Operating Water Distribution Networks during Water Shortage Conditions Using Hedging and Intermittent Water Supply Concepts — **Source link** ⎘

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Hedging in Water Distribution Systems under Shortage Condition with the concept of Intermittent Water Supply

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Abstract

Increase in population and requirements, considerations of economic criteria and water resources limitations; reveal the necessity of optimum operation of water resources. Choosing convenient policies in operation of WDNs, would be done based on optimization and simulation models with the aim of achieving the best situation. Since WDNs would directly affect lifestyles, arranging plans for confronting abnormal condition would be necessary. National and international experiences show that in confrontation to water shortage juncture, if transferring water from other basins or using uncommon waters etc. is inapplicable or insufficient and continuous operation of WDNs would not be possible anymore. Because in large time scale it would lead to usable water resources completion and hard water shortage impact on consumers lives. So hedging or intermittent water supply as a contrasting way against water shortage juncture is proposed. This method of operation is in the manner that in a specific time of operational period, the amount of water, which is supplied to two consumers, could differ from each other even if their demand is equal. Therefore choosing a policy which guarantees justice in supplying consumers' demands has to be considered. In addition, supplying demands with sufficient pressure, would promote consumers satisfaction. Therefore, the aforementioned method of operation needs an exact planning which studies different parameters like justice, welfare, climatic condition, consumption fluctuations and

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other social and humanity constraints beside hydraulic parameters influencing the behavior of WDNs and the interaction between them. To quantify the previously mentioned parameters and constraints, mathematical models, which can simulate the behavior of the networks and optimize the mentioned goals, are surely required. In this research operation of Two Loop and Tehran reservoir number 30's WDNs have been performed. Finally, in order to compare different methods of facing to water shortage, performance criteria were calculated. As the result of applying different methods, it is seen that 100% resiliency criterion for hedging and intermittent water supply is 25-50% more than fixed priorities method. Also considering the equality of total amount of allocated water in operational period under different operational methods, irrespective of initial storage volume of the reservoir, permanent superiority of nodal resiliency criterion under intermittent water supply rather than other approaches shows the efficient management of allocating the amount of available water in operational period.

Keywords: Water Distribution Network, Water Juncture, Hedging, Intermittent, Performance Criteria.

1. Introduction

Domestic water demand is a complicated function of social characteristics, climatic parameters and the policies relevant to water use. In addition, water demand would increase with respect to the population and on the other hand achieving new resources or developing the available ones is not usually possible. Therefore, optimal use of water is in a great level of importance. In case that enough water with sufficient pressure is not available, in addition to public dissatisfaction, the health level of the society would intensely decrease. Therefore, WDNs, which are the main water conveying arteries and domestic water demand suppliers, are one of the most important infrastructural structures in every urban area. Therefore, it is needed that the urban water distribution engineers have enough knowledge about the water distribution science and technology to be able to take measures on planning for convenient operation. The necessity of availability of water in different urban areas and consumption patterns and the importance of water supply in shortage condition are some problems, which need the perception of hydraulic behavior of WDN to be able to solve them. WDNs involve pipes, valves, pumps, reservoir tanks and groundwater wells, that the complex connection of them requires a wide operation plan. Because the plan has to include available resources, predicted demands and economic considerations in order to make it certain that the water delivery would be satisfactorily done. On the other hand, water shortage condition and unavailability of enough water resources makes it impracticable to operate WDNs continuously. Therefore, the aforementioned situation makes the operators to supply demands in an intermittent way (Totsuka, 2004). In the south Asia, at least 350 million of people receive the water intermittently in a few hours during the day, whereas in Latin America the water is rationed for more than 50 million of residents (Yepes et al, 2000).

Operational planning is to satisfy at least four basic terms, which are respectively a clear definition of desired purposes, availability of mathematical models, required facilities to

process these models and finally the knowledge of the system. Real time operation of WDNs is an important and complex matter, which has attracted the attention of many of researchers. This is because of the need to get assured of services reliability, economic use of equipment and the reliability of satisfying the demands with desired pressure. The aim of reliability herein involves giving services to consumers under abnormal condition as well. Biscos et al. (2003) developed an optimization approach for operation of WDNs with the use of mixed integer linear programming, for maximum use of power with low cost (e.g. pumping during the night) and keeping the concentration of chlorine in desired range in delivery points. The applicable results of the algorithm show its ability for controlling delivering process in WDNs.

Considering the operational costs and hydraulic benefits, Carrijo and Reis (2004) proposed a methodology based on multi objective GA and a hydraulic simulation model to obtain optimal operation of the system. Rao et al. (2007) presented an adaptive optimization system for dynamic operational control of water supply and distribution networks. Based on the combined use of an artificial neural network for predicting the consequences of different pumps and valve settings and a genetic algorithm for optimization, the energy cost minimization system is designed to assist water distribution system operators to select optimal operating control settings that will best meet demands. Misiunas et al. (2005) inspected the possibility of using available data about WDN's elements regarding the improvement of their operational situation, reliability, and safety. They considered continuous pressure control as a data collection source related to network condition.

Operational optimization of WDNs using GA has a good initial convergence. However, after finding a near-optimal solution there will be slowness in finding an optimal solution. Van zyl et al. (2004) improved the GA efficiency using a hybrid method based on a combination of a hill-climbing search method and GA.

In the recent years, simulation of social behavior of insects such as ants and bees has been developed as the optimization algorithms to solve optimization problems. Ant colony optimization (ACO) algorithm that was first presented by Dorigo (1992), is one of the aforementioned algorithms. Zecchin et al. (2007) compared five different ACO algorithms on four case studies and finally proposed the best of different ACO algorithms for WDNs design application. Eusuff and Lansey (2003), using the combination of Shuffled Frog Leaping Algorithm (SFLA) and EPANet 2 as the hydraulic simulator and finally developing the SFLANet design model for optimizing the diameters of WDNs. Afshar et al. (2007) used the honey-bee mating optimization (HBMO) algorithm to solve an operational optimization problem of a reservoir with minimization of the sum of squared errors of demands as the objective. Results showed the superiority of HBMO over GA. They also showed the nearness of HBMO results to the global solution of Lingo 8 in optimal reservoir operation. Bozorg Haddad et al. (2008) developed an optimal rehabilitation method for WDN using the HBMO algorithm for 30- and 100-year operation periods. Results indicated that WDN operation considering rehabilitation depends more on cost than the operation without rehabilitation. Ghajarnia et al. (2009) to determine the least-cost design of WDN with respect to different levels of reliability during an operational period also used the HBMO algorithm. They also identified critical nodes of the network by considering different nodal pressure reliabilities. Mohan and Babu (2010) worked on the design of the WDNs by means of HBMO algorithm and showed the faster progression process of the algorithm in comparison with other well-established stochastic optimization algorithms by comparing the number of function evaluations. Ghajarnia et al. (2010) by the use of the combination of Modified Cellular Automation Network Design Algorithm (MCANDA) and HBMO algorithm (MCANDA-HBMO) designed WDN with the aim of minimization of design cost. Also Soltanjalili et al. (2011) minimized the cost of design of WDNs considering the reliabilities of supplying

demands with desired pressure under breakage level one condition (the situation that one pipe breaks at a single period of time).

Water shortage condition would cause the water demands and water resources to get unbalanced. Water shortage crisis could occur in two different ways. One of them is the situation in which the amount of water resources decreases and is not anymore sufficient for satisfying the demands. The other one would happen when some factors like increase in municipal population and on the other hand impossibility of development of the amount of available water resources disturb the balance between demands and available water resources. One of the solutions to overcome the water shortage problem is to transfer water from another basin to the one, which is facing to shortage. Another one could be continuously supplying water even with the use of uncommon water or accepting the pressure in the network less than desired one. The other solution is hedging or supplying water in an intermittent way. Hedging means delivering an amount of water between zero and demand and intermittent water supply means to supply either zero water or full demand. In this method, during some hours of day the demands would be completely satisfied in some nodes while the others are not having any supply. The superiority of intermittent water supply in comparison with hedging is its 100% desirability during supply hours. On the other hand, in developing countries like Iran, WDNs are designed and skeletonized with the aim of continuous water delivery. Obviously, operation in the way, which the WDN has not been designed for, would cause some consequences for the system and consumers. Difficulties and problems of intermittent water supply are significantly divided into two categories. The first category, as it is mentioned previously, includes the problems, which are caused as the result of intermittent operation of the systems, which have been designed for continuous operation, which are not that important and could be ignored in case that high technology and enough equipment are available. The second category includes the problems and costs, which are

straightly resulted of the nature of intermittent water supply. As some examples, increase in operator costs for intermittent control and maintenance costs because of destructions that water pressure fluctuations would cause (Subhash et al. (2008)).

Wilchfort and Lund (1977) developed a water shortage management model using a two stage linear model. The model with its optimization aspect could be used for expanded urban water supply problems. Utilization of this model in several cases shows its ability to determine the effects of seasonal water shortages and uncertainties relevant to long term and short term managerial alternatives.

Tu et al. (2003) developed a linear mixed integer-planning model for management and operation of a multi reservoir WDN considering hedging rules. They used weighted multipliers for combination of the objectives but the percentage of supply from each reservoir was assumed the same. Therefore Barros et al. (2008) optimized the percentage of supply from each reservoir, in order to operate WDN considering hedging rules. The objectives in the order of priority consist of 1- minimizing the insufficiency of water, 2- maximizing the reservoir storage volume and 3- minimizing the operational costs.

In this research considering social constraints and defining logical limits for duration and the amount of supply, the intermittent supply has been mathematically investigated and using some criteria the desirability of intermittent water supply is compared with the other operational periods.

2. Justification of optimization for applying hedging or intermittent water supply

Considering that in hedging or intermittent supply in some periods, the demands of some nodes are partially supplied or even stopped, and simultaneously there are some nodes, which their demands are being fully satisfied, this question comes to mind that how is it possible to get assured of equity of supply among consumers. Therefore, a rule curve is needed to show the exact time of stopping and connecting water beside parameters that

illustrate the amount of supplied water in each consumption node. Also considering the importance of water demands, it is not practicable to stop water supply for a long time (e.g. one whole day or more). Therefore, the periods of stopping and connecting water have to be chosen reasonable. Also in order to satisfy desirability criteria and managerial maneuvers for promoting welfare, considering an operational period longer than one or two days is needed. Considering the number of consumption nodes in a real WDN and the product of the number of nodes and the number of periods of stopping and connecting water during operational period, with an approximate estimation, a considerable number of decisions which have to be made during operational period could be expected. Therefore using a tool that is capable to choose the optimum state among possible ones, and optimizes the desirability criteria and managerial maneuvers is unavoidable.

3. Aims, criteria and effective parameters on desirability of method

Since in hedging or intermittent water supply, the amount and duration of cutting and supplying water among different nodes is disparate, therefore considering equity parameter in supplying consumers' demands whether in respect of time or volume, could be the first concern, which has to be investigated, and needs an exact planning and comprehensive management.

3.1. Objective function

In this research, two pressure and demand desirability criteria for consumption nodes during an operational period are being simultaneously optimized. Simultaneity of considering pressure and demand desirability criteria would cause balanced hydraulic situation on consumption nodes. Considering only one of them, would lead to report an equal desirability for two nodes with the same amount of supplied water (or pressures), but different pressures (or amount of supplied water) that is not compatible with the aim of appointing quantitative and qualitative equity among consumers.

3.2. Constraints

The constraints considered in this research are divided into two hydraulic and humanity constraints. The hydraulic ones include the limits of pressure and demand supplied in consumption nodes, upper and lower reservoir storage volume, reservoir capacity and so on. Humanity constraints totally include maneuvers, which are considered to promote welfare in consumers water demand supply.

3.3. Decision variables

The decision variables considered in this research are multipliers between 0 and 1 (including 0 and 1) which multiplied to demand, specify the amount of supplied water for each consumption node in each simulation period.

3.4. Reservoir capacity

The reservoir storage capacity for different considered scenarios in this research has been assumed equal to 24-hour design water demand of the network.

4. Hourly fluctuations multipliers

Hourly fluctuations multipliers for each node show the proportion of consumption in each moment of the day to the daily average of its demand (Taebi and Chamani, 2006). The time of start and end of each period have been chosen in order to make maximum possible difference between the maximum and the minimum multipliers. This maneuver helps to make a meaningful difference between connecting or cutting flow for each node among different periods. Otherwise, it does not make any difference for the optimization algorithm to supply the demand of a consumption node in a specific period or cut it. Therefore, the algorithm would not be able to reach to a fixed condition. The method of derivation of the aforementioned multipliers for each period of the day has been shown in Figure (1).
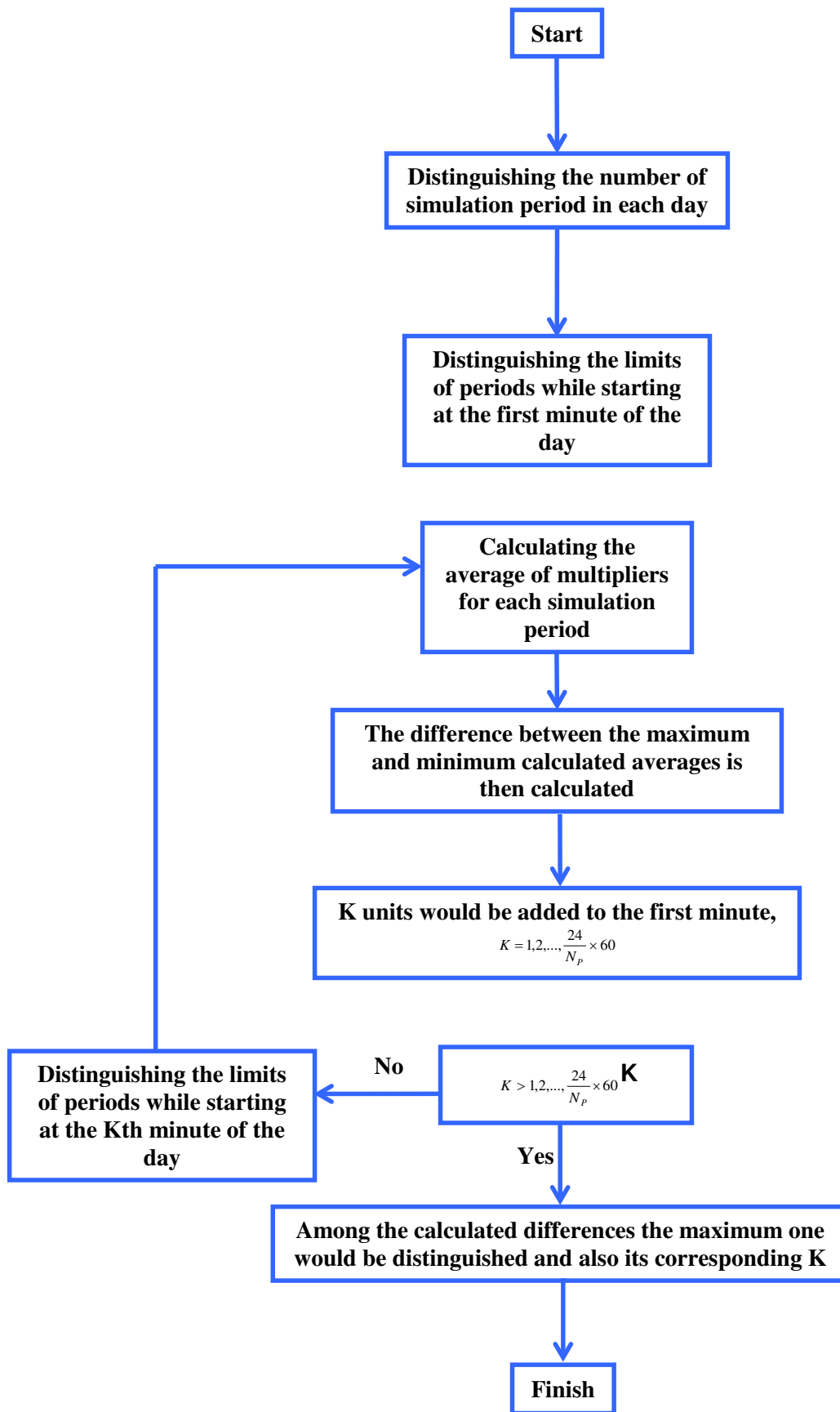
Figure 1- The flowchart of considered procedure for calculating the hourly fluctuations multipliers

Figure (2) shows the hourly fluctuations of consumption for two summer days beside the start and end of different periods of each day.
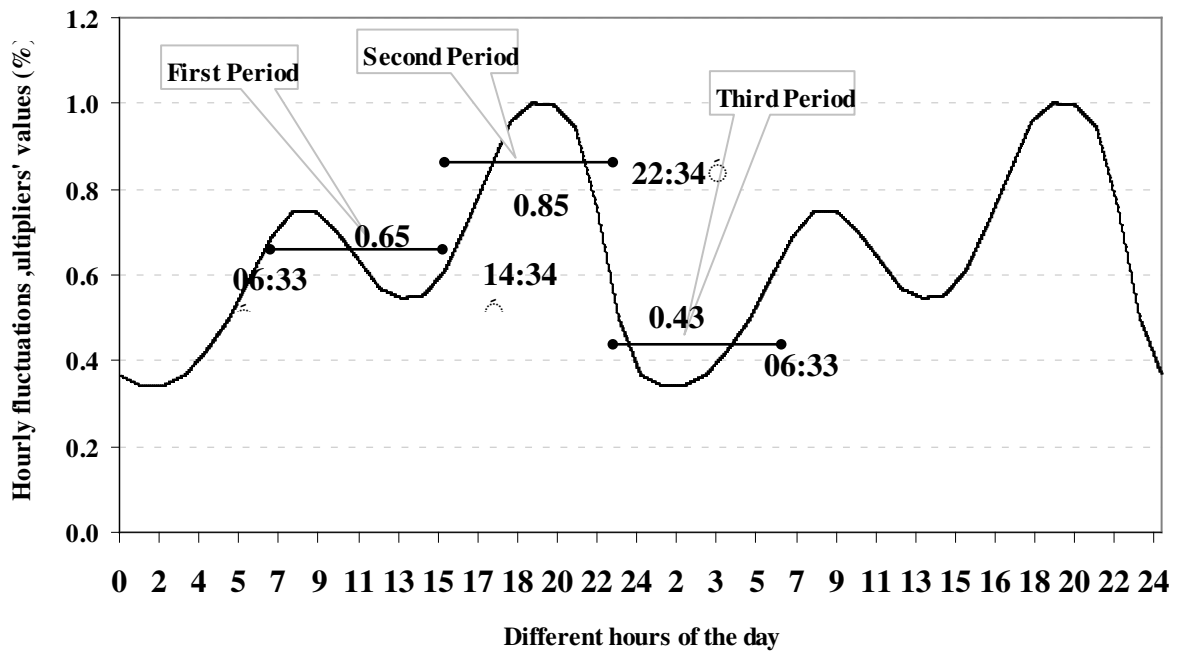
Figure 2- hourly fluctuations of consumption for two summer days beside the start and end of different periods of each day

5. The optimization model for hedging and intermittent water supply in WDN

Considering the explanations about the basic criteria for applying hedging and intermittent water supply, the optimization model is presented as below. Equation (1) is introduces the objective function.

$$O.F. = Max \; \frac{\prod_i (\sum_p (RP_{i,p} \times RQ_{i,p}))}{(Np \times NDay)^{Ni}} \tag{1}$$

In the above equation i=shows the number of each network's node, p=shows the number of each simulation period in operational period. Ni=the number of consumption nodes in WDN. Np=the number of simulation periods in each day and $NDay$=the number of days included in operational period. $RP_{i,p}$ and $RQ_{i,p}$ are defined in equations (2) and (3).

$$
RP_{i,p} = \begin{cases} \dfrac{P_{i,p}}{P_{i,\min}} & , & \text{if } \dfrac{P_{i,p}}{P_{i,\min}} \le 1 \\[4mm] 1 & , & \text{if } \dfrac{P_{i,p}}{P_{i,\min}} > 1 \end{cases} \tag{2}
$$

In equation (2), $P_{i,p}$=the pressure of node i in simulation period p and $P_{i,\min}$=the

minimum pressure required in node i. Finally $RP_{i,p}$=pressure desirability criteria in simulation

period p for node i.

$$
RQ_{i,p} = \begin{cases} 0 & , & \text{if } \alpha_{i,p} = 0 \\[4mm] \dfrac{Q_{i,p}}{RDe_{i,p}} & , & \text{if } \alpha_{i,p} \ne 0 \end{cases} \tag{3}
$$

In the above equation $\alpha_{i,p}$=decision variable of the optimization model which is a

multiplier that varies between 0 and 1 and shows the proportion of demand which is supplied

in simulation period p for node i. $RDe_{i,p}$ and $Q_{i,p}$=respectively are demand and the amount

of supplied water in simulation period p in node i. $RQ_{i,p}$=supply desirability criteria in

simulation period p in node i. In the defined objective function in equation (1) three main

maneuvers have been considered which are being described herein. As it is seen from the

equation, the value of the objective function is formed from three components, of three nodal,

temporal and network levels. The first component is the product of pressure and demand

supply desirability criteria in each simulation period for each consumption node. Since the

desirability of delivering water depends on both pressure and the amount of supplied water,

so by multiplication of the two aforementioned parameters, the total desirability of delivering

water in each simulation period for each consumption node would be satisfactory when

demand is supplied with a pressure equal or greater than the minimum required pressure. The

second component or the temporal one is sum of the nodal desirabilities during the

operational period for each node. Since the aim of selection of this objective function is to

rise, the desirability of supply in the operational period as much as possible, at the end of

operational period a desirability value would be achieved for each node. The third component, which shows the desirability of delivering water to the whole network, guarantees equity of supply among different consumers. This is perceptible considering the rule, which is true in case of multiplications of some sets of digits, which have a same sum. Since the product of some sets of numbers, which have a same sum, is maximum whenas the numbers be as close as possible, therefore with maximizing the product of temporal components or value of the objective function, the temporal components would be as close as possible, and it verifies the equity criterion in the objective function. As it is stated previously the temporal components for each node shows the desirability of supply during operational period. Therefore, when these components are close to each other, it means that the different consumers have experienced equal or semi-equal desirability during operational period. The equations, which are being stated hereafter, are the constraints of the optimization model. Equations (4) until (6) are maneuvers, which have been considered in order to rise the welfare of hedging or intermittent water supply.

$$\alpha_{i,p} + \alpha_{i,p+1} \geq \frac{Q_{in}}{Ave.RDe} \tag{4}$$

$$\alpha_{i,p} + \alpha_{i,p+Np} \geq \frac{Q_{in}}{Ave.RDe} \tag{5}$$

$$\alpha_{i,p} + \alpha_{i,p+7\times Np} \geq \frac{Q_{in}}{Ave.RDe} \tag{6}$$

In the above equations Q_{in}=the input flow to the reservoir, which has a fixed amount during different hours of the day. $Ave.RDe$=the average demand flow of the network, which in every simulation period of the day, would be achieved by dividing the sum of network's hourly demand flow during a day to the number of simulation periods considered for each day. As it is stated before and it is seen in the above equations, the supplied flow in every simulation period in each node would be compared with the supplied flow for that node in the next simulation period, with the corresponding simulation period of the next day and

with the corresponding simulation period of the corresponding day of the next week. Therefore it would not be possible to supply a node less than the amount defined in the equations above, in two consecutive simulation periods, two corresponding ones of two consecutive days and two corresponding ones of two corresponding days of two consecutive weeks. Equations (7) until (11) show the method of calculating reservoir storage volume at the beginning of the operational period and each simulation period as well.

$$S_1 = \begin{cases} 0 & , if \quad S_{\max} - (2 \times (Ln \times Q_{in}) - Ln \times MinRDe) < 0 \\ S_{\max} & , if \quad S_{\max} - (2 \times (Ln \times Q_{in}) - Ln \times MinRDe) > S_{\max} \\ S_{\max} - (2 \times (Ln \times Q_{in}) - Ln \times MinRDe) & , if \quad 0 \le S_{\max} - (2 \times (Ln \times Q_{in}) - Ln \times MinRDe) \le S_{\max} \end{cases} \tag{7}$$

$$S_{p+1} = S_p + Ln \times (Q_{in} - \sum_i Q_{i,p}) \tag{8}$$

$$0 \le S_p \le S_{\max} \tag{9}$$

$$S_{\max} \ge \frac{\sum_i \sum_p^{Np} RDe_{i,p}}{NDay} \tag{10}$$

$$S_{Np \times NDay+1} \ge S_1 \tag{11}$$

In the above equation Ln =the length of each simulation period (hour) in which the flow could be connected or cut. $S_{\max}$, S_1, S_p, S_{p+1} and $S_{Np \times NDay+1}$ are respectively the maximum reservoir storage volume, the initial storage volume of the reservoir at the beginning of the operational period, the storage volume of reservoir at the beginning of the simulation period p, the reservoir storage volume at the end of the simulation period p (the beginning of simulation period $p+1$), the reservoir storage volume at the end of the last simulation period. $Min.RDe$ = is the minimum demand flow of the network among different simulation periods of a day. NHR = the number of hours, which multiplied to the average hourly demand flow, gives the storage capacity of the reservoir. It is worthy of mention that equation (11) dictates the carry over constraint in operation of WDN. In addition, it is seen that the initial storage volume is calculated in equation (7). Otherwise, the algorithm had to choose from innumerable two-member sets, which its first and second members would be respectively the initial and final storage volume at the beginning and end of the operational period that does

not make any difference in the value of objective function and the desirability of final solution, it could be a problem for the algorithm in case of selecting the best solution. Since the reason of considering the reservoir for the network is to make the possibility of supply in emergency (a situation in which water is not delivered to the network temporarily), therefore the more water available in the reservoir at the beginning of the operational period, the more demand supply safety factor. Another point, which has been considered for assigning a value to the initial storage volume, is keeping the storage volume less than maximum reservoir storage capacity, even in the situation that the maximum probable water storage happens in two consecutive simulation period. As it is seen in the equation (7), two uninterrupted simulation periods have been considered in such a manner, that the former would not receives any supply and the demand of the latter which is being supplied is *Min.RDe*.

$$RDe_{i,p} = \sigma \times \beta_p \times DDe_i \tag{12}$$

$$Q_{i,p} \le RDe_{i,p} \tag{13}$$

In the above equations DDe_i = is the design demand in node i and β_p = are the hourly fluctuations multipliers which in respect to each simulation period of the day have a specific value. It is mentionable that for the case studies considered in this research in each simulation period the hourly fluctuations multipliers have been assumed equal. σ = is the multiplier, which increases the demands in comparison with their design demands.

$$\sum_i Q_{i,p} \le \lambda \times \sum_i RDe_{i,p} \tag{14}$$

In the above equation λ = is a multiplier between 0 and 1 that shows the intensity of water shortage.

6. Shortcomings of hedging and operation in the manner of intermittent water supply

As it is stated previously in hedging method, the water supply in every simulation period in each node would be assigned according to the decision variables of the optimization model, which are multipliers between 0 and 1. Considering only two integer values 0 and 1 for these multipliers, the hedging method would transform to intermittent water supply. In

hedging method, in different hours of the day it is needed to regulate the flow from consumption nodes, which varies between zero and the demand. Therefore, application of hedging would be much more expensive economically and hydraulically. So intermittent water supply idea with the definition presented previously could ease the matter in respect to economic constraints and make it more applicable. Therefore, in this research, while hedging method is theoretically applied to achieve the best possible value for the objective function, intermittent water supply would be executed and compared with the results of hedging to show the difference of intermittent supply desirability and hedging method.

7. Different WDN operational methods in critical situation

In this section, four possible methods of operating WDNs in water shortage condition will be defined. It should be mentioned that the methods in question, are discussed whenas the WDN are assumed to have flow control equipment. Then calculating the values of performance criteria, would give the desirability of supply in accordance of application of each operational method.

7-1. Distributing the shortage constantly along the operational period

The amount of available water and its ratio to the needed one during the operational period are clear. Applying this ratio on the amount of supplied water in every node and every simulation period, would cause that none of the nodes would experience water stop and 100 percent supply as well. Therefore the ratio of the amount of supply to the amount of demand in all the nodes and so in the whole network for all simulation periods equals to the ratio of available water to the network's demand in the operational period.

7-2. Constant priorities

In the second method while water is available, it is allocated to supply consumption nodes and while water is not available, consumers do not experience any supply. In this method, which will be identified as the second method hereafter, the priority over supply in

every simulation period belongs to the nodes with fewer demands. Considering the amount of available water, possibly some nodes' may have partial demand supply and even water stop in some simulation periods (which is expected to happen for higher demand nodes).

7-3. Hedging

The third method simulates a condition like the first method, but instead of choosing equal values for the multipliers (decision variables) for all the nodes in all simulation periods, a more exact management in comparison with the first method would optimize the multipliers in order to maximize the theoretical desirability of supply.

7-4. Intermittent water supply

The fourth method is somehow similar to the second one, but instead of prioritizing fewer demand nodes careless to the higher demand nodes, in order to establish maximum equity the priorities of supply would be optimized regarding the whole operational period.

8. Basis of scenarios and description of the parameters, which make different scenarios

8.1. Hedging or intermittent water supply

The scenarios considered in the current research for different case studies are divided into two hedging and intermittent supply categories.

8.2. Incommensurateness of the available water and consumption demand

As it is stated previously drought condition or population increase are two main factors, which cause shortage of water. In this research, for the scenarios, which point drought condition, a multiplier, which decreases the input water to the network, has been considered. For the other states or scenarios, which point the increase in consumption demands, the input water to the network has been assumed equal to average daily design demand of the network, but the demands are increased using a multiplier, in respect to some factors such as the growth in city population. The reason of considering two aforementioned categories is the difference between hydraulic situations, which is resulted from simulation of them. In case

that the reason of water shortage crisis is the lack of enough water resources, since the water supplied in consumption nodes is equal or less than their design demands, it is possible to supply demands with minimum required pressure. Therefore, in this case the desirability of pressure supply does not have any negative influence on the value of objective function. However, in case that the reason of water shortage crisis is the increase in consumption demands, or In other words the demands have increased in comparison with the design demands, full demand supply in some nodes would lead to pressures less than the minimum required one.

9. Performance criteria

9.1. Reliability

For water systems, during water shortage time, failure in supply would possibly occur. According to the definition of hashimoto et al. (1982), reliability means the probability of that no failure happens in water supply in a specific period. In this research reliability criterion has been calculated in two ways. In one of them (equation (17)) the criterion returns the situation of demand supply in the whole network regardless to one by one of the consumption nodes and another one (equation (18)), evaluates the water demand supply of the network regarding all consumption nodes. In addition, it should be mentioned that in this research calculation of this research has been done for different performance thresholds.

$$\omega_\theta = \frac{N\left(\sum_i Q_{i,p} \geq \theta \times \sum_i RDe_{i,p}\right)}{Np \times NDay} \times 100 \tag{17}$$

$$\omega'_\theta = \prod_i \frac{N\left(Q_{i,p} \geq \theta \times RDe_{i,p}\right)}{(Np \times NDay)} \times 100 \tag{18}$$

Where ω_θ = is the value of network reliability criterion and ω'_θ = the nodal reliability criterion, θ = performance thresholds considered for calculating the value of reliability criterion. The other parameters are described in the part of defining the details of

optimization model. In this research, performance criteria have been calculated for 70% to 100% thresholds.

9.2. Resiliency

According to the definition of Hashimoto et al. (1982), resiliency shows the probability of system return to the desired conditions after a failure. If there are too many of uninterrupted failures on after another and the return of the system to the desired situation would occur slowly, so this would be a warning about the disability of the operational plan in satisfying plan demands in many consecutive periods. For calculation of this criterion, also two states of nodal and network resiliency have been considered. The network and nodal resiliency criteria in this research are respectively as equations (19) and (20).

$$\gamma_\theta = \frac{N(\sum_p \sum_i Q_{i,p-p'} < \sum_i \theta \times RDe_{i,p-p'})}{N(\sum_p \sum_i Q_{i,p} < \theta \times \sum_i RDe_{i,p})} \times 100 \tag{19}$$

$$\gamma'_\theta = \prod_i \frac{N(Q_{i,p-p'} < \theta \times RDe_{i,p-p'})}{N(Q_{i,p} < \theta \times RDe_{i,p})} \times 100 \tag{20}$$

Where γ_θ and $\gamma'_\theta =$ are respectively the network and the nodal resiliency of the network. $Q_{i,p-p'} =$ is the amount of flow delivered to node i in each of the simulation periods between periods p to p' in which the ratio of supplied water to the demand has been achieved less than performance threshold. The other parameters have been previously described.

10. Honey bees mating optimization (HBMO) algorithm

Social behavior of different animal species can be an accommodating natural phenomenon to be simulated by evolutionary algorithm. The HBMO algorithm is one of the evolutionary algorithms based on bee behavior that works as a hybrid tool including GA, SA and local search (LS) algorithms, which has improved the capability of the aforementioned individual algorithms with combining them together. The HBMO algorithm includes three repetitive stages, which respectively are: (1): selection, (2): reproduction, and (3):

improvement. More information about HBMO algorithm is included in Bozorg Haddad et al. (2008).

11. Case studies

The researchers always for evaluating and approving their suggested methods, firstly simplify the problem and after primary evaluation and performing required verifications, the final developed model will be used for real and larger problems. In this research, also scenarios have been considered for operation of a small WDN. After evaluating the results and getting assured of the reliable performance of the method, some of predefined scenarios have been utilized for operation of a larger WDN with a huge decision space. Two case studies considered in this research are being introduced herein.

11.1. Two-loop network

Two-loop network is a benchmark network that has been used as the first case study in this paper. Alperovits and Shamir (1977) presented this simple network, which does not have any pump and storage tank. Consumption nodes' characteristics and the schematic of this network have been introduced in Table (1) and Figure (3). This network has eight pipes and six consumption nodes. Length of all pipes is 1000 meters and hazen Williams' coefficient has been assumed 130 for all pipes. The minimum required pressure in all nodes ($P_{i,\min}$) is equal to 30 m-H_2O.
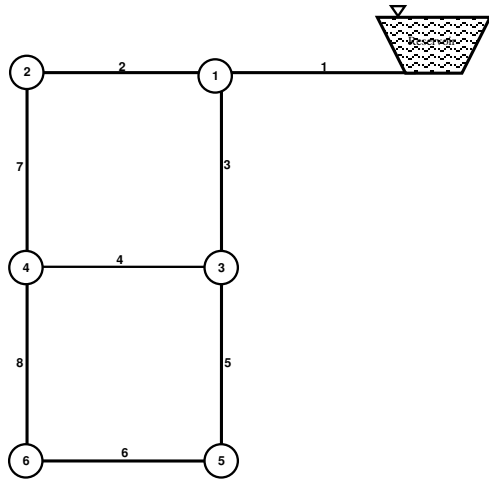
Table 1- Information of Two-loop network's nodes (Alperovits and Shamir, 1977)

Node	Demand (M3/Hr)	Elevation(M)
Reservoir	-1120	210
1	100	150
2	100	160
3	120	155
4	270	150
5	330	165
6	200	160

Figure 3- Schematic of Two-loop Network (Alperovits and Shamir, 1977)

11.2. Tehran reservoir number 30, WDN

The second case study used in this research is the network downstream of the reservoir number 30 of Tehran WDN. Its consumption nodes' and pipes' characteristics and schematic are respectively presented in Tables (2), (3), and Figure (4). Hazen Williams' coefficient has been assumed 85 for all pipes. Minimum required pressure in all nodes ($P_{i,\min}$) is equal to 30 m-H$_2$O.

Table 2- Information of Tehran's reservoir number 30 network nodes (Alperovits and Shamir, 1977)

Node	Demand (CMH)	Elevation (M)	Node	Demand (CMH)	Elevation (M)	Node	Demand (CMH)	Elevation (M)	Node	Demand (CMH)	Elevation (M)	Node	Demand (CMH)	Elevation (M)
1	2.74	1722	14	2.16	1685	27	5.76	1683	40	8.14	1708	53	2.88	1667
2	2.74	1717	15	1.08	1686	28	8.53	1682	41	0.72	1715	54	5.76	1659
3	5.11	1707	16	2.52	1684	29	5.40	1687	42	1.44	1714	55	4.32	1688
4	4.86	1701	17	12.96	1680	30	1.44	1686	43	2.16	1717	56	0.83	1698
5	9.58	1693	18	2.88	1685	31	1.80	1690	44	4.07	1717	57	4.97	1700
6	4.90	1702	19	2.88	1680	32	2.16	1699	45	6.16	1677	58	6.62	1670
7	6.73	1710	20	17.64	1679	33	1.08	1695	46	5.62	1677	59	3.24	1708
8	8.42	1699	21	9.72	1684	34	0.72	1696	47	3.53	1660	60	0.83	1703
9	8.75	1691	22	5.40	1670	35	3.24	1701	48	0.90	1660	61	2.52	1701
10	5.80	1696	23	0.50	1667	36	2.05	1702	49	7.20	1660	62	3.60	1690
11	1.80	1681	24	8.28	1666	37	5.04	1712	50	4.32	1668	63	3.24	1707
12	13.79	1680	25	13.32	1664	38	3.06	1708	51	2.88	1664	64	2.16	1690
13	1.80	1686	26	16.56	1672	39	2.56	1696	52	2.52	1663	65	4.32	1671

Table 3- Information of Tehran's reservoir number 30 network pipes (Alperovits and Shamir, 1977)

| Pipe	Length (m)	Diameter (mm)	Pipe	Length (m)	Diameter (mm)	Pipe	Length (m)	Diameter (mm)
1	68.56	250	28	89.67	80	55	108.24	60
2	127.68	250	29	52.07	80	56	54.8	80
3	98.93	250	30	111.01	80	57	43.68	80
4	61.85	250	31	49.26	80	58	87.47	80
5	28.65	250	32	231.69	150	59	93.98	80
6	76.46	200	33	26.35	60	60	137.97	80
7	122.39	80	34	289.92	60	61	93.79	100
8	136.29	250	35	133.04	200	62	89.79	100
9	140.1	60	36	40.16	200	63	107.31	100
10	101.51	100	37	23.23	200	64	58.63	150
11	189.83	250	38	64.65	200	65	54.38	100
12	26.53	150	39	81.6	100	66	59.99	60
13	62.53	150	40	69.25	60	67	51.66	150
14	100.86	150	41	157.07	150	68	61.15	150
15	189.71	100	42	163.79	150	69	30.7	80
16	188.38	100	43	95.85	150	70	65.71	80
17	61.51	60	44	93.89	100	71	40	250
18	86.82	60	45	87.34	150	72	113.87	100
19	83.67	150	46	54.8	80	73	43.9	150
20	89.47	150	47	100.11	80	74	118	100
21	38.01	150	48	66.6	150	75	28.95	250
22	75.99	60	49	46.58	150	76	34	150
23	68.45	150	50	45.04	150	77	14.29	100
24	57.82	150	51	119.47	150	78	53.87	100
25	90.75	100	52	91.93	150	79	68.96	80
26	46.73	100	53	13.92	150	80	5	100
27	44.26	80	54	112.89	60	81	90.78	150
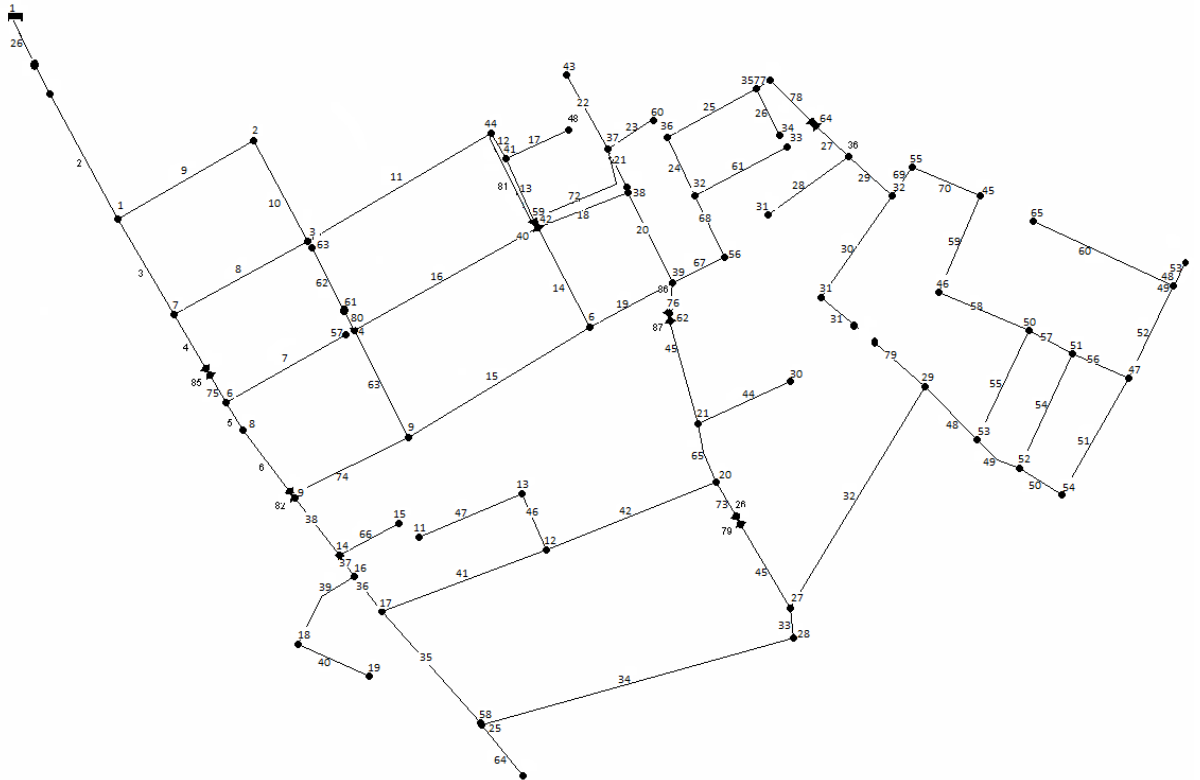
Figure 4- Schematic of Tehran's reservoir number 30 network

12. Introducing considered scenarios and analyzing the results of their application

In this section after defining different considered scenarios regarding each case study, the results of their application is presented. Then the influence of performing of each operational method under water shortage condition, which has been discussed previously, would be compared. Finally, the hydraulic condition of the network under application of every scenario is analyzed. Considered scenarios in this research are introduced in Tables (4) and (5).

Table 4- Considered scenarios for the first case study

Hedging				Intermittent Supply			
Scenario	Q'_{in}/Qin	RDe'/RDe	Np	Scenario	Q'_{in}/Qin	RDe'/RDe	Np
1	1	1	3	**4**	1	1	3
2	0/75	1	3	**5**	0/75	1	3
3	1	1/25	3	**6**	1	1/25	3

Table 5- Considered scenarios for the second case study

Hedging				Intermittent Supply			
Scenario	Q'_{in}/Qin	RDe'/RDe	Np	Scenario	Q'_{in}/Qin	RDe'/RDe	Np
1	0/75	1	3	**2**	0/75	1	3
3	1	1/25	3	**4**	1	1/25	3

In the above tables Q_{in} and $RDe =$ are respectively the network's design input and demand and Q'_{in} and $RDe' =$ are respectively input and demand of the network in each specific scenario. Hereafter respectively, the hedging and intermittent scenarios for the first and second case studies would be discussed. In the first scenario, each day has been divided into three simulation periods. In this scenario that will be identified hereafter as "No-shortage three periods scenario", the value of input flow to the network is equal to the product of average of hourly fluctuations multipliers' values and design demands of consumption nodes. The second scenario, which will be identified hereafter as "Shortage of water resources three periods scenario", differs from the first scenario in the input flow to the network, which has been considered here 75% of the first scenario. The third scenario, which will be identified hereafter as "Demand increased three periods scenario", differs from the first scenario in the

demands of the consumption nodes, which have been considered 1.25 times of the first scenario's demands. The first scenario would be analyzed with the aim of verifying the reliable performance of the model in which the manner of supplying demands in different simulation periods and its effect on the reservoir storage volume would be clearly observed. The second scenario analyzes the hydraulic situation of the network in case that the network has faced to 25% water resources shortage. In the third scenario, the consequences of increase in demands would be inspected. In this case, the ratio of the network's real demand to the design demand has been considered 1.25. The scenarios 4 to 6 are similar to scenarios 1 to 3, but the network is being operated in the way of intermittent water supply instead of hedging method. The first and second scenarios considered for the second case study, investigate the hydraulic situation of the network under water shortage condition (like scenarios number 2 and 5 of the first case study) and the third and fourth scenarios would be similar to scenarios 3 and 6 of the first case study.

In Table (6), the considered values for each entrancing parameter into the optimization model relevant to the first case study are listed.

Table 6- considered values for each entrancing parameter into the optimization model

Scenario	Volume of input water (m3/day)	Volume of network's demand (m3/day)	Initial reservoir storage volume (m3)	Reservoir storage capacity (m3)
1	17280	17280	12365	20000
2	12960	17280	15244	20000
3	17280	21600	13335	20000
4	17280	17280	12365	20000
5	12960	17280	15244	20000
6	17280	21600	13335	20000

In Table (7), the considered values for each entrancing parameter into the optimization model relevant to the second case study are listed.

Table 7- considered values for each entrancing parameter into the optimization model

Scenario	Volume of input water (m3/day)	Volume of network's demand (m3/day)	Initial reservoir storage volume (m3)	Reservoir storage capacity (m3)
1	3600	4793	3677	5000
2	3600	4793	3677	5000
3	4800	5992	3147	5000
4	4800	5992	3147	5000

In Table (8), the values of objective function related to five runs of the algorithm beside some statistical parameters for checking the convergence of the algorithm results, are presented.

Table 8- the values of objective function related to five runs of the algorithm for the first case study

		Run					Minimum	Mean	Maximum	Standard deviation	Coefficient of variation
		1	2	3	4	5					
Scenario	1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00
	2	0.36	0.37	0.35	0.35	0.36	0.35	0.36	0.37	0.01	0.02
	3	0.46	0.47	0.46	0.46	0.47	0.46	0.46	0.47	0.01	0.01
	4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00
	5	0.28	0.30	0.29	0.30	0.28	0.28	0.29	0.30	0.01	0.03
	6	0.43	0.39	0.39	0.41	0.40	0.39	0.41	0.43	0.02	0.04

The values that are listed in the column named "maximum" have been chosen as the final solution of each five run of the algorithm. As it is observed from the table standard deviation and coefficient of variation for each five run of every scenario have been achieved negligible. This approves the suitable convergence of the algorithm in finding the final solutions. In Table (9) the best values of objective function for the scenarios of the second case study are presented.

Table 9- the values of objective function related to five runs of the algorithm for the second case study

Scenario			
1	2	3	4
2.70E-07	4.40E-08	3.40E-06	1.60E-06

Considering the size and dimensions of the second case study and time-consuming process of applying the model on it and suitable convergence of the results of the algorithm, for each scenario of the second case study only one run has been considered. As it is seen in Table (9), the trend of the best values of the objective function in the second case study is similar to the first one. In this manner, that the value of the objective function in the first scenario is greater than the second scenario and in the third scenario is greater than the fourth one. In addition, the values of objective function for hedging scenarios have been achieved greater than the corresponding ones of intermittent supply scenarios.

13. Comparing the performance of different methods of operating WDNs under the condition of water shortage crisis, considering the objective function values and different performance criteria

In Table (10), the results of applying the first and second methods in the coincident condition with scenarios 2 and 5 are compared with third and fourth methods.

Table 10- Comparison of the values of objective function and performance criteria among four methods in scenarios 2 and 5

3 Period-shortage of resources	Method 1	Method 2	Method 3	Method 4
The value of unconstrained objective function	0/2	<u>0/5</u>	0/37	0/3
w_{100}	0	<u>50</u>	31	33/3
w'_{100}	0	<u>36/9</u>	8/1	29/9
w_{90}	0	<u>50</u>	35/7	35/7
w'_{90}	0	<u>36/9</u>	11/9	29/9
w_{70}	<u>100</u>	73/8	66/7	71/4
w'_{70}	<u>100</u>	38/1	20/5	29/9
γ_{100}	2/4	52	44/8	<u>60</u>
γ'_{100}	2/4	52/4	23/1	<u>100</u>
γ_{90}	2/4	<u>52/4</u>	51/9	48/1
γ'_{90}	2/4	52/4	26/8	<u>100</u>
γ_{70}	-	<u>100</u>	64/3	75
γ'_{70}	-	52/4	35/9	<u>100</u>
η_{100}	<u>25</u>	43	58	71
Φ_{100}	0	<u>15</u>	5/9	4

In Figure (5), the percentage of supply delivered as the result of application of methods one to four is seen.
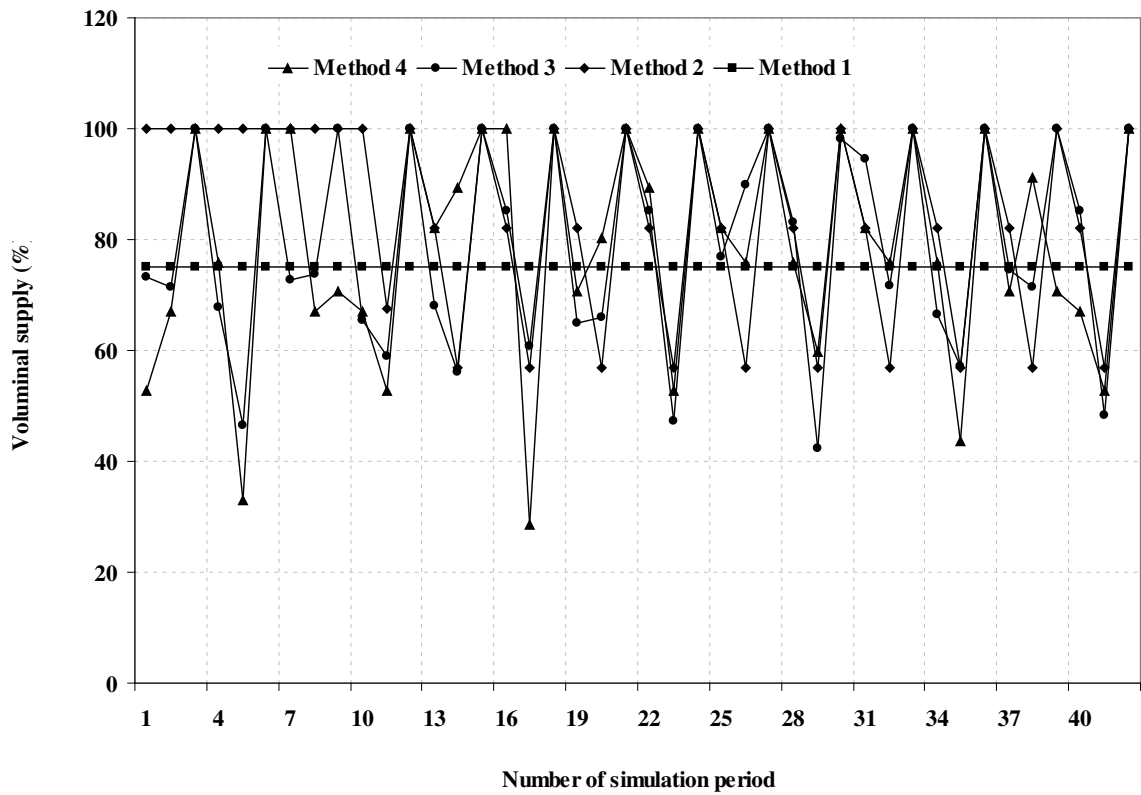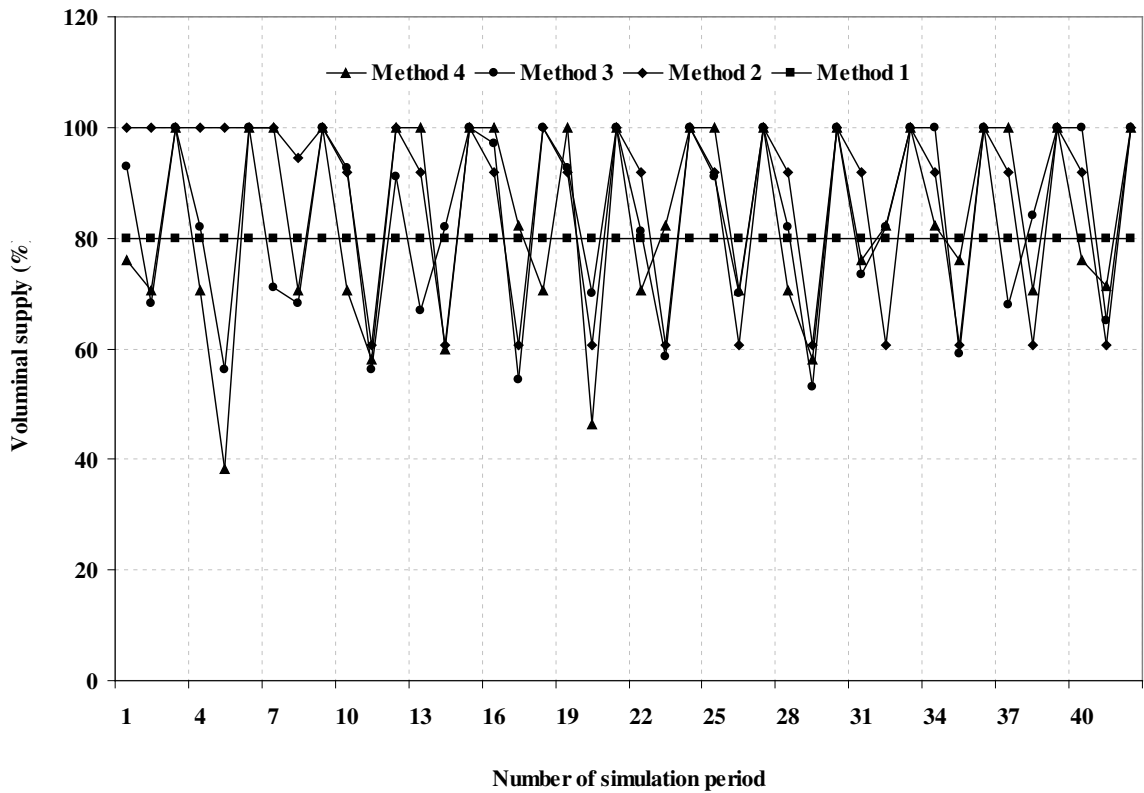

Figure 5- percentage of supply delivered as the result of application of methods one to four under scenarios 2 and 5

In Table (11) the results of application of methods one and two in coincident situation with scenarios three and six are compared with the methods three and four.

Table 11- Comparison of the values of objective function and performance criteria among four methods in scenarios 3 and 6

3 Period-demand increase	Method 1	Method 2	Method 3	Method 4
The value of unconstrained objective function	0/3	<u>0/6</u>	0/47	0/43
w_{100}	0	<u>45/2</u>	35/7	<u>45/2</u>
w'_{100}	0	33/4	15/4	<u>43</u>
w_{90}	0	<u>73/8</u>	50	45/2
w'_{90}	0	33/4	24/1	<u>43</u>
w_{70}	<u>100</u>	73/8	73/8	88
w'_{70}	<u>100</u>	54/5	39/5	43
γ_{100}	2/4	52	48	<u>61</u>
γ'_{100}	2/4	52/2	28/3	<u>100</u>
γ_{90}	2/4	<u>100</u>	66/7	60/9
γ'_{90}	2/4	52/2	47/1	<u>100</u>
γ_{70}	-	<u>100</u>	100	<u>100</u>
γ'_{70}	-	<u>100</u>	86/7	<u>100</u>
η_{100}	<u>20</u>	39	47	62
Φ_{100}	0	<u>14</u>	9	11

In Figure (6), the percentage of supply delivered as the result of application of methods one to four is seen.

Figure 6- percentage of supply delivered as the result of application of methods one to four under scenarios 3 and 6

It should be mentioned that in Tables (10) and (11), the greatest values of objective function and the values of different thresholds of performance criteria in each row (among different methods of operation) are specified with underline. As it is seen in table (10), the first method has small values for high thresholds of reliability and resiliency criteria. But the third method which in regard to the possibility of supply between zero and demand is similar to the first method, has achieved more values for the objective function and performance criteria in comparison with the first method. Since the value of the reliability criteria depends on the number of periods which have been supplied, in the first, second and third methods, the less thresholds for calculation of the criterion, the more supplied periods considering each threshold. However, in view of the fact that in the fourth method only two states of perfect stop and 100 percent supply could occur, the value of nodal reliability criterion in different thresholds are equal. Furthermore, the value of nodal resiliency criterion in 100% threshold for all scenarios under investigation has been achieved more than other methods. Nevertheless, the main concern about the achieved values for criteria is that the value of nodal resiliency criterion in the fourth method has been achieved more than other methods in all scenarios. The reason of this matter is considering the constraints related to promotion of welfare level of supply, which has been described in equations (4) to (6). In fact, objective function and the constraints of the optimization model are two main effective parameters on the values of supply multipliers. The three levels of objective function that have been described previously, respectively guarantee the desirability of supply in each simulation period for every node (the first level component), welfare for consumption nodes during the operational period (considered constraints in equations (4) to (6)) and conformity of the method with equity in water delivery under water shortage condition (the product of second

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level components). Therefore, if it is not seen any specific trend for the achieved values of reliability criterion, this is because it has not been the objective function of the optimization model nor a part of it. In addition, the constraint considered in the optimization model proposed in this research, emphasizes on the resiliency criterion, and guarantees as fast departure of failure of supply as possible for each consumption node of the network. This should be considered as well, that the reliability criterion is calculated based upon the number of the periods, which have been supplied. In case, that in calculation of this criterion for each consumption node, it had been considered a weight according to its demand, much smaller values would be achieved for the nodal reliability criterion of the second method in comparison with the fourth method for certain. The interesting point regarding the values of objective function in the above tables is the permanent superiority of its values under application of fixed priorities method. Two reasons exist to explain this matter. The first is inferable observing the Figures (5) and (6) and that is, as it is seen in the mentioned figures, though the supply trend in the second, the third and the fourth methods are similar during the operational period, but in the prior periods of the operational period (the first two to three days), 100 percent supply have been occurred under the second method. The reason is fully utilizing the reservoir storage volume. The second reason is nonexistence of any constraint related to welfare of supply and inconsideration of equity in supplying the demands of different consumption nodes. as it is stated previously, in the second method, while the water is available, the demands of lower demands nodes would be supplied and if any water is still available, the demands of higher demand nodes would be supplied as well. This would cause repetitive water stop or paltry supply in higher demand nodes that is not allowed in proposed method in this research. Therefore, in methods three and four, sometimes with the aim of satisfying the constraints of equations (4) to (6), it would be needed to stop the water supply of low demand nodes in order to supply higher demand nodes. Considering that the value of

objective function straightly depends on decision variables, this would be evidently inferred that supply stop in several low demand nodes in order to supply higher demand nodes would cause fewer number of values 1 (and closed to 1) for decision variables in method four (and three) and therefore the higher values for the calculated value for objective function of the optimization model using the results of applying method two. Comparing methods three and four shows that usually the reliability of supply in the fourth method is greater than the third one.

13.2. Analyzing the results of applying different scenarios for the first case study

Figures (7) to (9) show the volumes of demand, supply, entrance water and reservoir storage volume related to scenarios four to six.
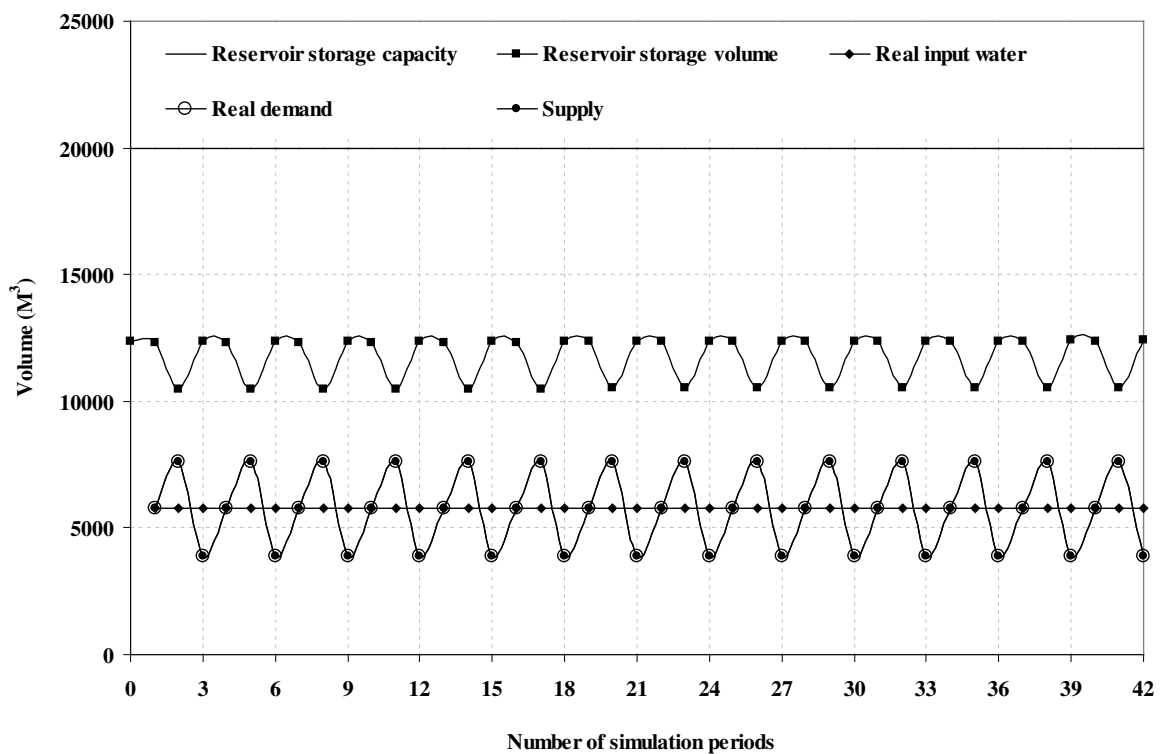
Figure 7- volumes of demand, supply, entrance water and reservoir storage volume

related to scenario four

As it is seen in Figure (7), the demands are supplied completely. Existence of reservoir makes it possible for the network that even in the periods in which the demand is more than

the entrance water into the network, sum of entrance water and storage volume satisfies network's demand. It should be mentioned that since the entrance water into the network in no-shortage condition is equal to the average of demand during the day, the demand in some of the hours of the day is greater than the fixed entrance water into the network. Therefore, nonexistence of the reservoir could lead to failure in network's demand supply in high demand periods.
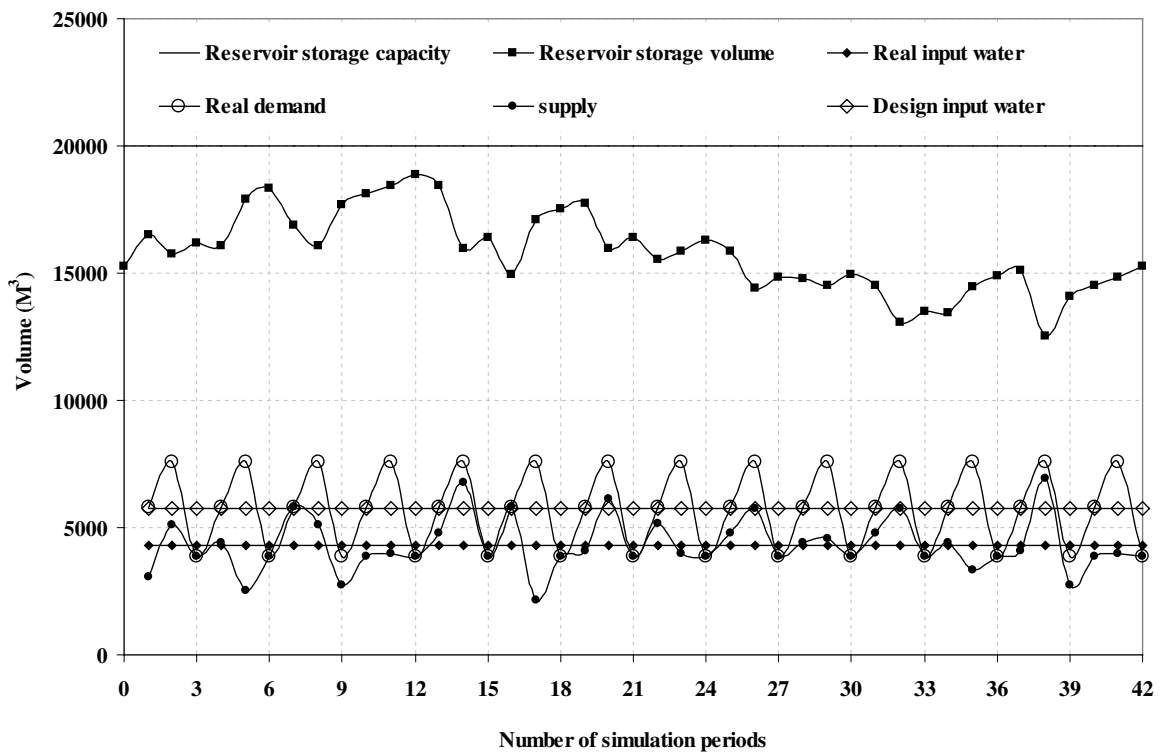
Figure 8- volumes of demand, supply, entrance water and reservoir storage volume related to scenario five
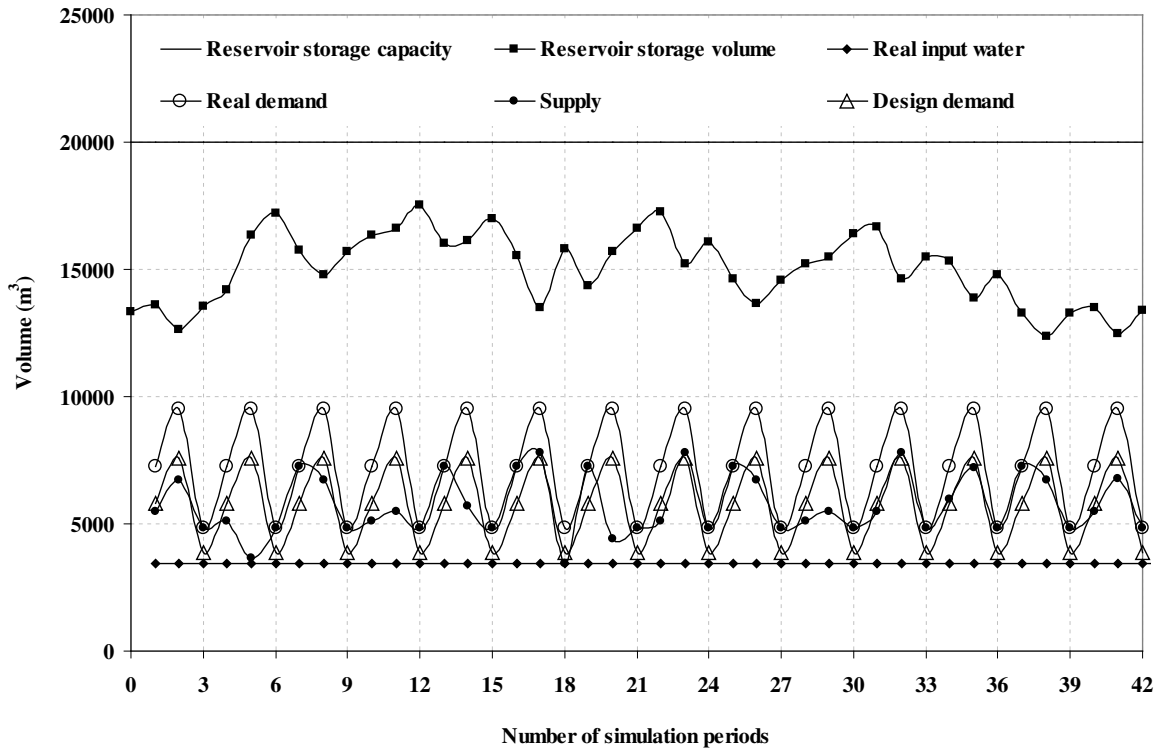
Figure 9- volumes of demand, supply, entrance water and reservoir storage volume

related to scenario six

Some parameters like the amount of supply in each simulation period, reservoir storage

volume and the parameters which are effective on their values, in scenarios 4 to 6 does not

have any special difference with the scenarios 1 to 3 and the trend of supply would be

calculated according to the amount of entrance water, demand and their proportion and also

reservoir storage volume. Figures (8) and (9) show that the third simulation period of each

one of operational period's days, in two scenarios two and three, usually have been

completely supplied. The main difference between the aforementioned scenarios, is the

simplicity of applying scenarios 4 to 6, in comparison with scenarios 1 to 3. As it is stated

previously, intermittent water supply is logically much more applicable and mechanically a

less damaging method of operation. The other aspect, which is comparable between different

scenarios, is the value of the objective function achieved for hedging and intermittent states.

As it is seen in Table (8), the achieved values for scenarios 1 to 3 respectively are 1, 0.37 and

0.47 and for the scenarios 4 to 6 are 1, 0.3 and 0.43. Comparing values of objective function of hedging and intermittent states show that hedging states gives greater values for objective function in comparison with the intermittent method. This is because of the mathematical nature of the objective function. Since in the hedging method it is possible for the algorithm to choose values between 0 and 1, obviously the value of the objective function would be greater than the intermittent state which is a specific state of hedging method and therefore the decision space is greater in hedging than intermittent method. In Figures (10) to (15), the achieved values for the pressures of consumption nodes of the first case study in scenarios 1 to 3 are shown.
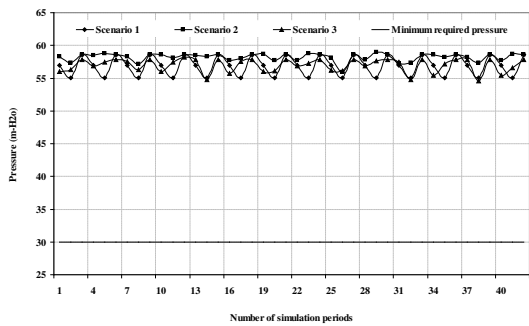
Figure 10- supplied pressures for node 1 in different simulation periods under scenarios 1 to 3 beside the minimum required one
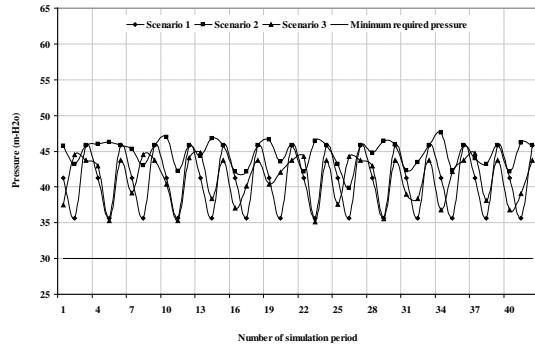
Figure 11- supplied pressures for node 2 in different simulation periods under scenarios 1 to 3 beside the minimum required one
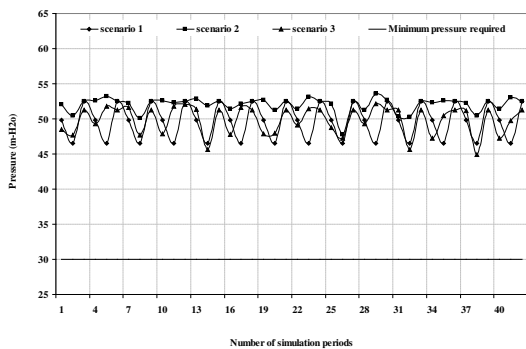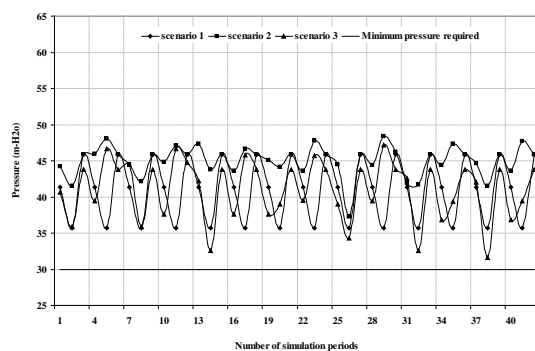

Figure 12- supplied pressures for node 3 in different simulation periods under scenarios 1 to 3 beside the minimum required one
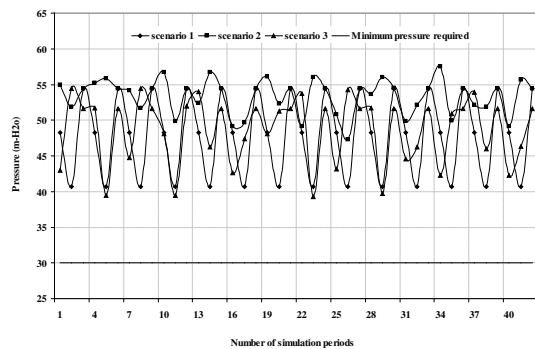
Figure 13- supplied pressures for node 4 in different simulation periods under scenarios 1 to 3 beside the minimum required one
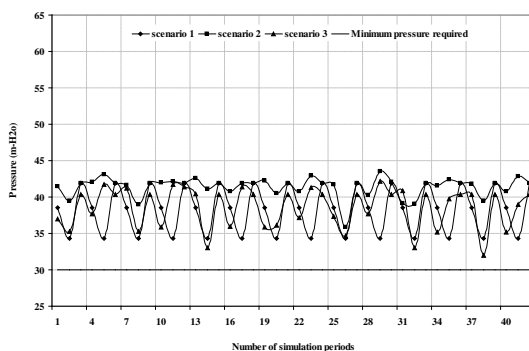
Figure 14- supplied pressures for node 5 in different simulation periods under scenarios 1 to 3 beside the minimum required one

Figure 15- supplied pressures for node 6 in different simulation periods under scenarios 1 to 3 beside the minimum required one

As it is seen in the figures, scenario 2 has resulted the highest values for supplied pressures in consumption nodes, whereas scenario 3 has resulted the lowest values and

scenario 2 is at the middle. This is because of ejection of greater flows from the consumption nodes under scenario 3 in comparison with the others and in scenario 1 in comparison with scenario 2. Figure (16) shows the voluminal percentage of supplied demand in each consumption node in the whole operational period for the scenarios 1 to 6.
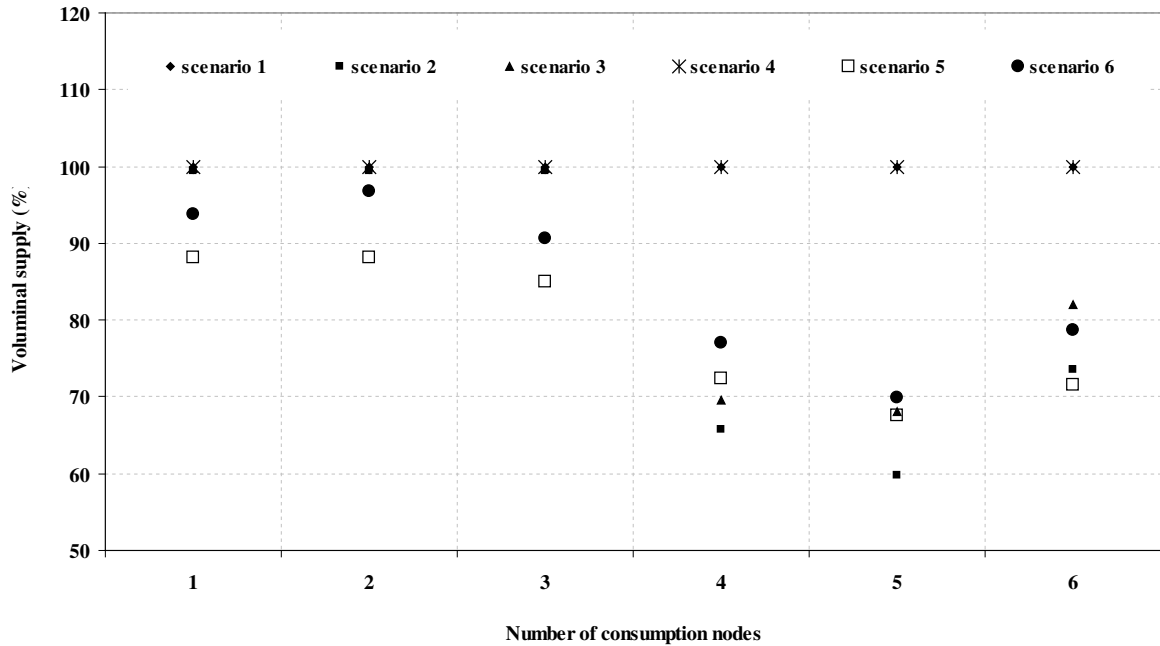

Figure 16- voluminal percentage of supplied demand in each consumption node in the whole operational period for the scenarios 1 to 6

As it is seen in the figure, the voluminal percentage of supplied demands in the nodes 1, 2 and 3 is considerably greater than the others. This is because of the less values of their demands in comparison with other nodes. In a specific simulation period, under shortage condition, when the network is not able to supply the demands of all consumption nodes, the model tries to satisfy the nodes with the less values of demand. This is because the dependence of the desirability of the objective function to the ratio of the supplied demands to the real amount of demands. The greater values (as close as possible to 1 in hedging method and 1 in intermittent method) for mentioned ratio the greater values for the objective function. Water shortage scenario has resulted less values of supply in comparison with demand growth scenario. This is because of the difference between the values of the ratio of

input water into the network to demand in each simulation period, under water shortage scenario, which is 0.75 in comparison with the demand growth scenario in which the mentioned ratio is 0.8.

13.3. Analyzing the results of applying different scenarios for the second case study

In Figures (17) and (18), the volumes of demand, supply, and reservoir storage volume related to scenarios 3 and 4 are shown.
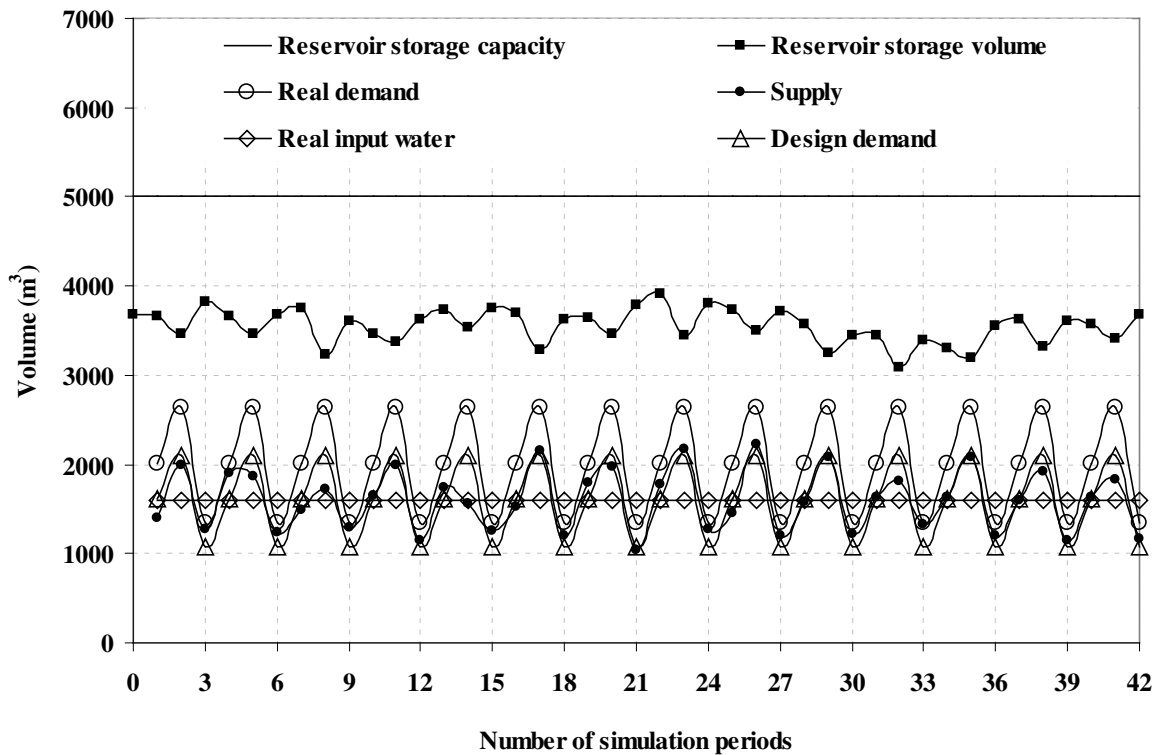

Figure 17- volumes of demand, supply, entrance water and reservoir storage volume related to scenario three
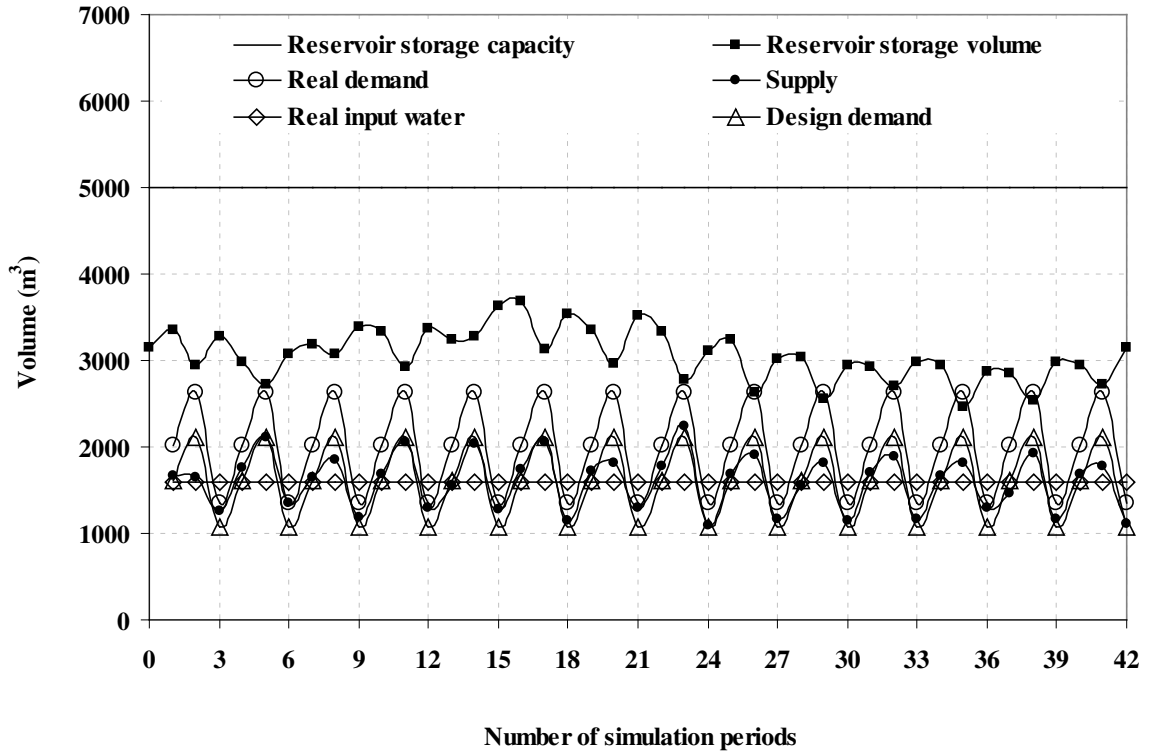
Figure 18- volumes of demand, supply, entrance water and reservoir storage volume

related to scenario four

As it is seen in all scenarios the second simulation period of the day has allocated the greatest volume of demand to itself. Therefore, the storage volume in the aforementioned simulation periods has experienced a comparative fall. In Figure (19), the values of pressures in normal condition are shown.
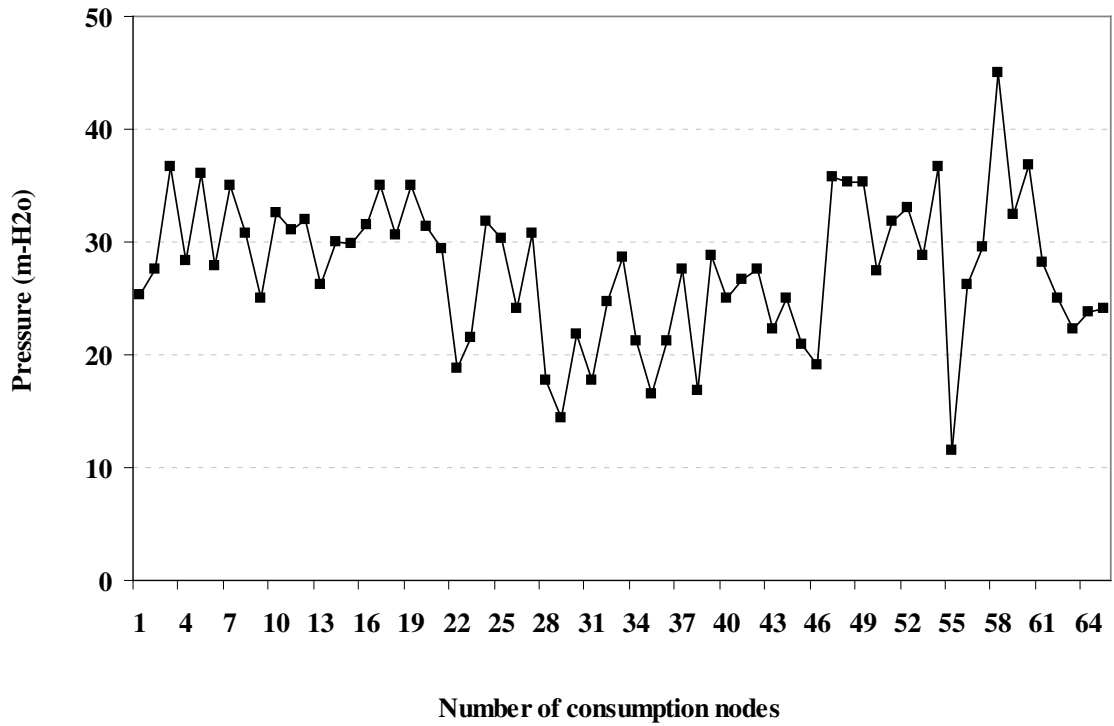
Figure 19- The values of supplied pressures for consumption nodes under normal

condition

Figure (20) shows the values of supplied pressures in three consumption node, which their pressures cover the minimum, middle, and maximum values of, supplied pressures in the whole network during the operational period in all scenarios.
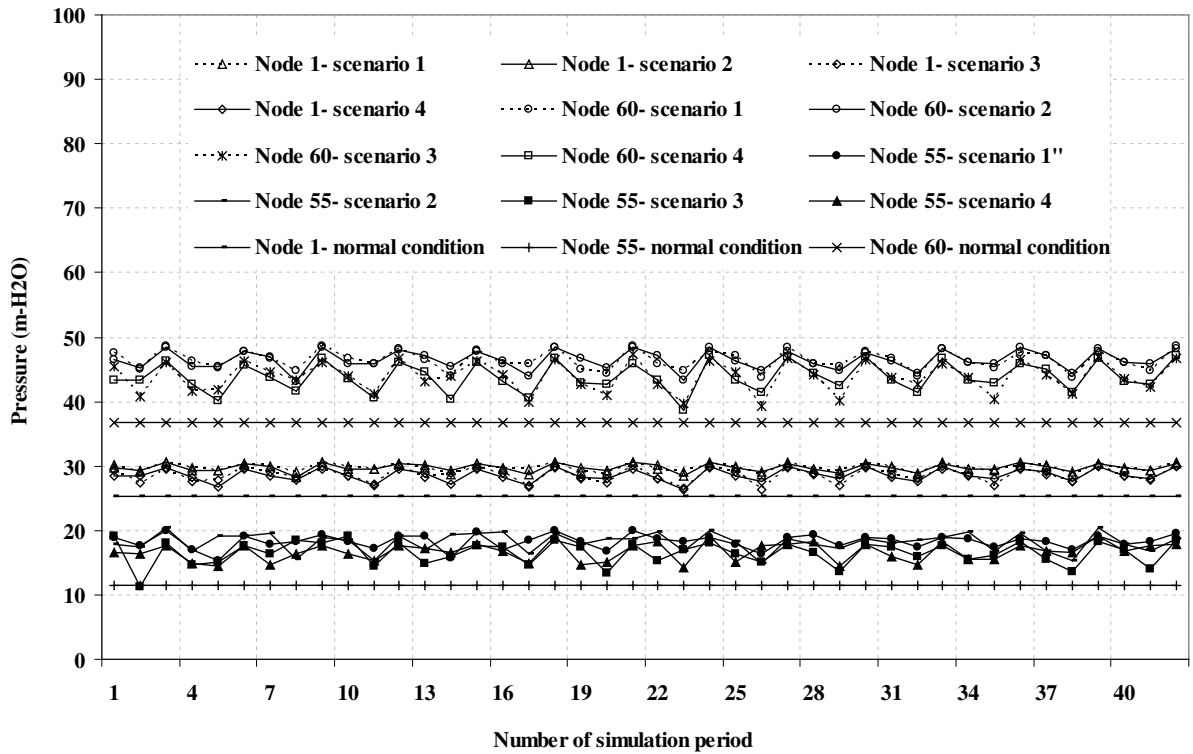
Figure 20- The values of supplied pressures for consumption nodes 1, 55, and 60 in the

whole simulation period in scenarios one to four

As it is seen again here, the values of supplied pressure in each consumption node, in

water shortage scenarios are higher than demand growth scenarios. Figure (21) illustrates the

values of velocity of water in different pipes of the network, in each simulation period of the

day under normal condition.
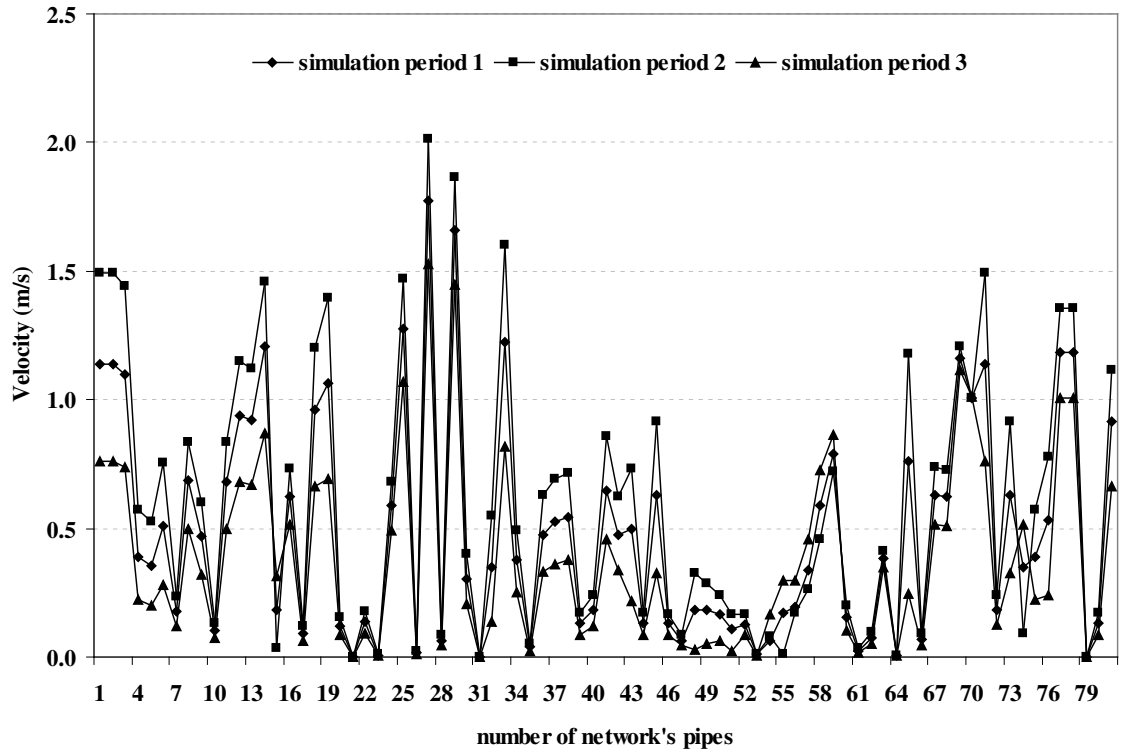
Figure 21- The values of network pipes' velocities in each simulation period of day

under normal condition beside velocities in scenario 4

As it is expected, in the second simulation period of each day, which is the highest demand one, the values of velocity in all pipes of the network are the greatest ones in comparison with the other two simulation periods. Figure (22) shows the maximum velocities in normal condition beside the maximum velocities in scenario 4.
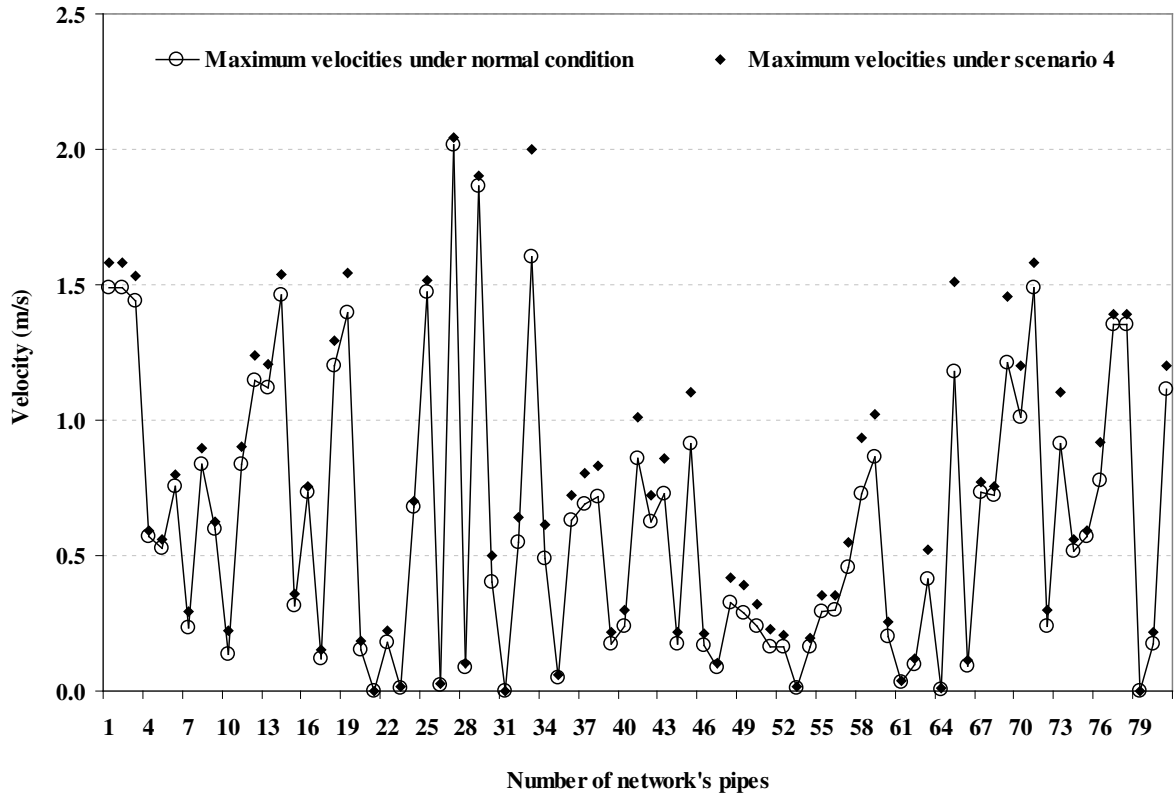
Figure 22- The values of network pipes' velocities in each simulation period of day

under normal condition

Since scenario 4 is a demand growth-intermittent method scenario, it is expected to have the greatest increase for the velocities. As Figure (22) illustrates, the greatest increase has happened for the pipe 33 in which the value of velocity has changed from 1.6 to 2 m/s.

14. Concluding remarks

Since under water shortage condition continuous operation of WDNs could be inapplicable, therefore intermittent water supply as an idea for operating WDNs in order to experience a safe departure of water shortage juncture could be of interest. Internal and foreigner experiences show that intermittent supply under water shortage condition is unavoidable in spite of mechanical consequences for WDN's components. Therefore the aim of this research is to develop a suitable method for intermittently supply the demands of WDNs under water shortage condition. This needs to pay attention to the parameters and constraints effective on the consumers' life. Therefore, in order to develop a plan for

intermittent water supply, two case studies have been investigated. The optimization model with the aim of maximum desirability of supply has been developed and solved using HBMO algorithm. Furthermore, different water shortage juncture confrontation methods have been compared. As the result of this comparison, it was inferred that the proposed method in this research, has more compatibility with operator's objective and consumers' needs and has the least irritation for them. Comparing the numerical results of methods 1 to 4 shows that network resiliency criterion in high levels and nodal resiliency under intermittent method have been achieved considerably greater than other methods. This matter shows the ability of the proposed method in departure of failure period. Since the fixed priorities method is not bound to any constraints, therefore in this method without considering some criteria like equity and welfare, the water is allocated to consumption nodes from the lower demand ones to the higher demand ones. Whiles in order to legalize the aforementioned method it is needed to consider some constraints related to human life. Resiliency criteria calculated in this research illustrate the amount of fixed priority method's violation from different constraints. Furthermore, in order to analyze the hydraulic condition of the network under different scenarios, hydraulic parameters have been investigated. Besides, the values of objective function are as expected. It was also seen that the effect of stopping and connecting water on pipes' velocities is negligible and it can be obviated using required maneuvers.

8. References

1. Taebi, A., and Chamani, M. (2007), "Urban water distribution network" Second publish, Center of publishment of university of Isfahan.
2. Afshar, A., Bozorg Haddad, O., Mariño, M. A. and Adams, B. J. (2007). "Honey-bee mating optimization (HBMO) algorithm for optimal reservoir operation", Journal of Franklin Institute, 344(5), 452-462.
3. Alperovits, E. and Shamir, U. (1977). "Design of optimal water distribution systems", Water Resource Research, 13(6), 885-900.
4. Barros, M. T. L., Zambon, R. C., Barbosa, P. S. F. and Yeh, W. W-G. (2008). "Planning and operation of large-scale water distribution systems with preemptive priorities", Journal of Water Resources Planning and Management, 134(3), 247-256.

5. Biscos, C., Mulholland, M., Le Lann, M. V., Buckley, C. A. and Brouckaert, C. J. (2003). "Optimal operation of water distribution networks by predictive control using MINLP", Water S. A., 29(4), 393-404.
6. Bozorg Haddad, O., Adams, B. J. and Mariño, M. A. (2008). "Optimum rehabilitation strategy of water distribution systems using the HBMO algorithm", Journal of Water Supply, Research and Technology, 57(5), 337-350.
7. Carrijo, I. B. and Reis, L. F. R. (2004). "Operational optimization of WDS using a genetic algorithm with multiobjective function and operating rules extracted through data mining", In Simposio Internazionale di Ingegneria Sanitaria Ambientale, 2004, Taormina. SIDISA 2004 - Proceedings. Catania - Italia: CSISA-Centro Studi Di Ingegneria Sanitaria Ambientale Onlus, 1, 1-325.
8. Dorigo, M. (1992). "Optimization, Learning and natural algorithms", Ph.D. Thesis, Politecnico di Milano, Milan, Italy.
9. Dorigo, M., Bonabeau, E. and Theraulaz, G. (2000). "Ant algorithms and stigmergy", Future Generation Computation Systems, (16), 851-871.
10. Eusuff, M. M. and K. E. Lansey, (2003). "Optimization of water distribution network design using the shuffled frog leaping algorithm", Journal of Water Resources Planning and Management (ASCE), 129(3): 210-225.
11. Ghajarnia, N., Bozorg Haddad, O. and Mariño, M. A. (2009), "Reliability based design of water distribution network (WDN) considering the reliability of nodal pressures", World Environmental and Water Resources Congress, (ASCE), DOI: 10.1061/41036(342)579.
12. Ghajarnia, N., Bozorg Haddad, O. and Mariño, M. A. (2010), "Performance of MCANDA–HBMO hybrid algorithm in design of water distribution networks", Water Management, 164(1), 1-19.
13. Hashimoto, T., Stedinger, J. R. and Loucks, D. P., (1982). "Reliability, resilience, and vulnerability criteria for water resource system performance evaluation", Water Resources Research, 18(1), 14-20.
14. Loucks, D. P. (1997), "Quantifying trends in system sustainability", Journal of Hydrology Science, 42(4), 513-530.
15. Mario, T. L., Barros., Renato, C., Zambon., S. F. and Yeh, W. W.-G. (2008). "Planning and Operation of Large-Scale Water distribution Systems with Preemptive Priorities." Journal of Water Resources Planning and Management, 134(3), 247-256.
16. Misiunas, D. (2005). "Failure monitoring and asset condition assessment in water supply systems", Ph.D. Thesis, Lund University, Lund, Sweden. 349 pp.
17. Mohan, S. and Jinesh Babu, K. S. (2010). "Optimal Water Distribution Network Design with Honey-Bee Mating Optimization", Journal of Computing in Civil Engineering, 24(1), 117-126.
18. Pradhan, A. and Tarai, A. (2006). "Modelling intermittent water supply systems with EPANET", 8th annual WD symposium EPA Cincinnati, August 27-30.
19. Rossman, L. A. (2000). "EPANET 2 Users Manual", United States Environmental protection Agency, Cincinnati, Ohio, US.
20. Seifollahi-Aghmiuni, S., Bozorg Haddad, O., Omid, M. H., and Mariño, M. A. (2011). "Long-term analysis of water distribution network's efficiency under demand uncertainty", Water Management, DOI: 10.1680/wama.1000039, (Available online).
21. Soltanjalili, M. J., Bozorg Haddad, O. and Mariño, M. A. (2011). "The effect of considering breakage level one in design of water distribution networks", Water Resources Management, 25(1), 311-337..

22. Subhash P. A. and Prakash S. K. (2008). "Influence of intermittent and continuous modes of water supply on domestic water consumption", Water Resources Management, DOI 10.1007/s11269-008-9396-8.
23. Totsuka, N. and Trifunovic, N. The Netherlands and K.Vairavamoorthy, UK. (2004). "Intermittent urban water supply under water starving situations" 30th WEDC International Conference, Vientiane, Lao PDR.
24. Van Zyl, J., Savic, D and Walters, G. (2004). "Operational optimization of water distribution systems using a hybrid genetic algorithm", Journal of Water Resources Planning and Management, 130(2), 160–170.
25. Wilchfort, O. and Lund, J.R. (1997). "Shortage management modeling for urban water supply systems", Journal of Water Resources Planning and Management, 123(4), 250-258.
26. Yepes, G., Ringskog, K. and Sarkar, S. (2001). "The High Cost of Intermittent Water Supplies", Journal of Indian Water Works Association, 33(2), 99-115.
27. Zecchin, A. C., Maier. H. R., Simpson. A. R., Leonard. M. and Nixon. J. B. (2007). "Ant colony optimization applied to water distribution system design: comparative study of five algorithms", Journal of Water Resources Planning and Management, 133(1), 87-92.

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