Title

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Permalink

https://escholarship.org/uc/item/7bt7b4sf

Journal

Water Supply, 20(7)

ISSN

1606-9749

Authors

Solgi, Mohammad
Bozorg-Haddad, Omid
Loáiciga, Hugo A

Publication Date

2020-11-01

DOI

10.2166/ws.2020.159

Peer reviewed

A multi-objective optimization model for operation of intermittent water distribution networks

Mohammad Solgi, Omid Bozorg-Haddad and Hugo A. Loáiciga

ABSTRACT

Intermittent operation of water distribution networks (WDNs) is an undesirable yet inevitable strategy under some circumstances such as droughts, development, electricity blackouts, and water pollution, mostly in developing countries. Intermittent utilization of WDNs poses several disadvantages encompassing water quality degradation, deterioration of the water-distribution system, and extra operational and maintenance costs due to frequently interrupted supply, unfair water distribution among consumers, and reduction of system serviceability. This paper proposes a multi-objective optimization model to address the negative consequences of intermittent water shortages. The model is intended to maximize the quantitative and qualitative reliability and the fairness in water supply, and to minimize the frequency of supply interruption. The developed model also considers pragmatic limitations, water quality, water pressure, and supply reservoir's constraints to plan the operation of intermittent water distribution systems under water shortage. The model's efficiency is tested with a WDN in Iran and compared with a standard operation policy (SOP) for water distribution. According to the evaluated efficiency criteria concerning reliability, resiliency, and vulnerability of water quality and quantity of water supply, the developed model is superior to the SOP rule and improves the performance of the network under intermittent operation. In addition, the results demonstrate there is a tradeoff between the uniformity of water distribution and the frequency of supply interruption that shows operators' and customers' conflicting priorities.

Key words | frequency of supply interruption, intermittent operation, reliability of safe water supply, uniformity of water distribution, urban water scheduling, water distribution networks

Mohammad Solgi
Hugo A. Loáiciga
Department of Geography,
University of California,
Santa Barbara, California 93106
USA

Omid Bozorg-Haddad (corresponding author)
Department of Irrigation & Reclamation
Engineering, Faculty of Agricultural Engineering
& Technology, College of Agriculture & Natural
Resources,
University of Tehran,
Karaj, Tehran,
Iran
E-mail: *obhaddad@ut.ac.ir*

HIGHLIGHTS

- Intermittent operation water distribution networks.
- Proposing a multi-objective optimization model.
- Maximizing the quantitative and qualitative reliability of water distribution systems (WDSs).
- Maximizing the fairness of WDSs.
- Minimizing the frequency of supply interruption of WDSs.

INTRODUCTION

Due to increasing water demand, limited resources and climate change, water resources management has been the subject of heightened attention (i.e. Fallah-Mehdipour *et al.* 2014; Jahandideh-Tehrani *et al.* 2015). Water distribution networks (WDNs) are an integral part of water systems. Several authors have developed optimization models for their hydraulic design (Jahanshahi & Bozorg-Haddad 2008; Ghajarnia *et al.* 2010; Fallah-Mehdipour *et al.* 2011; Bozorg-Haddad *et al.* 2016a, 2016b), operation (Seifollahi-Aghmiuni *et al.* 2011, 2013); rehabilitation and maintenance

doi: 10.2166/ws.2020.159

(Dandy & Engelhardt 2006; Nafi *et al.* 2008; Roshani & Filion 2012; Sabbaghpour *et al.* 2012), and water quality (Tryby *et al.* 2002; Munavalli & Kumar 2003; Prasad *et al.* 2004; Lansey *et al.* 2007). Several publications have presented optimization models addressing jointly water quality and hydraulics of WDNs (Sakarya & Mays 2000; Biscos *et al.* 2003; Duzinkiewicz *et al.* 2005; Kang & Lansey 2010; Kurek & Ostfeld 2014).

Intermittent operation of WDNs is not desirable, but it is sometimes inevitable because of severe water shortage, poor technical and economic development, electricity blackouts, and water pollution, to cite common causes. Intermittent supply in WDNs has several shortcomings including water quality degradation, accelerated water network depreciation and operational and maintenance costs due to repetitively turning on and off the water supply in the system, uneven distribution of water, and reducing the efficiency of water supply. Several studies have been conducted to minimize the cited disadvantages. Soltanjalili *et al.* (2013) reported an optimization model that maximizes the system's reliability for intermittent operation of WDNs. Solgi *et al.* (2015) considered consumers' welfare in intermittent supply and developed an associated optimization model. Solgi *et al.* (2016) presented a single-objective optimization model that addresses water quality constraints for intermittent operation of WDNs. Bozorg-Haddad *et al.* (2016c) reported a multi-objective optimization model that considers supply resiliency and mechanical reliability simultaneously for intermittent water supply in WDNs. Galaitsi *et al.* (2016) presents a literature review about intermittent water supply. Solgi *et al.* (2018) discussed the evaluation of efficiency of intermittent water supply with WDNs and compared it with the efficiency of continuously supplied networks. Taylor *et al.* (2018) introduced an analytical model considering steady-state and flushing phases to ameliorate intermittent WDNs.

Several meta-heuristic and evolutionary algorithms with enhanced multi-objective capabilities have been introduced in the last decades (Deb 2001; Bozorg-Haddad *et al.* 2017) among which is the honey-bee mating optimization (HBMO) algorithm inspired by the reproductive strategies of honey-bees. The HMBO algorithm was developed by Bozorg-Haddad *et al.* (2006). Several authors have demonstrated the HBMO's effectiveness in various types of optimization problems such as water reservoir operation (Afshar *et al.* 2007; Bozorg-Haddad *et al.* 2008a, 2010a), project management (Bozorg-Haddad *et al.* 2010b), and water distribution networks (Bozorg-Haddad *et al.* 2008b, 2016a; Ghajarnia *et al.* 2009; Soltanjalili *et al.* 2013; Solgi *et al.* 2015, 2016). Moreover, the multi-objective HBMO algorithm (MOHBMO) was introduced and successfully applied to solve multi-objective optimization problems pertinent to WDNs (Bozorg-Haddad *et al.* 2016a, 2016b).

All of the cited studies regarding operation of intermittent WDNs presented single objective optimization models, or, if they applied multi-objective models, they did not address water quality. Evidently, a comprehensive multi-objective optimization model is needed that addresses the operational goals of intermittent systems together and provides a Pareto front by implementing novel multi-objective evolutionary optimization algorithms. This paper's aim is developing a multi-objective optimization model that addresses the idiosyncracies of intermittent operation, including quantitative and qualitative reliability, fairness in water supply, and the frequency of supply interruption. This study develops and tests a multi-objective optimization model aimed at maximizing reliability and uniformity in water distribution and to minimize the number of water-supply interruptions of WDNs under water shortage. The developed model considers pragmatic limitations, water quality, water pressure, and supply reservoir's constraints to schedule the operation of WDNs under intermittent water supply. Single- and multi-objective HBMOs are implemented.

The next sections present the optimization model and water quality simulation. The applied efficiency criteria for assessing the performance of the developed optimization model are presented afterward. Lastly, the performance of the developed optimization model is evaluated with a WDN in Iran and compared with the standard operation rule that supplies water based on constant priorities among consumers.

MATERIALS AND METHODS

The optimization model

The optimization model for WDN operation allocates water to each node of the network during the operational period. The action to allocate or not to allocate water to a node at any time during the WDN's operation is the decision variable of the optimization problem. The decision variable is thus a binary, discrete number: it takes the value 1 if water allocation occurs at a node, and it equals 0 otherwise. Equanimity of water distribution is achieved with the first objective of the developed optimization model, which maximizes the minimum volumetric reliability of water supply among all WDN's nodes. The second objective minimizes the frequency of supply interruptions and maximizes the safe water supply reliability in the network, simultaneously. The developed optimization model is described next.

The first objective function:

$$Maximize \quad F1 = \min_i \left(\frac{\sum_{h=1}^{NH} S_{i,h}}{\sum_{h=1}^{NH} De_{i,h}} \right) \quad i = 1, 2, \ldots, NCNode \tag{1}$$

in which, $F1$ = the objective function that maximizes the minimum volumetric reliability among consumption nodes; $NCNode$ = the number of consumption nodes of the network; NH = the number of hydraulic time intervals during the period of analysis; $S_{i,h}$ = the volume of water supply at node i in hydraulic time interval h; $De_{i,h}$: the volume of water demand at node i in hydraulic time interval h. The first objective $F1$ of the developed optimization model maximizes the minimum of the nodal volumetric reliability of water supply among nodes of the network to assure uniformity of water distribution among the nodes of the network.

The second objective function:

$$Minimize \quad F2 = \left(\sum_{i=1}^{Nnode} \sum_{h=0}^{NH} Switch_{i,h} \right) + (1 - OF) \tag{2}$$

in which $F2$ = the objective function that minimizes the number of water supply shut downs and maximizes the safe water supply reliability in the network; $Switch_{i,h}$ = the index of water-supply interruption at node i in hydraulic time interval h, defined by Equation (3); $Nnode$ = the number of nodes of the network; OF = the safe water supply reliability of the WDN, defined by Equation (4). OF ranges between zero and one. The objective of minimizing $F2$ includes two parts. The integer part of $F2$ is the first term within parentheses on the right-hand side of Equation (2). It equals the total number of water supply interruptions. The fractional part is the second term within parentheses on the right-hand side of Equation (2). It measures the reliability of safe water supply in the network (OF). The value of $F2$ is equal to zero if there are no water supply interruptions in the network, while the reliability of safe water supply in the network is equal to its best value ($OF = 1$). Increasing the number of water-supply interruptions and reducing the value of OF increases the value of $F2$.

Definition of the index of index of water-supply interruption:

$$Switch_{i,h} = \begin{cases} 1 & if \quad SS_{i,h} + SS_{i,h+1} = 1 \\ 0 & Otherwise \end{cases} \quad h = 0, 1, \ldots, NH, \quad i = 1, 2, \ldots, Nnode \tag{3}$$

where $SS_{i,h}$, $SS_{i,h+1}$ = the water-supply index at node i and hydraulic time intervals h and $h + 1$, respectively (defined by Equation (6)).

The function OF:

$$OF = \left(\frac{\sum_{i=1}^{Nnode} \sum_{h=1}^{NH+ST} SWSI_{i,h}}{Nnode \times (NH + ST)} \right) \tag{4}$$

in which $SWSI_{i,h}$ = the index of safe water supply at node i in hydraulic time interval h; ST = the number of hydraulic time intervals during which continuous supply is simulated for determination of the influence of intermittent supply on water quality of the WDN (see water quality simulation section). The index of safe water supply ($SWSI_{i,h}$) is equal to 1, that is its best value, if the water demand of node i in hydraulic time interval h is fully satisfied ($SS_{i,h} = 1$) and the chlorine concentration exceeds $Cmin$ during hydraulic time interval h. If the demand of node i in hydraulic time interval h is fully satisfied but the chlorine concentration in node i during hydraulic time interval h falls below $Cmin$, then $SWSI_{i,h}$ is equal to the index of water quality at node i and hydraulic time interval h. If the demand of node i at hydraulic time interval h is not satisfied

($SS_{i,h} = 0$), $SWSI_{i,h}$ is equal to zero.

$$SWSI_{i,h} = SS_{i,h} \times SQ_{i,h} \tag{5}$$

where:

$$SS_{i,h} = \begin{cases} \delta_{i,m} & if \quad h \leq NH \\ 1 & if \quad h > NH \end{cases} \quad m = \lceil \frac{h}{Rh} \rceil \tag{6}$$

$$\delta_{i,m} = \{0, 1\} \quad i = 1, 2, \ldots, Nnode, \quad m = 1, 2, \ldots, M \tag{7}$$

$$Rh = \frac{Li}{Lh} \tag{8}$$

in which $Lh =$ the length of hydraulic time intervals; $Li =$ the length of allocation schedule time intervals; and $\delta_{i,m} =$ the decision variable of the optimization model that equals 0 when node i does not receive any water in time interval m of the allocation schedule, or equals 1 when the water demand of node i is fully satisfied in time interval m of the allocation schedule; $\lceil x \rceil =$ the integer function of x (i.e. the smallest integer greater than or equal to x); and $Rh =$ the ratio of the allocation schedule time interval to the hydraulic time interval, which is an integer coefficient.

The proposed model differentiates the hydraulic time intervals from the allocation schedule time interval because pragmatic limitations may limit the length of the allocation schedule time interval to not be the same as that of the hydraulic time interval. For instance, operators may be able to switch the supply of water not sooner than every four hours, while the demand may change every hour. This differentiation also increases flexibility in the operation of the water distribution network, and reduces the number of decision variables in the model and the computational burden of solving the optimization problem.

The index of water quality at node i in hydraulic time interval h is defined as follows:

$$SQ_{i,h} = \begin{cases} \dfrac{SC_{i,h}}{C\min} & if \quad \dfrac{SC_{i,h}}{C\min} < 1 \\ 1 & Otherwise \end{cases} \quad \begin{matrix} i = 1, 2, \ldots, Nnode, \\ h = 1, 2, \ldots, NH + ST \end{matrix} \tag{9}$$

$$SC_{i,h} = \min_{p} (C_{i,p}) \quad i = 1, 2, \ldots, Nnode, \quad (h-1) \times Rp \leq p < h \times Rp \tag{10}$$

in which $SC_{i,h} =$ the minimum of chlorine concentration at node i during hydraulic time interval h; $Cmin =$ the minimum allowable chlorine concentration in the network; $C_{i,p} =$ the chlorine concentration at node i in water quality monitoring time interval p; and:

$$RP = \frac{Lh}{Lp} \tag{11}$$

where $Rp =$ the number of water quality monitoring time intervals within a hydraulic time interval, and $Lp =$ the length of water quality monitoring time intervals.

The constraints of the model are as follows:

Pressure constraints:

$$P\min \leq P_{i,h} \leq P\max \tag{12}$$

in which $P_{i,h} =$ the pressure at node i at hydraulic time interval h; $P\max =$ maximum allowable pressure in the network; $P\min =$ minimum allowable pressure in the network.

Reservoir constraints:

Maximum storage:

$$0 \leq V_h \leq V\max \tag{13}$$

where $V_h =$ the volume of water stored in the supply reservoir at the start of the hydraulic time interval h; $V\max =$ the reservoir capacity;

Water balance in the reservoir:

$$V_{h+1} = V_h + I_h - O_h \tag{14}$$

where I_h and $O_h =$ the inflow to and outflow from the reservoir in hydraulic time interval h (volume units), respectively;

Final storage is not less than the initial storage.

$$V_{Final} \geq V_1 \tag{15}$$

in which $V_{Final} =$ the final water volume in the reservoir at the end of the intermittent operation period; $V_1 =$ the reservoir storage at the start of the intermittent operation period (this is an input parameter to the model).

Water quality simulation

Water quality is accounted for in the evaluation of the reliability of the network (*OF*) while the chlorine concentration in the reservoir (or at injection stations) is a predetermined value. This work simulates water quality in the WDN according to Solgi *et al.* (2016). Briefly, first-order reaction kinetics are applied if hydraulic and the concentration of chlorine in injection sources are cyclic, in which case water quality of the network is also periodic after a time *ST* from the beginning of simulation of the network (Boccelli *et al.* 1998). In addition, it is known that the water quality of the WDN prior to intermittent operation affects the water quality of the network in the course of the intermittent supply, and the effects of hydraulic transformations on residual chlorine concentration in the network are not exclusively limited to the intermittent period, and may affect the network even after the intermittent operation is over. Assessing the effect of intermittent operation on residual chlorine concentration encompasses three phases: first, simulation of the network in continuous mode when all demands are fully supplied during at least a time *ST* from the beginning of simulation (this phase stabilizes the residual chlorine concentration in the WDN and eliminates the effects of initial values). Second, the intermittent operation is simulated. Finally, the simulation of continuous supply is maintained until time *ST* after the end of intermittent supply for complete investigation of the effect of intermittent operation on the water quality of the WDN. The results of the first phase in simulation do not directly affect the value of *OF*. In fact, it is assumed that water is supplied continuously for a long time before the intermittent operation starts (see Solgi *et al.* 2016). However, the safe water supply reliability is evaluated during the intermittent utilization ($1 \leq h \leq NH$) and until time $NH + ST$ to assess the water quality status of the WDN after the end of the intermittent operation period.

Efficiency criteria for the assessment of the developed optimization model

This study applies several efficiency criteria including temporal reliability, volumetric reliability, resiliency, and vulnerability introduced by Solgi *et al.* (2016) to assess the results of the intermittent operation affecting water quality and quantity. Solgi *et al.* (2018) presented a discussion of the calculation of efficiency criteria for assessing intermittent operation of WDNs and its differences with the calculation of the efficiency of continuous water supply.

The efficiency criteria rely on the definition of system failure as: (1) not meeting the water demand, and (2) reduction of the chlorine concentration below *Cmin*.

The efficiency criteria are calculated as follows (Solgi *et al.* 2016):

Temporal reliability of the WDN (ω):

$$\omega = 100 \times \left(\frac{\sum_{i=1}^{NCNode} \sum_{h=1}^{NH} SS_{i,h}}{NCNode \times NH} \right) \tag{16}$$

The temporal nodal reliability (ω') (this is a geometric mean involving the *NCNode*-th root):

$$\omega' = 100 \times \sqrt[NCNode]{\prod_i \left(\frac{\sum_{h=1}^{NH} \begin{cases} 1 & if \quad S_{i,h} \geq De_{i,h} \\ 0 & Otherwise \end{cases}}{NH} \right)} \tag{17}$$

$$i = 1, 2, \ldots, NCNode$$

The network's water quality reliability (ψ):

$$\psi = 100 \times \left(\frac{\sum_{i=1}^{Nnode} \sum_{p=1}^{NP} \begin{cases} 1 & if \quad C_{i,p} \geq C\min \\ 0 & Otherwise \end{cases}}{NNode \times (NP)} \right) \tag{18}$$

where $NP =$ the number of water quality monitoring time intervals.

The nodal water-quality reliability (ψ') (this is a geometric mean involving the *NNode*-th root):

$$\psi' = 100 \times \sqrt[NNode]{\prod_i \left(\frac{\sum_{p=1}^{NP} \begin{cases} 1 & if \quad C_{i,p} \geq C\min \\ 0 & Otherwise \end{cases}}{NP} \right)} \tag{19}$$

$$i = 1, 2, \ldots, NNode$$

The network's volumetric reliability (ϕ):

$$\phi = \frac{\sum_{i=1}^{NCNode} \sum_{h=1}^{NH} S_{i,h}}{\sum_{i=1}^{NCNode} \sum_{h=1}^{NH} De_{i,h}} \tag{20}$$

The nodal volumetric reliability (ϕ') (this is a geometric mean involving the *NCNode*-th root):

$$\varphi' = \sqrt[NCNode]{\prod_{i} \frac{\sum_{h=1}^{NH} S_{i,h}}{\sum_{h=1}^{NH} De_{i,h}}} \quad i = 1, 2, \ldots, NCNode \tag{21}$$

The network's resiliency (γ):

$$\gamma = 100 \times \frac{\sum_{h=1}^{NH} \begin{cases} 1 & if \quad \sum_{i=1}^{NCNode} S_{i,h} < \sum_{i=1}^{NCNode} De_{i,h}, \\ & \quad \sum_{i=1}^{NCNode} S_{i,h-1} \geq \sum_{i=1}^{NCNode} De_{i,h-1} \\ 0 & Otherwise \end{cases}}{\sum_{h=1}^{NH} \begin{cases} 1 & if \quad \sum_{i=1}^{NCNode} S_{i,h} < \sum_{i=1}^{NCNode} De_{i,h} \\ 0 & Otherwise \end{cases}} \tag{22}$$

The nodal resiliency (γ') (this is a geometric mean involving the *NCNode*-th root):

$$\gamma' = 100 \times \sqrt[NCNode]{\prod_{i} \frac{\sum_{h=1}^{NH} \begin{cases} 1 \;\; if \;\; S_{i,h} < De_{i,h} \;\;,\;\; S_{i,h-1} \geq De_{i,h-1} \\ 0 \quad Otherwise \end{cases}}{\sum_{h=1}^{NH} \begin{cases} 1 \;\; if \;\; S_{i,h} < De_{i,h} \\ 0 \quad Otherwise \end{cases}}} \quad i = 1, 2, \ldots, NCNode \tag{23}$$

The water-quality resiliency (ρ) (this is a geometric mean involving the *Nnode*-th root):

$$\rho = 100 \times \sqrt[Nnode]{\prod_{i} \frac{\sum_{p=1}^{NP} \begin{cases} 1 \;\; if \;\; C_{i,p} < C\min \;\;,\;\; C_{i,p-1} \geq C\min \\ 0 \quad Otherwise \end{cases}}{\sum_{p=1}^{NP} \begin{cases} 1 \;\; if \;\; C_{i,p} < C\min \\ 0 \quad Otherwise \end{cases}}} \quad i = 1, 2, \ldots, Nnode \tag{24}$$

The water-quantity vulnerability (τ):

$$\tau = \max\left(\frac{De_{i,h} - S_{i,h}}{De_{i,h}}\right) \quad \begin{array}{c} i = 1, 2, \ldots NCNode, \\ h = 1, 2, \ldots NH, \\ S_{i,h} < De_{i,h} \end{array} \tag{25}$$

The water-quality vulnerability (σ):

$$\sigma = \max\left(\frac{C\min - C_{i,p}}{C\min}\right) \quad \begin{array}{c} i = 1, 2, \ldots Nnode, \\ p = 1, 2, \ldots NP \quad , \quad C_{i,p} < C\min \end{array} \tag{26}$$

The network's resiliency and reliability are calculated using arithmetic averages. The nodal efficiency criteria are calculated as the geometric means of the nodes of the network, so that the evaluated efficiency criteria provide a complete understanding of t performances of the whole network and the individual nodes.

In addition, for efficiency criteria pertinent to chlorine concentration, the criteria are estimated for all nodes of the network (*Nnode*) and not just consumption nodes (*NCNode*), because the residual chlorine concentration must be maintained in the required range throughout the network to disinfect the water during its travel from the reservoir to the consumption points.

The standard operation rule (Rule)

The performance of the developed optimization model was compared to the standard operation rule (Rule) obtained with the standard operation policy (SOP). Rule ranks the nodes of the network according to their water demands while the node with maximal water demand has the first priority. The nodal demands are supplied based on the amount of available water so that the demand of a node with specific priority is fully supplied when the demands of the nodes with higher priority can be satisfied (Solgi *et al.* 2015).

CASE STUDY

Tehran's WDN is used to test the developed optimization model under a water shortage scenario that poses intermittent operation. The schematic of this network is depicted in Figure 1. This network has 81 pipes and 78 nodes

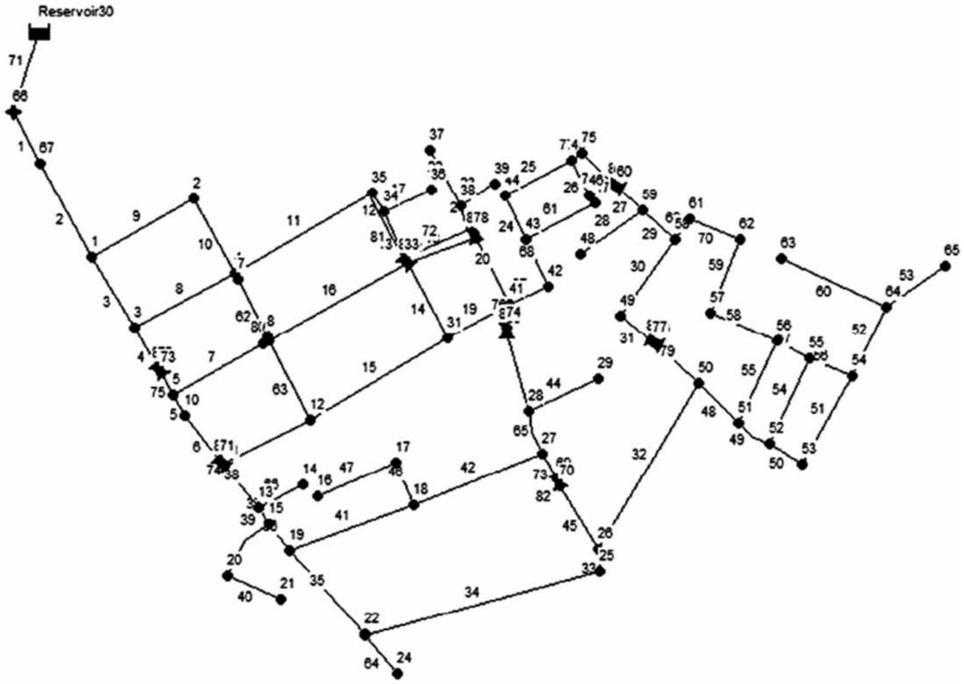

Figure 1 | Schematic of Tehran's WDN.

(*Nnode*), 65 of which are consumption nodes (*NCNode*). A reservoir with the capacity of 5,000 m^3 supplies Tehran's network. The WDN is driven by gravity. Other data pertinent to this WDN are available in Solgi *et al.* (2015). The implemented scenario is that of water shortage in which the available water is equal to 70% of the network's water demand. The network's demand equals 4,794 m^3/day and the available water is 3,360 m^3/day. The length of water shortage (intermittent operation) is equal to one day and the length of the water allocation time interval is four hours. Every four hours ($Li = 4$ hours), 560 cubic meters of water are poured into the reservoir. The starting hour of the intermittent operation is 1 a.m. The minimum and maximum allowable pressure heads are equal to 10 (*Pmin*) and 50 (*Pmax*) m, respectively. The length of the network's hydraulic cycle equals one day. The water quality simulation is executed with the assumption of first-order reaction kinetics. In addition, the bulk reaction parameter for chlorine was set equal to 0.55 day^{-1}, while the reaction of chlorine with pipes' walls was neglected. The minimum allowable chlorine concentration throughout the network was set equal to 0.2 mg/L, and the maximum allowable chlorine concentration at the reservoir, the only injection point in the WDN, equals 0.5 mg/L. The minimum chlorine concentration that is required in the reservoir to maintain chlorine concentration in the allowable range under continuous supply in the WDN equals 0.378 mg/L. This value was determined using the linear optimization model of Boccelli *et al.* (1998). The *ST* is estimated as equal to 96 hours (Solgi *et al.* 2016). This means that water quality stabilizes under continuous supply after four days ($ST = 96$ hours). The intermittent operation was started at $ST = 96$ hours after the start of the WDN simulation. Water demands were fully satisfied before intermittent operation. The chlorine concentration at the reservoir was kept identical to the continuous operation's during intermittent operation.

Single-objective optimization

The best possible values of the objective functions *F1* and *F2* were determined with the single-objective HBMO algorithm to evaluate the results of the MOHBMO (Bozorg-Haddad *et al.* 2016a, 2016b). The parameters of the applied algorithms are reported in Table 1. The results of five independent runs

Table 1 | The parameters of the HBMO and the MOHBMO

Algorithm	Parameter	Value
MOHBMO	Population	1,205
	Iteration	250
	Number of queens	5
	Crossover	Uniform
	Mutation	Uniform
	Probability of mutation	0.3
HBMO	Population	121
	Iteration	500
	Number of queens	1
	Crossover	Uniform
	Mutation	Uniform
	Probability of mutation	0.2

of the HBMO algorithm are listed in Table 2. It is seen in Table 2 that the small values of the coefficient of variation and the standard division for both objective functions show proper convergence of the HBMO algorithm. The best values of *F1* and *F2* are 0.6046 and 28.0313, respectively. This means concerning *F1* that in best possible situation every node of the network approximately meets about 60% of its water demand under a water shortage situation when the total available water is equal to 70% of the network's demand. Concerning *F2*, the minimum possible number of water supply switching needed to operate the Tehran's WDN under the defined water shortage scenario is equal to 28, and the value of the safe water supply reliability of the network (*OF*) (see Equation (4)) is equal to 0.9687.

Table 2 | The results of five independent runs of the HBMO algorithm for Tehran's network

	Objective	
Run	*F1*	*F2*
1	0.6046	28.0359
2	0.6046	28.0313
3	0.6046	28.0339
4	0.6046	28.0360
5	0.6046	28.0335
Best	0.6046	28.0313
Average	0.6046	28.0341
Worst	0.6046	28.0360
Standard division	0.0	0.00173
Coefficient of Variation	0.0	0.00006

Trade-off curve between F1 and F2

The MOHBMO algorithm was applied to find the Pareto-optimal solutions for operation of Tehran's WDN under the defined shortage scenario. Figure 2 depicts the final Optimal Pareto Front (OPF) of five independent runs of the MOHBMO and the unconstrained objective functions (in which the violation of the constraints of the optimization model does not affect the value of objective functions) pertinent to the rule of supply with constant priorities (Rule). The best values of *F1* and *F2* achieved with the HBMO algorithm are also shown in Figure 2. Substantial variability of the OPF is seen in Figure 2 so that the two corner points of the OPF of the MOHBMO correspond with the best possible values of *F1* and *F2*. Notice that the OPF is discrete. Figure 2 shows that the solution obtained by the Rule is dominated by the OPF of the MOHBMO. All the solutions of the OPF of the MOHBMO algorithm are feasible. It is also seen in Figure 2 that the value of *F1* (the minimum of the volumetric reliability of water supply among all nodes of the network) of Solution 1 is equal to zero while the number of supply switching (the integer part of *F2*) of Solution 1 is equal to 28. Figures 3 and 4 graph the envelope curve of the change of the reservoir storage and the envelope curve of the nodal pressure during the intermittent operation for all solutions of the OPF, respectively. It can be seen in Figure 3 that the reservoir storage is always equal to or greater than zero and less than the reservoir capacity for the all solutions of the OPF. Figure 4 shows that the pressures are always in the allowable range for all solutions of the OPF. Evidently all the solutions of the OPF satisfy the constraints of the optimization model.

Reduction of the frequency of supply interruption in contrast to the uniformity of water distribution among consumers

Figure 5 depicts the volumetric reliability of water supply for all nodes of the network for the two corner points of the OPF (Solution 1 and Solution 25) and a middle point of the OPF (Solution 10) chosen based on the method

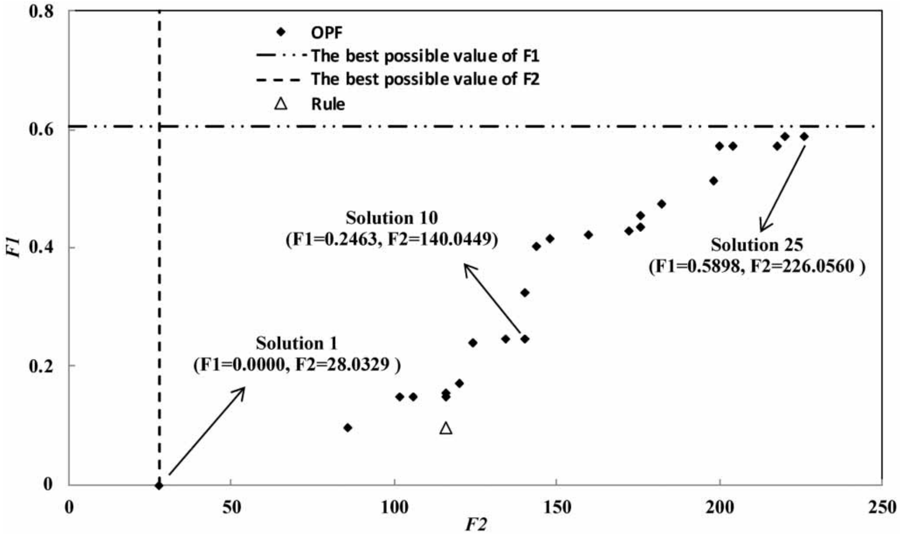

Figure 2 | The final optimal Pareto front of five independent runs of the MOHBMO.

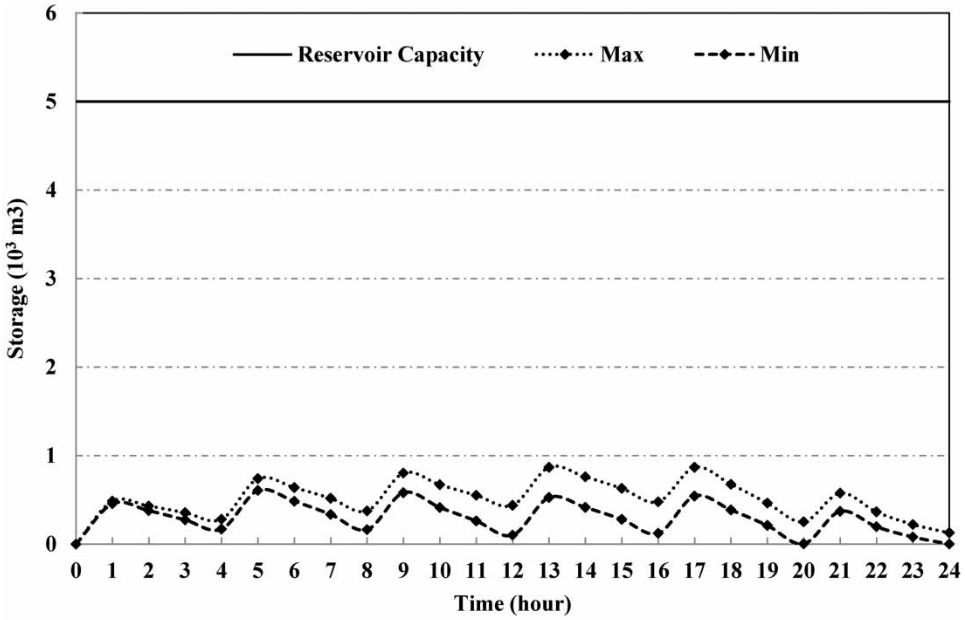

Figure 3 | The envelope curve of the change of the reservoir storage during the intermittent operation for all solutions of the optimal Pareto front.

presented by Young (1993). The latter three points are highlighted in Figure 2. It is seen in Figure 5 that the volumetric reliability of water supply is equal to 100% for most nodes of the network but it is equal to zero for 11 nodes of Solution 1. The uniformity of water supply among nodes of the network improves and there are no nodes without water supply in Solution 10, which is the middle point of the OPF. The value of *F1* of Solution 10 is equal to 0.2463 and the number of water supply switching increases to 140, which is 115 times larger than that of Solution 1. The uniformity of water supply among nodes of the network is much better and the value of *F1* increases to 0.5898 in

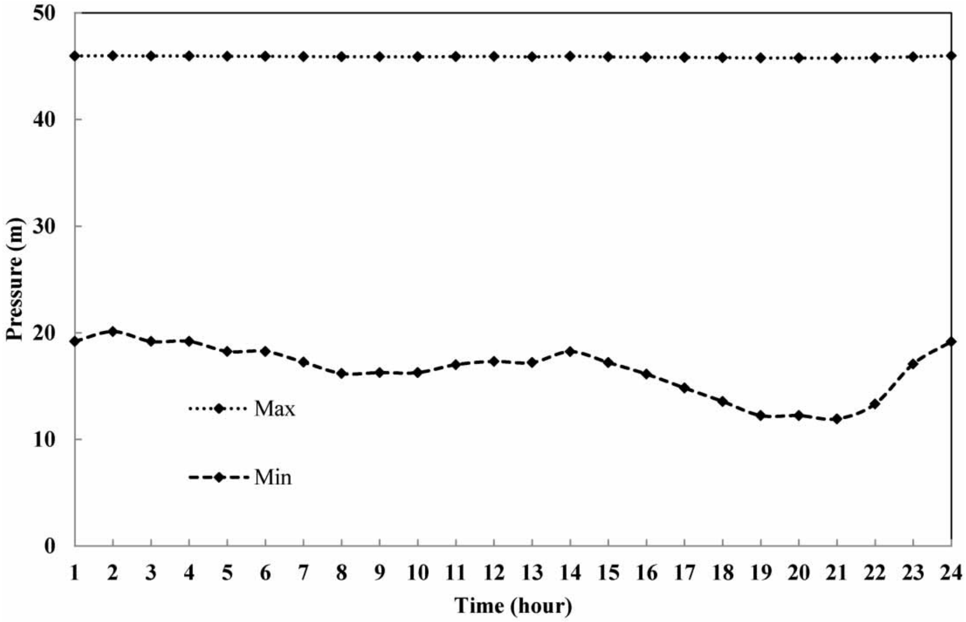

Figure 4 | The envelope curve of the nodal pressure during the intermittent operation for all solutions of the optimal Pareto front.

Solution 25 but the number of supply interruptions (the integer part of *F2*) of Solution 25 increases significantly to 226. Figure 6 shows the number of hours of supply in the network for solutions 1, 10 and 25 that are highlighted in Figure 2. It is seen in Figure 6 that the uniformity of hours of water supply among nodes of the network improves from Solution 1 to Solution 25. Several nodes have access to water 24 hours a day in Solution 1, but there are several nodes that do not have water during the intermittent operation. All the nodes of the network have access to water at least 8 hours a day in Solution 10, but water is distributed non-uniformly and the hours of access to water vary from 8 to 24. The uniformity of hours of water supply among nodes of the network is much better in Solution 25, wherein all nodes of the network have access to water at least 16 hours a day.

The purpose of improving the uniformity of water supply among consumers under intermittent operation is in conflict with the purpose of decreasing the frequency of supply switching. Given the direct and indirect costs of water supply interruption, operators are inclined to choose solutions that have fewer water supply interruptions and connections at the expense of water distribution among consumers that is less uniform than otherwise. On the other hand, consumers benefit from uniform distribution of water. These results demonstrate that there is a conflict of interests between operators and customers.

Safe water supply reliability of the network

Figure 7 depicts the value of the safe water supply reliability of the network (*OF*) for all solutions of the OPF and for the solution of the Rule. It is seen in Figure 7 that the values of *OF* related to all solutions of the OPF are larger (better) than those of the Rule. It was shown in previous sections that the solutions associated with the Rule are dominated by the OPF of the MOHBMO algorithm. Therefore, the performance of the developed optimization model is superior based on all objectives including minimizing the number of valve shutdowns (interrupting water supply), maximizing the minimum of the volumetric reliability of water supply among the WDN's nodes, and maximizing the WDN's safe water supply reliability.

Increasing the value of the safe water supply reliability of the network does not alone guarantee a satisfactory water provision for all consumers in the network. It is seen in Figure 7 that Solution 1 has the best value of safe water supply reliability of the network (*OF*), but Figures 6 and 5 demonstrate that there are several nodes without any supply during intermittent operation in Solution 1.

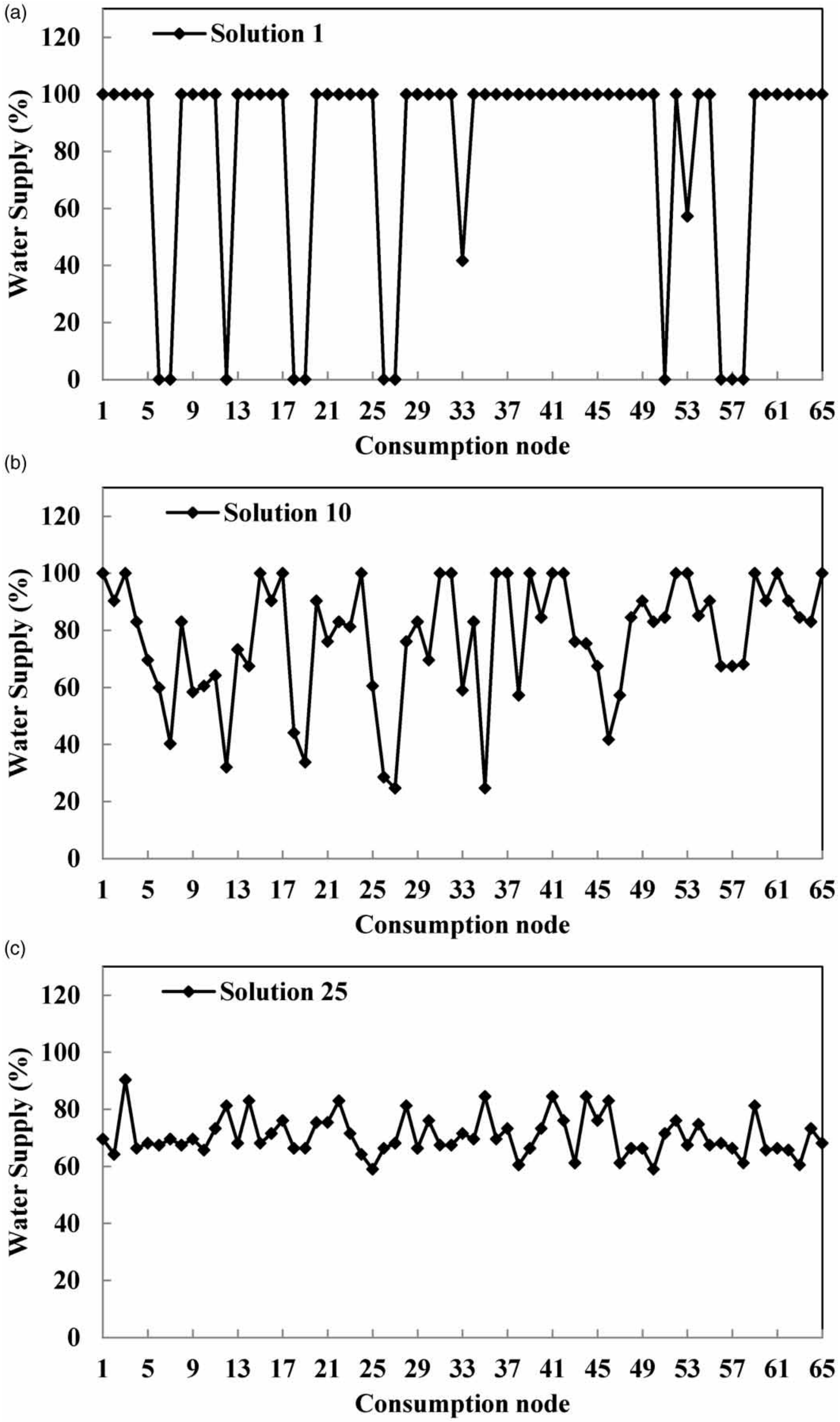

Figure 5 | The volumetric reliability of water supply for nodes of the network for Solutions (a) 1; (b) 10 and (c) 25.

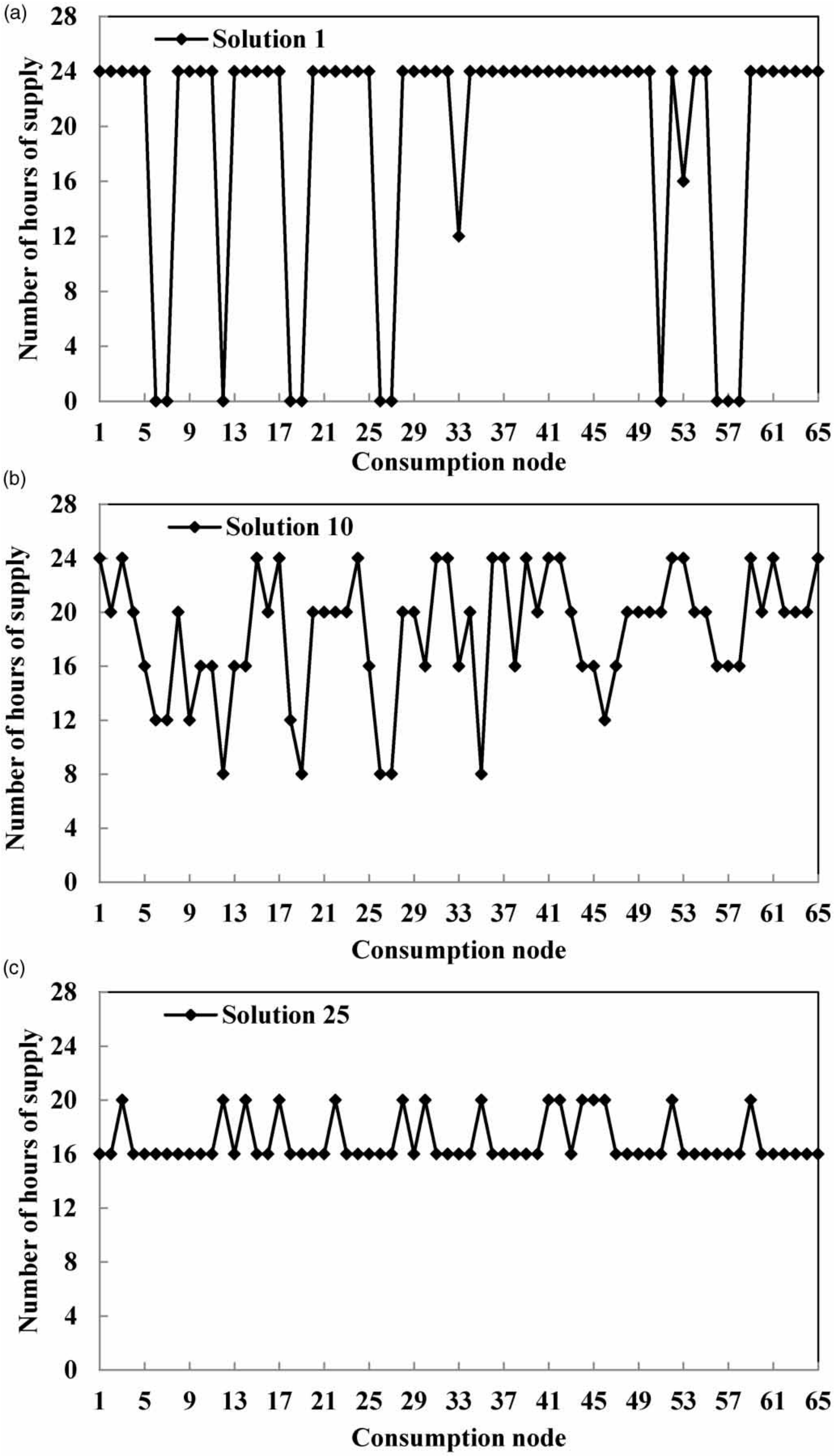

Figure 6 | The numbers of hours of water supply in the network for Solutions (a) 1; (b) 10 and (c) 25.

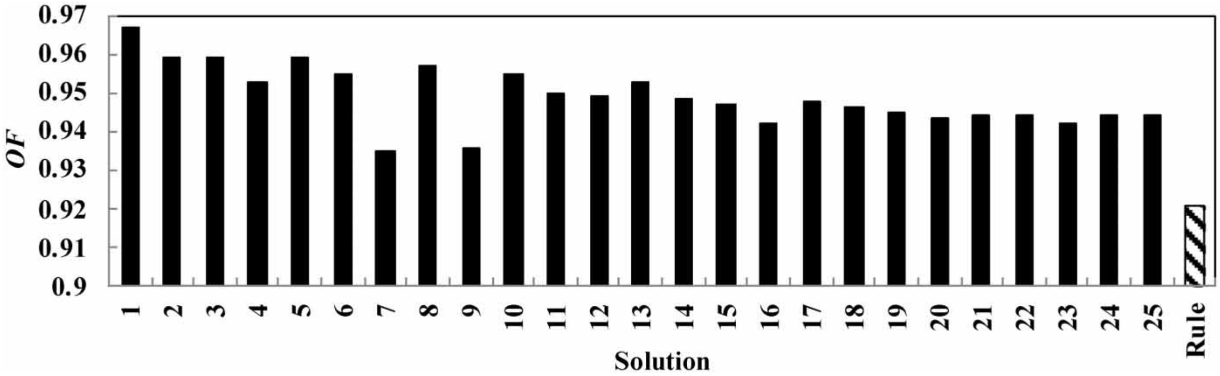

Figure 7 | The value of the safe water supply reliability of the network [*OF*, Equation (4)] for all solutions of the optimal Pareto front of the MOHBMO and Rule.

Therefore, the selection of a water allocation schedule for operating WDNs must consider the performance of all its nodes under intermittent utilization. In other words, in assessing the efficiency under intermittent operation, considering network reliability solely is not sufficient, and the reliability of all nodes should also be taken into consideration.

Qualitative efficiency criteria

All the solutions of the OPF must be conducive to improving the water quality of the WDN. This is so because the residual chlorine concentration must be maintained in the required range throughout the network for disinfection purposes regardless of the number of supply switches and the level of uniformity of water distribution among consumers. Figure 8 portrays the values of the qualitative efficiency criteria including the network's qualitative reliability (ψ), the nodal qualitative reliability (ψ'), the qualitative resiliency (ρ) and the qualitative vulnerability (σ) for all solutions of the OPF of the MOHBMO and the solution associated with the Rule. It is seen in Figure 8 that the values of the network qualitative reliability (ψ), the nodal qualitative reliability (ψ'), and the qualitative resiliency (ρ) for all solutions of the OPF are close to 100% (the best possible value) and they also are larger (better) than those of the Rule. Also, the value of the qualitative vulnerability (σ) of all the OPF's solutions except solution 1 are equal to or less (better) than that of the Rule. For example, the value of the qualitative vulnerability of Solution 6 is approximately equal to zero, and the other qualitative efficiency criteria for Solution 6 are equal to 100%. Solution 6 maintains the chlorine concentration above *Cmin* throughout the network under intermittent operation. It is also seen in Figure 8 that different water allocation schedules have different effects on water quality situation of the network. Therefore, water quality must be considered when choosing an allocation schedule for intermittent operation of WDNs.

Quantitative efficiency criteria

Figure 9 shows the values of the quantitative efficiency criteria including the network's temporal reliability (ω), the nodal temporal reliability (ω'), the network volumetric reliability (φ), the nodal volumetric reliability (φ'), the network resiliency (γ), the nodal resiliency (γ') and the quantitative vulnerability (τ) for all solutions of the OPF of the MOHBMO and the solution corresponding to the Rule. These criteria show water demands are satisfied during the water shortage. It is seen in Figure 9 the value of all nodal quantitative efficiency criteria of all the OPF's solutions calculated at the nodes are better than those of the Rule. This is a result of considering *F1* in the optimization model that maximizes the minimum of the volumetric reliability of water supply among the WDN's nodes. The reliabilities of the OPFs solutions are better than those of the Rule, which shows the better performance of the developed optimization model compared to the Rule's. Only the values of the nodal temporal reliability and the nodal volumetric reliability for Solution 1 are equal to zero and are less than those of the Rule; yet, Solution 1 is still superior to the Rule's because of the

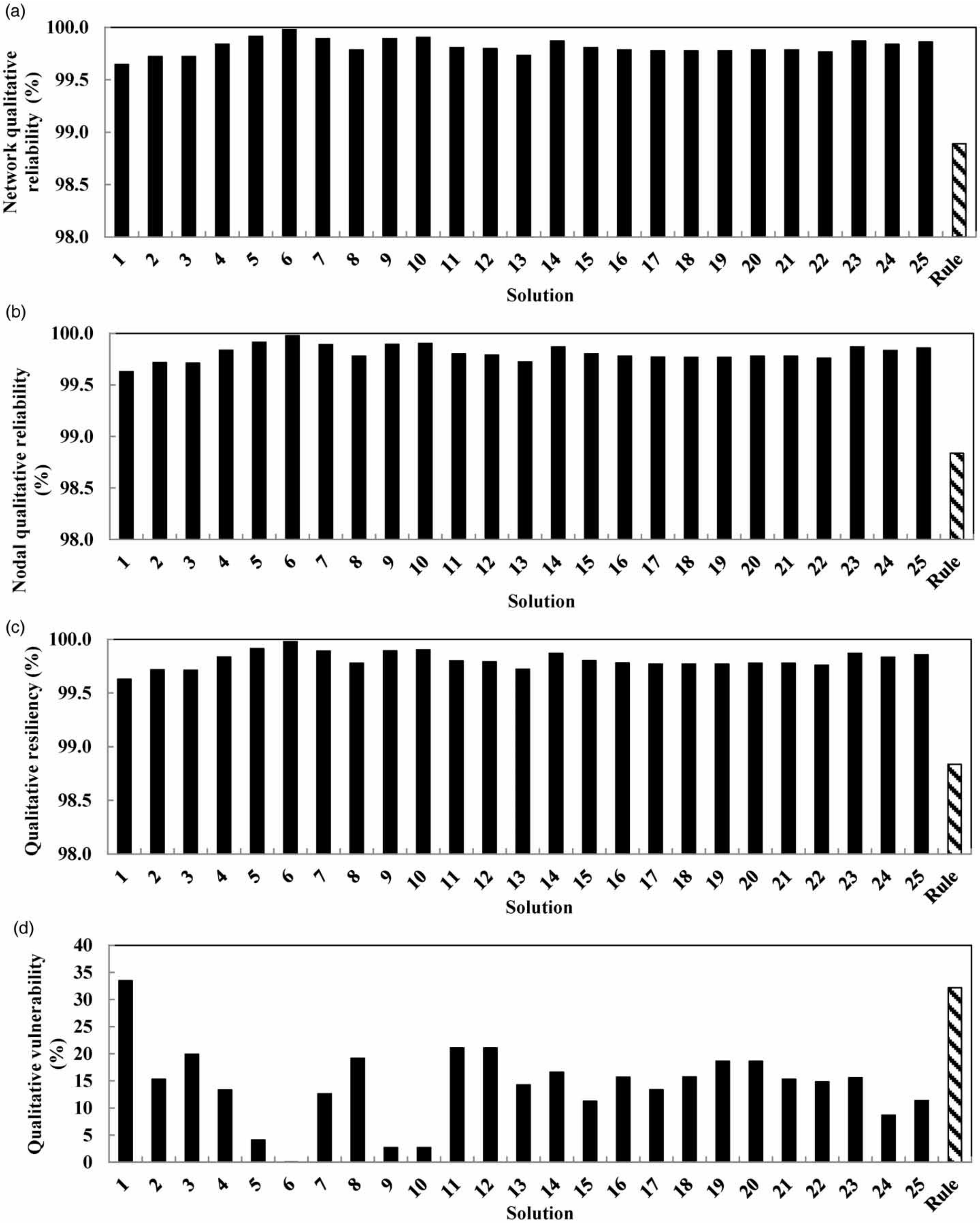

Figure 8 | The values of the qualitative efficiency criteria for all solutions of the optimal Pareto front of MOHBMO and Rule.

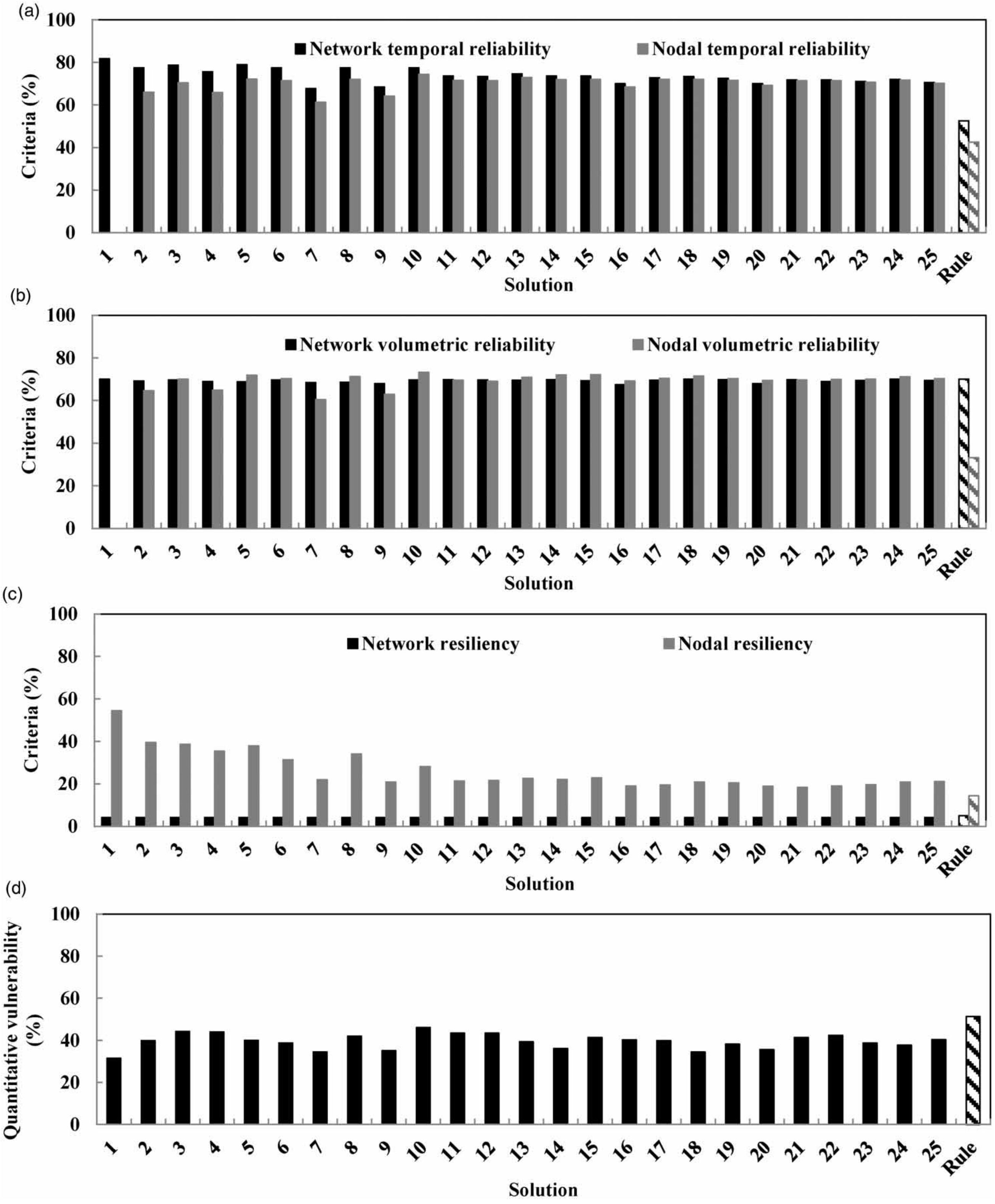

Figure 9 | The values of the quantitative efficiency criteria for all solutions of the optimal Pareto front of MOHBMO and Rule.

number of supply switches involved (Figure 3). It is also seen in Figure 9 that the values of the quantitative vulnerability for all the OPF's solutions of the MOHBMO are less (better) than those of the Rule.

The network's volumetric reliability, which is equal to the ratio of the total water supplied to the network's total volumetric demand, is approximately equal to 70% for all the OPF's solutions under water shortage. This means that the MOHBMO algorithm delivered to consumers all the available water during water shortage as expected of an optimal solution.

CONCLUDING REMARKS

This work developed a multi-objective optimization model for the operation of intermittent water distribution networks (WDNs) under water shortages. The performance of the developed optimization model was investigated in a real WDN and compared with that of the standard operation rule (Rule). The solution of the developed optimization model was achieved with the multi-objective honey-bee mating optimization algorithm (MOHBMO). The superiority of the developed optimization model on the Rule was proven based on the studied qualitative and quantitative efficiency criteria. The Pareto-optimal front of the developed optimization model dominated the solution of the Rule while satisfying the reservoir and pressure constraints. Furthermore, this study's results demonstrated that improving the uniformity of water supply among consumers under water shortage is in conflict with minimizing the frequency of water-supply interruption, which can be seen as a conflict of interests between operators and consumers. Moreover, this study revealed that the efficiency of intermittent WDNs cannot be thoroughly assessed only based on network reliability, and reliability of all nodes must also be individually taken into account. In addition, it was shown that various water allocation schedules have different influences on water quality situation of the network. Therefore, water quality must be considered to plan operation of intermittent WDNs. Finally, we propose the result of the presented optimization model to be further investigated using pressure-based simulators in the presence of leakage.

ACKNOWLEDGEMENTS

The authors thank Iran's National Science Foundation (INSF) for its financial support of this research.

This material is based upon work supported by the University of Tehran Research Institute under Award No. 73148796/1/07. We would like to thank the University of Tehran Research Institute for financial support.

CONFLICT OF INTERESTS

On behalf of all authors, the corresponding author states that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 23 March 2020; accepted in revised form 6 July 2020. Available online 21 July 2020