Leakage control management in water distribution systems by a multi-objective approach

LEAKAGE CONTROL MANAGEMENT IN WATER DISTRIBUTION SYSTEMS BY A MULTI-OBJECTIVE APPROACH

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Abstract

More than thirty percent of drinking water loss in many water distribution systems (WDSs) in Iran has made a major concern for Iranian water utilities. Pressure management is a well known and useful tool for reducing leakage. This paper presents an optimized pressure management model through optimizing PRV locations. The PRVs location and their setting are formulated here as a multi-objective optimization problem. The objectives are to minimize the total invisible leakage through pipes of the network and to minimize the number of installed PRVs. A multi-objective genetic algorithm is used as the optimization model coupled with EPANET software as the hydraulic simulation model. The model is applied to a real WDS in Iran with a high percentage of water loss. Three management scenarios are analyzed with respect to the existing and new PRVs. The results show that the proposed leakage control management is able to considerably reduce the high pressure values and mitigate the relevant leakage in the network (e.g. 61% of leakage reduction relative to the initial leakage). The results show that the asset will be conserved significantly by using a relatively low capital investment of system renovations, compared to the total value of drinking water which is annually lost. Furthermore, the analysis of the scenarios shows that the optimal setting of the existing PRVs can even decrease the leakage through the network without any capital investments.

Keywords

Leakage control, PRV location, multi-objective genetic algorithm, water distribution system

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 [1]. 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 pressure management is one of the most basic and cost-effective forms of optimizing a system and can in many instances provide fast paybacks on large investments [2].

Pressure management may be carried out in several ways, from the sectorization of a system with isolating valves to the installation of flow control or pressure reducing valves [3]. One useful scheme to achieve the most aims of pressure management would be the 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 [3].

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 purpose here is to minimize leakage from the system pipes as invisible leakage due to the excess pressure in WDS. It is assumed that invisible leakage from each pipe is dependent on the pressure head of 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 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. The first step is the preparation of hydraulic model by EPANET software. Next step is to determine the potential locations for installing PRVs. Note that the less number of potential PRV locations would increase the computational effort of optimization search. Then, optimization model can be developed. Objective functions of the optimal pressure management by PRV are as follows:

- Objective function#1: to minimize total leakage in the network (F_1)
- Objective function#2: to minimize total cost of installing PRV stations (F_2)

The decision variables of the optimization model are (1) decision variable *N*: number of PRVs; (2) decision variable *L*: vector with *N* arrays containing the location of installing PRVs; (3) decision variable *S*: vector with *N* arrays containing the relevant settings of PRVs. Also, N_{max} is maximum number of PRVs installed in the network.

First objective function is calculated based on the leakage estimation in pipes. Germanopulos's relationship is used for this purpose as the estimation of the leakage in pipes which were used frequently by previous researchers [3, 4, 5]:

$$Q_{L_i} = C.L_i.(P_i^{av})^{1.18} \tag{1}$$

where C = constant coefficient relating the leakage per unit length of pipe to service pressure (a coefficient which indicates the network characteristics); L_i = length of pipe *i;* P_i^{av} = average pressure at end nodes of pipe *i*. The constant coefficient *C* is assumed to be 10^{-5} based on the available data and previous research [3]. Thus, the first objective function defined as leakage objective function can be written as

$$Minimize\ F_1 = \sum_{i=1}^{npl} C.L_i.(P_i^{av})^{1.18} \tag{2}$$

where npl =number of leaking pipes which here it is assumed that all pipe in WDS are leaking pipes. The second objective function is related to the cost of installing PRVs and their operational cost. The number of PRVs can be a good surrogate for this type of costs. Therefore, the second objective function is defined as minimizing the number of PRVs installed in the network

$$Minimize\ F_2 = N_V \tag{3}$$

where N_V is the number of PRVs installed. The constraints of the objective functions are divided into two categories: (1) implicit constraints including energy and mass equations in the network; (2) explicit constraints including upper and lower limits of decision variables and the network. The first group of constraints are satisfied by hydraulic simulation model. The second category is explicitly considered in the optimization model as follows:

1. Upper and lower limits of decision variables *S* and upper limits of decision variable *N*:

$$S_i \geq P_{alw}^{\min} \tag{4}$$

$$S_i \leq P_{app}^{\max} \tag{5}$$

$$N \leq N_{\max} \tag{6}$$

Where S_i=setting of *i*th PRV; $P_{alw}^{\min}$ =minimum allowable pressure head; $P_{app}^{\max}$ = maximum appropriate pressure head; N_{max}=maximum number of PRVs installed in the network. Note that $P_{alw}^{\min}$ is defined as the pressure head lower than which is caused unsatisfactory by customers. $P_{app}^{\max}$ is considered the pressure head more than which would increase the risk of number of bursts in the high pressure zones. Based on the local data available, the amount of P_{alw}^{min} and P_{app}^{max} is assumed to be 30 m and 70 m.

2. The constraint of minimum nodal pressure head: 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, penalty function is considered in the optimization model so that such solutions are removed from the set of solutions in the optimization process.

After defining objective functions and constraints, an appropriate algorithm is required to solve the optimization model. As the proposed optimization model is a two-objective problem, a multi-objective algorithm is required for solving the model. Different approaches of multi-objective algorithms have been proposed by different researchers [6]. Here, NSGA-II developed by Deb et al. which is an effective algorithm for solving multi-objective problems is used [7]. Integer encoding is used here. The number of genes for each chromosome equals twice maximum number of PRVs installed in the network (N_{max}) half of them for the location of PRVs and the rest for the relevant setting. Zero number assigned for a gene indicates when considering no PRV for that gene.

A sensitivity analysis-based approach was used here for setting the NSGA-II 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 60 chromosomes, 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 optimization model was developed using a computer code in MATLAB software. The toolkit of EPANET 2 was also linked with the optimization model to perform the hydraulic simulation model [8].

3. CASE STUDY

The case study used here is Mahalat WDS located in the central part of Iran. The WDS covers approximately 46 km2, with a population of around 160,000. Model demands are predominantly domestic with some commercial users. The WDS is supplied by gravity from three wells and two service tanks (reservoirs) around the city. The average water demand is 158.9 L/S. The water is pumped into the system with a constant rate. The WDS model was made of 237 pipes and 195 junctions, which is shown in Figure 1.

As Mahalat WDS was suffering excess pressure within its network, six pressure reduced vales (PRVs) were introduced and installed by Expert Choice (EC) to decrease pressure heads to a fixed pre-specified values. To assess the effectiveness of the PRVs' selection made by EC, three scenarios for optimal PRV locations are defined and compared in the WDS. These scenarios are as follows:

1. <u>Sc#1 (possibility of PRVs selection among both all potential PRVs and the ones made by EC):</u> In this scenario, the optimization model is searching among both potential locations for installing PRVs and existing PRVs selected by EC. In other word, it is assumed that the optimization model is able to select any set of PRVs in the network including or not the PRVs locations made by EC. Thus, the comparison between the knowledge of experts and the optimization model can be provided.

2. <u>Sc#2 (Considering existing PRVs and their settings made by EC as fixed PRVs and selection of other PRVs among potential PRVs):</u> In this scenario, it is assumed that the PRVs and their setting made by EC are existing and installed in the network and the optimization model is searching for other PRVs locations. In other words, the model is searching for other locations except for six installed PRVs.

3. <u>Sc#3 (Considering existing PRVs made by EC as fixed PRVs and selection of other PRVs among potential PRVs as well as the posibility of changing the settings of the existing PRVs)</u>: In this scenario, it is assumed that the six existing PRVs made by EC are constant and fixed PRVs in the model. The optimization model is only able to change their settings. In other words, optimization model is searching for installing other PRVs among potential PRV locations other than six existing PRVs as well as optimizing the setting of six existing PRVs.

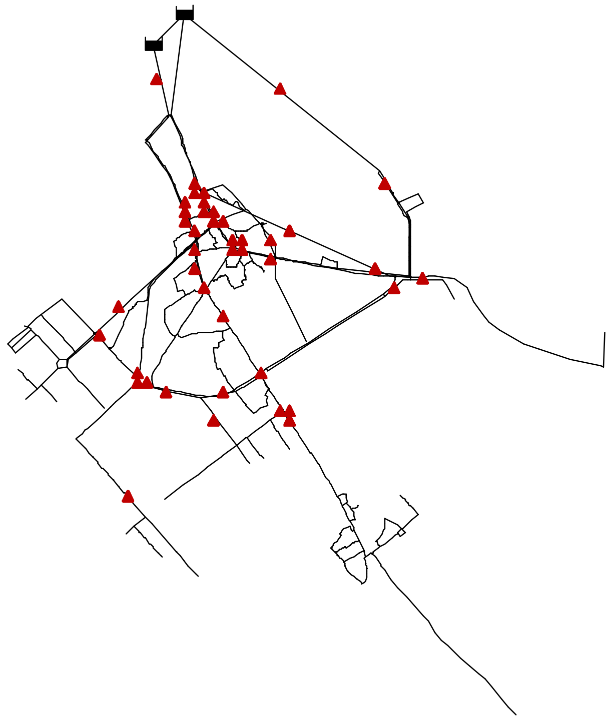


Figure 1. Mahalat WDS model with potential locations for PRV installation (triangular shapes) [6]

4. RESULTS AND DISCUSSION

The Pareto optimal fronts resulted from solving optimization model are shown in Figure 2. As it can be seen in the Figure, a significant reduction in leakage amount of 61%, 49% and 47% relative to the initial leakage is obtained in Sc#1, Sc#2 and Sc#3, respectively. Furthermore, the Figure shows that Sc#1 in which the model has been able to select freely among all potential PRV locations including existing PRVs, the better results were obtained rather than other Scenarios in which the model had to inevitably select six existing PRVs. In addition, as the number of optimal PRVs increases, the influence of this constraint is reduced in such a way that after ten PRVs, all Pareto optimal fronts closely match to each other. The difference between Sc#2 and Sc#3 is marginal although Sc#3 outperforms relative to Sc#2 because in Sc#3 the model was able to change the setting of the existing PRVs. Therefore, the marginal improvement is due to the optimal setting of existing PRVs.

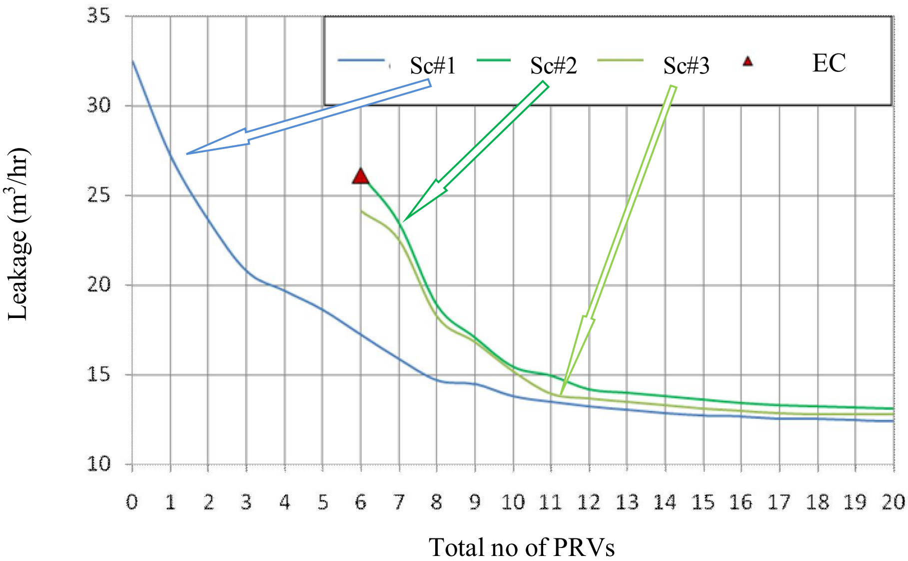


Figure 2. Comparison between Pareto-optimal fronts among three scenarios in relation to the two objective functions

As it can be seen in Figure 2, each solution on the Pareto optimal fronts in each scenario can be selected as an optimal solution. The selection of final solution can be performed by decision makers based on the main criteria including [6]: (1) determining final solution based on the pre-specified number of PRVs in the network; (2) determining final solution based on the minimum required decrease in leakage from the network; (3) determining final solution based on the point on the Pareto optimal front in which meaningful decrease in leakage is provided while increasing the number of PRVs; (4) determining final solution based on the maximum budget for the pressure management plan.

Moreover, the results obtained from the optimization models considerably improve rather than the PRVs selection made EC. The comparison between the leakage resulted from EC and the model is shown is Table 1. As it can be seen in the Table, the improvement resulted from installing six PRVs made by EC is equivalent to the ones from installing two optimal PRVs in Sc#1. Further, using six optimal PRVs in Sc#1 would cause 47% reduction to be occurred while only 20% reduction would be obtained for the selection made by EC. In other words, 34% improvement would occur in the optimization model (Sc#1) rather than the selection of EC for six PRVs. Among the selection of EC, only the PRV no of 2 and 6 are observed in the results of the optimization model. Even if we consider no difference in the total number of PRVs and no budget is available for installing any new PRVs, 6% improvement rather than EC can be obtained based on the result of six PRVs in Sc#3 with only changing in the settings of existing PRVs.

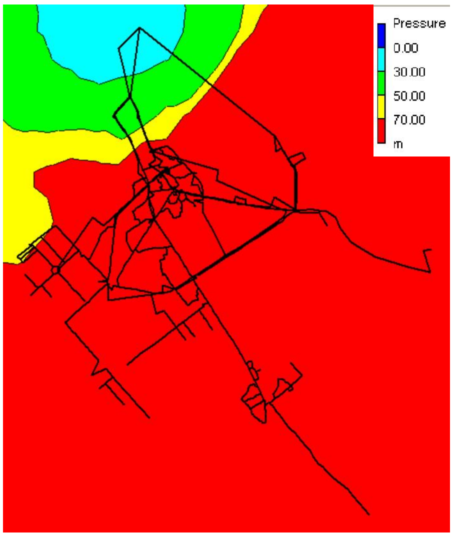
Also, Figure 3 shows the comparison of pressure contours in four states in the WDS including (a) before installing any PRVs; (b) after installing six PRVs of EC; (c) after installing two optimal PRVs (Sc#1) and (d) after installing six optimal PRVs (Sc#1).

Table 1. Comparison among the results of the Expert Choice and the two scenarios of the optimization model

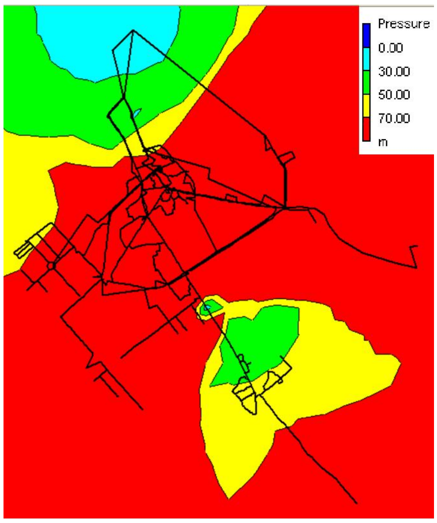
Method	Total no. of PRVs	PRV no.						Leakage (m^3/hr)
EC	6	1	2	3	4	5	6	26.14
Sc#1 (optimization model)	2	2	6					23.635
Sc#2 (optimization model)	6	2	6	12	14	26	33	17.223

5. CONCLUSIONS

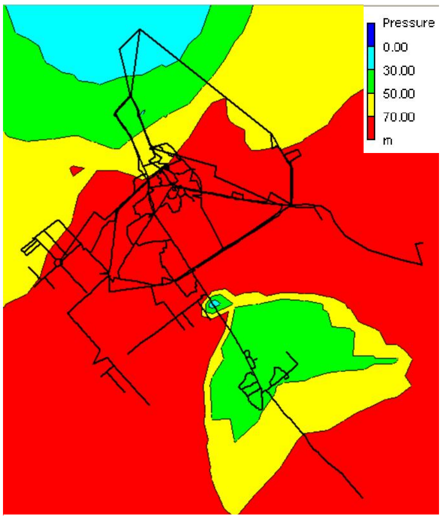
In this paper, a multi-objective optimization model based was developed for pressure management in water distribution system in which the optimal number and location of PRVs were found. The model was applied to a steep slope case study known as Mahalat WDS located in the central part of Iran. The Expert Choice had installed six PRVs in the WDS. A comparison was made between the selection of EC and the results of the optimization model. Three scenarios were considered in the optimization model based on the assumption of existing six PRVs and their settings in the model. The results of the model showed that 61%, 49% and 47% reduction in leakage amount rather than initial leakage can be obtained for scenarios 1, 2 and 3 respectively. The results also showed that considerable improvement of 34% would occur in the optimization model rather than the selection of EC for six PRVs. Even if no difference in the total number of PRVs is assumed, 6% improvement rather than EC can be obtained based on the result of six PRVs with only changing in the settings of existing PRVs.



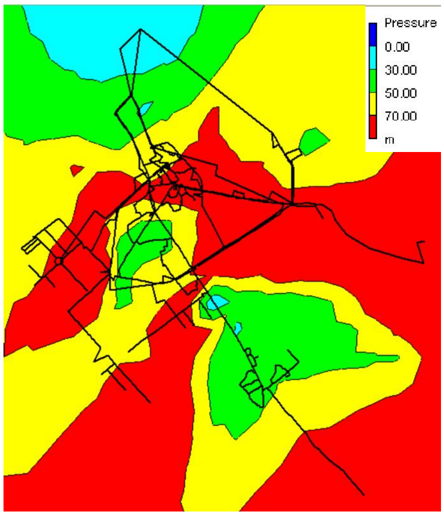
(a) before installing any PRVs



(b) after installing six PRVs of EC



(c) after installing two optimal PRVs (Sc#1)



(d) after installing six optimal PRVs (Sc#1)

Figure 3. Comparison of pressure contours in the WDS resulted from EC and the optimization model (Sc#1)

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