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RESEARCH ARTICLE

Estimation of the benefits yielded by pressure management in water distribution systems

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The occurrence of water losses in Water Distribution Systems is inevitable. Knowing that most of the real losses take place in distribution mains and in service connections, the methodology proposed in this paper is based on several leakage-assessment approaches from literature and on water distribution network modeling. This allows assessment of the benefits that can be achieved by pressure management in Water Distribution Systems, particularly in terms of water production reduction. Moreover, this approach can be useful for cost benefit analysis to help establish the level after which there is no more economic interest in reducing water losses (Economic Level of Leakage). Finally, the results from hypothetical case studies are presented and discussed, assuming the installation of Pressure Reducing Valves at District Metered Areas entry points.

Keywords: water losses; pressure management; minimum night flow

1. Introduction

Water loss in water supply and distribution systems is now an issue of growing importance and greater efforts are being made to ensure the sustainability of these public services. This subject has high social and political impacts, especially during shortages or when water supply systems face a rapid growth. The amount of water actually lost varies from system to system, depending on the local topography and urban density, and on the quality of the system's maintenance and operation. The high losses and scarcity of water resources observed in recent years worldwide have prompted water companies to detect, locate and repair leaks in Water Distribution Systems (WDS) (Pilcher *et al.* 2007). According to the terminology established by the International Water Association (IWA) for the various elements of the water balance, details of which can be found in several publications (Alegre *et al.* 2000; Lambert and Hirner 2000), the total volume of water entering the system and not generating income is termed non-revenue water, and it includes apparent and real losses. It is not easy to quantify and manage apparent and real losses in a WDS; since losses cannot be measured directly, their evaluation is not straightforward and their management can become quite complex. To overcome this difficulty, an iterative calculation procedure can be used, involving both measured and reference values.

Nowadays the reduction of water loss is a major concern in Portugal. According to Marques, Gomes and Monteiro (2005), in Portugal water losses account for about 35% of the water production. Although the water companies have started to show greater awareness of the need to renew and replace their infrastructure, the large investment needed and the low tariffs charged mean that many of the smaller WDS cannot afford it and therefore still face high levels of water loss. So, in order to ensure the continuity of the service, even during periods of scarcity, the sector must reorganize and group a lot of small systems together to form a few of more suitable size, and allocate more funds to rehabilitate the 'weak' ones. With the implementation of these measures WDS should become more effective and efficient and be closer to achieving service sustainability.

The methodology proposed in this paper follows the 'water losses management international best practices' and makes it possible to evaluate the benefits that can be achieved by pressure management in WDS, particularly in terms of water production reduction. It is based on the Minimum Night Flow (MNF), Bursts and Background Estimates (BABE) and Fixed and Variable Area Discharges (FAVAD) concepts, and uses a simulation model to predict the network hydraulic behaviour. This and other similar issues

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have been tackled in the literature with different approaches, including: using water balance and minimum night flow analysis in combination with a network hydraulic simulation model (Buchberger and Nadimpalli 2004, Almandoz *et al*. 2005, Tabesh *et al*. 2009); pressure at the average zone point and critical node (Mckenzie and Langenhoven 2001); incorporated leakage terms and effect of valve control in network analysis (Jowitt and Xu 1990, Vairavamoorthy and Lumbers 1998, Awad *et al*. 2008, Giustolisi *et al*. 2008b), and optimal location and control of valves in WDS (Reis *et al*. 1997, Tucciarelli *et al*. 1999, Pezzinga and Pititto 2005, Araujo *et al*. 2006, Awad *et al*. 2009, Nicolini and Zovatto 2009).

2. MNF, BABE and FAVAD concepts

The evaluation of water loss in WDS is quite complex because it is influenced by a number of factors, including: system operating pressure; frequency of bursts; speed and quality of repair; age of pipes and fittings; quality of construction; soil characteristics; and traffic and earth movements. Any initiative aimed at controlling losses requires knowledge of the system's components and how they are interrelated. MNF analysis allows relatively strict criteria to be established for calculating the factors related to losses, since most of the population is not 'active' during the night and that is when consumption can be more easily measured and/or estimated. On the other hand, during the MNF period there is little fluctuation in consumption, while during the day the scenario is completely different: consumption changes over the year due to seasonality, and over the day due to household, commercial and industrial activity. A study was conducted in the UK that lasted nearly 4 years and involved experts from the country's leading water companies, and this led to the specification of the terminology and the recommendation of procedures that are most appropriate to measure and estimate each loss component and consumption. This study can be found in nine reports called, Managing Leakage Reports (WRc 1994).

As the Managing Leakage Reports series was being published, new empirical concepts for evaluating the relation between real night losses and pressure came out, along with procedures to estimate the benefits from pressure management. In this context, the methodologies proposed by Lambert and May are very important. Lambert (1994) first assessed the various parameters that influence real losses and then presented a methodology known as Bursts and Background Estimates (BABE). The BABE concept is used to define the upper and lower bound of real losses at a given pressure for a specified reference flow. May (1994) presented the concept of Fixed Area and Variable Area Discharges (FAVAD) applied to real networks through the use of a power function that defines the pressure/leakage relationship. The exponent of that function can take values from 0.5 (pipes not very sensitive to pressure fluctuation, like steel pipes or other rigid pipes) up to 2.5 (for pipes highly sensitive to pressure fluctuation, like HDPE pipes or other flexible pipes).

These concepts were the basis for several models aimed at helping the management and control of water losses (Mckenzie and Langenhoven 2001, Fantozzi and Lambert 2007, Awad *et al*. 2008, Giustolisi *et al*. 2008a, b). Although leakage takes place in distribution mains and in service connections, assuming that leakage is a part of the node total outflow, if the pressure is reduced from P_0 to P_1, the discharge from existing leaks changes from QL_0 to QL_1, and from Equation (1) the extent of that change depends on the exponent N1 (Lambert 2000, Farley and Trow 2003):

$$\text{QL varies with } P^{N1}: \frac{QL_1}{QL_0} = \left(\frac{P_1}{P_0}\right)^{N1} \tag{1}$$

Similarly, pressure-dependent consumption changes from QC_0 to QC_1, and the extent of that change depends on the exponent N2. Regarding the consumption before pressure reduction (QC_0), it should be noted that a part of it can be assumed as pressure-independent (e.g., toilet flushing, roof tanks, washing machines, dishwashers) and the remaining as pressure-dependent (e.g., shower use, hand washing, watering gardens). While pressure-independent consumption ($QC_{indep,0}$) is not affected by pressure fluctuation (which only influences the time while consumption is occurring until the pre-established volume is reached), the excess pressure (the amount above that strictly required to meet consumption, without affecting the duration of consumption) increases the pressure-dependent consumption ($QC_{dep,0}$), thereby affecting the total consumption after pressure reduction (QC_1). As a result, the generalization of Equation (1) leads to Equation (2), where QT_1 is the node total outflow after pressure reduction:

$$\text{QT varies with } P^N: QT_1 = QL_0 \times \left(\frac{P_1}{P_0}\right)^{N1} + QC_{dep,0} \times \left(\frac{P_1}{P_0}\right)^{N2} + QC_{in\,dep,0} \tag{2}$$

In Equations (1) and (2), exponent N1 expresses the pressure/leakage relationship while exponent N2 expresses the pressure/consumption relationship (applied solely to the pressure-dependent consumption). Some reference studies concluded that for N1 a value of 1.0 will usually be reasonable (combination of fixed and variable area leaks). Assuming that pressure-dependent consumption varies with pressure in accordance with a square root relationship, the value of N2 should be taken as 0.5 (Lambert 2000, Mckenzie and Langenhoven 2001, Fantozzi and Lambert 2007, Giustolisi *et al*. 2008b).

3. Integration of water loss concepts and the network simulation model

Pressure can be controlled by Pressure Reducing Valves (PRV) and this is undoubtedly a quick and sometimes easy way to achieve significant water loss savings in WDS with high service pressure. To evaluate the economic feasibility of different pressure management solutions, the authors developed a methodology implemented in the form of a computational tool written in FORTRAN language, which makes use of a hydraulic simulator previously developed by Sousa (2006). It assumes that the pressure control can be exerted inside a District Metered Area (DMA) or at a DMA entry point (more common in practice). The minimum consumption and real losses can be calculated during the MNF period, when most people are not 'active' and it is easier to estimate and/or measure consumption. This methodology divides water consumption in two parts: the pressure-independent and the pressure-dependent. Moreover, real losses downstream of the customer meter are supposed to be billed and they are regarded as pressure-dependent (important for systems with a high density of metered properties).

The Portuguese WDS can be briefly described as follows (Marques *et al*. 2005, IRAR 2007): (1) water supply and distribution systems currently serve about 93% of the population; (2) water losses represent, on average, about 35% of the water production; (3) service connections are at a property's boundary; (4) water consumption is usually metered; (5) water supply service is continuous; (6) the delivery points correspond to the water meters; and (7) the water company is responsible for the system upstream and the customer is responsible for the system downstream of the delivery point.

3.1. *Estimation of the benefits yielded by pressure management in a DMA*

The direct consequence of pressure management is the reduction of real losses (direct benefits are lower costs of water production and conveyance), but it always goes hand in hand with lower water consumption (although very often this is not significant, in fact it does generate a small loss of revenue). Furthermore, pressure management gives rise to another very important benefit, although it is indirect and difficult to evaluate: it leads to less frequent bursts and, as a consequence, a reduction of real losses. This means that the existing infrastructure can better face higher future consumption and avoid the need to expand the existing production and distribution systems.

The methodology proposed in this paper follows the 'water losses management international best practices' and allows evaluation of the benefits that can be achieved by pressure management in WDS, particularly in terms of reducing water production. Moreover, this approach can be useful for cost benefit analysis to help establish the level after which there is no more economic interest in reducing water loss – Economic Level of Leakage (WRc 1994, Awad *et al*. 2008, 2009, Thornton *et al*. 2008). Once the DMA consumption has been calculated and bursts repaired, total losses can be estimated by the difference between the total volume of water entering the DMA and the authorized consumption. As a result of pressure management, the total reduction of water loss volume at the DMA entry point (ΔVL) is given by the difference between the current water loss volume (VL^{Phase1}) and the estimated water loss volume after pressure reduction (VL^{Phase2}):

$$\Delta VL = (VL^{Phase1} - VL^{Phase2}) \tag{3}$$

As pressure is known to influence consumption, however, the total billed water will decrease with the pressure reduction (ΔVR), and this decrease can be estimated by the difference between the actual billed water (VR^{Phase1}) and the estimated billed water after pressure reduction (VR^{Phase2}):

$$\Delta VR = (VR^{Phase1} - VR^{Phase2}) \tag{4}$$

Knowing the cost of water production per m^3 (C_p) and the selling price per m^3 (C_v), Equation (5) estimates the direct benefits that can be achieved with pressure management in WDS (reduction of water production minus the reduction of billed water):

$$\text{Benefits} = C_p \Delta VL - (C_v - C_p)\Delta VR \tag{5}$$

3.2. *Methodology*

This methodology does not take into consideration the cost/benefit of active leakage control policies, the existence of pipe bursts (it is assumed that all the bursts have been reported and quickly repaired), illegal connections, fire flow, measurement and data acquisition errors, and equipment installation/maintenance costs. In addition, it is assumed that the water distribution simulation model is already calibrated

(Walski *et al.* 2003) and the PRV is located at the DMA entry point (most common place in practice). In order to obtain the benefit from pressure management, a head-driven kind of network simulation model is required to estimate the variation in the pressure-dependent consumption and leakage due to pressure changes. In the first phase of the methodology presented here, consumption and water losses are estimated, taking as reference the service pressure at each node and the pressure/leakage and the pressure/consumption relationships during MNF (Phase 1). Afterwards the pressure is reduced and the corresponding consumption and water losses are estimated by adjusting the Phase 1 values to the Phase 2 pressure conditions (see flowchart in Figure 1).

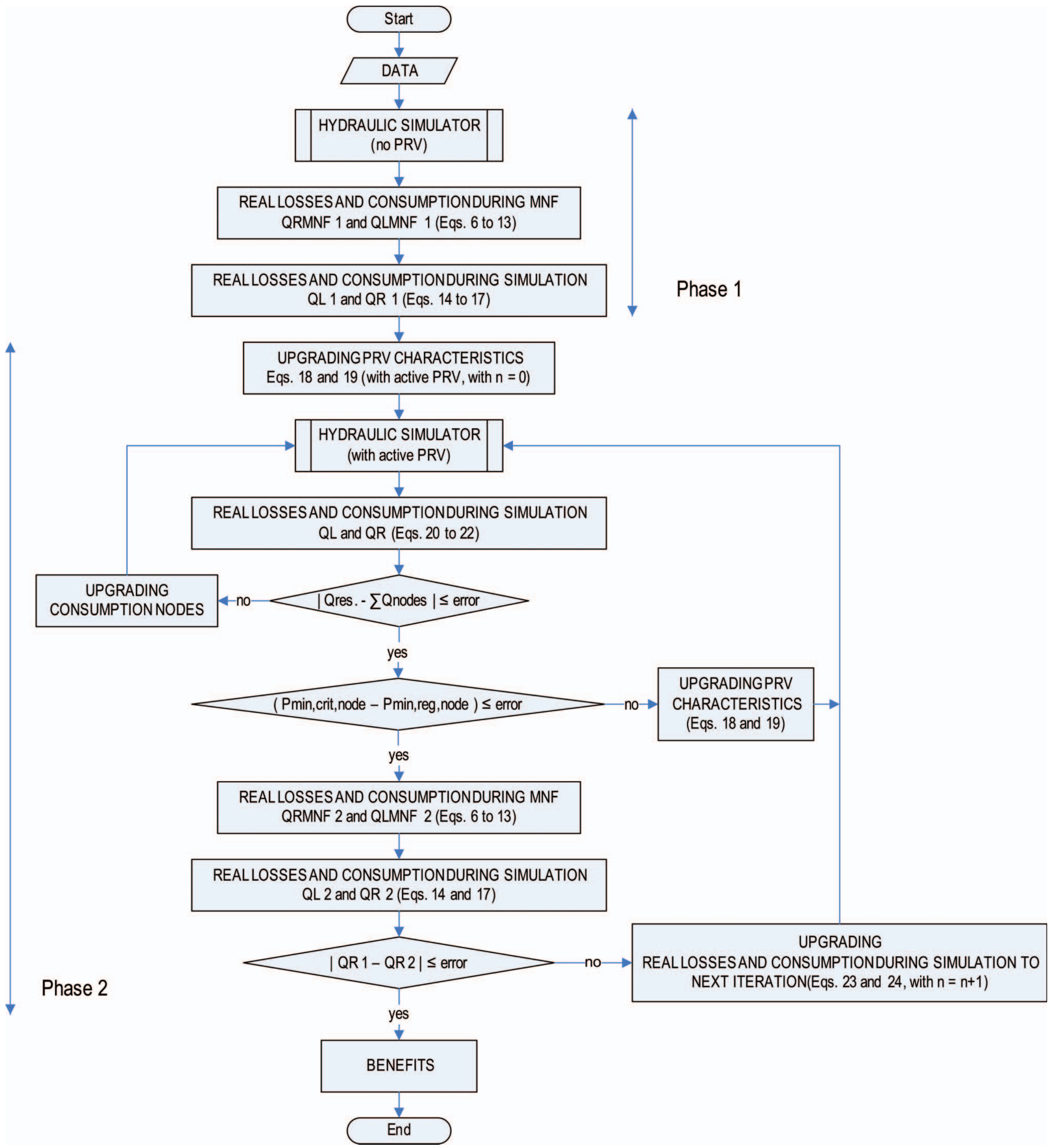

Figure 1. Methodology flowchart.

3.2.1. *Phase 1 or Phase 2*

To evaluate the benefits of pressure management in terms of water loss reduction, the consumption/losses must first be measured/estimated at the DMA during the MNF period, when consumption is lowest and service pressure is closer to static pressure. Using these consumption and loss figures as reference, and knowing that most real losses occur in the main pipes and in the service connections, the minimum consumption can be estimated, for each node j of the network, by expression (6). The methodology presented here assumes that leakage is a part of the node total outflow and is related to its pressure. This criterion seems to be more suitable for allocating water loss when the topography between adjacent nodes is fairly irregular.

$$QR_j^{MNF} = QLP_{dow.,j} + QC_{dom.,j} + QC_{small,j} + QC_{large,j} \tag{6}$$

where

$$QLP_{dow.,j} = (QLPE_{dow.} \times N_{service,dow.,j}) \times \left(\frac{P_{service,j}}{P_{ref.}}\right)^{N1} \tag{7}$$

$$QC_{dom.,j} = (Pop_j \times Pop_{active,j}) \times \left[QCE_{dom.,indep.} + QCE_{dom.,dep.} \times \left(\frac{P_{service,j}}{P_{service,\,ref.,j}}\right)^{N2}\right] \tag{8}$$

$$QC_{small,j} = QCM_{small,indep.,j} + QCM_{small,dep,j} \times \left(\frac{P_{service,j}}{P_{service,ref.,j}}\right)^{N2} \tag{9}$$

$$QC_{large,j} = QCM_{large,indep.,j} + QCM_{large,dep,j} \times \left(\frac{P_{service,\,j}}{P_{service,\,ref.,\,j}}\right)^{N2} \tag{10}$$

$$P_{service,\,ref.,j} \geq P_{minimum,req.,j} \tag{11}$$

$$P_{service,\,j} \geq P_{minimum,req.,j} \tag{12}$$

where QR_j^{MNF} is the minimum consumption during MNF (m^3/h) at node j; $QLP_{dow.,j}$ is losses downstream of the customer meter (m^3/h) at node j; $QC_{dom.,j}$ is the domestic night consumption (m^3/h) at node j; $QC_{small,j}$ is the small non-domestic night consumption (m^3/h) at node j; $QC_{large,j}$ is the large non-domestic night consumption (m^3/h) at node j; $QLPE_{dow.}$ is the estimated losses downstream of the customer meter (m^3/h/service connection) (WRc 1994); $N_{service,dow.,j}$ is the number of service connections downstream of the customer meter at node j; $P_{service,j}$ is the service pressure at node j (m), without PRV (Phase 1) or with PRV (Phase 2); $P_{ref.}$ is the reference pressure (m) (WRc 1994); N1 is the exponent of the pressure/leakage relationship; $QCE_{dom.,indep.}$ is the estimated domestic night consumption (m^3/h/inhabitant), pressure independent (WRc 1994); Pop_j is the number of inhabitants at node j; $Pop_{active,j}$ is the percentage of active population at node j (WRc 1994); $QCE_{dom.,dep.}$ is the estimated domestic night consumption (m^3/h/inhabitant), pressure dependent (WRc 1994); $P_{service,ref.,j}$ is the reference service pressure at node j (m), without PRV (Phase 1 or Phase 2); $QCM_{small,indep.,j}$ is the measured small non-domestic night consumption (m^3/h) at node j, pressure independent; $QCM_{small,dep,j}$ is the measured small non-domestic night consumption (m^3/h) node j, pressure dependent; N2 is the exponent of the pressure/consumption relationship; $QCM_{large,indep.,j}$ is the measured large non-domestic night consumption (m^3/h) at node j, pressure independent; $QCM_{large,dep,j}$ is the measured large non-domestic night consumption (m^3/h) at node j, pressure dependent; $P_{minimum,req.,j}$ is the minimum service pressure required for supplying consumption at node j (m).

Losses from main pipes and service connections upstream of the customer meter (QL_j^{MNF}), for node j, results from the subtraction of the consumption during MNF (QR_j^{MNF}), calculated by (6), from the total outflow (QT_j^{MNF}) assigned to node j (consumption and losses during MNF):

$$QL_j^{MNF} = QT_j^{MNF} - QR_j^{MNF} \tag{13}$$

Taking these losses as reference, the amount of losses and consumption can be extrapolated for the remaining simulation period, at node j, by Equations (14) and (15), respectively:

$$QL_{j,t} = QL_j^{MNF} \times \left(\frac{P_{service,j,t}}{P^{MNF}_{service,j}}\right)^{N1} \tag{14}$$

$$QR_{j,t} = QT_{j,t} - QL_{j,t} \tag{15}$$

where $QL_{j,t}$ is losses upstream of the customer meter (m^3/h) at time t at node j; QL_j^{MNF} is losses upstream of the customer meter during MNF (m^3/h) at node j; $P_{service,j,t}$ is the service pressure (m) at time t at node j, without PRV (Phase 1) or with PRV (Phase 2); $P^{MNF}_{service,j}$ is the service pressure during MNF (m) at node j, without PRV (Phase 1) or with PRV (Phase 2); $QR_{j,t}$ is the consumption (m^3/h) at time t at node j; $QT_{j,t}$ is the total outflow (m^3/h) at time t at node j.

Assuming that the period of simulation comprises T time steps (Δt in hours) and the network has N nodes, the amount of daily water losses ($VL^{Phase1\ or\ Phase2}$) and daily consumption ($VR^{Phase1\ or\ Phase2}$), in m^3, for the entire network, can be estimated by Equations (16) and (17), respectively:

$$VL^{Phase1\ or\ Phase2} = \sum_{t=1}^{T}\sum_{j=1}^{N} QL_{j,t} \times \Delta t \tag{16}$$

$$VR^{Phase1\ or\ Phase2} = \sum_{t=1}^{T}\sum_{j=1}^{N} QR_{j,t} \times \Delta t \tag{17}$$

3.2.2. Phase 2

To assume good consumption conditions, service pressure must reach or exceed the minimum pressure required (18). However, as the pressure increases so does water loss. Once the water losses (QL) and consumption (QR) have been estimated for the actual service pressure conditions (Phase 1), the piezometric head downstream of the PRV must be defined. For a fixed-outlet PRV there is a single working condition (the head downstream of the PRV is always the same). For a time-modulated PRV there can be several working conditions (for instance, one during the night period – from 01:00 to 06:00 h, and another during the rest of the day). The pressure-modulated PRV is certainly the most efficient system because it constantly adjusts the working conditions to reach the minimum pressure required at the monitoring node (usually the critical node). In this case, if the simulation period is 24 h and it comprises 24 time steps of 1 h each, then the PRV working conditions will switch 24 times. To summarize, no matter what type of PRV is used, it is necessary to define the most suitable working conditions for that PRV. The procedure adopted here consists of determining the adjustments of the piezometric head downstream of the PRV, that is, the head loss the PRV must produce to reach the desired working conditions (ΔH_{PRV}). For each working period of the PRV, the adjustment equals the minimum difference between the service pressure (initially the Phase 1 pressure and afterwards the consecutive estimated pressures for Phase 2) and the minimum pressure required, evaluated at the critical node for all time steps of that working period (19):

$$P^{Phase2}_{service,j,t} \geq P_{minimum,req.,j} \tag{18}$$

$$\Delta H_{PRV,s} = \min\left(P^{Phase1\ or\ Phase2}_{critical\ node,s} - P_{minimum,req.}\right) \quad \text{for} \quad s = 1,\cdots,S \tag{19}$$

where $\Delta H_{PRV,s}$ is the adjustments of the piezometric head downstream of the PRV (m) for each working period s; S is the number of the PRV working periods during the simulation period.

After pressure reduction, the total outflow at node j can be estimated (Phase 2). Initially, the consumption ($QR^{Phase2}_{j,t}$) is assumed fixed (20) and the water losses can be estimated by Equation (21) – adjustment of Phase 1 water losses to the Phase 2 pressure conditions. Then, the total outflow, at node j, is the sum of the consumption and the water losses (22).

$$QR^{Phase2}_{j,t} = QR^{Phase1}_{j,t} \tag{20}$$

$$QL^{Phase2}_{j,t} = QL^{Phase1}_{j,t} \times \left(\frac{P^{Phase2}_{service,j,t}}{P^{Phase1}_{service,j,t}}\right)^{N1} \tag{21}$$

$$QT^{Phase2}_{j,t} = QR^{Phase2}_{j,t} + QL^{Phase2}_{j,t} \tag{22}$$

After updating the nodal flow and executing the hydraulic simulation, the piezometric head downstream of the PRV (Phase 2) must be checked. If necessary, the next correction must be made by applying Equations (18) to (22). This process stops when the service pressure equals the minimum pressure required at one of the network nodes, meaning that the PRV working condition has reached the limit. Finally, for the new pressure conditions (step n), the water losses (QL^{Phase2}) and consumption (QL^{Phase2}) can be estimated by Equations (6) to (17) – adjustment of Phase 1 to Phase 2 pressure conditions. If the consumption for the new pressure conditions is different from the consumption used in the process (20), the consumption and losses for the next iteration in Phase 2 (step n + 1) must be upgraded by (23) and (24):

$$QR^{Phase2(n+1)}_{j,t} = QR^{Phase2(n)}_{j,t} \tag{23}$$

$$QL^{Phase2(n+1)}_{j,t} = QT^{Phase2(n)}_{j,t} - QR^{Phase2(n)}_{j,t} \tag{24}$$

This procedure ends when, after pressure reduction, node consumption across two consecutive iterations is sufficiently close.

4. Case studies

The methodology proposed in this paper was designed to estimate the benefits from pressure management at a DMA (by establishing the piezometric head downstream of a PRV located at the DMA entry point). To assess the potential benefits in terms of water loss reduction that can be achieved from pressure management in WDS, two case studies were undertaken in which all the regulatory provisions were satisfied. In the first case study a fixed-outlet PRV was used to analyze the importance of pressure-dependent and pressure-independent consumption. The second case study shows the influence of using different types of PRV and the influence of the pressure available at the DMA entry point. The four steps needed to estimate the benefits accruing from pressure management are: (1) detecting and repairing bursts; (2) analyzing network and consumption data; (3) designing and calibrating the network hydraulic simulation model; and (4) estimating the benefits. Calculations were performed using reference data reported in the literature (see Table 1) (WRc 1994).

4.1. *Case study I*

For the hypothetical network shown schematically in Figure 2, the average flow at the entry of the DMA is 52.08 m^3/h and the reservoir elevation is 50 m. The network is 6.50 km long and comprises high density

Table 1. Reference parameters (WRc 1994).

Losses downstream of the delivery point at 50 m: $QLPE_{dow}$	0.5	l/service connection/h
Minimum domestic night flow pressure-independent: $QCE_{dom.,indep.}$	8	l/inhabitant/h
Minimum domestic night flow pressure-dependent: $QCE_{dom.,dep.}$	2	l/inhabitant/h
Percentage of active population: Pop_{active}	6	%
Exponent of the losses-pressure relationship: N1	1.0	–
Exponent of the consumption-pressure relationship: N2	0.5	–

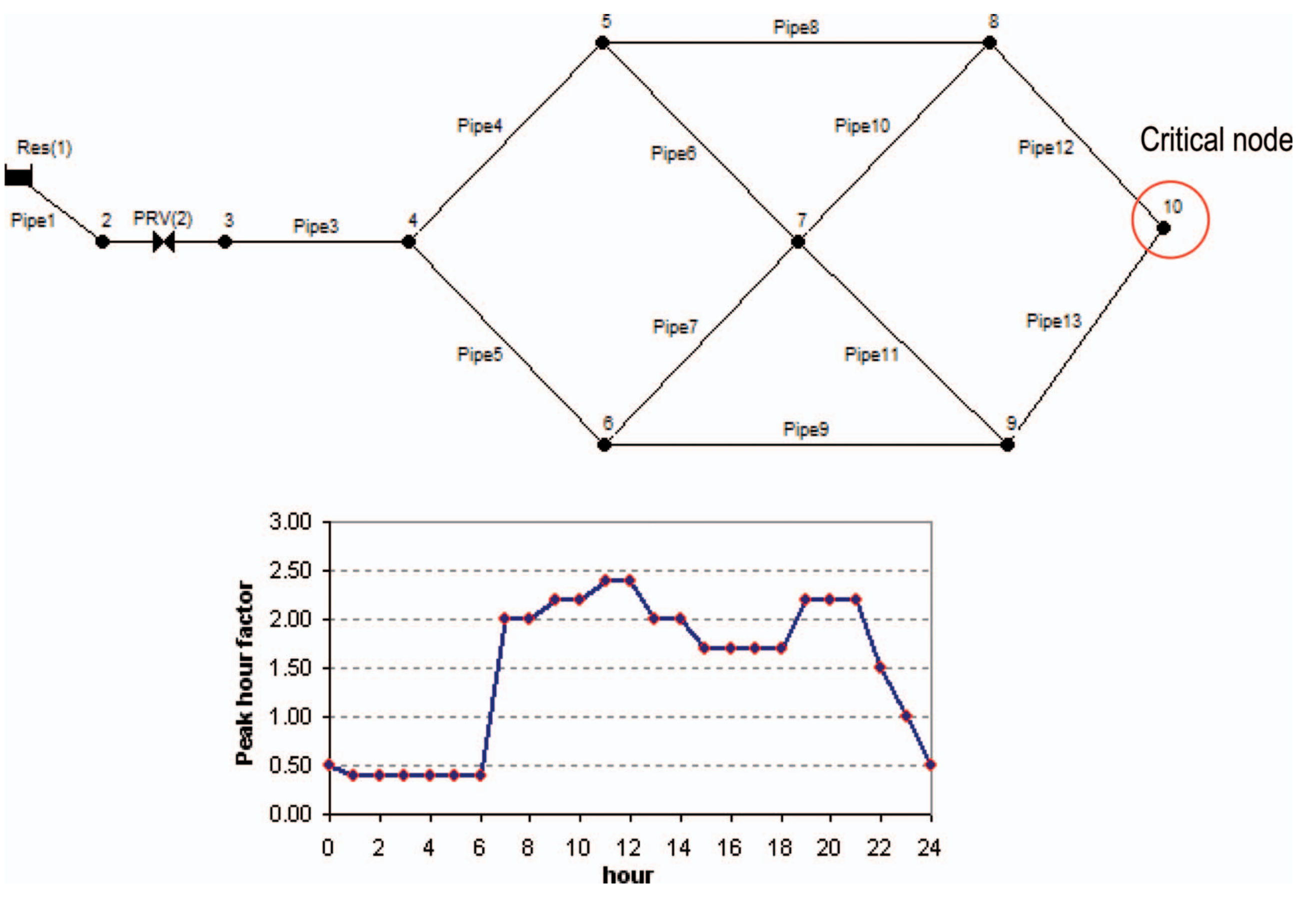

Figure 2. Scheme of the hypothetical network and water consumption pattern.

polyethylene (HDPE) pipes. It supplies a mostly residential area of buildings with three storeys above ground. Tables 2 and 3 show the physical characteristics of the system and the average total outflow from the nodes (consumption and losses). Node 10, the farthest node from the DMA entry point, is the critical node.

Knowing the system's physical characteristics and average consumption for each node, the information from Table 4 was used to estimate water losses and consumption during the MNF period. This table shows the number of inhabitants, households and service connections assigned to each node of the network (non-domestic consumers were not considered).

The process starts by estimating the water losses (main pipes and service connections upstream of the customer meter) and consumption, for each node over the 24 h simulation period (Phase 1). The maximum and minimum hourly flow at the DMA entry point were respectively 125.00 and 20.83 m^3/h, and the maximum and minimum service pressure at the critical node (node 10) were, respectively, 49.82 and 45.74 m. The total water volume entering the DMA was 1 875.02 m^3 and the total billed water was 1 476.62 m^3, indicating 398.40 m^3 of water loss. After performing a few adjustments to the piezometric head downstream of the PRV until the minimum pressure required at the critical node (22.45 m) was reached, the optimum head loss in the PRV was found to be 23.78 m (Phase 2). As mentioned before, the value of the piezometric head downstream of the PRV was reduced at each iteration by the difference between the service pressure obtained for the critical node and its required minimum pressure. After pressure reduction, the total water volume entering the DMA and the total consumption were estimated as 1 675.46 and 1 464.42 m^3, respectively. Water losses, which initially amounted to 21.25%, fell with pressure reduction to 12.60% (a reduction of more than 8%). The implementation of pressure management led to a 10.64% reduction in water production – a daily reduction of almost 200 m^3. The reduction of billed water (difference in water consumption before and after the implementation of pressure management) was 0.83% – a daily reduction of

Table 3. Nodes characteristics.

ID Nodes	Elevation (m)	$P_{minimum,req.}$ (m)	Population	$Q_{average}$ (m^3/h)
Res. (1)	50	–	–	52.08
2	0	22.45	0	0.00
3	0	22.45	0	0.00
4	0	22.45	417	4.34
5	0	22.45	833	8.68
6	0	22.45	833	8.68
7	0	22.45	834	8.68
8	0	22.45	833	8.68
9	0	22.45	833	8.68
10	0	22.45	417	4.34

$P_{minimum,req.}$: Minimum pressure required at each node.

Table 4. Information needed to estimate losses and consumption during the MNF period.

ID Nodes	Inhabitants	Households	Service connections
Res. (1)	–	–	–
2	0	0	0
3	0	0	0
4	417	139	139
5	833	238	238
6	833	238	238
7	834	278	278
8	833	238	238
9	833	238	238
10	417	139	139

Table 2. Pipes characteristics.

ID Pipes	Upstream node	Downstream node	L (m)	Dc (mm)	Di (mm)	k (mm)	Material
1	Res. (1)	2	1	280	248.2	0.01	HDPE
PRV (2)	2	3		Phase 1 (no PRV)/Phase 2 (with active PRV)			
3	3	4	500	280	248.2	0.01	HDPE
4	4	5	500	200	177.2	0.01	HDPE
5	4	6	500	200	177.2	0.01	HDPE
6	5	7	500	125	110.8	0.01	HDPE
7	6	7	500	125	110.8	0.01	HDPE
8	5	8	1000	125	110.8	0.01	HDPE
9	6	9	1000	125	110.8	0.01	HDPE
10	7	8	500	125	110.8	0.01	HDPE
11	7	9	500	125	110.8	0.01	HDPE
12	8	10	500	110	97.4	0.01	HDPE
13	9	10	500	110	97.4	0.01	HDPE

L, length of pipe; Dc, Commercial diameter; Di, Internal diameter; k, Equivalent roughness (Colebrook-White formula).

12 m³. The economic benefits yielded by pressure management amounted to 181.25 €/day, or nearly 66 000 €/year. Table 5 presents the results obtained and the estimated benefits for this case study (the production cost and selling price of water were taken as 1.00 and 1.50 €/m³, respectively).

As expected, the pressure reduction caused a decrease of both water consumption and water production. However, as water production fell much more than water consumption, the final conclusion is that effective pressure management can produce considerable benefits.

This methodology is based on the separation of the pressure-dependent from the pressure-independent consumption during the MNF period. Table 6 presents some results that illustrate the influence of the relation between these two components of water consumption on the daily benefits. As the pressure-dependent consumption has a considerable influence on the reduction of the total billed water, the daily benefits

Table 5. Estimated benefits from pressure reduction.

	Phase 1 (no PRV)			Phase 2 (with active PRV)						
	DMA flow			DMA flow			Reduction			
Hour	QL m³/h	QR m³/h	Critical node m	QL m³/h	QR m³/h	Critical node m	QL + QR m³/h	QR m³/h	Critical node %	Daily benefit €
1	17.08	3.75	49.82	9.23	3.23	26.14	8.37	0.52	47.5	7.59
2	17.08	3.75	49.82	9.23	3.23	26.14	8.37	0.52	47.5	7.59
3	17.08	3.75	49.82	9.23	3.23	26.14	8.37	0.52	47.5	7.59
4	17.08	3.75	49.82	9.23	3.23	26.14	8.37	0.52	47.5	7.59
5	17.08	3.75	49.82	9.23	3.23	26.14	8.37	0.52	47.5	7.59
6	17.08	3.75	49.82	9.23	3.23	26.14	8.37	0.52	47.5	7.59
7	16.38	87.78	46.93	8.60	87.28	23.57	8.29	0.50	49.8	7.54
8	16.38	87.78	46.93	8.60	87.28	23.57	8.29	0.50	49.8	7.54
9	16.25	98.34	46.36	8.46	97.84	23.03	8.28	0.50	50.3	7.53
10	16.25	98.34	46.36	8.46	97.84	23.03	8.28	0.50	50.3	7.53
11	16.10	108.90	45.74	8.32	108.41	**22.45**	8.27	0.49	50.9	7.53
12	16.10	108.90	45.74	8.32	108.41	**22.45**	8.27	0.49	50.9	7.53
13	16.38	87.78	46.93	8.60	87.28	23.57	8.29	0.50	49.8	7.54
14	16.38	87.78	46.93	8.60	87.28	23.57	8.29	0.50	49.8	7.54
15	16.57	71.97	47.71	8.78	71.46	24.29	8.30	0.51	49.1	7.54
16	16.57	71.97	47.71	8.78	71.46	24.29	8.30	0.51	49.1	7.54
17	16.57	71.97	47.71	8.78	71.46	24.29	8.30	0.51	49.1	7.54
18	16.57	71.97	47.71	8.78	71.46	24.29	8.30	0.51	49.1	7.54
19	16.25	98.34	46.36	8.46	97.84	23.03	8.28	0.50	50.3	7.53
20	16.25	98.34	46.36	8.46	97.84	23.03	8.28	0.50	50.3	7.53
21	16.25	98.34	46.36	8.46	97.84	23.03	8.28	0.50	50.3	7.53
22	16.68	61.44	48.17	8.88	60.93	24.71	8.31	0.51	48.7	7.55
23	16.91	35.17	49.11	9.09	34.66	25.56	8.34	0.52	48.0	7.56
24	17.06	8.98	49.74	9.22	8.46	26.08	8.36	0.52	47.6	7.58
Σ =	**398.40**	**1476.62**	Σ =	**211.04**	**1464.42**		**10.64%**	**0.83%**	Σ =	**181.25**

Table 6. Influence of the pressure-dependent and pressure-independent consumption on the daily benefits.

	Phase 1 (no PRV) DMA volume		Phase 2 (with active PRV)					
			DMA volume			Reduction		
Test	VL m³	VR m³	VL m³	VR m³	ΔH_{PRV} m	VL + VR %	VR %	Daily benefit €
(a)	398.40	1476.62	211.04	1464.42	23.78	10.64	0.83	181.25
(b)	398.40	1476.62	210.06	1466.35	23.78	10.59	0.70	183.20
(c)	398.40	1476.62	209.08	1468.28	23.78	10.54	0.56	185.15

(a) Minimum domestic night flow (pressure-independent = 8 l/inhabitant/h; pressure-dependent = 2 l/inhabitant/h).
(b) Minimum domestic night flow (pressure-independent = 9 l/inhabitant/h; pressure-dependent = 1 l/inhabitant/h).
(c) Minimum domestic night flow (pressure-independent = 10 l/inhabitant/h; pressure-dependent = 0 l/inhabitant/h).

increase when that portion of the consumption decreases. In fact, if the consumption was totally pressure-independent, the reduction of billed water would be much smaller, due simply to water losses downstream of the water meters.

4.2. *Case study II*

This case study, schematically represented in Figure 3, was designed to illustrate the influence of the pressure at DMA entry point on the pressure management benefits. The calculation procedure is the same as described for case study I.

The reservoir is initially at an elevation of 100 m and the average flow at the DMA entry point is 312.50 m^3/h. The system's topography varies between 26.50 and 48.50 m and the total pipe length is 9.20 km. It comprises PVC and cast iron pipes and supplies an area where consumption is mostly domestic, in buildings with four storeys above ground. The production cost and selling price of water were considered as 1.00 and 1.50 €/m^3, respectively.

For this case study, the critical nodes are: node 74 during the period of maximum consumption (the farthest node from the DMA entry point) and node 77 during the period of minimum consumption (the highest node in the DMA). Tables 7 and 8 show the benefits yielded by pressure management using different types of PRV at the DMA entry point (fixed-outlet, time-modulated and pressure-modulated). For a fixed-outlet PRV, the adjustment to the piezometric head downstream of the PRV is obtained as the difference between the service pressure at the critical node and its required minimum pressure, evaluated during the period of maximum consumption (one single working condition). For a time-modulated PRV, the adjustments to the piezometric head downstream of the PRV are determined in such a way that, during each working period (there are two working conditions, one during the night period – from 00:00 to 06:00 h,

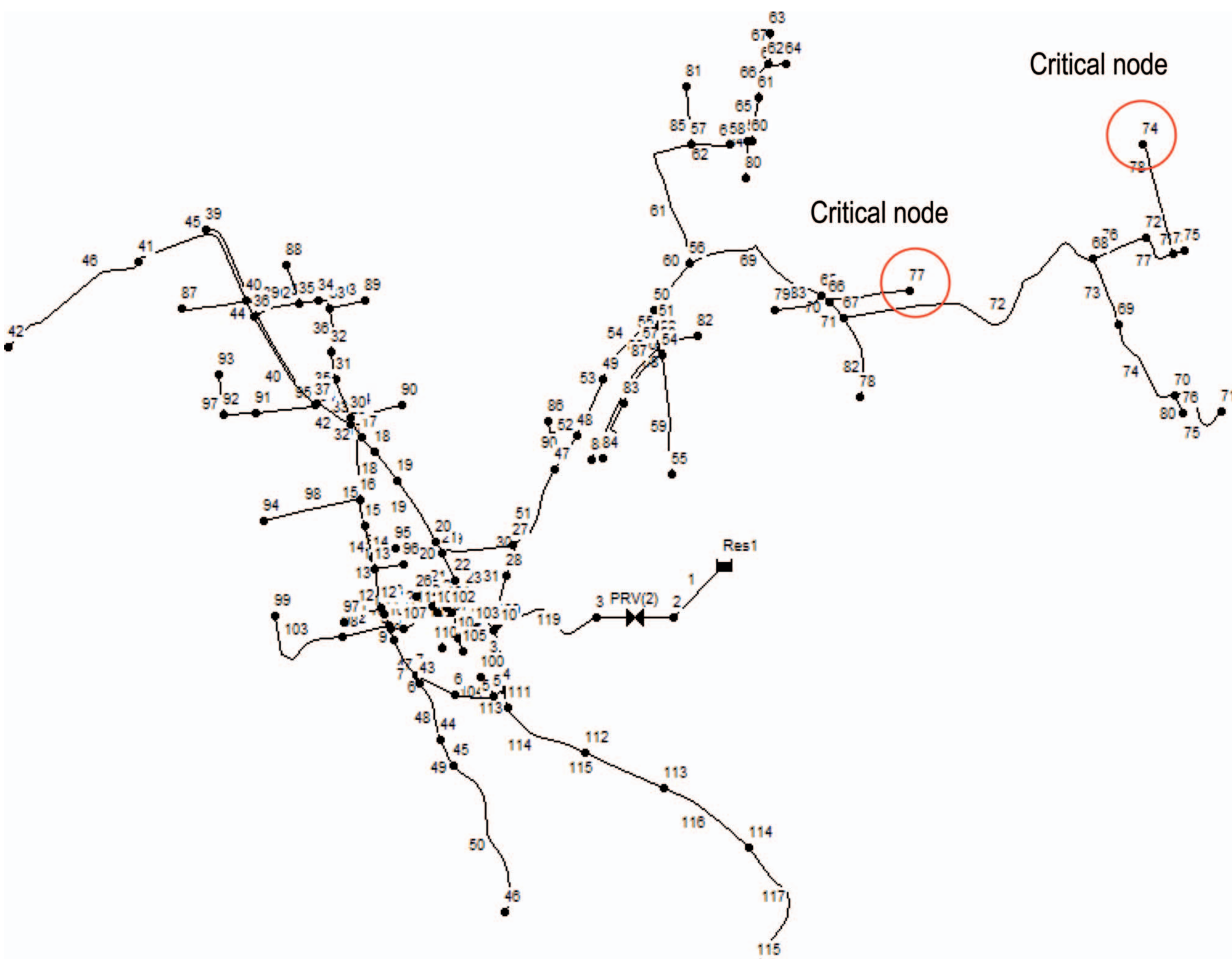

Figure 3. Network scheme.

Table 7. Influence of different types of PRV on the daily benefits.

Types PRV	Phase 1 (no PRV) DMA volume		Phase 2 (with active PRV) DMA volume		Reduction		Daily benefit
	VL m^3	VR m^3	VL m^3	VR m^3	VL + VR %	VR %	€
Fixed-outlet	2371.99	8878.02	1572.18	8811.35	7.70	0.75	766.47
Time-modulated	2371.99	8878.02	1543.56	8800.03	8.06	0.88	789.43
Pressure-modulated	2371.99	8878.02	1499.80	8800.03	8.45	0.88	833.19

Table 8. Estimated benefits from pressure reduction using different types of PRV.

	Phase 2 (Fixed-outlet PRV)					Phase 2 (Time-modulated PRV)					Phase 2 (Pressure-modulated PRV)				
	DMA flow			Critical nodes		DMA flow			Critical nodes		DMA flow			Critical nodes	
Hour	QL m^3/h	QR m^3/h	ΔH_{PRV} m	74 m	77 m	QL m^3/h	QR m^3/h	ΔH_{PRV} m	74 m	77 m	QL m^3/h	QR m^3/h	ΔH_{PRV} m	74 m	77 m
1	67.38	21.34	21.41	31.48	30.03	61.72	20.86	24.91	27.99	**26.53**	61.72	20.86	24.91	27.99	**26.53**
2	67.38	21.34	21.41	31.48	30.03	61.72	20.86	24.91	27.99	**26.53**	61.72	20.86	24.91	27.99	**26.53**
3	67.38	21.34	21.41	31.48	30.03	61.72	20.86	24.91	27.99	**26.53**	61.72	20.86	24.91	27.99	**26.53**
4	67.38	21.34	21.41	31.48	30.03	61.72	20.86	24.91	27.99	**26.53**	61.72	20.86	24.91	27.99	**26.53**
5	67.38	21.34	21.41	31.48	30.03	61.72	20.86	24.91	27.99	**26.53**	61.72	20.86	24.91	27.99	**26.53**
6	67.38	21.34	21.41	31.48	30.03	61.72	20.86	24.91	27.99	**26.53**	61.72	20.86	24.91	27.99	**26.53**
7	64.68	524.30	21.41	28.05	27.83	64.97	523.84	21.41	28.05	27.82	62.76	523.84	22.72	26.76	**26.53**
8	64.68	524.30	21.41	28.05	27.83	64.97	523.84	21.41	28.05	27.82	62.76	523.84	22.72	26.76	**26.53**
9	64.10	587.41	21.41	27.32	27.35	64.39	586.94	21.41	27.32	27.35	63.03	586.94	22.22	**26.53**	26.55
10	64.10	587.41	21.41	27.32	27.35	64.39	586.94	21.41	27.32	27.35	63.03	586.94	22.22	**26.53**	26.55
11	63.48	650.57	21.41	**26.53**	26.84	63.77	650.11	21.41	**26.53**	26.84	63.77	650.11	21.41	**26.53**	26.84
12	63.48	650.57	21.41	**26.53**	26.84	63.77	650.11	21.41	**26.53**	26.84	63.77	650.11	21.41	**26.53**	26.84
13	64.68	524.30	21.41	28.05	27.83	64.97	523.84	21.41	28.05	27.82	62.76	523.84	22.72	26.76	**26.53**
14	64.68	524.30	21.41	28.05	27.83	64.97	523.84	21.41	28.05	27.82	62.76	523.84	22.72	26.76	**26.53**
15	65.44	429.74	21.41	29.02	28.45	65.74	429.27	21.41	29.02	28.45	62.45	429.27	23.35	27.11	**26.53**
16	65.44	429.74	21.41	29.02	28.45	65.74	429.27	21.41	29.02	28.45	62.45	429.27	23.35	27.11	**26.53**
17	65.44	429.74	21.41	29.02	28.45	65.74	429.27	21.41	29.02	28.45	62.45	429.27	23.35	27.11	**26.53**
18	65.44	429.74	21.41	29.02	28.45	65.74	429.27	21.41	29.02	28.45	62.45	429.27	23.35	27.11	**26.53**
19	64.10	587.41	21.41	27.32	27.35	64.39	586.94	21.41	27.32	27.35	63.03	586.94	22.22	**26.53**	26.55
20	64.10	587.41	21.41	27.32	27.35	64.39	586.94	21.41	27.32	27.35	63.03	586.94	22.22	**26.53**	26.55
21	64.10	587.41	21.41	27.32	27.35	64.39	586.94	21.41	27.32	27.35	63.03	586.94	22.22	**26.53**	26.55
22	65.89	366.76	21.41	29.59	28.82	66.19	366.29	21.41	29.58	28.82	62.28	366.29	23.72	27.31	**26.53**
23	66.77	209.55	21.41	30.71	29.54	67.08	209.07	21.41	30.71	29.53	61.94	209.07	24.43	27.71	**26.53**
24	67.31	52.67	21.41	31.40	29.97	67.62	52.19	21.41	31.40	29.97	61.74	52.19	24.86	27.96	**26.53**

and another during the rest of the day), pressure at the critical node just fulfils the required minimum pressure. The procedure is similar for the pressure-modulated PRV. The main difference is that the adjustments to the piezometric head downstream of the PRV must be calculated for all the time steps of the simulation period. The simulation period considered here is 24 h and the time step is 1 h, and so there can be 24 different working conditions. As the pressure-modulated system exploits the pressure to its limit (for each time step, there is always one node reaching the required minimum pressure), the benefits are maximized.

Table 9 shows the influence of the reservoir elevation on the daily benefits, for a fixed-outlet PRV located at a DMA entry point (here used to illustrate the pressure upstream of the DMA entry point). As the initial service pressure (Phase 1) at the critical node gets closer to its required minimum pressure, the benefits from pressure management get lower. At the limit, when the reservoir elevation just ensures the required minimum pressure at the critical node (approximately 80 m), pressure management is no longer possible. Figures 4, 5 and 6 show, for this case study network, respectively, the influence of the

Table 9. Influence of the reservoir elevation (pressure upstream the DMA entry point) on the daily benefits.

	Phase 1 (no PRV)			Phase 2 (with active PRV)				Reduction		
	DMA volume			DMA volume						
Reservoir elevation m	VL m^3	VR m^3	Critical node m	VL m^3	VR m^3	ΔH_{PRV} m	Critical node m	VL + VR %	VR %	Daily benefit €
100	2371.99	8878.02	47.43	1572.18	8811.35	21.41	26.53	7.70	0.75	766.47
95	2379.40	8870.60	42.43	1712.02	8819.01	16.32	26.53	6.39	0.58	641.58
90	2385.89	8864.11	37.43	1879.74	8828.04	11.22	26.53	4.82	0.41	488.12
85	2391.15	8858.86	32.43	2084.79	8838.87	6.10	26.53	2.90	0.23	296.36
80	2394.68	8855.32	27.43	2341.55	8852.17	0.94	26.53	0.50	0.04	51.55

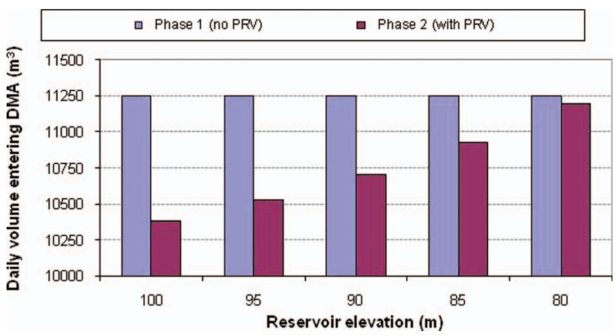

Figure 4. Daily volume entering the DMA (m^3).

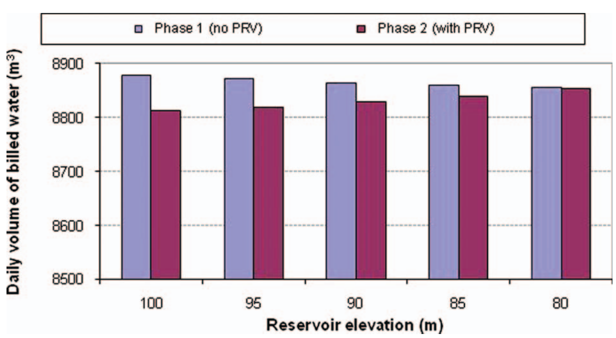

Figure 5. Daily volume of billed water (m^3).

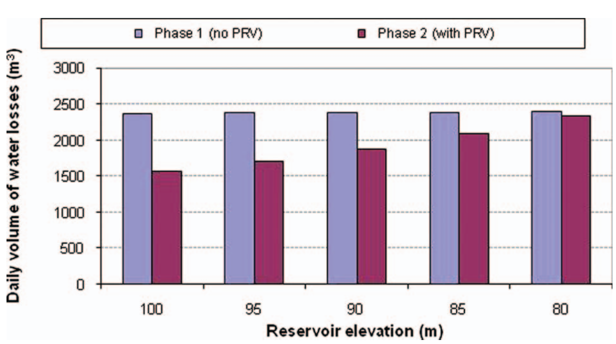

Figure 6. Daily volume of water losses (m^3).

reservoir elevation on the daily flow entering the DMA, the daily volume of billed water and the daily volume of water losses, before and after the implementation of pressure management.

5. Conclusions

As high rates of leakage represent a significant economic loss, water loss control is an important issue for water companies today, and pressure management is one of the available measures to achieve it. Water losses vary from system to system according to the length of the network, number of service connections, pressure fluctuation over the day, pipe material, soil characteristics, quality of construction, level of internal and external pipe protection, kind of maintenance and upkeep of the network and age of the system. In recent years the water companies have found that hydraulic network models are very important support tools for WDS management. The methodology proposed in this paper uses a network simulation model and the pressure/leakage and pressure/consumption relationships during MNF to estimate the water loss reduction that can be achieved from pressure management in WDS (given by the difference between the reduction of water production costs and the reduction of water sales revenue). Moreover, it can be very useful in cost benefit analysis to establish the level after which there is no more economic interest in reducing water losses (Economic Level of Leakage). The methodology was tested on two examples (a small and a large network) and the results demonstrate that pressure management can lead to significant economic savings in terms of water loss reduction, but it also results in a reduction of the water sales revenue, although its magnitude makes it irrelevant. As expected, the higher the pressure at the DMA entry point the greater the benefits that can be achieved by pressure management, and of the three different types of PRV used the most efficient is the pressure-modulated one, followed by the time-modulated and, finally, the fixed-outlet. It was also shown that the weight of the pressure-dependent consumption in the total consumption during the MNF period influences the benefits. Results showed that the daily benefits can increase slightly as the pressure-dependent consumption decreases.

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