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The effect of considering breakage level one in design of water distribution networks

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Abstract

Designing the water distribution networks (WDNs) without considering performance criteria would possibly lead to less cost but it could also decrease the pressure reliability in abnormal conditions like a breakage through the pipes of the network. Thus, being aware of the situation of consumption nodes, considering the pressures and the amount of water which is being supplied, could be an effective source of information for designing the high performance WDNs. In this paper, Two-loop and Hanoi networks have been selected for least cost design, considering the pressures and the amount of water supplied on each consumption node under breakage level one, using honey-bee mating optimization (HBMO) algorithm. In each state of design, a specific pressure has been defined as the minimum expected pressure under breakage level one which holds the pressure reliability in the considered range. Also, variations of some criteria such as reliabilities of pressure and demand, vulnerability and flexibility have been analyzed as a tool for choosing the appropriate state of design. The results have shown that a minor raise in the cost of design could lead to a considerable improvement in reliabilities of pressure and demand under breakage level one.

Keywords: Water distribution networks, Design, Performance criteria, Honey-bee mating optimization (HBMO) algorithm, Breakage level one.

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1. Introduction

Nowadays, supplying enough water with appropriate pressure is one of the most important needs of modern societies. Thus, increasing public dissatisfaction, level of health, and welfare of society are decreased by left meeting the needs. Water distribution networks (WDNs) design has started since nineteenth century when the industrial facilities were brought to cities. In the beginning, optimal design had been summarized in minimizing the economic cost. But, it is not possible to supply demands in some conditions using absolutely economic design approach, such as: consumption pattern changes, emergency needs (fire need), and water network operation in times of breakage network pipes. Thus, it is necessary to make more researches in the field of reliable urban water distribution network.

In most of the existing researches, minimization of design cost is considered as the objective function of WDNs design problem and diameters of network's pipes as its decision variables. For example in a discrete optimization problem with 10 locations for the pipes and 10 commercial diameters available for each pipe, the decision space of such a problem would be 10^{10} different state.

It is clear that searching in such an expanded discrete decision space, without using an optimization tool is not possible. In addition, finding solution in an appropriate time is an important factor. Linear programming (LP) and nonlinear programming (NLP) are two tools in optimization problems which are capable to find optimal solutions. Traditional optimization methods are categorized in two different methods: (1) direct search methods and (2) gradient search methods. The objective function values and constraints are used to find optimal solution in the direct search methods. While, the first and second order derivatives of objective function and constraints have the same role as the aforementioned factors (objective function values and constraints) in the gradient search methods. Alperovits and Shamir (1977) used LP method to find optimal solution. They proposed a new method using linear

relations instead of nonlinear relations. Quindry et al. (1981), Goulter et al. (1986), Kessler and Shamir (1989), and Fujiwara and Khang (1990) developed and modified previous researches about using LP and NLP.

Some defects such as: the time consuming process of direct search methods and inefficiency of gradient methods faced to discrete problems decrease the efficiency of the traditional algorithms. Thus, evolutionary algorithms especially genetic algorithm (GA) have been applied as the optimization tools in these problems since ninths centaury. Simpson et al. (1994) used the GA to solve discrete and nonlinear problems. The pipe diameters are discrete variables which cause more application of the GA. Dandy et al. (1996), Savic and Walters (1997), and Montesinos et al. (1999) used different methods based on the GA to solve WDNs problems. Cunha and Sousa (1999) used simulated annealing (SA) algorithm for optimal design of WDNs (Hanoi and New York). Lippai et al. (1999) applied Opt-Quest software in optimal design of New York WDNs which includes tabu search (TS) algorithm as an optimization tool. But, the result of using this software is not as well as the result of using GA. Geem (2005) proposed harmonic search (HS) algorithm in the design of two benchmark problems (Two-loop and Hanoi) in the field of WDNs design. The proposed algorithm had converged in the less function evaluation compared to GA.

Walski (2001) expresses that, concentration of cost minimization without using performance criteria, such as: reliability of supplying demand or nodal pressure, and network reliability in failure condition of system were presented as the most important reason for inefficiency of the proposed models in the design of WDNs. Thus, design of WDNs model should be included minimization of cost project subject to supplying acceptable pressure. Fujiwara and Silva (1990) identified a method based on the cost minimization considering a specific reliability. In this method, the network is designed and then by an acceptable increasing in the cost of project the reliability will be improved during a feedback process.

Todini (2000) presented a criteria to show existing extra energy in the critical node. In this problem, minimizing cost and maximizing system flexibility were considered as the objective functions and the optimal trade off between these two objectives was found. Prasad and Park (2004) modified the previous criteria presented by Todini (2000). They demonstrated that increasing flexibility criteria is not enough reason for the increasing reliability criteria.

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 which was first presented by Dorigo (1992), is one of the aforementioned algorithms. Afshar et al. (2007) used honey bees mating optimization (HBMO) algorithms to solve nonlinear constrained and unconstrained problems. They also solved 60 period operation optimization problems with minimizing the sum of squared deviations from demand. Results showed the more capability of HBMO to find near optimal solution compared to GA and considerable proximity of its answers compared to Lingo 8. Bozorg Haddad et al. (2008) used the HBMO algorithm to extract an optimal policy for rehabilitation of WDN for two periods of 30 and 100 years. Results showed that proposed algorithm can easily find feasible solutions and converge to the optimal one. It was approved that rehabilitation included operation will cost much more than operation without rehabilitation.

Since pressure reliability of WDNs, specially at the time of pipe breakage is an important issue, in this paper, the HBMO algorithm is used as the optimization tool for optimal design of Two-loop and Hanoi networks considering pressure reliability conditions when breakage level one happens. In the most existing researches, the reliability criterion has been calculated after least cost design. But in this paper least cost design of WDNs subjected to pressure reliability has been considered as the optimization problem. Results show that an

acceptable raise in the amount of cost could lead to a considerable improvement in reliability of WDNs.

2. 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).

3. Optimal design model of WDNs in breakage level one condition

In this model, pipe diameters have been considered as decision variables which should be selected from the commercial available diameters. The objective function is the total cost of network pipes. Thus, the total cost of WDNs is the factor which gives preference to solutions over each other. The constraints which have been considered in this model are relevant to the pressure provided in each consumption node after hydraulic analysis of the set of solutions in which every node have to be at least more than minimum pressure requirement in normal condition and also more than minimum expected pressure when breakage level one happens. In this optimization model, there are two penalty functions: (1) the one related to the providing less pressure of P_{Min} in normal condition, and (2) the penalty function related to less pressure of P_{exp} when breakage level one happens. The penalty functions should be defined in order to prevent the best infeasible solution to be better than any feasible one. So the described relations of optimization model are as follows:

$$\text{Min. } OF = \sum_{i=1}^{NI} Cost_i + PF_1 + PF_2 \quad (1)$$

$$Cost_i = C_i(D_i, L_i) \quad (2)$$

$$PF_1 = \sum_{j=1}^{NJ} K \times (P_{\min} - P_j + 1)^2 \quad , \quad \text{If } P_j < P_{\min} \quad (3)$$

$$PF_2 = \sum_{j=1}^{NJ} K \times (P_{\exp} - P_j + 1)^2 \quad , \quad \text{If } P_j < P_{\exp} \quad (4)$$

where $Cost_i$ = cost of i^{th} pipe, $PF(1 \text{ and } 2)$ = penalty functions for providing respectively minimum pressures in normal and breakage level one conditions, $C(D_i, L_i)$ = cost function of i^{th} pipe with diameter of D and length of L , P_j = pressure of j^{th} node, $P_{\exp}$ = the minimum expected pressure in breakage level one conditions which varies under each state of design, NJ = number of consumption nodes, and NI = number of pipes. It should be noted that the hydraulic calculations are done using EPANET2 software which has been linked to the HBMO algorithm.

4. Performance criteria in the WDNs

In this study, three different criteria have been defined that present performance of system under different costs and conditions.

4. 1. Reliability (Re)

This criterion contains the concept of providing minimum required pressure ($P_{\min}$) under different hydraulic simulation states which is calculated as follows:

$$Re = \frac{NS \times NJ - N_{P < P_{\min}}}{NS \times NJ} \quad (5)$$

where, NS = number of different states for design and consequently hydraulic simulations of network which would lead to a set of pressures achieved for each consumption node of network. The aforementioned states involve simulations of looped designed network without considering pressure reliability under breakage condition, reliable looped designed network under normal condition and again this reliable network under breakage of just one pipe solely

which could be every pipe of network except the pipe number one. $N_{P < P_{\min}}$ = total number of nodes that their pressure are less than the minimum required under all aforementioned designs and simulations states.

It should be noted that the minimum pressure required is a fixed value for all of the states of design. On the other hand, the penalty function are added to the objective function in: (1) least cost design when the pressure provided in each one of nodes is less than $P_{\min}$ and (2) reliable designing of WDN when the pressure is less than $P_{\exp}$ under breakage level one condition.

4. 2. Vulnerability (Vu)

In breakage level one condition, some nodal pressure possibly could be provided less than $P_{\min}$. Therefore vulnerability presents the maximum difference between provided pressures in all nodes and $P_{\min}$ among different reliable designs under breakage level one that is achieved as follows:

$$Vu = \frac{P_{\min} - \min(P)}{P_{\min}} \quad (6)$$

where $\min(P)$ = minimum pressure among all consumption nodes considering a specific value for minimum expected pressure in each state of simulation (NS).

4. 3. Flexibility criteria (Fl)

This criterion involves both reliability and vulnerability of system that is calculated by equation (7):

$$Fl = Re \times (1 - Vu) \quad (7)$$

4. 4. Hydraulic benefit of pressure (HB_P)

In order to calculate this criterion (HB_P), two positive values should be considered as the minimum and maximum permissible pressures for each node. Then, the pressure of each

node and pressure hydraulic benefit of it (ψ_j) are calculated regarding equations (8) and (9).

Finally HB_P would be sum of (ψ_j) in all consumption nodes.

$$HB_P = \sum_{j=1}^{N_j} \psi_j \quad (8)$$

$$\psi_j = \begin{cases} \left(\frac{P_j - P_{\min}}{P_{\max} - P_{\min}} \right)^{0.5} & \text{if } P_{\min} < P_j < P_{\max} \\ 0 & \text{if } P_j < P_{\min} \text{ or } P_j > P_{\max} \end{cases} \quad (9)$$

The greater amount of ψ_j shows the more reliability on node j^{th} . Figure 1, shows the relation between P_j and ψ_j . According to this figure, there is an increasing relation between two aforementioned factors. It should be noted, if the existing pressure of a node gets out of the allowable boundaries, its ψ_j will be equal to zero. It seems not to be a right option for ψ_j to increase straightly same as the amount of P_j along the interval between minimum and maximum defined allowable pressures. Because both the little values and also the excessive ones for the pressure provided at nodes would affect reversely on the performance of WDNs. Thus, preferably the criterion HB_P should be defined in order to its maximum amount would be achieved between minimum and maximum allowable pressures. Figure 1, shows the change of ψ_j in respect to P_j raise. In above equations $P_{\max}$ is the maximum allowable nodal pressure in the network.

4. 5. Hydraulic benefit of demand (HB_D)

This criterion is similar to HB_P and is weighted considering the amount of demand in each specific node. So the more demand in each node the more prior it is.

$$HB_D = \sum_{j=1}^{N_j} \left(\frac{P_j - P_{\min}}{P_{\max} - P_{\min}} \right)^{0.5} \times \left(\frac{Q_{D_j}}{\sum_{j=1}^{N_j} Q_{D_j}} \right) \quad (10)$$

where Q_{D_j} = demand of j^{th} node.

5. Case study

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 doesn't have any pump and storage tank. Figure 2, shows the schematic of Two-loop network with eight pipes and seven 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_{Min}) is equal to 30 m-H₂O and the values of P_{exp} are discrete values between zero and 30 with 3 m-H₂O as intervals.

Hanoi network is a simple network in Vietnam that has been used as the second case study. This network involves 34 pipes and 32 nodes without any pump and storage tank. Elevation of all nodes is zero and here the hazen Williams' coefficient of all pipes is 130.6325. Figure 3, shows a schematic of Hanoi network.

6. Results and discussion

In this paper, optimal design of WDNs (Two-loop and Hanoi) with the aim of minimizing their total cost have been designed in order to provide minimum required pressures in normal conditions and minimum expected ones in breakage level one conditions.

6.1. Two-loop network

Under each state of design which guarantee minimum expected pressures 0, 3, ..., 30 m-H₂O under breakage level one condition the diameter of each pipe varies in a specific range (Figure 4). Table (1) presents statistical measures relevant to mentioned variability. Figure 4, shows the changes of each pipe's diameter for different states of design. In the first state (tree shaped network on the horizontal axis) the model has been allowed to select zero value for diameters. Therefore least cost design has lead to a tree shaped network. In the second state (unreliable looped network) the model has not been allowed to select zero value for diameters and also the network is not expected to provide discrete values of minimum expected pressures under breakage level one condition. This has lead to a looped network but

unreliable to provide specific amounts of pressure under breakage level one conditions. In both mentioned states of design, providing minimum required pressure (30 m-H₂O) has been considered necessary. Other states guarantee providing minimum required pressure under normal condition and also minimum expected pressures 0 to 30 (each discrete value on the horizontal axis) m-H₂O under breakage level one condition. As it is seen in Figure 4, diameters of most of network's pipes have been increased in respect to the raise in the amount of minimum expected pressure. This is more obvious looking at the curves related to forth and eighth pipes. Also under two tree shaped and unreliable looped states, diameter of these pipes have been achieved zero and nearly zero respectively. Considering the next values for diameter of these pipes along horizontal axis, it could be inferred that increasing their diameter would lead to raise in the amount of reliability under breakage level one. On the other hand, when the minimum expected pressure in breakage condition is 21 m-H₂O, diameters of different pipes are closer to each other in comparison with other states. This would practically ease preparation and installation of the network's elements. Figure 5, shows the relation between performance criteria and total cost under different design states. It shows the ascending trend of reliability and flexibility criteria and descending trend of vulnerability criterion with raise in the cost of network. The reliability of system in the state of 21 m-H₂O as the minimum expected pressure is equal to 0.85 that seems an acceptable value. It should be noted that closeness of pipes reaching to a consumption node would cause that if one of the pipes were broken, the other could considerably cover its portion of the node's demand. Otherwise, if the larger one breaks, the smaller one is not able to supply critical node. Figure 6, presents the ascending relation between the total costs in respect to raise in minimum pressure expected. It is seen here again that after point 21 on the horizontal axis, the change in cost curve is occurring with steeper slope. Also considering the figures 5 and 6 show that increasing in the minimum expected pressure from 0 to 21 under breakage condition has

increased the cost of design from 514 to 680 thousands dollars (33% raise in cost) and also has increased the reliability of the system in the value of 15%. But, between the points 21 and 30 on the horizontal axis of figure 6, it is seen that the raise in cost is 190 thousands dollars. This will again confirm desirability of this point for selecting diameters of network's pipes. Figures 7 and 8 respectively present pressure and demand hydraulic benefit in all nodes under breakage of each pipe solely. It is shown in the figures that as minimum expected pressure increases, the value of these criteria increases as well. Also it could be inferred from the figures that in each state of hydraulic simulation of the network breakage of pipes two and three have the most influence on sum of these criteria in the network. This could be rationalized considering the location of these pipes at the beginning of network. It is shown in figure 4, which introduces suggested diameters for different pipes under each state of design, that in the most of reliable design states, suggested diameter for pipes two and three are close to each other. Since these two pipes are in role of distributors of the water delivered from reservoir, and also considering their close diameters, it would be expected that breakage of each of them, would make a serious hardship for the other one and will cause a shortage of pressure provided on consumption nodes. Also it is seen that in the most of reliable design states, breakage of pipe two has harder influence on reliability criteria of network. This is because of the bigger diameter for this pipe suggested by the model. When pipe two does not exist, it will force pipe three to supply the network, while its diameter is smaller than pipe two. Naturally this would negatively affect demand and pressure reliability criteria. In figures 9 and 10 sum of pressure and demand hydraulic benefits criteria in each consumption node in respect to breakage of different pipes are shown. The values of pressure hydraulic benefit criterion in nodes six and seven and also in node two have been achieved more than others. The reason which causes node five to be located at the top of demand hydraulic benefit curve is the high value of pressure and supply in comparison with other nodes. Node six has the

greatest portion of total demand of the network. But because of low pressures provided in this node in the most of design states (especially in the states that their minimum expected pressures are less than 24 m-H₂O), this node has been located at the lowest level in figure 10. In figure 11, sum of the number of nodes that the pressure provided in them is less than 30 m-H₂O under breakage of different pipes have been delineated for different design states. The curves are cumulative for more clarity. Thus, the vertical distance between each two curves shows the number of nodes with pressure provided less than 30 m-H₂O, under the design state related to upper curve. The uppermost curve guarantees 30m-H₂O in breakage level one condition. As it is expected, as we go down from the uppermost one, the distance between curves has an ascending trend.

6.2. Hanoi network

Reliable design of Hanoi network was impossible using available commercial diameters. Thus, the model is allowed to select more than one pipe for each location, till three pipes. If it was necessary to install more than one pipe between two nodes, it has been assumed that they are installed parallel. Table 2 presents statistical measures relevant to diameters of pipes selected for different locations of network. Figure 4, shows the changes of diameter of equivalent pipe for each location of network for different states of design. As it is seen in Figure 12, diameters of most of network's locations have been increased in respect to the raise in the amount of minimum expected pressure. This is more obvious looking at the curves related to the diameter of equivalent pipes for locations 1st, 2nd, 14th and 31st, that shows the prominent increase in reliability of network in respect to raise in their diameters, when breakage level one happens. On the other hand, when the minimum expected pressure in breakage condition is 20 m-H₂O, diameters of equivalent pipes are closer to each other in comparison with other states. This would practically ease preparation and installation of the network's elements. Figure 13, shows the relation between performance criteria and total cost

under different design states. It is seen that the difference between reliability criteria under different states is at its uppermost level between unreliable state and reliable ones in comparison with the difference between each two reliable states. Because in unreliable state the network has not been designed for breakage condition, so facing to this condition would shock the network and will cause lots of nodes to fail in supplying the demands and providing required pressures. As it is expected with increase in cost, the trend of flexibility and vulnerability are vice versa. Considering the equations defined for each of them, low (nearly zero) pressures would cause the vulnerability criteria to reach to undesirable value of one and so the value of zero (or nearly zero) for flexibility of network under two states of design which are unreliable looped network and minimum expected pressure of zero under breakage condition. Figure 14, presents the ascending relation between the total costs in respect to raise in minimum expected pressure. It is seen that the slope of the curve has been decreased after the point 20 on the horizontal axis. Considering figure 14 it is clear that the diameter of pipes has not been increased considerably between the points 20 and 30. Figures 15 and 16 respectively present pressure and demand hydraulic benefit in all nodes under breakage of each pipe solely. As it is seen in the figures, these criteria have the least value under failure in locations 3th, 4th, 18th, 19th and 20th that shows the importance and sensitivity of these pipes in supplying the demands and providing required pressures of consumption nodes. In figure 17, sum of pressure hydraulic benefits for each consumption node has been delineated in respect to breakage different pipes. It is obvious that the nodes 8 to 14 and also 28 to 32 are more sensitive than others. In figure 18, sum of demand hydraulic benefits for each consumption node has been delineated in respect to breakage different pipes. This criterion gives specific weights to pressure hydraulic benefit in the nodes regarding the amount of their demand. It means that the importance of providing the required pressure in each node depends on its value of required demand. For example, considering nodes four and five, at the point of 20

m-H₂O, as minimum expected pressure, the pressure provided in node four is six units more than its value in node five. But because of the demand of node five in comparison with node four, the value of demand hydraulic benefit of node five is almost five times more than its value in node four. As going ahead along the figure it is seen that the peaks of the curves are related to the nodes that their demand are more than others. But comparing nodes three and seven which are almost the same in their value of demand, it is seen that providing more pressure in node three has caused more value for demand hydraulic benefit for this node. In figure 19, sum of the number of nodes that the pressure provided in them is less than 30 m-H₂O under breakage of the pipes of different locations have been delineated for different design states. It is seen here again (like Two-loop network), as we come down along the figure, the vertical distance between the curves are increasing, specially under the failure of locations 3rd, 4th, 18th, 19th. Also it is seen that the curve related to minimum expected pressure of 30, is conform to the curve related to minimum expected pressure of 20, it means that under these states no node has the minimum pressure provided less than 30.

7. Conclusions

In this research the optimization of reliable design of Two-loop and Hanoi WDNs, using the HBMO algorithm, under breakage level one condition have been done. The objective function has been considered as minimizing the total cost of design. Considering the constraints related to providing defined minimum expected pressures under breakage of each pipe in Two-loop network and failure of each pipe location in Hanoi network, pressure and demand hydraulic benefits and also other performance criteria has been hold in an acceptable range. Analyzing the results of Two-loop network, shows that the composition of pipes that guarantees 21 m-H₂O in breakage level one condition is acceptable, considering performance criteria and the cost of design. The interesting point about the states of design which guarantee 21 m-H₂O in Two loop and 20 m-H₂O in Hanoi networks is the closeness of

diameters achieved for the networks that considerably ease preparation and installation of network's elements. It could be inferred that the number of nodes with provided pressure less than 30 m-H₂O are at their maximum plurality under breakage of pipes, those their breakage will cause the reliability of network to reach to its minimum value. But the reason which causes pressure and demand hydraulic benefits under unreliable state of design, to be more than their value under some of states of reliable design, is that breakage of some pipes would lead to incalculable pressures as the result of hydraulic simulation of network. So it seems to be necessary to do researches about discovering methods which could help to make these situations known.

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., Marino, M. A., and Adams, B. J. (2007), "Honey-bee mating optimization (HBMO) algorithm for optimal reservoir operation" Journal of the Franklin Institute, 452-462. DOI: 10.1016/j.
- [3] Alperovits, E., and Shamir, U. (1977), "Design of optimal water distribution systems" Water Resource Research. 13 (6), 885-900.
- [4] Bozorg Haddad, O., Adams, B.J., and Marino, M.A. (2008), "Optimum rehabilitation strategy of water distribution systems using the HBMO algorithm" Journal of. Water supply: Research and Technology. DOI: 10.2166/aqua.1-16.
- [5] Cunha, M. C., and Sousa, J. (1999), "Water distribution network desing optimization simulated annealing approach" Journal of Water Resource Planning and Management. 125 (4), 215-221.
- [6] Dandy, G. C., Simpson, A. R., and Murphy, L. J. (1996), "An improved genetic algorithm for pipe network optimization" Water Resource Research. 32 (2), 449-458.
- [7] Dorigo, M., Bonabeau, E., and Theraulaz, G. (2000), "Ant algorithms and stigmergy" future Generation Computational Systems. 16, 851-871.
- [8] Dorigo, M. (1992), "Optimization, Learning and natural algorithms," Ph.D. Thesis, Politecnico di Milano, Milan, Italy.

- [9] Fujiwara, O., and Khang, D.B. (1990), "A two-phase decomposition method for optimal design of looped water distribution networks" *Water Resource Research*. 26 (4), 539-549.
- [10] Fujiwara, O., and De Silva, U. (1990). "Algorithm for reliability-based optimal design of water networks," *Journal of Environmental Engineering*. 116 (3), 220-230.
- [11] Geem, Z. W. (2005), "Optimal cost design of water distribution networks using harmony search" *J. Engineering Optimization*. 38 (3), 259-280.
- [12] Goulter, I. C., Lussier, B. M., and Morgan, D. R. (1986), "Implications of head loss path choice in the optimization of water distribution networks" *Water Resource Research*. 22 (5), 819-822.
- [13] Kessler, A., and Shamir, U. (1989), "Analysis of the linear programming gradient method for optimal design of water supply networks" *Water Resource Research*. 25 (7), 1469-1480.
- [14] Lippai, I., Heaney, J. P., and Laguna, M. (1999), "Robust water system design with commercial intelligent search optimizers" *Journal of Computational in Civil Engineering*. 13 (3), 135-143.
- [15] Montesinos, P., Garcia-Guzman, A., and Ayuso, J. L. (1999), "Water distribution network optimization using a modified genetic algorithm" *Water Resource Research*. 35 (11), 3467-3473.
- [16] Prasad, T. D., and Park, N. S. (2004), "Multiobjective genetic algorithms for design of water distribution networks" *Journal of Water Resource Planning and Management*. 130 (1), 73-82.
- [17] Quindry, G. E., Brill, E. D., and Liebman, J. C. (1981), "Optimization for looped water distribution systems" *Journal of Environmental Engineering*. 107 (4), 665-679.
- [18] Rossman, L. A. (2000), "EPANET 2 users manual" United States Environmental protection Agency, Cincinnati, Ohio, US.
- [19] Savic, D. A., and Walters, G. A. (1997), "Genetic algorithms for least-cost design of water distribution networks" *Journal of Water Resource Planning and Management*. 123 (2), 67-77.
- [20] Simpson, A. R., Dandy, G. C., and Murphy, L. J. (1994), "Genetic algorithms compared to other techniques for pipe optimization" *Journal of Water Resource Planning and Management*. 120 (4), 423-443.
- [21] Todini, E. (2000), "Looped water distribution networks design using a resilience index based heuristic Approach" *Journal of Urban Water*, 2(3), 115– 122.

[22] Walski, T. M. (2001), "The wrong paradigm-Why water distribution optimization doesn't work" *Journal of Water Resource Planning and Management*. 127(4), 203-205.

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Table 1. Diameters achieved for each pipe of Two-loop Network under different design states

Table 2. Diameters achieved for each location's pipes of Hanoi Network under different design states

Table 1- Diameters achieved for each pipe of Two loop network under different design states

pipe Numbers	Minimum (inches)	Average (inches)	Maximum (inches)	ST.DEV.	Variance	C.V.	Median (inches)	Mode (inches)
1	18	20	20	0.93	0.87	0.05	18	18
2	16	20	20	1.62	2.62	0.08	16	16
3	14	18	18	1.35	1.82	0.07	16	14
4	10	16	16	1.96	3.85	0.12	12	12
5	12	14	14	0.93	0.87	0.07	14	14
6	10	14	14	1.75	3.05	0.12	12	10
7	14	18	18	1.40	1.96	0.08	16	16
8	12	16	16	0.89	0.80	0.06	14	14

Table 2- Diameters achieved for each location's pipes of Hanoi network under different design states

pipe Numbers	Minimum (inches)	Average (inches)	Maximum (inches)	ST.DEV.	Variance	C.V.	Median (inches)	Mode (inches)	pipe Numbers	Minimum (inches)	Average (inches)	Maximum (inches)	ST.DEV.	Variance	C.V.	Median (inches)	Mode (inches)
1	0	20	40	23	533	1	20	0	18	0	10	40	20	400	2	0	0
	0	28	40	19	358	1	35	40		0	30	40	20	400	1	40	40
	40	40	40	0	0	0	40	40		0	0	0	0	0	—	0	0
2	40	40	40	0	0	0	40	40	19	0	20	40	23	533	1	20	0
	0	10	40	20	400	2	0	0		0	20	40	23	533	1	20	40
	0	30	40	20	400	1	40	40		0	3	12	6	36	2	0	0
3	0	10	40	20	400	2	0	0	20	0	15	40	19	367	1	10	0
	0	10	40	20	400	2	0	0		0	18	40	21	425	1	15	0
	0	20	40	23	533	1	20	40		0	8	30	15	225	2	0	0
4	0	25	40	17	300	1	30	30	21	0	5	20	10	100	2	0	0
	0	14	30	16	249	1	12	0		0	12	24	14	192	1	12	24
	0	3	12	6	36	2	0	0		0	5	20	10	100	2	0	0
5	0	20	40	23	533	1	20	0	22	0	9	20	11	111	1	8	0
	0	10	40	20	400	2	0	0		0	0	0	0	0	—	0	0
	0	10	40	20	400	2	0	0		0	7	16	8	68	1	6	0
6	0	18	40	21	425	1	15	0	23	0	18	40	21	425	1	15	0
	0	13	40	19	356	1	6	0		0	3	12	6	36	2	0	0
	0	8	30	15	225	2	0	0		0	18	40	21	425	1	15	0
7	0	0	0	0	0	—	0	0	24	30	38	40	5	25	0	40	40
	0	10	40	20	400	2	0	0		0	0	0	0	0	—	0	0
	0	25	40	17	300	1	30	30		0	0	0	0	0	—	0	0
8	0	11	24	13	164	1	10	0	25	0	20	40	23	533	1	20	0
	0	19	30	13	169	1	22			0	8	30	15	225	2	0	0
	0	11	24	13	164	1	10	0		0	8	30	15	225	2	0	0
9	0	23	30	15	225	1	30	30	26	0	10	40	20	400	2	0	0
	0	10	40	20	400	2	0	0		0	10	40	20	400	2	0	0
	0	0	0	0	0	—	0	0		0	20	40	23	533	1	20	0
10	20	26	30	5	24	0	27	30	27	0	20	40	23	533	1	20	0
	0	0	0	0	0	—	0	0		0	0	0	0	0	—	0	0
	0	3	12	6	36	2	0	0		0	20	40	23	533	1	20	40
11	0	3	12	6	36	2	0	0	28	0	8	30	15	225	2	0	0
	0	9	20	11	111	1	8	0		0	10	40	20	400	2	0	0
	16	20	24	3	11	0	20	20		0	20	40	23	533	1	20	0
12	0	16	24	11	117	1	20	20	29	0	14	20	10	91	1	18	20
	0	5	20	10	100	2	0	0		0	0	0	0	0	—	0	0
	0	3	12	6	36	2	0	0		0	8	20	10	96	1	6	0
13	0	10	40	20	400	2	0	0	30	0	0	0	0	0	—	0	0
	0	8	30	15	225	2	0	0		0	14	20	10	91	1	18	20
	0	15	30	17	300	1	15	30		0	8	20	10	96	1	6	0
14	0	23	30	15	225	1	30	30	31	0	9	20	11	111	1	8	0
	0	0	0	0	0	—	0	0		0	9	20	11	111	1	8	0
	0	10	40	20	400	2	0	0		0	3	12	6	36	2	0	0
15	0	20	40	23	533	1	20	40	32	0	6	12	7	48	1	6	12
	0	10	40	20	400	2	0	0		0	7	16	8	68	1	6	0
	0	10	40	20	400	2	0	0		0	3	12	6	36	2	0	0
16	0	10	40	20	400	2	0	0	33	0	8	16	9	85	1	8	0
	0	30	40	20	400	1	40	40		0	3	12	6	36	2	0	0
	0	0	0	0	0	—	0	0		0	8	20	10	96	1	6	0
17	0	10	40	20	400	2	0	0	34	0	12	16	8	64	1	16	16
	0	10	40	20	400	2	0	0		0	0	0	0	0	—	0	0
	0	20	40	23	533	1	20	40		0	4	16	8	64	2	0	0

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