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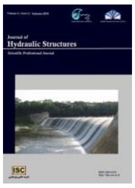

Full scale optimization of chlorine injection pattern in Khansar water distribution network using WaterGEMS

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Abstract

Chlorine is the most widely used disinfectant in the water treatment process for eliminating pathogenic microorganisms that may be present in the distribution network. Maintaining minimum residual chlorine in water distribution networks is challenged by its decay over time and distance travelled. Chlorine dosage must be optimized by adjusting its injection rates and placement. This study utilized WaterGEMS software to model the water network of Khansar city and analyze its current chlorine levels. It was found that some end-of-line pipes had chlorine concentrations that fell below the standard limits. Through optimization of chlorine dosing at the reservoirs while simultaneously reducing chlorine consumption, approximately 65% of the pipes with non-compliant chlorine levels were brought into compliance. Additionally, 66% of the water volume that previously had insufficient chlorine now meets the standard and is delivered to consumers. It should be noted that these results were obtained at the same time as the amount of chlorine consumed daily decreased from 1130.4 to 656.7.

Keywords: Residual chlorine; Disinfection; Bulk decay; Wall decay; WaterGEMS.

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1. Introduction

Water quality in distribution networks must meet both potability and aesthetic standards. Potability implies that the levels of chemical, physical, and microbiological contaminants do not exceed permissible limits, and aesthetic factors, including parameters such as color, odor, taste, and turbidity. Declining water quality in distribution networks poses a serious risk to public health; thus, effective management of these networks is essential for maintaining water quality. Moreover, as a hygienic product, treated water helps prevent many harmful microorganisms' proliferation [1].

Disinfection is considered the minimum treatment for drinking water sources. Among the available disinfectants, chlorine and its derivatives are widely used due to their low cost, ease of

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application, and ability to inactivate microorganisms in drinking water distribution networks. As chlorinated water travels through pipes, it reacts with substances in the water and pipe walls, causing a decrease in chlorine levels in the network [2]. Maintaining residual chlorine within the limits specified by standards in water supply networks ensures the quality and safety of drinking water. However, it is important to note that residual chlorine concentrations are not uniform throughout the network and exhibit fluctuations. In some parts of the network, chlorine levels may exceed permissible limits, leading to off-flavors and odors, and formation of toxic disinfection byproducts. Conversely, residual chlorine levels may fall below permissible limits in other parts of the network, increasing the risk of waterborne disease outbreaks. This phenomenon of chlorine reduction in water distribution networks is called chlorine decay [3].

The amount of chlorine added can be adjusted by controlling the chlorine concentration in reservoir before the water enters the network or in the booster stations through the network. If these locations are not specified correctly, it can result in excessive residual chlorine concentrations in pipes near the injection locations and insufficient residual chlorine concentrations in pipes further away at certain times. Therefore, to effectively manage water quality in distribution networks, it is essential to determine the optimal amount and location of chlorine injection to ensure that concentrations remain within the specified range throughout the network [4]. Optimizing the chlorine injection in water distribution networks has been studied in several research focusing on the locations and/or the scheduling of chlorine dosing stations [5-13]. Various studies examined simulation models such as EPANET for residual chlorine prediction in a network [13-17]. However, WaterGEMS software has only been used in a limited number of studies to determine residual chlorine in water distribution networks [9,18,19].

The aim of this study is to determine the chlorine injection for the water distribution network of Khansar city. This distribution network has 7 independent pressure zones, each fed by one or two reservoirs. To optimize chlorine injection, WaterGEMS software was used for hydraulic and water quality simulation. According to the separation of the distribution network of the whole city into independent zones, the pattern of chlorine injection in the reservoirs was considered. The optimization of the chlorine dose rate was achieved by changing the injection dose rate in the reservoirs so that the chlorine concentration maintains the permissible limits at demand junctions and pipes.

2. Residual Chlorine Concentration

The reduction in residual chlorine concentration within water distribution networks is attributed to two primary mechanisms: bulk decay and wall decay.

In bulk decay, chlorine reacts with mineral and organic molecules present in the water, leading to a decrease in its concentration. This reduction in chlorine concentration within the water network is termed bulk chlorine decay. Over the past few decades, researchers have conducted extensive investigations into bulk chlorine decay. The general reaction form and the differential equation employed in these studies are presented in Equations (1) and (2), respectively [20,21].

$$Cl + A \rightarrow Product \tag{1}$$

$$\frac{dC}{dt} = -k'C^n R^m \tag{2}$$

where k represents the bulk kinetic coefficient, C is the chlorine concentration (mg/L), R is the concentration of chlorine demand substances (mg/L), and m and n are the reaction orders for the chlorine demand substance and chlorine, respectively. Since the concentration of chlorine demand substances is significantly higher than the concentration of the chlorine, the concentration of chlorine demand substances is assumed to be constant over time. Consequently, the developed Equation (3) is proposed [21].

$$\frac{dC}{dt} = k_b C^n \tag{3}$$

In wall decay, the reaction between chlorine and the inner surface of pipes in distribution and transmission networks leads to a decrease in chlorine concentration. This type of chlorine concentration reduction is termed wall decay. According to Equation (4), there is a direct correlation between the rate of wall decay, the surface-to-volume ratio of the pipe, the mass transfer coefficient, and the chlorine concentration [22]. Many researchers, including Hallum et al., Rossum et al., and Jisberg, emphasize the primary nature of wall decay reactions, and the differential equation for this process is represented as follow [23,24,25].

$$\frac{dC}{dt} = \frac{A}{V} k_w C^n \tag{4}$$

The physical, chemical, and microbiological parameters of water within distribution networks must adhere to the permissible limits outlined in the drinking water quality standard [26]. Consequently, in accordance with the provisions of the 43rd publication of the Technical Regulations and Criteria for the Water Industry in Iran, sequential and regular sampling of the network should be conducted to measure residual chlorine at various points [27].

According to the Iranian drinking water standard, to prevent and control secondary contamination within the water network, a minimum residual chlorine concentration of 0.6 mg/L is required, and based on the US Environmental Protection Agency (USEPA) guidelines, the maximum residual chlorine concentration should not exceed 4 mg/L at any point in the distribution network [28].

This chlorination method significantly increases the likelihood of insufficient standard chlorine concentrations at certain points within the network, especially at the end points. Studies and research have shown that consumers at the end of the network do not receive adequate quality drinking water. Therefore, they are at a higher risk of waterborne contamination. Conversely, excessive chlorine levels in water can also pose problems [29]. The permissible limits for free residual chlorine in drinking water for various water supply systems and sampling locations are presented in Table 1.

Table 1. Permissible limits for free residual chlorine.

Water supply system and harvesting site	Amount of residual free chlorine (mg/L)
Public Water Tap	0.5-1.0
Water Delivery Point	0.2-0.8
Mobile drinking water tankers at the water intake site	1.0-2.0
Mobile drinking water tankers at the delivery point	0.8-1.0

3. Methodology

3.1. Case Study

Khansar city, with an area of 953 km^2, and an altitude of 2215 m above sea level, located in the west of Isfahan province, Iran, was selected as the case study for this research. Figure 1 presents a schematic image of the location of Khansar city. WaterGEMS Connect Edition Update 10 software was employed for hydraulic and water quality simulations of the network. Necessary data, such as water distribution network map of Khansar city, network specification, and water demand and consumption pattern, were obtained from the Isfahan Water and Wastewater Company.

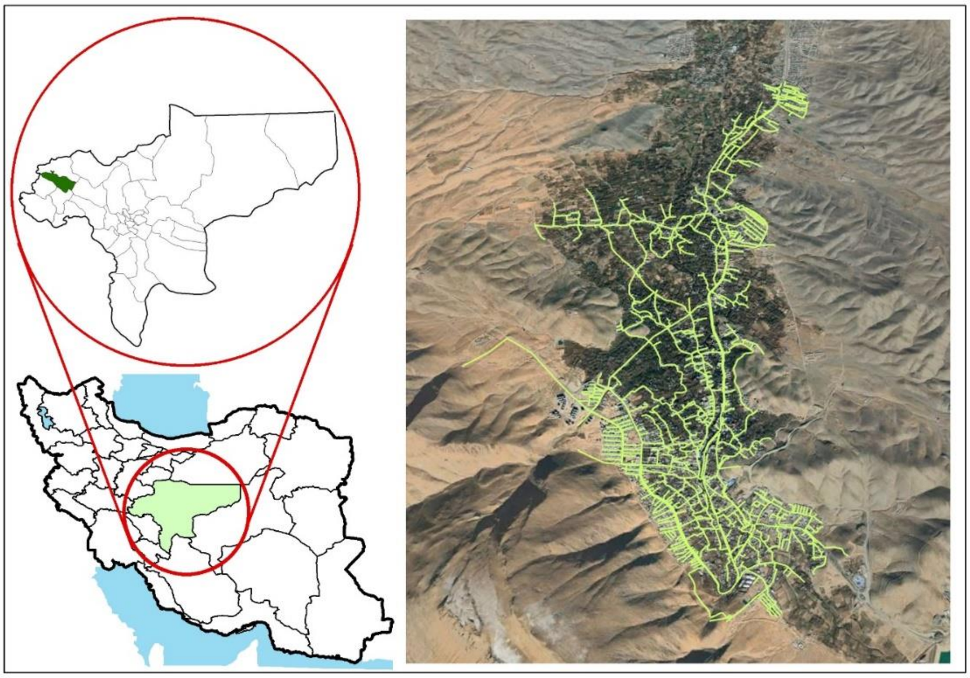


Figure 1. Schematic image of the location of Khansar city.

3.2. Hydraulic Characteristics and Zones

The water distribution network of Khansar city is about 130 km long. The city's water supply is mostly sourced from wells and, a few times a year, through the Baghkal Dam. The transmission line from Baghlak dam to the water treatment plant is 7.6 km long and has 400 and 500 mm diameters. The diameter of the pipes used in the distribution network is 32 to 400 mm, and they are made of asbestos cement, polyethylene, ductile iron, and steel.

The water distribution network consists of 7 completely independent pressure zones. Each zone is fed by one or two reservoir. Figure 2 shows the water distribution network of Khansar city and its pressure zones. Table 2 gives the length and type of pipes used in each zone.

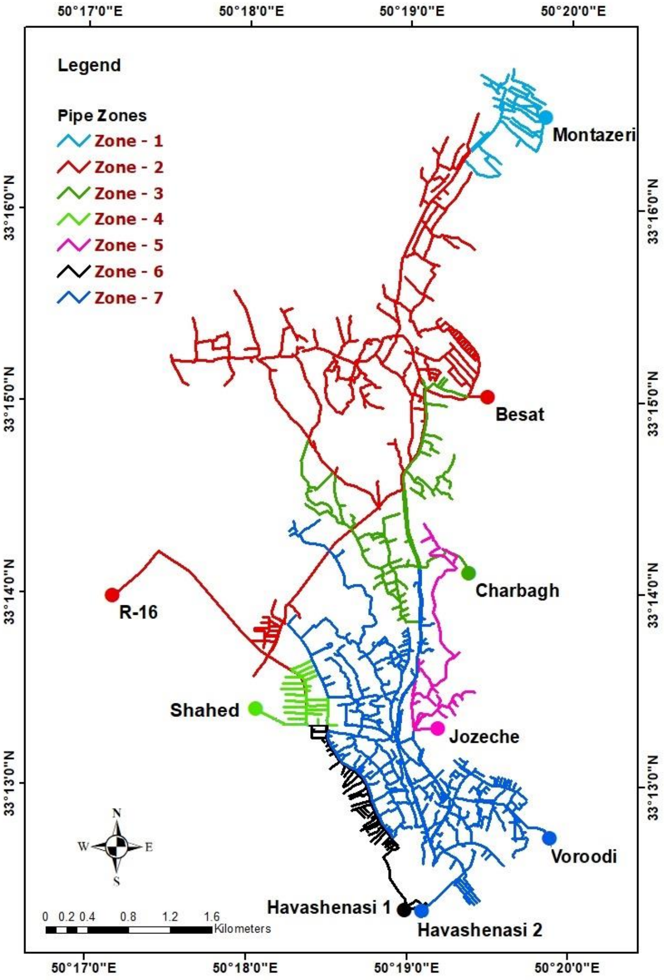


Figure 2. Zoning of Khansar water distribution network.

Table 2. Specifications of water distribution network pipes of Khansar city.

Zone name	Material				Total
	Asbestos cement	Ductile Iron	Polyethylene	Steel	
Zone1	2506	475	4721	0	7702
Zone2	26260	3321	11978	10	41626
Zone3	9613	37	3908	0	13558
Zone4	3740	82	940	0	4762
Zone5	4782	233	843	0	5858
Zone6	6328	0	892	0	7245
Zone7	22173	13432	9177	827	45846
Total	78529	18101	32633	837	130419

As shown in Figure 3, the consumption pattern exhibits significant diurnal variations. The minimum hourly coefficient is 0.792 at 4:30 AM, and the maximum is 1.51 at 12:30 PM.

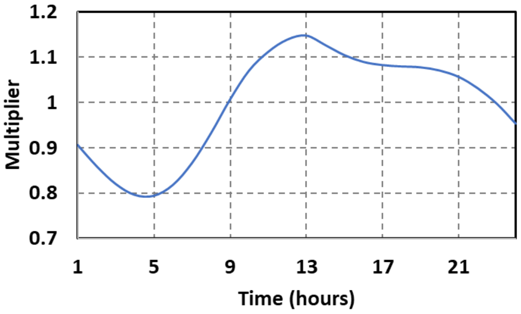


Figure 3. Hourly water consumption pattern.

3.3. Water Quality Analysis

To simulate chlorine decay in the network, diffusion coefficient, bulk decay and wall decay coefficients are needed. The diffusion coefficient of chlorine in water for a temperature of 20 °C equals 1.208e-9 m^2/s [30]. The bulk chlorine coefficient can vary depending on water temperature, and therefore, a value of 0.3 $(mg/L)^{(1-n)/d}$, which represents an average from various studies, was used [31]. The wall decay coefficient varies based on the pipe material. Given that most of the pipes in the network are made of asbestos and considering the significant impact of pipe age on wall decay, the maximum and conservative value of this coefficient was extracted from relevant tables and applied. According to most researchers, this coefficient is considered first-order [21, 24]. In this study, a network runtime of 96 hours (4 days) was considered to achieve a steady-state chlorine concentration. In other words, the residual chlorine concentration in the entire distribution network was monitored every 24 hours. Considering that the chlorine concentration on the fourth day was not significantly different from the third day, 96 hours duration was chosen as the appropriate time for simulation.

3.4. Chlorine Dosing Optimization

Optimization of chlorine dosing was conducted individually for each zone to minimize daily chlorine consumption while maintaining residual chlorine levels within permissible limits. The chlorine dose injected into the reservoirs was varied from 0.2 to 3 mg/L in increments of 0.1. Then, for each zone, the graphs of the water volumes versus the injected chlorine concentration were drawn, and the optimal amount of injected chlorine was determined according to the constant values of the water volume. Optimization of chlorine concentration for zones connected to two water tanks was carried out similarly to other zones, with the difference that for zones with two tanks, the chlorine injection concentration was performed separately for each tank. Therefore, more runs were required for these zones. The maximum and minimum chlorine concentrations in each zone were monitored to ensure compliance with both the upper and lower limits of the permissible chlorine range. The corresponding chlorine consumption was calculated based on the 24-hour diurnal demand pattern and optimum chlorine concentration and compared with the conditions before optimization.

4. Results and Discussion

4.1. Chlorine Distribution Simulation in the Existing Condition

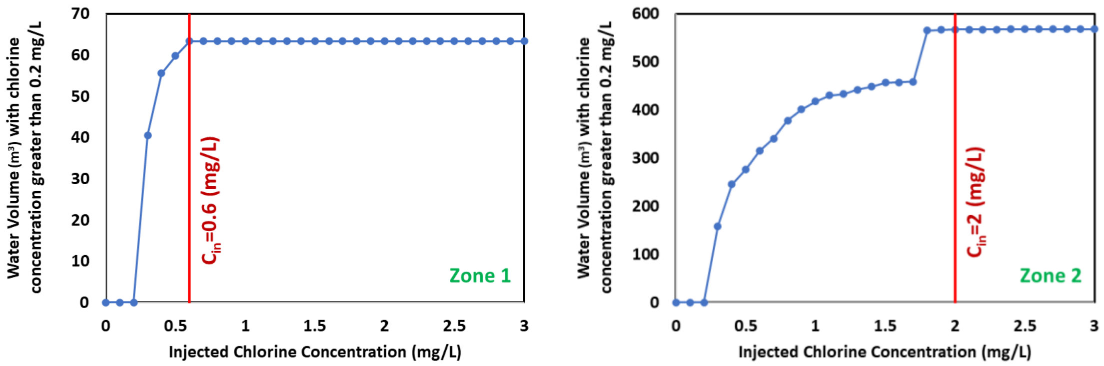
Based on the data obtained from the Isfahan Water and Wastewater Company, the current chlorine dose in all reservoirs is 2 mg/L at all times. The network was analyzed under existing conditions, and the daily chlorine consumption was calculated based on the average flow rate of each reservoir, as shown in Table 3. It is worth noting that due to the fluctuations in consumption over 24 hours, the maximum chlorine consumption was 1202.4 g/h, and the minimum consumption was 842.4 grams per hour.

Table 3. Calculation of mass flow rate of injected chlorine before optimization.

Zone	Reservoir name	Injected chlorine concentration (mg/L)	Flowrate (L/s)	Injected chlorine (g/h)
Zone1	Montazeri	2	28	201.6
Zone2	R16	2	9	64.8
	Besat	2	19	136.8
Zone 3	Charbagh	2	12	86.4
Zone 4	Shahed	2	40	288
Zone 5	Jozeche	2	6	43.2
Zone 6	Havashenasi 1	2	8	57.6
Zone 7	Havashenasi 2	2	8	57.6
	Voroodi	2	27	194.4
		Total		1130.4

4.2. Finding the Optimal Amount of Injected Chlorine

According to Iran's drinking water standard 1053, the chlorine concentration in each designated zone must not fall below 0.2 mg/L. So, as mentioned earlier, water volume with chlorine concentration greater than 0.2 mg/L was plotted versus injected chlorine concentration in the reservoir for various zones to achieve the optimal amount of injected chlorine. In order to obtain the data for these graphs, 29 runs were performed for each zone, and the minimum and maximum chlorine concentration values were recorded. As shown in Figure 4, the volume of water containing chlorine with a concentration of more than 0.2 mg/L increases with the increase of injected chlorine until it reaches a constant value. This means that injecting more chlorine increases the residual chlorine in the water distribution network, while the concentration of 0.2 mg/L is sufficient. The optimal amount of chlorine for each zone is shown in the graphs in Figure 4.



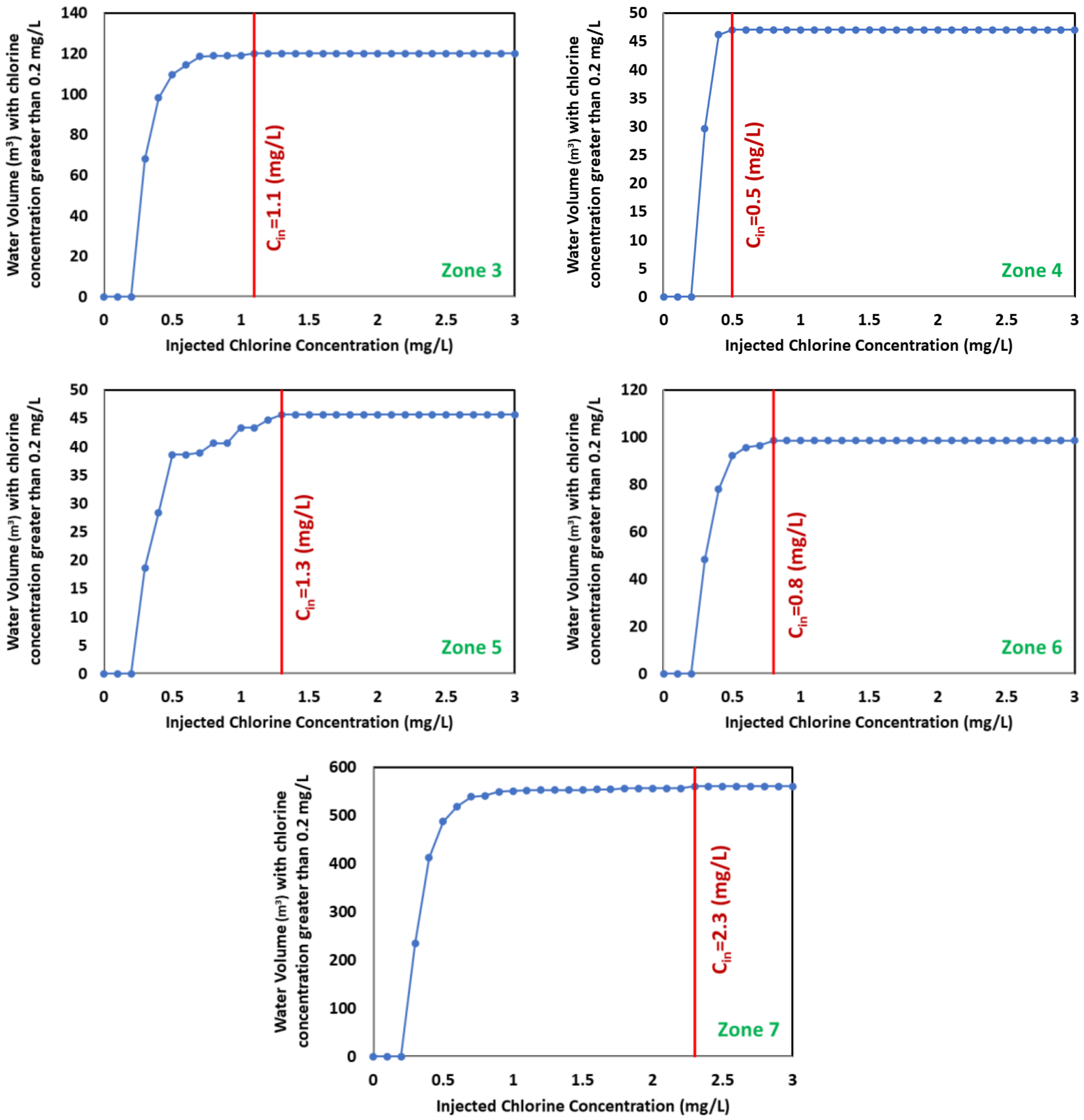


Figure 4. Water volume with chlorine concentration greater than 0.2 mg/L vs injected chlorine concentration in reservoir for various zones.

After finding the optimal amounts of injected chlorine, the remaining chlorine map in the entire water distribution network was prepared before and after optimization, as shown in Figure 5. The amount of chlorine needed per hour was also calculated using the coefficients of the consumption pattern. The optimal amount of chlorine and the results are given in Table 4.

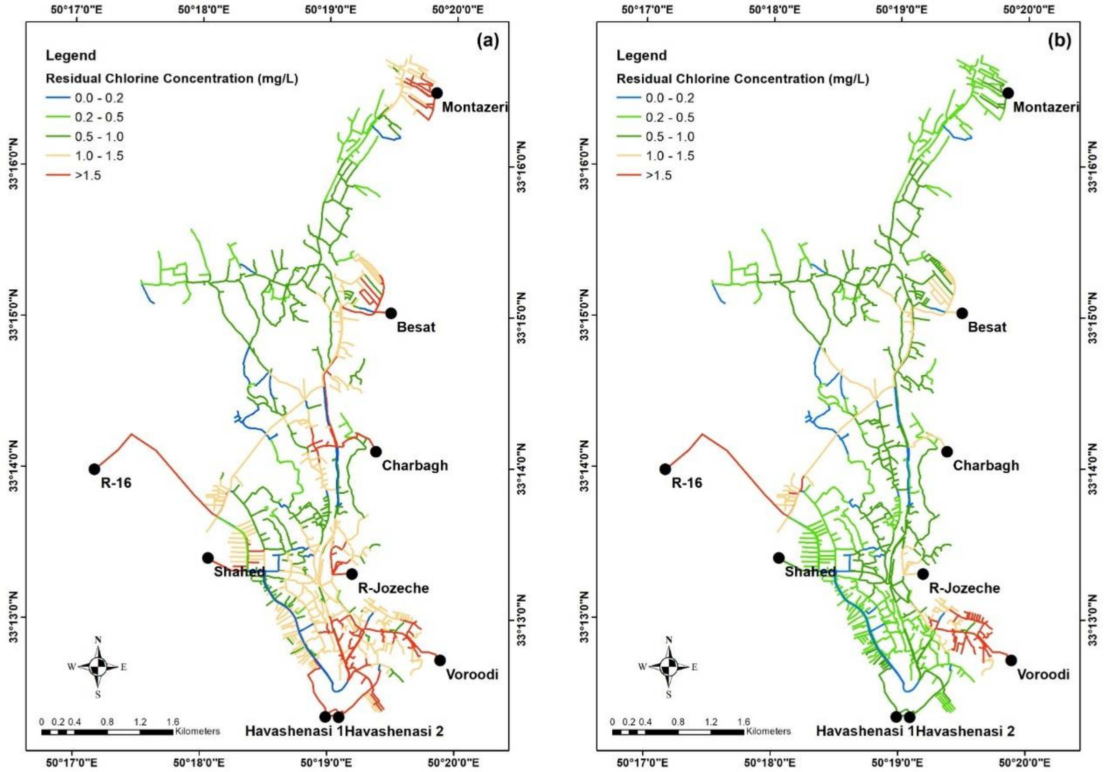


Figure 5. The amount of residual chlorine in the existing condition (a) after 2 hours (b) after 24 hours.

Table 4. Calculation of mass flow rate for injected chlorine after optimization.

Zone	Reservoir name	Injected chlorine concentration (mg/L)	Flowrate (L/s)	Injected chlorine(g/h)
Zone1	Montazeri	0.6	28	60.5
Zone2	R16	2.1	9	68
	Besat	1.5	19	102.6
Zone 3	Charbagh	1.1	12	47.5
Zone 4	Shahed	0.6	40	86.4
Zone 5	Jozeche	1.3	6	28
Zone 6	Havashenasi 1	0.8	8	23
Zone 7	Havashenasi 2	0.6	8	17.3
	Voroodi	2.3	27	223.5
		Total		656.7

Analysis of the existing and optimized conditions revealed that, of the 1127 pipes in the water supply network, 34 pipes had residual chlorine concentrations below the standard (0.2 mg/L) in the existing condition. However, following optimization and adjustments to the chlorine dosing in the reservoirs, this number decreased to 12. It should be noted that because the water in these pipes is stagnant, increasing the amount of injected chlorine cannot increase the residual chlorine in the pipes. In the existing condition, 51.9% of the pipes had residual chlorine below 1 mg/L, while in the optimized condition, this percentage decreased to 61.8%. Although the amount of chlorine was reduced by 42%, the volume of water that did not meet the standard in the existing condition was

34.37 m³, which decreased to 11.8 m³ after optimization. In other words, 99.2% of the network has a concentration more than 0.2 mg/L after optimization. Therefore, by adjusting the chlorine dosing, 66% of the water volume with insufficient chlorine was brought up to standard.

5. Conclusion

This study optimized the chlorine dosing in various reservoirs of the Khansar city network through trial and error. WaterGEMS software was used for the simulation of the hydraulic and water quality of the distribution network. In the first step, the existing conditions of residual chlorine in the distribution network were investigated. According to the results, 34 pipes out of 1127 pipes in the distribution network had residual chlorine concentrations less than 0.2 mg/L. In the next step, in order to optimize the chlorine dose, the distribution network was analyzed under the various concentrations of injected chlorine in each reservoir and the optimal dosing rate was determined for each reservoir. The results indicate that chlorinating the network with the newly obtained concentrations significantly improved the network's performance compared to the existing condition. Changes in the chlorine dosing to the reservoirs not only did not increase the daily chlorine consumption but also reduced it. This study demonstrated that appropriate chlorine dosing, especially during peak hourly consumption, resulted in a more uniform distribution and improved conditions in critical network points.

After optimization, a higher percentage of pipes had chlorine concentrations between 0.2 and 1 mg/L. Additionally, 66% of the previously substandard-quality water volume met the standard after implementing the optimized dosing strategy. Zones connected to a single reservoir had consistently standard chlorine levels due to the shorter network length. Zones connected to two reservoirs had the highest number of pipes with below-standard chlorine levels due to their longer lengths.

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