Title
Intermittent Operation of Water Distribution Networks Considering Equanimity and Justice Principles

Journal
Journal of Pipeline Systems Engineering and Practice, 6(4)

ISSN
1949-1190

Authors
Solgi, Mohammad
Haddad, Omid Bozorg
Seifollahi-Aghmiuni, Samaneh
et al.

Publication Date
2015-11-01

DOI
10.1061/(asce)ps.1949-1204.0000198

Peer reviewed

Intermittent Operation of Water Distribution Networks Considering Equanimity and Justice Principles

Mohammad Solgi[1]; Omid Bozorg Haddad[2]; Samaneh Seifollahi-Aghmiuni[3]; and Hugo A. Loáiciga[4]

Abstract: Water shortages cause intermittent operation of distribution networks in many developing countries. Under limited economic resources and frequent water shortages, the expansion of water supply for municipal use is slow and sometimes infeasible, hence supply management becomes a viable solution for operating water supply networks. One form of demand management is intermittent supply, wherein some parts of the water supply network are cut off from service during certain times and the entire network is in service at other times. Because intermittent water supply causes consumer dissatisfaction and complicates the operation of water supply networks, it is crucial to consider the principles of equanimity and justice in its implementation. This paper develops an optimization model to find the optimal scheduling of intermittent supply that reaches the maximum number of network nodes with desired pressure under various conditions of water shortage and considering the principles of equanimity and justice in a water distribution network. The network operation optimization problem is solved using the honey bee mating optimization (HBMO) algorithm linked to in a hydraulic simulator. The efficiency of the developed scheduling method is demonstrated by implementing it to two distribution networks considering different scenarios of water shortage. **DOI: 10.1061/(ASCE)PS.1949-1204.0000198.** © *2015 American Society of Civil Engineers.*

Author keywords: Distribution network; Water shortage; Intermittent supply; Equanimity; Justice; Optimization; Mathematical models.

Introduction

The main challenge for municipal water supply systems is that of meeting existing demands. This challenge is aggravated by hydrological droughts, natural hazards (such as earthquakes), human events (such as war), and pollution accidents (Hou et al. 2013). If the expansion or repair of a compromised water supply system is infeasible, water rationing may become inevitable. One of the rationing methods is intermittent water supply. A continuous water supply system features a distribution network that is pressurized 24 h every day and meets consumer demands permanently. On the other hand, when the total amount of available water is less than users' demands, operators must reduce the water supply to some parts of the network regularly during parts of the day. This is the mode of operation of an intermittent water supply system, which this paper seeks to optimize by introducing novel methodology.

Several optimization techniques have been recently reported and applied in many fields of water resources systems such as reservoir operation (Bozorg Haddad et al. 2011a; Fallah-Mehdipour et al. 2011b, 2012a, 2013a), hydrology (Orouji et al. 2013), project management (Bozorg Haddad et al. 2010b; Fallah-Mehdipour et al. 2012b), cultivation rules (Bozorg Haddad et al. 2009; Noory et al. 2012; Fallah-Mehdipour et al. 2013b), pumping scheduling (Bozorg Haddad et al. 2011b), hydraulic structures (Bozorg Haddad et al. 2010a), water distribution networks (WDNs) (Bozorg Haddad et al. 2008; Fallah-Mehdipour et al. 2011a; Seifollahi-Aghmiuni et al. 2011, 2013), operation of aquifer systems (Bozorg Haddad and Mariæo 2011), site selection of infrastructures (Karimi-Hosseini et al. 2011), and algorithmic developments (Shokri et al. 2013). Only a few of these works dealt with the intermittent operation of water distribution networks considering the equanimity and justice principles.

Batish (2003) presented a method for designing the intermittent water supply networks in northern India. Sashikumar et al. (2003) analyzed intermittent water supply using field experiments. Totsuka et al. (2004) described problems of intermittent supply and classified them. Jeong and Abraham (2006) developed a model to identify intermittent supply optimal programs using the genetic algorithm (GA) and *EPANET* (Rossman 2000). Andey and Kelkar (2009) studied effects of continuous and intermittent supply of municipal water consumers in four Indian cities. Ameyaw et al. (2013) developed a multiobjective optimization model to improve equanimity and minimize costs in intermittent water distribution networks.

In the cited studies the intermittent supply was zonal. The zoning method has several important quantitative and qualitative problems such as rise of pollution through seepage due to low pressure and the creation of negative pressures, the uneven distribution of water pressure in the pipe network, drastic pressure changes, network failure to supply fire demands in zones of water cutoff, variations of the Hazen-Williams coefficient due to mixing of air and water in the network's pipes, inappropriate performance of water measuring equipment, and lack of existing simulation software for modeling of these networks (Batish 2003; Sashikumar et al. 2003; Totsuka et al. 2004; Soltanjalili et al. 2013).

[1]M.Sc. Student, Dept. of Irrigation and Reclamation Engineering, Faculty of Agricultural Engineering and Technology, College of Agriculture and Natural Resources, Univ. of Tehran, Karaj, 3158777871 Tehran, Iran. E-mail: Solgi_Mohammad@ut.ac.ir

[2]Associate Professor, Dept. of Irrigation and Reclamation Engineering, Faculty of Agricultural Engineering and Technology, College of Agriculture and Natural Resources, Univ. of Tehran, Karaj, 3158777871 Tehran, Iran (corresponding author). E-mail: OBHaddad@ut.ac.ir

[3]Ph.D. Candidate, Dept. of Irrigation and Reclamation Engineering, Faculty of Agricultural Engineering and Technology, College of Agriculture and Natural Resources, Univ. of Tehran, Karaj, 3158777871 Tehran, Iran. E-mail: Seifollahi@ut.ac.ir

[4]Professor, Dept. of Geography, Univ. of California, Santa Barbara, CA 93106-4060. E-mail: Hugo.Loaiciga@ucsb.edu

Note. This manuscript was submitted on June 30, 2014; approved on December 2, 2014; published online on January 13, 2015. Discussion period open until June 13, 2015; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Pipeline Systems Engineering and Practice***, © ASCE, ISSN 1949-1190/04015004(11)/$25.00.

Metaheuristic optimization algorithms are useful tools for solving optimization models in WDNs. One of them is the honey bee mating optimization (HBMO) algorithm inspired by the life cycle of honey bees in nature. It has been used in many researches related to distribution networks in recent years and its superiority is proven compared with other algorithms such as GA (Bozorg Haddad et al. 2006, 2008; Jahanshahi and Bozorg Haddad 2008; Karimi et al. 2013).

The purpose of this research is to develop an optimization model to find the optimal scheduling of intermittent supply considering the principles of equanimity and justice in WDNs. The next section describes the meaning of equanimity and justice in the context of this paper. Thereafter, this paper develops an optimization model to find the optimal scheduling of intermittent supply. This model is solved using the HBMO algorithm and is tested with two WDNs under various scenarios to assess its efficiency.

Description of Equanimity and Justice

Equanimity is defined as a condition in which the ratio of the total water supply to the total water demand is equal at all the nodes of a WDN during a period of intermittent supply [Eq. (1)]

$$\frac{\mathrm{TS}_i}{\mathrm{TDe}_i} = \frac{\mathrm{TS}_{i'}}{\mathrm{TDe}_{i'}} \qquad i, i' = 1, 2, \ldots, N_i \tag{1}$$

in which N_i = number of consumption nodes in the distribution network; TS_i and TDe_i = total supply and total demand in the ith nodes during the intermittent supply period, respectively (units of volume or time); and $\mathrm{TS}_{i'}$ and $\mathrm{TDe}_{i'}$ = total supply and total demand in the i'th nodes during the intermittent supply period, respectively (units of volume or time).

Justice refers to a condition in which the ratio of the total supply to the total demand in each node of a WDN is greater than or equal to a specific value during a period of intermittent supply [Eq. (2)]

$$\frac{\mathrm{TS}_i}{\mathrm{TDe}_i} \geq \theta \times R \qquad i = 1, 2, \ldots, N_i \tag{2}$$

$$R = \frac{\mathrm{TA}}{\mathrm{TD}} \tag{3}$$

where θ = justice limit, which can be between 0 and 1; TA = total available water during the intermittent supply period in a network (units of volume or time); TD = total water demand during the intermittent supply period in a network (units of volume or time); and R = ratio of the TA to the TD. Equanimity and justice are considered in the scheduling of intermittent supply by using Eqs. (1) and (2) in the optimization model for an intermittent WDN. Eqs. (1) and (2) are independent. If values of supply, demand, and availability of water are expressed in volumetric units, then equanimity and justice are also expressed in volumetric units. If the duration of supply, demand, and the availability of water are used, then equanimity and justice are expressed in units of time.

Optimization Model

The optimal scheduling of intermittent supply distributes water among the nodes at different times during the intermittent supply period so that the nodal demand is met with the desired pressure in each node when water is available. Moreover, the principles of equanimity and justice are taken into account in the operation of WDNs to achieve optimal scheduling of water supply. The developed optimization model is described in the following sections.

Objective Function

The objective function of the developed optimization model is given by Eq. (4), whose components are defined as follows ($i = 1,2, \ldots, N_i$):

$$\text{Maximize OF} = K_1 \times \frac{\sum_{h=1}^{N_h} \sum_{i=1}^{N_i} \mathrm{MP}_{i,h} \times \alpha_{i,h}}{N_h \times N_i} - K_2 \times \mathrm{COV}_{R_i} \tag{4}$$

$$\mathrm{COV}_{R_i} = \frac{\sigma_{R_i}}{\mu_{R_i}} \tag{5}$$

$$R_i = \sum_{h=1}^{N_h} \mathrm{MP}_{i,h} \times \alpha_{i,h} \tag{6}$$

$$\mathrm{MP}_{i,h} = \begin{cases} \frac{P_{i,h}}{P\min_i} & \frac{P_{i,h}}{P\min_i} < 1 \\ 1 & \frac{P_{i,h}}{P\min_i} \geq 1 \end{cases} \qquad h = 1, 2, \ldots, N_h \tag{7}$$

$$\alpha_{i,h} = \delta_{i,m} \qquad (m-1) \times L_i \leq h < m \times L_i \qquad \begin{matrix} h = 1, 2, \ldots, N_h \\ m = 1, 2, \ldots, M \end{matrix} \tag{8}$$

$$L_i = C \times L_s \tag{9}$$

$$\delta_{i,m} = \{0, 1\} \qquad m = 1, 2, \ldots, M \tag{10}$$

$$E\mathrm{Pat}_{i,h} = \alpha_{i,h} \times \mathrm{Pat}_{i,h} \qquad h = 1, 2, \ldots, N_h \tag{11}$$

in which OF = objective function; $\mathrm{MP}_{i,h}$ = pressure index at node i in hydraulic interval h; $\alpha_{i,h}$ = index of demand supply at node i in hydraulic interval h; R_i = summation of the products of the pressure index $\mathrm{MP}_{i,h}$ times the demand index ($\mathrm{MD}_{i,h}$) at node i during all hydraulic intervals; COV_{R_i} = coefficient of variation of R_i; σ_{R_i} and μ_{R_i} = standard deviation and the average R_i, respectively; $P_{i,h}$ = pressure at node i in hydraulic interval h (m); $P\min_i$ = minimum allowable pressure at node i; K_1 and K_2 = positive real coefficients that are used as weighting coefficients and show the importance of the two objectives in Eq. (4); $\delta_{i,m}$ = decision variable of the optimization model that equals 0 (failure to supply water at node i during the time interval of intermittent supply) or 1 (success in supplying water at node i during the interval of intermittent supply); L_i = duration of the time intervals of intermittent supply; L_s = duration of the hydraulic time interval; C = ratio of L_i to L_s; N_h = total number of hydraulic intervals in an intermittent supply period; M = total number of intervals of intermittent supply during a period; $\mathrm{Pat}_{i,h}$ = coefficient of the consumption time pattern at node i in hydraulic interval h; and $E\mathrm{Pat}_{i,h}$ = coefficient of the modified time pattern at node i in hydraulic interval h, used in the hydraulic computations. If the water demand is not met in the hydraulic interval h, then $E\mathrm{Pat}_{i,h}$ equals 0 due to the 0 value of $\alpha_{i,h}$, and if $\alpha_{i,h}$ is equal to 1, i.e., water demand is met in the hydraulic interval h, the value of $E\mathrm{Pat}_{i,h}$ is equal to $\mathrm{Pat}_{i,h}$, which is the consumption coefficient of variation in different hydraulic intervals. The value of $E\mathrm{Pat}_{i,h}$ is entered to the hydraulic simulator (*EPANET*) as the consumption coefficient of variation for network hydraulic simulation and calculating the pressure in each hydraulic interval.

The objective function has two parts. The first part is the summation term on the right-hand side of Eq. (4). It is related to the maximization of water supply in a WDN. The second part is the term with a preceding negative sign on the right-hand side of Eq. (4). It is related to minimizing the coefficient of variation of the total number of water supplies in the nodes of the WDN. The best value of the objective function is achieved when the nodal demands are completely met with desired pressure at all nodes and in all intervals. In this situation, the values of the first and second parts are equal to 1 and 0, respectively, and the value of the objective function would equal one if the values of K_1 and K_2 are selected equal to 1.

Model Constraints

Those solutions that maximize the number of consumption nodes and exhibit a better time equanimity in water supply are dominant. Yet, the objective function might converge to solutions that meet lower demands but do not supply the consumption nodes at peak times. In this situation, the value of the objective function increases but the water volume supplied in a node might not be enough compared with the total nodal demand during the intermittent supply period. In other words, the proposed objective function [Eq. (4)] considers temporal equanimity through its second part directly and temporal justice by increasing the number of nodal supplies indirectly. Considering only the temporal equanimity and justice in WDNs in which water demand changes during the day at various nodes is not desirable. Therefore, a constraint is added to the optimization model that focuses on the volume justice in a WDN [Eq. (12)]

$$\frac{\mathrm{SQ}_i}{\mathrm{SDe}_i} \geq \mathrm{VL(RW)} \qquad i = 1, 2, \ldots, N_i \tag{12}$$

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

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

$$\mathrm{SQ}_i = \sum_{h=1}^{N_h} Q_{i,h} \qquad \mathrm{SDe}_i = \sum_{h=1}^{N_h} \mathrm{De}_{i,h} \qquad i = 1, 2, \ldots, N_i \quad h = 1, 2, \ldots, N_h \tag{15}$$

in which $Q_{i,h}$ = value of the volume supply at node i and in hydraulic interval h; $\mathrm{De}_{i,h}$ = demand value at the node i in hydraulic interval h; SQ_i and SDe_i = summation of the $Q_{i,h}$ and $\mathrm{De}_{i,h}$ at node i during all hydraulic intervals, respectively; RW = ratio of the total available water volume (TVA) to the total volume of demand in the network (TVD) during the intermittent supply period; and VL(RW) = minimum volume ratio of water supply corresponding to RW considering justice at each node. If the value of θ is set equal to 1, Eq. (12) causes the model to find solutions in which the percentage of the water shortage at each node is equal to or less than the percentage of the water shortage in the network during the intermittent supply period.

The value of the objective function decreases when the pressure at node i in hydraulic time interval h becomes less than a specified $P\min_i$. The value of the pressure must be greater than or equal to an allowable positive threshold. Therefore, Eq. (16) is added to the optimization model

$$0 \leq P_{i,h} \leq P\max_i \qquad i = 1, 2, \ldots, N_i \qquad h = 1, 2, \ldots, N_h \tag{16}$$

in which $P\max_i$ = maximum allowable pressure in the network.

The following constraints are related to the reservoir volume (this supplies the WDN) during the shortage period, which must be considered in the model

$$0 \leq S_h^j \leq S_{\max}^j \qquad j = 1, 2, \ldots, N \quad h = 1, 2, \ldots, N_h \tag{17}$$

$$S_{h+1}^j = S_h^j + I_h^j - \mathrm{Re}_h^j \qquad j = 1, 2, \ldots, N \quad h = 1, 2, \ldots, N_h \tag{18}$$

$$S_{\text{final}}^j \geq S_1^j \qquad j = 1, 2, \ldots, N \quad h = 1, 2, \ldots, N_h \tag{19}$$

in which N = total number of existing reservoir in the system; S_h^j and S_{h+1}^j = stored water volume in the reservoir j at the beginning of the hydraulic intervals h and $h+1$, respectively; $S_{\max}^j$ = storage capacity of the reservoir j, which is an input to the model; I_h^j = inflow to reservoir j during the hydraulic interval h; Re_h^j = water release from reservoir j during hydraulic interval h; S_{final}^j = existing water volume in the reservoir j at the end of the intermittent supply period; and S_1^j = initial volume of the reservoir j at the beginning of the intermittent supply period, which is a known value.

There may be water shortage after an intermittent supply period. For this reason the existing water volume at the end of the intermittent supply period must be equal to or greater than the reservoir volume at the beginning of this period. In this instance, if the water shortage continues and Eq. (19) is satisfied, the previous scheduling of water supply in the WDN is repeatedly used in its operation.

It is possible to simulate a WDN using *EPANET* provided that the network's pipes are pressurized during an intermittent supply period. On the other hand, if there is a negative pressure at a node due to a change in scheduling of water deliveries, Eq. (16) causes cause the solution to become infeasible.

Efficiency Criteria: Reliability and Resiliency

Two efficiency criteria are used in this paper: reliability and resiliency. Hashimoto et al. (1982) defined the temporal reliability of a water resources system as the probability of no failure during the operation period. Duckstein and Plate (1988) defined the quantitative reliability as the percentage of demand satisfied by water supply. The temporal and quantitative reliability are calculated in the entire network [Eqs. (20) and (22), respectively] and at the consumption nodes of the network [Eqs. (21) and (23), respectively]

$$\omega_\beta = \frac{100}{N_h} \times \sum_{h=1}^{N_h} \begin{cases} 1 & \sum_{i=1}^{N_i} Q_{i,h} \geq \beta \times \sum_{i=1}^{N_i} \mathrm{De}_{i,h} \\ 0 & \sum_{i=1}^{N_i} Q_{i,h} < \beta \times \sum_{i=1}^{N_i} \mathrm{De}_{i,h} \end{cases} \tag{20}$$

$$\omega'_\beta = 100 \times \prod_{i=1}^{N_i} \left(\frac{\sum_{h=1}^{N_h} \begin{cases} 1 & Q_{i,h} \geq \beta \times \mathrm{De}_{i,h} \\ 0 & Q_{i,h} < \beta \times \mathrm{De}_{i,h} \end{cases}}{N_h} \right) \tag{21}$$

$$\varphi_\beta = \frac{\sum_{i=1}^{N_i} \mathrm{SQ}_i}{\sum_{i=1}^{N_i} \mathrm{SDe}_i} \tag{22}$$

J. Pipeline Syst. Eng. Pract., 2015, 6(4): 04015004

$$\varphi'_\beta = \prod_{i=1}^{N_i} \frac{\mathrm{SQ}_i}{\beta \times \mathrm{SDe}_i} \qquad (23)$$

in which ω_β and ω'_β = values of the temporal reliability in the network and at the nodes, respectively; φ_β and φ'_β = values of the quantitative reliability in the network and at the nodes, respectively; and β = efficiency threshold [a network efficiency larger (lower) than this threshold is defined as success (failure) of water supply]. It ranges between 0 and 100%.

Hashimoto et al. (1982) defined the resiliency of a water resources system as the return probability of a system from a failure situation to a normal one. Based on this, one can define the failure intervals as those intervals in which the system fails to supply the demands and the failure periods as those periods in which the system fails in all its intervals. The resiliency is calculated by the ratio of the number of failure intervals followed by success intervals to the number of the failure intervals during the operation period of a WDN. Small values of the return probability in a system establish its low resiliency. In the same manner as is done with the reliability, the resiliency is calculated in the entire WDN [Eq. (24)] and at the consumption nodes of the network Eq. (25)

$$\gamma_\beta = 100 \times \frac{\sum_{h=1}^{N_h} \begin{cases} 1 & \sum_{i=1}^{N_i} Q_{i,h} < \beta \times \sum_{i=1}^{N_i} \mathrm{De}_{i,h}\,, \quad \sum_{i=1}^{N_i} Q_{i,h+1} \geq \beta \times \sum_{i=1}^{N_i} \mathrm{De}_{i,h+1} \\ 0 & \text{Otherwise} \end{cases}}{\sum_{h=1}^{N_h} \begin{cases} 1 & \sum_{i=1}^{N_i} Q_{i,h} < \beta \times \sum_{i=1}^{N_i} \mathrm{De}_{i,h} \\ 0 & \sum_{i=1}^{N_i} Q_{i,h} \geq \beta \times \sum_{i=1}^{N_i} \mathrm{De}_{i,h} \end{cases}} \qquad (24)$$

$$\gamma'_\beta = 100 \times \prod_{i=1}^{N_i} \frac{\sum_{h=1}^{N_h} \begin{cases} 1 & Q_{i,h} < \beta \times \mathrm{De}_{i,h}\,, \quad Q_{i,h+1} \geq \beta \times \mathrm{De}_{i,h+1} \\ 0 & \text{Otherwise} \end{cases}}{\sum_{h=1}^{N_h} \begin{cases} 1 & Q_{i,h} < \beta \times \mathrm{De}_{i,h} \\ 0 & Q_{i,h} \geq \beta \times \mathrm{De}_{i,h} \end{cases}} \qquad (25)$$

in which γ_β and γ'_β = resiliency of the network and the node, respectively.

Case Studies

The optimization model for WDN operation is first used with a sample two-loop network (Alperovits and Shamir 1977) considering intermittent supply. Second, the optimization model is used with a real network to find the optimal scheduling of intermittent supply under different shortage scenarios. The same temporal consumption time pattern (Fig. 1) is used with both WDNs.

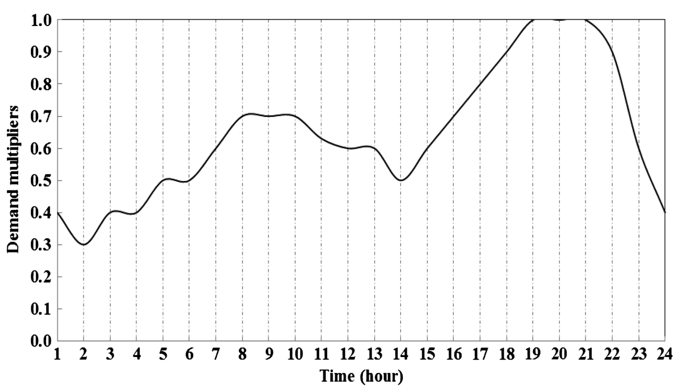

Fig. 1. Coefficients of the consumption time pattern on a summer day

First Case Study: Two-Loop Network

This network has eight pipes, six consumption nodes, and one water supply reservoir. The characteristics of the pipes and nodes are listed in Table 1. Fig. 2 shows the network schematic. All pipe lengths equal 1,000 m and the Hazen-Williams coefficient for all pipes equals 130. The minimum required pressure ($P\mathrm{min}_i$) and the maximum allowable pressure ($P\mathrm{max}_i$) equal 30 and 1,000 m at all consumption nodes, respectively, and the reservoir elevation is 250 m.

Thirteen different scenarios of the water stress are considered for the two-loop network. The scenarios are listed in Table 2. The reservoir capacity equals 5,000 m^3 in all scenarios, and the duration of the intermittent period equals 24 h. The intermittent supply intervals and the hydraulic intervals are equal to 1 h. The total inflow volume to the reservoir is defined based on the

Table 1. Characteristics of Consumption Nodes and Pipes in the Two-Loop Network

Consumption node or pipe	Pipe diameter (mm)	Node elevation (m)	Base demand (m^3/h)
1	457.2	150	100
2	254.0	160	100
3	406.4	155	120
4	101.6	150	270
5	406.4	165	330
6	254.0	160	200
7	254.0	—	—
8	254.0	—	—

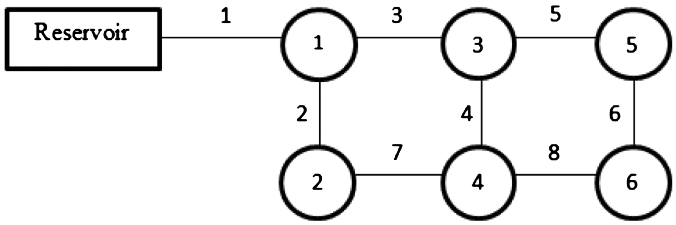

Fig. 2. Schematic of the two-loop network

Table 2. Data for the Scenarios in the Two-Loop Network

Scenario	ISV (m^3)	I (m^3/h)	TVD (m^3)	RW (%)	ST (h)
1	2,000	720	17,282	100	1:00
2	0	504	12,098	70	1:00
3	0	504	12,098	70	14:00
4	0	504	12,098	70	19:00
5	0	360	8,641	50	1:00
6	0	360	8,641	50	14:00
7	0	360	8,641	50	19:00
8	0	216	5,185	30	1:00
9	0	216	5,185	30	14:00
10	0	216	5,185	30	19:00
11	2,000	504	12,098	70	1:00
12	2,000	360	8,641	50	1:00
13	2,000	216	5,185	30	1:00

Note: I = hourly inflow to the reservoir; ISV = available water in the reservoir at the beginning of the intermittent supply period; RW = ratio of the total available water volume (TVA) to the total volume of demand in the network (TVD) during the intermittent supply period; ST = starting hour of intermittent supply; TVD = total volume of demand in the network.

available daily water volume. The total volume of demand in the WDN (TVD) equals 17,282 m^3/day. The TVD is calculated based on the basic nodal water demands and the hourly coefficients of water consumption during the day. The inflow to the reservoir is computed hourly during the intermittent supply period and is equal to the total available water in a day divided by 24 h.

It is seen in Table 2 that there are no water shortages in Scenario 1: the water demand should be supplied at all nodes at all times. Scenario 1 is a baseline used to test the performance of the optimization model and the ability of the HBMO algorithm in finding optimal solutions. The reservoir initial storage is set equal to 0 in Scenarios 2–10. The starting times of the water shortage are 1:00, 14:00, and 19:00 h, which correspond to low, mean, and high water consumption, respectively. These starting times allows testing the performance of the WDN's optimization model under a wide range of initial water consumption.

The initial storage equals 2,000 m^3 under Scenarios 11, 12, and 13. Therefore, the starting time of water shortage has no effect on the optimization model's solution. Thus, the performance of the WDN optimization model can be assessed considering the existing initial storage in the reservoir under Scenarios 11, 12, and 13.

The values of θ [Eq. (13)], K_1, and K_2 [Eq. (4)] are equal to 0.9, 1, and 1 in all 13 scenarios, respectively. The number of the decision variables used in the optimization model equals the number of the intermittent supply intervals multiplied by the number of consumption nodes ($24 \times 6 = 144$). The number of mating flies (iteration) and the number of bees equal 200 and 110 in each run, respectively. The values of the objective function and the efficiency criteria calculated with Scenarios 2–13 are listed in Tables 3–5.

In Tables 3–5 UCOF stands for the value of the unconstrained objective function in which the violation of the constraints of the optimization model does not incur any penalties in the objective function. Method 1 is the optimization model developed in this paper (includes intermittent water supply). Method 2 is the operation rule of supply with the constant priority (Soltanjalili et al. 2013). In Tables 3–5, the best (largest) values of the objective function and the efficiency criteria are written in bold font. The best (smallest) values of the COV_{R_i} are also written in bold font to facilitate the comparison between the best values calculated with Methods 1 and 2. The network temporal reliability values, the nodal volume reliability, and the network resiliency were calculated for efficiency thresholds equal to 100, 70, and 60% in Table 3. The efficiency threshold of 100% was selected to compare water shortage and normal water supply in the network. The threshold of 70% was

Table 3. Unconstrained Values of the Objective Function, COV_{R_i}, and the Efficiency Criteria Related to the Solutions Obtained with Methods 1 and 2 for the Two-Loop Network with Low Water Consumption: Scenarios 2, 3, 4, and 11

	Scenario						
	2		3		4		11
	Method						
Criterion	1	2	1	2	1	2	1
UCOF	**0.708**	0.593	**0.750**	0.581	**0.708**	0.603	0.708
$COV_{R_i} \times 100$	**0.0**	26.1	**0.0**	27.3	**0.0**	25.2	0.0
ω_{100}	16.7	**41.7**	20.8	**37.5**	20.8	**41.7**	4.2
ω_{70}	54.2	**70.8**	62.5	**75.0**	66.7	**75.0**	62.5
ω_{60}	**75.0**	70.8	**79.2**	75.0	**83.3**	75.0	79.2
ω'_{100}	12.6	**29.5**	17.8	**28.1**	17.8	**29.9**	12.6
γ_{100}	**25.0**	14.3	**15.8**	13.3	**26.3**	21.4	8.7
γ_{70}	**45.5**	28.6	**44.4**	16.7	**62.5**	50.0	55.6
γ_{60}	**66.7**	28.6	**40.0**	16.7	50.0	50.0	100.0
γ'_{100}	**12.7**	4.1	**9.3**	2.2	6.9	**10.7**	19.3
φ'_{100}	11.3	**17.6**	12.5	**16.9**	12.3	**18.3**	10.6
φ'_{70}	**91.5**	36.0	**93.5**	34.5	**89.7**	40.0	83.0
φ'_{60}	**100.0**	49.0	**100.0**	44.3	**100.0**	50.8	100.0
φ	**69.4**	**69.5**	**69.7**	69.6	**69.9**	69.8	69.1

Note: UCOF = unconstrained value of the objective function; Method 1 is the optimization model developed in this paper that includes intermittent water supply; Method 2 corresponds to no water shortage; values given in bold are the best (largest) values of the objective function and the efficiency criteria and the best (smallest) values of the COV_{R_i}.

Table 4. Unconstrained Values of the Objective Function, COV_{R_i}, and the Efficiency Criteria Related to the Solutions Obtained with Methods 1 and 2 for the Two-Loop Network with Mean Water Consumption: Scenarios 5, 6, 7, and 12

	Scenario						
	5		6		7		12
	Method						
Criterion	1	2	1	2	1	2	1
UCOF	**0.542**	0.221	**0.500**	0.214	**0.542**	0.214	0.542
$COV_{R_i} \times 100$	**0.0**	49.5	**0.0**	50.2	**0.0**	50.2	0.0
ω_{100}	4.2	**12.5**	8.3	8.3	0.0	**8.3**	12.5
ω_{50}	**58.3**	33.3	**45.8**	37.5	**58.3**	37.5	54.2
ω_{40}	70.8	**83.3**	79.2	**83.3**	**66.7**	83.3	70.8
ω'_{100}	2.5	**3.5**	2.5	**2.6**	2.5	**2.6**	2.5
γ_{100}	8.7	**14.3**	**13.6**	9.1	4.2	**9.1**	14.3
γ_{50}	**50.0**	25.0	**38.5**	13.3	**50.0**	26.7	27.3
γ_{40}	**57.1**	50.0	**80.0**	50.0	50.0	50.0	85.7
γ'_{100}	1.0	**1.8**	**2.9**	0.6	**6.7**	1.2	2.7
φ'_{100}	**1.6**	1.2	**1.6**	0.9	**1.6**	0.9	1.5
φ'_{50}	**87.8**	6.5	**87.2**	4.8	**92.7**	4.7	85.7
φ'_{40}	**100.0**	10.1	**100.0**	7.5	**100.0**	7.4	100.0
φ	**50.0**	49.6	49.7	**49.8**	**50.0**	49.5	49.0

Note: UCOF = unconstrained value of the objective function; Method 1 is the optimization model developed in this paper that includes intermittent water supply; Method 2 corresponds to no water shortage; values given in bold are the best (largest) values of the objective function and the efficiency criteria and the best (smallest) values of the COV_{R_i}.

Table 5. Unconstrained Values of the Objective Function, COV_{R_i}, and the Efficiency Criteria Related to the Solutions Obtained with Methods 1 and 2 for the Two-Loop Network with High Water Consumption: Scenarios 8, 9, 10, and 13

	Scenario						
	8		9		10		13
	Method						
Criterion	1	2	1	2	1	2	1
UCOF	**0.292**	−0.305	**0.333**	−0.287	**0.333**	−0.272	0.333
$COV_{R_i} \times 100$	**0.0**	82.6	**0.0**	81.5	**0.0**	79.9	**0.0**
ω_{100}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ω_{30}	**45.8**	33.3	**54.2**	29.2	**50.0**	33.3	37.5
ω_{20}	62.5	**79.2**	70.8	**83.3**	70.8	**79.2**	58.3
ω'_{100}	**0.1**	0.0	**0.1**	0.0	**0.1**	0.0	0.1
γ_{100}	4.2	4.2	4.2	4.2	4.2	4.2	4.2
γ_{30}	**38.5**	18.8	**54.5**	17.6	**41.7**	18.8	53.3
γ_{20}	55.6	**60.0**	**71.4**	25.0	**57.1**	40.0	60.0
γ'_{100}	**0.2**	0.0	**0.2**	0.0	**0.3**	0.0	0.4
φ'_{100}	**0.1**	0.0	**0.1**	0.0	**0.1**	0.0	0.1
φ'_{30}	**83.4**	0.0	**86.3**	0.0	**85.5**	0.0	85.8
φ'_{20}	**100.0**	0.0	**100.0**	0.0	**100.0**	0.0	100.0
φ	29.4	**29.6**	**29.9**	29.8	30.0	30.0	30.0

Note: UCOF = unconstrained value of the objective function; Method 1 is the optimization model developed in this paper that includes intermittent water supply; Method 2 corresponds to no water shortage; values given in bold are the best (largest) values of the objective function and the efficiency criteria and the best (smallest) values of the COV_{R_i}.

selected according to the ratio of the total available water to the total demand during the intermittent supply period (that is, the value of the RW is equal to the 70% in Scenarios 2, 3, 4, and 11). The threshold of 60% was selected according to the lowest ratio of adequate supply to the demand [VL(RW)] in the network nodes. An efficiency threshold of 100% was considered for the nodal temporal reliability and the nodal resiliency only. The values of the nodal temporal reliability and the nodal resiliency are the same for all efficiency thresholds. An efficiency threshold of 100% was considered for the volume reliability in the network. The efficiency thresholds in Tables 4 and 5 were selected in the same manner as was done in Table 3.

The results corresponding to the low, mean, and high water consumption cases shown in Tables 3–5, respectively, establish that the unconstrained values of the objective function calculated with Method 1 are always larger than those calculated with Method 2. The value of the COV_{R_i} is equal to 0 for all scenarios with Method 1, while it is approximately equal to 25, 50, and 80% for the low, mean, and high water consumptions with Method 2, respectively. This means that there is no equanimity in the supply of the network's water demand using Method 2. The objective function value obtained with Method 2 is always inferior to that obtained with Method 1. On the other hand, the inequality increases when the shortage intensity increases with Method 2 to the extent

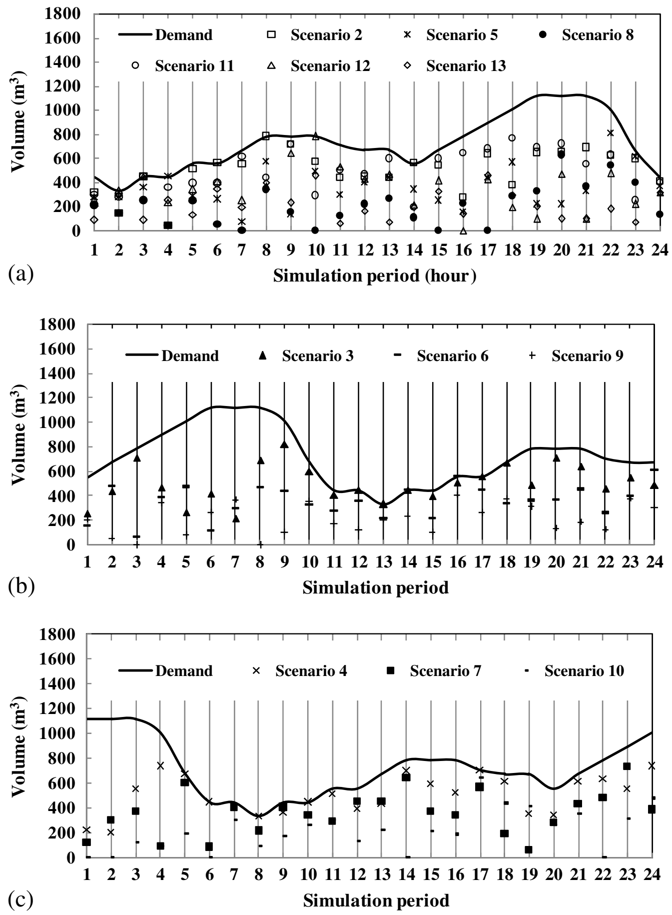

Fig. 3. Supplied water and two-loop network demand in each hydraulic interval under Scenarios (a) 2, 5, 8, 11, 12, and 13 (starting at 1:00 h); (b) 3, 6, and 9 (starting at 14:00 h); (c) 4, 7, and 10 (starting at 19:00 h) obtained by Method 1

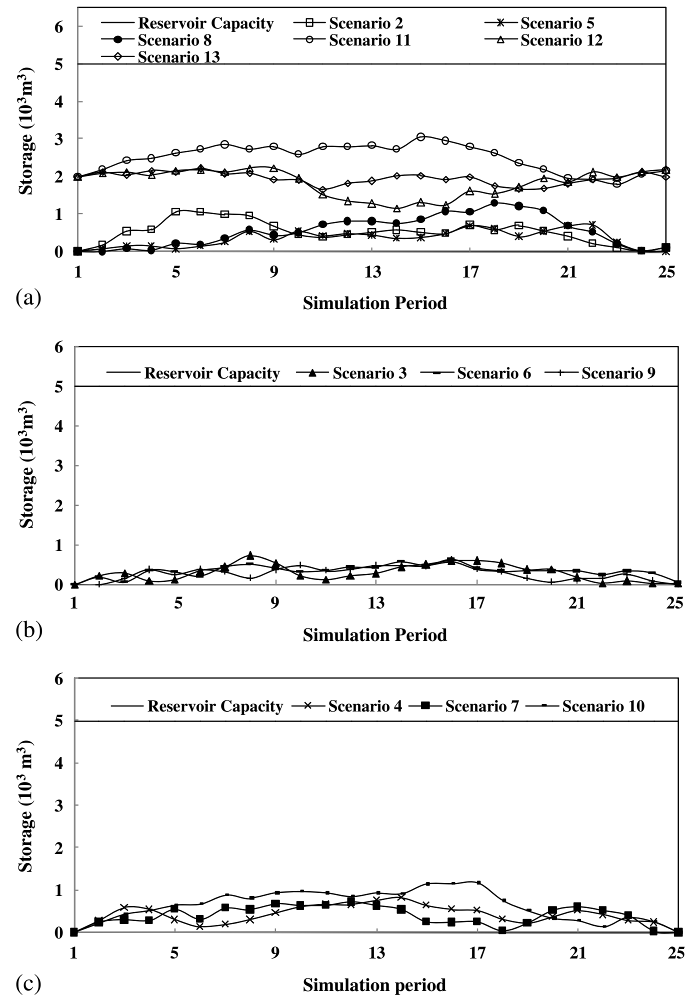

Fig. 4. Stored water in the reservoir of the two-loop network during the intermittent supply period under Scenarios (a) 2, 5, 8, 11, 12, and 13 (starting at 1:00 h); (b) 3, 6, and 9 (starting at 14;00 h); (c) 4, 7, and 10 (starting at 19:00 h) obtained by Method 1

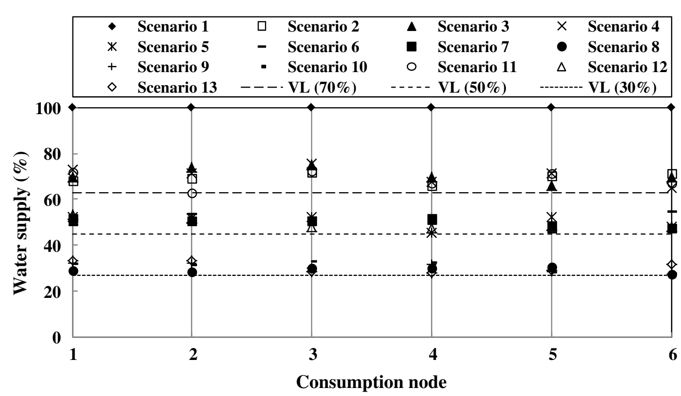

Fig. 5. Ratio of the total supplied water to the total required water in the two-loop network during the intermittent supply period under Scenarios 1–13 related to Method 1, and the lowest allowable (fair) ratio of supply to demand corresponding to various water shortage situations

that makes the objective function value negative (Table 5). A COV_{R_i} equal to 0 under all scenarios with Method 1 shows the optimization models' ability to take into account the equanimity of nodal supply with different water consumptions. In general, the network temporal reliability of Method 2 is superior to that of Method 1. Method 1 has superior resiliency than Method 2 as a whole. In Method 2 the water demands are completely supplied during the hours in which the inflow to the network exceeds the demands. Also, water demands are supplied to the extent possible when the inflow to the network is less than the demands. Given the constant values of the inflows to the network and the variable values of the demands during the day in the case study network, Method 2 fails to supply the demands in the high-consumption hours. But Method 1, which is an optimization procedure, delivers less water during the lower consumption hours, thus allowing more water to be stored in the reservoir. This storage supplies the demands during the high-consumption hours. With Method 1 the number of failure periods increases but the duration of the failure periods decreases. This improves the resiliency and decreases the network temporal reliability. Under severe water consumption (Table 5), the nodal temporal reliability is equal to 0 in all scenarios with Method 2, which means that at least one node was not supplied during the intermittent supply period. The temporal reliability never equals 0 with Method 1, which means that all nodes are supplied during the intermittent supply period even under severe water consumption. It can be seen in Tables 3–5 that the nodal volume reliability with Method 1 is larger than that with Method 2 for all efficiency thresholds and all scenarios, which is due to the use of Eq. (12) in the optimization model. Furthermore, the network volume reliability is approximately equal to RW under the different

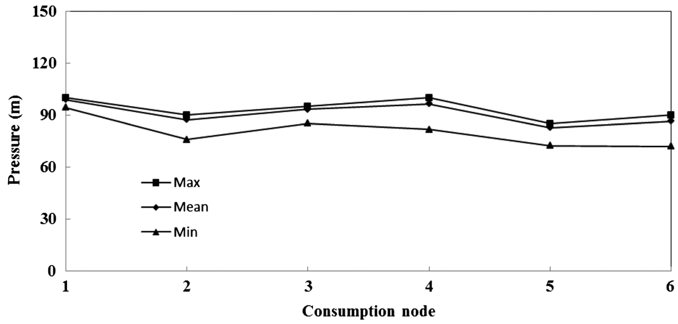

Fig. 6. Envelope curve of the nodal pressure in the two-loop network during the intermittent supply period under Scenarios 1–13 obtained by Method 1

water consumptions in all scenarios, and the small differences are due to the use of 0 or 100% for the supply to demand ratio. This equality shows that the value of consumption water is equal to the network inflow during periods of intermittent supply. It also shows the correct convergence to the optimal solution of the optimization model (Method 1).

Fig. 3 shows the water supply and demand values in each hydraulic interval under different scenarios. In the scenarios without initial storage in which the intermittent supply period starts during a low consumption hour (1:00 h), Scenarios 2, 5, and 8, perform better during the highest consumption hours than in those situations in which the intermittent supply period starts during higher consumption hours (14:00 and 19:00 h). This is because of water storage during the low consumption hours and the use of stored water during the high consumption hours. Generally, the optimization model performance and its results become independent of the starting time of the intermittent supply period if there is sufficient initial storage at the beginning of the intermittent supply period (Scenarios 11–13). Starting the intermittent supply period during the lowest consumption hours of the day improves the supply during the highest consumption hours if there is no initial storage.

The change of the reservoir storage during the intermittent supply period under Scenarios 2–13 is shown in Fig. 4. It can be seen in Fig. 4 that the existing water in the reservoir is equal to or greater

Table 6. Data for the WDN Attached to Reservoir Number 30 in Tehran, Iran

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

J. Pipeline Syst. Eng. Pract., 2015, 6(4): 04015004

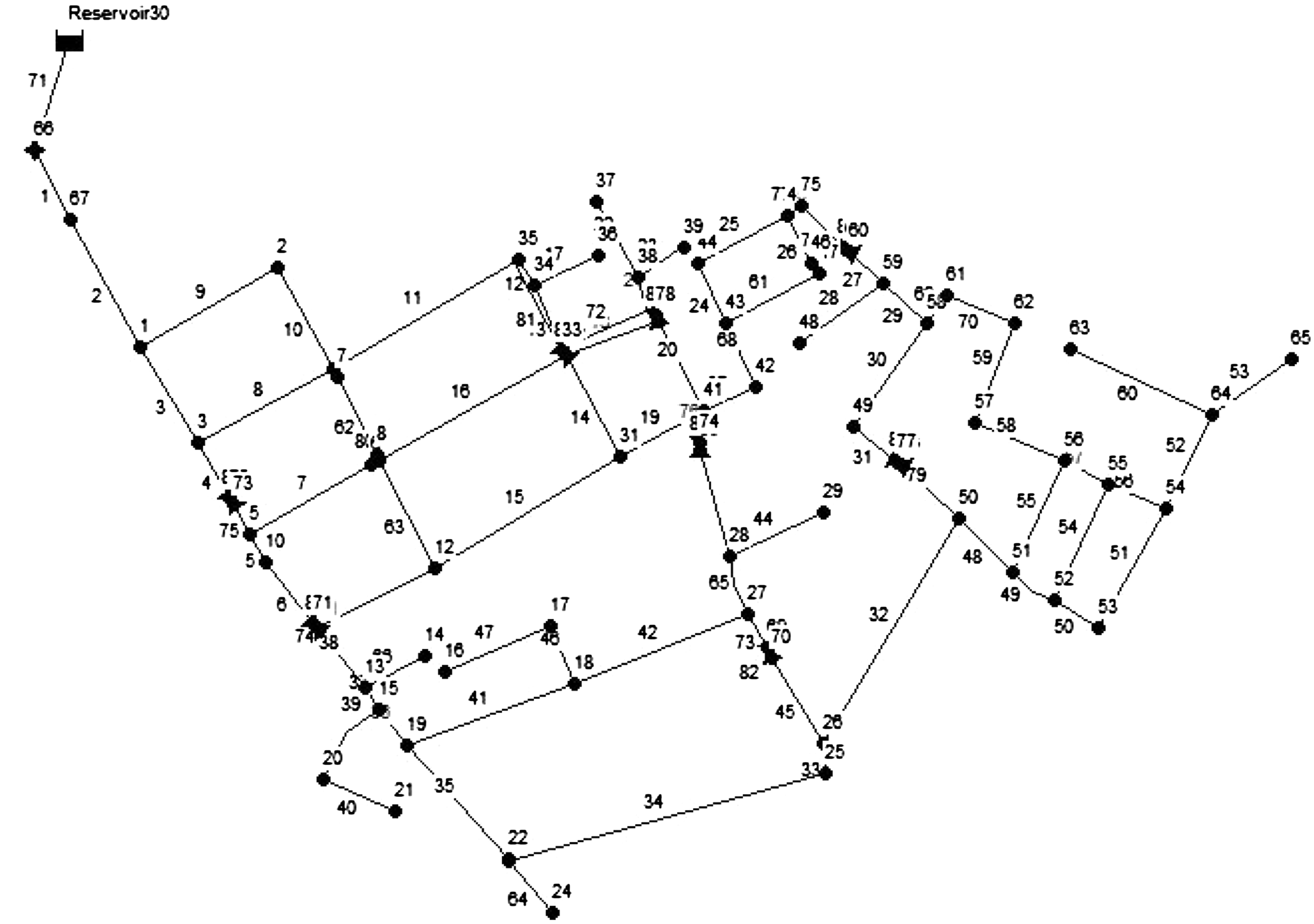

Fig. 7. Schematic of the WDN attached to reservoir 30 in Tehran, Iran

than the initial storage value that is input to the optimization model. In other words, the optimization model uses approximately all the available water to supply demands under all the entertained scenarios.

Fig. 5 shows the ratio of the total supply to the total demand in the network under Scenarios 1–13. Fig. 5 also shows the value of the VL(RW) for the various water consumption states (low, mean, and high). Recall that VL(RW) is the minimum volume ratio of water supply corresponding to RW considering justice at each node. It is evident in Fig. 5 that the justice constraint is satisfied under all scenarios. For example, in Scenarios 2, 3, 4, and 11 the ratio of the available water to the total network demand during the intermittent supply period (RW) equals 70%, and Fig. 5 shows that under these scenarios the ratio of the total supply to the total demand during the intermittent supply period is at the top of the VL (RW) lines for all nodes.

Fig. 6 is the envelope curve of the nodal pressures during the intermittent supply period for all scenarios. It shows that the pressures are always in the appropriate range for all shortage situations during the intermittent supply period.

Second Case Study: Real Network

The real network corresponds to the WDN attached to reservoir number 30 in the City of Tehran, Iran. Network data are listed in Table 6, and its schematic is shown in Fig. 7.

The reservoir has an elevation equal to 1,754 m. Network pressure is driven by gravity. The Hazen-Williams coefficient for all the network pipes is equal to 85 and the reservoir capacity equals 5,000 m^3. The minimum required pressure head ($P\min_i$) and the maximum allowable pressure head ($P\max_i$) are equal to 14 and 50 m in all consumption nodes, respectively. Three different scenarios have been defined for this network based on different shortage situations, which are listed in Table 7. The value of θ [Eq. (13)] was set equal to 90% under the three scenarios.

It is seen in Table 7 that the initial reservoir storage is equal to 2,000 m^3 under all scenarios. The optimization model's solution is independent of the starting time of the intermittent supply period when there is sufficient initial storage at the beginning of the intermittent supply period. The intermittent supply period starts at 1:00 h under the three scenarios. Scenarios 1, 2, and 3 are similar to Scenarios 11, 12, and 13, respectively, used in the two-loop network example of the previous section. The coefficients K_1 and K_2 were set equal to 1. The duration of intermittent supply and hydraulic intervals were selected equal to 2 and 1 h, respectively,

Table 7. Data for Defined Scenarios and the Results of the HBMO Algorithm for Each Scenario in the WND Attached to Reservoir 30 in Tehran, Iran

Scenario	OF	ST (h)	ISV (m^3)	I (m^3/h)	TVD (m^3)	RW (%)	$100 \times COV_{R_i}$
1	0.611	1:00	2,000	140	3,356	70	9.3
2	0.409	1:00	2,000	100	2,397	50	10.23
3	0.194	1:00	2,000	60	1,438	30	12.8

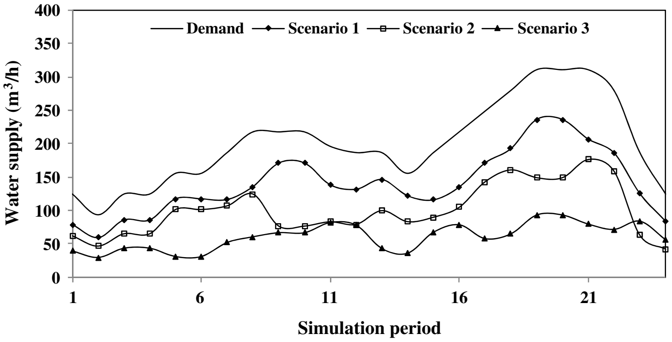

Fig. 8. Supplied water and water demand in the WDN attached to reservoir 30 in Tehran, Iran, during each hydraulic interval under all scenarios

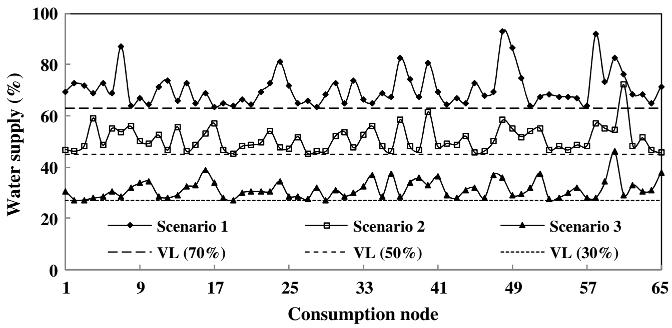

Fig. 9. Ratio of the total supplied water to the total required water in the WDN attached to reservoir 30 in Tehran, Iran, during the intermittent supply period and the lowest allowable (fair) corresponding to various water shortage situations

under Scenarios 1, 2, and 3. The number of decision variables of the optimization model equals 780. The number of mating flies (iteration) and the number of bees were made equal to 1,500 and 110 in each run, respectively. The processing time of each run using a computer with CPU of 2.53 GHz and RAM of 4 GB is approximately 30 min.

The value of the volume of water supply for all hydraulic intervals is shown in Fig. 8. Figs. 9 and 10 show the ratio of the total water supply to the total demand and the number of supply hours during the intermittent supply period for all consumption nodes, respectively. Fig. 9 shows that the ratio of the total water supply to the total required water is always larger than the specified minimum for the given water consumption (low, mean, high) during the intermittent supply period at all consumption nodes under each scenario. Fig. 10 indicates that there is a very small difference between the number hours of water supply among the network nodes, which is in agreement with the value of COV_{R_i} in Table 7. Because the values of K_1 and K_2 are set equal to each other, the coefficient of variation COV_{R_i} in this case study did not converge to 0. Because the first (two-loop) case study is a small network, one unit change in the number of hours of water supply in one node has a large effect on COV_{R_i} value. On the other hand, when the network becomes larger, this effect becomes smaller. Thus, a worthy consideration in the selection of the values of K_1 and K_2 is the network size. The reservoir storage during the intermittent supply period is shown in Fig. 11, and the comparison between the average pressure head during the intermittent supply period and that calculated when it is operated to avoid water shortages (normal operation) is depicted in Fig. 12. It is evident in Fig. 12 that the average water pressure head at all nodes under all scenarios is larger than its value during normal operation. Therefore, the intermittent supply operation leads to an increased average water pressure head in the network.

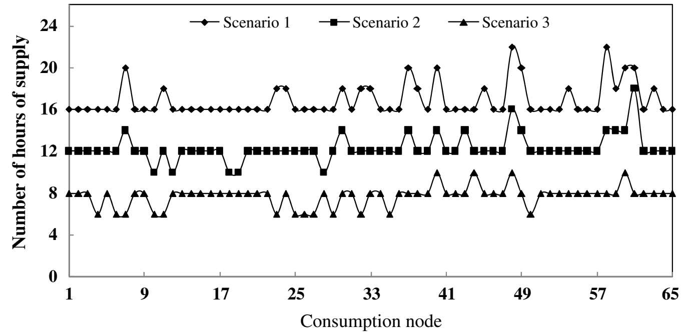

Fig. 10. Total number of water supply hours during the intermittent supply period at all the consumption nodes of the WDN attached to reservoir 30 in Tehran, Iran

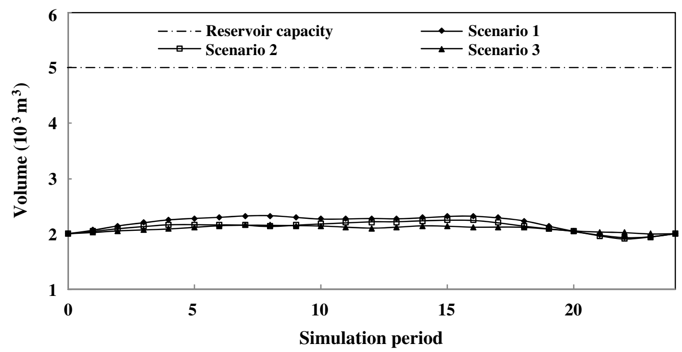

Fig. 11. Reservoir storage in the reservoir of the WND attached to reservoir 30 in Tehran, Iran, during the period of intermittent water supply

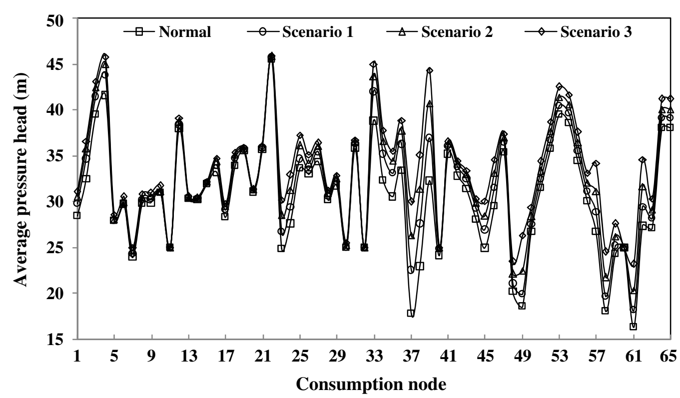

Fig. 12. Average pressure head at the consumption nodes of the WDN attached to reservoir 30 in Tehran, Iran, corresponding to normal operation (no water shortage) during the intermittent supply period under all scenarios

Conclusion

This paper developed an optimization model that finds optimal operating schedules for water distribution networks subjected to intermittent supply. The optimal schedule optimizes water supply considering the principles of equanimity and justice in the network. These two principles were quantified in the objective function of the optimization model. The optimization model for WDNs was applied to a two-loop network and the resulting problem was solved with the HBMO algorithm linked to the *EPANET* hydraulic simulator. The results demonstrated that the optimization model finds optimal scheduling of intermittent water supply that preserves the principles of equanimity and justice among all network nodes even when there are severe water shortages. A similar satisfactory performance of the optimization model for optimizing the operation of WDNs was determined by applying it to a gravity-driven WDN in the City of Tehran, Iran.

References

Alperovits, E., and Shamir, U. (1977). "Design of optimal water distribution systems." *J. Water Resour. Res.*, 13(6), 885–900.

Ameyaw, E. E., Memon, F. A., and Bicik, J. (2013). "Improving equity in intermittent water supply systems." *J. Water Supply Res. Technol.*, 62(8), 552–562.

Andey, S. P., and Kelkar, P. S. (2009). "Influence of intermittent and continuous modes of water supply on domestic water consumption." *Water Resour. Manage.*, 23(12), 2555–2566.

Batish, R. (2003). "A new approach to the design of intermittent water supply networks." *Proc., World Water and Environmental Resources Congress*, Philadelphia.

Bozorg Haddad, O., Adams, B. J., and Mariño, M. A. (2008). "Optimum rehabilitation strategy of water distribution systems using the HBMO algorithm." *J. Water Supply Res. Technol.*, 57(5), 337–350.

Bozorg Haddad, O., Afshar, A., and Marino, M. A. (2006). "Honey-bees mating optimization (HBMO) algorithm: A new heuristic approach for water resources optimization." *Water Resour. Manage.*, 20(5), 661–680.

Bozorg Haddad, O., Afshar, A., and Mariño, M. A. (2011a). "Multireservoir optimisation in discrete and continuous domains." *Proc. Inst. Civ. Eng. Water Manage.*, 164(2), 57–72.

Bozorg Haddad, O., and Mariño, M. A. (2011). "Optimum operation of wells in coastal aquifers." *Proc. Inst. Civ. Eng. Water Manage.*, 164(3), 135–146.

Bozorg Haddad, O., Mirmomeni, M., and Mariño, M. A. (2010a). "Optimal design of stepped spillways using the HBMO algorithm." *Civ. Eng. Environ. Syst.*, 27(1), 81–94.

Bozorg Haddad, O., Mirmomeni, M., Zarezadeh Mehrizi, M., and Mariño, M. A. (2010b). "Finding the shortest path with honey-bee mating optimization algorithm in project management problems with constrained/unconstrained resources." *Comput. Optim. Appl.*, 47(1), 97–128.

Bozorg Haddad, O., Moradi-Jalal, M., and Mariño, M. A. (2011b). "Design-operation optimisation of run-of-river power plants." *Proc. Inst. Civ. Eng. Water Manage.*, 164(9), 463–475.

Bozorg Haddad, O., Moradi-Jalal, M., Mirmomeni, M., Kholghi, M. K. H., and Mariño, M. A. (2009). "Optimal cultivation rules in multi-crop irrigation areas." *Irrig. Drain.*, 58(1), 38–49.

Duckstein, L., and Plate, E. G. (1988). "Engineering reliability and risk in water resources." *CLEAN-Soil Air Water*, 16(4), 451–452.

Fallah-Mehdipour, E., Bozorg Haddad, O., Beygi, S., and Mariño, M. A. (2011a). "Effect of utility function curvature of Young's bargaining method on the design of WDNs." *Water Resour. Manage.*, 25(9), 2197–2218.

Fallah-Mehdipour, E., Bozorg Haddad, O., and Mariño, M. A. (2011b). "MOPSO algorithm and its application in multipurpose multireservoir operations." *J. Hydroinf.*, 13(4), 794–811.

Fallah-Mehdipour, E., Bozorg Haddad, O., and Mariño, M. A. (2012a). "Real-time operation of reservoir system by genetic programming." *Water Resour. Manage.*, 26(14), 4091–4103.

Fallah-Mehdipour, E., Bozorg Haddad, O., and Mariño, M. A. (2013a). "Developing reservoir operational decision rule by genetic programming." *J. Hydroinf.*, 15(1), 103–119.

Fallah-Mehdipour, E., Bozorg Haddad, O., and Mariño, M. A. (2013b). "Extraction of multicrop planning rules in a reservoir system: Application of evolutionary algorithms." *J. Irrig. Drain. Eng.*, 10.1061/(ASCE)IR.1943-4774.0000572, 490–498.

Fallah-Mehdipour, E., Bozorg Haddad, O., Rezapour Tabari, M. M., and Mariño, M. A. (2012b). "Extraction of decision alternatives in construction management projects: Application and adaptation of NSGA-II and MOPSO." *Expert Syst. Appl.*, 39(3), 2794–2803.

Hashimoto, T., Stedinger, J. R., and Loucks, D. P. (1982). "Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation." *Water Resour. Res.*, 18(1), 14–20.

Hou, D., Song, X., Zhang, G., Zhang, H., Loáiciga, H. A. (2013). "An early-warning and control system for urban, drinking, water quality protection: China's experience." *Environ. Sci. Pollut. Res.*, 20(7), 4496–4508.

Jahanshahi, G., and Bozorg Haddad, O. (2008). "Honey-bee mating optimization (HBMO) algorithm for optimal design of water distribution systems." *Proc., World Environmental and Water Resources Congress*, Honolulu.

Jeong, H. S., and Abraham, D. M. (2006). "Water rationing model for water networks under short-term water supply shortage." *Proc., Pipeline Division Specialty Conf.*, Chicago.

Karimi, S., Mostoufi, N., and Soutodeh Gharebagh, R. (2013). "Evaluating performance of Honey bee mating optimization." *J. Optim. Theor. Appl.*, 160(3), 1020–1026.

Karimi-Hosseini, A., Bozorg Haddad, O., and Mariño, M. A. (2011). "Site selection of rain gauges using entropy methodologies." *Proc. Inst. Civ. Eng. Water Manage.*, 164(7), 321–333.

Noory, H., Liaghat, A. M., Parsinejad, M., and Bozorg Haddad, O. (2012). "Optimizing irrigation water allocation and multicrop planning using discrete PSO algorithm." *J. Irrig. Drain. Eng.*, 10.1061/(ASCE)IR.1943-4774.0000426, 437–444.

Orouji, H., Bozorg Haddad, O., Fallah-Mehdipour, E., and Mariño, M. A. (2013). "Estimation of Muskingum parameter by meta-heuristic algorithms." *Proc. Inst. Civ. Eng. Water Manage.*, 166(6), 315–324.

Rossman, L. A. (2000). *EPANet 2 users manual*, U.S. Environmental Protection Agency, Cincinnati.

Sashikumar, N., Mohankumar, M. S., and Sridharan, K. (2003). "Modelling an intermittent water supply." *Proc., World Water and Environmental Resources Congress*, Philadelphia.

Seifollahi-Aghmiuni, S., Bozorg Haddad, O., Omid, M. H., and Mariño, M. A. (2011). "Long-term efficiency of water networks with demand uncertainty." *Proc. Inst. Civ. Eng. Water Manage.*, 164(3), 147–159.

Seifollahi-Aghmiuni, S., Bozorg Haddad, O., Omid, M. H., and Mariño, M. A. (2013). "Effects of pipe roughness uncertainty on water distribution network performance during its operational period." *Water Resour. Manage.*, 27(5), 1581–1599.

Shokri, A., Bozorg Haddad, O., and Mariño, M. A. (2013). "Algorithm for increasing the speed of evolutionary optimization and its accuracy in multi-objective problems." *Water Resour. Manage.*, 27(7), 2231–2249.

Soltanjalili, M., Bozorg Haddad, O., and Marino, M. A. (2013). "Operating water distribution networks during water shortage conditions using hedging and intermittent water supply concepts." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000315, 644–659.

Totsuka, N., Trifunovic, N., and Vairavamoorthy, K. (2004). "Intermittent urban water supply under water starving situation." *Proc., 30th WEDC Int. Conf.*, Vieutiane, Lao PDR.