Residual Chlorine Modeling by EPANET in Drinking Water Distribution Networks: A Study on Chlorine Dissipation in Al Seeb, Sultanate of Oman

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Research Article

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Posted Date: May 29th, 2024

DOI: https://doi.org/10.21203/rs.3.rs-4205528/v1

Residual Chlorine Modeling by EPANET in Drinking Water Distribution Networks: A Study on Chlorine Dissipation in Al Seeb, Sultanate of Oman

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Abstract

Controlling the residual chlorine concentrations is crucial in the management of water quality in drinking water systems to avoid overdosing or insufficient doses issues. The research employs EPANET to simulate chlorine dissipation in a part of the Sultanate of Oman's drinking water distribution network. To estimate chlorine bulk and wall decay rates through the real network, a combination of bottle tests and a pilot-scale pipe system were involved in this research. EPANET simulations conducted under two scenarios reveal that the first scenario aligns most closely with actual network conditions. The results shed light on the critical consideration of wall decay, particularly in aging pipe sections, suggesting that neglecting this factor may lead to inaccurate predictions. Model validity is shown to be influenced by initial chlorine concentrations, underscoring the significance of obtaining precise data about the network starting from the main reservoirs' outlet to the last pipes section. This study suggested further investigations into the latest part of the selected distribution network that showed a necessity to enhance free residual chlorine. Potential strategies should be developed for effective monitoring and management of residual chlorine concentrations, taking into consideration the factors that may affect its dissipation.

Keywords Chlorine dissipation, Bulk and Wall decay, Drinking water quality, Microbiological hazard, Water supply network modelling, EPANET, Domestic storage tanks

1. Introduction

Controlling chlorine residual concentrations is a matter of the utmost importance in the management of water quality in drinking water systems. While excessive concentrations of chlorine residual due to overdosing may lead to taste and odor-related complaints and carcinogenic disinfection byproducts formation, concentrations below 0.2 mg/L may not be enough to counteract microbial growth. Thus, effective monitoring and assessment of chlorine levels in drinking water systems are crucial for maintaining sufficient disinfectant residuals at the point of consumption.

The loss of disinfectant residuals in drinking water distribution systems and storage tanks is a major concern. Free chlorine in water may not only be lost by the disinfection process of microorganisms, but also reduced by reactions

with any reducing agent like inorganic or organic substances, combine with compounds that exist in the water, or loss by several factors related to the physical characteristics of bulk water, the system carrying that water or even losses resulted from catalyzed or light decomposition.

Residual chlorine decay may be caused by reactions of chlorine with compounds present in the bulk water (bulk decay) as well as reactions with the pipe's inner walls (wall decay). The factors that affect bulk decay are different from the ones that affect wall decay. Therefore, they must be separated.

Demonstrating the real water distribution network through modeling software ease visualizing and understanding the parameters that can be linked to the dissipation of chlorine. Many simulation programs were developed to track water quality throughout water distribution systems. EPANET, Bentley products (WaterGEMS and WaterCAD), AQUIS, InfoWorks WS, MikeNet, H_2ONET, and Pipe2000 are examples of hydraulic and water quality modeling software packages that can be used as effective tools to predict residual chlorine within the network (Kowalska et al., 2018). The simplicity, ability to perform extended analyses, and being a public domain and open-source program made EPANET the most common program for chlorine dissipation modeling.

EPANET is a software developed by United States Environmental Protection Agency (U.S. EPA) to effectively simulate the movement of water within any distribution network by modeling the water hydraulic behavior and tracking the potential water quality changes for unlimited size of a network. Numerous studies used EPANET to model the fate of reactive substances like chlorine and its reactions with the bulk water and at the pipe's walls. After setting and calibrating the water distribution network hydraulic model, the bulk and wall coefficients can be controlled to fit the actual residual chlorine dissipation trend.

To give an instance of the countless chlorine decay studies by EPANET, Vîrlan et al. (2021) found that when water consumption is high, the water velocity gets higher, which means water passes faster through the network making the contact time of chlorine with the dissipation-causing materials becomes less.

Abokifa et al. (2018) also used EPANET to find the optimal location for re-chlorination units. They mentioned that as EPANET is an advection-reaction transport model that does not account for dispersion as a solute transport mechanism, it is only able to accurately predict the disinfectant concentrations in the main transmission lines and its accuracy significantly reduced in the dead-end branches. EPANET as an open-source program, Abokifa et al. (2018) was able to introduce a tool to solve the dead-end parts issue.

In addition, Alsaydalani et al., (2019) by EPANET modeling found that the increase in the pipe roughness with pipe age resulted in significantly low-pressure heads at the end of the network causing an increase in chlorine decay rates.

The bulk and wall decay constants inputs in EPANET vary depending on the conditions of the studied area. For instance, García-Ávila et al., (2021) obtained wall decay values for pipelines of different diameter and flow velocity.

This paper focuses on outlining the current situation of the residual chlorine in drinking water supply networks and storage tanks and determining the circumstances and factors that may affect chlorine dissipation. This will assist in deducing if boosting free chlorine residual is necessary and what is the best way to get that done.

2. Methodology

2.1. Chlorine Bulk Decay

This part was conducted to examine the effect of the temperature, water source, chlorine source, and initial chlorine concentration. This was done by carrying out bottle tests.

The effect of temperature was investigated under two procedures. The first one was examining the dissipation of chlorine under constant temperatures. An incubator was used to set the temperature at 22℃, 32℃, and 42℃. The test was done for 1 liter of distilled water with $Ca(OCl)_2$ as the source of free chlorine. The initial free chlorine concentration was 2.5 ppm. The investigated dissipation rate was the main factor to determine the analysis time at each temperature. At 22℃, free chlorine readings were taken every day for two weeks. However, the water was analyzed every half an hour for 4 hours at temperatures 32℃ and 42℃.

The second part was examining the dissipation of chlorine when temperature increases gradually over time. The incubator temperature was set to increase the water temperature by about 3 to 5℃ per 10 minutes. Two chlorine sources were tested (NaOCl and $Ca(OCl)_2$). For both chlorine sources, 0.5 ppm and 1 ppm were the initial chlorine concentrations tested. To discover if the water source used may affect the chlorine dissipation, groundwater from the Agriculture Experimental Station (AES) in Sultan Qaboos University and distilled water were examined separately.

2.2. The Total Chlorine Decay Through a Pilot Scale Supply Network System

A pilot-scale water distribution system was designed to mimic residual chlorine dissipation in the real drinking water distribution networks under different conditions. A 12 m PVC pipe loop was assembled and connected to a 0.75 hp submersible pump, flow meter, and a water tank (Fig. 1). The water was recirculated from the tank through the pipe-loop network by using the pump. This design was assembled to examine the decay of chlorine with regards to the water flow rate and the source of chlorine. The dissipation was examined under three flow rate (4 m^3/h, 3 m^3/h, and 1.5 m^3/h). These flow rates gave a velocity of 2.2 m/s, 1.64 m/s, and 0.82 m/s, respectivly. Sodium hypochlorite and calcium hypochlorite were the two sources of chlorine utilized in the trials with an initial concentration of 0.6 ppm. The initial concentration of chlorine was selected depending on the amount maintained by desalination plants before the water leaves the plant (0.6-0.9 ppm). In all trials, the groundwater from the AES was the source of water.

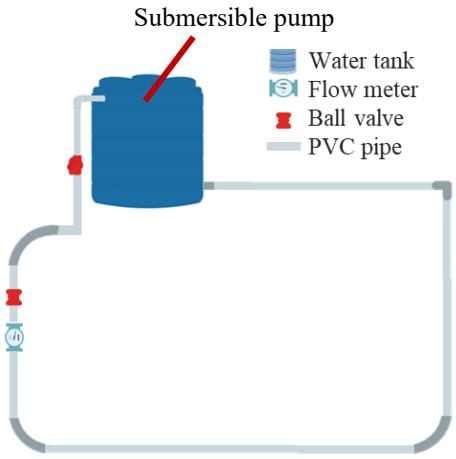

Figure 1. The pilot scale pipe system design.

To maintain a consistent water quality in all trials, groundwater from the AES utilized in the trials were disinfected prior examining the dissipation of chlorine to ensure a zero chlorine demand before starting each run. This was done by adding the free chlorine source and leaving the water stagnant for 30 minutes as a sufficient contact time to reach the breakpoint chlorination. After running the system, the water samples were taken every 30 minutes from the tank to be analyzed for free chlorine.

2.3. Chlorine dissipation simulation by EPANET in the drinking water distribution network

The selected area in this reseach was part of Al Seeb city in Sultanate of Oman. Al Seeb is a city in Muscat governorate where most occupants depend on the drinking water supplied by the Oman Water & Waste Water Services Company (OWWSC) which was changed recently to Nama. For this area, OWWSC relay on the produced drinking water from two desalination plants- Barka desalination plant and Al Ghobrah desalination plant- as well as the groundwater pumped from Al Khoudh dam wells to overcome the deficiencies. Diam as a part of OWWSC is responsible for the maintenance of chlorine residuals and other quality parameters in the drinking water distribution network.

The calibrated hydraulic model of the selected area water distribution network was acquired from Oman Water & Waste Water Services Company (OWWSC) which was changed recently to Nama. This part of Al Seeb network main source of water is the Barka desalination plant and does not consist of any re-chlorination unit. As OWWSC uses Bentley products, the calibrated hydrualic model was exported to EPANET. The selected area have 3903 junctions, 4860 pipes, and two pumps to convey the water from the main reservoir. The approximate length of the network is more than 25 km with an average flow rate of 444 $L.s^{-1}$ at the starting point.

No changes were done to the hydraulic model and the work was mainly about modeling chlorine dissipation through the network. The applied scenarios were based on the resulted wall and bulk decay rate coefficients obtained from previous analyses in this research. The validity of each scenario was examined by matching the predicted chlorine

concentration by EPANET models to the actual chlorine concentrations in the real distribution network. Water samples were collected from 8 sampling points and were analyzed for free chlorine.

3. Results and Discussion

Chlorine decay can be expressed by the general equation (Equation 2) that relates the change of concentration rate with time to the reactant concentration.

$$\frac{dC_A}{dt} = \pm K C_A^n \qquad \textbf{Equation 2}$$

In which, C_A is the reactant concentration, K is the reaction rate constant, and n is the reaction order (n = 0 signifies zero order, n = 1 signifies first order, and so on). In the zero order reactions, the reaction rate is constant as its independent of the reactant concentration. On the other hand, the rate of reactant concentration change is proportional to its concentration in first order reactions.

3.1. Chlorine Bulk Decay

3.1.1. Temperature effect

3.1.1.1. Constant temperature

Figure 2 shows the dissipation of chlorine in the bulk water at a temperature of 22, 32, and 42°C as first-order reaction. The initial chlorine concentration was ~ 2.5 ppm in this part of the research.

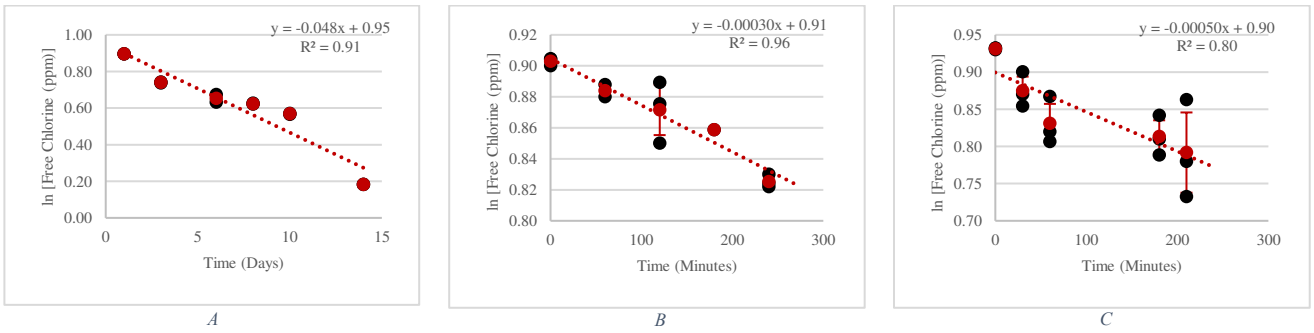

Figure 2. Chlorine dissipation as a first-order reaction at A (22°C), B (32°C), and C (42°C).

By comparing the first-order reaction rate constants of free chlorine decay under 22°C and 42°C, increasing the temperature by 20°C caused an increase in the dissipation rate constant by about 15 folds. This could represent the effect of the temperature fluctuation between seasons on the dissipation of chlorine in water systems. Figure 3 shows the influence of the water temperature on the decay constant of the first-order reaction by employing Arrhenius law $[\ln(k) = \ln(A) - E_A/(RT)]$. From the results' linear fitting, E_A/R was 12676 K and A was 2.8×10^{17}. The Arrhenius equation linear fittings of the results allowed estimations of k for different temperatures. For instance, increasing the temperature from 25°C to 30°C will lead to about two folds increase in the rate constant of disinfectant decay (from about 0.096 day^{-1} at 25°C to about 0.19 day^{-1} at 30°C). This matches Fisher et al. results. As mentioned in the literature

review part of the temperature as a factor affecting chlorine decay, chlorine dissipation may double with the increase of 5°C in temperature (Fisher et al., 2011). Goodarzi et al. (2020) also mentioned that high inflow temperatures led to a chlorine decay increase of up to 75%. For instance, the rise in temperature from 15°C to 20°C resulted in an increase in the chlorine decay rate from 38% to 53%.

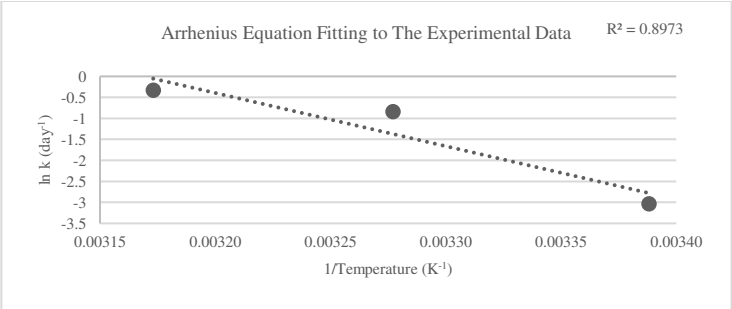

Figure 3. Arrhenius equation fitting to the experiment data as a First-order reaction.

3.1.1.2. Gradual increase in temperature over time

Chlorine decay was also investigated over time under the gradual increase in temperature. Table 1 shows chlorine dissipation rate constants of the first order in the bulk water. Regardless of initial chlorine concentration, representing the decay over time showed that $Ca(OCl)_2$ is marginally more stable than NaOCl. Generally, for the same concentration of $Ca(OCl)_2$ and NaOCl, $Ca(OCl)_2$ has a higher concentration of free chlorine (Leonardo et al., 2016). However, in this research, both forms were added in different concentrations to give the same free chlorine concentrations (0.5 ppm and 1 ppm). This difference can be neglected as the statistical analysis showed no significant difference in the decay of both forms. Liao et al. (2022) also observed a slight increase in decay rate constants from around 0.0019 min^{-1} to 0.0020 min^{-1} when initial chlorine concentrations increased from 0.43 mg/L to 1.03 mg/L.

Table 1. Chlorine decay rate constants in min^{-1} for the first-order of NaOCl and $Ca(OCl)_2$ as sources of free chlorine added to the AES groundwater and distilled water with regards to the gradual increase in temperature.

Initial Chlorine Concentration	Chlorine Form	NaOCl	$Ca(OCl)_2$
0.5 ppm	AES Groundwater	0.0045	0.0036
	Distilled Water	0.0054	0.0039
1 ppm	AES Groundwater	0.0023	0.0025
	Distilled Water	0.0035	0.0020

3.2. Total Chlorine Decay in the Pilot Scale Supply Network System

Chlorine decay data collected from the flowing water in the pilot scale pipe system represents the total chlorine decay that includes both bulk and wall decay. The dissipation was examined with regard to the flow rate, and the free chlorine form applied. Chlorine dissipation was represented as a first-order reaction not only for its simplicity but also because they have been widely used in previous studies.

As mentioned previously, three different flow rates were examined by using two chlorine forms. Representing chlorine decay as first order manifested contrasting decay rate coefficients. Figure 4 represents the free chlorine dissipation as a first-order reaction under 4, 3.2, and 1.5 m^3/h flow rates when sodium hypochlorite and calcium hypochlorite were used as a source of free chlorine. The dissipation equations were as follow (Table 2):

Table 2. Chlorine dissipation equations under 4, 3,2, and 1.5 m^3/h flow rates where t (time) is in minutes.

Flow rate m^3/h	NaOCl	$Ca(OCl)_2$
4	$\ln[Free\ Chlorine] = -0.010t - \ln(0.61)$	$\ln[Free\ Chlorine] = -0.0046t + \ln(0.66)$
3.2	$\ln[Free\ Chlorine] = -0.0075t - \ln(0.70)$	$\ln[Free\ Chlorine] = -0.0049t + \ln(0.61)$
1.5	$\ln[Free\ Chlorine] = -0.0034t - \ln(0.65)$	$\ln[Free\ Chlorine] = -0.0027t + \ln(0.60)$

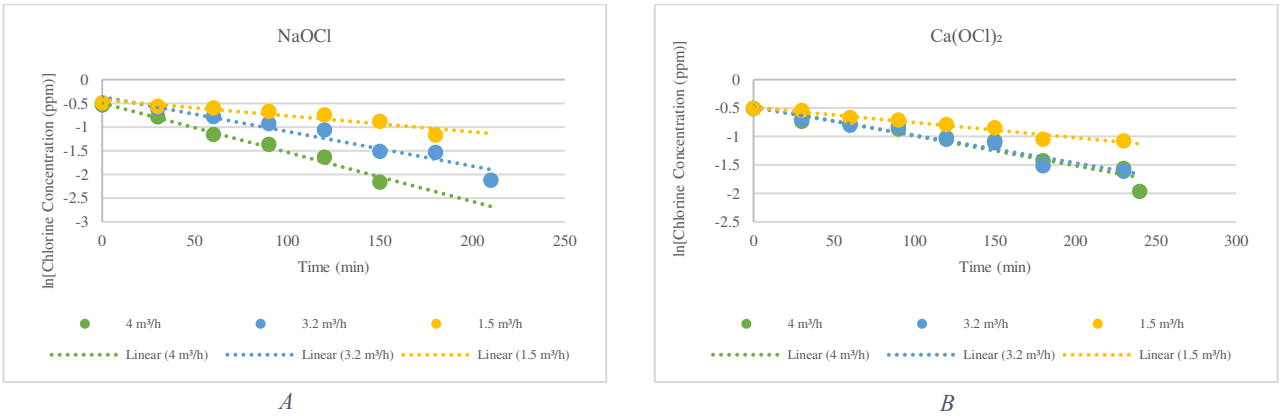

Figure 4. Chlorine dissipation as first-order reaction for 1″pipes diameter, flow rates of 4, 3.2, 1.5 m^3/h, and an initial chlorine concentration of ~ 0.6 ppm for A (NaOCl) and B ($Ca(OCl)_2$).

The water flow rates of 4, 3.2, and 1.5 m^3/h in 1″ pipe size gave flow velocities of 2.2, 1.75, and 0.82 m/s, respectively. These velocities have a Reynolds number of around 70000, 55600, and 26000.

Ramos et al. (2010) evaluated the effect of different flow conditions in chlorine dissipation and fitted their results by using a parallel first-order model. The parallel first order illustrates the dissipation as two separate reactions. A fast reaction and a slow reaction. Ramos et al. (2010) represented the variation of decay constants with the Reynolds number. For the fast decay, the linear equation of decay constants vs Reynolds number was:

$$k_1 = 3 \times 10^{-6} Re + 0.0234 \qquad \textbf{Equation 3}$$

The slow chlorine decay was expressed as:

$$k_2 = 9 \times 10^{-8} Re + 0.0011 \qquad \textbf{Equation 4}$$

As the slow phase represents the reaction of chlorine with less reactive substances, it was selected to compare the decay rate constants of the current research assuming a negligible bulk water chlorine demand.

An obvious similarity between the resulted decay rate constants from applying the slow chlorine decay equation by Ramos and the dissipation rate constants found experimentally for the first order decay rate with regards to Reynolds number were observed (Table 3). The empirical free chlorine dissipation when NaOCl was applied is closer to the estimated values than the dissipation rate constants when $Ca(OCl)_2$ was the tested source. The standard deviation between the experiment results of free chlorine dissipation and the Ramos equation estimated dissipation rate constants were between zero to 0.0021. Low standard deviation indicates a low percentage difference.

Table 3. The estimated chlorine decay rate constants in min^{-1} by Ramos equation and the experimental decay constants of NaOCl and $Ca(OCl)_2$ with regards to Reynolds number.

Re	Estimated dissipation rate constant by Ramos equation	The experimental dissipation rate constant	
	$k_2 = 9 \times 10^{-8} Re + 0.0011$	NaOCl	$Ca(OCl)_2$
70000	0.0074	0.010	0.0046
55600	0.0061	0.0075	0.0049
26000	0.0034	0.0034	0.0027

The influence of flow rate in the dissipation of chlorine may vary depending on other factors contributing to the dissipation. In this research, as the pipes were new with no biofilms, deposits, and no rusting products as the pipes are PVC pipes, one reason behind the increase in the decay could be the effect of friction between the bulk water with the pipe's walls. The turbulence caused by increasing the flow rate could be another reason behind the acceleration in chlorine decay. Moreover, a high Reynolds number can not only accelerate the rate constants of chlorine decay but also contribute to a higher total of disinfection by-products (DBPs) (Liao et al., 2022).

The temperature was the main factor contributing to the dissipation of chlorine in the pipes systems. The gradual increase in temperature over time in the trials was not uniform nor consistent. This was an obstacle while analyzing for the bulk decay under a gradual increase in temperature. Thus, impacted the wall decays obtained by subtracting the bulk decay from the total decay (Table 4).

Table 4. The total, bulk, and wall decay rate constants of free chlorine as NaOCl and $Ca(OCl)_2$ for the AES groundwater.

Flow Rate	**Chlorine Decay Rate Constants (day^{-1})**					
1.5 m^3/h	**NaOCl**			**$Ca(OCl)_2$**		
	Total Decay	Bulk Decay (0.5 ppm, GW)	Wall Decay	Total Decay	Bulk Decay (0.5 ppm, GW)	Wall Decay
	4.9	6.05	-1.2	4.3	5.2	-0.86
3.2 m^3/h	**NaOCl**			**$Ca(OCl)_2$**		
	Total Decay	Bulk Decay (0.5 ppm, GW)	Wall Decay	Total Decay	Bulk Decay (0.5 ppm, GW)	Wall Decay
	10.8	6.05	4.8	7.06	5.2	1.9

4 m³/h	NaOCl			$Ca(OCl)_2$		
	Total Decay	Bulk Decay (0.5 ppm, GW)	Wall Decay	Total Decay	Bulk Decay (0.5 ppm, GW)	Wall Decay
	4.3	2.7	1.6	15.0	6.05	8.9

If the negative wall decay rate constants values obtained for a flow rate of 1.5 m^3/h were neglected and considered zero, then the wall decays ranged from 0 to 8.9 day^{-1} and an average of 2.8 day^{-1} for the first-order decay.

Hallam et al. (2002) studied chlorine wall decay for different pipe materials. For the PVC pipes, they found that the wall decay ranged from about 0.05 hr^{-1} to 0.5 hr^{-1} and an average of 0.09 hr^{-1} when the decay was represented as a first-order reaction. These results are comparable to the current research findings as the first-order wall decay average was 0.12 hr^{-1} which indicates a trivial difference. On the contrary, Arbiv et al. (2023) noted that while decay rates displayed a direct correlation with pipe velocity in unlined cast iron (UCI) and cement-lined ductile iron (CLDI) pipe, PVC pipe showed no notable effect on decay rates across different velocity ranges.

3.3. Chlorine Dissipation Simulation by EPANET

Figure 5 represents a part of Al Seeb drinking water distribution network modeled by EPANET 2.2.

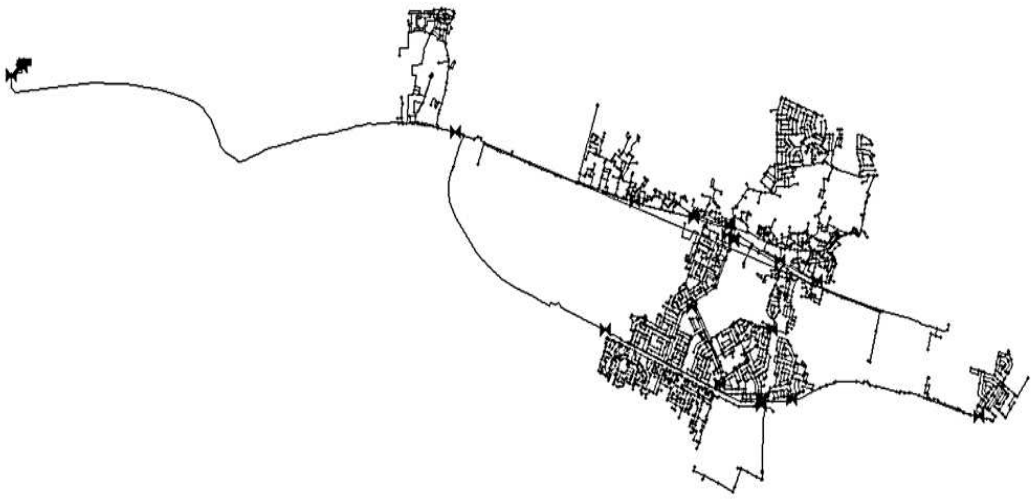

Figure 5. EPANET model of a part of Al Seeb area drinking water distribution network.

The bulk decay rate constant was predicted by using obtained E_A/R and A values from fitting the empirical results in the Arrhenius equation $[\ln(k) = \ln(A) - E_A/(RT)]$. From the results' linear fitting, E_A/R was 12676 K and A was 2.8×10^{17} for the first-order. The E_A/R ratio may vary from 5023 K (Zhong et al., 2021) to 14707 K (Kastl et al., 2003). The Arrhenius equation linear fittings of the results allowed estimations of k for different temperatures. The temperature of the collected samples from the selected drinking water distribution network varied from around 27°C

to 29°C. Thus, 28°C was the temperature selected to predict the bulk decay rate constants. Therefore, the zero-order dissipation rate constant is 0.30 ppm.day^{-1}, and it is 0.15 day^{-1} for the first-order decay rate.

According to EPANET 2.2 manual (Rossman et al., n.d.), the wall decay is represented as m.day^{-1} for the first-order and mg.day^{-1}.m^{-2} for the zero-order. Thus, it is mandatory to represent the wall constants as m.day^{-1} for the first order and mg.day^{-1}.m^{-2} for the zero-order rather than day^{-1}, and ppm.day^{-1}, respectively. The first-order decay constant was calculated by the equation:

$$K = k_b + \frac{2k_w k_f}{R_h(k_w + k_f)}$$

Where K is the total decay constant (day^{-1}), k_b is the bulk decay rate constant (day^{-1}), k_w is the wall decay rate constant (m.day^{-1}), k_f is the mass transfer coefficient (m.day^{-1}), and R_h is the pipe hydraulic radius (m).

The mass transfer coefficient (k_f) was found by using the equation:

$$k_f = \frac{S_h D}{d}$$

In which S_h is the dimensionless Sherwood number, D is the ability of the fluid (water) to transport substances by molecular means (molecular diffusivity, m^2.day^{-1}), and d is the pipe diameter. Sherwood number can be determined by the equation mentioned by Vasconcelos et al. (1997):

$$S_h = 0.023\, Re^{0.83} Sc^{0.33}$$

The Schmidt number (Sc) equals to the kinematic viscosity of water divided by D. D was estimated from the experimental results by Tang et al. (1985) to be 1.94 x10^{-4} m^2/day. Thus, Sc equals to 3.58 x10^2. For the Reynolds numbers of the velocities 2.2, 1.75, and 0.82 m/s, S_h values are 1.68 x10^3, 1.39 x10^3, and 7.4 x10^2, respectively. Therefore, k_f values are 2.95, 2.44, and 1.30 m.day^{-1}, respectively.

By considering the above results, EPANET was run under two scenarios. The validity of each scenario was examined by comparing the free chlorine concentration obtained from these models with chlorine concentrations of the real distribution network obtained from analyzing the water from eight sampling points selected randomly. The scenarios were based on wall decays under 4 m^3/h as there is no significant difference between the wall decay rate constants for 4 m^3/h and 3.2 m^3/h. The maximum Reynolds number in the selected section of the network is around 650,000. Even though this is much less than 70,000 which is the Reynolds number in the pilot scale pipe system when the flow rate was 4 m^3/h, in both cases, the flow is turbulent.

The first scenario assumes that both bulk and wall decay follow the first-order reaction in the network (Fig. 6).

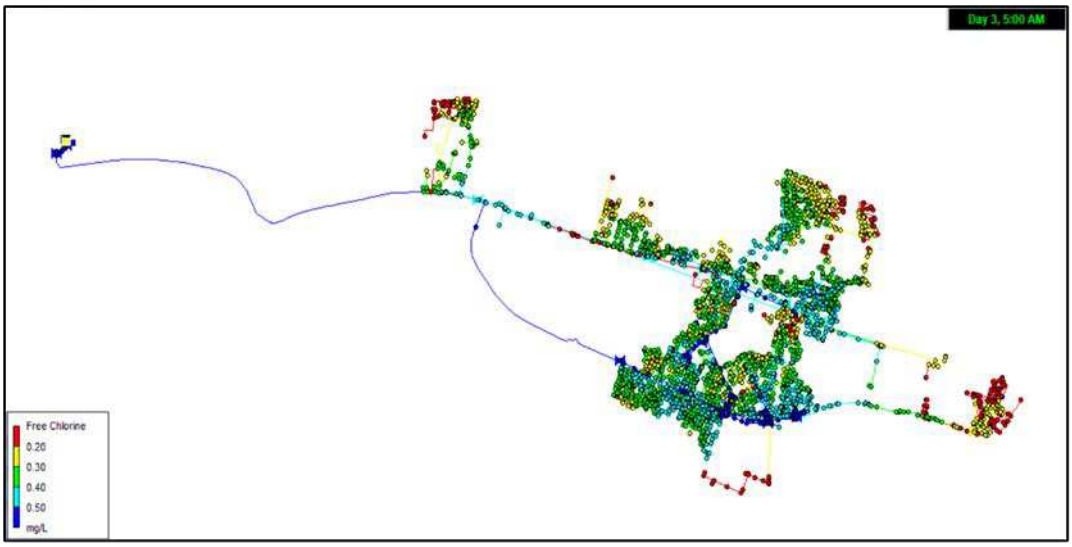

Figure 6. EPANET model for the first scenario assuming both -bulk and wall decay- follow the first-order reaction with values of 0.15 day^{-1} and 0.12 m.day^{-1}, respectively.

256

257 The validity of this scenario with regard to the actual network chlorine concentration was examined by conducting t-
258 tests. From the t-test p-value, there is no significant difference between the actual chlorine concentrations and the
259 predicted values as the p-value was 0.6 (>0.05).

260 The second scenario was based on the results of the previous scenarios' best decay order and trial and error method.
261 It was assumed by Naamani et al., (2021) that the wall decay is zero because the pipes material in Oman's network is
262 mainly ductile Iron (DI) and high-density polyethylene (HDPE) pipes. Therefore, for this scenario, only bulk decay
263 was considered (Fig. 7). Table 5 shows the predicted chlorine concentration when the bulk decay was assumed to
264 follow the first-order reaction with a value of 0.9. The determined p-value of the t-test of this assumption was 0.68
265 (>0.05) indicating no significant difference.

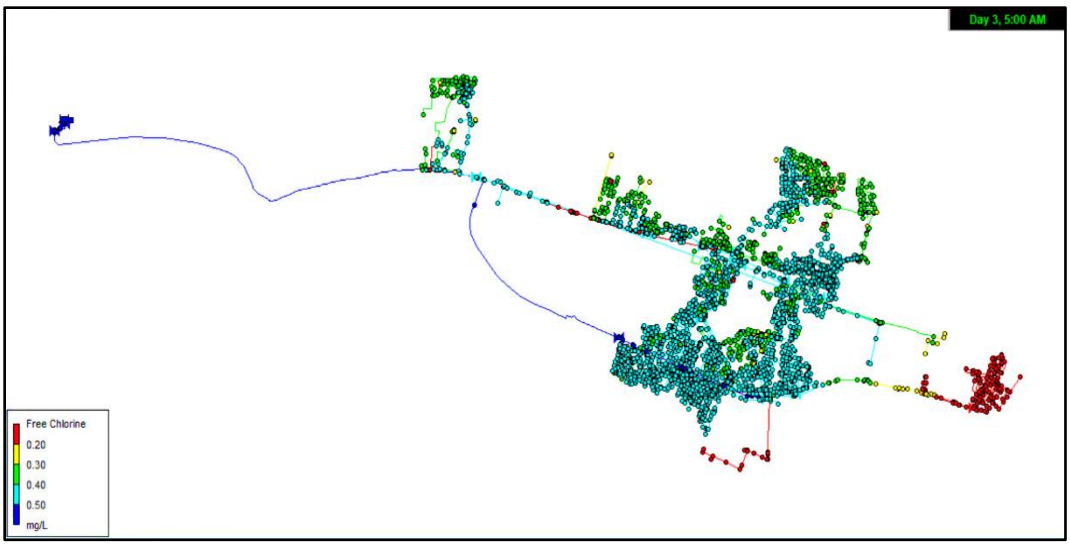

Figure 7. EPANET model for the third scenario assuming the wall decay is zero.

Table 5. The network's actual free chlorine concentration and the predicted free chlorine values from EPANET's second scenario.

Sampling point #	Actual chlorine concentration	Scenario #2 predicted chlorine concentration
1	0.50	0.43
2	0.31	0.34
3	0.32	0.34
4	0.42	0.44
5	0.39	0.44
6	0.43	0.4
7	0.38	0.37
8	0.29	0.37

Even though the second scenario gave a good approximation for the actual chlorine level in the water distribution network, neglecting the wall decay doesn't sound right unless all pipes' sections are new. Leaky pipes, tubercles resulted from wears in the inner pipe side and the unsteady flow conditions caused by pipe opening and closing status and the turbulence created by the flowing water velocity are all factors that might influence the rapid chlorine decay.

In EPANET modeling, the variation in chlorine level caused by changing the bulk decay constant is less significant than the variation when changing the wall decay. For instance, when selecting a node in the network randomly and increasing the bulk decay from 0.3 to 0.6 day^{-1} while keeping the wall decay 0.3 $m.day^{-1}$ reduces the chlorine concentration by around 11% (Figs. 8 & 9). However, increasing the wall decay from 0.3 to 0.6 $m.day^{-1}$ while keeping the bulk decay as 0.3 day^{-1} caused a reduction of about 32.5% in the chlorine concentration (Fig. 10).

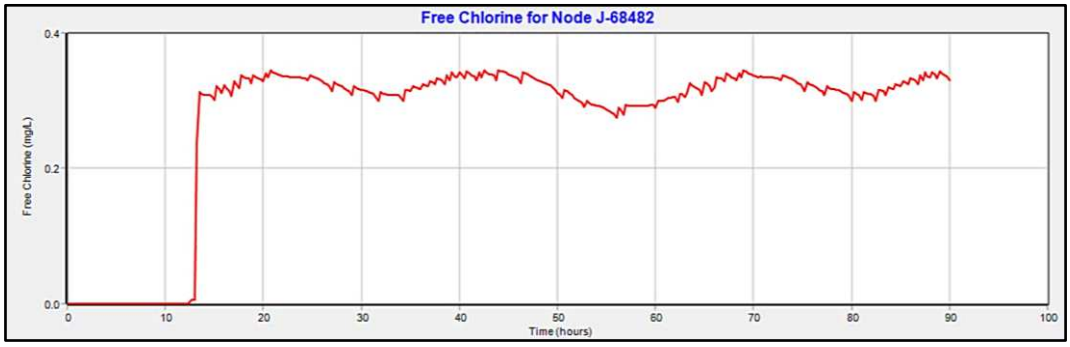

Figure 8. Free chlorine concentration in node J-68482 over time when the bulk decay is 0.3 day^{-1} and the wall decay is 0.3 $m.day^{-1}$.

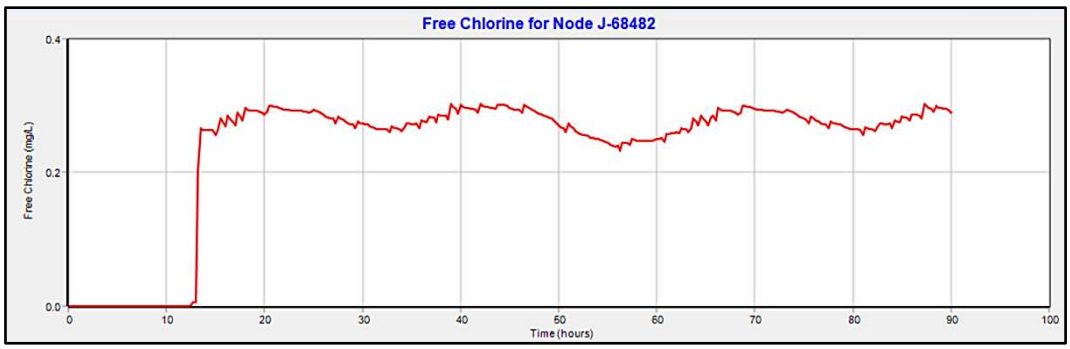

Figure 9. Free chlorine concentration in node J-68482 over time when the bulk decay is 0.6 day^{-1} and the wall decay is 0.3 m.day^{-1}.

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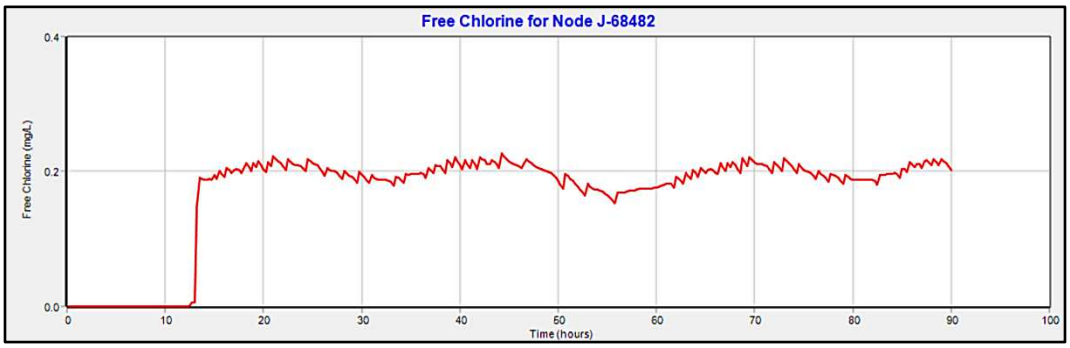

Figure 10. Free chlorine concentration in node J-68482 over time when the bulk decay is 0.3 day^{-1} and the wall decay is 0.6 m.day^{-1}.

287 The minor spikes in chlorine concentrations at a specific node over time can be related to the water flow rate and the
288 water demand. Figure 11 shows the time series of water demand at node J-68482. The variation in the demand affects
289 the flow rate inside the pipe which in result may affect the chlorine concentration.

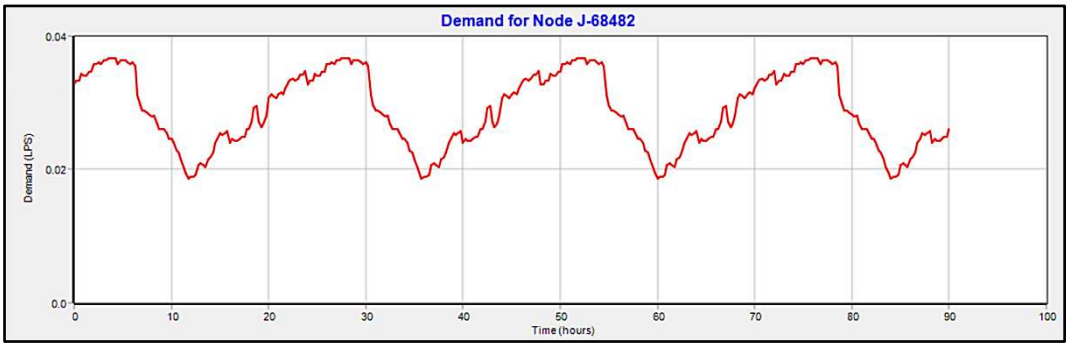

Figure 11. Water demand at node J-68482.

290

291 EPANET model validity in predicting the concentration of free chlorine in the actual network is affected by the
292 chlorine concentration in the main reservoir outlet. For instance, when considering the second scenario and assuming
293 the source chlorine concentration is 0.8 ppm rather than 0.7 ppm reduced the p-value of the t-test to 0.15 when
294 comparing the actual chlorine concentrations with the predicted values. Similarly, assuming the source chlorine
295 concentration is 0.6 ppm reduced the p-value of the t-test to 0.2. Nevertheless, the model is still considered valid as
296 there is no significant difference between the actual and predicted chlorine concentrations. The variation in free
297 chlorine concentration with regard to the initial chlorine in the water source (reservoir) is illustrated in Figures 12, 13,
298 and 14. Chlorine will reach a concentration of less than 0.2 ppm in a shorter distance if chlorine concentration at the
299 outlet of the main reservoir that supplies the network is 0.6 ppm (Fig. 12) than when it is 0.7 ppm or 0.8 ppm (Figs.
300 13 & 14).

301

Figure 12. Contour plot of chlorine concentration when the sources' free chlorine concentration was assumed to be 0.6 ppm.

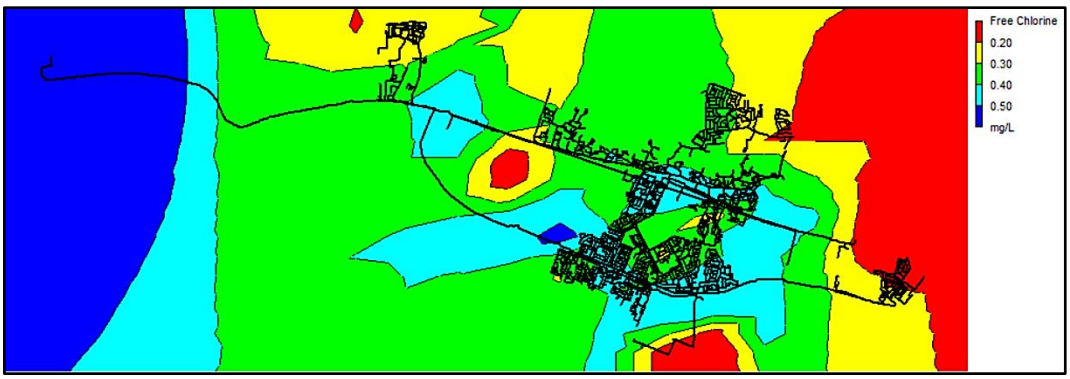

Figure 13. Contour plot of chlorine concentration when the source free chlorine concentration was assumed to be 0.7 ppm.

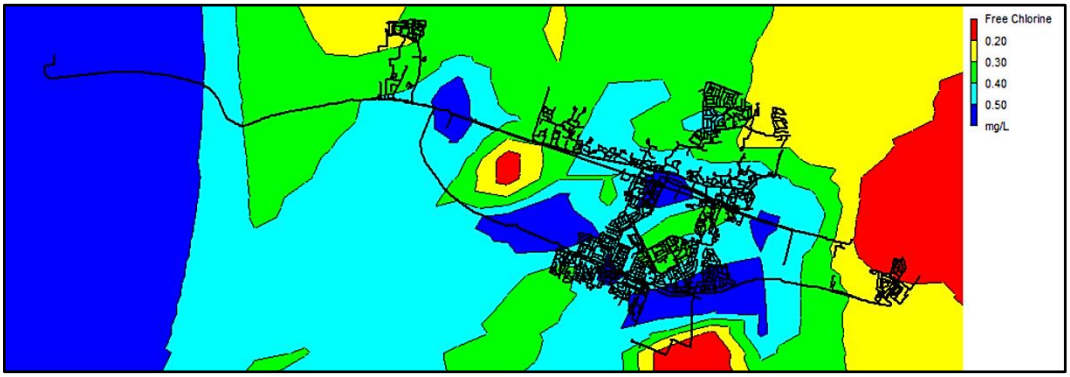

Figure 14. Contour plot of chlorine concentration when the source free chlorine concentration was assumed to be 0.8 ppm.

In all scenarios, chlorine unmistakably dissipates through the distribution network from the reservoir on the left to the end of the selected section on the right. However, there are small areas at the very beginning of the network where chlorine reaches a concentration of less than 0.2 ppm. This is attributed to the high friction factor of the pipes in that particular section.

3.4. Water Quality in Storage Tanks and Household Survey

From the circulated survey that was filled out by 86 householders from all governorates in Oman, 91.9% of householders rely on the water supplied by local companies (Nama and other private companies), and the remaining abstract their water demand from private groundwater wells. This may indicate that most houses in Oman get chlorinated drinking water which means microorganism-free water. Out of 86 responses, 40 householders admitted that the water has a chlorine odor. Chlorine in water odor threshold is 0.31 ppm (U.S. Department of Health and Human Services Public Health Service Agency for Toxic Substances and Disease Registry, 2002). This indicates that water smelling slightly like chlorine is normal especially since the Omani drinking water standard for chlorine is between 0.2 – 0.5 ppm. 15% of those who smelled chlorine in their water claimed that the chlorine smell is strong. This could be because of the nearness of their houses to the distribution network main reservoir outlets that supply

water with chlorine concentration between 0.6 - 0.9 ppm to ensure sufficient residual chlorine at the point of consumption in far places of the network.

Even though most householders admitted that it is necessary to clean domestic water storage tanks (81.4% of the respondents) , around 41.4% of them do not clean their tanks. Moreover, only 10.5% of those who clean their tanks follow the announced preferable tank cleaning frequency by OWWSC (Every 6 months).

Tank cleaning frequency may vary from one household to another due to their observations that determine if cleaning the tank is required. 60.5% of those who clean their tanks avered that the purpose of cleaning is removing the accumulated sediments like the ones caused by hard water (calcium and magnesium carbonates). Additionally, 24.4% of them clean their tanks to avoid algae, and 2.4% to eliminate bacteria growth. This could be either because they are convinced of the absence of microorganisms in their water, or because these microorganisms can not be detected by the naked eye in most cases. According to the circulated survey results, most householders believe that water source quality, stagnation periods, not cleaning the tank regularly, and poor supply network are the main causes of impurities.

Although only 44.2% of the people who responded to the survey use the stored water for drinking and direct oral consumption, 95.3% use the water to wash vegetables and fruits. This raises the cruciality of maintaining sufficient residual chlorine in the drinking water to reduce the potential of microbes growth in the water and their transmission to faucet water consumers' plates considering that only 9.3% will boil the water before consuming it according to the survey responses.

Checking residual chlorine levels in household tanks complement the work of ensuring microorganism-free water comes out of the faucets. Most household tanks have a continuous water flow depending on their demand and the maximum tank refilling period in the sampled tanks was 6 days. Only 3 householders who have ever cleaned their water storage tanks and only 1 of them cleans the tank frequently every 6 months. This indicates that cleaning water storage tanks is not a common practice in most houses in Oman. Free chlorine analysis showed that 73.5% of water samples from storage tanks had chlorine concentrations below Omani's drinking water standards (Fig. 15). This investigation is not considered a concerning situation because coliform test results showed zero presence of coliform in all analyzed samples. Even though coliform bacteria are considered harmless bacteria, their existence in the water may indicate the presence of other disease-causing microorganisms. Thus, water is considered microbes-free if coliform was not detected.

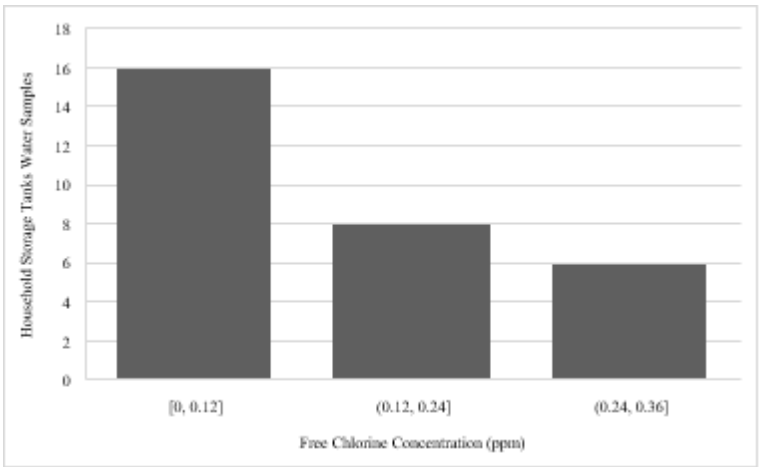

Figure 15. Free chlorine concentration in the sampled water from storage tanks.

4. Conclusion

To summarize what was examined in this research, maintaining adequate free chlorine levels in drinking water systems is of vital importance to ensure high-quality water and compliance with water quality standards. Therefore, understanding the factors that lead to disinfectant loss within these systems is required.

The temperature was the most important factor affecting the dissipation of chlorine among the tested factors. Increasing the temperature by 5℃ could increase the dissipation by about 2 folds. Regarding the pilot scale water supply system, chlorine dissipation was linearly related to flow rate. Although using the obtained bulk and wall decay from the pilot scale systems in the EPANET simulation model gave no significant difference to the actual chlorine concentration in the distribution network, it may differ in larger-scale systems. Changing certain inputs in the model may affect the validity of the decay constants applied.

The outcomes of this research will aid companies that supply drinking water in Oman in optimizing chlorine concentrations through the distribution network by shedding light on the points of low chlorine within the network through simulations. Moreover, this research will provide a better comprehension of the locations to boost residual chlorine in the distribution network and whether to center the attention on the drinking water supply network or storage tanks.

References

Abokifa, A. A., & Biswas, P. (2018). Optimal Placement and Operation of Booster Chlorination Stations Using an Advection-Dispersion Transport Model for Chlorine Decay in the Dead-End Pipes. *World Environmental and Water Resources Congress 2018: Hydraulics and Waterways, Water Distribution Systems Analysis, and Smart Water - Selected Papers from the World Environmental and Water Resources Congress 2018*, 380–389. https://doi.org/10.1061/9780784481424.040

Alsaydalani, M. O. A. (2019). Simulation of Pressure Head and Chlorine Decay in a Water Distribution Network: A Case Study. *The Open Civil Engineering Journal*, *13*(1), 58–68. https://doi.org/10.2174/1874149501913010058

Arbiv, I., Almuhtaram, H., & Andrews, R. C. (2023). Science of the Total Environment Comparison of pipe loop and pipe section reactor methods for estimating chloramine decay in harvested distribution system pipes. *Science of the Total Environment*, *884*(April), 163722. https://doi.org/10.1016/j.scitotenv.2023.163722

Fisher, I., Kastl, G., Sathasivan, A., & Jegatheesan, V. (2011). Suitability of chlorine bulk decay models for planning and management of water distribution systems. *Critical Reviews in Environmental Science and Technology*, *41*(20), 1843–1882. https://doi.org/10.1080/10643389.2010.495639

García-Ávila, F., Avilés-Añazco, A., Ordoñez-Jara, J., Guanuchi-Quezada, C., Flores del Pino, L., & Ramos-Fernández, L. (2021). Modeling of residual chlorine in a drinking water network in times of pandemic of the SARS-CoV-2 (COVID-19). *Sustainable Environment Research*, *31*(1). https://doi.org/10.1186/s42834-021-00084-w

Goodarzi, D., Abolfathi, S., & Borzooei, S. (2020). Journal of Water Process Engineering Modelling solute transport in water disinfection systems : Effects of temperature gradient on the hydraulic and disinfection efficiency of serpentine chlorine contact tanks. *Journal of Water Process Engineering*, *37*(May), 101411. https://doi.org/10.1016/j.jwpe.2020.101411

Hallam, N. B., West, J. R., Forster, C. F., Powell, J. C., & Spencer, I. (2002). The decay of chlorine associated with the pipe wall in water distribution systems. *Water Research*, *36*(14), 3479–3488. https://doi.org/10.1016/S0043-1354(02)00056-8

Kowalska, B., Hołota, E., & Kowalski, D. (2018). Simulation of chlorine concentration changes in a real water supply network using epanet 2.0 and watergems software packages. *WIT Transactions on the Built Environment*, *184*, 39–48. https://doi.org/10.2495/FRIAR180041

Leonardo, N. G. E. S., Carlotto, I. B., Luisi, S. B., Kopper, P. M. P., Grecca, F. S., & Montagner, F. (2016). Calcium hypochlorite solutions: Evaluation of surface tension and effect of different storage conditions and time periods over pH and available chlorine content. *Journal of Endodontics*, *42*(4), 641–645. https://doi.org/10.1016/j.joen.2016.01.006

Liao, P., Zhang, T., Fang, L., Jiang, R., & Wu, G. (2022). Chlorine decay and disinfection by-products transformation under booster chlorination conditions: A pilot-scale study. *Science of the Total Environment*, *851*(June), 158115. https://doi.org/10.1016/j.scitotenv.2022.158115

Naamani, A. Al, & Sana, A. (2021). Operational and technical performance of a water distribution network in

Oman. *Water Supply*, *21*(8), 4593–4607. https://doi.org/10.2166/ws.2021.203

Ramos, H. M., Loureiro, D., Lopes, A., Fernandes, C., Covas, D., Reis, L. F., & Cunha, M. C. (2010). Evaluation of chlorine decay in drinking water systems for different flow conditions: From theory to practice. *Water Resources Management*, *24*(4), 815–834. https://doi.org/10.1007/s11269-009-9472-8

Rossman, L. A., Tryby, M., & Janke, R. (n.d.). *EPANET 2 . 2 User Manual*.

Tang, A., & Sandall, O. C. (1985). Diffusion Coefficient of Chlorine in Water at 25–60 °C. *Journal of Chemical and Engineering Data*, *30*(2), 189–191. https://doi.org/10.1021/je00040a017

Vasconcelos, J. J., Rossman, L. A., Grayman, W. M., Boulos, P. F., & Clark, R. M. (1997). Kinetics of chlorine decay. *Journal / American Water Works Association*, *89*(7), 54–65. https://doi.org/10.1002/j.1551-8833.1997.tb08259.x

Vîrlan, C. M., Toma, D., Stătescu, F., Marcoie, N., & Prăjanu, C. C. (2021). Modeling the chlorine-conveying process within a drinking water distribution network. *Environmental Engineering and Management Journal*, *20*(4), 487–494. https://doi.org/10.30638/eemj.2021.048

Authors Contributions:

Arwa Al Sukaiti conducted the experimental work, carried out analyses, interpreted the results, and prepared the initial draft of the paper. Mushtaque Ahmed played a supervisory role as the thesis supervisor, providing guidance and oversight throughout the research process.

Funding: None.

Declarations

Ethical Approval: Not required.

Consent to Participate: All authors have confirmed their participation.

Consent to Publish: All authors agreed to publication.

Competing Interests: None.

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