Pressure Management in Water Distribution Systems in Order to Reduce Energy Consumption and Background Leakage

H.Monsef [a], M. Naghashzadegan [a], R. Farmani [b], A. Jamali[a]

[a] University of Guilan, Department of Mechanical Engineering, Rasht, Iran
[b] University of Exeter, Exeter, Devon, UK

Abstract
Due to the seriousness of the water shortage crisis over the past decades, the need to manage water use has become more and more important. Pressure management in urban water distribution networks is one of the options that can significantly reduce water loss. The pressure reducing valve (PRV) and the variable speed pump (VSP) are two devices that are most used in WDS's pressure management. In the present study, an optimization code was first proposed to estimate the instantaneous water demand based on the reported network pressures. According to the estimated instantaneous water demand, another optimization code is presented based on the DE algorithm to control the installed PRVs and VSPs. So that the uniform distribution of the pressure and reducing the excessive pressure on the water network for all hours of the day, reducing the water leakage and energy consumption accordingly. The provided method has been applied to a real water distribution network in northern of Iran. The results showed that by applying this method, the network background leakage and the energy consumption have been reduced by 41.72% and 28.4%, respectively, compared to a non-management mode.

Key Words
Pressure management, Water Distribution System, Background Leakage, Energy Consumption, Pressure Reducing Valve, Variable Speed Pump,

Introduction
Due to increasing water demand in urban communities as well as reducing water resources, water loss management is one of the major challenges engineers face these days. Reports indicate that about 30%, or even more, of the total water entering the distribution network is wasted (Araujo et. al. 2006).There are many factors that are effective in leakage quantity in Water Distribution Systems (WDSs) such as the water pressure, the Pipe age, the quality of fittings, the characteristics of the soil around the pipe, etc. Due to the direct relationship between pressure and leakage, pressure management is one of the effective methods to reduce leakage in the WDSs.

The WDS is designed to deliver adequate water to the consumers with the minimum acceptable pressure in all the operation time, especially during the peak hours of peak days. In other operation time 'which water demand is lower' the network's nodal pressure is more than minimum the acceptable pressure. This event causes to increase the background leakage, the pipe failure and also energy losses (in order to create surplus pressure on the WDS). Therefore, pressure management of WDS can play an important role in decreasing the water and energy losses which is effective on the sustainability of consumption and the protection of the environment. The pressure reducing valve (PRV) and variable speed pump (VSP) are most used for WDS's pressure management. The PRVs regardless of changing the inlet pressure or flow rate can reduce inlet pressure to a steady lower set pressure. PRVs can be controlled with different approaches such as hydraulic or electronic controllers (Vicente, 2016). The second one can be used perfectly in supervisory control and data acquisition (SCADA) systems according to the momentary operation conditions. The VSPs are pumps with Variable Speed Drive (VSD). The VSD regulates the rotational speed of the pump's electric motor by changing the frequency of the input power. Changing the speed of the electric motor can change the hydraulic performance of the pump (such as power consumption, outlet flow, and pressure).

Many articles have been presented about pressure management methods in WDSs. Germanopoulos and Jowitt (1989) described the relationship between network pressures and leakage losses and evaluated the effect of pressure control on the water network leakage. They presented a linear theory method to find the optimal control valve settings to minimize the nodal excess pressure and also water leakage. The set point of control valve should be adjusted so that the pressure at the critical point (junction with the highest elevation or at the far end of the water network) remains within the allowable range.

Araujo et. al. (2006) presented a model to specify the optimal number, the location and the output pressure of the control valves in order to minimize the pressures and consequently leakage of WDSs. They used the genetic algorithms to find roughness coefficient of pipelines in order to minimize surplus nodal head. The pipes with higher roughness coefficient are potential points for installation of the control valve. They optimized the set point of control valves to reduce the network leakage.

In a case study, Marunga et al. (2006) reduced the WDS's background leakage of Mutare city in Zimbabwe with pressure management. They reduced the minimum night flow (MNF) about 25% with nodal pressure reduction from 77 m to 50 m with controlling the outlet pressure of PRV.

Nicolini and Zovatto (2009) proposed a multi-objective optimization method to find the optimal number, location and also set point of installed PRVs. The first objective function in their study was to minimize the total number of installed PRVs where the second objective function was to minimize the total leakage in the WDS. They achieved a Pareto front that shows the total leakage versus the number of the installed PRVs.

Skworcow et al. (2009) provided a method for energy and pressure management in WDSs in order to minimize the operation cost. They changed pump scheduling (Determining the number of fixed speed pumps in the operation state) and the speed of VSP and also the PRV set-points to reduce the excess pressure and dependent leakage. Their method has been applied to a medium scale WDS and it was shown that the daily electricity cost has been reduced about 34%.

Bakker et al. (2013) presented an active pressure control model to manage the outlet pressure of a pump station according to off-line pressure loss prediction in transmission pipelines. The model is a combination of a predictive and a feedback controller. Their results showed a decrease of 31% in pump energy consumption and a decrease of 20% in water losses by applying the model on a water treatment plant pump station in the Midwest of Poland.

Tricarico et al. (2014) suggested a novel methodology for the pressure management of WDSs. They used the turbines instead of the conventional PRVs to reduce network's pressure and to generate electricity simultaneously, whereas the minimization of the pump operation cost by reducing the surplus pressures in water network and also maximization of the generated electricity with turbines at the same time have been the objectives of their study.

Pecci et al. (2015) surveyed a mathematical programming method to find the optimal place of PRVs and their operation control in order to reduce excess pressure in WDS under multiple demand scenarios.

In all of the previously mentioned literature, the demand profile should be known to decide on the status of pumps and valves settings for pressure management and leakage control. Due to the influence of ambient temperature, date, resident's culture and other parameters on the instantaneous water consumption, using a fixed daily or seasonal demand profile may not correspond to the reality for many times. In this paper, a feedback control leakage management method will be presented in order to minimize the background leakage and energy consumption in WDSs with controlling the outlet pressure of PRVs and speed of VSP, individually or together.

In this method, the amount of instantaneous demand is estimated by an optimization code, which was based on the transmitted data from the installed sensors on the WDS. To analyze the effect of the control device (PRV/VSP) on leakage and energy reduction in a case study, the method has been run three times: 1) control with PRVs, 2) control with VSPs and 3) control with PRVs and VSPs simultaneously

Methodology

In this study, the measured pressure of one or more points of the WDS 'where the pressure gauges have been installed there' has been applied as an input for a demand estimator code to find the instantaneous demand multiplier. The estimated instantaneous multiplier is then used as an input parameter of another optimization procedure to reduce the excess nodal pressure in the WDS in order to reduce the background leakage and energy consumption. For this purpose, the optimization code should find the optimal set points of installed PRVs and optimal speed of VSPs respectively. Figure 1 shows the flow diagram of this methodology.

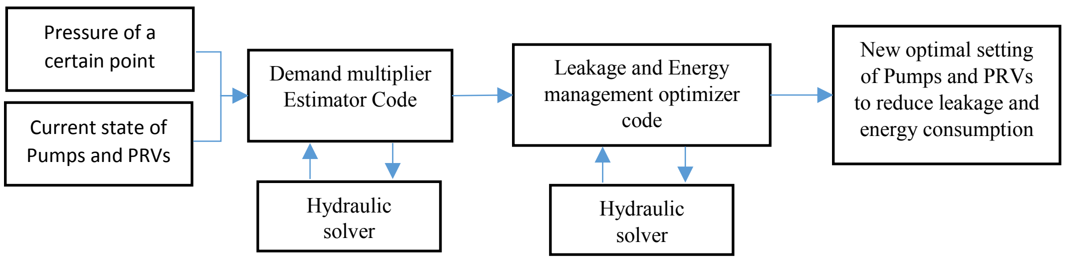

Figure 1. Flow diagram of the optimization process.

In the above method, the following assumptions have been considered:

1- The hydraulic model is calibrated.
2- The pressure sensor error is ignored.
3- The demand pattern of all consumption nodes is the same.

In the first part of this study, to estimate the instantaneous demand multiplier, an optimization code was developed using differential evolution (DE) algorithm in MATLAB software based on the provided algorithm by Storn and Price (1997). The Epanet 2.0 hydraulic solver (Rossman, 2000) used as the hydraulic solver and linked to the optimization code. The nodal pressure of one or more points of WDS (according to the complexity of the network) via the current settings of PRVs and VSPs are used as the inputs of the optimization code. The demand multiplier has been considered as the design variable in optimization procedure. Also, minimizing the difference between measured and calculated nodal pressure 'in nodes where the pressure sensors installed' considered as the objective function. The code can find the actual demand multiplier with minimum error due to transferred data from WDSs.

In the next part, another optimization code has been presented using DE algorithm in order to find the optimal set point of installed PRVs (outlet pressure) and VSPs (pump's speed). The purpose of this section is the pressure management of the WDS to reduce the background leaks and energy consumption. In the presented code, the estimated demand multiplier is used as the model input, the outlet pressure of PRVs and/or speed of VSPs are the design variables and minimizing the mathematical sum of the total nodal leakage and energy consumption (in the same order of magnitude) is the objective function.

Due to the inverse relationship between water consumption and network pressure, the pressure on WDSs in the non-maximum peak hours is more than minimum acceptable pressure and more surplus pressure increases the leakage in WDS. The relation between leakage and pressure has been often described by equation 1. (Thornton and Lambert, 2005).

$$L_i = k_i \times {P_i}^n \qquad (1)$$

Where L_i is leakage flow in node i, k_i is constant leakage coefficient of node i which depends on the length and number of the connected pipes to the node, P_i is the nodal pressure of node i and n is a fixed parameter between 0.5 and 2.5 which depends on the type of leak.

Case study

A real WDS has been selected to apply the above methodology in order to reduce the water leakage and energy consumption. Mehr water distribution system (MWDS) is located in the north of Iran in the Rasht city and serves up to 44,000 people. The covered area by this network is 144 acres and its daily average demand is 366 m^3 per hour. The altitude difference of MWDS is about 4 meters and it has 371 pipes with the length of 33 kilometers, 366 junctions, one reservoir, 2 PRVs and a pump station with 3 pumps. This network was made up of 8 commercially available pipes size (90 to 500 mm). Because of the existence of a household water tank and a pumping system in the apartments of that area, the minimum acceptable pressure of all nodes was considered as 20 meters. The pipe configuration and elevation of MWDS have been shown in figure 2.

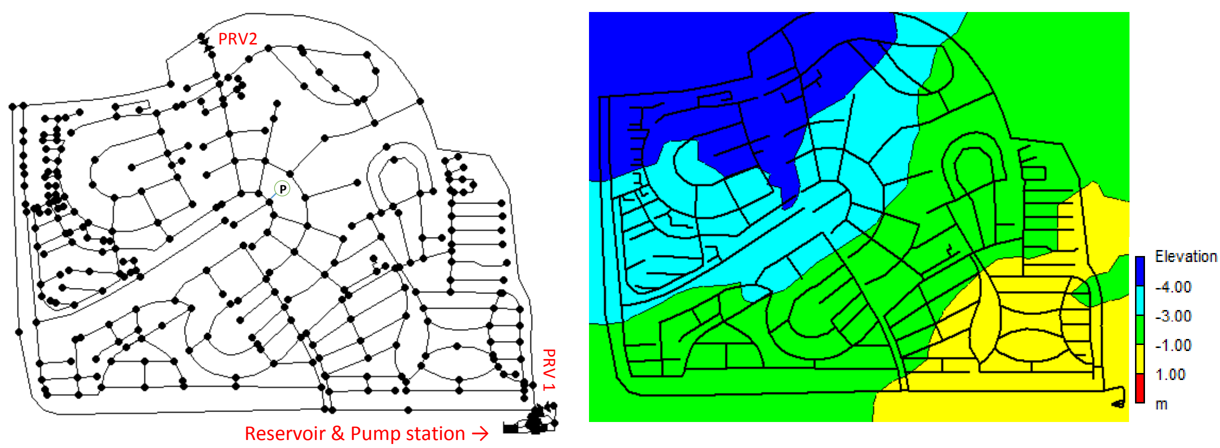

Figure 2. Pipe configuration (left) and ground elevation (right) of MWDS

According to the demand profile of MWDS (Figure 4), in the absence of control equipment such as PRVs or VSPs, the minimum and maximum of nodal pressure in maximum demand time (21:00) are 23 and 49 meters respectively and the minimum and maximum pressure in the minimum demand time (3:00)are 45 and 55meters respectively. According to the equation 1, the calculated leakage in maximum and minimum peak time is 83. 36 m^3/h (22.77% of average hourly demand) and 115.41 m^3/h (31.53% of average hourly demand). Also, the consumed power in pump station at peak and non-peak time are 135.16 kW and 158.82 kW respectively. The purpose of this case study is minimizing the background leakage and electrical energy consumption of the MWDS at all hours of the day, by using the transferred data from the installed pressure sensor in the network.

To validate the demand multiplier estimator code, more than 100 random multipliers have been generated in the range of 0.4 to 1.4. The hydraulic model runs to analyze the nodal pressure of

network after applying each generated multiplier. The calculated pressure in the middle point of the city (the point where the pressure gage has been installed) used as the input parameter of estimator code instead of the transferred data from installed pressure gage. Comparing the input and estimated demand multiplier show an acceptable accuracy. Selecting the initial population of 10 and generation number 40 for estimation procedure lead to the accuracy of 99.9% within 6 seconds for each multiplier in a PC with 8GB of RAM and Intel i7 2.4GHz CPU. This result guarantees that the amount of consumption for any given moment will be presented correctly to the pressure management optimization code. For pressure management of the MWDS, three different states were implemented as follows:
State 1- Finding the optimal set points of PRVs (outlet pressures) individually.
State 2- Finding the optimal set points of VSPs (fraction of speed in percent) individually.
State 3- Finding the optimal set points of PRVs and VSPs together.

In state 1, set points of two installed PRVs have been used as design variables. In state 2, regardless of the PRVs, set points of three VSPs have been used as design variables and in state 3 the set point of PRVs and VSPs have been used as design variables together. In all of the above states, the objective functions of the optimization have minimized the mathematical sum of total nodal leakage and energy consumption on WDS. The initial population and also the generation number of DE optimization procedure considered 100 and 150 respectively. Figure 3 shows the counterplot of optimal pressure distribution for MWDS in different states in demand non-peak time (3:00 AM) alongside the pressure distribution graph of uncontrolled mode.

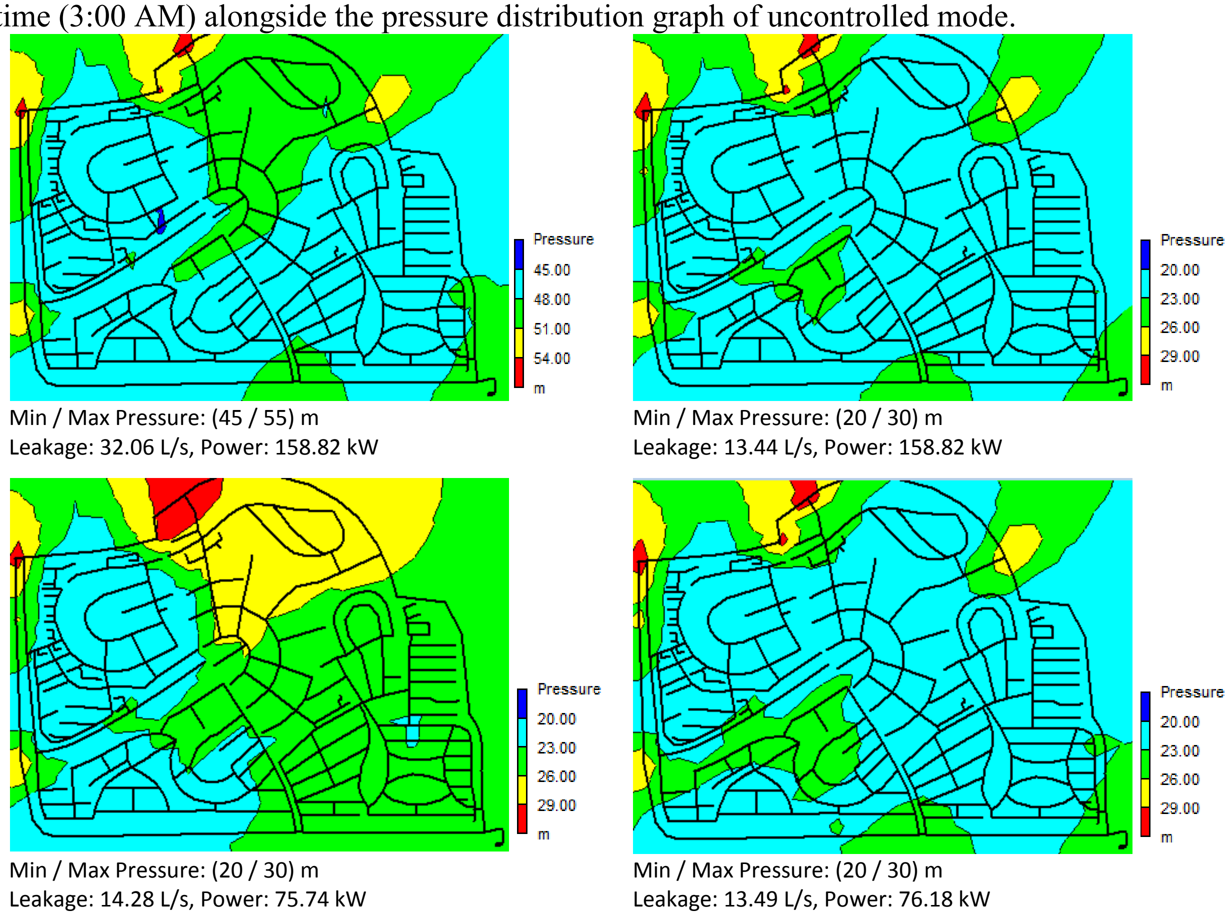

Figure 3. Pressure distribution of MWDS in 3:00 AM (non-peak time), without pressure controlling (up-left) with PRVs controlling (up-right) with VSPs controlling (down-left) with simultaneous PRVs and VSPs controlling (down-right)

Results show that using PRVs to pressure management of the WDS (state 1) can reduce the background leakage significantly but it cannot reduce the pump station electricity consumption. Using VSPs to pressure controlling of the WDS (state 2) shows better results because of the simultaneous reduction of leakage and electricity consumption. Also, using of PRVs and VSPs together in the network pressure controlling (state 3) has the best result.

To investigate the effect of the mentioned method for a full day pressure management, the reported demand multiplier (Figure 4) has been applied to the optimization code. This information may be sent by the SCADA, telemetry system or demand multiplier estimator code to the central control unit. Figure 5 shows the leakage, energy consumption, min/max nodal pressure and PRV/VSP set point in different states versus time.

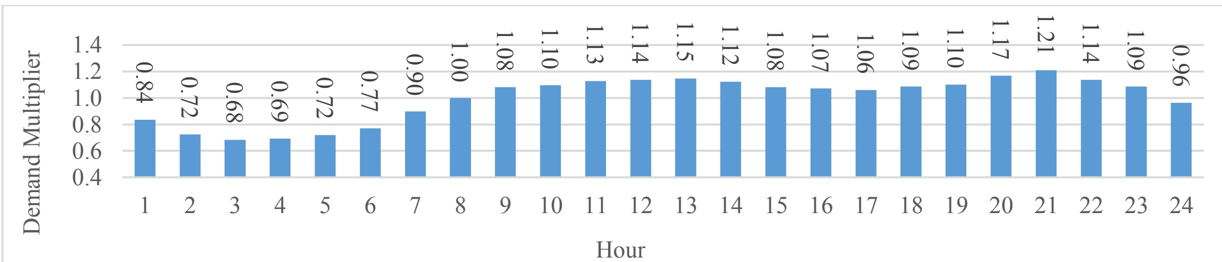

Figure 4. Demand multiplier versus time in MWDS

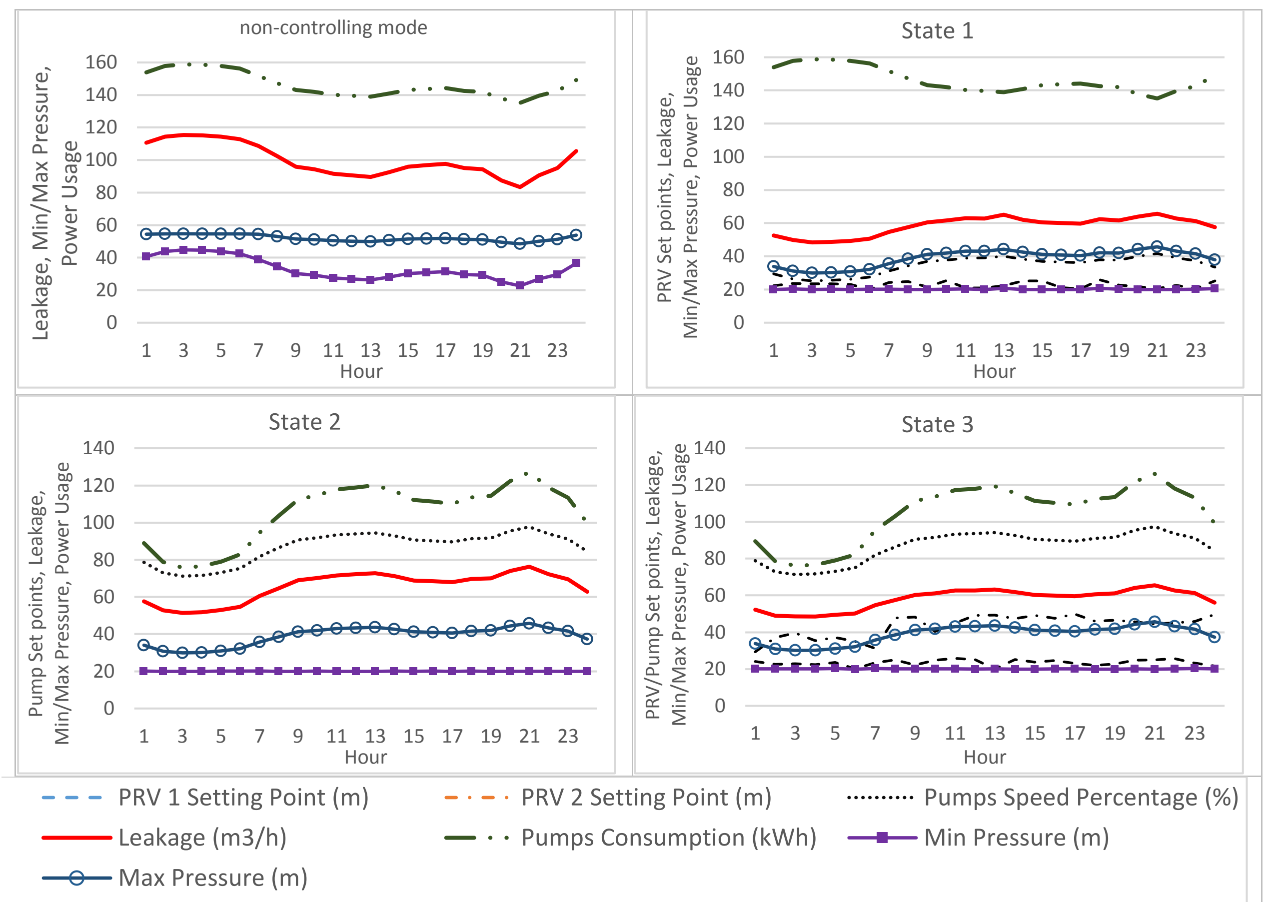

Figure 5. Background leakage, energy consumption, min/max nodal pressure and PRV/VSP set point in different states versus time.

The results shown in figure 5 show that reducing water consumption during the night will increase pressure, leakage and energy consumption in non-controlling mode. In state 1, the best PRV's set point has been shown in different times in order to reduce minimum nodal pressure and remove excess pressure. During the night, the PRVs (Especially PRV2) experienced the lowest output pressure. In this state, the background leakage has a significant reduction but the energy consumed by the pumps was not reduced. In state 2, the VSPs set point (percentage of pump's speed) calculated with optimization code in different time, by applying the mentioned set point on the hydraulic model cause to reduced minimum nodal pressure to the minimum acceptable pressure. As the result, leakage and pump's energy consumption decreased simultaneously. In state 3, the set points of PRVs and VSPs have been shown at different times. Results showed that the background leakage and energy consumption have a greater reduction than the two previous states.

Also, the results show that unlike the uncontrolled state, the nodal pressure and leakage at non-peak times of states 1, 2 and 3 is less than the nodal pressure and leakage in peak times. The reason for this phenomenon is the reduction of network surplus pressure during non-peak hours by PRVs and VSPs, which reduces the pressure and background leakage in WDS. It should be noted that the reduction of surplus pressure does not increase the quality of service to customers.

Therefore, the simultaneous use of the PRVs and VSPs for pressure management of WDS will bring the best results to reduce the background leakage and energy consumption. In this state, the calculated leakage in maximum and minimum demand peak time are 65.51 m3/h (17.9% of average hourly demand) and 48.56 m3/h (13.27% of average hourly demand). Also, the consumed power in pump station in maximum and minimum demand peak time are 126.09 kW and 76.18 kW respectively. These values are significantly better than uncontrolled state. The summarized results of a full day have been shown in Table 1.

Table 1. Leakage and Energy consumption reduction in a full day for MWDS with different states

	Total leakage (M^3/Day)	Leak Reduction (%)	Energy consumption (Kwh)	Energy cons. Reduction (%)
Without Pressure Man.	2390	-	3507	-
State 1	1403	41/30	3506	0/03
State 2	1573	34/18	2524	28/03
State 3	1393	41/72	2511	28/40

Conclusion

In this study, a momentary demand multiplier estimator code presented to guesstimate the water demand according to the reported nodal pressure from the installed pressure meter in the WDS. The estimated demand multiplier used as input parameter to another optimization code in order to pressure management of WDS. The presented code has been written with DE optimization algorithm and it can find optimal set points of installed PRVs and VSPs in WDS. Reducing the background leakage and pump's energy consumption is the objective function of the optimization code. The methodology applied on a real WDS in the north of Iran. The results showed that using PRVs and VSPs simultaneously can improve pressure management process and it can show the highest reduction in leakage and energy consumption versus the single use of one of this equipment. In the case study, controlling the PRVs and VSPs by the provided optimization code causes the reduction of background leakage and power consumption by 41.72% and 28.4%, respectively, compared to uncontrolled mode.

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