## Title

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## Journal

Journal of Pipeline Systems Engineering and Practice, 7(3)

**ISSN**
1949-1190

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**Publication Date**
2016-08-01

**DOI**
10.1061/(asce)ps.1949-1204.0000233

# Optimal Operation of Water Distribution Networks under Water Shortage Considering Water Quality

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**Abstract:** Water shortages are caused by hydrological droughts and by the disruption of the operation of water distribution networks (WDNs). The water pressure and residual chlorine concentration are examples of quantitative and qualitative indexes, respectively, of a WDN's performance. This work considers quality and quantity variables simultaneously in the operation of WDNs under water shortages. An optimization model is developed to find the optimum water allocation schedule in WDNs. The objectives of the optimization model are maximizing the number of node-times in which the chlorine concentration is in the allowable range, and maximizing the number of supply nodes under desirable pressure. These objectives satisfy the principle of justice in water distribution under water shortage. The optimization model was solved for a real WDN under different scenarios using the honey-bee mating optimization (HBMO) algorithm linked to a hydraulic simulator. The performance of the developed model was compared to an operation rule based on standard operation policy (SOP) that allocates water among consumers based on constant priority of water supply. The results show that water-shortage operation affects water quality and decreases the chlorine concentration below the allowable minimum in the network, and that applying a water allocation schedule obtained with the developed optimization model minimizes this effect so that this allocation schedule maintains residual chlorine concentration mostly within the allowable range throughout the network. The optimized operation of the WDN satisfies consumer demands fairly under desired pressure while reservoir and hydraulic constraints are satisfied. **DOI: 10.1061/(ASCE)PS.1949-1204.0000233.** *© 2016 American Society of Civil Engineers.*

**Author keywords:** Water distribution network; Water-shortage management; Water quality; Chlorine; Mathematical models; Optimization.

## Introduction

Many recent publications dealing with newly developed models for water-shortage management have covered several domains of water resources systems, such as reservoir operation (Ashofteh et al. 2013a, 2015a, b), design-operation of pumped-storage and hydropower systems (Bozorg Haddad et al. 2014), levee layouts and design (Bozorg Haddad et al. 2015a), hydrology (Ashofteh et al. 2013b, 2015c), qualitative management of water resources systems (Bozorg Haddad et al. 2015b). However, very few reported models have focused on the optimal operation of water distribution networks under water shortage considering water quality.

The possibility always exists that a water distribution network will be unable to fulfill demands because of the reduction of water resources due to hydrological drought, physical events, or intentional and inadvertent pollution (Solgi et al. 2015). Several studies have developed operating rules and optimization models to counter droughts (Barros et al. 2008; Wilchfort and Lund 1997; Xuning et al. 2010). Soltanjalili et al. (2013) reported water-demand management in which the allocation or nonallocation of water to each node of the water network at each time was considered as a decision variable of an optimization model. The purpose of the optimization model was maximization of the number of water supply nodes with desired pressure. The hydraulic network was simulated with *EPANET* (Rossman 2000), and the developed optimization model was solved applying the honey-bee mating optimization (HBMO) algorithm. Solgi et al. (2015) considered equanimity and justice principles for allocation of water among customers under water shortage and developed an optimization model to find the optimal allocation schedule that divides available water among customers fairly, so that the number of water supply nodes with the desired pressure was maximized.

In addition to quantitative indexes (such as water pressure), qualitative ones such as residual chlorine concentration in the network must be considered in the operation of municipal WDNs. There must always be a minimum concentration of chlorine in a WDN's water after treatment and during water conveyance to delivery points to ensure water with a desirable quality for human use. The chlorine concentration at injection stations must be enough to maintain adequate residual chlorine throughout the WDN. At the same time, water chlorination causes disinfection by-products (DBPs) such as trihalomethanes. The DBPs are carcinogenic and harmful to consumer health. Therefore, WND operators attempt to maintain the chlorine concentration in an allowable range

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Note. This manuscript was submitted on April 13, 2015; approved on November 4, 2015; published online on January 20, 2016. Discussion period open until June 20, 2016; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Pipeline Systems Engineering and Practice***, © ASCE, ISSN 1949-1190.

J. Pipeline Syst. Eng. Pract., 2016, 7(3): 04016005

throughout the network by using a minimum amount of chlorine at injection stations to disinfect the water on the one hand, while reducing the generation of DBPs in the network on the other hand (Boccelli et al. 1998; Tryby et al. 2002; Munavalli and Kumar 2003; Prasad et al. 2004; Lansey et al. 2007).

Several researches have simultaneously considered water quantity and quality in the operation of WDNs. Sakarya and Mays (2000) developed a methodology that considers water quality for determining the optimal operation of pumps in WDNs. Biscos et al. (2003) developed the optimization model that maximizes the use of low-cost power (e.g., midnight pumping) and maintains desired chlorine concentration at delivery points. Duzinkiewicz et al. (2005) introduced an integrated hierarchical approach to control quantity and quality in water supply and distribution systems that optimizes operational costs. Kang and Lansey (2010) considered optimal operation of existing valves by injection schedule of chlorine to maintain chlorine concentration in an allowable range throughout the network. Vrachimis et al. (2014) introduced an adaptive water-quality control algorithm. Kurek and Ostfeld (2014) reported a multiobjective model to optimize pumping cost and water quality. Flows, pressures, water storage, and periodical tank operation were considered as the model constraints.

Maintaining the desired quantitative and qualitative indexes during a water-shortage operation is as important as during normal operation of a WDN. However, the management of water quality in WDNs during a water shortage has received minimal attention in the literature. This paper considers water quality and quantity in choosing optimal operation of a WDN during water-shortage periods. For this purpose, an optimization model is developed and compared with an operation rule for WDNs. The following sections describe (1) the rule of water supply with constant priority obtained by standard operation policy (SOP) of a WDN; and (2) an optimization model in which the HBMO algorithm is linked to a hydraulic simulator to solve a real WDN under different water-shortage scenarios. The results obtained with the developed optimization model are compared with those achieved with the rule of supply with constant priority.

## Rule of Supply with Constant Priority

Based on the rule of supply with constant priority obtained by the SOP, the nodes of the network are ranked based on the amount of their water demands while the node with maximal water demand is the first priority. Then the demands of nodes are supplied based on the amount of available water. In this method, the demand of an anode with specific priority is supplied when the demands of the nodes with higher priority can be satisfied. The following mathematical statements reflect the schedule of water allocation among the nodes of the network based on the rule of supply with constant priority, in which the first priority is placed on rank 1:

$$\alpha_{b,h} = \begin{cases} 1 & V_{h-1} + I_h \geq \sum_i De_{i,h} \quad R(i) \leq R(b) \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

$$V_h = V_{h-1} + I_h - O_h \quad h = 1, 2, \ldots, Nh \tag{2}$$

$$O_h = \sum_{i=1}^{NCi} \alpha_{i,h} \times De_{i,h} \tag{3}$$

$$0 \leq V_h \leq V\text{max} \quad h = 1, 2, \ldots, Nh \tag{4}$$

in which $\alpha_{b,h}$ = demand supply index in the consumption node $b$ at the hydraulic time step $h$ (the demand of the node $b$ at the hydraulic time step $h$ is supplied if $\alpha_{b,h} = 1$, and it is not supplied if $\alpha_{b,h} = 0$); $h$ = counter of hydraulic time step; $V_h$ = volume of water stored in the reservoir at the beginning of the hydraulic time step $h$; $I_h$ and $O_h$ = inflow and outflow of the reservoir at the hydraulic time step $h$ (volume units), respectively; $De_{i,h}$ = demand of consumption node $i$ at hydraulic time step $h$ (volume units); $R(i)$ = rank of node $i$; $V\text{max}$ = volume of the reservoir capacity as the model input; $Nh$ = number of hydraulic time steps in the shortage duration; and $NCi$ = number of consumption nodes in the network.

The network quality before a shortage period affects the network quality during the shortage period. Also, hydraulic changes of the network during a shortage period affect the quality of the network after a shortage. Therefore, water-quality simulation during a water shortage period alone does not indicate the actual situation of the network. Generally, it is assumed that the chlorine injection schedule at water-quality sources and network hydraulic dynamics are periodic. Unlike hydraulic simulation, water-quality simulation is cyclical, because the water quality at each time depends on the water quality and hydraulic situation in past times. For first-order reaction kinetics, Boccelli et al. (1998) have shown that there is a time $M$ beyond which the chlorine concentration in the corresponding nodes and corresponding times in the consecutive cycles are the same as long as the hydraulic behavior of the network and chlorine injection schedule in the water-quality sources are periodic. The value of $M$ is estimated as the time when the difference of chlorine concentration in corresponding nodes at corresponding times in two successive cycles is less than a threshold value (e.g., $10^{-12}$ mg/L), and it depends on system size and travel time (Boccelli et al. 1998). Each hydraulic change in the network at time $t$ can affect water quality until time $t + M$. In other words, chlorine concentration in time $t$ is independent of concentrations before $t - M$. Thus, it is necessary to continue water-quality simulation for a period of time as $M$ after the end of the water-shortage period to investigate the effect of water shortage period on water quality. After the end of the shortage period, the normal operation of the network is in effect. On the other hand, it is also necessary to run the water-quality simulation for a period of time $M$ before the start of the water shortage period (before the shortage period, the operation is done normally). In summary, the effect of the operation of the network by the rule of supply with a constant priority on water quality is realistically investigated when the period of simulation consists of three steps. Step 1 is the normal operation of the network for the period of time $M$ (it is done to achieve sustainability of chlorine concentration throughout the network); Step 2 is the operation of the network by the rule of supply with a constant priority (when water shortage occurs), and Step 3 is the normal operation of the network for a period of time $M$ after the end of the water deficit period to completely assess the effect of water-shortage operation on the water quality of the network.

## Developed Optimization Model

This study develops an optimization model to find the optimum water allocation schedule in a WDN. The optimal allocation schedule maintains residual chlorine concentration mostly within the allowable range throughout the network under water-shortage operation. Also, it meets consumers' water demands fairly under a desired pressure while satisfying reservoir constraints.

The objective function of the optimization model is

$$\text{Maximize}\, OF = \sum_{i=1}^{Ni}\sum_{h=1}^{Nh} MQ_{i,h} + \frac{\sum_{i=1}^{NCi}\sum_{h=1}^{Nh} MP_{i,h}\times\alpha_{i,h}}{Nh\times NCi} \tag{5}$$

$$MP_{i,h} = \begin{cases} \dfrac{P_{i,h}}{P\text{min}} & \dfrac{P_{i,h}}{P\text{min}} < 1 \\ 1 & \dfrac{P_{i,h}}{P\text{min}} \geq 1 \end{cases}$$
$$i = 1, 2, \ldots, NCi,\; h = 1, 2, \ldots, Nh \tag{6}$$

$$MQ_{i,h} = \begin{cases} 0 & C_{i,h} < C\text{min}' \\ 1 & C_{i,h} \geq C\text{min} \end{cases} \quad i = 1, 2, \ldots, Ni,\; h = 1, 2, \ldots, Nh \tag{7}$$

$$\alpha_{i,h} = \delta_{i,r} \quad (r-1)\times Li \leq h < r\times Li \tag{8}$$

$$Li = F\times Ls \tag{9}$$

$$\delta_{i,r} = \{0, 1\} \quad i = 1, 2, \ldots, NCi, \quad r = 1, 2, \ldots, R \tag{10}$$

in which $OF$ = value of objective function; $MQ_{i,h}$ = quality index in node $i$ at hydraulic time step $h$; $i$ = counter of node number; $Ni$ = number of network nodes; $MP_{i,h}$ = pressure index in the consumption node $i$ at hydraulic time step $h$; $P_{i,h}$ = pressure in the consumption node $i$ at hydraulic time step $h$; $P$min = minimum allowable pressure; $C_{i,h}$ = chlorine concentration in the node $i$ at the end of the hydraulic time step $h$; $C$min = minimum allowable chlorine concentration in the network; $r$ = counter of water-allocation time steps; $R$ = total number of time steps of allocation schedule in the shortage period for each node; $Ls$ = length of hydraulic time steps; $Li$ = length of allocation schedule time steps; $F$ = ratio of the allocation schedule time step to the hydraulic time step which should be an integer coefficient; and $\delta_{i,r}$ = decision variable of the optimization model, which can be equal to 0 (cut the water) or 1 (supply the demand) for consumption node $i$ at allocation schedule time step $r$ so that each allocation schedule time step $r$ can include one or more hydraulic time step. The choice of the length of the allocation schedule time step may be limited in practice due to restrictions that are imposed on operators. For example, the supply of water could be switched not more than six times in a day (every 4 h), so that each 4-h period, a decision is made to supply water or cut the water supply. Yet the water demand varies every hour due to hourly fluctuations of consumption in the water distribution network. The demand supply index at hydraulic time step $h$ is related to $\delta_{i,r}$ by Eq. (8).

The consumption time pattern is modified for hydraulic and qualitative calculations as

$$MPat_{i,h} = \alpha_{i,h}\times Pat_{i,h} \quad i = 1, 2, \ldots, NCi,\; h = 1, 2, \ldots, Nh \tag{11}$$

in which $Pat_{i,h}$ = coefficient of consumption time pattern for node $i$ at hydraulic time step $h$; and $MPait_{i,h}$ = modified coefficient of time pattern for node $i$ at hydraulic time step $h$. $MPait_{i,h}$ is used for hydraulic simulation.

In Eq. (5), the maximum value of $\sum_{i=1}^{Ni}\sum_{h=1}^{Nh} MQ_{i,h}$ is equal to $Ni\times Nh$ obtained when the chlorine concentration exceeds $C$min in all network nodes at all hydraulic time steps. Also, the value of $\sum_{i=1}^{Ni}\sum_{h=1}^{Nh} MQ_{i,h}$ is always an integer number. The value of $\sum_{i=1}^{NCi}\sum_{h=1}^{Nh} MP_{i,h}\times\alpha_{i,h}/(Nh\times NCi)$ is always in the range [0,1], so that it would be equal to 1 or less than 1, if all consumption nodes in the network are supplied at all hydraulic time steps or otherwise, respectively. Thus, the objective function includes integer and decimal parts under water shortage. Its integer part is equal to the number of node-times in which the chlorine concentration is larger than $C$min, and the decimal part represents the number of adequate water supplies.

Using the objective function [Eq. (5)], solutions that provide the best qualitative condition in the network are superior to other solutions, and among those that have the same qualitative conditions, solutions with larger water supply are superior to other solutions. Because the purpose is increasing the number of water supplies, the optimization model would find solutions in which the nodes with more demand have not been supplied and the nodes with less demand have been supplied during more hydraulic time steps. To avoid this problem, Eq. (12) was introduced as a constraint in the optimization model. Solgi et al. (2015) defined Eq. (12) for fair allocation of water among consumers during water shortage

$$\frac{\sum_{h=1}^{Nh} S_{i,h}}{\sum_{h=1}^{Nh} De_{i,h}} \geq VL(RW) \quad i = 1, 2, \ldots, NCi \tag{12}$$

in which $S_{i,h}$ = volumetric water supply in consumption node $i$ at hydraulic time step $h$, and $VL(RW)$ = fairly minimum ratio of demand supply. Based on Eq. (12) the water allocation in the network with shortage condition is fair when the water supply in each consumption node is larger than a specific value $VL(RW)$. $VL(RW)$ has been determined based on the ratio of the total available water during the shortage period to the total network demand

$$VL(RW) = \theta\times RW \tag{13}$$

$$RW = \frac{TVA}{TVD} \tag{14}$$

in which $TVA$ and $TVD$ = total available water and total volumetric demand of the network during the shortage duration, respectively; and $\theta$ = threshold of fairness in the range of [0,1]. Eq. (15) is introduced in the optimization model to preserve the pressures in the allowable range in the network

$$0 \leq P_{i,h} \leq P\text{max} \quad i = 1, 2, \ldots, Ni \tag{15}$$

in which $P$max = maximum allowable pressure in the network. The following equations are related to the water stored in the reservoir:

$$0 \leq V_h \leq V\text{max} \quad h = 1, 2, \ldots, Nh \tag{16}$$

$$V_{h+1} = V_h + I_h - O_h \quad h = 1, 2, \ldots, Nh \tag{17}$$

$$V_{\text{Final}} \geq V_1 \tag{18}$$

in which $V_{\text{Final}}$ = existing water volume in the reservoir at the end of the shortage interval. The value $V_1$ (the initial reservoir storage volume at the beginning of the shortage period) is considered as a known value.

The chlorine injection schedule at water-quality sources is usually assumed to be periodic. Therefore, when the shortage period is longer than one cycle, the length of the shortage period is considered equal to one cycle. Then, a schedule is determined for the first cycle, which can also be used for the following cycles. For this purpose, two issues must be considered. First, the existing water volume in the reservoir at the end of the shortage period must be larger than or equal to the reservoir water volume at the beginning of this period [Eq. (18)] (Solgi et al. 2015). Second, the variations of hydraulic condition during the shortage period can affect the chlorine concentration in the network even at times after the end of this period. So, if a shortage period starts immediately after the previous one, the schedule allocation that was optimal for the previous shortage period would not be appropriate for the next one. To avoid this problem, it is necessary to restrict quality effects of the water shortage operation during the shortage period. This is accomplished with Eq. (19) as a model constraint when the normal operation of the network has been effected at least during the period of time $M$ before the onset of the shortage period

$$C_{i,Nh} = C_{i,0} \quad i = 1, 2, \ldots, Ni \tag{19}$$

in which $C_{i,0}$ = chlorine concentration in node $i$ at the beginning of the shortage period.

Lansey et al. (2007) have demonstrated that for first-order reaction kinetics, chlorine concentration of each node at each time has a linear relationship with dosage of chlorine injected in water-quality sources during the cycle and chlorine concentration of all of the nodes in the network at the start of the cycle. Thus, if the chlorine concentrations of corresponding nodes in two separate cycles are equal to one another at the start of the cycles, then the chlorine concentration at another time will also be equal to one another in both cycles. As the length of the shortage period is considered to be equal to a cycle and the shortage period starts at time $M$ in the simulation, if chlorine concentrations in all nodes of the network at the end of the shortage period are equal to the concentrations at the start of this period, chlorine concentrations during the normal cycle after the shortage period will be the same as the concentrations in a normal cycle in which the water quality has stabilized. Although the water quality after the shortage period is related to the hydraulics of the network during the shortage period, the optimization model, that considers Eq. (19) as a constraint, finds an allocation schedule that does not change water quality after the shortage period, and the reduction of chlorine concentration in the network nodes only occurs during this period. Defining this constraint in the optimization model has three advantages. First, if the duration of the lack of the water is longer than one cycle, the model can be run for a cycle, and the obtained schedule is used for the subsequent cycles. Second, deleting this constraint of the optimization model extends the losses of chlorine concentration outside of the water shortage period. In the absence of this constraint, consecutive deficits affect one another, and the water-quality situation during water shortage will be worse than the situation in which consecutive deficits do not affect one another. Third, by means of this constraint, the computational burden is decreased because it is not necessary to simulate the network after the end of the water shortage. Finally, if the length of the shortage period is longer than that is predicted and the constraints of Eqs. (18) and (19) are satisfied, the network will keep its ability to cope with the shortage as it did before the shortage.

The developed optimization model is solved with the HBMO algorithm. The HBMO algorithm is inspired by the life cycle and reproduction of honey bees and is a metaheuristic optimization algorithm. This algorithm is a useful tool to solve the optimization problems dealing with WDNs. In recent years, the HBMO algorithm was used in research related to diverse fields of water resources, and its good performance in comparison to another algorithm such as the genetic algorithm (GA) has been demonstrated (Bozorg Haddad et al. 2006, 2008, 2010a, b, 2011b, a; Jahanshahi and Bozorg Haddad 2008). Fig. 1 shows the flowchart of the developed optimization and the steps of the HBMO algorithm.

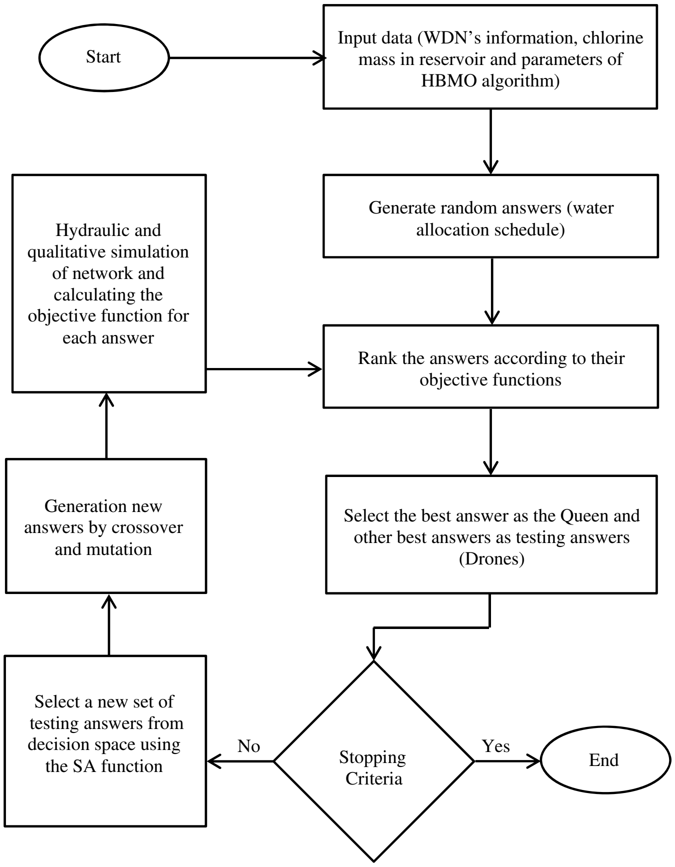

**Fig. 1.** Flowchart of the developed optimization model and the HBMO algorithm

## Efficiency Criteria

Three criteria of reliability, resiliency, and vulnerability were used for assessing the obtained results. In these efficiency criteria definitions, failure takes two forms: (1) failure in meeting water demand, and (2) reduction of chlorine concentration below $C$min.

### *Temporal Reliability*

The likelihood of success in an operation period is called temporal reliability (Hashimoto et al. 1982)

$$\omega_\beta = \frac{100}{Nh}\sum_{h=1}^{Nh}\begin{cases}1 & \sum_{i=1}^{NCi} S_{i,h} \geq \sum_{i=1}^{NCi} \beta \times De_{i,h}\\ 0 & \sum_{i=1}^{NCi} S_{i,h} < \sum_{i=1}^{NCi} \beta \times De_{i,h}\end{cases} \tag{20}$$

$$\omega'_\beta = 100 \times \sqrt[NCi]{\prod_i \left(\frac{1}{Nh}\sum_{h=1}^{Nh}\begin{cases}1 & S_{i,h} \geq \beta \times De_{i,h}\\ 0 & S_{i,h} < \beta \times De_{i,h}\end{cases}\right)}$$
$$i = 1, 2, \ldots, NCi \tag{21}$$

$$\mu = 100 \times \sqrt[Ni]{\prod_i \left(\frac{1}{Nh}\sum_{h=1}^{Nh}\begin{cases}1 & C_{i,h} \geq C\text{min}\\ 0 & C_{i,h} < C\text{min}\end{cases}\right)}$$
$$i = 1, 2, \ldots, Ni \tag{22}$$

in which $\omega_\beta$ and $\omega'_\beta$ = network and nodal temporal reliability, respectively; $\beta$ = efficiency threshold (the network efficiency above this threshold means success and less than this refers to failure); and

$\mu$ = value of nodal qualitative temporal reliability. These parameters are in the range of [0,100%].

### Volumetric Reliability

Duckstein and Plate (1988) defined the percentage of meeting water demand as reliability. In the present study, it is named volumetric reliability

$$\phi = 100 \times \frac{\sum_{i=1}^{NCi}\sum_{h=1}^{Nh} S_{i,h}}{\sum_{i=1}^{NCi}\sum_{h=1}^{Nh} De_{i,h}} \qquad (23)$$

$$\phi'_\beta = 100 \times \sqrt[NCi]{\prod_i \left(\frac{\sum_{h=1}^{Nh} S_{i,h}}{\beta \times \sum_{h=1}^{Nh} De_{i,h}}\right)} \quad i = 1, 2, \ldots, NCi \qquad (24)$$

in which $\varphi$ and $\varphi'_\beta$ = network and nodal volumetric reliability, respectively.

### Resiliency

The likelihood of a system returning from a failure situation to a normal situation has been defined as the resiliency (Hashimoto et al. 1982). A high probability of a system returning from a failure situation to a normal situation shows resilience of a water system

$$\gamma_\beta = 100 \times \frac{\sum_{h=1}^{Nh}\begin{cases}1 & \sum_{i=1}^{NCi} S_{i,h} < \sum_{i=1}^{NCi}\beta \times De_{i,h}, \sum_{i=1}^{NCi} S_{i,h-1} \geq \sum_{i=1}^{NCi}\beta \times De_{i,h-1}\\ 0 & \text{Otherwise}\end{cases}}{\sum_{h=1}^{Nh}\begin{cases}1 & \sum_{i=1}^{NCi} S_{i,h} < \sum_{i=1}^{NCi}\beta \times De_{i,h}\\ 0 & \text{Otherwise}\end{cases}} \qquad (25)$$

$$\gamma'_\beta = 100 \times \sqrt[NCi]{\prod_i \left(\frac{\sum_{h=1}^{Nh}\begin{cases}1 & S_{i,h} < \beta \times De_{i,h}, S_{i,h-1} \geq \beta \times De_{i,h-1}\\ 0 & \text{Otherwise}\end{cases}}{\sum_{h=1}^{Nh}\begin{cases}1 & S_{i,h} < \beta \times De_{i,h}\\ 0 & \text{Otherwise}\end{cases}}\right)} \quad i = 1, 2, \ldots, NCi \qquad (26)$$

$$\rho = 100 \times \sqrt[Ni]{\prod_i \left(\frac{\sum_{h=1}^{Nh}\begin{cases}1 & C_{i,h} < C\min, C_{i,h-1} \geq C\min\\ 0 & \text{Otherwise}\end{cases}}{\sum_{h=1}^{Nh}\begin{cases}1 & C_{i,h} < C\min\\ 0 & \text{Otherwise}\end{cases}}\right)} \quad i = 1, 2, \ldots, Ni \qquad (27)$$

in which $\gamma_\beta$ and $\gamma'_\beta$ = network and nodal resiliency, respectively; and $\rho$ = nodal qualitative resiliency.

### Vulnerability

Maximum intensity of probable failure in a system is named vulnerability (Hashimoto et al. 1982)

$$\sigma = \text{MAX}\left(\frac{C\min - C_{i,h}}{C\min}\right) \quad i = 1, 2, \ldots, Ni, \quad h = 1, 2, \ldots, Nh,\ C_{i,h} < C\min \qquad (28)$$

in which $\sigma$ = qualitative vulnerability.

The nodal efficiency criteria have been formulated in root forms with which to restore them to their original scales. If some values less than one multiply one another, their product will be less than each of them. Also, if the number of multiplication factors that is less than one is increased, their product will become closer to zero than otherwise. Thus, in the networks with a large number of nodes, such a root formulation is recommended so that the obtained results are conveniently represented.

## Case Study

The WDN supplied by Reservoir 30 in Tehran (Solgi et al. 2015) is used to illustrate the performance of the developed optimization model, and its results are compared to the rule of supply with constant priority. Fig. 2 shows a schematic of the network, and the network's information is presented in Table 1.

The network under Reservoir 30 in Tehran has a reservoir with a capacity of 5,000 $m^3$ in the elevation of 1,754 m. The pressures are supplied by gravity from the reservoir. The material of pipes of the network under Reservoir 30 in Tehran is cast iron, with a Hazen-Williams coefficient estimated equal to 85 in all pipes. The network has 65 consumption nodes ($NCi$) among 79 nodes ($Ni$). The minimum and maximum allowable pressure heads at the consumption nodes are equal to 14 ($P$min) and 50 ($P$max) m, respectively. First-order reaction kinetics were considered for chlorine in the network's water-quality simulation. The bulk reaction parameter for chlorine was assumed to be equal to 0.55 $\text{day}^{-1}$, and the reaction with the wall was neglected. The allowable range of chlorine was 0.2 to 0.5 mg/L (WHO 2011). It is assumed that the length of hydraulic cycle of the network under study is equal to 1 day. The coefficients of the time pattern of consumption are shown in Fig. 3 for different hours in a day.

The operation of the network is conducted normally for a long time before a water shortage, and it has been assumed that the network has an ideal water-quality condition during normal operation. This means that the chlorine concentration is in the allowable range

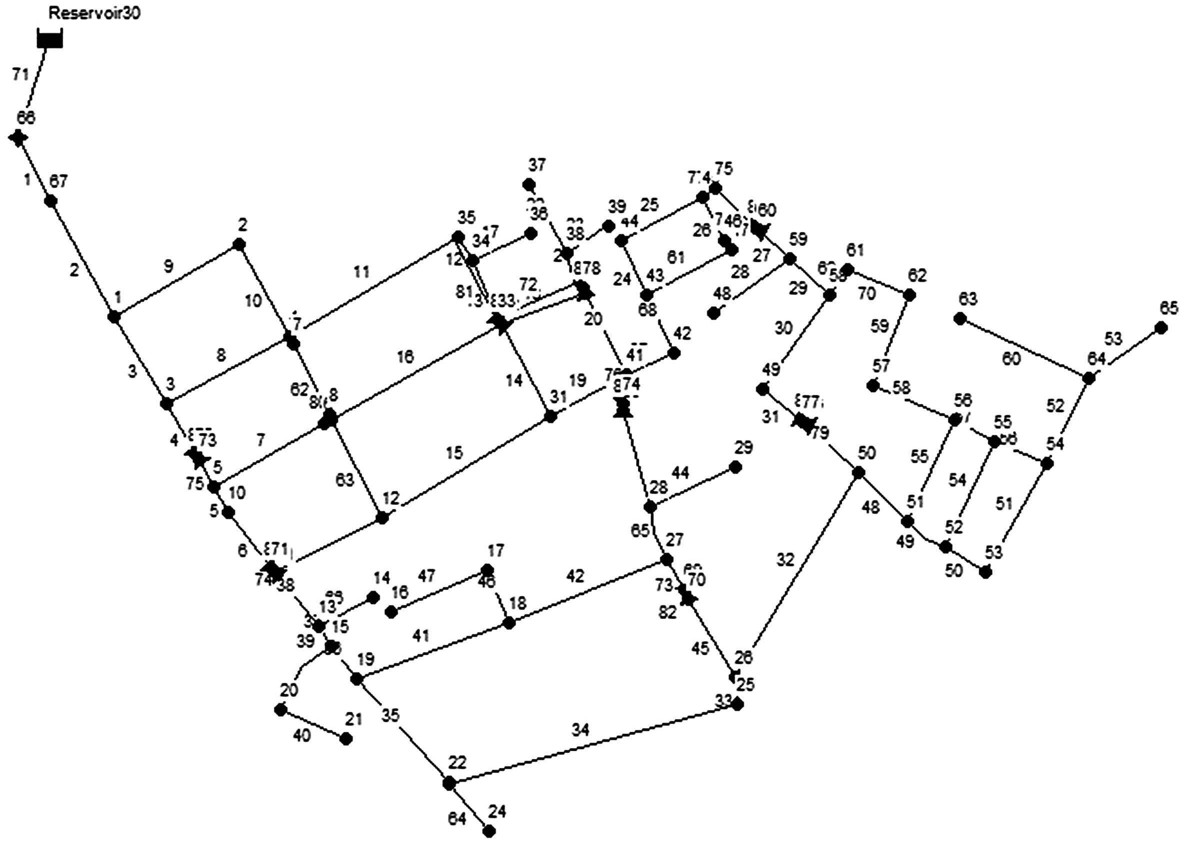

**Fig. 2.** Schematic of the network fed by Reservoir 30 in Tehran, Iran

throughout the network by means of the minimum chlorine mass injected into the reservoir during the normal operation. The reservoir is the only qualitative source for the studied network. The minimum (allowable) chlorine concentration throughout the network is equal to 0.378 mg/L. This value was assigned based on Boccelli et al. (1998). The length of the hydraulic and qualitative monitoring time steps were set equal to 1 h, and the chlorine injection time step was made equal to 24 h, respectively. This concentration must be always in the reservoir to keep chlorine concentration in the allowable range (0.2–0.5 mg/L) throughout the network in the normal operation. The time $M$ after which the quality situation stabilizes under normal operation is 4 days for this network. Fig. 4 depicts the average of the differences of chlorine concentrations from the desired value at corresponding times in two successive cycles for all nodes. Fig. 4 shows that the average of the differences of chlorine concentration in the network tends to zero after 72 h from the start of simulation, and it is less than $10^{-12}$ mg/L after 96 h from the start of simulation. Therefore, the start time of the water-shortage period is at 96 h after the start of simulation. Normal operation is simulated before water shortage. The envelope curve of chlorine concentration throughout the network and chlorine concentration in the reservoir for a normal cycle after time $M$ (the time after which the quality situation is stabilized) is graphed in Fig. 5.

Six scenarios of water shortage were considered in this research. The ratio of the total available water to the total network demand is equal to 70% for all scenarios. The length of the water shortage is equal to 1 day for all scenarios. The total network demand is 4,794 $m^3$/day. Thus, the amount of available water would be equal to 3,356 $m^3$ during the water shortage. Also, the input water to the network is a constant value for different hours of a day. A volume of water equals to 140 $m^3$ enters the network's reservoir hourly. The HBMO algorithm was used to solve the WDN operation under the six water-shortage scenarios. The number of bees and the number of mating flights (iterations) were set equal to 110 and 500, respectively, in each run of the HBMO algorithm. Also, the value 0.9 was used for $\theta$ in all scenarios. The information of scenarios, objective function, and number of water supplies related to the water allocation schedule calculated with the optimization model for each scenario are listed in Table 2. In this table, $SH$ is the starting hour of the water shortage period, and $NS$ is the number of times in which the water was supplied at consumption nodes.

Scenarios 1, 2, and 3 were used to compare the developed optimization model with the operating rule of supply with constant priority. In these scenarios, the initial storage volume of the reservoir was assumed to be equal to zero for a fair comparison between both methods, because the supply with constant priority method is an operation rule that uses all the initial reservoir storage in addition to the hourly input water to the reservoir. However, if the optimization model uses a nonzero initial storage, then it must give it back according to Eq. (18). Thus, if there is a positive initial storage at the beginning of the water shortage period, the rule of supply with constant priority has access to more water than the optimization model. The start time of the water shortage period may affect the results if the initial storage is equal to zero, because the amounts of input water to the reservoir are the same for all hours during water shortage, but the network demands change hourly. Thus, Scenarios 1, 2, and 3 were respectively started at 1 a.m., 2 p.m., and 7 p.m., which are low, mean, and high consumption hours, respectively.

Unlike Scenarios 1, 2, and 3, in Scenarios 4, 5, and 6 the value of 2,000 $m^3$ was considered as the initial reservoir storage. The latter three scenarios started at 1 a.m., and the purpose of their definition

**Table 1.** Characteristics of Nodes and Pipes in the Network Fed by Reservoir 30 in Tehran

| | Pipe | | Node | |
|---|---|---|---|---|
| Node/pipe | Diameter (mm) | Elevation (m) | Length (m) | Base demand ($m^3/h$) |
| 1 | 250 | 1,722 | 68.56 | 2.74 |
| 2 | 250 | 1,717 | 127.68 | 2.74 |
| 3 | 250 | 1,710 | 98.93 | 6.73 |
| 4 | 250 | 1,707 | 61.85 | 5.11 |
| 5 | 250 | 1,702 | 28.65 | 4.90 |
| 6 | 200 | 1,700 | 76.46 | 4.97 |
| 7 | 80 | 1,707 | 122.39 | 3.24 |
| 8 | 250 | 1,701 | 136.29 | 2.52 |
| 9 | 60 | 1,701 | 140.10 | 4.86 |
| 10 | 100 | 1,699 | 101.51 | 8.42 |
| 11 | 250 | 1,691 | 189.83 | 8.75 |
| 12 | 150 | 1,693 | 26.53 | 9.58 |
| 13 | 150 | 1,686 | 62.53 | 2.16 |
| 14 | 150 | 1,685 | 100.86 | 1.08 |
| 15 | 100 | 1,684 | 189.71 | 2.52 |
| 16 | 100 | 1,681 | 188.38 | 1.80 |
| 17 | 60 | 1,686 | 61.51 | 1.80 |
| 18 | 60 | 1,680 | 86.82 | 13.79 |
| 19 | 150 | 1,680 | 83.67 | 12.96 |
| 20 | 150 | 1,685 | 89.47 | 2.88 |
| 21 | 150 | 1,680 | 38.01 | 2.88 |
| 22 | 60 | 1,670 | 75.99 | 6.62 |
| 23 | 150 | 1,670 | 68.45 | 5.40 |
| 24 | 150 | 1,667 | 57.82 | 0.50 |
| 25 | 100 | 1,664 | 90.75 | 13.32 |
| 26 | 100 | 1,666 | 46.73 | 8.28 |
| 27 | 80 | 1,679 | 44.26 | 17.64 |
| 28 | 80 | 1,684 | 89.67 | 9.72 |
| 29 | 80 | 1,683 | 52.07 | 5.76 |
| 30 | 80 | 1,690 | 111.01 | 3.60 |
| 31 | 80 | 1,696 | 49.26 | 5.80 |
| 32 | 150 | 1,708 | 231.69 | 8.14 |
| 33 | 60 | 1,707 | 26.35 | 3.24 |
| 34 | 60 | 1,715 | 289.92 | 0.72 |
| 35 | 200 | 1,717 | 133.04 | 4.07 |
| 36 | 200 | 1,714 | 40.16 | 1.44 |
| 37 | 200 | 1,717 | 23.23 | 2.16 |
| 38 | 200 | 1,712 | 64.65 | 5.04 |
| 39 | 100 | 1,703 | 81.60 | 0.83 |
| 40 | 60 | 1,708 | 69.25 | 3.06 |
| 41 | 150 | 1,696 | 157.07 | 2.56 |
| 42 | 150 | 1,698 | 163.79 | 0.83 |
| 43 | 150 | 1,699 | 95.85 | 2.16 |
| 44 | 100 | 1,702 | 93.89 | 2.05 |
| 45 | 150 | 1,701 | 87.34 | 3.24 |
| 46 | 80 | 1,696 | 54.80 | 0.72 |
| 47 | 80 | 1,695 | 100.11 | 1.08 |
| 48 | 150 | 1,690 | 66.60 | 1.80 |
| 49 | 150 | 1,682 | 46.58 | 8.53 |
| 50 | 150 | 1,672 | 45.04 | 16.56 |
| 51 | 150 | 1,667 | 119.47 | 2.88 |
| 52 | 150 | 1,663 | 91.93 | 2.52 |
| 53 | 150 | 1,658 | 13.92 | 5.76 |
| 54 | 60 | 1,660 | 112.89 | 3.53 |
| 55 | 60 | 1,664 | 108.24 | 2.88 |
| 56 | 80 | 1,668 | 54.80 | 4.32 |
| 57 | 80 | 1,677 | 43.68 | 5.62 |
| 58 | 80 | 1,687 | 87.47 | 5.40 |
| 59 | 80 | 1,686 | 93.98 | 1.44 |
| 60 | 80 | 1,690 | 137.97 | 2.16 |
| 61 | 100 | 1,688 | 93.79 | 4.32 |
| 62 | 100 | 1,677 | 89.79 | 6.16 |
| 63 | 100 | 1,671 | 107.31 | 4.32 |
| 64 | 150 | 1,660 | 58.63 | 7.20 |
| 65 | 100 | 1,660 | 54.38 | 0.90 |
| 66 | 60 | 1,752 | 59.99 | 0 |
| 67 | 150 | 1,749 | 51.66 | 0 |
| 68 | 150 | 1,691 | 61.15 | 0 |
| 69 | 80 | 1,675 | 30.70 | 0 |
| 70 | 80 | 1,675 | 65.71 | 0 |
| 71 | 250 | 1,690 | 40.00 | 0 |
| 72 | 100 | 1,705 | 113.87 | 0 |
| 73 | 150 | 1,705 | 43.90 | 0 |
| 74 | 100 | 1,690 | 118.00 | 0 |
| 75 | 250 | 1,696 | 28.95 | 0 |
| 76 | 150 | 1,678 | 34.00 | 0 |
| 77 | 100 | 1,678 | 14.29 | 0 |
| 78 | 100 | 1,705 | 53.87 | 0 |
| 79 | 80 | — | 68.96 | — |
| 80 | 100 | — | 5.00 | — |
| 81 | 150 | — | 90.78 | — |

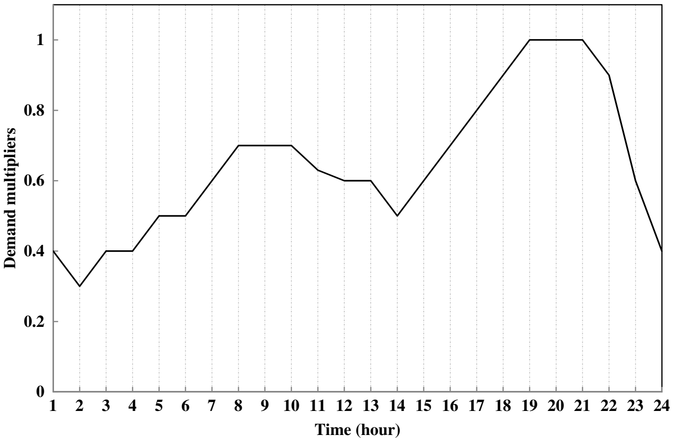

**Fig. 3.** Coefficients of the time pattern of water consumption for a summer day

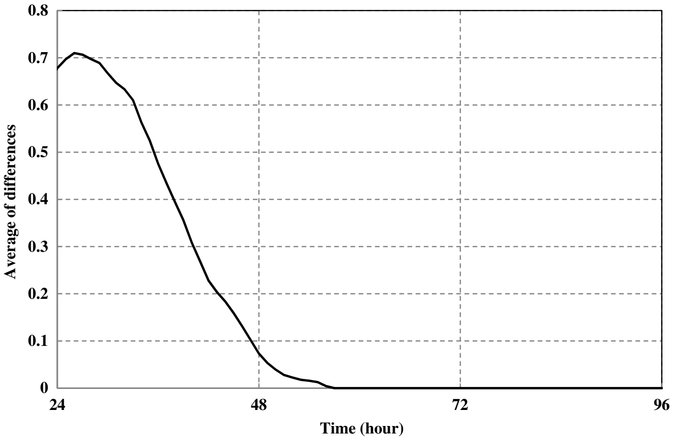

**Fig. 4.** Average of the differences of chlorine concentrations with respect to a reference level in two successive cycles for all nodes under normal operation

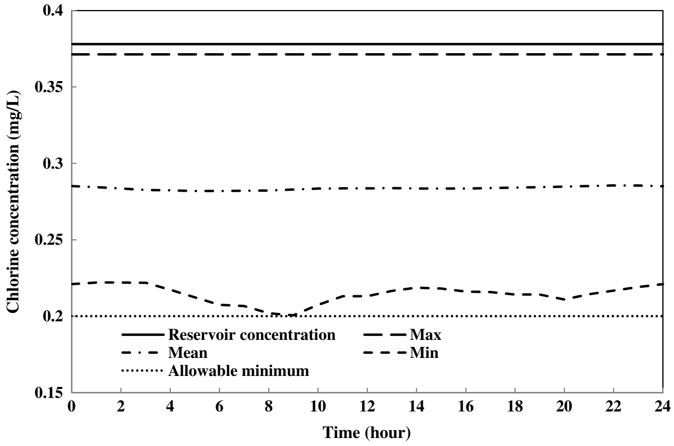

**Fig. 5.** Envelope curve of chlorine concentration throughout the network and chlorine concentration in the reservoir for a normal cycle in which the quality has stabilized

**Table 2.** Information of the Scenarios and the Value of the Objective Function Obtained by the HBMO Algorithm

| Scenario | $Li$ (h) | $V_1$ ($m^3$) | $SH$ (o'clock) | $OF$ | $NS$ |
|---|---|---|---|---|---|
| 1 | 1 | 0 | 1 a.m. | 1,892.7449 | 1,162 |
| 2 | 1 | 0 | 2 p.m. | 1,891.7423 | 1,158 |
| 3 | 1 | 0 | 7 p.m. | 1,896.7603 | 1,186 |
| 4 | 1 | 2,000 | 1 a.m. | 1,896.7417 | 1,157 |
| 5 | 2 | 2,000 | 1 a.m. | 1,895.7423 | 1,158 |
| 6 | 4 | 2,000 | 1 a.m. | 1,886.6846 | 1,068 |

is assessing the effect of the length of allocation schedule time step on the optimization results and the qualitative (chlorine) condition in the network.

*EPANET2* was applied for the hydraulic and quality simulation of the network. Hydraulic time intervals are equal to 1 h, and the chlorine concentration in the reservoir during the water shortage operation is equal to its value in the normal operation condition so that there is not variation in the schedule of chlorine injection into the network in comparison to the normal operation.

## Comparison of the SOP and the Optimized WDN Operations

The results of Scenarios 1, 2, and 3 are presented and the performance of the rule of supply with constant priority (SOP) was compared with that of the developed optimization model.

### Qualitative (Chlorine) Results

First, the WDN was operated by the rule of supply with constant priority (Method 1) to demonstrate the effect of water shortage operation on chlorine concentration. Then, the optimization approach (Method 2) was implemented to find an optimal allocation schedule to operate WDN under water shortage. Table 3 lists the qualitative efficiency criteria for both methods, in which the smallest (best) values of the qualitative vulnerability and the largest (best) values of the other criteria are written in bold format to compare the two methods. Qualitative reliability, resiliency, and vulnerability are presented with symbols $\mu$, $\rho$, and $\sigma$, respectively. In normal operation mode, these criteria are equal to their best values. The best values of the reliability and resiliency are 100%, and the best value of vulnerability is 0%. It can be inferred from Table 3 that the chlorine concentration fell below the allowable minimum when applying Method 1 (the SOP). This means that Method 1 leads to the degradation of the chlorine quality of the network. The value of vulnerability ($\sigma$) for Method 1 in Scenario 1 is approximately 30%. This means that the minimum chlorine concentration in the network equals 0.13 mg/L when operating the network with Method 1 and Scenario 1. In Table 3, Method 2 refers to the optimization model. Based on the values of qualitative efficiency criteria, Method 2 has better performance than Method 1. Method 2 achieves a better level of quality than Method 1 in the WDN. All the qualitative efficiency criteria related to Method 2 are better than those of Method 1. The value of qualitative vulnerability has been significantly decreased by Method 2. For example in Scenario 1, the qualitative vulnerability is reduced (becomes better) to 4.33% with Method 2 compared with 30.33% for Method 1. In Scenario 3, Method 2 makes an ideal qualitative situation in the network equivalent to that of normal operation while there was a shortage in the network and achieves values of qualitative reliability, resiliency, and vulnerability equal to 100%, 100%, and 0.00%, respectively. These results demonstrate that the optimal water allocation schedule that is obtained with Method 2 maintains the chlorine concentration above $C$min in all the nodes and times under water shortage.

**Table 3.** Qualitative Efficiency Criteria for Scenarios 1, 2, and 3

| | Scenario | | | | | |
|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 | |
| | Method | | | | | |
| Criteria | 1 | 2 | 1 | 2 | 1 | 2 |
| $\mu$ | 99.32 | **99.96** | 99.62 | **99.95** | 99.65 | **100.00** |
| $\rho$ | 84.80 | **99.48** | 93.78 | **99.48** | 93.88 | **100.00** |
| $\sigma$ | 30.33 | **4.33** | 13.30 | **2.03** | 21.76 | **0.00** |

Note: Bold values indicate best values.

From a comparison of different scenarios in Table 3, it follows that the qualitative vulnerability ($\sigma$) for Method 2 in Scenario 3 that starts at a high consumption hour has better qualitative vulnerability than other scenarios. This demonstrates that starting from a high consumption hour (Scenario 3) causes better qualitative vulnerability than starting from a low consumption hour (Scenario 1).

Fig. 6 portrays the minimum chlorine concentration in the network during water shortage and 1 day after the shortage period for both methods in all scenarios. Fig. 6 shows that reduction in chlorine concentration is not limited to the water shortage with Method 1. Method 1 produces a minimum chlorine concentration in the network below the allowable range hours after the end of the water shortage period. Fig. 6 shows that after the water shortage, the minimum chlorine concentration in the network was continuously larger than 0.2 mg/L with Method 2, such as under normal operation. This demonstrates the correct performance of Eq. (19), and it is not necessary to simulate the network after the shortage period for Method 2, because the allocation schedule obtained by Method 2 does not change the water quality relative to normal operation after the shortage period due to the optimization constraint [Eq. (19)].

### Quantitative Results

Method 2 (the optimization model) is superior to Method 1 (the rule of supply with constant priority) according to the qualitative condition just examined. This section compares the two models (Methods 1 and 2) based on their quantitative results on reliability and resiliency. Table 4 lists the quantitative efficiency criteria for

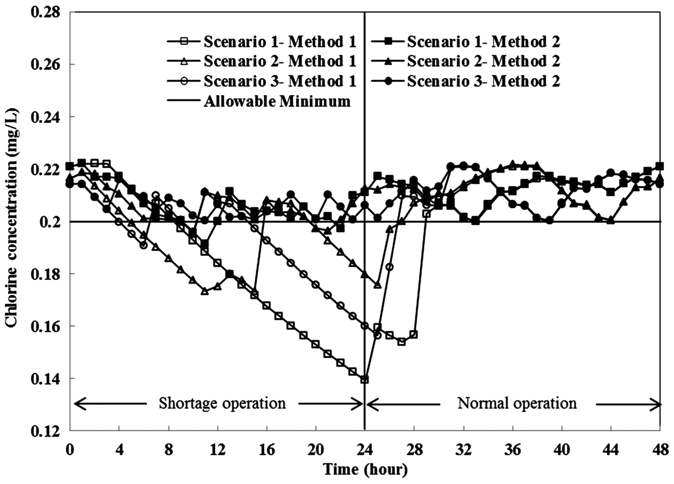

**Fig. 6.** Minimum chlorine concentration in the networks during water shortage and for a day after shortage period for both methods in all scenarios

both methods, where better values are in bold font. The values of the water distribution network's temporal reliability ($\omega_\beta$), nodal volumetric reliability ($\varphi'_\beta$), and network resiliency ($\gamma_\beta$) were calculated for efficiency threshold equal to 100, 70, and 63%, respectively. The threshold of 100% was selected to compare the supply of water demand under shortage with the normal operation condition. The threshold of 70% was selected according to the ratio of the total available water to the total demand during the shortage period, and finally the threshold of 63% was chosen based on the lowest allowable ratio of the demand supply in nodes $[VL(RW)]$. Other criteria correspond to a threshold of 100%, because the ratio of demand supply in each node at each hydraulic time step can be equal to 0 or 1 in Methods 1 and 2, which causes no differences between values of the efficiency criteria for different thresholds for other criteria. For example, in Table 4 Scenario 3, the criteria related to demand supply for Method 2 are better than for Method 1 in most cases. The nodal temporal reliability ($\omega'_\beta$), nodal resiliency ($\gamma'_\beta$), and nodal volumetric reliability ($\varphi'_\beta$) for threshold of 100% were 52.58, 27.99 and 41.29% for Method 2 compared to those of Method 1 equal to 75.77, 75.52, and 73.29% in Scenario 3.

## Effect of Length of Allocation Schedule Time Step on the Optimization Results

Table 5 lists the efficiency criteria calculated with the optimization model (Method 2) related to Scenarios 4, 5, and 6. Table 5 denotes the smallest (best) values of the qualitative vulnerability and the largest (best) values of the other criteria in bold font. The efficiency criteria for Scenario 4 are better than those for Scenarios 5 and 6. The largest changes are associated with the qualitative vulnerability for Scenarios 4, 5, and 6 that increased from the desirable value of 0.0% in Scenario 4 to the undesirable value of 8.24% in Scenario 6. Therefore, improvement of qualitative conditions has an inverse relationship with the length of the time steps of the allocation. Longer time steps cause reduction in network operation costs.

### Velocities

The main factor of chlorine concentration reduction under water shortage is the velocity reduction in the network. The ratio of the average velocity under water shortage to the average velocity under normal conditions ($FV$) is depicted in Fig. 7 for both methods under Scenarios 1, 2, and 3 for all pipes of the network. Fig. 7 shows that some pipes have an average velocity larger during water shortage than under normal operation. For example, the value of $FV$ for pipe 10 under water shortage is 6 times larger than the average velocity of this pipe under a normal condition. However, the average velocities in most pipes of the network during water shortage are less than the average velocities in normal operation ($FV < 1$). Also, the statistics of $FV$ are listed in Table 6 for all scenarios. In Table 6, Max$FV$ is the maximum value of $FV$ among network pipes (dimensionless); Mean$FV$ is the average value of $FV$ for all network pipes; Min$FV$ is the minimum value of $FV$ among network pipes; and $NV$ is the percentage of network pipes in which the average velocity under water shortage is less than under normal condition. According to Table 6, the value of Min$FV$ in all scenarios for Method 2 (optimization model) is larger than that of Method 1 (the rule of supply with constant priority). Conversely, the value of Max$FV$ for Method 2 is less than that of Method 1 in all scenarios. The value of Mean$FV$ is approximately equal for the two methods. It follows that the maximization of

**Table 4.** Quantitative Efficiency Criteria for Scenarios 1, 2, and 3

| | Scenario | | | | | |
|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 | |
| | Method | | | | | |
| Criteria | 1 | 2 | 1 | 2 | 1 | 2 |
| $\omega_{100}$ | **33.33** | 0.00 | **33.33** | 0.00 | **33.33** | 0.00 |
| $\omega_{70}$ | **62.5** | 45.83 | **62.50** | 58.33 | 62.50 | **70.83** |
| $\omega_{63}$ | 75.00 | **79.17** | **75.00** | 70.83 | 75.00 | **83.33** |
| $\omega'_{100}$ | 52.15 | **74.02** | 52.58 | **73.93** | 52.58 | **75.77** |
| $\gamma_{100}$ | **6.25** | 4.17 | **12.50** | 4.17 | **12.50** | 4.17 |
| $\gamma_{70}$ | 2.22 | **61.54** | **22.22** | 20.00 | 33.33 | **57.14** |
| $\gamma_{63}$ | 16.67 | **80.00** | 16.6 | **28.57** | **33.33** | 25.00 |
| $\gamma'_{100}$ | 18.32 | **76.51** | 22.75 | **71.11** | 27.99 | **75.52** |
| $\varphi'_{100}$ | 40.79 | **73.63** | 41.26 | **72.29** | 41.29 | **73.29** |
| $\varphi'_{70}$ | 54.21 | **97.56** | 54.83 | **97.88** | 54.87 | **97.92** |
| $\varphi'_{63}$ | 58.49 | **100.00** | 59.13 | **100.00** | 59.20 | **100.00** |
| $\varphi$ | **69.76** | 69.64 | **70.00** | 70.00 | **70.00** | 70.00 |

Note: Bold values indicate better values.

**Table 5.** Efficiency Criteria for the Results Obtained by Method 2 for Scenarios 4, 5, and 6

| | Scenario | | |
|---|---|---|---|
| Criteria | 4 | 5 | 6 |
| $\omega_{100}$ | 0.00 | 0.00 | 0.00 |
| $\omega_{70}$ | **62.50** | 33.33 | 50.00 |
| $\omega_{63}$ | 83.33 | **100.00** | 83.33 |
| $\omega'_{100}$ | **73.61** | 73.50 | 68.29 |
| $\gamma_{100}$ | 4.17 | 4.17 | 4.17 |
| $\gamma_{70}$ | **88.89** | 25.00 | 16.67 |
| $\gamma_{63}$ | **100.00** | **100.00** | 25.00 |
| $\gamma'_{100}$ | **77.23** | 42.15 | 21.76 |
| $\varphi'_{100}$ | 73.64 | **74.00** | 70.54 |
| $\varphi'_{70}$ | 97.68 | **97.89** | 97.26 |
| $\varphi'_{63}$ | 100.00 | 100.00 | 100.00 |
| $\varphi$ | 70.07 | 70.06 | **70.08** |
| $\mu$ | **100.00** | 99.99 | 99.89 |
| $\rho$ | **100.00** | **100.00** | 97.96 |
| $\sigma$ | **0.00** | 1.37 | 8.24 |

Note: Bold values indicate best values.

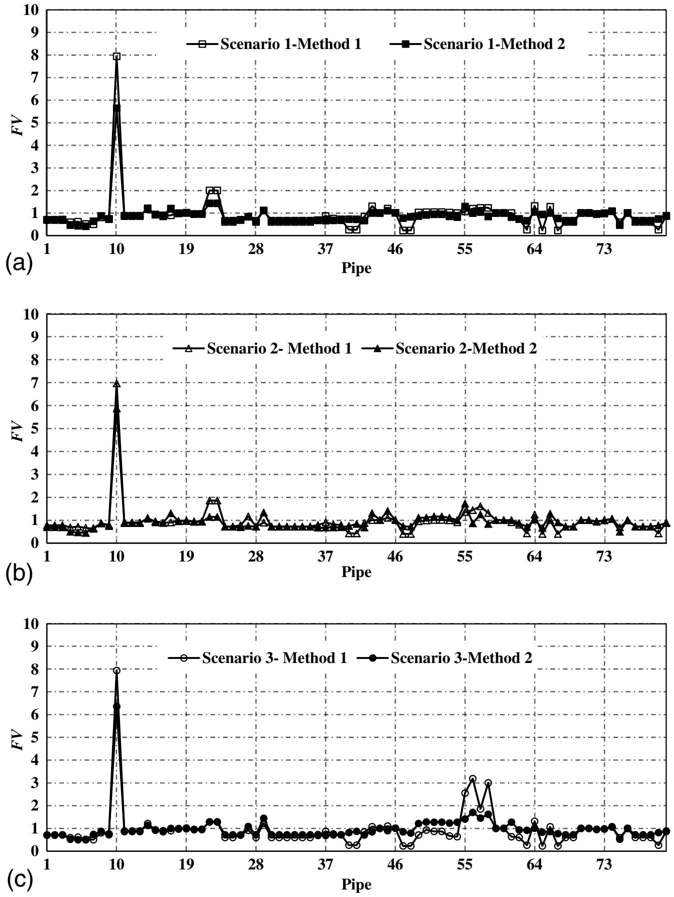

**Fig. 7.** Ratio of average velocity in the shortage condition to the average velocity under normal operation ($FV$) for all pipes in Scenarios: (a) 1; (b) 2; (c) 3

**Table 6.** Data for the Pipe Velocity for All Scenarios

| | Scenario | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 | | 4 | 5 | 6 |
| | Method | | | | | | | | |
| Criteria | 1 | 2 | 1 | 2 | 1 | 2 | 2 | 2 | 2 |
| Max$FV$ | 7.95 | 5.65 | 6.98 | 5.88 | 7.95 | 6.37 | 6.13 | 5.77 | 7.74 |
| Mean$FV$ | 0.92 | 0.90 | 0.95 | 0.94 | 0.94 | 0.99 | 0.96 | 0.96 | 0.96 |
| Min$FV$ | 0.23 | 0.41 | 0.40 | 0.44 | 0.23 | 0.50 | 0.47 | 0.44 | 0.48 |
| $NV$ (%) | 69.14 | 80.25 | 74.07 | 71.60 | 76.54 | 66.67 | 71.60 | 72.84 | 75.31 |

Min$FV$ is one of the reasons that Method 2 achieves better quality results than Method 1. On the other hand, the value of $NV$ is increased (becomes worthier) from 69.14% with Method 1 to 80.25% with Method 2 under Scenario 1. These results demonstrate the necessity of implementing the optimization model to find an optimal allocation schedule to achieve better quality in the network during water shortage. Also, the value of $NV$ in Scenario 3 for the allocation schedule obtained by the optimization model (Method 2) is equal to 66.67%, but the chlorine concentration throughout the network is within the allowable range, which shows the satisfactory performance of the optimization model.

## Constraints

Figs. 8 and 9 show the ratio of the total supplied water to the total required water for consumption nodes of the network during water shortage, corresponding to Scenarios 1, 2, and 3, and to Scenarios 4, 5, and 6, respectively. Figs. 7 and 8 show that the ratio of the total supplied water to the total required water for all consumption nodes is always larger than 63% for Method 2 in all scenarios. On the other hand, this ratio is less than 63% for Method 1 in many nodes.

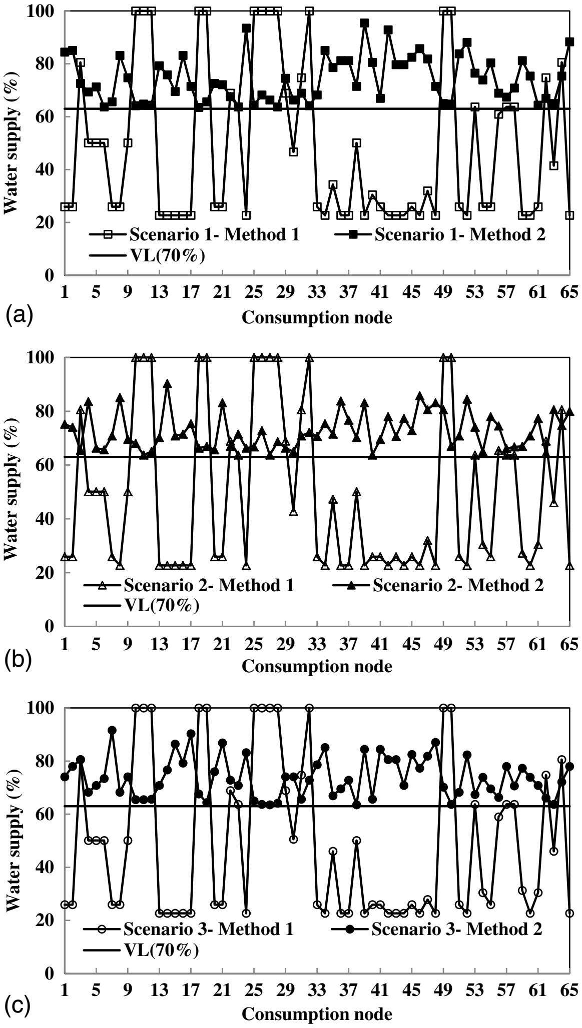

**Fig. 8.** Ratio of the total supplied water to the total required water for consumption nodes of the network during water shortage in Scenarios: (a) 1; (b) 2; (c) 3

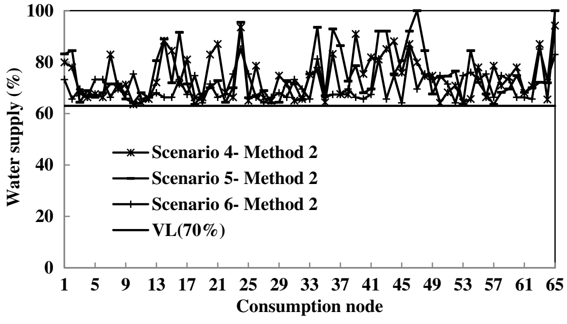

**Fig. 9.** Ratio of the total supplied water to the total required water for consumption nodes of the network during water shortage in Scenarios 4, 5, and 6

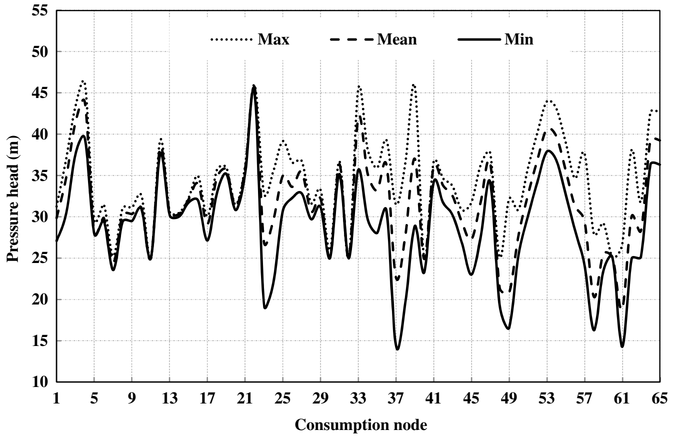

**Fig. 10.** Envelope curve of pressure head at consumption nodes corresponding to Method 2 in all scenarios

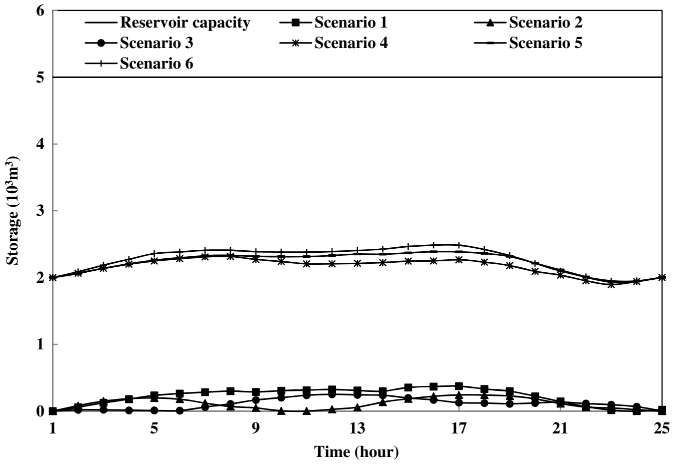

**Fig. 11.** Reservoir storage volume during water shortage corresponding to water allocation schedule obtained by Method 2

This indicates that the allocation schedule obtained by Method 2 is adequate so that each consumption node of the network receives a volume of water in excess of 63% of its demand during water shortage. The results of Figs. 8 and 9 confirm previous findings discussed already in the context of Tables 4 and 5.

The envelope curve of pressure heads for all hydraulic time steps for Method 2 with all scenarios are graphed in Fig. 10, in which the minimum refers to the minimum pressure calculated at each consumption node at all hydraulic time steps for all scenarios. Fig. 10 shows that pressures are always in the allowable range using the optimization model (Method 2).

The reservoir storage volume during water shortage related to the water allocation schedule obtained by Method 2 is shown in Fig. 11 for all different scenarios, in which the satisfactory performance of the optimization model in satisfying the constraints imposed on the reservoir is demonstrated. According to Fig. 11, the initial volume of the reservoir is approximately equal to the final volume of the reservoir for all scenarios. This means that the optimization model uses all the available water during the shortage period. This also confirms the correct convergence of the optimization algorithm because approximately all of the available water during shortage period was used to supply the water demands. Recall that in Tables 4 and 5, the network volumetric reliability ($\varphi$) is approximately equal to 70% for all scenarios, which is equal to the ratio of the total available water to the total network demand during water shortage.

## Concluding Remarks

A new optimization model was developed and presented in this work to find an optimal time schedule for operation of water distribution networks under water shortage. The objectives of the optimization model were maximizing the number of node-times in which the chlorine concentration is in the allowable range, and maximizing the number of adequate water supplies. These objectives were subjected to the consideration of the justice principle in water distribution among different nodes during water shortages. The developed optimization model was solved with an HBMO algorithm in different scenarios for the network fed by Reservoir 30 in Tehran, Iran. The results obtained with the developed optimization model were superior to those calculated with the rule of supply with constant priority. The results show the more desirable conditions in supplying water demands using the developed optimization model. In other words, under similar water-shortage conditions, the developed model can fairly distribute water among different nodes; it provides desirable hydraulic conditions in the network (such as desirable pressure at consumption nodes) and satisfactory qualitative (chlorine) conditions in the network. The method that relies on the rule of supply with constant priority, on the contrary, renders the chlorine concentration less than the minimum allowable concentration in many nodes at different times.

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