, the water ages measured with tracers are higher than those estimated by the simulation model. This difference could be due to the fact that the tracers used in the

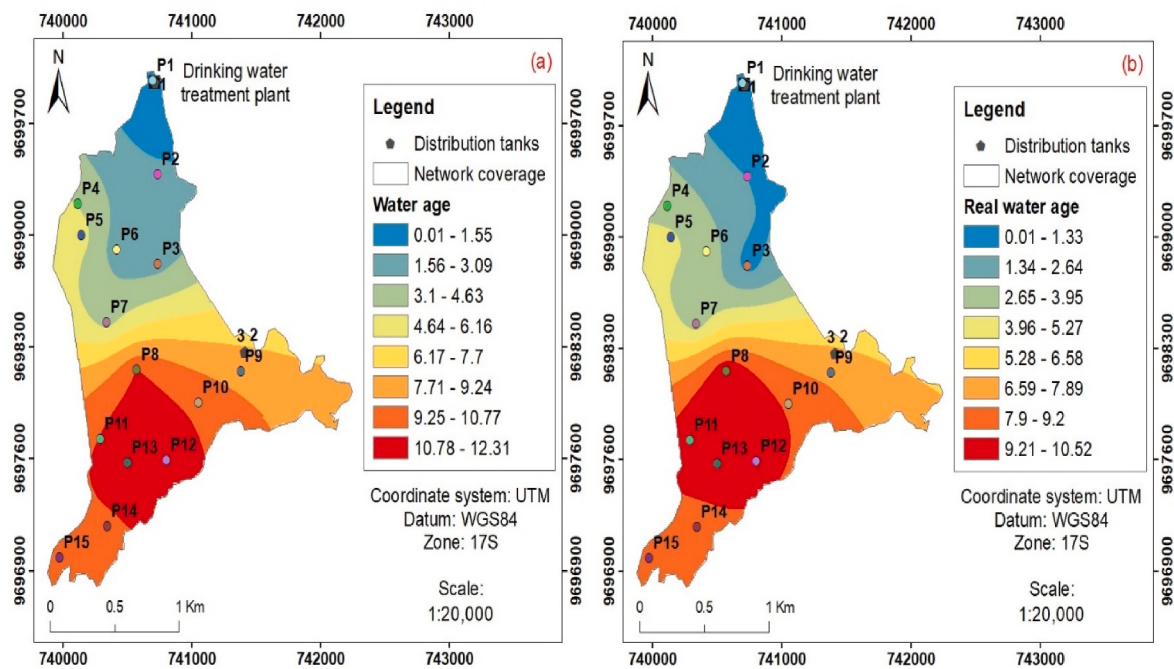


Fig. 5. Spatial distribution of water ages along the distribution network. (a) determined by the method of Delisle et al. (2015), (b) determined by the residence time distribution function method $E(t)$

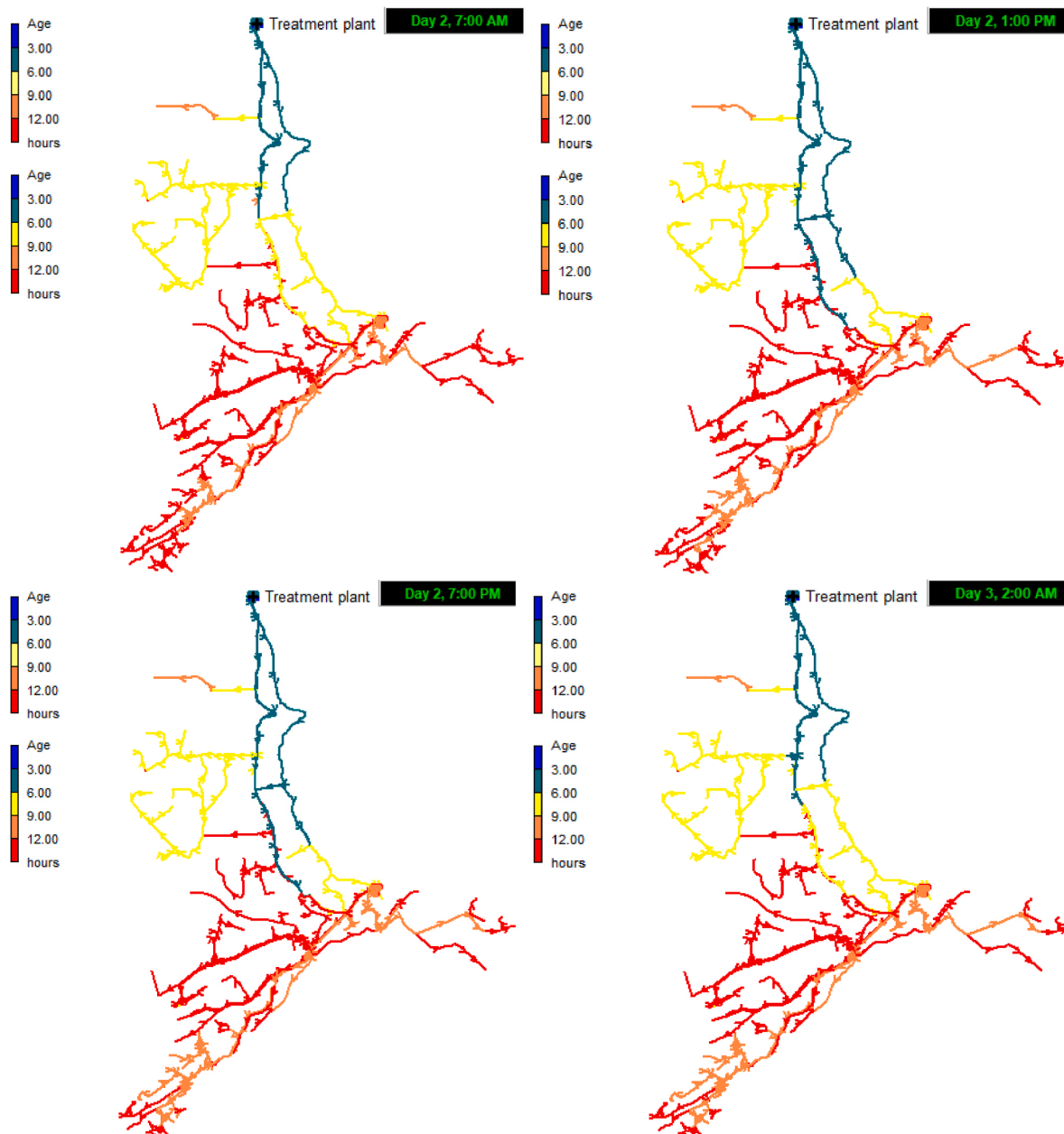


Fig. 6. Spatial distribution of water ages along the distribution network at different times of the day using EPANET.

measurements can be adsorbed or retained on the walls of the pipes or accessories of the distribution system, which can cause the tracer to take longer to reach the sampling points, which would result in an over-estimation of the age of the water. However, it could be that the EPANET model could be underestimating the residence times of water in this section of the network. Factors such as model calibration, simplified network representation or the presence of preferential flows could explain these differences.

At the furthest points from the treatment plant, in this case from P7 to P14, the water age values obtained with tracers and EPANET become more similar. This indicates that the simulation model manages to better capture the behavior of water in the most distant areas of the distribution network. Possibly, the effects of model simplifications or inaccuracies will be attenuated as the water travels throughout the network. In general, there is a tendency for tracers to estimate water ages higher than those obtained with EPANET, especially in the initial and intermediate sections of the network. The above shows the importance of using a combination of methods to obtain a more complete and reliable

evaluation of the behavior of the retention time in the distribution network.

The longer retention time obtained with the tracer studies compared to the EPANET model could be because the retention time obtained with the tracer studies includes the effects of temporal variations in water demand, mixing of water in the pipe joints and other important operating parameters, such as filling and emptying storage tanks. This suggests that the age obtained by the tracer technique could be affected by reactions or retention of the tracer on the pipe walls, which would not be adequately captured in the EPANET hydraulic model.

Statistical analysis was carried out to determine if there is a significant difference between the water retention times in the distribution network obtained by the three methodologies (Table 1). The results of this statistical analysis are presented in Table 2. The p-values of the normality test are greater than 0.05, which indicates that the data follow a normal distribution. This allowed us to subsequently apply the ANOVA parametric statistical test, the F value obtained was 159.1, which is a very high value, the associated p-value is less than 0.0001, which means that

Table 2

Results of the statistical analysis: Normality Tests, ANOVA and Post-Hoc (Tukey).

Statistic analysis	Results
Normality Test	- Delisle et al. (2015): p-value = 0.2364 (Normal Distribution) - Distribution function E(t): p-value = 0.7295 (Normal Distribution) - EPANET: p-value = 0.6073 (Normal Distribution)
ANOVA test	- F value: 159.1 - p-value <0.0001 There is a significant difference between at least one of the methodologies
Post-Hoc Test (Tukey)	- Delisle et al. (2015) vs Distribution function E(t): p-value <0.0001 - Delisle et al. (2015) vs Epanet: p-value <0.0001 - Distribution function E(t) vs EPANET: p-value <0.0001 There are significant differences between all pairs of methodologies

there is sufficient statistical evidence to affirm that there are at least a significant difference between the results of the three methodologies analyzed. When applying the Post-Hoc Test (Tukey), the p-values obtained in the pairwise comparisons (Delisle et al. vs. Function E(t), Delisle et al. vs. EPANET, and Function E(t) vs. EPANET) are all less than 0.0001. This indicates that there are statistically significant differences between the results of the three methodologies evaluated. These findings suggest that the three methods for estimating the water age in drinking water distribution systems produce significantly different results from each other.

3.4. Comparison with other studies

Table 3 presents water age values determined in other similar studies. Comparing these, it can be said that the RDAP analyzed in this study has good residence times. The present study shows a shorter water age range compared to some other studies, the ranges most similar to the present study are those of Desta et al. [30] of 4.8–20 hours and Kourbasi et al. [13] of less than 22.46 hours. However, the aforementioned studies have different characteristics, such as demands, number of users, distributed flow and total distance from the network, which directly influence their calculation of the age of the water.

At all monitoring points in the present study, the age of the water is below the limit of 10 h proposed by Coelho [31] and less than the 48 h indicated by Shokoohi et al. [32]. Kanakoudis et al. [33] indicates that the average water age in a distribution network is between 1.3 days,

Table 3

Comparison of water age values with other studies.

Author	Water age range (hours)	Population	Distributed flow (L/s)	Technique
Present study	1.83–12.33 1.31–10.52 0.30–9.68	6200	16.8	Tracers EPANET
Rakstang [14], Delisle et al. [16]	0–96 6–33	205000	750	Tracers
Rubulis et al. [17]	3–60	700000	1500	EPANET
DiGiano et al. [15]	8–30 3–28	250000	1840	Tracers EPANET
Desta et al. [30]	4.8–20	220212	416	WaterGEMS
Monteiro et al. [3]	less than 48 hours	34000		EPANET
Kourbasi et al. [13]	Less than 10:46 p.m.	3429	18.38	EPANET
Świętochowska and Bartkowska [35]	37.5–112		6.1–10.78	EPANET
Machell and Boxall [36]	24–122			Aquis

while the maximum is 3.0 days. According to Shamsaei et al. [34] older water ages indicate flow problems, low pressure or stagnation of water, which can negatively affect the quality of the supply; this being the cause of the higher retention time values. Areas with shorter residence times indicate better water circulation and greater turnover, which can contribute to better water quality [12,34]. High water retention times are associated with water quality problems, such as the generation of disinfection byproducts, nitrification processes, microbial growth, entry of pathogens, increase in temperature, sediment accumulation, among others [10,33].

Increasing water age is associated with greater deviations in water quality from the service line to the tap. As such, stagnation is often considered an indicator of poor water quality [37]. Evaluating these results, it can be said that the RDAP studied complies with the recommended times, being a small network that supplies a small area, it does not present significant problems with the age of the water. However, as the population increases, therefore, the number of consumers that will need to be supplied may mean future problems in the network.

3.5. Challenges and priorities

There is still a need to develop more detailed and accurate hydraulic and water quality models that can adequately represent the water age in distribution networks. This implies improvements in the algorithms and techniques for calibration and validation of these models, using greater quantity and quality of field data. With respect to tracer techniques, research is required on tracer injection techniques that allow obtaining an input closer to the ideal stimulus (step or pulse). Additionally, a deeper understanding of the interactions between tracers and pipe walls is necessary to quantify retention and reactivity effects. The development of standardized protocols for conducting and interpreting tracer studies in distribution systems is also needed.

Regarding practical and management applications, research is needed on how to effectively use water age information for decision making in the operation and management of distribution systems. The development of guides and tools is also required to facilitate the implementation of water age studies in the practice of water supply companies, as well as the analysis of the impact of water age on water quality and in the processes of degradation of disinfectants and formation of byproducts. Tracer techniques, while providing direct measurements, can also have certain limitations that could lead to overestimating the age of the water. Likewise, incomplete mixing of the tracer, reactions or adsorption of the tracer on the walls of the pipes may occur, altering its transport, which is why it is necessary to continue investigating and repeat the studies to capture the seasonal variability of the age of the water.

Regarding the integration between model and field, it is a challenge to achieve a good correlation between the model results and the data obtained in the field. Additionally, there may be differences between retention times calculated by the model and those measured with tracers, and it is difficult to identify and quantify all sources of uncertainty in the comparison.

4. Conclusions

In this work, two approaches were used to improve the determination of the water age in a distribution network, combining the application of tracers (Delisle et al. [16], and E(t) function) and modeling with software such as EPANET. The water age values were within the range considered “short” according to the standards established by the Environmental Protection Agency (EPA), indicating that, in general, the quality of the water in the distribution network is adequate. The results indicated that there is a significant difference between the water retention times in the distribution network obtained by the three methodologies analyzed. However, the results obtained through tracers and modeling with EPANET indicate that all points in the network have

residence times less than 12 hours, which is positive according to EPA standards and does not represent a problem for water quality in the network. Therefore, the importance of combining field and modeling techniques for comprehensive water quality management is highlighted. The integration of the controlled addition of sodium chloride as a tracer with the hydraulic and water quality simulation in EPANET allowed obtaining a detailed and accurate view of the residence times of water in the distribution network, identifying areas of interest and optimizing the Management of the quality of water supplied to the community. It is necessary to further analyze the impact of water age on the quality of water supplied to end users. This involves investigating how the residence times of water in the distribution network affect the presence of contaminants, the formation of disinfection byproducts and other parameters relevant to public health.

CRedit authorship contribution statement

Fernando García-Avila: Writing – original draft, Methodology, Investigation, Conceptualization. **Geovanna Asitimbay-Barbecho:** Investigation, Formal analysis, Data curation. **Melisa Espinoza-Bustamante:** Investigation, Formal analysis, Data curation. **Lorgio Valdiviezo-Gonzales:** Validation, Software. **Esteban Sánchez-Cordero:** Project administration, Funding acquisition. **Rita Cabello-Torres:** Writing – original draft, Supervision. **Horacio Gutiérrez-Ortega:** Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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