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Consumption management in water distribution systems by optimizing pressure reducing valves' settings using genetic algorithm

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ABSTRACT

In this paper an optimization approach is presented to minimize pressure and consequently water consumptions in water distribution networks using Genetic Algorithm (GA) technique. To reduce water consumption a pressure management scheme is considered which uses pressure reducing valves (PRVs). When the PRV outlet head is reduced pressure is decreased in the down stream. This leads to reduction of all uncontrolled output flow from the system (e.g. leakage or sprinkler outlets) and the unwanted consumption by the ordinary customer which is usually happened by excess pressure in the system. In this procedure PRV outlet setting is decision variable of the optimization model. To evaluate pressure values of the system resulted from different PRV's settings an extended period head driven simulation program (EXPHDA) is prepared and is linked to the optimization model. Finally a test network is considered to apply the proposed methodology. It is shown that how much the real consumption is reduced when using the optimum PRVs' settings.

Keywords: Consumption management; Water distribution networks; Pressure; Hydraulic analysis; PRV; Genetic algorithm

1. Introduction

Limitation of water resources and increasing demand due to population growth and industrial development are leading to water crisis in many countries. To reduce the problem, demand and consumption management programs should be designed and performed in water distribution systems. Some decision makers just focus on change of the consumption behaviors of the consumers by using some special valves inside the properties or consider some cultural activities to reach this goal. However, it seems that this kind of scenario requires a long time to be effectively concluded. As a mid or short term activity, pressure management is the most practical and economical method among various ways of controlling the consumption. In this procedure nodal pressures would be set in their optimum magnitude (relating to the minimum standard pressures) by using reservoirs, valves and suitable pressure zones. Uncontrolled pressure reduction, although leads to consumption reduction, may also cause reduction of the system reliability. The best situation is when nodal heads approach to design values as much as possible. This situation is obtained by using optimization procedures.

In order to find the real amount of consumption in the network and minimize it by optimization procedures, the real condition of the network should be first determined by means of network's hydraulic analysis methods. Most of the existing commercial hydraulic analysis software is based on the demand driven simulation method (DDSM). In this method it is assumed that the amount of demand at each node is constant and it can be

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supplied at any normal and abnormal situation. Recent researches showed that the amount of flow at each node is related to its pressure and this fact should be considered at any hydraulic simulation model to analyze the hydraulic performance of the system, realistically. Considering a head-discharge relationship, the realistic analysis can be performed by the head driven simulation method (HDSM) [1]. Some researchers just use a demand driven based model (e.g. EPANET) and try to simulate leakage like an emitter outflow [2]. However, to represent the realistic performance of the system a full head driven method should be applied which considers both controlled consumption and leakage [1].

The most existing researches are focused on pressure reduction for leakage minimization objectives. Most of them have used Flow Control Valve (FCV) [3–5] and just some of them have applied PRV [6,7]. However application of PRV is more appropriate for water distribution networks considering operational point of view [8].

Different objective functions such as minimizing total leakage or nodal heads have been addressed in the last researches. Vairavamoorthty and Lambers [5] mentioned that minimizing the nodal excess pressures are more appropriate for water networks.

Also several optimization procedures are used to solve the optimization problem such as linear programming [3], non linear programming [5,7] and genetic algorithm [2,4]. Applications of search methods like GA are growing in pipe networks because of their capabilities to solve complex problems.

This paper aims to present an optimization procedure using GA to minimize the water consumption in water systems. Pressure reducing valves are used for pressure reduction. A fully integrated extended period pressure driven simulation model is prepared to be linked with the optimization program to simulate the hydraulic performance of the network realistically.

2. Methodology

For the optimization procedure the following objective function is considered:

$$\mathrm{OF} = \mathrm{Minimize}\ F = \sum_{i=1}^{\mathrm{NPN}} \left(H_i - H_i^{\mathrm{des}} \right)^2 \tag{1}$$

Subject to:

$$F_j = \sum_{i=1}^{\mathrm{NPN}} \left(\frac{\left| H_i - H_j \right|}{K_{ij}} \right)^{0.54} Sgn\left(H_i - H_j \right) - Q_j^{\mathrm{req}} \left(\frac{H_j - H_j^{\mathrm{min}}}{H_j^{\mathrm{des}} - H_j^{\mathrm{min}}} \right)^{0.5} - 0.5 \sum_{i \in I} C_l L_{ij} \left(\frac{H_j - z_i + H_2 - z_j}{2} \right)^{1.18} = 0 \tag{2}$$

$$H_i^{\mathrm{des}} - \varepsilon \le H_i \le H_i^{\mathrm{max}} \qquad i = 1,\ldots,\ \mathrm{NPN} \tag{3}$$

in which H_i and H_i^{des} express nodal available and design heads, respectively and NPN is number of pressure nodes.

Eq. (2) is the continuity equation at node j according to the pressure driven simulation method. The first term is the pipe discharge which is obtained from the normal head loss relationship based on the end nodes pressure values of each pipe (H_i and H_j). Sgn ($H_i - H_j$) indicates the sign of flow in the pipe.

The second term of Eq. (2) represents the pressure dependent demand value at each node according to the Wagner et al. [9]. As can be seen in this method the available discharge at each node is not constant and is a function of nodal pressure. The available nodal flow is equal to the nodal demand (Q_j^{req}) if existing pressure is equal to or greater than the minimum standard design value (H_j^{des}). There is no water available at node *j* when pressure is equal to or less than the absolute minimum pressure (H_j^{min}) which is usually considered the same as the nodal ground level. Also available flow is a portion of nodal demand if the pressure is between H_j^{des} and H_j^{min}.

Furthermore, a full pressure driven model should include leakage as well as nodal demand. The third term of Eq. (2) expresses the inclusion of nodal leakage in the continuity equation. Leakage in pipe *ij* ($Q_{L_{ij}}$) can be evaluated by the following relationship [10]:

$$Q_{L_{ij}} = C_l L_{ij} \left[\frac{1}{2} \left\{ \left(H_i - z_i \right) + \left(H_j - z_j \right) \right\} \right]^{1.18} \tag{4}$$

where C_l is a coefficient which indicates the network characteristics. L_{ij} is the pipe length and H_i and z_i are head and the ground level of node *i*, respectively.

Eq. (3) shows the possible range of nodal pressure variations. The lower bound is the minimum standard design value which is normally between 15–30 m according to the building levels. The maximum allowable pressure (H_j^{max}) may also be considered between 50–70 m, based on the topographical situation of the network.

It should be noted that during a pressure reducing scheme sometimes it is possible that some nodes reach to the lower bound very quickly, while the other remaining nodes still face excess pressure. Therefore, the decision maker and operator may permit that the pressure at some nodes can be reduced from the minimum design level and consequently more nodes could be able to reach to their minimum possible level. For this purpose a parameter (ε) is introduced in Eq. (3) which is determined by the network operator.

To solve the optimization problem a computer code is developed in MATLAB7 using genetic algorithm tool box. The population size is considered as 40. Also the probability of crossover and mutation is determined as 0.8 and 0.05, respectively. Number of generations is 100 and time limit is set to 1000 seconds. Also, an extended period head driven program has been written in MATLAB7 to be linked with the optimization model to calculate hydraulic constraints.

3. Case study

To evaluate capabilities of the proposed methodology, it is applied to a well known test network which has been used in many previous papers such as Vairavamoorthy and Lambers [5] shown in Fig. 1. Pipe and nodal data are presented in Tables 1 and 2. Water level variations for all three reservoirs can be seen in Fig. 2. For extended period simulation of the hydraulic model a demand pattern is required which is presented by Fig. 3. It is assumed that the minimum design pressure for each node is 30 m above the ground level, i.e. $H_j^{des} = 30$ m and $H_j^{min} = 0$ m. The allowable tolerance value from the design pressure is 5 m (i.e. $\varepsilon = 5$ m).

Table 1
Pipe data

Pipe No.	Start node	End node	Dia. (m)	Length (m)	C_{HW}
1	23	1	0.457	606	110
2	23	24	0.457	454	110
3	24	14	0.229	2782	105
4	25	14	0.381	304	135
5	10	24	0.305	3383	100
6	13	24	0.475	1767	110
7	14	13	0.381	1014	135
8	16	25	0.381	1097	6
9	2	1	0.457	1930	110
10	3	2	0.305	5150	10
11*	12	13	0.457	762	110
12	15	16	0.229	914	125
13	17	16	0.305	822	140
14	18	17	0.152	411	100
15	20	18	0.229	701	110
16	19	17	0.229	1072	135
17	20	19	0.152	864	90
18	21	20	0.152	711	90
19	21	15	0.152	832	90
20	22	15	0.152	2334	100
21*	12	15	0.229	1996	95
22	11	12	0.229	777	90
23	10	11	0.229	542	90
24	8	12	0.457	1600	110
25	8	10	0.305	249	105
26	9	8	0.229	443	90
27	6	8	0.381	743	110
28	22	8	0.229	931	125
29*	22	21	0.152	2689	100
30	4	3	0.152	326	100
31	5	4	0.229	844	110
32	6	3	0.152	1274	100
33	5	6	0.229	1115	90
34	7	6	0.381	615	110
35	5	22	0.152	1408	100
36	5	7	0.381	500	110
37	6	9	0.229	300	90

* Location of PRV

Figs. 4–6 show the excess pressure values for all demand nodes resulted from the optimization procedure for three different demand factors. It can be seen that most nodes are intended to reach the lower pressure bound and just in a few nodes the lower bound is violated because of considering the tolerance value. Actually no node is seen in which its real violation reach the ultimate value of 5 m because the model considers penalty for nodes in which pressures are less than the minimum design value. Besides, Fig. 7 presents variations of excess pressures at 4 example nodes in which nodal trend toward design pressures is illustrated.

The resulted nodal pressures are produced by the optimum PRV's outlet setting values which are obtained through the optimization procedure. The optimum settings can be observed in Fig. 8 for all three PRVs. It is seen that in PRV3 the discrepancy of the optimal values at each hour is more than the optimum settings of PRV1

Table 2
Nodal data

Node No.	Elev. (m)	H^{min} (m)	Demand (L/s)
1	18	48	5
2	18	48	10
3	14	44	0
4	12	42	5
5	14	44	30
6	15	45	10
7	14.5	44.5	0
8	14	44	20
9	14	44	0
10	15	45	5
11	12	42	10
12	15	45	0
13	23	53	0
14	20	50	5
15	8	38	20
16	10	40	0
17	7	37	0
18	8	38	5
19	10	40	5
20	7	37	0
21	10	40	5
22	15	45	20

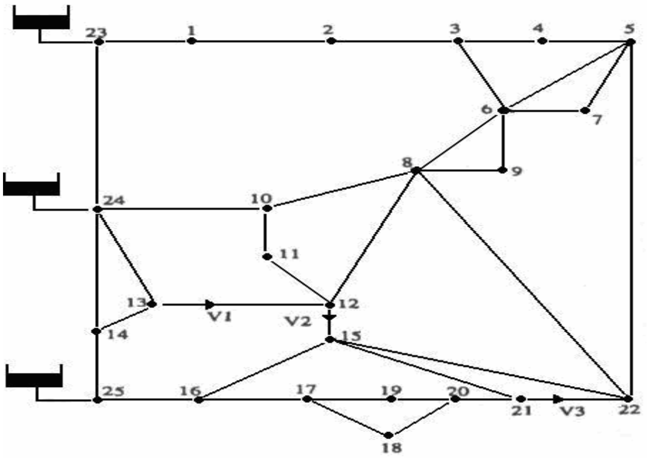

Fig. 1. The test network.

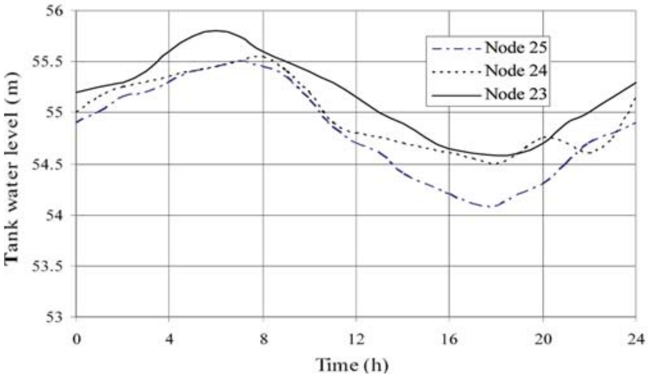

Fig. 2. Variations of water level in different reservoirs.

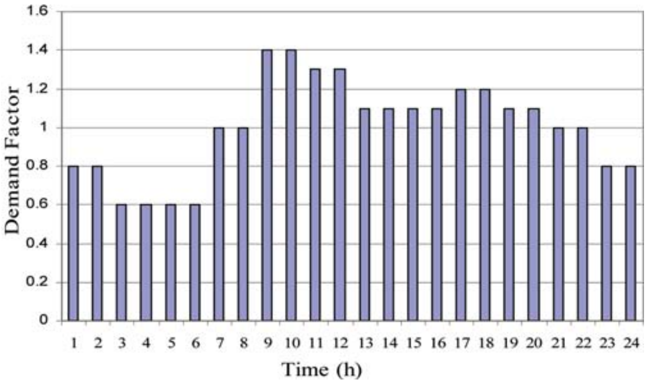

Fig. 3. Diurnal demand pattern.

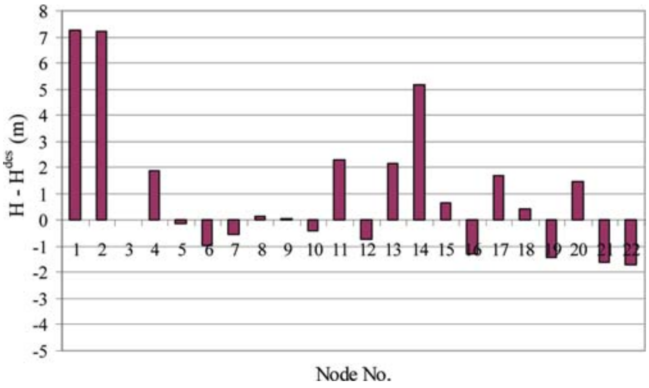

Fig. 4. Excess pressure values at 3 a.m. (demand factor = 0.6).

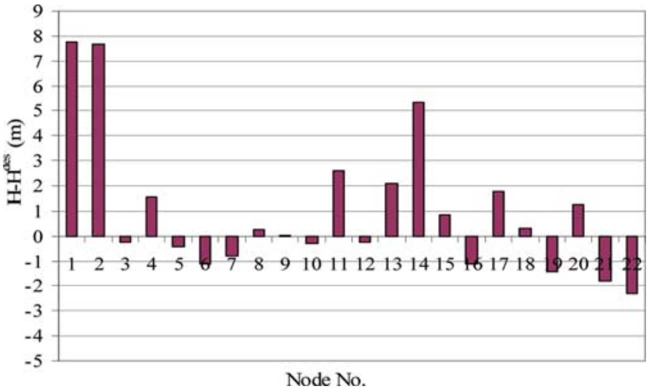

Fig. 5. Excess pressure values at 7 a.m. (demand factor = 1).

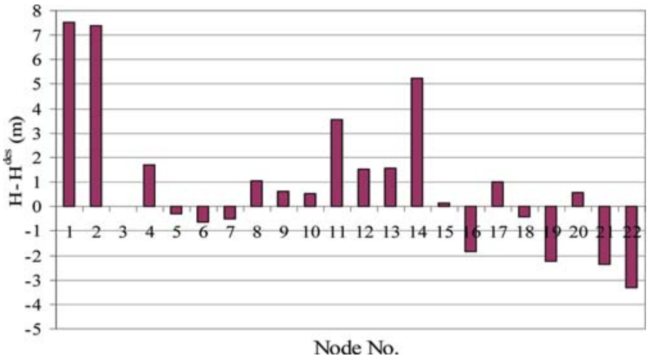

Fig. 6. Excess pressure values at 9 a.m. (demand factor = 1.4).

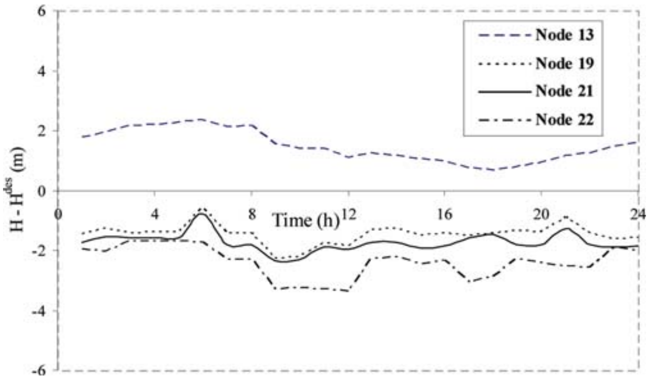

Fig. 7. Excess pressure values at some nodes during the day.

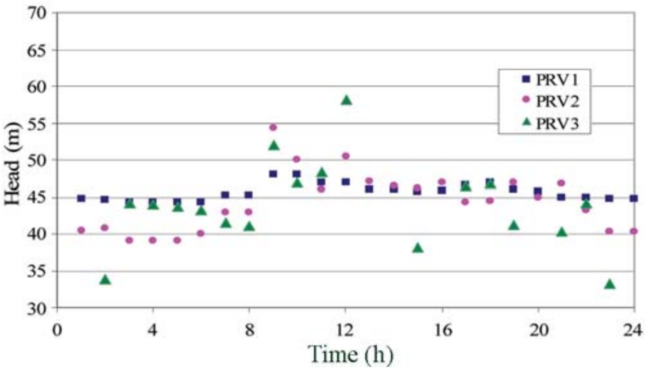

Fig. 8. The optimum setting values for 3 available PRV in the network.

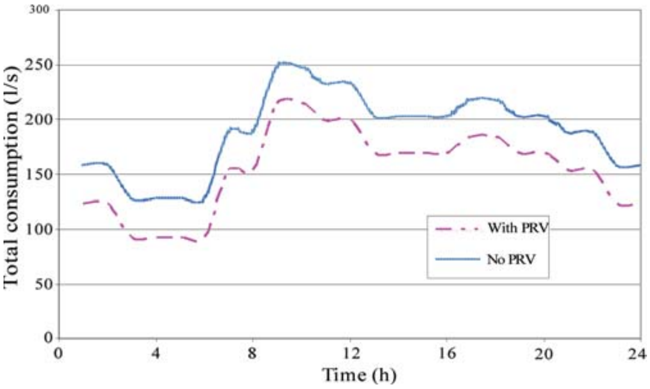

Fig. 9. Comparison of the total consumption values before and after consumption management.

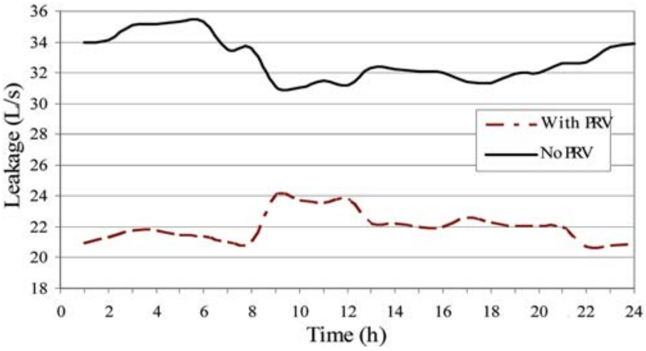

Fig. 10. Comparison of the total leakage values before and after consumption management.

and PRV2. The reason is that the PRV1 and PRV2 are closer to the reservoirs and pressure values at their down stream nodes have high sensitivity to variations of their settings. On the other hand, PRV3 is located in the end of network and have farthest distance from the reservoirs. Therefore, any change of its outlet's setting has less sensitivity on the pressure of node 23.

Fig. 9 shows the values of total consumptions for two different cases of no valve and using 3 PRVs. As it is seen considerable amount of water (about 15–25%) is saved (for both parts of demand) when PRVs are used for pressure and consumption reduction through an optimized pressure management scheme.

Furthermore, Fig. 10 illustrates total reduction of network leakage value in this procedure. It is seen that the most reduction is happened during midnight when pressure is higher because of lower consumption. It should be mentioned that comparison of total cost of the consumption management scheme with economical and uneconomical benefits of the total saved water concluded from a cost-benefit analysis can demonstrate benefits of such programs.

4. Conclusions

In this paper a methodology is presented for reducing consumption (both controlled and uncontrolled) through a pressure management scheme by pressure reducing valves. This method is based on an optimization procedure which has been linked with an extended period pressure dependent analyzer. The method shows that only head driven simulation based hydraulic models are capable of such kind of programming because no demand driven based models can recognize the pressure dependent nature of demand. Therefore they are not able to evaluate actual nodal available flow and nodal leakage values, realistically. The results indicate that the proposed scenario especially with consideration of tolerance value at each node is very useful and helpful for more pressure reduction and saving more water.

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