LEAKAGE CONTROL IN WATER DISTRIBUTION NETWORKS BY USING OPTIMAL PRESSURE MANAGEMENT: A CASE STUDY

Mohammad Mahdi Mahdavi*, Kourosh Behzadian, Khosro Hosseini***, Abdollah Ardehsir******

*MSc student, Civil Engineering Department, Semnan University, Semnan, Iran. *E-mail: m.mahdavi85@gmail.com*

**Assistant professor, Environmental Research Center, Amirkabir University of Technology (Tehran polytechnic), Tehran, Iran. *E-mail: behzadian@aut.ac.ir*

***Assistant professor, Civil Engineering Department, Semnan University, Semnan, Iran. *E-mail: khhoseini@semnan.ac.ir*

****Associate professor, Head of Environmental Research Center, Department of Civil and Environmental Engineering, Amirkabir University of Technology (Tehran polytechnic), Tehran, Iran.

Abstract:

More than thirty percent of drinking water loss through water distribution systems (WDS) in Iran has made a major concern for Iranian water utilities, which has been located in a semi-arid area. In many cases, invisible leakage in the pipelines of WDS, particularly old WDSs, causes a high proportion of total annual losses. Pressure management is a well known and useful tool for reducing invisible leakage since leak is a pressure dependent function. This paper presents an optimization model for pressure management by optimizing pressure reducing valves (PRV) locations and settings. The PRVs location and setting is formulated here as an optimization problem with: (1) the objective function of maximizing the coverage of end-node users' pressures in an appropriate range; (2) the objective function of minimizing total leakage in the network. Genetic algorithm is used here as the optimization model, in which EPANET toolkit is used as the simulation engine. The model is applied to a case study in Iran known as Mahalat WDS which has assigned a high value of water loss in the networks. The results show that the system is able to considerably moderate the high pressure values and total value of drinking water which is annually lost.

Keywords:

leakage control, valve location optimization model, genetic algorithm

1. INTRODUCTION

Lack of potable water resources accompanying by rapid growth in demand due to the development of populations and industries, and also high expenses of providing, treatment and conveyance of water leading to an economic, social and even political crisis in many countries.
Many experts, engineers and decision makers all over the world have been paid attention to this problem. Nowadays some useful methods are known for reducing the problem and leakage management programs may be designed and performed in water distribution systems (WDS).

Recent studies and research have shown that leakage volume and also new leakage frequency is reduced greatly by the reduction and stabilization of pressure within a WDS (Thornton et al., 2008). So, among the various leakage control strategies, pressure management is known as one of the most basic and cost-effective forms of optimizing a system and can in many instances provide fast paybacks on large investments (Thornton et al., 2008).

In addition to benefits in reducing leakage and lowering the risk of new leaks, pressure management has benefits in (Pilipovic and Taylor, 2003): 1- Demand Management (Less consumption from pressure related uses of water); 2- System Deterioration (Extended useful life of infrastructure); 3- Maintenance costs (Reduced frequency of main breaks); 4- Customer service (Better service due to less water supply interruptions).

Pressure management may be accomplished in several ways, from the sectorization of a system with isolating valves to the installation of flow control or pressure reducing valves (Nicolini and Zovatto, 2009).

One useful scheme to achieve the most aims of pressure management would be installation of pressure reducing valves (PRVs). This may be considered as an optimization problem with specific objective functions and constraints.

Many authors have worked on the problem of optimal location and/or optimal setting of control valves in WDSs. Some used mathematical approaches and some used genetic algorithms (GA). For more details, refer to Nicolini and Zovatto (2009).

Among the various methods of optimization, applications of search methods like GA are growing in pipe networks because of their capabilities to solve complex problems (Tabesh and Hoomehr, 2009).

In this paper, the methodology of the optimization model including objective function approaches and applied genetic algorithm are first presented. The case study is introduced and associated problem and solutions proposed by experts is described next. Then, the optimization model is applied on the case study and results are discussed. Finally, the relevant conclusions are drawn.

2. METHODOLOGY

The main purpose of this paper is to control the leakage in a WDS through development of an optimization model. The optimization model is defined here for optimal locations of a fixed number of PRVs and their relevant setting in a WDS. Two different approaches of objective function for leakage control are defined in the following. They are compared in a real-world case study with various numbers of PRVs in the network. The optimization problem is formulated and solved here using a standard single-objective genetic algorithm (GA). The details of the GA are described below.

2.1. Optimization Model

To control leakage in a WDS, two different approaches exist: (1) to directly control the leakage by minimizing the leakage leaving through the system pipes as invisible leakage due to excess pressure in a WDS; (2) to indirectly control the leakage by maximizing the number of appropriate-pressure nodes in a WDS and consequently minimizing high-pressure zones. In the first approach, it is assumed that invisible leakage from each pipe is dependent on the pressure of the pipe. The pressure is also calculated by averaging the pressures of the two end nodes of the pipe. Total leakage from all leaking pipes is to be minimized in a WDS using reduction in the amount of nodal pressures. Optimal location of a number of PRVs as well as their setting can provide the objective function for this type of optimization. In the second approach, locating PRVs and their relevant setting are again selected as decision variable. However, the percentage of nodal pressures ranging between appropriate values is defined as the objective function. In other word, the purpose is to maximize appropriate-pressure zones (henceforth is called appropriate-pressure coverage or APC) in a WDS.
The objective function considering total leakage from all pipes can be written as:

$$\text{Minimize } f = \sum_{i=1}^{npl} C_i L_i P_{avr,i}^{1.18} \quad (1) \text{ (Germanopoulos, 1985)}$$

where C_i = constant coefficient relating the leakage per unit length of pipe to service pressure at pipe *i* (a coefficient which indicates the network characteristics); L_i = length of pipe *i;* $P_{avr,i}$ = average pressure at end nodes of pipe *i*; *npl* =number of leaking pipes (here it is assumed that all pipe in a WDS are leaking pipes).

It should be noted that during the main objective function is being optimized, it is possible that nodal pressure in some nodes reduce to lower than minimum pressure allowable. Therefore, the following constraint may be considered to avoid such conditions:

$$P_i \geq P_{\min} \quad i = 1,\ldots, N_n \quad (2)$$

where P_i=nodal pressure in each node of a WDS; $P_{\min}$=minimum allowable pressure at each node.

Considering the second approach, the objective function for reducing the pressure within a WDS can be written as follows:

$$\text{Maximize } f = \frac{APN}{TNN} \times 100 \quad (3)$$

where TNN = total number of nodes in a WDS; APN =appropriate-pressure nodes or number of nodes having the pressure within appropriate pressure which defined as follows:

$$P_{\min,app} \leq P_i \leq P_{\max,app} \quad (4)$$

where $P_{\min,app}$=minimum appropriate pressure and $P_{\max,app}$=maximum appropriate pressure.

Minimum appropriate pressure is usually considered to be minimum allowable pressure providing by water utilities. This value of pressure originally refers to the amount of pressure in which customers can comfortably consume the water without any inconvenience for low water pressure. This amount is regionally varied depending on many influencing factors such as topography of a WDS, pumping system for WDS, demand management, culture of people and so on. In addition, $P_{\min,app}$ is usually more than minimum allowable pressure ($P_{\min}$). $P_{\min}$ defined by many utilities is normally between 15–30 m according to the height of buildings in the region. As a whole, minimum appropriate pressure equal to 30 m is assumed here for the case study. Maximum appropriate pressure ($P_{\max,app}$) is also referred to the amount more than which the probability of leakage is exponentially increased. This amount is also smaller than maximum allowable pressure which is defined based on the maximum pressure tolerated by pipes and joints in a WDS. Therefore, this value ($P_{\max,app}$) should be considered between 50–70 m. In this study, 48 m is assumed as maximum appropriate pressure. As a result, the range of appropriate pressure is assumed to be between 30-48 m according to the characteristics of the case study.

The other constraints are mass and energy equations of hydraulic equality, which are handled through a well-known simulation model (EPANET) (Rossman, 2000).

2.2. Genetic Algorithm

A standard genetic algorithm (GA) is used in this study. Each chromosome represents a set of PRV locations and their associated settings within the WDS model. The length of each chromosome (i.e. the number of genes) is twice the number of PRVs. A schematic view of a typical chromosome for three required PRVs is shown in Figure 1. As it can be seen, half of the genes are assigned for PRV locations. Integer values indicating a PRV location among the range of potential locations can be assigned to these genes. The other half of the chromosome is considered for the settings associated with the PRVs. Integer values in the range of possible settings for a PRV can be assigned for these genes. Note that the setting of a PRV limits and regulates the pressure of the PRV in three different states as follows (Rossman, 2000): (1) partially opened (i.e., active) to achieve its pressure setting on its downstream side when the upstream pressure is above the setting value; (2) fully open if the upstream pressure is below the setting value; (3) closed if the pressure on the downstream side exceeds that on the upstream side (i.e., reverse flow is not allowed).

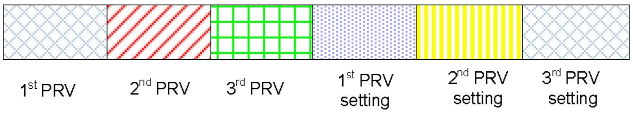


Figure 1. Schematic representation of a typical chromosome for three PRVs

A fitness function is assigned for each chromosome according to the objective function which defined earlier. Since the fitness function needs to take into account infeasible solutions in it, a penalty value is considered in the fitness. As two opposite approaches (i.e. minimization of leakage or maximization of appropriate-pressure zones) have defined here as the objective function, two states of fitness function can be defined here:

$$Fitness = objective\ function \times (1 + penalty) \quad (4)$$

$$Fitness = objective\ function / (1 + penalty) \quad (5)$$

The first fitness function (equation 4) is related to when an objective function is going to be minimized (i.e. the objective function defined in equation 1) and the last fitness function (equation 5) is related to when an objective function is going to be maximized (i.e. the objective function defined in equation 3).

The GA operators are selection, crossover, and mutation. Elitism operator is also used in this study to keep the best solution in the next generations. The GA generation is repeated until some finishing criteria are met. In this study, after a pre-specified number of generations in which all GA runs converge, the GA is stopped.

A sensitivity analysis-based approach was used here for setting the GA model parameters. Therefore, they were determined after a limited number of trial runs using different randomly created initial populations. The parameters used in the problem are as follows: population size of 50 chromosomes, roulette wheel selection operator, mutation with the probability of 0.1 and one point crossover with the probability of 0.8. These values were rigorously checked for the parameters in such a way that the fastest convergence of finding optimal solution is obtained and the solutions are robust in various runs with randomly created initial population. Note that there is no systematic approach to find the best composition of GA parameters setting.

The GA optimization model was developed using a computer code in MATLAB software. The toolkit of EPANET 2 (Rossman, 2000) was also linked with the optimization model to perform the hydraulic simulation models.

3. CASE STUDY

Proposed optimization problem is applied to Mahalat WDS model as a real world case study. The city of Mahalat is located in the central part of Iran. The general layout is presented in Figure 2. A brief summary of the case study is given here; for more details, refer to Behzadian et al. (2008) and Sabour (2005).

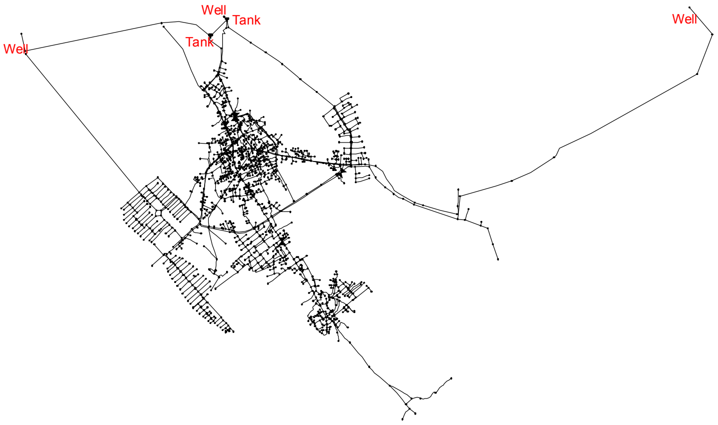


Figure 2. Layout of Mahalat WDS model

The WDS covers approximately 46 km^2, with a population of around 160,000. Model demands are predominantly domestic with some commercial users. Without applying an optimization model, expert choice (EC) empirically suggested some critical points of the system for PRV installation in order to reduce the high pressure head induced by steep slope of the city. Thus EC presented six PRVs which are already used to decrease pressure heads to a fixed pre-specified values.

The WDS is supplied by gravity from three wells and two service tanks (reservoirs) around the city, whose position are shown in Figure 2. The average water demand is 158.9 L/S. The water is pumped into the system with a constant rate. Estimation of pipe roughness coefficients (Hazen-Williams C-factor) were performed based on the main characteristics of the pipes and water quality (Behzadian et al., 2008).

A skeletonized model of Mahalat WDS was used to reduce the time of hydraulic simulations (Behzadian et al., 2009). Figure 3 shows the Layout of the skeletonized model.

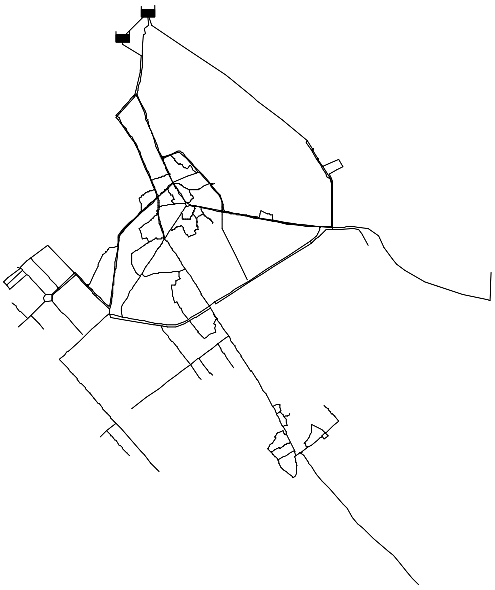


Figure 3. Layout of the skeletonized model

The minimum and maximum elevations of the WDS are equal to 1554.4 m and 1924.4 m above sea level, respectively. Then, The WDS was divided into 13 pressure zones with respect to elevation variations and water supply sources. 42 potential locations for installing PRVs are initially selected to reduce high pressure in the WDS. These points are depicted in Figure 4.

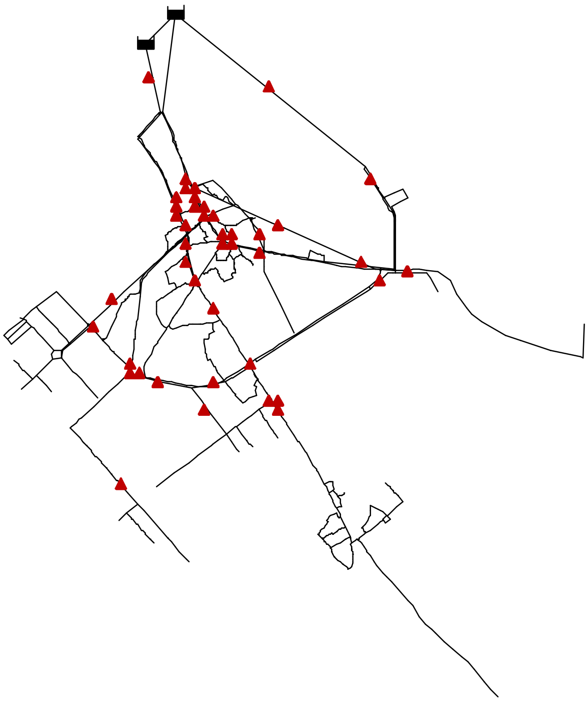


Figure 4. Potential locations for PRV installation

4. RESULTS AND DISCUSSION

As one of our purposes is to compare the results of PRVs selection using GA with the ones obtained from the EC, the optimization problem is first solved to find the best 6 locations (equal to number of the EC's PRVs locations) as the positions for PRV installation. After skeletonizing the WDS model, 42 points of the system were selected as potential PRV locations. Therefore, number of sets of possible solutions for finding six PRV location is equal to $\binom{42}{6} \cong 5.2 \times 10^6$. This amount must be added to very large space for states of PRV settings. This shows a very large space of feasible solutions which justify the use of genetic algorithm as an optimization model to solve the problem.

Due to the large space of feasible solutions, the optimal solutions obtained by GA should be treated as suboptimal solutions. It means there is no guarantee to find the global optimum. Therefore, GA was run by twenty different times, each time with different randomly generated initial populations. Then, the most frequently selected measurement locations were determined as a suboptimal solution of optimization model. All GA runs converged after 1,000 generations. Figure 5 shows a typical GA run convergence of fitness functions for the best solution.

Figure 6 shows the pressure contours of the WDS with no PRV installed. As it can be seen, in the northern part of the city having higher elevation, the pressure seems to be in the normal range. However, the southern parts of the city have to tolerate high pressure due to lower elevation and excess water pressure. Figure 7(a) shows the pressure contours of the WDS considering six PRVs installed in the WDS, which have been suggested by EC. As it can be seen, in a large portion of the city suffering high water pressure, water pressure reduced to a normal range, especially southern part of the city. However, some parts of the city especially in the middle of the city are still suffering high water pressure. This can be because the PRVs may not be properly located. The amount of each aforementioned objective function for Expert Choice is given in Table 1. GA optimization model was first run for locating six PRVs in the WDS. Minimization of total leakage was assumed as the objective function of GA. The results are given in Table 1 including the location of six PRVs as well as their relevant setting. Comparison of result between EC and GA optimal solutions shows that total leakage decreased from 60.36 m3/h for EC to 46.08 m3/h for GA optimal solution. Although the objective function of GA optimization model is to minimize total leakage, the percentage of appropriate-pressure zones is better in GA optimal solution (12.2%) compared to the relevant percentage in EC solution with only 6.0%. In addition, Figure 7(b) shows the pressure contours of the WDS considering six optimal PRVs obtained from GA optimization model. As it can be seen, the high pressure zones were almost completely removed compared to Figure 7(a) obtained by EC. To absolutely remove the high pressure zones, more number of optimal-located PRVs may be required.

GA was analyzed more to find optimal solutions with different number of PRVs. Thus, optimal set of locations were found for number of PRVs from 1 to 10. The GA optimization model was also solved with two different objective function defined above. Thus, the results of GA with the objective function of minimizing total leakage and maximizing APC are presented in Table 2 and 3, respectively. The amount of two proposed objective functions are also given in the Tables for each specified number of PRVs. It should be noted that for each specified number of PRVs, the GA optimization model has been run separately.

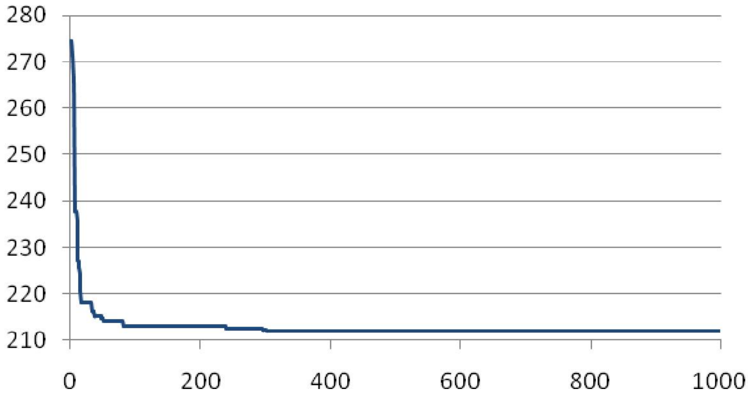


Figure 5. A typical convergence of a GA model run

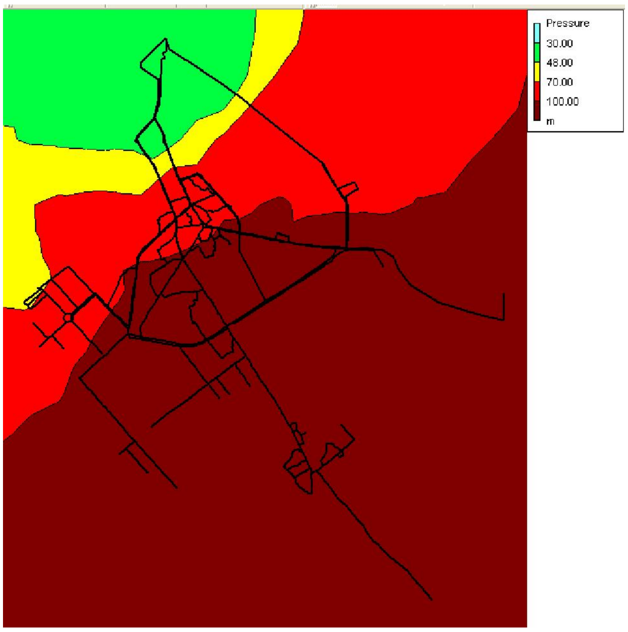
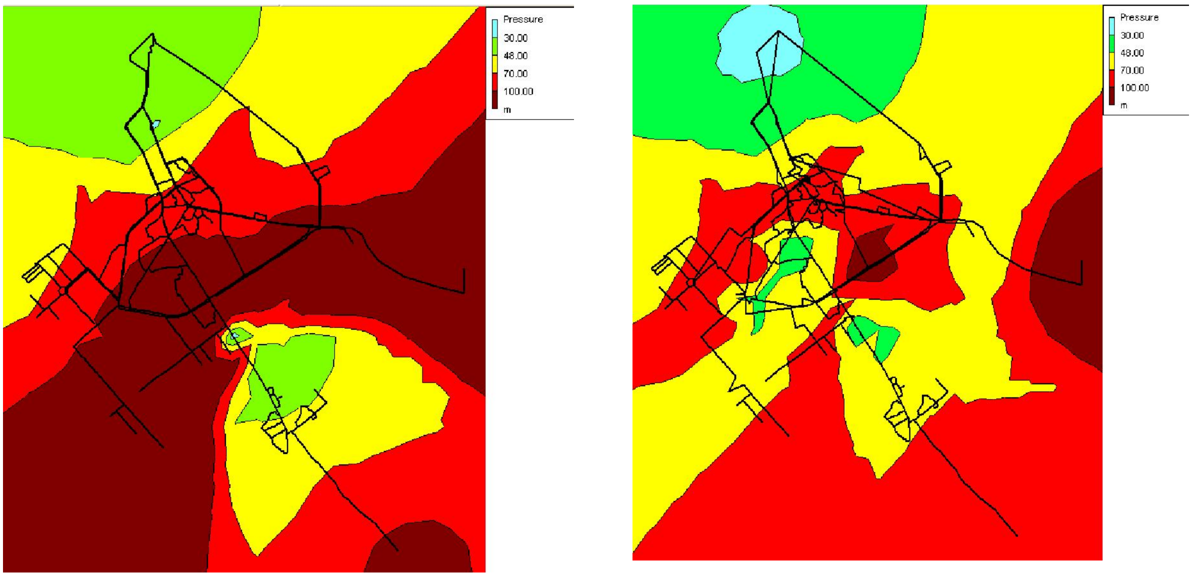


Figure 6. Pressure contours in the WDS when no PRV is installed

Furthermore, Figure 8 shows the trade-off between different numbers of PRVs and associated total leakage according to the GA optimal solutions. Similarly, Figure 9 shows the same trade-off between different numbers of PRVs and associated APC. Also, the amount of total leakage and APC corresponding to the six PRVs suggested by EC is also shown in Figure 8 and 9, respectively.



(a) EC selection result (b) GA optimization model result

Figure 7. Pressure contours in WDS after installing six PRVs obtained from (a) EC select; (b) GA optimization model

Table 1. PRVs Location and their relevant setting suggested by EC and GA optimization model

Method	PRV locations and settings							Total leakage (m^3/hr)	Appropriate-pressure coverage (%)
Expert Choice	PRV ID	1	2	3	4	5	6	60.36	6.0
	setting (m)	15	10	15	15	10	30		
GA optimal solution	PRV ID	2	4	12	14	27	34	46.08	12.2
	setting (m)	59	30	30	30	32	37		

The following can be noted from the Figs. and Tables: (1) It can be seen from the Figure 8 that six PRVs presented by EC are equal to two optimal PRVs when objective function is to minimize total leakage. (2) It can also be seen from the Figure 9 that six PRVs presented by EC are equal to approximately only one optimal PRV when APC is going to be maximized. (3) As the number of PRVs increases, the rate of reduction in total leakage decreases more. For instance, the rate of reduction in total leakage is decreasing rapidly until 11 optimal PRVs. Then, the rate of reduction is neglected until 20 optimal PRVs. Therefore, 11 optimal PRVs can be selected as cost-effective number of PRVs with respect to minimizing total leakage. (4) A relatively similar rate is also seen in Figure 9 for maximizing APC. However, the number of PRVs more than which the rate of increase in APC is ignored is equal to 16. Before this number, the rate of APC is steadily increased and no cost-effective number of PRVs can be chosen from economical point of view.

Table 2. Results of GA optimization model with the objective function of total leakage minimization

number of PRVs	PRV locations and their relevant settings											Total leakage (m^3/hr)	Appropriate-pressure coverage (%)
1	Node ID	4										68.8	3.3
	Settings (m)	30											
2	Node ID	2	4									61.43	3.3
	Settings (m)	59	30										
3	Node ID	2	12	13								52.88	16.7
	Settings (m)	59	33	30									
4	Node ID	2	12	13	14							50.86	17.4
	Settings (m)	59	31	30	30								
5	Node ID	2	12	13	14	25						49.47	20.8
	Settings (m)	59	31	30	49	30							
6	Node ID	2	4	12	14	27	34					46.08	12.2
	Settings (m)	59	30	30	30	32	37						
7	Node ID	2	3	4	12	14	27	34				44.87	13.0
	Settings (m)	59	35	30	30	30	38	39					
8	Node ID	2	4	12	14	20	27	34	36			44.10	14.8
	Settings (m)	60	30	32	30	31	54	41	68				
9	Node ID	2	3	4	12	14	17	27	20	34		43.20	13.7
	Settings (m)	60	30	30	30	30	30	47	56	38			
10	Node ID	3	4	12	15	19	20	22	25	27	34	41.16	13.3
	Settings (m)	30	30	30	38	60	42	61	30	69	35		

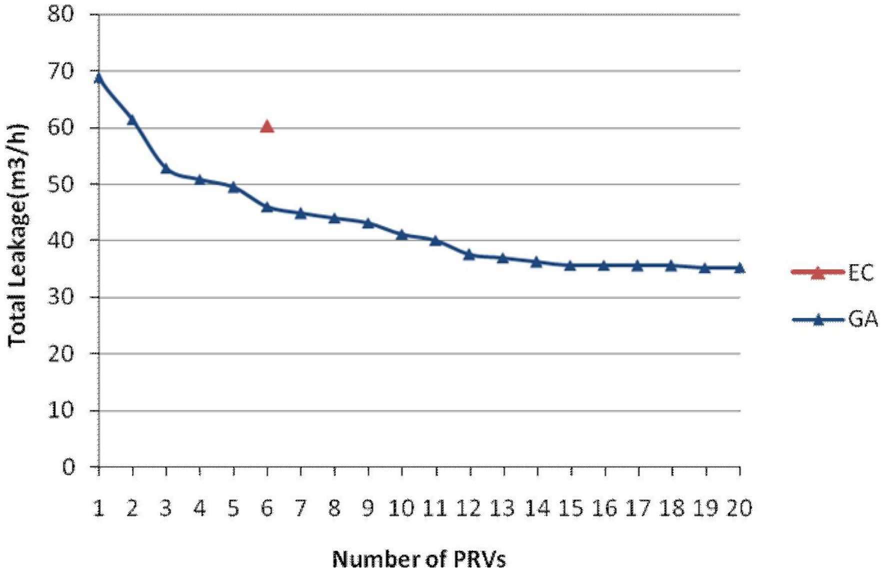


Figure 8. Trade-off between number of PRVs and associated total leakage obtained from GA optimization model with the objective function of total leakage minimization

Table 3. Results of GA optimization model with the objective function of appropriate-pressure coverage maximization

Number of PRV	PRV locations and their relevant settings											Appropriate-pressure coverage (%)	Total leakage (m^3/hr)
1	Node ID	38										4.08	78.0
	Settings (m)	30											
2	Node ID	13	12									16.72	59.1
	Settings (m)	30	36										
3	Node ID	38	13	12								18.58	58.6
	Settings (m)	37	30	37									
4	Node ID	14	13	25	12							20.81	54.7
	Settings (m)	34	30	30	31								
5	Node ID	13	3	25	12	14						23.42	54.6
	Settings (m)	30	34	31	31	34							
6	Node ID	13	38	12	25	3	14					25.27	54.2
	Settings (m)	30	31	31	30	43	32						
7	Node ID	12	14	13	34	25	3	38				26.76	50.2
	Settings (m)	31	30	30	57	30	47	32					
8	Node ID	25	12	39	38	29	3	14	13			28.25	52.4
	Settings (m)	31	31	59	37	41	41	34	30				
9	Node ID	34	29	38	13	39	25	3	12	14		29.73	48.3
	Settings (m)	41	36	33	30	58	30	44	31	30			
10	Node ID	13	39	3	38	14	42	25	12	29	34	30.48	48.3
	Settings (m)	30	58	37	34	32	35	31	31	58	53		

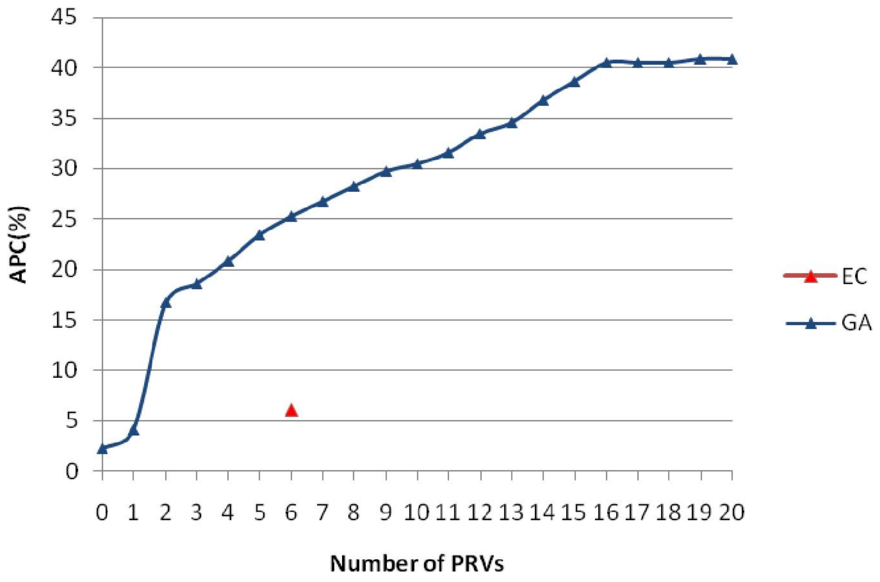


Figure 9. Trade -off between number of PRVs and APC obtained from GA optimization model with the objective function of appropriate-pressure coverage maximization

To make a better comparison between the optimal solutions obtained from two different objective functions, optimal solutions obtained from one objective function was used to calculate the other objective function. Then, the two objective functions were plotted in a graph versus different numbers of PRVs. Figure 10 and 11 shows these comparison. The following can be noted from the Figs.: (1) For APC objective function in Figure 10, no high correlation exists between the optimal solutions obtained from the two objective functions. Therefore, an optimization model for minimizing total leakage can not explicitly correspond with the objective of maximizing the coverage of appropriate-pressure zones. (2) For total leakage objective function in Figure 11, there is a good correlation between the two sets of solutions. Therefore, if the objective function is to maximize APC, the resulted optimal solutions can be a good representative for total leakage objective function. However, to minimize total leakage in a WDS, this objective function should be explicitly placed in the optimization model.

The reason of above occurrence may be found out in the nature and the definition of functions. When APC is the objective function, the optimization model is trying to reduce the nodes with high pressure and cover more nodes in the appropriate range. This implicitly means that more pressure reduction at end nodes occurs and consequently total leakage decreases more accordingly. On the other hand, when the objective is to reduce total leakage, the model is trying to only reduce head pressure at end nodes in order to reduce the leakage in all pipes. However, this does not specifically imply that high pressure nodes particularly decrease and the coverage of appropriate pressure zones increases. Nevertheless, in the later state, average pressure of the region decreases because the objective functions of both models are somehow trying to reduce head pressure

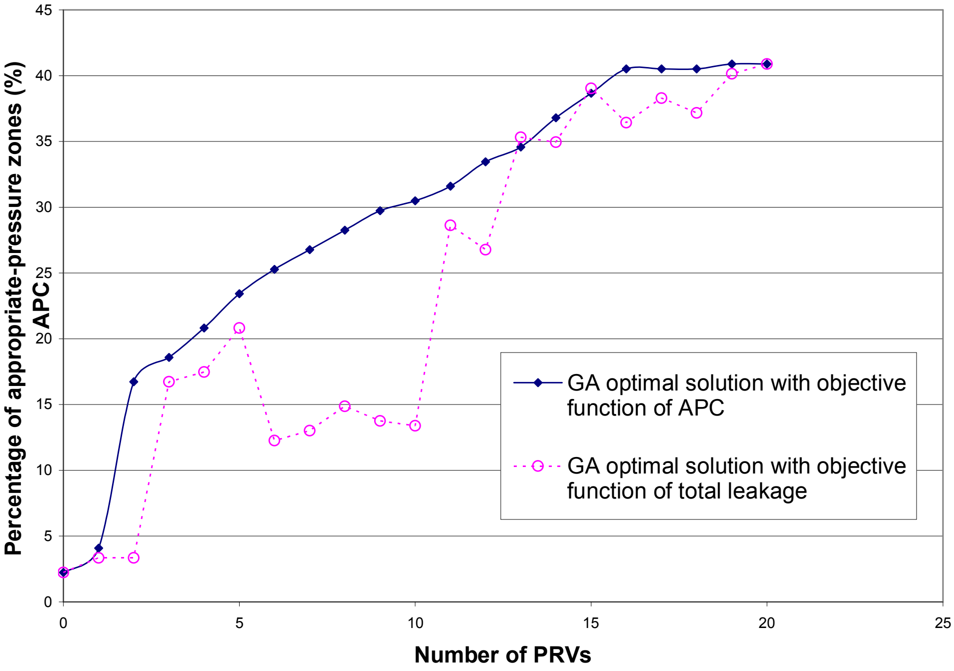


Figure 10. Comparison of APC objective function for GA optimal solutions obtained from each objective function versus different numbers of PRVs

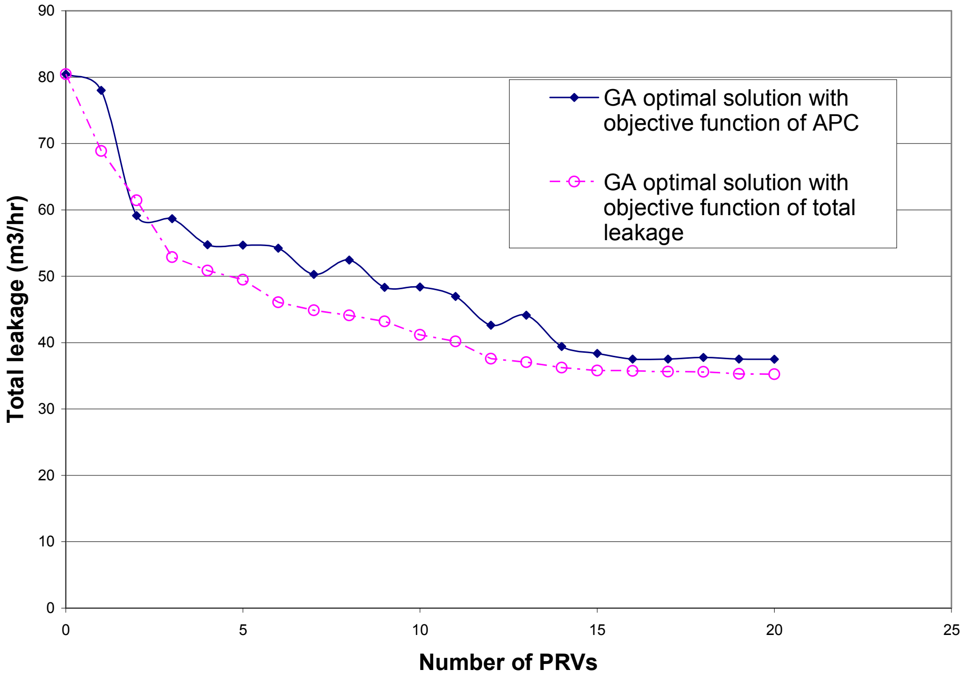


Figure 11. Comparison of total leakage objective function for GA optimal solutions obtained from each objective function versus different numbers of PRVs

5. CONCLUSION

A single objective genetic algorithm was used here to solve the leakage control problem in a WDS case study. Two approaches of main objective function for leakage control was defined here including minimizing total leakage in the WDS and maximizing appropriate pressure zones in the WDS. A GA optimization model was used to solve the problem and find the best locations and their relevant settings for installing a specified number of PRVs. Different numbers of PRVs were tested in the case study. The model applied to a real world case study in Mahalat city, which is large enough to use an optimization model. A skeletonized model of Mahalat WDS was used to reduce the time of the simulation process. To avoid occurring low head pressure in the WDS, a penalty function was defined to deteriorate the fitness of such solutions. A comparison was also made between the choices proposed by expert (EC) and GA optimal solutions.

The result shows that the improvement rate of the objective functions decrease when the number of PRVs increase. Therefore, 11 optimal PRVs can be selected as cost-effective number of PRVs with respect to minimizing total leakage. When maximizing APC, the number of PRVs more than which the rate of increase in APC is neglected is equal to 16. Also six PRVs presented by EC are equal to two optimal PRVs when objective function is to minimize total leakage. While, six PRVs presented by EC, are equal to approximately only one optimal PRV when APC is going to be maximized.

According to the results, no high correlation was observed between the optimal solutions obtained from the two objective functions. However, a relatively good correlation observed between the two sets of solutions when the APC is the objective function. This may be because maximizing appropriate pressure coverage implies that more pressure reduction at end nodes is required and consequently total leakage decreases more accordingly.

References

Behzadian, K., Ardeshir, A. and Sabour, F. (2008). "Optimal sampling design for model calibration using genetic algorithm: a Case Study." *Amirkabir Journal of Science and Technology*, Vol. 19, No. 68-C

Behzadian, K., Ardeshir A., Kapelan Z. and Savic D. (2009). "Stochastic sampling design using a multi-objective genetic algorithm and adaptive neural networks", *Environmental Modeling & Software,* 24, 530–541.

Germanopoulos, G. (1985). "A technical note on the inclusion of pressure dependent demand and leakage terms in water supply network models." *Civil Eng. Systems*, 2, 171–179.

Nicolini, M., and Zovatto, L. (2009). "Optimal Location and Control of Pressure Reducing Valves in Water Networks." *JOURNAL OF WATER RESOURCES PLANNING AND MANAGEMENT,* Volume 135, Issue 3, 178-187.

Pilipovic, Z., and Taylor, R. (2003). "Pressure management in Waitakere City, New Zealand –a case study" *Water Science and Technology: Water Supply*, IWA, Vol. 3, No 1–2, 135–141.

Rossman, L. A. (2000) *Epanet2 user manual*, US EPA, Washington, D.C.

Sabour, F. (2005) "Optimization Study of Mahalat Water Distribution System", *Sadra Negar Consulting Engineers*, Water and Wastewater Company of Markazi Province (in Farsi).

Tabesh, M., and Hoomehr, S. (2009). "Consumption management in water distribution systems by optimizing pressure reducing valves' settings using genetic algorithm" *Desalination and Water Treatment*, Volume 2, Issues 1-3 ,95–100.

Thornton, J., Sturm, R. and Kunkel G. (2008) *Water Loss Control,* 2nd Ed., McGraw-Hill, New York.