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Minimizing Excess Pressures by Optimal Valve Location and Opening Determination in Water Distribution Networks

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Abstract

Water leakage, which could be defined as supplied, treated, transmitted and finally lost volume of a water source; needs to be minimized in a water distribution network (WDN). This paper presents a heuristic optimization model to minimize excess nodal pressures in a water distribution network by determining the location and setting of control valves. The optimization technique is based on Genetic Algorithms (GA) which could be defined as a search heuristic that imitates the process of natural selection. The eventual optimization objective is to find optimal setting of control valves to decrease excess pressures and water leakage proportionally. The main body of the methodology is divided into sub-sections. These sections allocate the operative valves considering both Steady State (SS) and Extended Period Simulation (EPS) cases consecutively. The setting of operative valves are then determined in the final step by employing Throttle Control Valves (TCVs) into the network. The developed model has been applied on a case study network that has 89 nodes and considerable excess pressure decrements are handled.

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1. Introduction

Within water transmission and distribution systems, from supply to consumer some proportion of drinking water is being lost. This phenomenon may basically be defined as leakage which holds a significant portion of non revenue

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water around the world. Thus, reducing leakage and water loss resulting from water distribution systems represent a significant issue for water authorities.

Pressure heads within the water distribution network are one of remarkable, measurable and manageable causes of leakages. Leakage among the system is directly proportional to the hydraulic pressures. Thus, decreasing nodal pressures may be considered to be an appropriate method for leakage minimization. Pressure minimization may be accomplished by employing several types of valves. Operation of isolation valves is one of the applicable methods for pressure minimization since; these types of valves are being widely used in current water supply projects. The isolation valves may be in open, partially open or closed positions.

This paper represents an excess pressure minimization methodology by valve operations. The methodology contains the steady and extended states of network for valve closures and also the partial openings. Genetic Algorithms based, excess pressure minimization method is applied to obtain the optimal set of valves in terms of valve closures and partial openings.

1.1. Review of Past Studies

Being one of the pioneers of the subject, Germanopulos and Jowitt [1] listed the causes of water leakage and chose the convenient way of reducing leakage as pressure control. They proposed a methodology for determination of optimal valve settings for pressure minimization involving a function relating nodal pressures and leakage amount. Jowitt and Xu [2] used linear theory for the problem of optimal valve setting. They improved their objective function which minimizes total volume of loss rather than total nodal pressure. An evolution program with principles of evolutionary design and genetic algorithms were introduced into the problem of leakage minimization by Savic and Walters [3]. In their methodology, a steady state network analysis model was used that is based on linear theory. Reis et al. [4] adopted the leakage-pressure model of Germanopulos and Jowitt [1] to their study to find the suitable location and setting of valves in a WDN using GA. Aiming to obtain maximum leakage reduction, the objective was defined as the determination of optimal valve settings for a given location of valves. Vairavamoorthy and Lumbers [5], introduced flow reduction valves into the problem of leakage minimization. They developed an optimization model to find the most effective settings of such valves which are placed on predefined places.

Özger and Mays [6] offered a reliability approach for optimal location of isolation valves. Though their aim is not the minimization of leakage in particular, but the network reliability; the optimization of valve locating problem is discussed in detail. They used the Node Flow Analysis [7] to solve the network instead of standard demand driven analysis. For the problem of optimal valve locating, simulated annealing was introduced. A pressure-driven demand and leakage simulation model is accomplished by Giustolisi et al. [8]. They used a steady-state network model to simulate the pressure-driven demand and leakages at pipes. Araujo et al. [9] used two phase optimization model using genetic algorithms for the problem of optimal pressure control. They used EPANET 2 for hydraulic network analysis for its robustness. They also used “elitism” to conserve the best member of each generation that lets the chromosome pass through to the next generation. For optimal pressure management, Nicolini and Zovatto [10] introduced the regulation of pressure reducing valves (PRVs). They also introduced the concept of multi-objective genetic algorithms into the problem of leakage minimization to determine the number, location and setting of these valves. EPANET 2 was again used as network simulation software and coupled with the optimization model. Nazif et al. [11] proposed a pressure management model, considering water levels of tanks in order to minimize the nodal pressures and leakages. To simulate the hydraulics of the network, “emitter” option of EPANET is used. Recently, Di Nardo et al. [12] and Diao et al. [13] focused on automatic recreation of district metered areas and pressure zones. They create metered areas by building boundaries with insertion of isolation valves.

2. Problem Formulation

The problem which has been investigated through this paper consists of determining the optimal location and setting of control valves to minimize the excess nodal pressures among the network. The valves are considered individually but the goal is to find the groups and combinations of them. The objective function is formulated as follows;

$$Minimize\ Z = \sum_{i=1}^{N_n} Pe_i \tag{1}$$

Subject to;

$$\mathrm{P_{t,i}} \geq \mathrm{P_{min}} \tag{2}$$

Where;
N_n: Number of demand nodes
Pe_i: Excess pressure head at the i^{th} Node (m)
$P_{t,i}$: Hydraulic pressure head of node i at time t (m)
P_{min}: Minimum node pressure head limit (m)

Excess pressure, Pe_i is a measure taken from the results of hydraulic simulation and is calculated as follows for each node;

$$Pe_i = \begin{bmatrix} 0 & \text{if } \mathrm{P_i} \leq \mathrm{P_{max}} \\ (\mathrm{P_i} - \mathrm{P_{max}}) \times \mathrm{C_{ep}} & \text{if } \mathrm{P_{max}} < \mathrm{P_i} \end{bmatrix} \tag{3}$$

Where;
P_i: Pressure head of node i (m)
P_{max}: Maximum node pressure head limit (m)
C_{ep}: Excess node pressure penalty constant

In this study, minimum and maximum node pressure head limits (P_{min} & P_{max}) are selected as 30 and 80 mwc respectively. Consequently, the nodal pressures above 80 mwc are considered to be excessive.

Besides the mentioned fundamental constraint, additional constraints are included in the optimization study such as nodal pressure and valve operation limit constraints. These constraints are included in the main objective function by employing penalization functions. By adding these penalty terms into the objective function, the modified form of the objective function is obtained which is shown below;

$$Min. Z = \sum_{i=1}^{N_n} Pe_i + P_{np} + P_{vo} \quad for\ EPS\ conditions \tag{4}$$

Where P_{np} and P_{vo} are nodal pressure and valve operation penalties respectively.

3. Proposed Model

3.1. Structure

The optimization model, proposed in this study consists of the combination of a hydraulic simulation software (EPANET) and decision making algorithm (Genetic Algorithms, GAs). EPANET is reliable, robust, quick, well known and widely applied ([10], [11], [14], [15], [16], [17]) hydraulic simulation software. It may perform steady state (SS) and extended period simulation (EPS) of hydraulic and water-quality behavior within pressurized pipe networks. EPANET was developed by the Water Supply and Water Resources Division (formerly the Drinking Water Research Division) of the U.S. Environmental Protection Agency's National Risk Management Research Laboratory.

For decision making, standard Genetic Algorithms are used in this study. GAs are one of the search techniques that is based on the mechanism of natural evolution. The idea behind is the Darwin's evolution theory and the survival of the fittest. GAs have been developed by Holland [18], his colleagues and his students at the University of Michigan. During the evolution process, three main parameters are employed; selection, crossover and mutation. The EPANET and GAs are interconnected with each other in MATLAB environment. The developed model uses binary coded GAs and optimizes the location and setting of valves stepwise which is explained in detail in the subsequent sections.

3.2. Methodology

To reduce pressures among the network, various types of valves may be applicable. In this study, the isolation valves are considered due to their widespread use among the water distribution networks. Isolation valve may be defined as the most common type of valve in water distribution systems which can be manually (or automatically) closed to block off the flow [19]. As the definition implies, these valves are supposed to be left open through normal process. However, in case of need; they could be kept closed or stay in partial open position. Therefore, pressure minimization problem should consider completely open, partially open or completely closed valve statuses.

In a water distribution network, it is obvious that some valves should be in fully open position. These valves could be considered as the ones, located on the main water transmission lines or on the branches that feeds the isolated district metered areas. However, many of the rest of valves may hold varying statuses. Due to complexity and nonlinear behavior of the problem, to find the ideal number and location of valves and obtain a feasible search space, the valve operation methodology is divided into three steps. First, the possible locations for valve operations are found (i), then their operability are confirmed (ii) and finally the setting of operable valves is found (iii).

(i) For valve locating study, middle of all pipes are considered to be a potential valve location. At this step, it is only aimed to select which valves are effective for pressure minimization. While applying the optimization method under Steady State (SS) condition, the demand loadings are chosen for two boundary times; maximum and minimum demand hours. During this step, the decision variables of GAs are the status of valves; on or off. By evaluating the results, closure percentage of each valve (pipe) is obtained, and the valves are grouped by 5% closure percentage intervals.

(ii) Using the defined closure percentage intervals found under SS conditions, model is applied to network under Extended Period Simulation (EPS). At the end of both SS and EPS studies, the combination of closed valves which gives the maximum pressure decrement is identified. In addition to closed ones; the valves that shall be left open are also determined.

(iii) After obtaining the valve groups with unchanged status (left open or closed) at valve locating step; valve opening determination study is applied. In this step, the open or closed valves of previous study (valve locating) are kept open or closed while partial openings are searched for the rest. Since the isolation valves do not have capability of partial opening in network simulation software point of view, these valves are modelled as Throttle Control Valves (TCVs). In this step, the decision variables of GAs are the partial openings of valves. The flowchart of these valve operation studies is shown in **¡Error! No se encuentra el origen de la referencia.**.

Initially, consider each pipe as valve and apply Valve Locating study for minimum and maximum hour demand loadings in Steady State conditions. Then, obtain the closure percentages of each valve (pipe) and group the valves according to their closure percentages with 5% intervals (i).

For each group of 5% interval, execute valve locating study for Extended Period Simulation of 24 hours and by evaluating the results, detect closed and non-closed (open) valves (ii).

Consider non-closed valves are effective valves for pressure minimization; re-model them as Throttle Control Valve and execute valve opening determination study (iii).

Fig. 1. Flowchart of Valve Operation Methodology

4. Application of the Methodology to the Study Network

4.1. Characteristics of the Study Network

Throughout this study, a network named Yayla, consisting of 107 pipes and 89 nodes is studied. The Yayla network is a district metered area of Northern Ankara (Turkey) WDN. As briefly described, there is no restriction on the number or location of valves in the network. The methodology decides on the number and the location of valves by itself.

4.2. Valve Locating Studies

4.2.1. Steady State Studies

In the first step of valve locating studies (i), network is run under SS conditions. At this step, it is only aimed to select which valves are effective for pressure minimization. While applying the optimization method under SS condition, the demand loadings are chosen for instant time. To reflect the characteristics of the whole daily demands into steady state in an efficient way, the minimum and maximum hour demands are taken into consideration and the developed program is applied to network 25 times for each demand loading. To investigate the results 50 runs conveniently, the closure percentages of valves are grouped using 5% intervals indicating the “closed” frequency of each valve (pipe). For example, if Pipe *n* is decided to be closed 20 times out of 50 runs; its closure percentage becomes (20/50) 40%. Beside outlining closure percentages, this stage revealed out the valves that shall be kept open and excluded from the valve opening determination studies.

4.2.2. Extended Period Simulation Studies

After obtaining the closure percentage of each pipe, the second step (ii) of the valve locating methodology is applied under EPS conditions by employing the closure percentages found in the i^{th} step. By considering EPS conditions, it is aimed to find the valves that are needless to operate; in other words, the valves that may remain open or closed for the whole day. The results of SS studies are transformed to EPS conditions using 5% closure percentage intervals. Using these closure percentages (CP), search space is narrowed starting from valves with C>0% to CP>55%. The objective function is kept same. Bu narrowing the search space, it is aimed to find the valves that may be kept closed for whole to obtain maximum excess pressure decrement. The methodology is applied to the valves having closure percentages with 5% increment steps starting from 0% to 55%. The results of EPS studies revealed out that, valves with CP >40% are needless to operate; they may be kept closed through the day. As the number of operable valves diminishes up to

CP>40 %, the excess pressures also decrease. From the point of 40%, by closing fewer valves, excess pressures again start to increase. Thus, the optimal closure percentage of valve groups to be kept closed is selected to be 40%. The results of EPS studies are shown in Table 1.

Table 1. Summary of Results for Valve Locating Study

Valve Closure Selection Interval	Excess Nodal Pressures (m)	Number of Valves to be Controlled	Number of Valves Kept Closed
CP > 0%	4.40E+11	64	0
CP > 5%	112.47	50	0
CP > 10%	102.64	41	0
CP > 15%	103.96	36	0
CP > 20%	92.39	31	0
CP > 25%	100.92	26	0
CP > 30%	94.92	18	2
CP > 35%	97.87	16	3
CP > 40%	**77.44**	**14**	**14**
CP > 45%	89.49	10	10
CP > 50%	94.06	7	7
CP > 55%	122.95	5	5

To visualize the effectiveness of valve locating study, nodal pressures of Yayla are calculated and compared for two cases; all valves open case, and valves with closure percentage >40% are closed case. By keeping the valves with closure percentage >40% closed, the nodal pressures of almost all nodes have been decreased. When the excess pressures are compared, summation of them is decreased at the level of 50%. In other words, by applying steps i and ii, the summation of excess pressures are decreased to its half value.

To integrate the outcomes of valve locating studies (i and ii) to the valve opening determination study (iii) the valves of Yayla network is divided into five groups. By grouping, the valves never been selected to be closed and the valves with closure percentage higher than 40% are kept in closed status and both types of valves are removed from valve opening determination search space. The rest of the pipes are divided into three groups. While grouping these valves, again closure percentages are taken into consideration. These groups are defined below.

Type I: Closure Percentage = 0 %
Type II: 10 % ≥ Closure percentage > 0%
Type III: 20 % ≥ Closure percentage > 10%
Type IV: 40 % ≥ Closure percentage > 20%
Type V: Closure Percentage ≥ 40%

4.3. Valve Opening Determination Studies

At the 3rd and the final step (iii) of the pressure minimization methodology, Yayla network is re-modeled using the types of valves that are found at the end of EPS studies. The valves that are open or closed through the day (Types I and V) are kept with unchanged status, while the others (Types II, III and IV) are changed into Throttle Control Valve.

Throttle Control Valve (TCV) is a type of valve that may produce resistance to flow by throttling itself. The produced resistance (minor loss) is a function of minor loss coefficient and the flow velocity. Often the throttling effect of a particular valve position is known, but the minor loss coefficients as a function of position are unknown. The formulation of minor loss is given below.

$$h_m = K_L \frac{V^2}{2g} \quad (5)$$

Where; h_m is minor loss (m), K_L is minor loss coefficient, V is flow velocity (m/s) and g is gravitational acceleration constant (9.81 m/s^2). For this study, the assumed K_L values are taken from Walski (2003) for 4 positions (100%, 75%, 50% and 25% open). Using the values for those 4 different positions, a polynomial regression is accomplished and K_L values for 8 different positions are produced. These taken and produced values are shown in Table 2.

Table 2. Valve Opening Positions and K_L Values

Valve Position	Valve Opening (%)	Calculated Loss Coefficient	Used Loss Coefficient
Closed	0.00%	83.21	1.00E+09
1/8 open	12.50%	49.88	49.88
2/8 open	25.00%	27.00	27.00
3/8 open	37.50%	12.62	12.62
4/8 open	50.00%	4.80	4.80
5/8 open	62.50%	1.61	1.61
6/8 open	75.00%	1.10	1.10
7/8 open	87.50%	1.34	0.74
Open	100.00%	0.39	0.39

Using the K_L values shown above and the objective function defined in Section 4.3, the program is run under SS conditions using three groups of TCVs separately. The results of TCV studies indicating the percentage of excess pressure decrement and evaluation times is shown in Table 3.

Table 3. Results of TCV Studies

	TCV Group I	TCV Group II	TCV Group III
Number of Valves in Operation	17	27	50
Percentage of Excess Pressure Decrement	20.72%	21.38%	15.50%
Evaluation Times (sec)	279	335	459

As can be seen from Table , by using TCV group II (40% ≥ CP >10%) the pressure decrement reaches at the level of % 21. As the number of TCVs increase, the effectiveness of algorithm decreases in terms of both pressure decrement and evaluation times. Therefore, 2nd group of TCVs could be considered to be applicable for valve opening determination study to reduce excess pressures. It can be summarized that, when compared to "all valves open" case, by valve locating under SS and EPS conditions 50%; and by valve opening determination studies additional 20% excess pressure decrement is obtained.

5. Conclusion

In this paper, the problem of excess pressure minimization is formulated and solved as a nonlinear optimization problem using a binary coded GA to determine the optimal valve location and valve opening setting. Standard Genetic Algorithms is used as optimization technique to find both the optimal location and opening of the control valves. The number of valves is not restricted within the problem, but kept equal to the number of pipes. The search space is narrowed by dividing the main methodology into three consecutive steps. The result of the case study network demonstrated the potential of the proposed method in reducing the excess pressures among the network. For the 89 node network Yayla DMA, the proposed method achieved an excess pressure reduction of around 60 %. When, direct relationship between leakages and excess pressures are considered, this methodology is considered to be helpful for preventing water leakages resulting from high pressures.

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