Water Losses in Aqueducts: Impacts and Management

Giuliano Ceseri[1] and Andrea Mesturini[2]

1. General Manager, Prometeo Srl, Montelupo Fiorentino, 50056, FI, Italia

2. Network Optimization Manager, CCAM, Moncalvo, 14036, AT, Italia

Abstract: Water leaks in aqueducts generate a significant economic and environmental impact, because the drinking water industry is extremely energy intensive. The paper outlines the scale of the problem. It then illustrates the guidelines defined by the IWA (International Water Association) for leak reduction. One of the approaches suggested by IWA is to implement efficient Active Leakage Control Systems, which allow for the daily monitoring of a district-level network, i.e., a network divided into Areas, which are in turn divided into Districts. Systems of this type require leak estimation algorithms, typically based on the district's MNF (minimum nighttime flow). However, the algorithms traditionally used for this estimation present several critical issues. For this purpose, an alternative algorithm (HP-Leakage Detector) was developed. By operating solely based on measurements of the flow rates entering and exiting the district, this algorithm eliminates any subjectivity in the estimate and automatically adapts to the district's constantly evolving characteristics. The paper further highlights the importance of monitoring not only leaks in the Distribution network, but also those in the Transmission network. Finally, a case study is presented that shows the significant benefits achievable through infrastructure management and pressure control, two other pillars of the IWA leak reduction strategy.

Key words: Water leaks, Active Leakage Control, pressure control, asset management.

1. Introduction: Environmental and Economic Impact of Water Losses in Aqueducts

Leaks in drinking water networks around the world have a significant environmental impact.

Table 1 shows the main data relating to water losses worldwide, in Europe, and in Italy [1-4].

The Italian situation in EU is very critical, as can be seen from Fig. 1, which highlights the losses in $m^3/km/y$ [5, 6].

The graph shows that there are significant differences across EU countries, with particularly positive outcomes in Germany, the Netherlands, and Denmark.

The impact of leaks is significant both economically and environmentally. Indeed, leaked water causes erosion, which often manifests itself dramatically, as can be seen in Fig. 2 (Lungarno Torrigiani, Florence, 2016).

The economic impact, on the other hand, is determined by various factors:

1. Lost water has been energized and treated;

therefore, it has a production cost. It is estimated that the integrated water cycle in the EU is responsible for approximately 3.5% of total electricity consumption. Therefore, not only we have enormous costs associated to losses, but it also results in significant and unnecessary CO_2 production.

2. The greatest cost however, at least in Italy, is the one related to finding and repairing leaks.

To provide an indication of the economic values at stake, in the event of significant losses, we report in Fig. 3 the losses data for an Italian District of approximately 2,000 inhabitants.

The figure highlights that, with a volume of approximately 1,482 m^3 of water introduced in the District, daily losses of approximately 823 m^3 (55.58%) occurred, which, with a production cost of € 0.2/m^3, produces an economic loss of approximately € 60,000.00 in dispersed water over a year: therefore, a very significant economic and environmental impact for a quite limited amount of inhabitants.

Corresponding author: Giuliano Ceseri, prometeo general manager, research field: aqueduct efficiency.

Table 1   World data of water losses in waterworks.

	World	Europe	Italy
Annual lost volume (m³)	126 billion m³	27 billion m³	3,4 billion m³
Average leak (%)	33%	24%	42%
Annual estimated economic value (€/$)	50 billion $	12 billion €	3 billion €
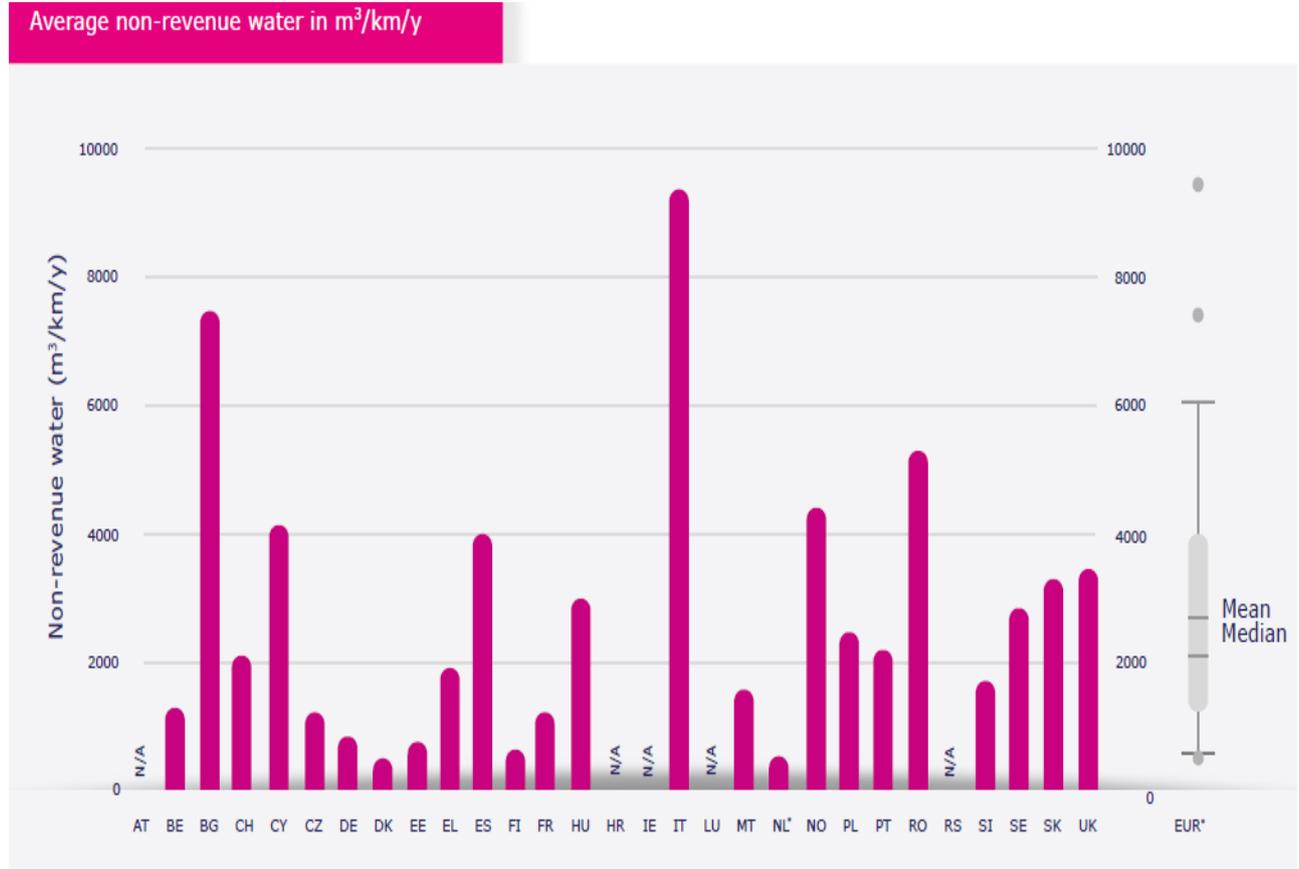
Fig. 1   Situation of losses in various EU countries.

Fig. 2   Erosion-related accident: Florence, 2016.

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Entered volume (cm)	1.482,17
Losses (cm)	823,75
Losses (%)	55,58%
Annual economic value (€)	60.133,75
HP Index (mc€/km/gg)	5,88
Water Value (€/mc)	0,20
Indicators: ⚠	

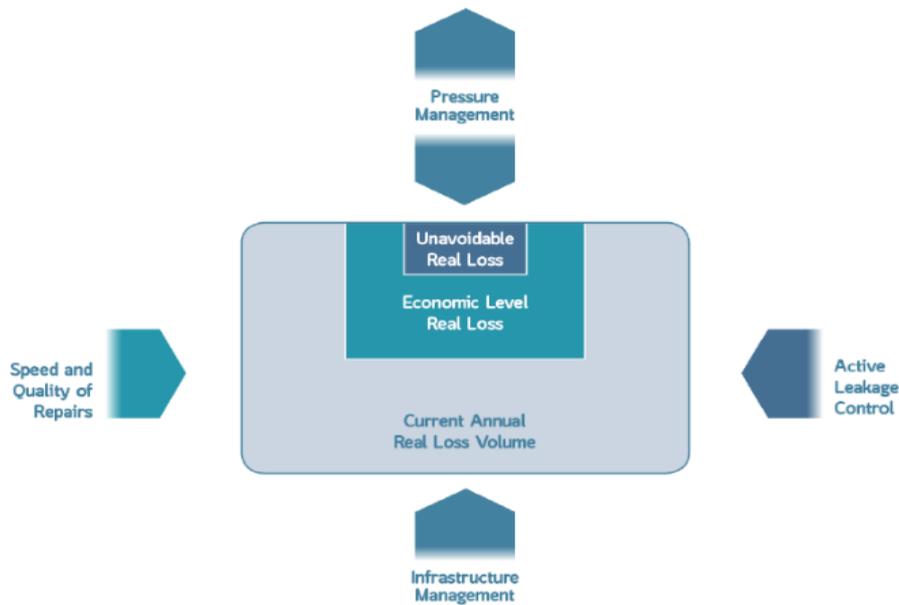**Fig. 3   Losses data in an Italian District of about 2,000 inhabitants.**

Fig. 4   The four crucial strategies for Leakage Control IWA (International Water Association).

Faced with such significant data, it is essential to ask ourselves how we can address this phenomenon with such a significant social impact,

IWA (International Water Association) suggests four lines of action for leak containment [7]. They are shown in Fig. 4.

The four proposed strategies are:

1. *Pressure management*: this is one of the most effective courses of action, in many cases the most effective at all. Optimal pressure control produces significant effects even on fragile networks. The impact of pressure reduction is enormous on losses, energy consumption and therefore on the carbon footprint, breakages and maintenance costs. Statistically, there is an average reduction in percentage losses of 1 for every percentage point of reduction in the average pressure of the water district, while the breakage rate has an even more significant correlation with the pressure, on average 1.4 [8].

2. *Active Leakage Control (ALC)*: this term refers to the availability of systems capable of monitoring leaks in the various districts of a water network, on a daily basis. Most of this paper is dedicated to this topic.

3. *Infrastructure management*: this area involves the identification of damaged pipes and their replacement with new ones. Replacing a damaged pipe is generally considered to produce economic benefits within 7-10 years, because of the associated reduction of repair costs. Therefore, even if the investment is significant, the return on investment is significant as well.

4. *Speed and quality of repairs*: this factor is strongly influenced by the performance of the ALC system discussed in Point 2. In fact, ALC allows for the rapid detection and quantification of daily leaks, thus allowing for timely planning of maintenance work and monitoring of repair efficiency.

2. Optimization of Aqueducts

Let's now examine the topic of waterworks optimization

2.1 Importance of Optimizing Maintenance Interventions on the Distribution Network

As already mentioned, a good ALC system is crucial for optimizing maintenance interventions for finding and repairing leaks.

Often, in fact, small hidden leaks produce greater dispersion than large breakages, which are immediately reported by the users: see the following Fig. 5 [7].

More specifically, the role of a good ALC system involves the following aspects:

1. Timely detection of hidden leaks through daily leak calculations and monitoring of leak trends.

2. Correctly prioritizing of interventions. In an aqueduct, water leaks occur daily in all Districts; therefore, it is essential to prioritize interventions based on the following criteria:

a. Intervene in districts with leaks exceeding the "normal" threshold.

b. Give priority to districts with the highest losses in m³/km, because their leaks are easier to locate.

c. Give priority to districts with the highest water production value, because those are the ones where leakage is more expensive.

d. In summary, correctly prioritizing the actions will result in lower losses and costs at the end of the year.

3. Especially in presence of damaged network branches, repairs are concentrated in specific areas and often they do not alleviate the problem. The ALC system is therefore crucial for verifying the post-intervention return to normality and consequently the effectiveness of the maintenance action.
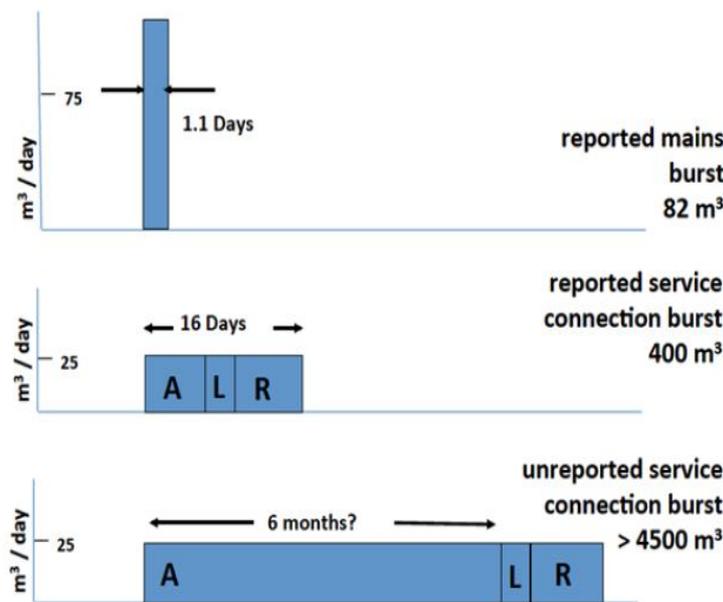

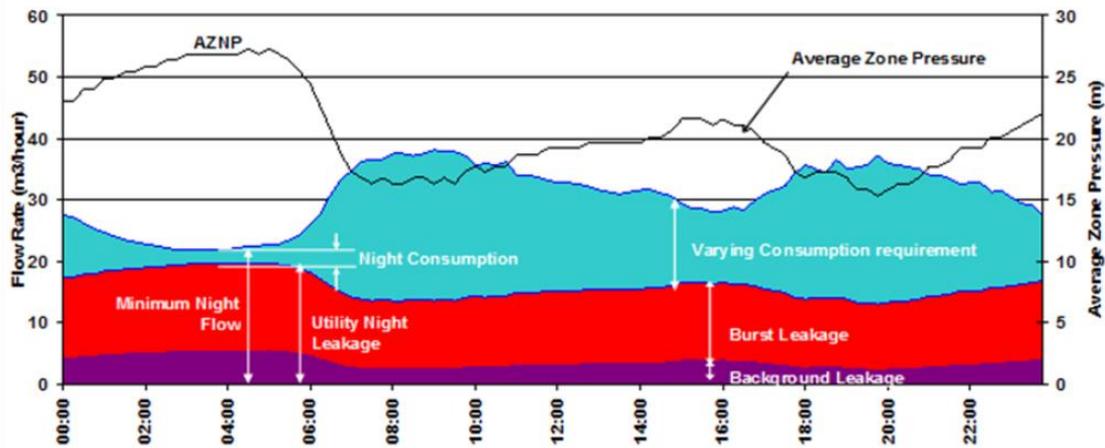**Fig. 5 Examples of the effect of various breakage typologies.**

Fig. 6   Conceptual scheme for the loss estimation in a district.

2.2 Estimating the Value of the Water Losses in the Distribution Network

If the districts are not equipped with a measure of the entering water and with smart water consumption meters with daily user data acquisition, the leakage estimate can only be performed with statistical calculations. The most widespread calculation method follows a conceptual framework illustrated in Fig. 6 [7] and is based on an elaboration of the district's MNF (minimum night-time flow) rate.

The standard formulas for calculating real losses are as follows:

$$Q_L = Q_{DMA} - Q_{CNU}$$

where Q_L is the night flow in m³/h attributable to the losses, Q_{DMA} is the total night flow (MNF) entering in the district (night time water balance) and Q_{CNU} is the legitimate night water consumption attributable to users.

$$Q_{CNU} = N_U * C_I$$

Q_{CNU} is in turn given by the product of the number of users served by the legitimate nightly consumption of a single user.

Finally

$$V_L = Q_L * HDF$$

where V_L is the daily leakage volume in m³/d and HDF is the so-called hour-day-factor, which considers the pressure difference at various times of the day and the nature of the pipe materials.

The formula for HDF is as follows:

$$HDF = \sum_{I = 1,24} (P_I / P_N)^{NI}$$

where P_I is the pressure at hour I at a significant point (AZP) of the DMA, P_N is the average night pressure and N1 is an exponent to be chosen based on the pipe materials.

The problem, however, is that the use of these formulas presents significant critical issues [9]:

1. The number of inhabitants served N_U can vary very much and with great frequency in certain areas, such as tourist areas or business districts. Furthermore, the Public Utility knows very well the number of connections in the district, but can only estimate the number of inhabitants served, especially for urban districts.

2. The legitimate night-time consumption per inhabitant C_I is subject to large variations depending on the type of District [10, 11], and varies on different days of the week (Monday is not like Saturday) and in different seasons (in August it is not like in February).

3. An accurate calculation of the HDF, on the other hand, is rather complex [12] (and certainly subject to a certain level of error) and can therefore generate further significant variations in the result of the loss estimate. For example, in the European Union Document [7] we find the following sentence: *the NDF (alternative acronym for HDF) can vary from 15 hours a day to 30 or more, depending on the pressure variation (over 24 hours).*

Fig. 7   District daily data of Web HP-Leakage Detector.

4. The consequence is that the Public Utility is forced to re-evaluate daily (manually or automatically) the three previous parameters for each district managed by its ALC system (usually hundreds). Otherwise, it may incur estimation errors that can reach up to 40% or more, consequently altering the maintenance intervention priorities, estimated by the ALC system [9].

This is why an innovative algorithm called HP-Leakage Detector [9, 13] was developed, capable of estimating the daily leakage value of the district through pattern recognition, applied only to the flows entering the district over a 24-hour period.

This algorithm has the following advantages:

1. It estimates leakage based on flow measurements alone, thus eliminating the need for subjectively defined (and therefore potentially arbitrary) parameters.

2. The absence of parameters allows for good results from the first day of use of the ALC system (while the implementation of an ALC using traditional algorithms typically takes years). Furthermore, the absence of parameters eliminates the daily work of continuously reconfiguring the ALC system.

3. It performs a sophisticated self-diagnosis of flow measurements. The self-diagnosis allows for the identification of days in which leakage estimation is not possible and the definition of the corrective actions necessary to restore correct operation (for example, maintenance of flow meters).

4. It performs an automatic reconfiguration (via machine learning) of the coefficients used in the measurement self-diagnosis system.

Fig. 7 shows the district's daily data screen produced by Web HP-Leakage Detector, a "Software as a Service" which uses the algorithm described above.

2.3 Importance of Optimizing Maintenance Interventions on the Water Transmission Network

Typically, ALC systems focus on analyzing water losses in Distribution networks.

This makes sense, because the amount of losses in Distribution networks is greater than that in Transission networks.

However, Transmission losses are sometimes significant.

In Italy, for example, the following data are available for 2022 [14]:

- Water withdrawal: 9.1 billion m^3.
- Delivery into cities: 8.0 billion m^3.
- Transmission losses: ~1.1 billion m^3 (12.1% of withdrawal).
- Distribution losses: 3.4 billion m^3 (42.4% of delivered).
- Therefore, Transmission losses constitute 24% of total losses.
- Furthermore, some Italian regions, such as Sicily, Sardinia, and Basilicata, have Transmission losses usually higher than the national average, because supply water is transported over longer distances.

It is therefore becoming important in a modern ALC system to include Transmission loss counting in the overall computation and to manage the daily losses for the various supply lines.

It must be noted, however, that the management of Transmission leaks is different from that of Distribution leaks.

The SaS Web HP-Leakage Detector will include Transmission leak management in the next release, with the following features:

1. Leak estimation will be performed using a different algorithm than the one used for Distribution, because Transmission leaks can normally be estimated by calculating the daily volumes on the supply lines.

2. The system will also allow the management of "virtual" flow meters, for managing lines where not all flows are measured.

3. The self-diagnosis system for flow measurements will be even more advanced than that for Distribution measurements, because flow measurements for large diameters are often particularly prone to technical malfunctions.

3. Results: Quantifying the Benefits of Optimization in a Real Case Study

We would like to conclude by presenting a real-world case study that highlights the enormous economic and environmental benefits that can be achieved through water network efficiency improvements.

The examined case is the Brusasco Cavagnolo District of CCAM, a small Public Utility in northwestern Italy.

The general characteristics of the District were as follows:

1. Network length: 13.27 km.

2. Number of user connections: 828.

3. Connections density: 62.4 per km.

4. Average pressure: 74 m.

CCAM's ALC had shown an anomalous loss figure for a long time, which prompted the Public Utility to initiate a study.

The District's study highlighted that there were some network pipes, several hundred meters long, that were producing significant pressure drops, requiring to keep high pressure in the District.

The following interventions were therefore planned in 2008:

1. Replacement of pipes in the two critical branches of the network.

2. Installation of a PRV (pressure regulating valve) with day/night regulation.

3. Reduction of the District's operating pressure.

The analytical results obtained were those highlighted in Table 2.

In economic terms, the investment of approximately €130,000 (including long-term interventions such as replacing pipes) produced a ROI (return on investment) in approximately 5 years. This ROI was computed considering also the reduction in water billing, resulting from the reduction in pressure, and not taking into account factors that are difficult to quantify, such as the extension of the asset's lifespan.

The District's overall operating costs were optimized as shown in Table 3.

Table 2   Results of the optimization of the CCAM District.

Indicators	April 2008	June 2010
Daily volume feeded to the District (m^3)	765 m^3	437 m^3
ILI	3.5	1
Volume feeded April-December (m^3)	200,000 m^3	130,000 m^3 (-35%)
Avarage pressure in the District (bar)	7.41	4.60

Table 3   Management costs for the CCAM District.

District management costs	2009	2010	2011
Management costs per km (€)	2,123 €	407 €	108 €
Repairs on network mains	12	3	3
Repairs on users connections	20	8	3

It should be noted that, in this case, the intervention reduced the average operating pressure by 38% but required the replacement of some pipes. On the other hand, it is often possible to achieve average pressure reductions of 20-25% simply by introducing advanced electronic pressure regulation, thus with investments having a ROI in 1-1.5 years.

4. Conclusions

The case study presented in the previous paragraph clearly shows the enormous economic and environmental benefits that can be achieved by adopting the IWA optimization approach, shown in Figure 4.

Of course, each district has different characteristics and consequently the achieved results will be different case by case, but our experience in Italy tells us that the following average goals can be reasonable in most of cases:

1. Pressure reduction: 20%.

2. Losses reduction: 20%.

3. Energy consumption and carbon footprint reduction: 30%.

4. Maintenance costs and breaks rate: 30%.

Furthermore, it should be considered that each optimization intervention brings an extension of assets life.

These results are particularly significant because they can be obtained with investments that frequently

have ROIs in 1 to 5 years (the latter only in case of pipes substitution).

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