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Decay process of free residual chlorine concentration affected by travel time in water distribution systems

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ABSTRACT

Chlorination is the most widely used method for disinfecting water for human consumption. While the chlorinated water travels through a distribution system, the concentration of free residual chlorine (FRC) declines depending on the natural water characteristics. This study investigated FRC decay in two types of water sources – ground and surface water – with varied concentrations of organic compounds. The travel time variable depended on water consumption patterns of both distribution systems which attend low density populations and their initial project needs. Based on mathematical simulation techniques of water quality models, the study also investigated the effects of water temperature and total organic carbon (TOC) on the kinetic constants (k_b) of chlorine decay. Results show that travel time in the most critical locations in the water networks and the minimum disinfectant concentrations required at the entry points were 40 hours and 0.27-0.28 mg L^{-1} at Vale dos Pássaros housing complex, and 144 hours and 0.30-0.36 mg L^{-1} at Terras Alphaville housing complex.

Keywords: disinfection, TOC, water quality.

Decaimento da concentração de cloro residual livre influenciado pelo tempo de percurso nas redes de abastecimento de água

RESUMO

A cloração é o método mais utilizado para promover a desinfecção da água para consumo humano. Durante a passagem de água clorada em sistemas de abastecimento de água, a concentração de cloro residual livre (CRL) decai, cuja taxa de reação depende das características da água natural. Neste trabalho, foi avaliado a decadência da concentração de residual de cloro livre em dois tipos de água, subterrânea e superficial, com diferentes concentrações de matéria orgânica, sob a perspectiva da influência do tempo de deslocamento da água, dependente dos cenários de consumo nas redes de distribuição, cujos módulos de abastecimento são caracterizados por baixa adensamento populacional e operam sob as condições iniciais de demanda previstas nos projetos. Foi considerado o efeito da temperatura e do carbono orgânico total (COT) sobre os valores das constantes cinéticas de decaimento de massa (k_b), utilizadas nos modelos matemáticos que simulam a qualidade da água. Os tempos de viagem nos nós mais críticos e as concentrações mínimas de desinfetante na entrada do módulo de abastecimento para cumprir a legislação foram iguais a 40 horas e 0,27-0,28 mg L^{-1} para as redes de distribuição do condomínio Vale dos Pássaros e 144 horas e 0,30-0,36 mg L^{-1} para o condomínio Terras Alphaville.

Palavras-chave: COT, desinfecção, qualidade da água.

1. INTRODUCTION

Appropriate knowledge of the behaviour of FRC concentration as it travels through water distribution systems assists in meeting the minimum and maximum residual disinfectant levels allowed by regulations and also ensures the quality of the water reaching the population. According to the World Health Organization (WHO), water contamination can occur by viruses classified as moderately and highly harmful to health: Hepatitis A and E, rotavirus and more recently the coronavirus (García-Ávila *et al.*, 2021). Thus, public water systems are required to monitor the behaviour and the disinfectant concentration to maintain acceptable levels in more distant areas and to meet the minimum residual chlorine concentration throughout the day, ranging from 0.10 mg L^{-1} to 0.20 mg L^{-1} (Ozdemir and Buyruk, 2018; Ababu *et al.*, 2019).

From the moment it is applied at the chlorination or rechlorination points, chlorine reacts with the organic and inorganic matter present in the liquid mass, resulting in the decay of its residual concentration over time. Due to the reactions between chemical species present in the water in the runoff volume (mass degradation) and with the iron released by corrosion, deposits and biofilms at the interface of the tube wall (wall decay) the concentration of FRC decreases along the pipes of the distribution networks in supply systems (Rossman, 2000; Liu *et al.*, 2015; Monteiro *et al.*, 2017). The decay of free chlorine in the liquid mass occurs due to the reaction with many substances, mainly with dissolved organic matter.

On the other hand, chlorine reacts with natural organic matter present in the water, forming disinfection by-products, such as trihalomethanes (THMs), and exposure to them can pose risks to human health. For this reason, in many countries, regulatory agencies have imposed maximum THM concentration limits for drinking water (Abhijith *et al.*, 2021).

Generally, the monitoring of water quality parameters at specific points in the network, including residual chlorine, is determined by a sampling plan that becomes the main option in technical management, including to verify compliance with legislation. This form of monitoring may not be the most appropriate, as the periods and locations of sample collection are not representative and do not demonstrate the actual behavior of the disinfectant in the supply system. In order to satisfy regulatory requirements and consumer needs in relation to the quality of treated water, management entities feel the need to better understand the movements and transformations that water intended for human consumption is subject to within distribution systems.

According to Rossman (2000), the water quality simulation model allows monitoring the growth or decay of a substance due to reactions as it moves along the water distribution network. Chlorine decay models are useful for managers of drinking water supply systems to predict the residual chlorine concentration across the network under various hydraulic conditions (García-Ávila *et al.*, 2021). The degradation of the FRC can be modeled by some known computer software that simulates the hydraulic behavior and water quality in distribution networks.

Examples are EPANET, which is free to access, and WaterCAD, which is commercially available (Izinyon *et al.*, 2010).

Prior to the development of EPANET software, basic nonlinear equations were solved using the Hardy-Cross method, which makes successive approximations from a set of initial guesses (Ibarra-Berastegi and García-Arriba, 2017). To make such predictions, it needs to know both the bulk and wall reaction rates, as well as the manner in which these rates are affected by the residual concentration. Meanwhile, EPANET allows a modeler to treat these two reaction zones separately. The coefficient of the total decay reaction rate (k), for the specific study of the reactions that occur inside the pipes of supply networks is represented by the sum of the coefficients kb (mass degradation) and kw (wall decay) (Rossman, 2000).

Studies have shown that the increase in the concentration of total organic carbon (TOC) caused an increase in the values of the “kb” coefficient (Powell *et al.*, 2000; Al Heboos and Licskó, 2017; Saidan *et al.*, 2017). Another important point to be considered is that different types of natural water cause different behaviors in the decay of the concentration of residual free chlorine in the distributed water. Sanabria and De Julio (2013) carried out a study to adjust the kinetic models found in the bibliography and concluded that, from the chlorine decay tests, it was possible to observe that of the three samples collected in different springs, those of underground origin had lower levels of chlorine reaction with chlorine.

The decay of the FRC depends directly on the travel time of the water inside the system and the residence time in the reservoirs. This effect is mainly verified in the initial years of operation in which the number of connections can still be relatively low, characterizing consumptions lower than the dimensioned ones that will correspond to low flow velocities and longer travel times. When the pressure in the distribution network decreases, the corresponding flow will be lower and the hydraulic residence time (water age) will be longer. An increase in residence time allows the chlorine concentration to decrease (Coelho *et al.*, 2006; Olaia, 2012; Seyoum *et al.*, 2012).

Water temperature has an effect on the decay of chlorine content, according to what has been concluded in most studies to date (Ozdemir and Buyryk, 2018), being one of the factors that most influence decay rates in systems of drinking water (Monteiro *et al.*, 2017). Tests performed on samples of treated water showed lower residual chlorine values, for the same time t, at higher temperatures (Monteiro *et al.*, 2015), under the same conditions of flow velocity and water age (Eck *et al.*, 2016).

This study uses the EPANET software to model calibrated hydraulic calculations and water quality behaviour as a means of assessing FRC bulk decay rates in two existing water-distribution systems. One of them is a surface water source and the other a groundwater source. Moreover, organic compound concentrations, travel time according to water consumption patterns among the population, and water temperature were also analysed.

2. MATERIAL AND METHODS

2.1. Study sites

This study investigated FRC decay in water supply networks serving the Vale dos Pásssaros and Terras Alphaville housing complexes (Figures 1 and 2). The raw water features are determined, respectively, by the surface water source drawn from Ribeirão Caldas in the Agroindustrial District of Anápolis – DAIA’s water supply system, and by the groundwater source from Terras Alphaville’s independent supply system. These survey locations are part of the water distribution system (WDS) in the city of Anápolis, in the state of Goiás (Brazil), and were selected considering that the number of connections to the systems indicated consumption data values below the demand forecast. Additionally, they have clearly marked areas of distribution.

Figure 1. Critical nodes for data evaluation after simulation: Vale dos Pássaros (N1798).

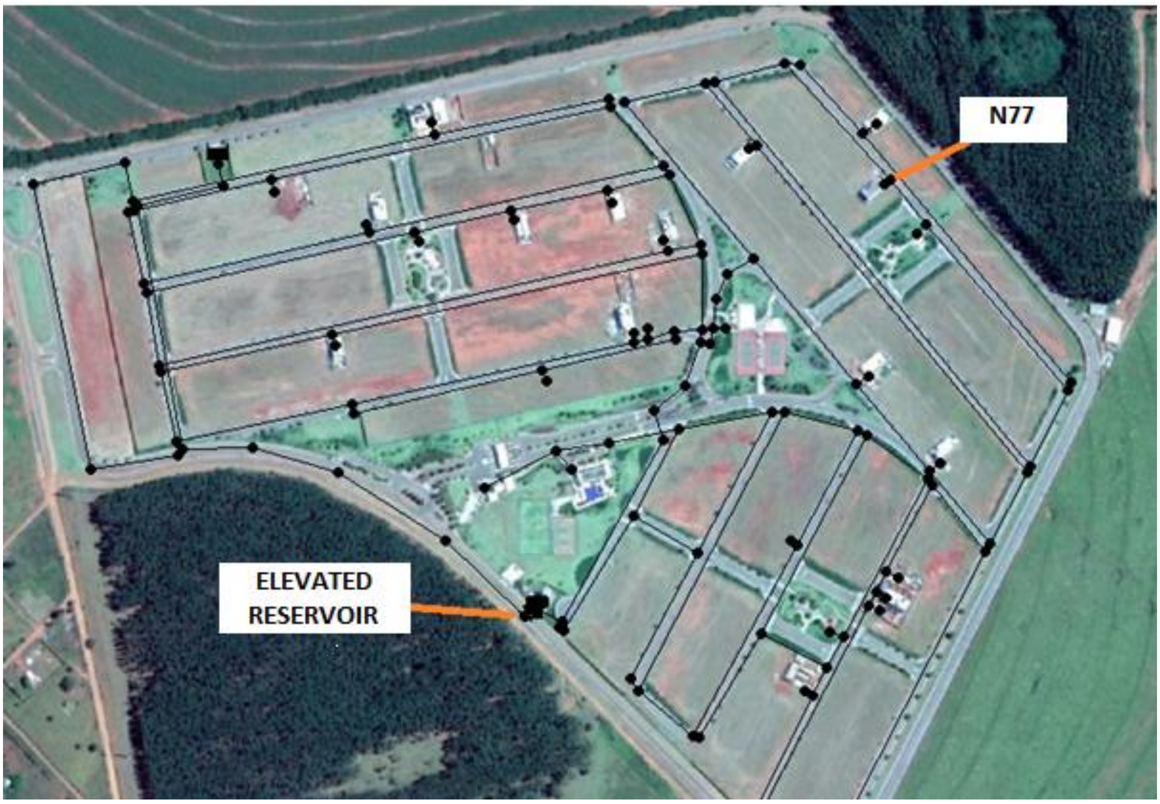

Figure 2. Critical nodes for data evaluation after simulation: Terras Alphaville (N77).

2.2. Scenarios to model

Scene 1: Simulation of travel time through each distribution system to identify the location receiving the last portion of water from the reservoir's exit point, considering consumer patterns.

Scene 2: Simulation of disinfectant decay in each distribution system, considering consumer patterns, to identify the initial chlorine concentration sufficient to ensure FRC of 0.2 mg L^{-1} in all nodes for different k_b coefficients obtained from bottle tests, depending on temperature variations.

2.3. Obtaining the kinetic coefficients "k_b" under the influence of temperature

Chlorine decay in the mass of water was evaluated by "bottle tests" (Monteiro *et al.*, 2017;

Ozdemir e Buyruk, 2018; Powell *et al.*, 2000; Saidan *et al.*, 2017; Sanabria and De Julio, 2013; García-Ávila *et al.*, 2021). Results were recorded onto forms and the measured data were processed by using Excel, which were then graphically represented. Decay rates in the mass of water were drawn from a graph value of $\ln(C_t/C_0)$ as a function of time recorded in hours.

Surface water samples were collected before chlorine application at the exit point of filter Number 1 in DAIA's treatment plant (16°25'32.63" S latitude and 48°54'41.60" O longitude), which serves the standing distribution reservoir at Vale dos Pássaros housing complex. The treatment process is of the conventional type.

Groundwater samples were collected from the discharge line of a submersible pump installed in a deep tube-well, before chlorine application, near the entry point of the standing reservoir at Terras Alphaville housing complex (16°21'4.11"S latitude and 48°52'50.56"O longitude), where the water is treated by simple disinfection process.

Samples were collected in 100 mL flasks, properly packed in a 1.5 L styrofoam box with ice and immediately sent to the laboratory of the Regional Center for Technological Development and Innovation - CRTI, located on the Samambaia Campus, of the Federal University of Goiás, in the city of Goiânia-GO (Brazil), for the analysis of the total carbon content using the Shimadzu TOC-L equipment. Measurements were performed in triplicate, with results equal to the average of the acquired values of organic and inorganic carbon present in the sample.

2.4. Model construction

2.4.1. Description of flows and consumption

The survey on the total volume of distribution involved the analysis of daily readings made by devices installed at the outlet of each water supply system. The study data also included microvolume levels and reference periods (base consumption) provided by reports from the company's commercial information system, which are consistent with the period of the macro network performance report, providing an oversight on physical losses within the sector.

2.4.2. Operational control

Information on operating conditions and routines of both distribution systems during simulations were obtained from technical record drawings, the information system for operation control, field study data, control charts and interviews with staff responsible for operating gate and pressure-relief valves as well as reservoir maintenance.

2.4.3. Model simulations

Reactions in the bulk flow (k_b) were the main input parameters during water quality simulations. Results show rates of water flow, velocity, mass deterioration, average reaction and FRC concentration along the tubes. Simulations have been modelled using EPANET 2.0, a reliable and free software used throughout the world.

2.4.4. Model calibration

The hydraulic model calibration used to simulate water quality and assess travel time and behaviour of FRC measured the amount of pressure in strategic points throughout the WDS, the water flow at the entry points (outlet of the water tanks) as well as consumption rates, aiming to define the consumption pattern and spatial distribution of demand.

Measurements of pressure within the distribution systems were recorded over a 24-hour period with a pressure gauge placed in key points of the network. Flow-through reservoir outlets were automatically measured and registered. Flow measurements were gathered at the entry point of the WDS between 01 February and 03 May 2018 at the Vale dos Pássaros complex and between 06 and 18 June 2018 at the Terras Alphaville complex.

In system areas with significant mass degradation or pressure, mean absolute errors between observed and simulated values were ± 2.0 m. It was also observed that the simulated flow rates should be within the 5% range of measured flows (Walski, 2003). However, the absolute value of maximum deviation was recalculated according to the precision of measuring instruments and to the limitations identified during calibration.

2.5. Data analysis

Bulk values related to flow, pressure, consumption and physico-chemical parameters are presented as average values, including those in the system information reports.

3. RESULTS AND DISCUSSION

3.1. Values of kinetic coefficients "k_b" depending on TOC and temperature

Non-chlorinated water samples from DAIA's WDS at 20.2°C showed TOC measurements of 0.4798 mg L^{-1} after filtration. The raw water samples collected from the tubular well at the reservoir's entrance integrated to the Terras Alphaville WDS at 27.5°C show TOC measurements of 0.1740 mg L^{-1}.

For initial chlorine concentrations of 1 mg L^{-1} ± 0.05, the coefficient values of mass decay k_b as a function of temperature are presented in Table 1.

Table 1. Values of "k_b" (d^{-1}) depending on temperature (°C): a) Groundwater samples; b) Surface water samples.

(a)		
Temperature (°C)	Initial concentration of FRC (mg L^{-1})	k_b (d^{-1})
20 a 21	$C_0$20=0,97	0,0264
30 a 31	$C_0$30=1,04	0,0480
(b)		
Temperature (°C)	Initial concentration of FRC (mg L^{-1})	k_b (d^{-1})
20 a 21	$C_0$20=0,94	0,0888
30 a 31	$C_0$30=1,05	0,1200

3.2. Description of the physical components of the supply sectors

The WDS at the Vale dos Pássaros housing complex is formed by two integrated systems composed of PVC pipes with nominal diameters of 50-100 mm, measuring a total of 3,336.40 m in length. It also has five iron valves with nominal diameters of 50-75 mm. It is made up of fifty-nine singular characteristics such as curves, reductions and tees, including the valves made of PVC or iron.

The WDS at the Terras Alphaville housing complex is formed by three integrated systems composed of pipes with nominal diameters of 50-150 mm, all made of DeFoFo and PVC (with diameters equivalent to those of the iron pipes), measuring a total of 10,355.33 m in length. It also has three iron control valves with nominal diameters of 50 mm. It is made up of one hundred and six singular characteristics such as curves, reductions and tees, including the valves made of PVC or iron.

The standing metallic tank at Vale dos Pássaros measures 6.68 m in diameter, has a total storage capacity of 120 m^3, and maximum water depth and level of 1,098 m and 1,101.30 m respectively. Chlorine concentrations at the exit point of the reservoir are determined by the dosage applied to DAIA's WDS, varying in accordance to system operation.

The standing concrete tank at the Terras Alphaville complex measures 6.10 m in diameter, has a total storage capacity of 150 m^3, and maximum water depth and level of 1,056.85 and 1,062.25 m, respectively. Chlorine concentration at the exit point of the reservoir is determined by the dosage applied inside the standing tank, varying in accordance to system operation.

3.3. Survey of consumption

Results related to flow rates and physical degradation during the survey period are shown in Table 2 for Vale dos Pássaros complex and for the Terras Alphaville complex in Table 3.

Table 2. Losses in the supply system at the Vale dos Pássaros housing complex.

Month/year	Macromeasured volume (m^3)[1]	Micromeasured volume (m^3)[2]	Losses (m^3)	Loss index (%)
Oct/17	2003	1055	948	47.33
Nov/17	2370	886	1484	62.62
Dec/17	2995	805	2190	73.12
Jan/18	2551	883	1668	65.39
Feb/18	1126	1003	123	10.92
Mar/18	1038	933	105	10.12
Apr/18	997	922	75	7.52

Source: Saneago (2018).
[1]There were daily readings on the measuring equipment.
[2]There was a monthly reading on the measuring equipment between the days 01 and 05.

Table 3. Losses in the supply system at the Terras Alphaville housing complex.

Month/year	Macromeasured volume (m^3)[1]	Micromeasured volume (m^3)[2]	Losses (m^3)	Loss index (%)
Oct/17	349	255	94	26.93
Nov/17	245	170	75	30.61
Dec/17	212	167	45	21.23
Jan/18	298	261	37	12.42
Feb/18	232	206	26	11.21
Mar/18	231	201	30	12.99
Apr/18	296	262	34	11.49

Source: Saneago (2018).
[1]There were daily readings on the measuring equipment.
[2]There was a monthly reading on the measuring equipment between the days 08 and 10.

Analysis of reports on “Control and Leaks in Neighbourhood areas – RS382B” (Saneago, 2018) showed no significant leak occurrences at Vale dos Pássaros and no leakage at Terras Alphaville.

At Vale dos Pássaros, a total of 38 water bills are issued by the first system within its WDS, a total of 23 by its second system, and the bill of the administration area of the housing complex is linked to the main system. At Terras Alphaville, its three integrated systems issued a total of eleven (11), six (6) and seven (7) water bills, respectively.

Each water bill showed associated base consumption rates obtained during predetermined periods and were generated by reports which were also issued by the information system. Consumption data were recorded from 01 February 01 to 03 May 2018 at the Vale dos Pássaros complex, and from 11-18 June 2018 at the Terras Alphaville complex.

During these periods, flow rates at the exit points provided average consumption rates, which divided by the mean daily value, were able to determine multiple factors viewed as a

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consumption pattern, then inserted in EPANET 2.0 for modelling. Flow rates obtained from the information system's database were illustrated in tables and graphs in 15-minute intervals.

The average consumption patterns that covered the working days of the week, Saturday and Sunday, within the periods considered and the average consumption patterns of Sunday and Monday used in the simulations in EPANET 2.0 are represented in Figures 3 and 4.

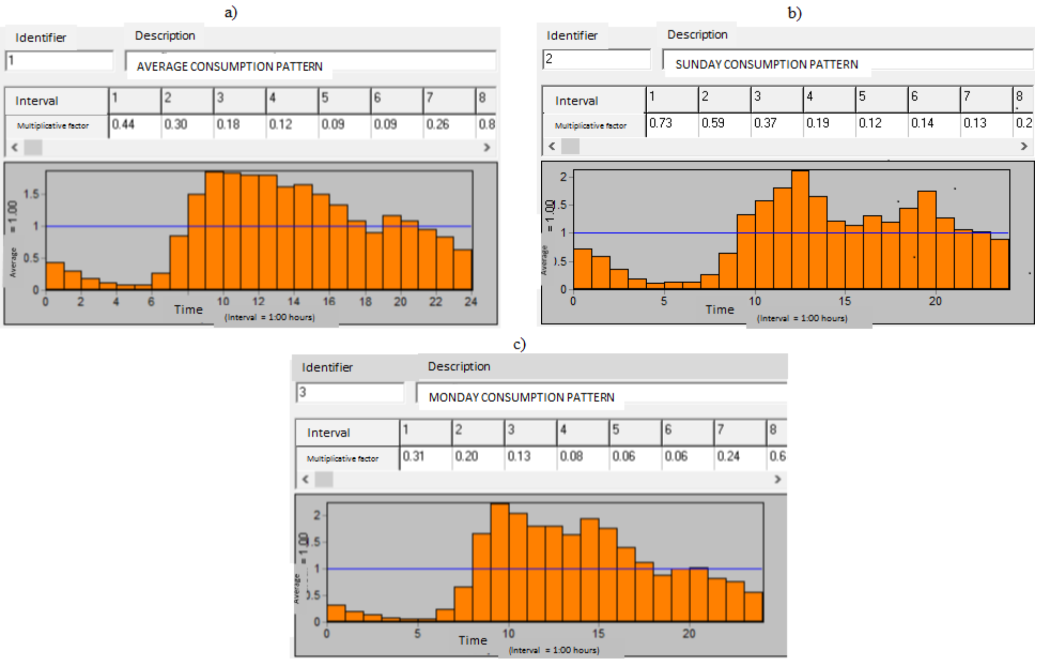

Figure 3. Consumption pattern in EPANET. Vale dos Pássaros in the period from 01/02/2018 to 03/05/2018: a) average consumption; b) Sunday consumption; c) Monday consumption. **Source:** EPANET.

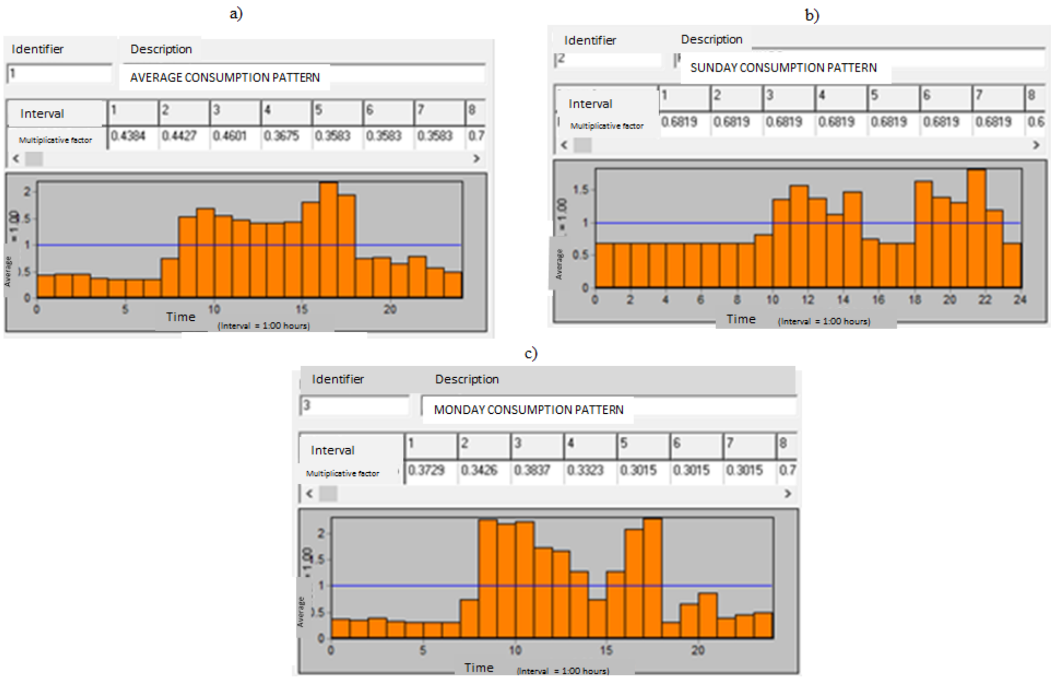

Figure 4. Consumption pattern in EPANET. Terras Alphaville in the period from 11/06/2018 to 18/06/2018: a) average consumption; b) Sunday consumption; c) Monday consumption. **Source:** EPANET.

It was found that the residences are of high constructive standard. During the field surveys, it was possible to perceive the high purchasing power of users, indicating that probably the high consumption on Monday is due to the fact that domestic services are preferably performed on this day of the week. The decrease in domestic activities is identified by Sunday consumption patterns.

3.4. Operational control detail

The inflow to the standing reservoir serving Vale dos Pássaros originates at the top. Its flow is controlled by a mechanical float level device in which the valve opens/closes the inlet pipe according to the level of the water.

The water serving the standing reservoir at Terras Alphaville is pumped up from a deep well through a pipe located at its top. The submersive pump works automatically, shutting down whenever the maximum and minimum water level points are reached.

Daily readings of both reservoir levels showed a relatively low variation of water level during the study period. Moreover, around 7.1 and 40.3% of all projected piped water connections for Terras Alphaville and Vale dos Pássaros were built, respectively. Both of these facts indicate low consumption rates, reduced flow velocity and long periods of water travel. Average hourly consumption rates were analysed between 25 January and 01 June 2018.

3.5. Simulations in EPANET

Hydraulic modelling results reproduced the behaviour of the existing WDS in terms of the flow and pressure variables. Similarly, water quality modelling results replicated FRC concentrations and travel time. EPANET 2.0 evaluated them as variable-level reservoirs. To carry out FRC decay simulations, each critical location was the basis for application of the initial quality parameter. Once network input data was incorporated by the software application along with consumption pattern information, pressure and flow calibrations were made. The results are described in Tables 4, 5, 6 and 7.

Table 4. Statistical treatment of pressure calibration data in the Vale dos Pássaros complex.

Localization	Observed number	Observed average (mca)	Simulated average (mca)	Absolute mean error (mca)	Standard deviation
2269563-0	24	34,33	32,99	1,344	1,447
2269528-1	24	35,13	37,93	2,805	3,380
Network	48	34,73	35,46	2,074	2,600

Table 5. Statistical treatment of calibration data for flow in the Vale dos Pássaros complex.

Localization	Observed number	Observed average ($L\ s^{-1}$)	Simulated average ($L\ s^{-1}$)	Absolute mean error ($L\ s^{-1}$)	Standard deviation
Reservoir output	24	0,37	0,36	0,009	0,011
Network	24	0,37	0,36	0,009	0,011

Table 6. Statistical treatment of pressure calibration data in the Terras Alphaville complex.

Localization	Observed number	Observed average (mca)	Simulated average (mca)	Absolute mean error (mca)	Standard deviation
2314843-8	24	21,71	23,03	1,325	1,343
Network	24	21,71	23,03	1,325	1,343

Table 7. Statistical treatment of calibration data for flow in the Terras Alphaville complex.

Localization	Observed number	Observed average (L s^{-1})	Simulated average (L s^{-1})	Absolute mean error (L s^{-1})	Standard deviation
Reservoir output	24	0,17	0,17	0,001	0,001
Network	24	0,17	0,17	0,001	0,001

Mean absolute errors between observed and simulated values reached the initial prediction (± 2,0 m). There was no need to check the obtained data and there were no complications that required more complex critical analyses regarding the calibration results. The differences between observed and simulated values were satisfactory due to the fact that the study areas have a reliable technical record with traceable operation procedure information, such as accurate records of pressure within pressure-relief valves and low incidence of physical deterioration.

Adequate knowledge of users' consumption patterns and the adoption of these base consumptions as being at the water connection points themselves, without using the artifice of concentrating these consumptions at the ends of the stretches, combined with the fact that simplifications of the networks were also not adopted. Distribution in the model leads to the conclusion that this may also have significantly influenced the obtainment of observed and simulated values close together.

The hydraulic calibration models allowed simulations on EPANET 2.0 as described in Scene 1 as well as the assessment of travel time in average consumption on Sundays and Mondays.

Analysis of temporal series of results produced by the software application shows that travel time to the critical zone in the Vale dos Pássaros distribution system was 42 hours attending consumption patterns on Sundays, 40 hours on Mondays and 40 hours as the average consumption time.

The travel time in the Terra Alphaville distribution system reached a total of 144 hours attending consumption patterns on Sundays, Mondays and average consumption.

Pressure behaviour data in Terras Alphaville was measured on 13 June 2018 during a 24-hour period. Low variability pressure rates ranged between 20.81 and 22.07 mca, validating the simulated values. This indicated consumption rates below the predicted values, resulting in longer periods of travel time compared to those observed at Vale dos Pássaros, even though the latter serves a higher density population and has a shorter length of total distribution pipeline.

Residual chlorine decay simulations occurred in scenarios with various mass reaction coefficients (k_b) obtained as a function of temperature variation (Table 1). Additionally, other coefficients obtained from the bottle tests were used. These were chlorinated water samples gathered from the exit points of the reservoirs.

Considering that this study aims to investigate FRC in the water supply systems, analysis of the disinfectant behaviour was not compromised even though k_b values were obtained from samples gathered at the exit point of DAIA's WDS and from raw groundwater instead of other samples from the reservoirs' exit points.

K_b values were obtained from water samples submitted to progressive and controlled temperature variations in the laboratory, ranging between 25 and 30°C.

Once the model is calibrated in EPANET software, it can be used to predict chlorine concentrations for various water supply needs (Danieli *et al.*, 2006; Fischer *et al.*, 2016; Sharif *et al.*, 2017).

In Scenario 2, to ensure the minimum residual concentration of 0.20 mg L^{-1} required by Brazilian regulations, values were randomly inserted using a trial and error method.

By using various simulated mass reaction coefficient values (k_b), namely $k_b = 0.0528\ d^{-1}$,

k_b = 0.0888 d^{-1} and k_b = 0.1200 d^{-1}, the minimum required chlorine concentrations obtained from Vale dos Pássaros tested samples were C_0 = 0.27 mg L^{-1}, C_0 = 0.27 mg L^{-1} and C_0 = 0.28 mg L^{-1}, respectively.

TOC results are consistent with another study that investigated FRC kinetic behaviour in samples gathered from three raw surface water sources, which showed different values of 2.1 ± 0.3 mg L^{-1}, 5.0 ± 0.9 mg L^{-1} and 3.3 ± 0.6 mg L^{-1} (Ferreira Filho and Sakaguti, 2008). Researchers concluded that the higher the amounts of TOC removed by coagulation, the lower the chlorine demand values. This suggests water coagulation has a larger impact on chlorine decay in liquid mass whenever it maximizes the removal of natural organic compounds.

K_b values shown in Table 1 indicate a larger reaction to the disinfectant with the substances present in surface water and also with higher test temperatures in both water sources. Results show a direct proportion between temperature range and FRC decay kinetic coefficient, which is consistent with results obtained from other studies (Eck *et al.*, 2016; Fischer *et al.*, 2012; Powell *et al.*, 2000; Saidan *et al.*, 2017).

A similar correlation occurred regarding the temperature range of the bottle tests, which was the same as the one adopted in this research (between 20 and 30°C). Samples were submitted to pre-oxidation with ozone, coagulation, flocculation, sedimentation, rapid sand filtration and final disinfection with chlorine. For example, after 100 hours, samples measuring between 20 and 30°C with the same initial disinfectant concentrations showed FRC rates of 0.20 m L^{-1} and 0.05 mg L^{-1}, respectively (Monteiro *et al.*, 2017).

Notwithstanding the reaction coefficient with the mass of water or travel time, initial FRC rates below the minimum requirements (equal to zero) were only found in samples obtained from a section of the WDS interrupted by a cap, located just before the entry point of the housing complex. It suggests that the residence time was high at this point resulting in significant reduction in disinfectant concentration.

Analysis of data simulation of FRC behaviour in samples from Terras Alphaville's water supply system resulted in initial chlorine concentrations of 0.30 mg L^{-1}, 0.31 mg L^{-1} and 0.36 mg L^{-1} for simulated mass reaction coefficient k_b = 0.0216 d^{-1}, k_b = 0.0264 d^{-1} and k_b = 0.0480 d^{-1}, ensuring minimum residual disinfectant concentrations at the most critical locations in the water network.

García-Ávila *et al.* (2021) obtained the mean value of kb equal to 3.7 d^{-1} and used it to simulate the decay of free residual chlorine in a distribution network using the EPANET software. They found that at the outlet of the supply reservoir it was necessary to maintain a minimum concentration equal to 0.87 mg L^{-1} to comply with the minimum value allowed by local legislation. However, the minimum value of 0.5 mg L^{-1} allowed by the WHO to fight the coronavirus was not reached in 45% of the samples from the nodes evaluated. The authors also observed that the value of k_b was lower (0.12 h^{-1}) for samples collected in the month that presented lower temperatures and higher (0.19 h^{-1}) for higher temperatures.

Many locations along Terras Alphavilles's supply system showed values below the minimum concentration required, considering the simulations with the minimum dosage to ensure 0.20 mg L^{-1} in the critical zone. This may be due to the lack of demand along these locations, therefore showing a higher residence time.

Relatively low mass reaction coefficient were obtained for 20 and 30°C (Table 1, a and b) as well as for 25 and 30°C. Results from a research study carried out in 2010 showed k_b values of 0.0642 d^{-1}, 0.1316 d^{-1} and 0.1989 d^{-1} for 15, 20 and 30°C temperatures, respectively. Researchers considered them low coefficient values due to low TOC levels in the water (between 0.10 mg L^{-1} and 1.02 mg L^{-1} and average of 0.34 mg L^{-1}), which resulted in lower chlorine demand (Karadirek *et al.*, 2015; Al Heboos and Licskó, 2017; Madzivhandila and Chirwa, 2017).

Even though low k_b values were used to simulate FRC behaviour for both ground and surface water samples, results show variations in disinfectant decay in some locations of the WDS.

Simulations developed in EPANET may be used to achieve initial target concentrations (C_0) necessary to obtain a specific product of disinfectant concentration-time (C_t) for primary disinfection, and also to study the minimum required concentration through every point in the system for secondary disinfection and the maximum acceptable concentration for aesthetic purposes.

4. CONCLUSION

The adopted methodology allowed analysis of the decay of the concentration of free residual chlorine during the course of water in supply networks. The results indicated the need for knowledge about the behavior of the disinfectant depending on the type of water, characterized by the concentration of organic matter and the temperature variation.

The variation in temperature ranges and concentrations of organic matter present in the samples used in the tests and the influences of these parameters demonstrated the need for detailed simulator studies in order to determine ideal values of the kinetic constants of chlorine decay in mass (k_b) in distribution networks to be used in simulation models, according to the characteristics of the waters that may vary throughout the year depending on seasonality.

EPANET successfully simulated the water travel times and the decay of residual chlorine in the supply networks. The results pointed to an efficient management tool that helps in decision-making when defining the sampling plan collection points for a given area and stipulates minimum values of FRC concentrations at the entry points of module supplies and consumption points, in this case, avoiding waste of chemical products for treatment. These technical assessments help to ensure public health and meet legal requirements.

5. REFERENCES

ABABU, T. T.; TESFAMARIAM Y. D.; STANLEY, J. N. Um Modelo Matemático para Taxas Variáveis de Decadência de Cloro. **Sistemas de Distribuição de Água, Modelagem e Simulação em Engenharia**, v. 2019, p. 1-11, 2019. https://doi.org/10.1155/2019/5863905

ABHIJITH, G. R.; KADINSKI, L.; OSTFELD, A. Modeling Bacterial Regrowth and Trihalomethane Formation in Water Distribution Systems. **Water,** v. 13, n. 4, 2021. https://doi.org/10.3390/w13040463

AL HEBOOS, S.; LICSKÓ, I. Application and Comparison of Two Chlorine Decay Models for Predicting Bulk Chlorine Residuals. **Periodica Polytechnica Civil Engineering,** v. 6, n. 1, p. 7-13, 2017. https://doi:10.3311/PPci.9273

COELHO, S. T.; LOUREIRO, D.; ALEGRE, H. **Modelação e análise de sistemas de abastecimento de água**. Manual, sperie IRAR-LNEC. Lisboa: Edições IRAR, 2006.

DANIELI, R. D.; GASTALDINI, M. C.; BARROSO, L. B. Modelagem do cloro residual em redes de distribuição – aplicação ao sistema de abastecimento de Santa Maria. **Revista Brasileira de Recursos Hídricos,** v. 11, n. 4, p. 201-208, 2006.

ECK, B. J.; SAITO, H.; MCKENNA, S. A. Temperature dynamics and water quality in distribution systems. **IBM Journal of Research and Development,** v. 60, n. 5-6, p. 1-8, 2016. https://doi:10.1147/JRD.2016.2594128

FERREIRA FILHO, S. S.; SAKAGUTI, M. Comportamento cinético do cloro livre em meio aquoso e formação de subprodutos da desinfecção. **Revista Engenharia Sanitária e Ambiental**, v. 13, n. 2, p. 198-206, 2008. https://doi.org/10.1590/S1413-41522008000200010

FISCHER, I.; KASTL, G.; SATHASIVAN, A. A suitable model of combined effects of temperature and initial condition on chlorine bulk decay in water distribution systems. **Water Research,** v. 46, n. 10, p. 3293-303, 2012. https://doi:10.1016/j.watres.2012.03.017

FISCHER, I.; KASTL, G.; SATHASIVAN, A. A comprehensive bulk chlorine decay model for simulating residuals in water distribution systems. **Urban Water Journal**, v. 14, n. 4, p. 361-368, 2016. https://doi:10.1080/1573062X.2016.1148180

GARCÍA-ÁVILA, F.; AVILÉS-AÑAZCO, A.; ORDOÑEZ-JARA, J. Modeling of residual chlorine in a drinking water network in times of pandemic of the SARS-CoV-2 (COVID-19). **Sustainable Environment Research**, v. 31, n. 12, 2021. https://doi.org/10.1186/s42834-021-00084-w

IBARRA-BERASTEGI, G.; GARCÍA-ARRIBA, R. Using open source software in engineering studies to teach water operation & management. *In:* IEEE GLOBAL ENGINEERING EDUCATION CONFERENCE (EDUCON), 25-28 Apr. 2017, Athens, Greece. **Documents[...]** IEEE, 2017. https://doi.org/10.1109/EDUCON.2017.7943030

IZINYON, O. C.; ANYATA, B. U. Modelling Water Age as Surrogate for Water Quality in a Distribution System: Modelling Water Age for Water Quality. **Ciências Biológicas - PJSIR**, v. 53, n. 4, p. 187-191, 2010.

KARADIREK, I. E.; KARA, S.; MUHAMMETOGLU, A.; MUHAMMETOGLU, H.; SOYUPAK, S. Management of chlorine dosing rates in urban water distribution networks using online continuous monitoring and modeling. **Urban Water Journal**, v. 13, n. 4, p. 345-349, 2015. https://doi.org/10.1080/1573062X.2014.992916

LIU, M. J.; CRAIK, S.; ZHU, D. Z. Determination of cast iron pipe wall decay coefficient for combined chlorine in a municipal water distribution system. **Canadian Journal of Civil Engineering**, v. 42, p. 250-258, 2015. https://dx.doi.org/10.1139/cjce-2014-0449

MADZIVHANDILA, V.; CHIRWA, E. M. N. Modeling Chlorine Decay in Drinking Water Distribution Systems using Aquasim. **Chemical Engineering Transactions**, v. 57, p. 1111-1116, 2017. https://doi.org/10.3303/CET1757186

MONTEIRO, L.; FIGUEIREDO, D.; COVAS, D.; MENAIA, J. Integrating water temperature in chlorine decay modelling: a case study. **Urban Water Journal**, v. 14, n. 10, 2017. https://doi.org/10.1080/1573062X.2017.1363249

MONTEIRO, L.; VIEGAS, R. M. C.; COVAS, D. I. C.; MENAIA, J. Modelling chlorine residual decay as influenced by temperature. **Water and Environment Journal**, v. 29, n. 3, p. 331-337, 2015. https://dx.doi.org/10.1111/wej.12122

OLAIA, A. I. S. **Gestão de Sistemas de Abastecimento de Água através de Modelação Hidráulica**. 2012. 120f. Dissertação (Mestrado em Engenharia do Ambiente – perfil Engenharia Sanitária) - Faculdade de Ciências e Tecnologia da Universidade de Nova Lisboa, Lisboa, 2012.

OZDEMIR, N. O.; BUYRUK, T. Effect of travel time and temperature on chlorine bulk decay in water Supply pipes. **Journal of Environmental Engineering**, v. 144, n. 3, 2018. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001321

POWELL, J. C.; HALLAM, N. B.; WEST, J. R.; FORSTER, C. F.; SIMMS, J. Factors, which control bulk chlorine decay rates. **Water Research,** v. 34, n. 1, p. 117–126, 2000. https://doi.org/10.1016/S0043-1354(99)00097-4

ROSSMAN, L. A. **EPANET 2.0 – Users manual**. Cincinnati: USEPA, 2000.

SAIDAN, M. N.; RAWAJFEH, K.; NASRALLAH, S.; MERIC, S.; MASHAL, A. Evaluation of factors affecting bulk chlorine decay kinetics for the zai water supply system in Jordan. Case study. **Environment Protection Engineering**, v. 43, n. 4, p. 223-231, 2017. https://doi.org/10.5277/epe170417

SANEAGO. **Método ME08.0068** – Determinação da temperatura da água e do ar. Goiania, 2018. p. 2.

SHARIF, M. N.; FARAHAT, A.; HAIDER, H.; AL-ZAHRANI, M. A.; RODRIGUEZ, M. J.; SADIQ, R. Risk-based framework for optimizing residual chlorine in large water distribution systems. **Environmental Monitoring and Assessment**, v. 89, n. 7, p. 307- 314, 2017. https://doi.org/10.1007/s10661-017-5989-0

SANABRIA, J. M.; DE JULIO, M. Decaimento do cloro residual em águas de abastecimento do município de Campo Grande/MS. **Revista de Engenharia e Tecnologia**, v. 5, n. 4, p. 92-104, 2013.

SEYOUM, A. G.; TANYIMBOH, T. T.; SIEM, C. Assessment of water quality modelling capabilities of EPANET multiple species and pressure-dependent extension models. **Water Science & Technology: Water Supply,** p. 1161-1166, 2012. https://dx.doi.org/10.2166/ws.2013.118

WALSKI, T. **Advanced water distribution modeling and management.** Watertown: E. Hasted Press, 2003. p. 1-800.