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# REDUCING LEAKAGE BY REDUCING PRESSURE ON FLEXIBLE PIPE MATERIAL WATER SYSTEMS IN SOUTH AFRICA

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**ABSTRACT:**

Water losses in distribution networks is a global problem that requires management strategies. One of its major components is the leakage from the pipes, joints, and fittings. Many field and laboratory studies have shown that flow rate of a leak is proportional to pressure; therefore pressure management is a key factor to reduce the volume of water losses. This paper analyses the water savings generated on flexible pipe water systems by reducing pressure on the network.

The study is based on data collected from Pressure Management Zones (PMZ) implemented on several water networks in the province of Kwazulu Natal, South Africa. The pressure on each PMZ was regulated through the installation of Pressure Reducing Valves (PRV). Tests were performed by reducing inlet pressures in various steps. Leakage rates were obtained by deducting night consumption from the Minimum Night Flow (MNF), which were compared to pressures measured at the Average Zone Pressure (AZP) to obtain estimates of the FAVAD N1 exponent for each PMZ. The Infrastructure Leakage Index (ILI) was calculated as the relationship between Technical Indicator for Real Losses (TIRL) and Unavoidable Annual Real Losses (UARL) for each PMZ. The analysis of the field tests enables to get a new relationship between pressure and leakage rates for flexible water systems.

**KEYWORDS:** Water Losses, Pressure Management, Pressure Reducing Valve

## INTRODUCTION

*Water is a vital resource and water losses a global problem.*

The water lost through leakage (real losses) and the volumes consumed without authorization (apparent losses) together with unbilled authorized consumption is the amount of Non Revenue Water (NRW) of a water system. The World Bank estimates that the actual figure for all levels of NRW in the developing world is probably in the range of 40-50% of the water produced (Ziegler, 2011).

Water losses occur in all water distribution networks, but for technical and economic reasons it is impossible to completely eliminate them. Even though, so much has been achieved over the last few years both in knowledge and technology that it is possible to reduce them within certain economic limits.

According to the International Water Association (IWA) there are four basic activities that help to reduce real water losses: a) Active Leakage Control, b) Infrastructure Management, c) Speed and Quality of Repairs, d) Pressure Management. Although the four are important, pressure management is the foundation of a good strategy to reduce real losses because it is interrelated with the other activities. Besides the decrease in the leakage flow rate, a proper management of pressure will diminish the number and frequency of leaks, improving the speed of leak repairs and accelerating leak detection surveys. This will ultimately prolong the lifetime of the pipes and fittings, which results in a extension of the periods of infrastructure replacement (Lambert, 2003).

In recent years these methods have been applied in many water utilities, obtaining meaningful results. South Africa is one of the developing countries that have implemented these methods to reduce real losses, mainly through pressure management on the networks. This document aims to present the results of different Pressure Management Zones (PMZ) implemented during the last year on different networks located in the province of Kwazulu Natal, South Africa. On each PMZ the pressure was regulated through the installation of a Pressure Reducing Valve (PRV), and several parameters were logged before and after pressure regulation. A new theory based on the results obtained is presented at the end of the paper.


**Figure 1.-** The four leakage management activities for reducing real water losses , according to the IWA.

## REAL LOSSES

Real losses consist of any water that is entered into the system and that is not consumed by the users, since it has been lost in the process of distribution. According to their location, losses can be classified into three categories: leaks and overflows in storage tanks, leaks in service connections or leaks in distribution pipes. It is important to note that real losses occur before the meters of the service connections.

Another important classification is made depending on the size and running time of the leaks. The range of flow rates may vary from 10 litres/hour at a joint leaking up to 10.000

liters/hour due to a break in a water main. The visible leaks generally present the highest flow rate (>500 litres/hour), which rise to the surface and require no special technique for detection. They can be easily reported; therefore the volume of water lost through this kind of leaks is called reported leakage. The rest of the leaks are not visible leaks and can be classified into unreported leakage and background leakage. Unreported leakage is composed by leaks with a flow rate between 250 and 500 liters/hour, which are easily found using traditional leak detection techniques. Background leakage refers to small undetectable leaks (usually from joints and fittings) which does not surface and with flow rates that are so low that they do not create enough sound to be detectable (Thornton, 2008).

There are five key factors that influence the level of real losses, and the importance of each one of them varies widely depending on the network being analyzed. They are:

- Number of service connections
- Length of water reticulation
- Location of meters
- Percentage of time in which the system is pressurized
- Average Zone Pressure

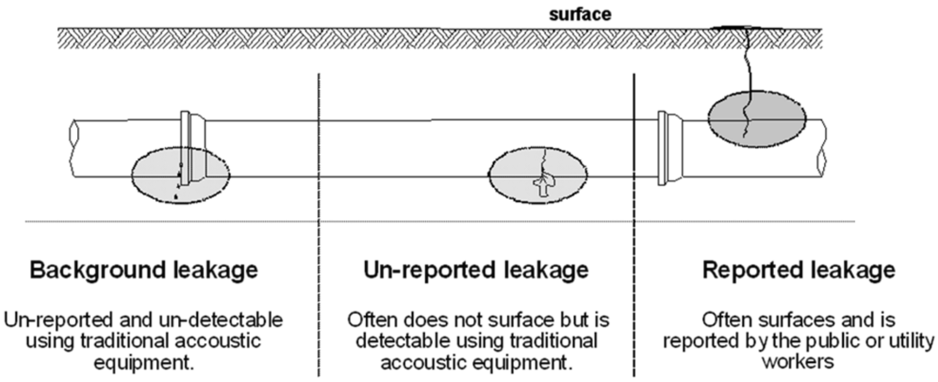



**Figure 2.-** Real Losses classification (Thornton, 2008)

## PRESSURE:LEAKAGE RELATIONSHIP

For a long time it was thought that the best way to estimate the volume lost through a leak was using the traditional orifice formula, which suggests that the flow (Q) is proportional to the square root of pressure (P) times the area (A) decreased by an orifice discharge coefficient (Cd):

$$Q = A.C_d.\sqrt{2.g.P} \qquad [1]$$

Leakage in a network is a more complex problem since there are different types of leaks: simple orifice (puncture on a pipe), crack, burst, etc. In addition, there are various pipe materials which behave differently. For example, a pressure variation on a metal pipe leak does not deform considerably the area of the orifice. On the other hand, the same pressure variation on a plastic pipe leak will deform significantly the area of it. Therefore it is extremely imprecise to use the orifice formula when analyzing leakage.

Several field and laboratory tests have proven that leakage flow rate (L) is proportional to the pressure on the pipe, and the function relating these two variables is a power law:

$$L \text{ varies with } P^{N1} \qquad [2]$$

Where N1 is the exponent FAVAD N1 Value ( Fixed and Variable Area Discharges, this concept was proposed by John May in 1994), which can vary between 0.5 and 2.5 depending on the characteristics of the type of leaks and the flexibility or rigidity of the pipes. Then if we reduce the average pressure P0 to P1, the volume lost through leakage will decrease from L0 to L1 and the magnitude of this decrement depends on the exponent N1:

$$\frac{L1}{L0} = \left(\frac{P1}{P0}\right)^{N1} \qquad [3]$$

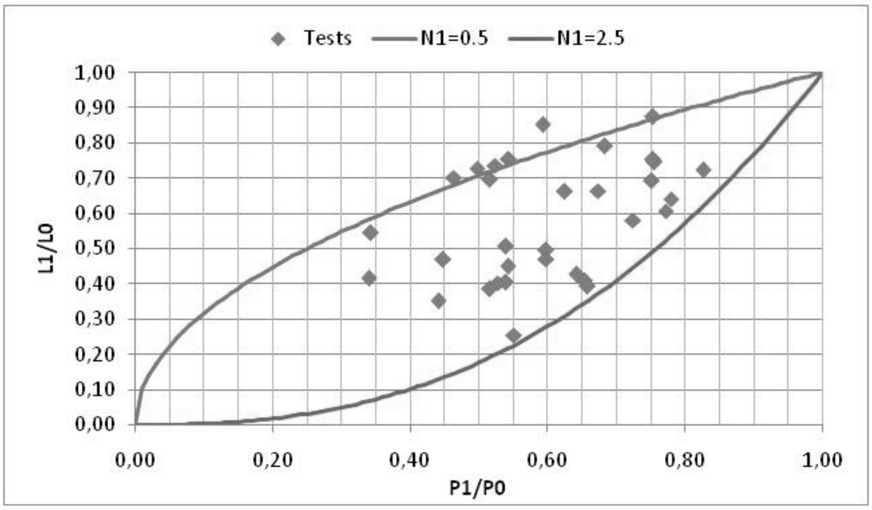



**Figure 3.-** Relationship between leakage and pressure rates, based on the traditional power law for N1=0.5 and N1=2.5. The dots show the values obtained on the Pressure Management Zones (PMZ) analyzed on this paper.

## PRESSURE MANAGEMENT

Pressure management for leakage control can be defined as:

*"the practice of managing system pressures to the optimum levels of service ensuring sufficient and efficient supply to legitimate uses and consumers, while reducing unnecessary or excess pressures, eliminating transients and faulty level controls all of which cause the distribution system to leak unnecessarily (Thornton, 2005)"*

When the pressure is regulated in a section of the network, it is called Pressure Management Zone (PMZ). A PMZ must be discreet; it has to be unlinked from the rest of the network, which can be achieved by closing isolation valves or permanently disconnecting the links (double end cap, double hydrant, etc.). Usually it has just one inlet on which a pressure reducing valve (PRV) and a flow meter are installed.

Any PMZ has a critical point (CP), which is the point of lowest pressure. It can be located anywhere on the area supplied by the PRV, depending on the particular features of the network such as topography, reticulation configuration, etc. On the other hand, there is a portion of the PMZ supporting the highest pressure. The average zone pressure (AZP) represents the medium pressure on the PMZ and it has more importance when estimating and analyzing leakage.

There are four basic ways to operate a PRV:

a) Fixed outlet: PRV modulates with changes of flow so downstream pressure remains constant over time (see figure 4).
b) Pressure modulation based on time: PRV is set to have different downstream pressures during certain periods of the day. Pressure is usually reduced during the night when minimum consumption happens.
c) Pressure modulation based on flow: PRV modulates giving different downstream pressures according to the flow rates measured on the flow meter.
d) Pressure modulation based on the CP: one data logger installed at the CP measuring the pressure communicates to the PRV which modulates in order to supply a constant pressure to the CP.

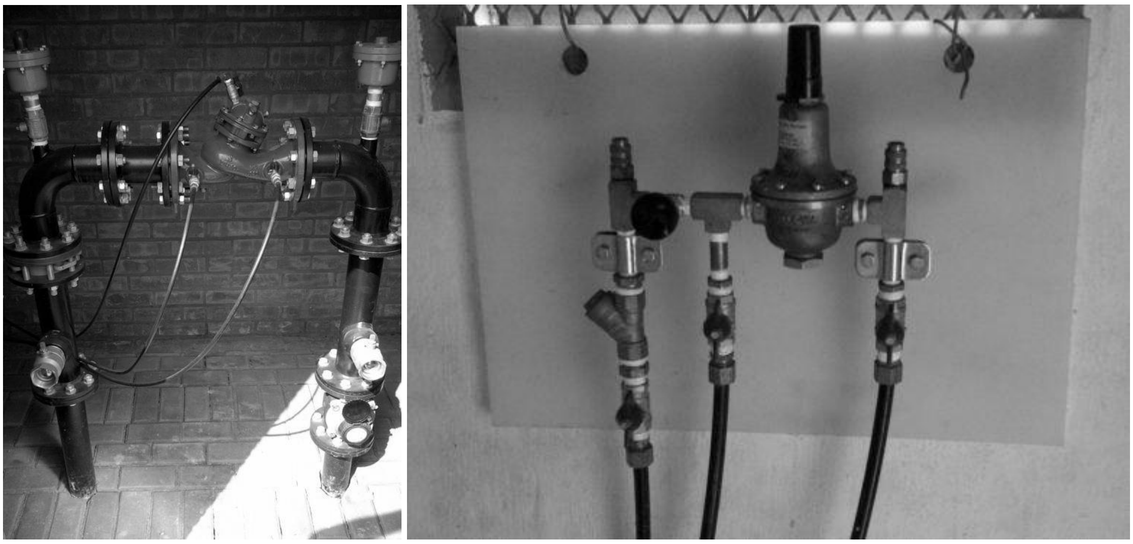


**Figure 4.-** Left: Pressure Reducing Valve (PRV). Right: Fixed Outlet pilot configuration.

## METHODOLOGY

Hundreds of PRVs were installed in Kwazulu Natal over the past two years, most of them configured with fixed outlet and/or time based modulation. 50 of these cases are analyzed in this paper, whose networks are pressurized 365 days a year (no intermittent supply). The consumers' meters are placed before the private property line, so leakage after the private property line is not considered as part of the real losses since this volume is metered so it is part of the network consumption. All the PMZs are located on urban areas and have different densities of connections (Dc = Number of Connections / Length of Mains) ranging from 22 to 124 connections per km of main. The AZP logged on the PMZs ranged from 43m to 121m (values measured before pressure regulation).

**Table 1.-** Main characteristics of the analyzed Pressure Management Zones (PMZ).

| | **Lm** [km] | **Nc** [con] | **Dc** [con/km] | **AZP before** [m] | **AZP after** [m] | **N1** [-] | **ILI** [-] |
|---|---|---|---|---|---|---|---|
| Minimum | 0.5 | 40 | 22 | 43 | 27 | 0.31 | 2.0 |
| Maximum | 30.7 | 1079 | 124 | 121 | 75 | 2.54 | 26.9 |
| Average | 5.3 | 265 | 58 | 83 | 54 | 1.30 | 8.5 |

Five data loggers were installed on each PMZ to obtain the main parameters: upstream pressure ($P_1$), downstream pressure ($P_2$), flow (Q), AZP and pressure at the critical point ($P_{CP}$). The data was captured during at least 7 days before the PRV commissioning and the same period after pressure reduction.

Length of mains (Lm), pipe materials, number of service connections (Nc), contour levels and other features of the networks were provided by the water utilities. The analysis of the results was done after collecting all the information.

The volume of real losses during the time when minimum night flow occurs ($RL_{MNF}$) was estimated for each PMZ as the difference between the minimum night flow (MNF) and the night use (NU):

$$RL_{MNF} = MNF - NU \qquad [4]$$

Pressure is not constant during the day, and its fluctuation influences the leakage flow rate. Therefore the daily pressure fluctuations were considered through the night day factor (NDF). Then the volume of real losses per day equals to $RL_{MNF}$ times NDF:

$$RL = NDF.RL_{MNF} \quad [5]$$

$$NDF = \sum_{i=0}^{24} \left(\frac{AZP_i}{AZP_{MNF}}\right)^{N1} \quad [6]$$

$AZP_i$: *Average Zone Pressure at the hour "i"*
*$AZP_{MNF}$: Average Zone Pressure during MNF*
*N1: FAVAD N1 Value*

It is impossible to compare performances of different networks using volumes of real losses obtained with the previous formulas, so performance indexes (PIs) are used. Traditionally this volume is divided per the length of mains or number of service connections, obtaining a volume of real losses per km of main or per service connection. Although both performance indexes (PIs) are useful, it is advisable to use real losses per connection when the density of connections is greater than 25 connections per km of main like in urban areas, and real losses per km of main instead when $D_C$ < 25 conn./km as in rural area (Farley, 2003). Real losses were estimated per connection because $D_C$ > 25 conn./km on the water systems analyzed on this paper. This parameter is known as Technical Indicator for Real Losses and is calculated as follows:

$$TIRL\ \left[\frac{litres}{conn.day}\right] = \frac{RL}{N_c} \quad [7]$$

Real losses cannot be eliminated from distribution systems, but there are some lower limits that have been determined during the last decades, which can be achieved at any operating pressure for well managed water utilities. When analyzing night flows, this is Unavoidable Background Leakage (UBL), consisting of individual small hidden leaks. For annual water balance, Unavoidable Annual Real Losses (UARL) consists of UBL plus losses from detectable reported and Unreported leaks and bursts. Formulas are presented below[1]:

$$UBL\ \left[\frac{litres}{hour}\right] = (20.Lm + 1.25.Nc).\left(\frac{AZNP}{50}\right)^{N1} \quad [8]$$

$$UARL\ \left[\frac{litres}{conn.day}\right] = (18.Lm + 0{,}8.Nc).\frac{AZP}{Nc} \quad [9]$$

The difference between RL and UARL represents the Potential Recovery Real Losses. On the other hand, the rate of RL and UARL is called the Infrastructure Leakage Index (ILI), which is a good PI when comparing the performance of different water systems. Formulas are presented below:

$$PRRL\ \left[\frac{litres}{conn.day}\right] = RL - UARL \quad [10]$$

$$ILI = \frac{RL}{UARL} \quad [11]$$

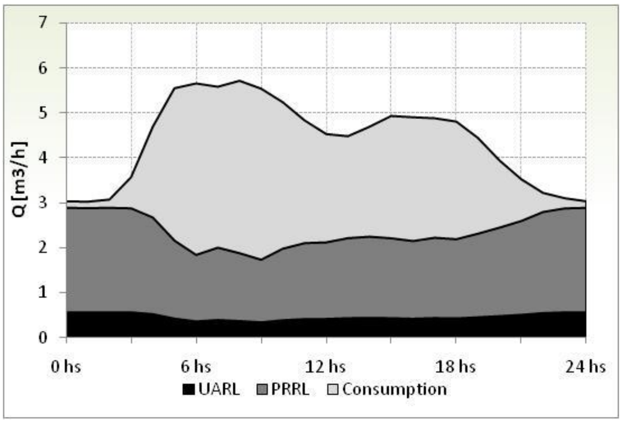
## RESULTS

The commissioning of the PRVs was successful, reducing and regulating pressure as well as decreasing the volume of water losses for each PMZ. Figures 5 and 6 show the results obtained for the PMZ called KWD1-2 before and after pressure management, in which pressure was reduced by a fixed outlet PRV. Figure 5 shows the diary inlet flow variation, which is divided into its three

[1] Worth mentioning that on the formula was not taken into account the term referring to the losses on service connections from property line to meter when customer meter is located inside the private property. The meters were not located after the property line in the water systems analyzed on this paper.

basic components: consumption (gray area), PRRL (dark gray area), and UARL (black area). Figure 6 shows the pressure variations at the critical point as well as the upstream and downstream pressure on the PRV.

Note that consumption increased from 51.0 $m^3$/day to 52.2 $m^3$/day, so was no affected despite the pressure reduction of 33.9 m (AZP was decreased from 73.5 m to 39.6 m, equivalent to a reduction of 41.6%); whereas the real losses were clearly diminished, falling from 56.1 $m^3$/day to 22.7 $m^3$/day (59.5%). The cost of water production[2] for this municipality at that time was R4.105/$m^3$, thus this installation does save about R50.000/year (US$ 5.400). The amount of water saved is similar to the cost of the installation, so the payback period for this PRV is about 1 year.



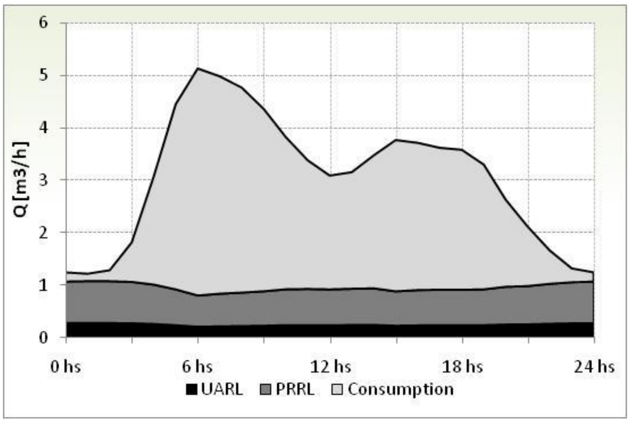




**Figure 5.** Average daily inlet flow rate to the PMZ SGP "KWD1-2", divided into the three basic components: consumption, Potential Recovery Real Losses (PRRL) and Unavoidable Annual Real Losses (UARL). The graph on the left shows the values logged before the PRV installation, while the graph on the right shows the situation after commissioning the PRV.

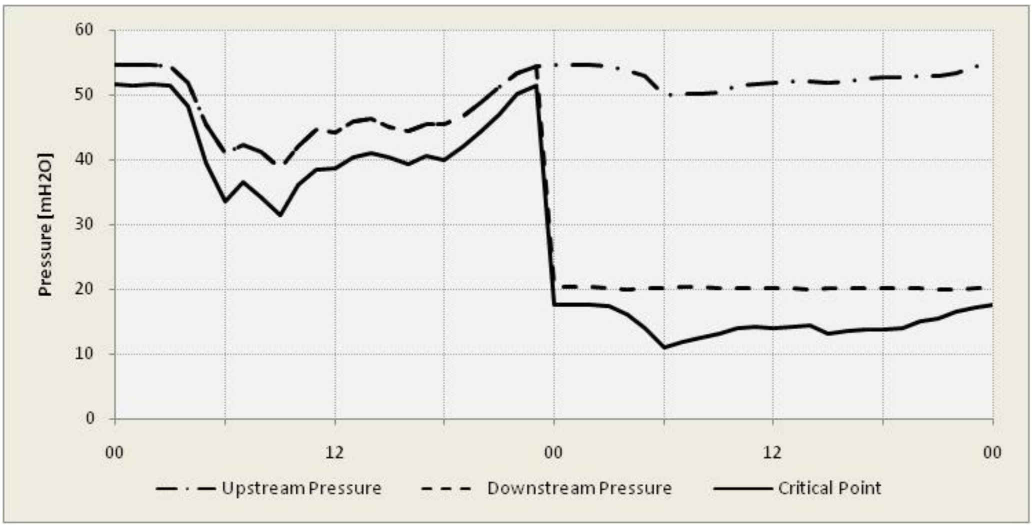



**Figure 6.** Pressure values logged before and after pressure regulation on PMZ "KWD1-2". The solid line represents the pressure on the critical point, the dash line represents the downstream pressure, and finally the dash-dot line represents the upstream pressure.

Two additional interesting aspects to highlight: the increment on the upstream pressure of the PRV and the stabilization of the pressure at the critical point, especially during peak hours. The reason of the first effect is the reduction in the inlet flow to the PMZ; this flow reduction entails a reduction of the head losses on the mains supplying the PRV, consequently producing an increment on the upstream pressure. The second effect has two different causes: a) the PRV modulation which allows to supply a constant pressure downstream of the PRV at any time, and b) the reduction of head losses on the reticulation due to the decrease of the flow rates flowing through it. The

[2] Cost of water production, which is lower than the billing cost.

reduction of flow within the PMZ consists of two processes: the first is the reduction of real losses, and the second the diminution of the flow rates used by some home accessories such as toilets, tanks, etc. The reduction of the flow rates does not affect the use of this devices, just prolong the time needed for filling.

As explained previously, the average zone pressure affects considerably the levels of TIRL and UARL. Figure 7 relates both parameters on logarithm scale with the average zone night pressure, the dots represent the values obtained for each PMZ. Field data validates the theory since TIRL and UARL increase proportionally to the AZNP following a power law, as the trend lines presented on the graph show to facilitate the understanding of the graphic.

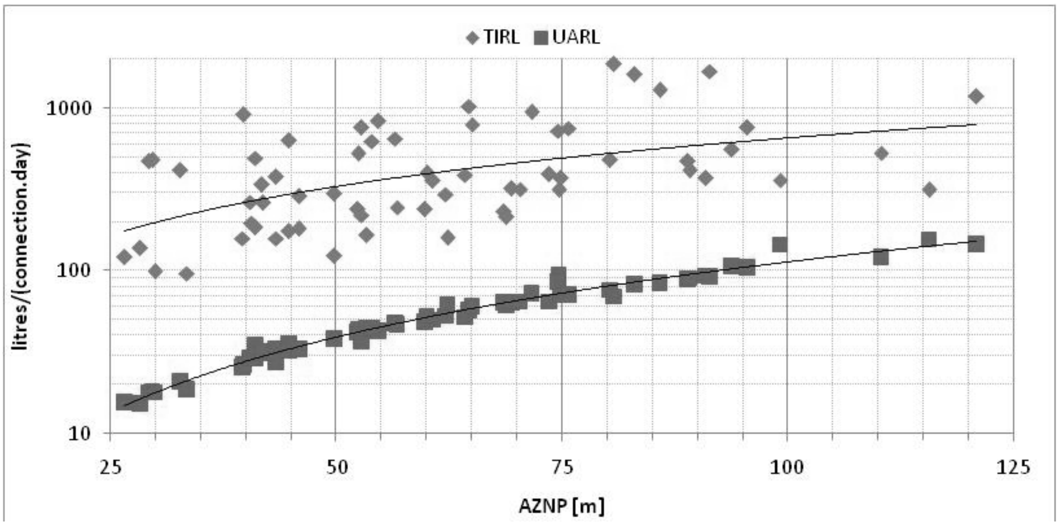



**Figure 7.** Technical Indicator for Real Losses (TIRL) and Unavoidable Annual Real Losses (UARL) related to the Average Zone Night Pressure (AZNP). The values were obtained from the logged data of the Pressure Management Zones (PMZs) analyzed.

Figure 8 shows the real losses per connection per day per m of operating pressure (TIRL/AZNP) for different values of ILI (logarithm scale). ILI is a performance index, a value of 1 happens when TIRL = UARL and indicates the best performance that can be achieved when managing a water system, whereas as it increases means that the performance deteriorates together with the level of real losses, as can be seen on the graph. The values were separated on three different groups depending on the operating pressures: a) AZP < 70m, b) 70m < AZP < 90m, and c) AZP > 90m. It proves that for a given network performance (same ILI) the volume of real losses per connection per m of pressure increases as the average zone pressure of the PMZ increments.

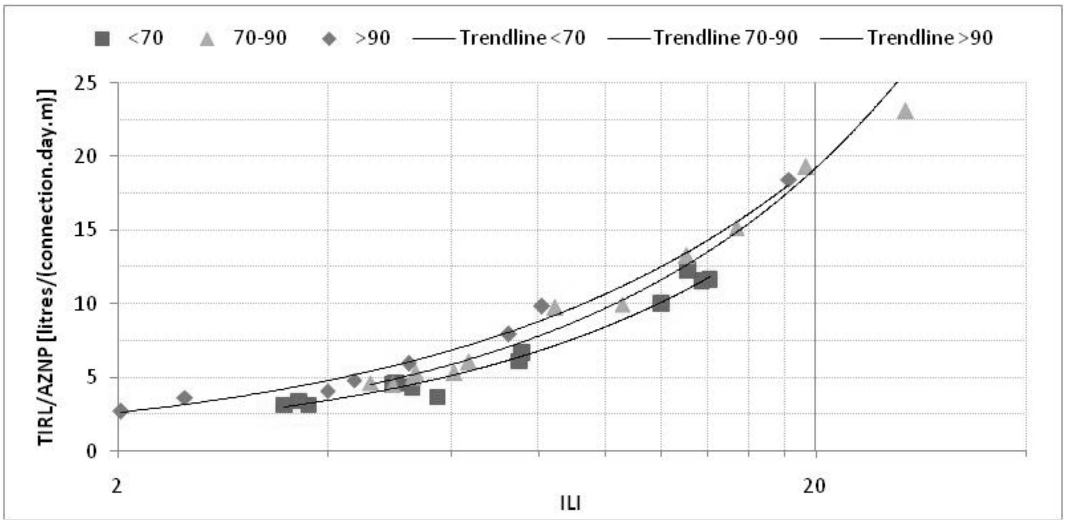



**Figure 8.** Technical indicator for real losses (TIRL) per meter of pressure, related to the infrastructure leakage index (ILI).

Finally a summary of the results is presented in Table 2 and described below:

- NDF increment: this parameter was incremented half an hour as average for all the PMZs. This means that the pressure fluctuations were diminished, consequently improving the water supply and reducing the frequency of new leaks.
- AZP reduction: Overall, there was a reduction of 29m equivalent to a 35% decrement of the previous AZP for all the PMZs. This reduction leaded to lower levels of real losses and to reduce the frequency of new leaks.
- RL reduction: real losses were reduced in 2702 $m^3$/day or 319 litres per connection per day, which generated a great water saving equivalent to R4.046.829/year (US$433.000). Figure 9 shows the real losses before and after for some PMZs analyzed.

**Table 2.-** Summary of the results

| | **NDF** [hours] | **AZNP** [m] | **RL** [$m^3$/day] | **TIRL** [l/(conn.day)] |
|---|---|---|---|---|
| Before | 22.7 | 82.9 | 6404 | 756 |
| After | 23.2 | 53.9 | 3702 | 437 |

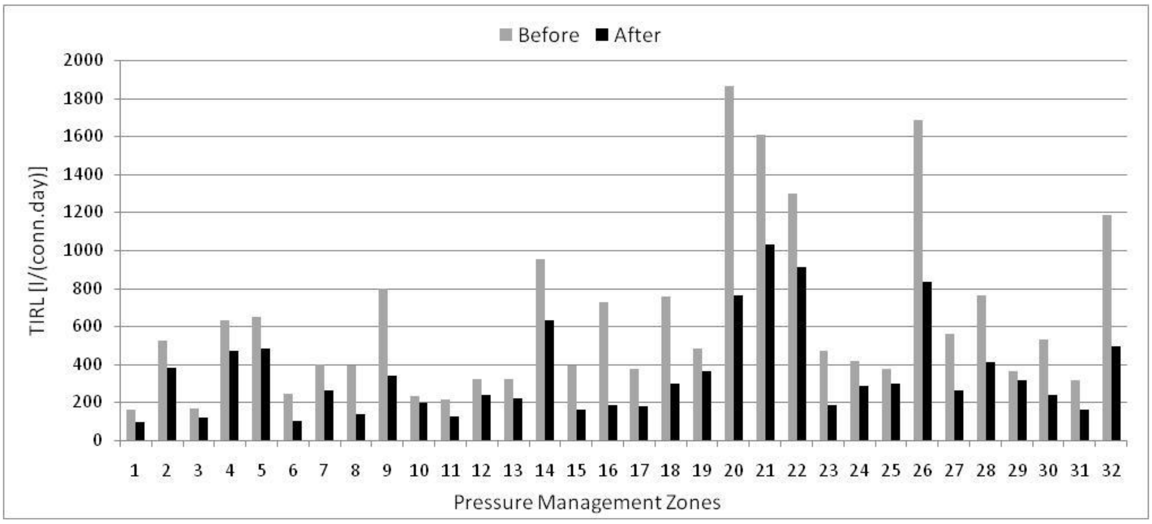



**Figure 9.** Technical Indicator for Real Losses (TIRL) before and after pressure management for 32 of the pressure management zones (PMZs) analyzed.

## NEW FUNCTION PRESION:PERDIDAS REALES

Leakage is a function of many variables: type of soil/ground, number of connections, density of connections, operating pressures, continuity of supply, etc. The data gathered from field tests suggest that the main factors (measureable factors) affecting Background and Unreported Leakage (BUL) are: Average Zone Night Pressure (AZNP), Length of Mains (Lm), Number of Service Connections (Nc) and the Night Day Factor (NDF):

$$BUL = f(NDF, AZNP, Nc, Lm) \qquad [12]$$

This problem has 5 variables, so is extremely difficult to find a function "f" to describe it. But it's possible to simplify it using "The Pi Theorem" or "The Buckingham Pi Theorem". The Pi Theorem is a method of reducing a number of dimensional variables into a smaller number of dimensionless groups. In order to use the Pi theorem a new variable is introduced: the density of the fluid (ρ). The dimensionless groups found are presented below:

$$\pi 1 = \frac{BUL.NDF.Nc}{Lm^3} = \frac{BUL.NDF.Dc}{Lm^2} \qquad [13]$$

$$\pi 2 = \frac{AZNP.NDF^2}{\rho.Lm^2} \qquad [14]$$

The values of $\pi 1$ and $\pi 2$ for each PMZ analyzed are shown in Figure 10 in a log-log graph. Accord to the results, the function relating the two dimensionless groups is a power law:

$$\frac{BUL.NDF.Nc}{Lm^3} = A\left(\frac{AZNP.NDF^2}{\rho.Lm^2}\right)^B \qquad [15]$$

$$A = constant = 7.10^{-16} \qquad [16]$$

$$B = constant = 1{,}1543 \qquad [17]$$

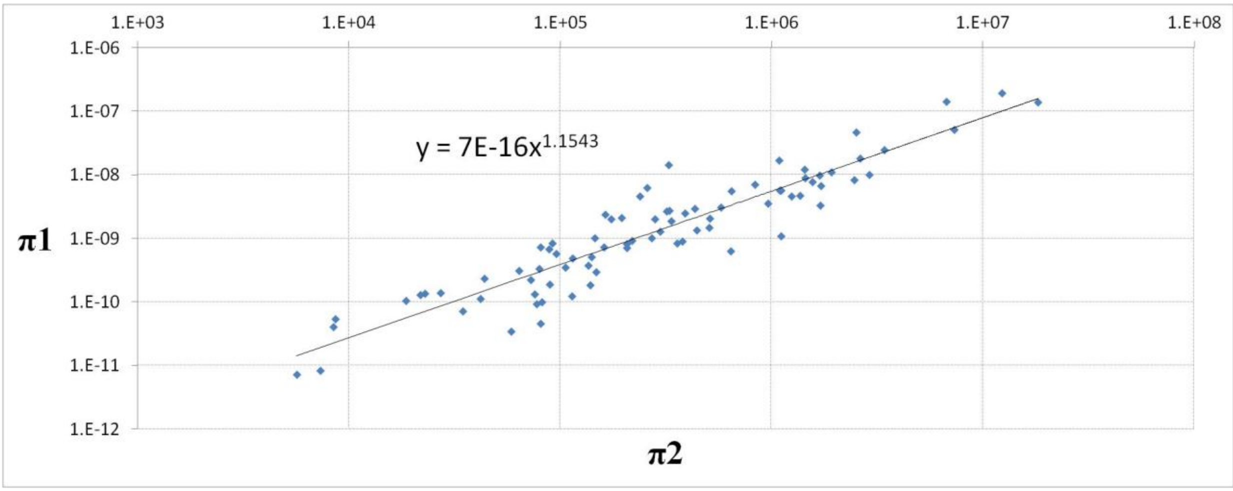



**Figure 10.** Values of π1 and π2 for each pressure management zone analyzed.

Isolating A from equation [15] and comparing a situation before and after pressure management for a system where Nc, Lm and ρ do not vary, the following formula can be reached:

$$BUL_{\boldsymbol{a}} = BUL_b.\left(\frac{AZNP_a}{AZNP_b}\right)^B.\left(\frac{NDF_a}{NDF_b}\right)^{2B-1} \qquad [18]$$

Assuming that the NDF does not change:

$$BUL_{\boldsymbol{a}} = BUL_b.\left(\frac{AZNP_a}{AZNP_b}\right)^B \qquad [19]$$

The formula [19] is equivalent to the formula [3] so it follows that B = N1. Checking the B constant obtained on this paper can be seen that this value is equal to 1.1543 which is similar to the Japanese average exponent value of 1.15 obtained by Ogura in 1979, which validates the formulas. Then the general formula for BUL is the [15] where A and B are constants. These constants will vary for each water system depending on the characteristics of the network: pipe materials, joint types, network performance, type of leaks, etc.

## CONCLUSIONS

- The installation of a pressure reducing valve on a pressure management zone increases the night day factor, which helps to stabilize and reduce daily pressure fluctuations.
- Average zone pressure reduction results in a reduction of the real losses.

- Pressure management generates increments on the upstream pressures of the pressure reducing valves.
- Consumption is not severely affected by the reduction in pressure.
- Real losses vary proportionally to the operating pressure of the system, following a power law trend line.
- For a given network performance (ILI), the real losses per connection per m of operating pressure of the network increase proportionally to the operating pressure of the sector.
- The data gathered from field tests suggests that the main factors (measureable factors) affecting background and unreported leakage (BUL) are:
    - Number of service connections
    - Length of mains
    - Average zone pressure
    - Night day factor
- The general formula for BUL is the [15] where A and B are constants. These constants will vary for each water system depending on the characteristics of the network: pipe materials, joint types, network performance, type of leaks, etc.

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