

The influence of pressure/leakage relationships from existing leaks in the benefits yielded by pressure management

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Abstract: Water loss in Water Distribution Systems (WDS) is now an issue of growing importance and greater efforts are being made to ensure the sustainability of these public services. In recent years the concept of Fixed Area and Variable Area Discharges (FAVAD) is the basis for several models developed to support the management and control of water losses. However, in many different real-world situations, the relationship between pressure and flow rates from existing leaks is not easy to estimate (different pipe materials exhibit different relationships) and usually is based on empirical approaches or field experiences. This paper presents the results from a study conducted to evaluate the influence of different pressure/leakage relationships on the benefit yielded by pressure management. To achieve this purpose, a methodology recently developed by the authors was conveniently adapted. The methodology 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 analysis of the minimum night flow and the FAVAD concept, and it uses a pressure driven simulation model to predict the network hydraulic behaviour under different pressure conditions. The results here presented show that the benefit yielded by pressure management can change significantly for different pressure/leakage relationship exponents (N1). In being thus, a special attention should be directed to this issue in pressure management projects.

Keywords: FAVAD; minimum night flow; pressure/leakage relationship; pressure management; water losses

1. INTRODUCTION

In spite of the efforts that have been made in the last years, many studies revealed that water losses in developing countries are at levels of between 40-60% of water supplied and are about 35% in developed countries. For that reason, the implementation of sustainable water losses reduction strategies in Water Distribution Systems (WDS) is one of the most important challenges for water companies in some countries worldwide – especially in older networks and in high service pressure zones (considerably above the minimum pressure required to ensure the consumption). On the other hand, as water losses cannot be measured directly, its evaluation is not straightforward and the management can become quite complex (Puust *et al.*, 2010).

The evaluation of water losses is influenced by several factors, including: system operating pressure; frequency of bursts; speed and quality of repairs; age of pipes and fittings; quality of construction; soil characteristics; and traffic and earth movements. Recently, IWA Water Loss Task Force proposed four principal strategies for combating water losses: i) pressure management, ii) active leak control, iii) speed and quality of repairs and iv) infrastructure as set management. A single strategy or a combination of different strategies should be used, to obtain the most efficient and economic instrument for water loss reduction in each situation (Pilcher *et al.*, 2007; Thornton *et al.*, 2008). This paper shows the influence of pressure/leakage relationships from existing leaks in the benefits yielded by pressure management (on leakage rate, water consumption and income).

Pressure in WDS can be controlled in different ways by using Pressure Reduction Valves (PRV) and smart controllers. Fixed-outlet PRV has a single working condition (the valve reduces the

pressure of the incoming water to a predetermined outlet value). The use of time-modulated PRV allows several working conditions (pressure is controlled in time bands according to demand profiles). Flow-modulated PRV is the more appropriate type of control for areas with different working conditions, variable head loss and high fire flow requirements (advanced control of outlet pressure related to demand). The most suitable relationship between pressure and flow rates from existing leaks is given by Equation (1), and represents the most basic application of the concepts of Burst and Background Estimate (BABE) and Fixed and Variable Area Discharge (FAVAD). 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 L_0 to L_1 , and the extent of that change depends on the appropriate assumptions for the exponent N_1 (Lambert, 2000).

$$L \text{ varies with } P^{N_1} : L_1 = L_0 \times \left(\frac{P_1}{P_0} \right)^{N_1} \quad (1)$$

The exponent of the above equation is a calculation factor based on the piping system and 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) and these relationships are shown in Figure 1. However, in real applications, the values obtained from several field experiences shows that the exponent N_1 generally varies between 0.50 and 1.50.

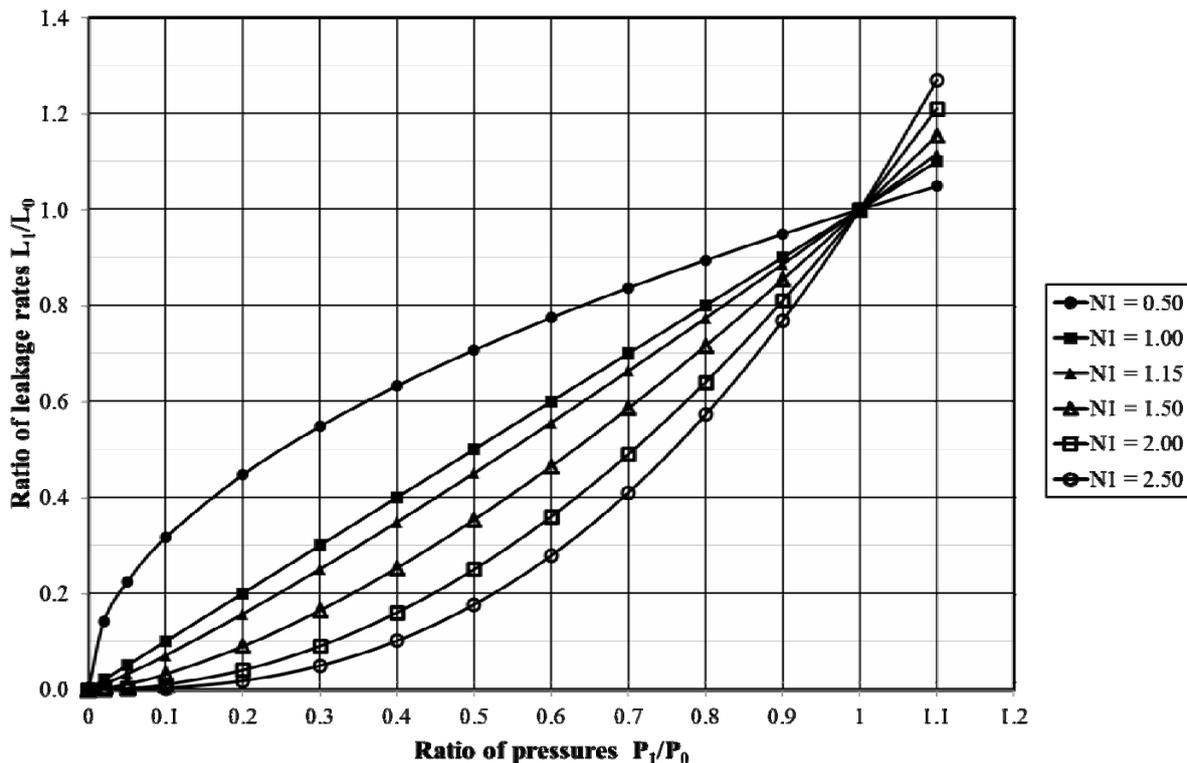


Figure 1. Relationships between pressure and leakage rate using the N_1 Approach (Lambert, 2000).

In many different real-world situations, the relationship between pressure and flow rates from existing leaks is not easy to estimate (different pipe materials exhibit different relationships) and usually is based on empirical approaches or field experiences. The remainder of this paper is used to illustrate the benefits yielded by pressure management on leakage rate, water consumption and income for different relationships between pressure and flow rates from existing leaks. The benefits

evaluation is performed by a computational application previously developed by the authors (Gomes *et al.*, 2011). It is based on the analysis of the Minimum Night Flow (MNF) and the FAVAD concept, and it uses a pressure driven simulation model to predict the network hydraulic behavior under different pressure conditions.

2. METHODOLOGY

2.1 Benefits yielded by pressure management

Once the WDS consumption has been calculated and the reported bursts repaired, total water losses can be estimated by the difference between the total volume of water entering the WDS and the authorized consumption. As a result of pressure management, the total reduction of water losses volume at the WDS entry point (ΔVL) is given by the difference between the current water losses volume (VL^{Phase1}) and the estimated water losses volume after pressure reduction (VL^{Phase2}):

$$\Delta VL = (VL^{\text{Phase1}} - VL^{\text{Phase2}}) \quad (2)$$

As pressure is known to influence water consumption, 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}):

$$\Delta VR = (VR^{\text{Phase1}} - VR^{\text{Phase2}}) \quad (3)$$

Knowing the cost of water production per m^3 (C_p) and the selling price per m^3 (C_v), equation (4) estimates the direct benefits that can be achieved with pressure management in WDS (reduction of water production minus the reduction of billed water):

$$\text{Benefits} = C_p \times \Delta VL - (C_v - C_p) \times \Delta VR \quad (4)$$

The computational application uses the ‘water losses management international best practices’ (BABE and FAVAD concepts) and can be summarized as follows (Gomes *et al.*, 2011):

- *Phase 1 (before pressure reduction)*

Considering that water losses reduction depends on the nodal pressure, first the total flow entering the WDS is divided by all nodes – according to the number of service connections (water consumption) and network length (water losses). Knowing that the minimum water consumption and water losses can be calculated during the MNF period (when most people are not ‘active’ and it is easier to estimate and/or measure water consumption), the total outflow at node j ($QT_{j,MNF}$) is divided into three parts (admitting that the whole water consumption is authorized and billed – revenue water): the pressure-independent consumption, QRC_{indep} (e.g. toilet flushing, roof tanks, washing machines, dishwashers), the pressure-dependent consumption, QRC_{dep} (e.g. shower use, hand washing, watering gardens) and the water losses as pressure-dependent – QRL_{dep} (water losses downstream of the customer meter) and $QNRL_{\text{dep}}$ (water losses upstream of the customer meter – non-revenue water). After that, taking the service pressure ($P_{j,MNF}$) and the non-revenue water ($QNRL_{\text{dep},j,MNF}$) as a reference, the amount of non-revenue water ($QNRL_{j,t}$) and total revenue water ($QR_{j,t}$) can be extrapolated for the remaining simulation period, at node j at time t , by Equations (5) and (6), respectively. The exponent $N1$ expresses the pressure/leakage relationship.

$$QNRL_{dep,j,t}^{Phase1} = QNRL_{dep,j,MNF}^{Phase1} \times \left(\frac{P_{j,t}^{Phase1}}{P_{j,MNF}^{Phase1}} \right)^{N1} \quad (5)$$

$$QR_{j,t}^{Phase1} = QT_{j,t}^{Phase1} - QNRL_{dep,j,t}^{Phase1} \quad (6)$$

▪ *Phase 2 (after pressure reduction)*

For each instant of the simulation period, the total outflow in each network node (QT^{Phase2}) can be estimated by Equation (7) – adjustment of Phase 1 revenue water ($QRL_{dep} + QRC_{dep} + QRC_{indep}$) and non-revenue water ($QNRL_{dep}$) to the Phase 2 pressure conditions. The exponent N1 expresses the pressure/leakage relationship and the exponent N2 expresses the pressure/consumption relationship (applied solely to the pressure-dependent consumption).

Q varies with P^N :

$$QT^{Phase2} = \left(QRL_{dep}^{Phase1} + QNRL_{dep}^{Phase1} \right) \times \left(\frac{P^{Phase2}}{P^{Phase1}} \right)^{N1} + QRC_{dep}^{Phase1} \times \left(\frac{P^{Phase2}}{P^{Phase1}} \right)^{N2} + QRC_{indep}^{Phase1} \quad (7)$$

3. CASE STUDY

In previous studies the authors demonstrated that a small reduction of the service pressure can produce a significant reduction of water losses through leaks (Gomes *et al.*, 2011; Gomes *et al.*, 2012a; Gomes *et al.*, 2012b). In order to study the influence of pressure/leakage relationships from existing leaks in the benefits yielded by pressure management (on leakage rate, water consumption and income), the water network presented in Figure 2 was used – urban area with 20,833 inhabitants (300 litres/inhabitant/day) and 5,212 service connections. This network has 42 pipes and 33 junction nodes and the nodes elevation varies between 134m and 146m. The network has approximately 10km and is gravity fed (reservoir elevation is 177m). The maximum and minimum service pressures are 41.94m (node 15) and 31.75m (node 32), respectively, and the maximum daily pressure fluctuation is 5.06m (node 32). The minimum pressure required is 18.37m. The pipe material is polyvinyl chloride.

The best practices from the water industry suggest that pressure management is an effective way to control the amount of water losses in WDS, especially in older networks and in high service pressure zones. A leak in a pipe has an expected leakage rate based on the size and shape of the hole and the pressure. Typical burst flow rates are specified at a standard pressure, and can be adjusted to actual pressure using appropriate assumptions for the exponent N1 values. However, the pressure reduction can also reduce authorised consumption in systems with no intermediate storage. For that reason, before implementing pressure management in WDS, it is necessary to understand the different types of water consumption and the pressure/leakage relationship. In real world WDS, the water consumption is likely to vary with the square root of pressure ($N2 = 0.5$) and the pressure/leakage relationship depends upon the type(s) of existing leaks and pipe material (N1 can change between 0.5 and 2.5, or more). Although pressure management reduce authorised consumption, in systems without residential water tanks, the impact in the benefits yielded by pressure management is reduced because it only affects the pressure-dependent consumption and the size of the hole does not change significantly with pressure (water consumption is controlled by taps). On the other hand, the unreported leakage can represent an important economic loss for water companies worldwide, and as it is not easy to define the exponent of the pressure/leakage relationship (N1), a sensitivity analysis is performed in this paper.

The exponent of the pressure/leakage relationship can be obtained from field experiences during the MNF, when most people are not ‘active’ and it is easier to estimate and/or measure water consumption. However, the inappropriate pressure/leakage relationship may lead to different

decision makers' options, and can affect the quality of service provided to customers. To understand the influence of different pressure/leakage relationships from existing leaks in the benefits yielded by pressure management, some reference data reported in the literature are used during the MNF (WRc, 1994):

- Losses downstream of the delivery point = 0.5 litres/service connection/hour
- Minimum domestic night flow pressure-independent = 8 litres/inhabitant/hour
- Minimum domestic night flow pressure-dependent = 2 litres/inhabitant/hour
- Percentage of active population = 6 %
- Exponent of the pressure/consumption relationship (N_2) = 0.5

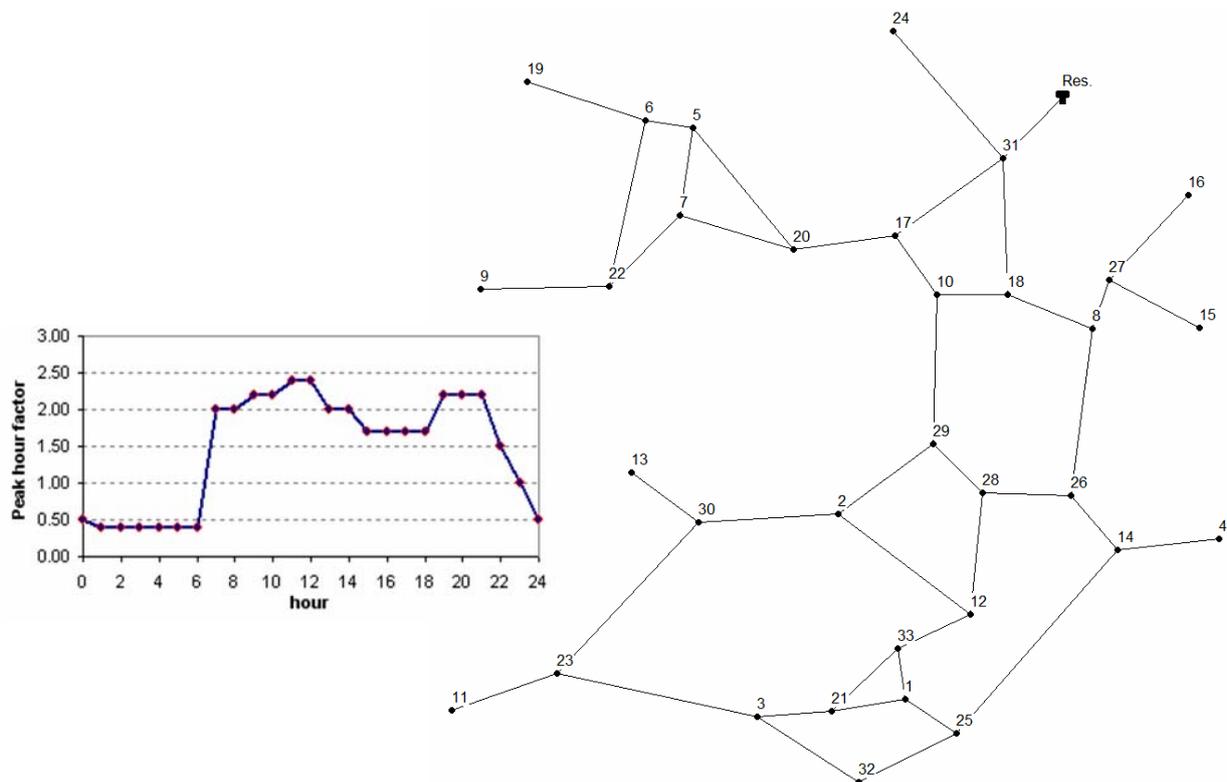


Figure 2. Network scheme and water consumption daily pattern.

In this case study, the net daily benefit yielded by pressure management corresponds to the difference between the cost reduction in water production and the reduction of billed authorised consumption. As the maximum daily pressure fluctuation was relatively low (about 5m at node 32), a fixed-outlet PRV was implemented at the system entry point. The procedure adopted here consists in 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. For a fixed-outlet PRV there is a single working condition and the adjustment equals the minimum difference between the service pressure and the minimum pressure required, evaluated at the critical node for all time steps of the working period. Table 1 and Figure 3 and 4 summarize the results obtained for the case study, using different exponents for the pressure/leakage relationship (N_1 changes between 0.5 and 2.5).

As expected, the results in Table 1 show that the net daily benefit from pressure management is significantly affected by the exponent of the pressure/leakage relationship. For example, based on estimates for the cost of water production (1.0 €/m³) and selling price of water in Portugal (1.75 €/m³), when the exponent of the pressure/leakage relationship changes from 0.5 to 2.5, the net daily benefits increase from 412 €/day to 1 302 €/day (i.e. more than 215%). On the other hand, the impact of pressure management on authorized consumption is considerably lower than in the water losses. The difference between the total billed authorized consumption, in the 1st Phase for different exponents N_1 , is related with the estimate of pressure-dependent consumption and water losses

during MNF, as well as the extrapolation of non-revenue water during MNF for the remaining simulation period, by Equation (5).

Table 1. Influence of pressure/leakage relationships from existing leaks in the net daily benefits yielded by pressure management.

| Exponent N1 | PRV head loss during peak flow (m) | Total water produced (m ³ /day) | Billed authorized consumption (m ³ /day) | Total water losses (m ³ /day) | Benefits yielded by reducing water production (€day) | Cost from reduction of billed authorised consumption (€day) | Net daily benefit (€day) |
|-------------|------------------------------------|--|---|--|--|---|--------------------------|
| 0.5 | 1 st Phase | 9 376 | 7 270 | 2 106 (22.5%) | 429 | 16 | 412 |
| | 2 nd Phase | 8 947 | 7 248 | 1 699 (19.0%) | | | |
| 1.0 | 1 st Phase | 9 376 | 7 302 | 2 074 (22.1%) | 768 | 21 | 747 |
| | 2 nd Phase | 8 608 | 7 274 | 1 334 (15.5%) | | | |
| 1.5 | 1 st Phase | 9 376 | 7 333 | 2 043 (21.8%) | 1 029 | 23 | 1 006 |
| | 2 nd Phase | 8 346 | 7 302 | 1 044 (12.5%) | | | |
| 2.0 | 1 st Phase | 9 376 | 7 364 | 2 012 (21.5%) | 1 227 | 24 | 1 203 |
| | 2 nd Phase | 8 148 | 7 332 | 816 (10.0%) | | | |
| 2.5 | 1 st Phase | 9 376 | 7 394 | 1 982 (21.1%) | 1 326 | 24 | 1 302 |
| | 2 nd Phase | 8 050 | 7 362 | 688 (8.5%) | | | |

Figure 3 shows the influence of the PRV head loss on the net daily benefits, when the exponent of the pressure/leakage relationship (N1) changes from 0.5 to 2.5. The increase of the net daily benefits with the PRV head loss is not linear, and is higher for lower N1 values. The ratio of pressure (P_1/P_0), during peak demand at the critical node, changes between 0.573 (N1=0.5; N2=0.5) and 0.565 (N1=2.5; N2=0.5) and is influenced by the exponents of the pressure/leakage relationship (N1) and the pressure/consumption relationship (N2) used in the pressure driven simulation model. The change in the net daily benefits is related to the ratio of the leakage rates (L_1/L_0) from pressure reduction and the variation observed lies between 0.807 (N1=0.5; N2=0.5) and 0.347 (N1=2.5; N2=0.5).

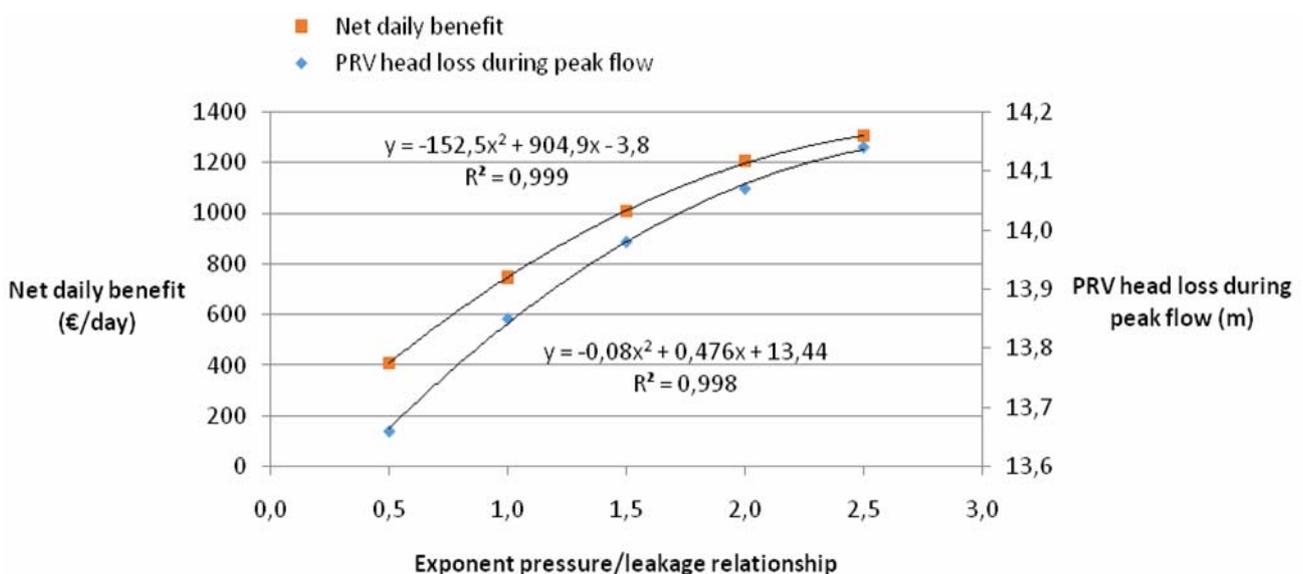


Figure 3. Influence of the PRV head loss on the net daily benefits.

Figure 4 shows the influence of pressure reduction in water production, water losses and authorized consumption, estimated from Equation (5). When the exponent $N1$ increases, the water production, water losses and authorized consumption get reduced and these relationships are not linear. Water losses observe the biggest reduction, followed by the water production and finally the authorized consumption observes only a slight reduction.

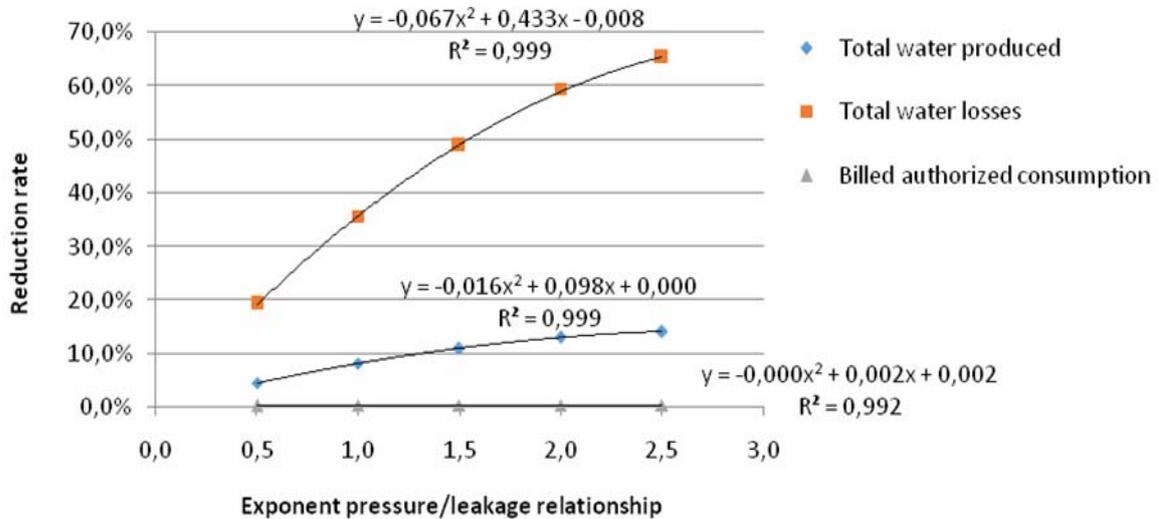


Figure 4. Influence of the pressure/leakage relationship exponent ($N1$) on the reduction of water production, water losses and water consumption.

For this case study the material used in pipes network was polyvinyl chloride and, according the literature specialized, in this case the exponent of pressure/leakage relationship ($N1$) should be around 1.5 (Gomes, 2011) – characteristic value in water distribution networks with flexible pipes materials. Looking for Table 1, when the exponent $N1$ is lower than 1.5, the daily net benefits reduces -25.75% (259 €/day; if $N1=1.0$) or -59.05% (594 €/day; if $N1=0.5$). On the other hand, if the exponent $N1$ is great than 1.5 the daily net benefits increase +19.58% (197 €/day; if $N1=2.0$) or +29.42% (296 €/day; if $N1=2.5$). So, in this case study, the estimative of global net benefits daily are more influenced when we adopted a lower value for pressure/leakage relationship, compared to the actual value of exponent $N1$ of the network. Once the daily net benefits are affected, and different decision makers' options can be obtained, a special attention should be given to this issue in pressure management projects.

4. CONCLUSIONS

Pressure management, using the BABE and FAVAD concepts, is an effective way to control the amount of water losses in WDS, but can also reduce authorized consumption in systems with no intermediate storage. However, the impact of pressure management on authorized consumption is considerably lower than in the water losses. In many different real-world situations, the relationship between pressure and flow rates from existing leaks is not easy to estimate (different pipe materials exhibit different relationships) and usually is based on empirical approaches or field experiences.

Based on the pressure/leakage relationship presented in the literature (see, Figure 1), in this paper a sensitivity analysis over the exponent $N1$ was performed for a specific water distribution network, assuming the value of 0.5 for the pressure/consumption relationship exponent ($N2$). The results here presented show that the benefit yielded by pressure management can change significantly for different pressure/leakage relationship exponents ($N1$). For example, in the case study presented, and based on values for the cost of water production and selling price of water in Portugal, when the exponent of the pressure/leakage changes from 0.5 to 2.5, the net daily benefits

increase from 412 €/day to 1 302 €/day (i.e. more than 215%). The ratio of pressure (P_1/P_0), during the peak demand at the critical node, changes between 0.573 ($N_1=0.5$; $N_2=0.5$) and 0.565 ($N_1=2.5$; $N_2=0.5$) and is influenced by the exponents of the pressure/leakage relationship (N_1) and the pressure/consumption relationship (N_2). The change in the net daily benefits is related to the ratio of the leakage rates (L_1/L_0) from pressure reduction and the variation observed lies between 0.807 ($N_1=0.5$; $N_2=0.5$) and 0.347 ($N_1=2.5$; $N_2=0.5$). Additionally, the results from a case study also demonstrate that the estimates of the global daily net benefits are more influenced when adopting a lower value of the exponent N_1 in the pressure/leakage relationship, compared to the actual value of the network. For that reason, a special attention should be given to this issue in pressure management projects.

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