Water saving evaluation applying a pressure management strategy

V. J. García*, E. Cabrera, E. Cabrera, Jr.*****

* Universidad Politécnica de Valencia
P.O. Box 22012 - 46071 Valencia
e-mail: vigarcar@ita.upv.es

** Universidad Politécnica de Valencia
P.O. Box 22012 - 46071 Valencia
e-mail: ecabrera@ita.upv.es

*** Universidad Politécnica de Valencia
P.O. Box 22012 - 46071 Valencia
e-mail: qcabrera@ita.upv.es

Keywords: Water saving, pressure reducing valves, network modelling

Introduction

Water distribution systems are often sectorized in order to enhance management efficiency. Sectorization implies to divide the network into several compartments (or sectors) of smaller size, which enable system operator to obtain a better knowledge of leaks and incidents, a better resources evaluation and a better pressure control.

When sectors are equipped with flowmeters, the sectors are called *District Metered Areas* (*DMA*s), and water entering or leaving the sector can be measured. Continuous or intermittent night flow measurements are habitually carried out, as a way to identify the sectors where the leakage levels are higher. This methodology can be considered as a part of an Active Leakage Control policy, which tries to reduce the time that detectable but unreported leaks are active, and nowadays its use has generalized (Brothers, 2005; MacDonald and Yates, 2005; Sturm and Thornton, 2005).

In a previous paper (García *et al.*, 2006) a revision of night flow methodology has been made. The procedures used to calculate the daily leakage rate from the leakage rate at the hour of minimum night flow have been analyzed, and the influence of the most relevant parameters that affect the method's accuracy has been explored by means of a sensitivity analysis.

Pressure management is another policy that can be implemented when a network is sectorized. It is a complementary method for an effective leakage management (Lambert *et al.*, 1998), and because of the relationship between pressure and leakage flow rates, pressure control has revealed as one of the most cost effective methods (Farley and Trow, 2003). Pressure Reduction Valves (PRVs) are customarily used to reduce excessive pressures at some hours of the day, as well as maintaining a minimum pressure at every node of the network.

In order to ascertain the economical viability of any pressure control program, it is necessary to evaluate previously the leakage reduction that this program will obtain. Because a mathematical model of the network is not always available, a simplified method has been proposed, and a computational program called PRESMAC has been implemented (McKenzie, 2001). This method consists basically of two steps. The first step calculates the leakage level when no PRV is present, based on the night flow methodology. Next, water losses are evaluated for the case in which a PRV is introduced, by means of an iterative process that uses the aforementioned leakage-pressure equation and a lumped head losses equation between the inlet and two representative points. The difference between water losses when no PRV is present, and water losses when a PRV is introduced, will represent the saving that a pressure management program can achieve.

The aim of this paper is to make a similar analysis to that corresponding to night flow methodology, for the simplified calculations when a PRV is introduced. An example network has been used in this paper to make all the calculations. The results obtained by the simplified method have been compared to those obtained by a mathematical model of the network that was implemented in Epanet 2.0 (Rossman, 2000).

Previous work

During night hours, leakage Q_L can represent a significant proportion of the total flow rate injected to the sector, and it can be estimated by means of a water balance, as the difference between the flow rate injected to the sector Q_{DMA} and the customer night use Q_U. Night flow methodology begins with a water balance at the minimum night flow (MNF) hour t_{MNF}:

$$Q_L\left(t_{MNF}\right) = Q_{DMA}\left(t_{MNF}\right) - Q_U\left(t_{MNF}\right) \tag{1}$$

In order to obtain the daily leakage level of the district, the hourly leakage rates for the rest of the day (23 hours) can be determined by using a simplified equation (May, 1994) that expresses the relation between leakage and pressure:

$$Q_L(t) = Q_L\left(t_{MNF}\right) \times \left(\frac{P_{AZP}\left(t\right)}{P_{AZP}\left(t_{MNF}\right)}\right)^{N_1} \tag{2}$$

where:

$Q_L(t)$: leakage rate at the hour t; $t \neq t_{MNF}$;

t_{MNF}: MNF hour;

$Q_L(t_{MNF})$: leakage rate at the MNF hour;

$P_{AZP}(t)$: average hourly *AZP* pressure at the hour t; $t \neq t_{MNF}$;

$P_{AZP}(t_{MNF})$: average hourly *AZP* pressure at the MNF hour;

N_1: power exponent (a lumped value for all losses of the district).

The point called AZP (Average Zone Point) represents the weighted average pressure for the whole district (McKenzie *et al.*, 2002), and it can be considered as a characteristic point of the network that allows to extrapolate water losses along the day. Because leakage flow rates vary with hourly node pressures, the accuracy of equation (2) will depend on the ability of node AZP to represent the pressure distribution of the whole network.

Assuming that the calculation of water losses at MNF hour is correct, and that pressure at AZP is known at every hour of the day, the relative error ε of daily leakage volume resulting from the use of the simplified method is:

$$\varepsilon = \frac{V_{L,NFM} - V_{L,EPA}}{V_{L,EPA}} = \frac{\left[\sum_{j=1}^{N} C_j \times P_j^{N_1}\left(t_{MNF}\right)\right] \times \left[\sum_{t=1}^{24} P_{AZP}^{N_1}(t)\right]}{\left[\sum_{t=1}^{24}\sum_{j=1}^{N} C_j \times P_j^{N_1}(t)\right] \times P_{AZP}^{N_1}\left(t_{MNF}\right)} - 1 \tag{3}$$

where:

$V_{L,NFM}$: daily leakage volume obtained by night flow methodology;

$V_{L,EPA}$: daily leakage volume obtained by Epanet;

C_j: discharge coefficient for node j;

$P_j(t)$: average hourly pressure at node j at the hour t;

N: number of nodes of the network.

The most significant parameters that affect the leakage volume deviation were analyzed, and the results are summarized herein. A basic network was used to make all the calculations (Figure 1).

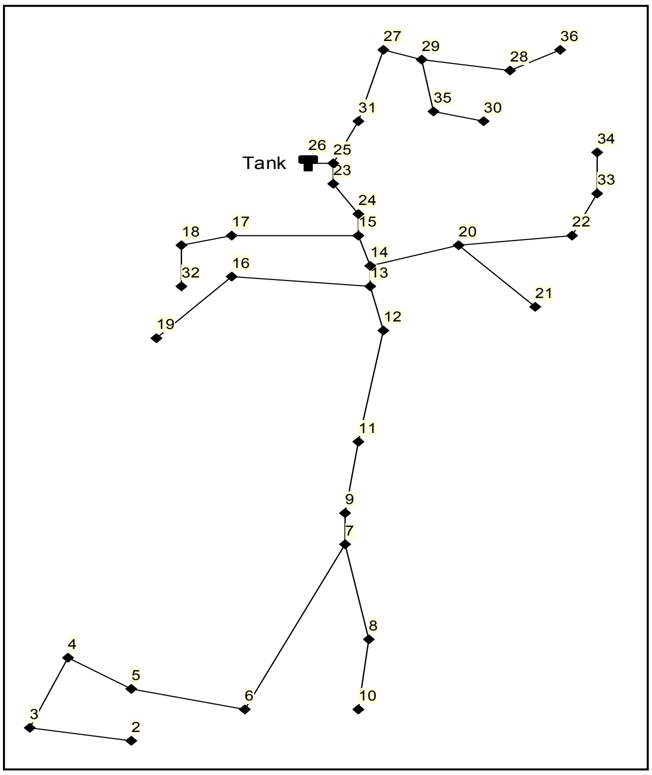

Figure 1. Example network

Firstly, the influence of the reference hour when the water balance is made was analyzed, by substituting t_{MNF} for any other hour of the day. It was shown that the minimum error does not correspond to the MNF hour, but to the hour in which the average demand applies (Figure 2).

In the absence of a mathematical model, pressures at every node of the network are not known and hence, the determination of node AZP is not always quite accurate. Sometimes a surrogate AZP is determined by calculating the weighted average ground level of the district, instead of the weighted average pressure. When using every node of the network as node AZP, the minimum error corresponds to the node where the hourly pressures are closest to the weighted average pressures (Figure 3). As far as hourly node pressures differ from weighted average pressures, the error grows exponentially. Therefore, an accurate calculation of node AZP is an important matter.

The leakage error variation with node AZP can also be represented versus the pressure error. The simplified methodology is implicitly assigning the following network pressure distribution along the day:

$$P_j^*(t) = P_j\left(t_{MNF}\right) \times \frac{P_{AZP}\left(t\right)}{P_{AZP}\left(t_{MNF}\right)} \tag{4}$$

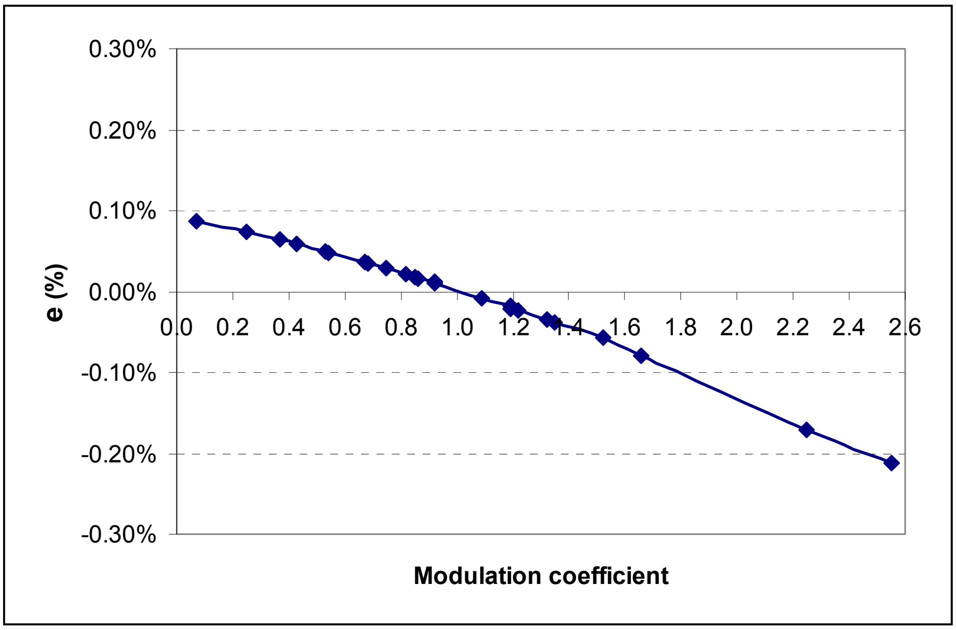

Figure 2. Correlation between the relative error and the modulation coefficient

where $P_j^*(t)$ is the estimated pressure at node *j* at the hour *t*. A parameter related to the pressure error can be defined as:

$$\Delta_C = \sum_{t=1}^{24} \sum_{j} C_j \times \left(P_j(t) - P_j^*(t) \right) \tag{5}$$

The ε variation versus Δ_C is represented in Figure 4, where a linear correlation between both variables is observed.

The last parameter analyzed was power exponent N_1. Although it can range from 0.5 to 2.5, the most common values (0.5 to 1.5) were considered. A linear relationship between the relative error and N_1 is observed (Figure 5), and the minimum error corresponds to N_1 = 1.0.

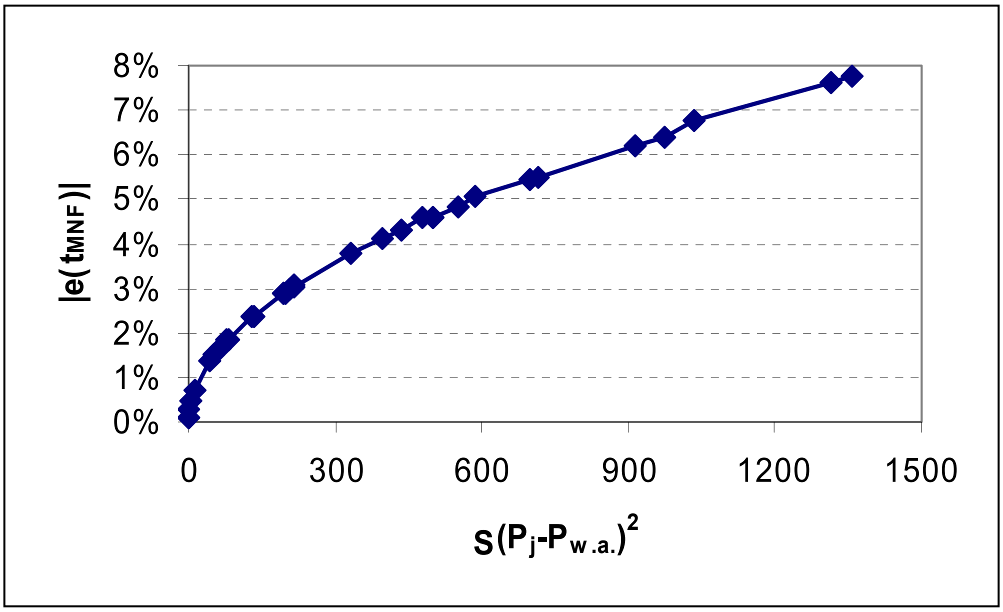

Figure 3. Correlation between the relative error and pressure deviation

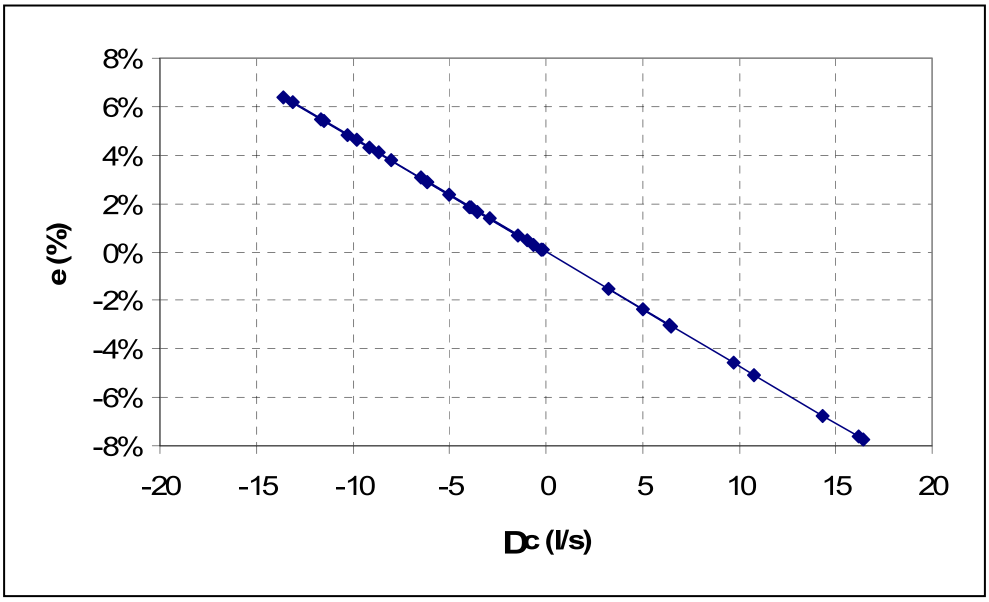

Figure 4. Correlation between the relative error and Δ_C

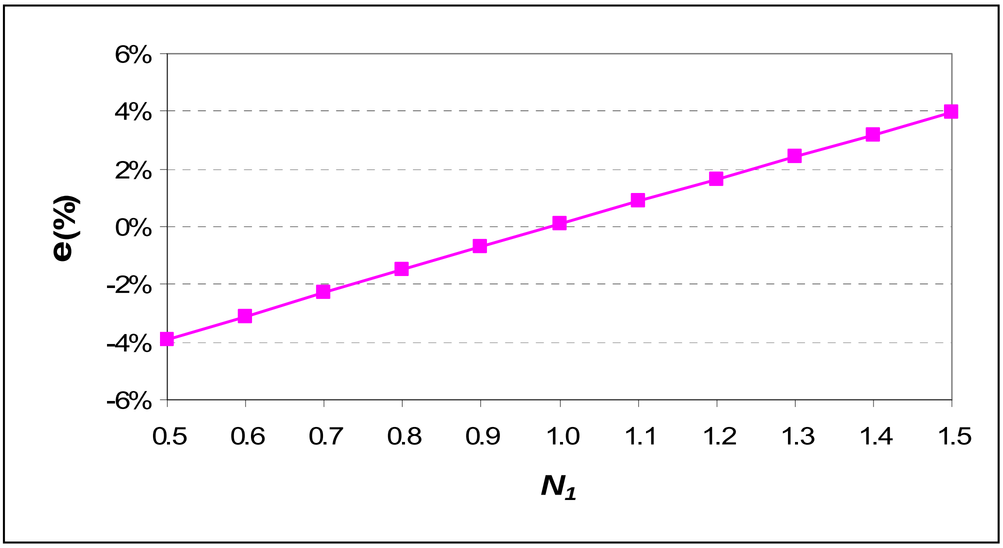

Figure 5. Correlation between the relative error and N_1

Simplified calculations with a PRV

Once water losses have been calculated for the initial network, they have to be evaluated for the case in which a PRV is introduced. The simplified method proposed by (McKenzie, 2001) uses the same AZP point as representative of pressure distribution along the whole network. The new hourly leakage rates can be determined by using the equation that relates leakage and pressure:

$$Q_{L,PRV}(t) = Q_L(t) \times \left(\frac{P_{AZP,PRV}(t)}{P_{AZP}(t)} \right)^{N_1} \tag{6}$$

where subindex PRV denotes the situation when a PRV is introduced.

The problem that arises is that the new hourly pressures at AZP are not known. A pressure drop at the inlet point will produce a pressure drop at AZP of a lesser amount. Moreover, when introducing a PRV, it is necessary to assure that the hourly pressures at the critical point of the network are above a minimum value.

In order to calculate the new pressures at AZP and the critical point, an iterative process is proposed. Besides the ground level at the inlet, AZP and critical points (z_i, z_{AZP} and z_c, respectively), it needs the following information, corresponding to the situation when no PRV is present:

- Hourly flow rate injected to the sector, $Q(t)$, t = 1, …, 24.
- Hourly pressures at the inlet point, $P_i(t)$, t = 1, …, 24.
- Hourly pressures at AZP, $P_{AZP}(t)$, t = 1, …, 24.
- Hourly pressures at the critical point, $P_C(t)$, t = 1, …, 24.

The head loss between the inlet point and both the AZP and critical points can be represented by means of simplified head loss equations that use lumped friction factors:

$$H_{L,AZP}(t) = K_{AZP}(t) \times Q(t)^2 \tag{7}$$

$$H_{L,C}(t) = K_C(t) \times Q(t)^2 \tag{8}$$

where:

$H_{L,AZP}(t)$, $H_{L,C}(t)$: head loss between the inlet point and AZP and critical points, respectively, for the hour t, t = 1, …, 24;

$K_{AZP}(t)$, $K_C(t)$: lumped friction factor for the path between the inlet point and AZP and critical points, respectively, for the hour t, t = 1, …, 24.

It is assumed that for each hour, the lumped friction factors will remain the same when the PRV is added, and so they are determined for the situation with no PRV.

The iterative process begins by assuming that the pressure drop at AZP will be equal to that corresponding to the inlet point. With this estimation of hourly pressures at AZP, the new hourly leakage rates are calculated by using equation (6). In the initial situation, the hourly flow rate $Q(t)$ can be split into the leakage rate $Q_L(t)$ and a pressure-independent component (typically consumption), $Q_{PI}(t)$, that will remain the same with the PRV. Therefore, the new hourly flow rate $Q_{PRV}(t)$ can be determined as:

$$Q_{PRV}\left(t\right) = Q_{L,PRV}\left(t\right) + Q_{PI}\left(t\right) \tag{9}$$

It is then possible to calculate the head loss between the inlet and AZP points by using equation (7), and compare it with the initial estimation. If there is a significant discrepancy, a new iteration can be made, by using the calculated AZP pressure. A summary of this iterative process is shown in Figure 6.

When the iterative process is completed, pressure at the critical point can be calculated from head loss between inlet and critical points, by using equation (8). If the resulting pressure at the critical point is below the minimum pressure requirement, the inlet pressure should be increased.

At this point we have to make an important remark. In this simplified method it is assumed that friction factors K_{AZP} and K_C vary from hour to hour, but remain the same when a PRV is introduced. They are conceptualised as the traffic flow patterns of a town, which tend to be similar from day to day, but may vary considerably from hour to hour. Although this assumption seems quite reasonable, the point is that friction factors also depend on the flow rate injected to the sector, which varies when the PRV is added. From an analytical point of view, the head loss between the inlet and AZP points can be evaluated as:

$$H_{L,AZP}(t) = \sum_{i \in T_{AZP}} 0{,}0826 \times f_i(t) \times \frac{L_i}{D_i^5} \times q_i^2(t) \tag{10}$$

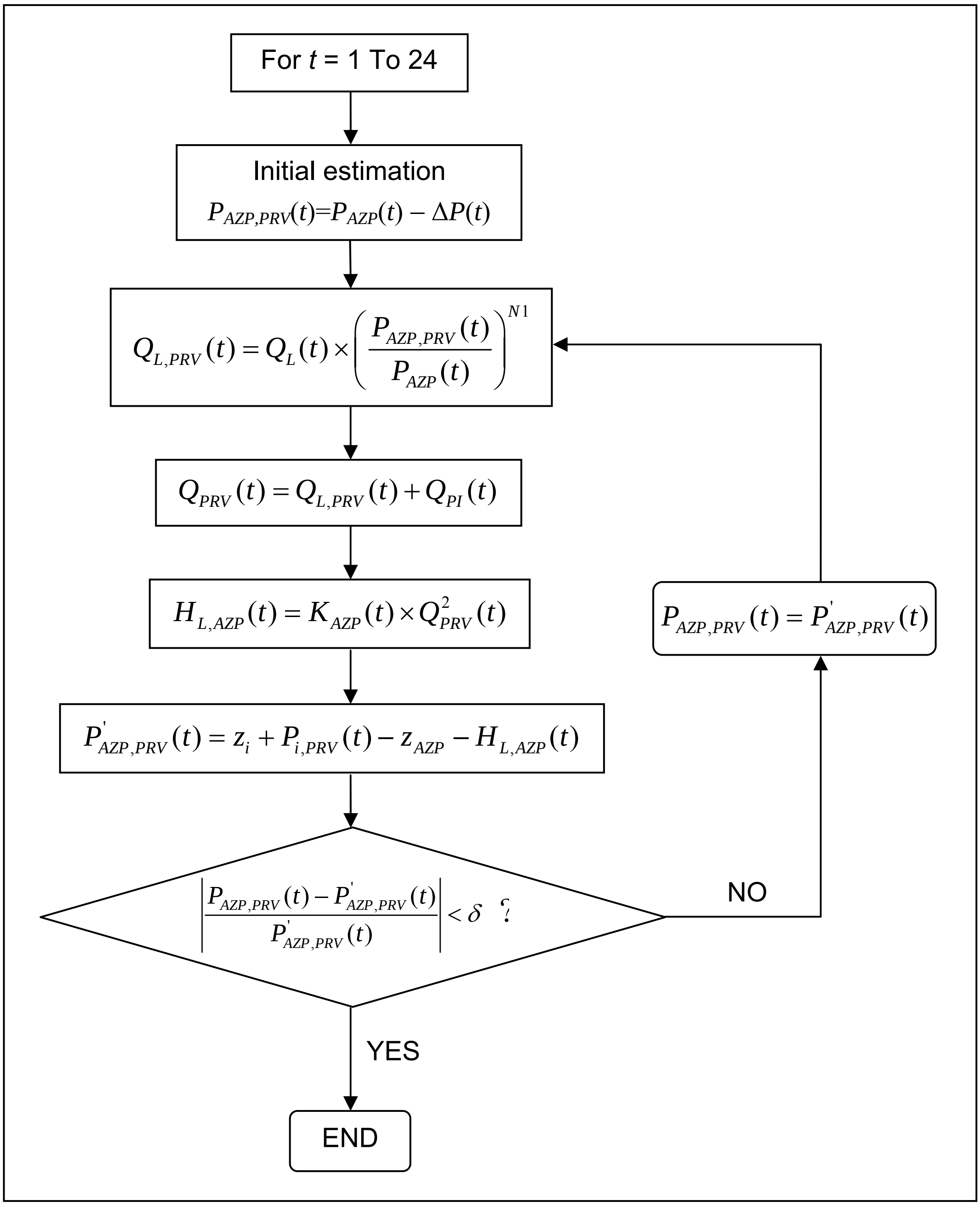

Figure 6. Flowchart of the iterative process

where:

T_{AZP}: path between the inlet and AZP points;

$f_i(t)$: friction factor for the link i at the hour t, t = 1, …, 24 (Darcy-Weisbach equation);

L_i: length of the link i (m);

D_i: diameter of the link i (m);

$q_i(t)$: flow rate for the link i at the hour t, t = 1, …, 24 (m^3/s).

When introducing a PRV all node pressures are reduced, and hence all pressure-dependent flow rates decrease, and all link flow rates will be smaller than those corresponding to the initial situation (no PRV). Friction factors f_i depend on the link relative roughness, which is invariable with the PRV and Reynolds, which is proportional to flow rate. According to the Moody's diagram, as Reynolds (or equivalently, flow rate) decreases, friction factor increases. Therefore, it seems clear that the new friction factors when the PRV is inserted, $K'_{AZP}(t)$, will be greater than the initial ones, $K_{AZP}(t)$.

A way to overcome this problem is to recalculate the friction factors in the iterative process shown in Figure 6. In each iteration, once the flow rate $Q_{PRV}(t)$ has been determined, a new friction factor can be calculated:

$$K'_{AZP}(t) = K_{AZP}(t) \times \frac{f'(t)}{f(t)} \tag{11}$$

where $f(t)$ and $f'(t)$ are the Darcy-Weisbach's friction factors corresponding to the initial and the new situation, respectively. In order to calculate these friction factors, it can be considered that the inlet and AZP points are connected by means of a single equivalent pipe, whose diameter is the weighted average diameter of all the links that belong to the path between those points. The weighting factors will be the relative lengths of the links.

When the iterative process is finished, a new $K'_c(t)$ can be determined, by using a similar equation to (11), in order to calculate the pressure at the critical point.

Sensitivity analysis

The simplified method described in the preceding section has been evaluated by using the same network shown in Figure 1. A similar analysis to that of the previous work has been carried out, and the results are included herein. In all cases the pressure at the inlet point equals to the pressure at the outlet of the PRV, and is constant along the day, although different values have been considered. In the following Figures, the graph called "original" refers to the calculations that have been made by the original method proposed by (McKenzie, 2001), whereas the graph called "modified" corresponds to the calculations where the friction factor $K_{AZP}(t)$ is re-calculated in the iterative process, as has been earlier described.

Reference network

In the reference network, some "ideal" assumptions are made:

- Node 11 is considered as AZP, because this is the node where the pressures are closest to the weighted average values of the network pressures.
- N_1 = 1.0 (power exponent).
- All demands are residential, and present the same hourly modulation coefficients (Figure 7).

The results for the reference network are represented in Figure 8. As can be seen, the errors of the calculations when a PRV is introduced are moderate, growing as the pressure at the inlet point decreases (or equivalently, as the pressure drop at the PRV increases). Besides, the errors of the modified method are around half of those corresponding to the original method.

When considering the first and second steps altogether (extrapolation of water losses at the minimum night hour followed by the evaluation of daily water losses with a PRV), it is observed that the errors are partially counterbalanced. The results are shown in Tables 1 and 2.

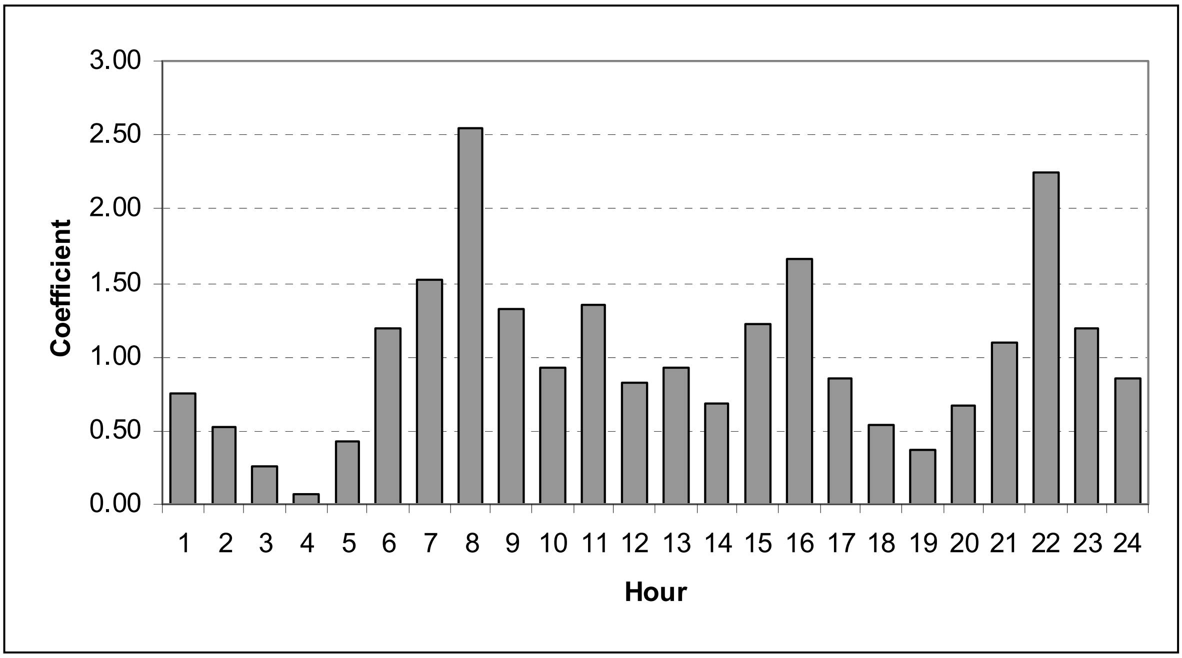

Figure 7. Modulation curve for all demands

Table 1. Absolute error (m^3/day) of daily leakage volume (original method)

Process	$P_{i,PRV}$ (m)					
	45	43	41	39	37	35
First step	0,67	0,67	0,67	0,67	0,67	0,67
Second step	0,82	0,87	0,92	0,97	1,02	1,06
Global	1,23	1,26	1,29	1,32	1,35	1,38

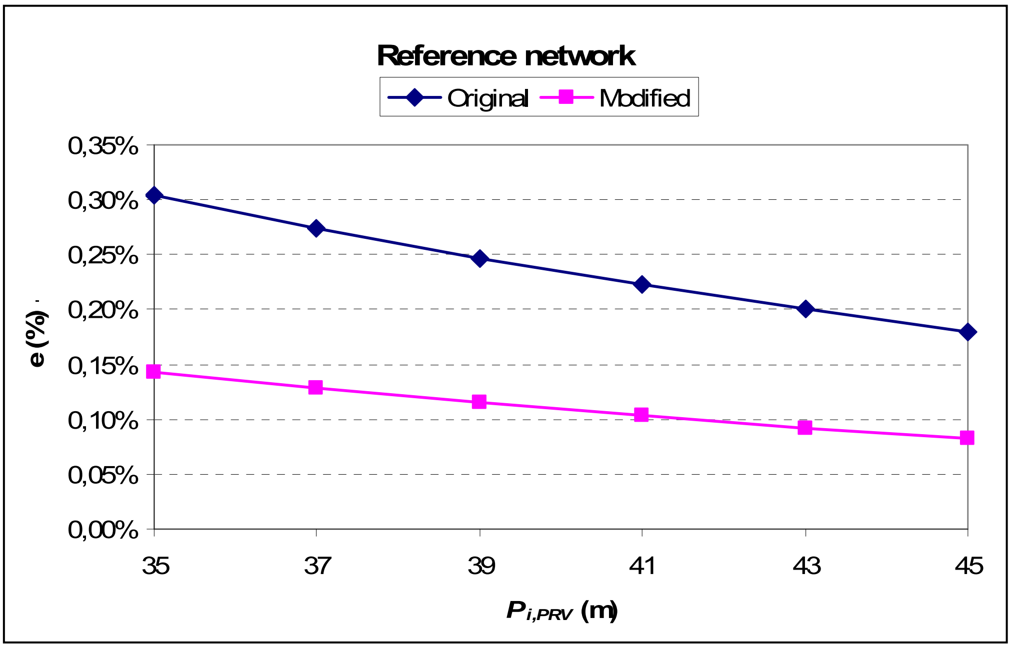

Figure 8. Relative error of daily leakage volume

Table 2. Absolute error (m^3/day) of daily leakage volume (modified method)

Process	$P_{i,PRV}$ (m)					
	45	43	41	39	37	35
First step	0,67	0,67	0,67	0,67	0,67	0,67
Second step	0,38	0,40	0,43	0,45	0,48	0,50
Global	0,78	0,79	0,79	0,80	0,81	0,81

Node selected as AZP

All nodes of the network have been considered as node AZP. The deviation between the hourly pressures and the weighted average pressures has been used as the independent variable to represent the results, which are shown in Figures 9 and 10.

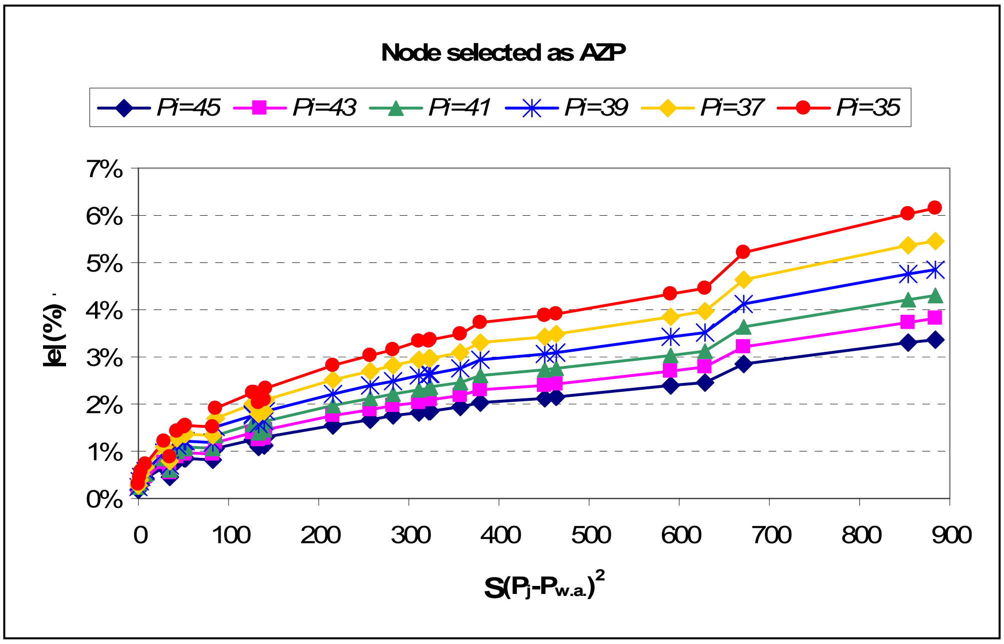

Figure 9. Relative error of daily leakage volume (original method)

A similar trend is observed for both the original and modified method. The error grows as the pressure deviation increases and also as the pressure drop at the PRV increases. Nevertheless, for the smaller values of pressure deviation, the errors of the modified method are lower than those of the original method. It is noteworthy to indicate that water losses calculated by the modified method are always lower than those calculated by the original method, because friction factors are greater and hence pressures are lower.

It is also observed that the errors of the first step are partially counterbalanced by those of the second step, even in those cases when the error is negative. For instance, the results corresponding to node 9 are indicated in Tables 3 and 4.

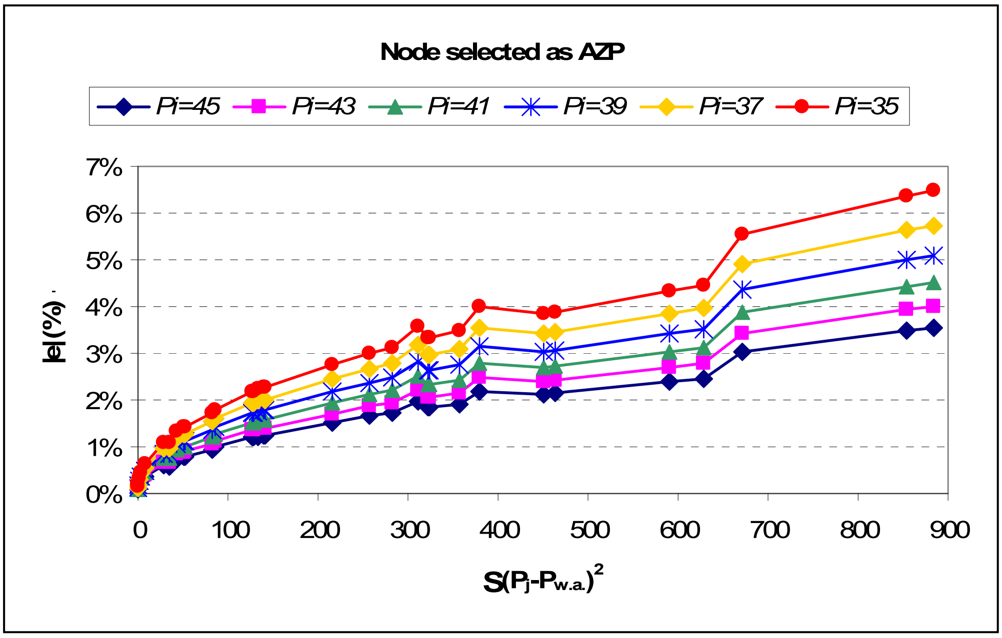

Figure 10. Relative error of daily leakage volume (modified method)

Table 3. Absolute error (m^3/day) of daily leakage volume (original method). Node 9

Process	$P_{i,PRV}$ (m)					
	45	43	41	39	37	35
First step	-11,60	-11,60	-11,60	-11,60	-11,60	-11,60
Second step	-2,15	-2,33	-2,51	-2,70	-2,88	-3,08
Global	-8,44	-8,29	-8,14	-7,99	-7,84	-7,70

Table 4. Absolute error (m^3/day) of daily leakage volume (modified method). Node 9

Process	$P_{i,PRV}$ (m)					
	45	43	41	39	37	35
First step	-11,60	-11,60	-11,60	-11,60	-11,60	-11,60
Second step	-2,70	-2,91	-3,12	-3,34	-3,55	-3,77
Global	-8,99	-8,87	-8,75	-8,63	-8,51	-8,39

Exponent N_1

The results for N_1 variation (between 0,5 and 1,5) are shown in Figures 11 and 12. In both cases the error grows as the pressure drop at the PRV increases. But whereas in the original method there is also an increment as N_1 grows, in the modified method the error decreases as N_1 increases. A discontinuity is observed around N_1 = 1,0 in the modified method, because at this point the curve that relates leakage and pressure (equation 2) changes its slope.

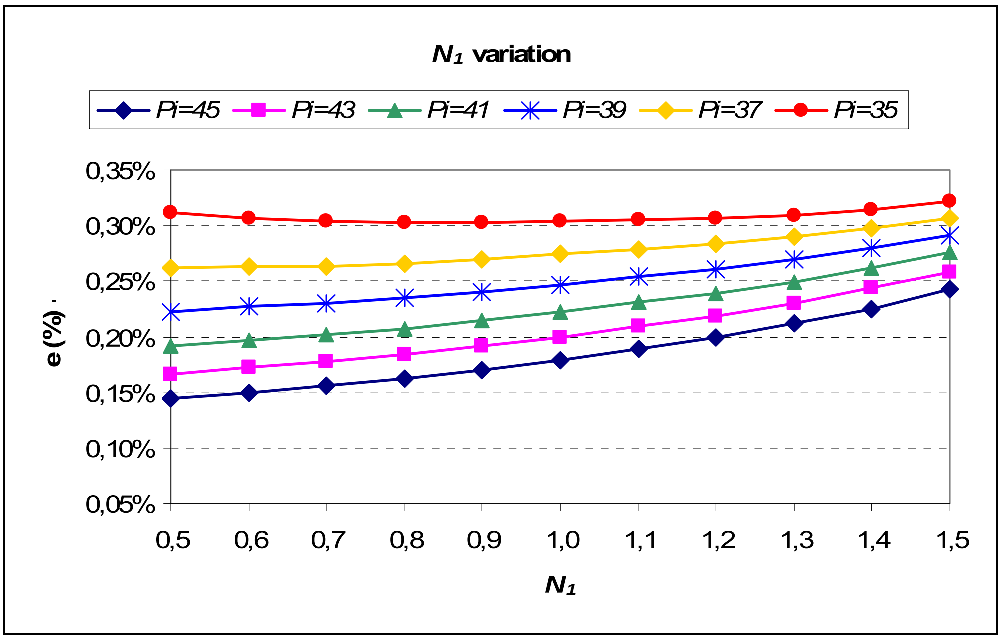

Figure 11. Relative error of daily leakage volume (original method)

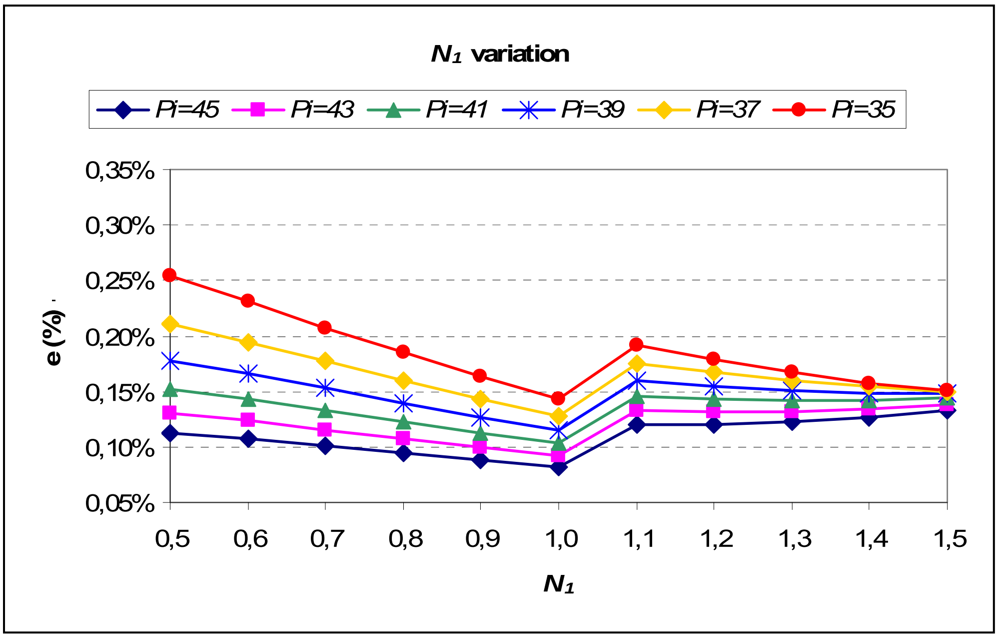

Figure 12. Relative error of daily leakage volume (modified method)

As in the previous cases analyzed, the errors of the first step are partially counterbalanced by those of the second step, and so the global error is lower than the sum of the individual errors.

Demand pattern

Several demand time variations have been considered (Figure 13), and the results are shown in Figures 14 and 15, in which the modulation coefficient at t_{MNF} has been used as the independent variable. In these cases pressures at the outlet of the PRV have adopted different values from previous cases (between 60 and 70 m), in order to avoid negative node pressures.

As can be observed, the error is not very sensitive to the demand pattern, although it grows as the drop at the PRV increases. A similar trend is appreciated for both the original and modified method, but the errors of the modified method are lower than those of the

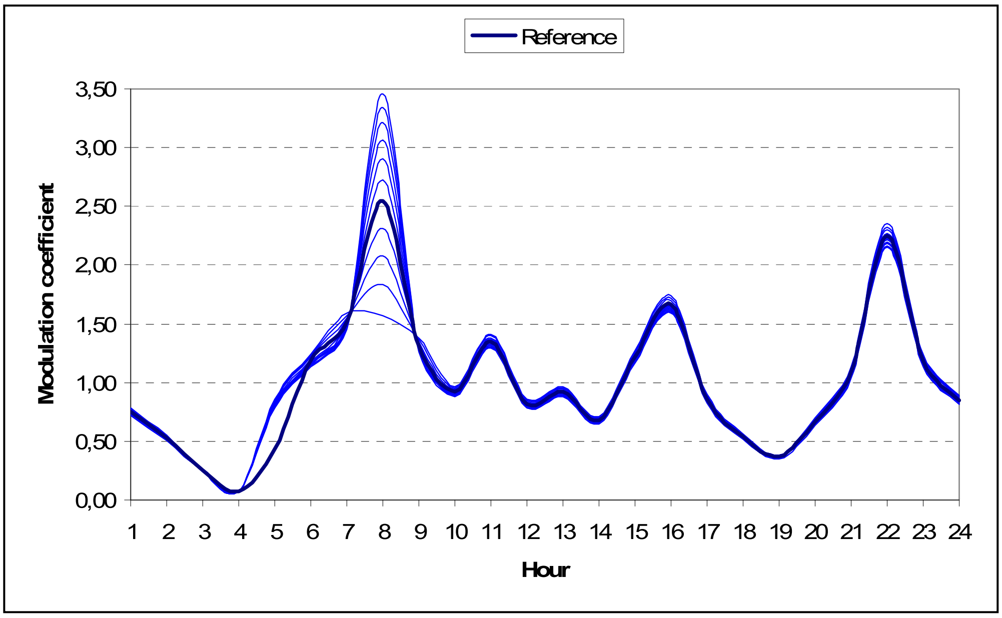

Figure 13. Demand patterns

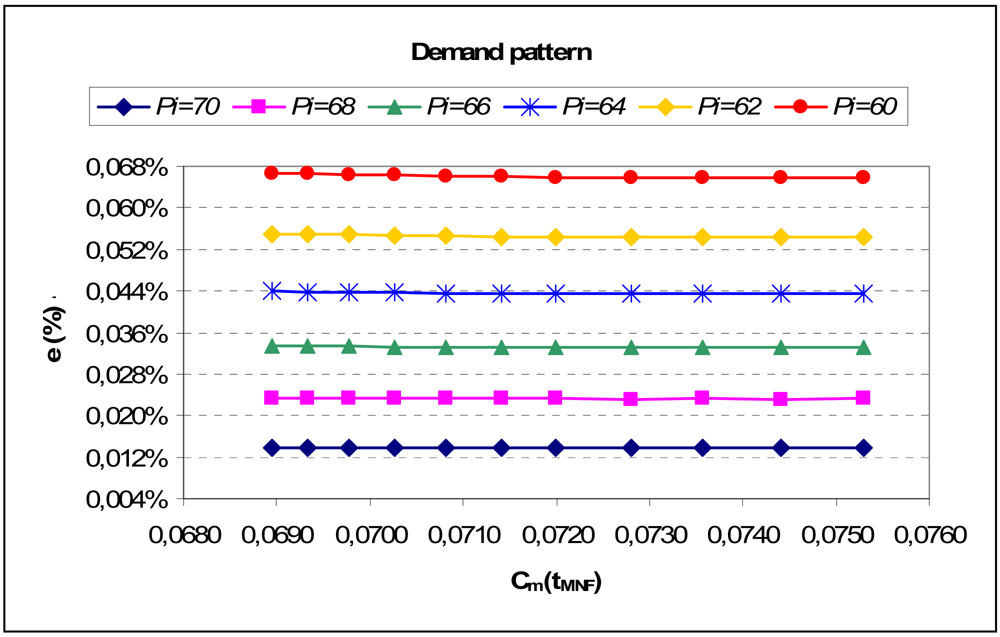

Figure 14. Relative error of daily leakage volume (original method)

original method. It is also confirmed that the global error is lower than the sum of the errors of the first and second steps.

Conclusions

Pressure management is one of the key strategies that can be implemented in order to reduce leakage, and its use has spread worldwide in the last years. A simplified method has been proposed in order to evaluate the water saving that can be achieved when a PRV is introduced in a sector. It consists of two steps, and only requires little information about the network, so it can be very convenient when a mathematical model is not available.

In this paper the procedure and the errors associated with the second step have been analyzed. It has been shown that there is an underestimation of the lumped friction factors, as a consequence of friction factor variation with flow rate. A way to recalculate friction factors has been suggested, and the error of the estimated water loss has been

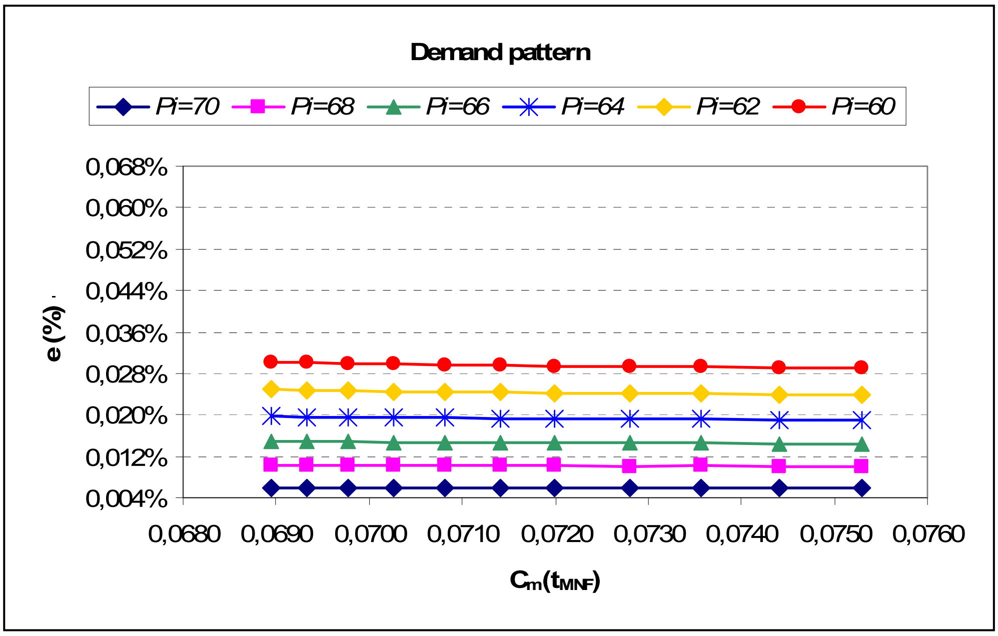

Figure 15. Relative error of daily leakage volume (modified method)

reduced. Nevertheless, both for the original and for the modified method, the resulting errors are quite moderate, so the simplified method can be quite accurate as a straightforward way to evaluate water losses.

Among the parameters that have been analyzed, the node selected as AZP has come out the most relevant parameter. Therefore, determination of node AZP should be made carefully, by measuring pressures in so many nodes as possible.

When analyzing the first and second steps altogether, it has been observed that the errors of the first step are partially counterbalanced by those of the second step. Besides, because the error of the first step is lower than the global error, if the method is used as a way to evaluate the water saving that a PRV can accomplish, the result will be on the conservative side, that is, the real saving will be a little greater than the estimated one.

Future research should be made in order to analyze other parameters and network configurations, as well as anticipating the errors of the simplified method.

References

Brothers, K.J. (2005). “IWA Approach to Water Loss Management”. Proceedings of the Leakage IWA Conference, Halifax, Canada.

Farley, M. and Trow, S. (2003). Losses in Water Distribution Networks. A Practitioner’s Guide to Assessment, Monitoring and Control. IWA Publishing, London, UK.

García, V., Cabrera, E., Cabrera, E., Jr. (2006). “The Minimum Night Flow Method Revisited”. Proceedings of the 8th Annual Water Distribution Systems Analysis Symposium. Cincinnati, Ohio, USA, August 27-30.

Lambert, A., S. Myers, and S. Trow (1998). Managing Water Leakage. Economic and technical issues. London. Financial Times Energy.

Lambert, Allan (2002). “International Report: Water Losses Management and Techniques”. *Water Science and Technology: Water Supply*, Vol. 2, No. 4, pp. 1-20.

MacDonald, G., and Yates, C. D. (2005). “DMA Design and Implementation, a North American Context”. Proceedings of the Leakage IWA Conference, Halifax, Canada.

May, J. (1994). “Pressure dependent leakage.” World Water and Environmental Engineering, October 1994.

McKenzie, R. (1999). Development of a standardised approach to evaluate bursts and background losses in water distribution systems in South Africa. Report TT 109/99. South African Water Research Commission.

McKenzie, R. (2001). PRESMAC (Pressure Management Program). User Guide. Water Research Commission, Pretoria, South Africa. http://www.wrc.org.za/software/presmac/TT%20152.PDF

McKenzie, R.S., N. Meyer and Lambert, A.O. (2002). Calculating Hour-Day Factors for Potable Water Distribution Systems in South Africa. Report TT 184/02. South African Water Research Commission.

Rossman, L. A. (2000). EPANET 2 Users Manual. U.S. Environmental Protection Agency, Cincinnati, Ohio, USA. http://www.epa.gov/ORD/NRMRL/wswrd/EN2manual.PDF

Sturm, R., and Thornton, J. (2005). “Proactive Leakage Management using District Metered Areas (DMA) and Presuure Management – Is it applicable in North America?” Proceedings of the Leakage IWA Conference, Halifax, Canada.

Thornton, Julian (2003). “Managing leakage by managing pressure: a practical approach.” *Water21*. October 2003, pp. 43-44.