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Estimating Leakages in Water Distribution Networks Based on Inlet Flow Data

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Abstract

The estimate of current real losses in water distribution networks (WDNs) is of crucial importance in order to plan investments for rehabilitation, assess the rise of leakages over time, and possibly drive procedures for failure identification and repair. Nonetheless, many WDNs worldwide do not have flow/pressure monitoring within the system yet, and the inlet water volume or flowrate is the only recorded data. Developing reliable procedures to estimate real losses in such circumstances is essential to assess the leakage phenomenon and, eventually, drive the upgrade of existing monitoring systems. This work proposes a simple *bottom-up* methodology to estimate leakages using WDN inflow data series only, exploiting the seasonal fluctuation of water consumptions. It resorts to a data assimilation strategy whose formulation is consistent with the physical behavior of WDNs and requires the estimate of few numerical parameters. As a side result, the methodology allows as well the estimation of user's daily and night water consumptions, thus being useful to verify or integrate other leakage estimate methods. The methodology is discussed and demonstrated on both synthetic and real WDNs.

Introduction

Most urban water distribution networks (WDNs) worldwide are facing the so-called "replacement era" (AWWA, 2011) because they are approaching the end of their technical life since their building *ex-novo* and/or expansion in mid-twentieth century. The main effect of WDN asset deterioration is the increase of water losses resulting into a wide spectrum of phenomena, ranging from striking burst events to diffuse and pervasive background leakages. Ten years ago, the World Bank (Kingdom *et al.*, 2006) estimated the huge economic impact of reducing water leakages from WDN. Indeed, besides reducing the waste of water and energy resources, water leakage reduction leads to the decrease of treatment and pumping costs (e.g. Colombo and Karney, 2005), the reduction of carbon footprint and the cut of third party damages related to infrastructure failure (European Commission, 2013).

Several studies have been carried out so far aimed at analysing the physical phenomenon, determining the most influencing factors, comparing different systems and providing best practices to leakage reduction. One of the earliest reports about leakage assessment and control practice was published in 1980 (Technical Working Group on Waste of Water, 1980). In this line, the water balance adopted by International Water Association (IWA) (e.g. Farley and Trow, 2003) distinguishes *apparent* water losses (water metering errors, illegal connections, etc.) from *real* losses (designated as *leakages* hereafter) which represent the actual water outflows from WDNs. Besides asset deterioration (e.g. Pelletier *et al.*, 2003), other concurrent factors for the increase of leakages include ineffective pressure control (e.g. Vicente et al., 2015), inefficient WDN operation and inadequate system monitoring.

Further studies were carried out to assess the natural rate of rise in leakage (NRR), representing the underlying rate at which leakage increases within a system (UKWIR 2006, 2009). NRR is a key tool in determining the intensity of active leakage control that is required to maintain leakage at a specific level, as well as a useful input in the determination of mains rehabilitation/replacement strategy.

Thus, estimating current volume of leakages in each single WDN is of crucial importance to quantify the proportion of the technical problem and to support WDN management. This estimate might drive prioritizing investments for implementing leakage reduction actions (e.g. pressure control, asset rehabilitation). Also, it might support the improvement of system monitoring for timely detection of new leakage occurrences in terms of anomalies in pressure/flow time series and trigger procedures to identify, localize and repair failures (e.g. Mounce *et al.*, 2010; Wu *et al.* 2010; Farley et al., 2013; Romano *et al.*, 2014(a, b); Laucelli *et al.*, 2015).

Some recent and quite detailed reviews of the leakage assessment methods are reported in Puust *et al.* (2010) and Mutikanga *et al.* (2013), distinguishing *top-down* and *bottom-up* approaches. *Top-down* leakage assessment is based on measures or estimates of different components of the system water balance. Depending on water metering frequency, the analysis periods for *top-down* leakage estimate can range from few hours up to one semester or one year. In fact, in case of Automatic Meter Reading (AMR) or Advanced Metering Infrastructures (AMI) data can be available every few hours. In case of off-site meter (OMR) reading, data may be collected every few weeks and the analysis can refer to about one month. In case of manual reading (usually performed one to four times per year), the analysis hardly refers to less than six months, and needs to include estimates of water consumptions for unavailable readings. In this latter circumstance, *top-down* approaches are useful to assess leakages on annual basis but do not provide any information about leakage variations over the year.

Bottom-up approaches exploit flow data monitored through the WDN, thus they require the most up-to-date data available. The Minimum Night Flow (MNF) analysis is actually quite a powerful tool for *bottom-up* leakage assessment. It is based on subtracting the expected legitimate water consumption overnight from the total WDN inflow during the minimum consumption hours (e.g. Farley and Trow, 2003; Araujo *et al.*, 2003; Covas *et al.* 2006; Garcia *et al.* 2006). If customers' metering is limited (or absent), the MNF analysis is the only viable methodology to assess leakages and draw the water balance. One of the uncertainties of the

MNF analysis concerns the estimate of the legitimate water consumption. If water metering is available, MNF analysis permits to detect day-by-day changes in leakages, besides checking and integration of the *top-down* water balance.

Unfortunately, the MNF by itself does not allow estimating the daily leakage volume since leakage flowrate fluctuates over the day according to varying pressure levels, which in turn are dependent on the demand. For this reason, the Fixed and Variable Area Discharge (FAVAD) concept, which was introduced to account for the pressure-leakage dependence (May, 1994; Lambert, 2000), has been used in conjunction with MNF analysis. Nonetheless, using the FAVAD concept requires pressure monitoring within the WDN in order to estimate the proportion between night and day leakage outflow.

Almandoz et al. (2005) reported an approach for leakage assessment that requires a well calibrated WDN hydraulic model, the knowledge of consumption patterns of typical consumers and reliable assumptions about one parameter of the pressure-leakage model adopted, besides the WDN inflow readings.

Among *bottom-up* approaches, that reported by Buchberger and Nadimpalli (2004), is worth to remark since it is based to a statistical analysis of flow data to estimate water losses. Apart from the originality and statistical consistency, it probably represents the most demanding option in terms of data acquisition, transmission and storage capabilities. Indeed, it requires high-resolution flow data with sampling intervals of 10, 5 or even 1 second. Actually, this sampling interval would require electric power lines to feed devices for metering and data transmission, thus, it is not viable for battery-powered smart meters that are cheaper and more versatile than the fixed ones, permitting to transmit daily the data sampled every 30-

60 minutes. Moreover, the storage of large amount data would require high capability servers for managing large data streams, without any other practical use for water utilities.

Unfortunately, many WDN worldwide are not yet equipped with monitoring of flow/pressure within the network and the only reliable information are data recorded at water inlet points (e.g. water volumes/flowrate from water "sources" like tanks, reservoirs or pumping stations), which are mainly used to draw annual water balance.

This work presents a novel *bottom-up* methodology for leakage assessment, exploiting seasonal fluctuation of water consumptions, based on WDN inflow data records only. A data assimilation approach (Bouttier and Courtier, 1999) permits *accumulation* of the observed system information (i.e. inflow data records) into a model whose formulation is consistent with the physical behavior of the WDN and requires the assessment of few numerical parameters. The main analysis framework reported herein permits the comparison of alternative formulations entailing pressure-leakage expected behavior, which enhances the robustness of the estimates when pressure measurements are not available. The novel methodology is readily applicable using inlet flowrate data already available in most water utilities. Furthermore, the methodology does not require real-time data transmission and is versatile with respect to sampling interval, which may range up to one hour. It is noteworthy that the methodology does not require prior assessment/measurement of the night water consumption, while the procedure by itself provides also the estimate of night and day users' consumptions. Finally, the application of the methodology permits to assess leakages across time (among different years or during the same year).

The methodology was originally inspired by the analysis of inflow data collected over years in several real WDNs located in Apulian region (Southern Italy), characterized by seasonal variation of water consumptions. Thus, the next section first reports the field observations that inspired the methodology. Thereafter, the main underlying hypotheses are discussed and the formulation of the data assimilation procedure is presented. The methodology is tested using both synthetic examples and a real case study.

Observed seasonal trends of water inflow

As mentioned above, the proposed methodology descends from the analysis of inflow data recorded at many WDNs serving towns in the Apulia region. For the sake of explanation, Figure 1 reports data of two sample WDNs where the flowrate at water inlet points (i.e. tanks feeding the system by gravity) was recorded every 10 minutes for one year. In more details, for each dth day, Q_d is the average daily inflow (i.e., the average of recorded flow data over time steps from 00:10 to 00:00) and $Q_{N,d}$ is the average night inflow (i.e., the average of recorded flow data over time steps from 02:00 to 04:00, when the minimum flow was usually observed). In both data series, some distinct decrease/increase in night and daily water inflow are due to some repair works/new leaks. For example, in the right-side graph, there is a new leak in April and a repair intervention few days after.

Figure 1 shows that, apart from the different flowrate values due to different size of the towns, the analyzed networks are characterized by a remarkable seasonality of water consumptions. This happens because those WDNs serve mainly residential (household) users and the summer peak mirrors the seasonal increase of residential population as well as the increase of the *per-capita* water consumption (due to higher summer temperatures). Consistently, the night inflow $Q_{N,d}$ follows a similar trend as the average daily inflow Q_d, meaning that the water usage daily pattern does not significantly change moving from summer (peak of consumptions in August) to other periods of the year.

Based on such observation one would expect that the ratio between night and daily average inflow $Q_{N,d}/Q_d$ does not change over the year, being related to human water consumption. Actually, the trend of $Q_{N,d}/Q_d$ in Figure 1 decreases during the peak consumption season, while remaining almost constant during other periods. This fact suggests that another component of WDN water outflow exists, which is not directly related to human water consumption and reflects a different WDN behavior between peak and off-peak seasons. From WDN hydraulic perspective, this water outflow component represents leakages in such aged WDNs.

These observations, which are recurrent in the abovementioned real WDNs, suggest exploiting the seasonality in WDN inflow in order to estimate *real* water losses (leakages). Indeed, the component of water outflow, which causes the decrease of ratio $Q_{N,d}/Q_d$, does not follow the daily pattern of human water usage. This, in turns, means that *apparent* losses due to metering errors and illegal connections following the same human water usage daily pattern are not included in such water loss estimate. This fact makes the methodology proposed herein of direct technical relevance to support decisions on WDN management actions (i.e., asset rehabilitation and/or pressure management), which are intended to reduce physical (i.e. *real*) water losses.

It is worth noting that the methodology, as outlined in the next sections, does not require any *prior* metering of water consumptions, being independent on customers' metering data. Conversely, it permits the assessment of the customers' water consumption, i.e. by deducting the estimated leakages from the total inflow, which can be useful to verify/integrate other leakage estimate approaches. Finally, the data sampling interval is compatible with flowrate data usually available in most WDNs.

It is worth mentioning that the leakage estimates of the proposed methodology, being "blind" with regard to customer water metering, will include not only leakages of the WDN mains, but also leakages of the private connections, if not negligible.

Methodology assumptions

This section discusses the hypotheses (i) to (iii) that suggest the proposed leakage assessment methodology, consistently with the observations in real WDNs. Some of the hypotheses are commonly matched in many WDNs worldwide or, more often, in sub-portions (i.e. DMAs), where inflow data are available.

i. The ratio between night and day customers' water consumptions, designated herein as parameter *K*, (see next Eq. (1)) is invariant over all days used for the analysis, including both peak and off-peak season. Such a hypothesis is sensibly verified when household water consumption prevails over others (e.g., industrial, commercial, business, etc.). Alternatively, for those WDN (or DMAs) where non-domestic water consumption exists, the methodology can be applied if they are measured or reliably assessed, so that they can be deducted from the total system inflow.

This first hypothesis also means that any exogenous factor changes the water usage daily patterns during the analyzed days (e.g. a change of energy tariff over the day that might shift the usage of household appliances like washing machines or dishwashing).

Due to this hypothesis, days with different expected water usage daily patterns (e.g. weekend and working days) may have different values of *K*. Accordingly, the methodology requires the prior selection of as many sets of data as the number of similar daily patterns (and K values), ranging from a minimum of two values (i.e. holidays/weekend and working days) up to seven values (i.e. two holidays/weekend and each of the five working weekdays).

ii. There is no rise of leakage nor repair/rehabilitation works are carried on over the analyzed days. If some changes in water leakages are expected over the analyzed period (e.g. due to some repair works as reported in Figure 1), the methodology should encompass only those days where the expected leakage rate does not change.

iii. The time series of water inflow data is available as a discrete sequence of data, each referred to a constant sampling time step Δt, which can be as large as 60 minutes. Alternatively, at least two cumulative inlet volume readings should be provided at the beginning and end of night flow period (e.g. from 02.00 to 04.00 a.m.), as discussed in the following (see Eq. (2)).

Following the hypotheses above, the Eq. (1) holds for any m day in which the ratio between night and day customers' consumptions is invariant:

$$\frac{Q_{N,d}-Q_{LN,d}}{Q_d-Q_{L,d}}=\frac{\frac{1}{N}\sum_{t=1}^{N}Q(t)-\frac{1}{N}\sum_{t=1}^{N}Q_L(t)}{\frac{1}{D}\sum_{t=1}^{D}Q(t)-\frac{1}{D}\sum_{t=1}^{D}Q_L(t)}=K \qquad \text{with} \qquad d=1,\ldots,m \tag{1}$$

Eq. (1) explicitly reports the formulation of the flow figures, where $Q(t)$ is the average inlet flowrate recorded at time t. D and N are the number of sampling time steps Δt over the entire day and night periods, respectively. $Q_{LN,d}$ and $Q_{L,d}$ are the average leakage flow during night (e.g. 02:00 to 04:00) and over the entire dth day, respectively. $Q_L(t)$ is the leakage water flow at time t. Consistently with the first hypothesis, the denominator of Eq. (1) represents the average water flow delivered to users over the entire day, and the numerator represents the water flow delivered to users during the night.

Eq. (1) can be easily manipulated and re-written in terms of water volumes, as:

$$\frac{Q_{N,d}-Q_{LN,d}}{Q_d-Q_{L,d}}=\frac{\frac{1}{\Delta t}\left[\sum_{t=1}^{N}\frac{V(t)}{N}\right]-\frac{1}{\Delta t}\left[\sum_{t=1}^{N}\frac{L(t)}{N}\right]}{\frac{1}{\Delta t}\left[\sum_{t=1}^{D}\frac{V(t)}{D}\right]-\frac{1}{\Delta t}\left[\sum_{t=1}^{D}\frac{L(t)}{D}\right]}=\frac{V_{N,d}-L_{N,d}}{V_d-L_d}=K \qquad \text{with} \qquad d=1,\ldots,m \tag{2}$$

where $V(t)$ and $L(t)$ are the inlet volume and the leakage volume during the t-th sampling interval Δt, respectively. Accordingly, V_d and $V_{N,d}$ are the daily and night average water inlet volumes over Δt; L_d and $L_{N,d}$ are the daily and the night average leakage volume over Δt. Actually, using volumes in place of flow figures is preferable from WDN operational perspectives. In fact, Eq. (2) shows that the methodology can be applied using just two readings of the cumulated inlet volume per day (e.g., at 02:00 a.m. and 04:00 a.m.) from which it is possible to obtain the average values V_d and $V_{N,d}$, by assuming D and N sampling intervals (e.g. D=24 and N=2). This, in turns, permits to use the methodology when only cumulated volume readings are available (instead of flowrate data). Besides, using cumulative volume data permits to overcome the implicit assumption of Eq. (1) that the water inlet flow $Q(t)$ is constant over Δt and facilitate the assessment of total leakage volume figures, which are used to draw the water balance.

As per first hypothesis, Eq. (1) and (2) should have different values of K for all days with different expected water usage daily patterns.

Accounting for pressure for estimating leakages in WDN

The effect of pressure variation during the day on leakage estimate in WDNs was reported first in the FAVAD concept (e.g May, 1994, Lambert, 2000). Among the pressure-leakage relationships investigated so far, the following monomial expression is probably the most used (e.g. as discussed in Schwaller and van Zyl, 2014):

$$Q_L(t) = \beta\left[P(t)\right]^{\gamma} \tag{3}$$

where $P(t)$ is the average network pressure at time t. In Eq. (3), the coefficient β depends on asset size and features (length, material, age, burying conditions, soil), while the exponent γ>0.5 mainly depends on expected mechanical behavior of pipe material (i.e. stiffness), resulting into the enlargement of leaking area along the pipe as pressure increases. The value of γ was reported to be theoretically lower than 2.5 by many authors (e.g. Farley and Trow, 2003) with average values around unit value (e.g. 1.0 (Lambert, 2000) or 1.15 (Ogura, 1979); more recently Schwaller and Van Zyl (2014) confirmed such finding about the average values but reported a narrower range of variation for γ between 0.5 and 1.5.

According to Eq. (3), night leakage outflow ($Q_{LN,d}$) is the highest during the dth day because the average night WDN pressure increases as a consequence of lowest water demands (and pipe flows) causing the lowest head losses.

On the one hand, because of the low night water consumption, significant variations of night leakages among days are not expected. Hence, the night average leakage volume over Δt (i.e., L_N) can be reasonably assumed invariant among the analyzed days (similarly to the parameter K), thus $L_{N,d} = L_N$. On the other hand, the average daily leakage volume L_d depends on pressure fluctuations over the dth day. Thus, the following relations hold:

$$Q_{L,d} \leq Q_{LN,d} \;\Rightarrow L_d \leq L_{N,d} \;\rightarrow\; L_d = a_d \cdot L_N \quad \text{with} \quad a_d \leq 1 \tag{4}$$

and Eq. (2) can be written as:

$$K = \frac{V_{N,d} - L_N}{V_d - [a_d] \cdot L_N} \qquad \text{with} \qquad [a_d] = \frac{L_d}{L_N} = \frac{\beta P_d^{\gamma}}{\beta P_N^{\gamma}} = \left(\frac{P_d}{P_N}\right)^{\gamma} \tag{5}$$

where a_d entails the effect of daily variation of customers' water usage on pressure and leakages. In the rightmost Eq. (5), a_d is estimated using the monomial formula of Eq. (3) where P_N is the night average pressure (over the *m* days) related to the invariant L_N, and P_d is the average daily pressure of the *d*th day related to L_d (i.e. $P_N \geq P_d$).

Nonetheless, that formula requires pressure monitoring within the WDN, which is not available in many real systems; thus, the rest of the paper includes some proposed alternative formulations for a_d based on inflow data only.

In most WDNs worldwide the inequality $[a_d]<1$ (Eq. (4)) holds since pressure increases overnight, while the bound $[a_d]\rightarrow 1$ applies for those WDN showing a roughly invariant pressure regime over the day. This happens in WDNs that are largely oversized with respect to normal operating conditions (e.g. to guarantee sufficient pressure under firefighting conditions) or where pressure is kept sensibly constant through remotely real-time controlled pressure control valves (RRTC-PCVs) based on target pressure set at the (remote) *critical* node (e.g. Creaco and Franchini, 2013; Giustolisi *et al.*, 2015).

It is worth noting that the assumption of invariant L_N ($L_{N,d} = L_N$) may not hold in case of significant seasonality of consumption causing substantial variation of night consumption and in turn major changes of the night pressure over the *m* days. Nonetheless, such circumstance would be likely to cause a drift from the main hypothesis (1) of similar daily patterns (and constant *K*) over the analyzed days.

Leakage assessment methodology

The proposed methodology entails a data assimilation approach (e.g. Bouttier and Courtier, 1999) where the observed information about a real system (i.e. WDN inlet flow/volume data records) is *accumulated into a model*, which is consistent with the physical behavior of the system matching the main hypotheses mentioned above. Assuming m days (out of all the observed days in one year) with similar water usage pattern (e.g. m working days with the same expected K), the estimate of invariant parameters K and L_N are obtained by solving the following system of non-linear equations:

$$\begin{cases} K \cdot V_{d=1} - K \cdot a_{d=1} \cdot L_N + L_N = V_{N,d=1} \\ K \cdot V_{d=2} - K \cdot a_{d=2} \cdot L_N + L_N = V_{N,d=2} \\ \vdots \\ K \cdot V_{d=m} - K \cdot a_{d=m} \cdot L_N + L_N = V_{N,d=m} \end{cases} \tag{6}$$

In order to preserve the consistency with WDN physical behavior, the parameters K and L_N should match the following conditions, which are also useful to bind the domain of solutions of system (6):

$$K \in \left[0,\ \max_{d=1,\ldots,m} \left(\frac{V_{N,d}}{V_d} \right) \right] \tag{7a}$$

$$L_N \in \left[0,\ V_N^{avg} \right] \tag{7b}$$

The upper bound for K descends from Eq. (4) by imposing that L_N>0 although the upper bound for K does not normally exceed 0.3, i.e. the night users' hourly consumption rarely exceeds 30% of the average daily one. Similarly, the average night leakages L_N cannot exceed the average night total inflow (i.e. over the m-days) V_N^{avg} because user consumption is not null.

Among several numerical techniques to solve the non-linear regression problem of system (6), the analyses reported in this work uses the trust-region-reflective algorithm, based on the interior-reflective Newton method (Coleman and Li, 1994; 1996). Actually, if the system (6) is applied over m=2 days only (or two peak and off-peak averaged periods), the estimate of L_N can be obtained using a closed mathematical form (e.g. Mazzolani et al., 2014), which clearly shows that $Q_{N,d}/Q_d$ decreases during a peak water consumption if leakage outflow is not negligible, as previously discussed (Figure 1).

From data assimilation perspective, the larger is the number m of days (i.e. training set for the data assimilation procedure), the more robust is the estimate of invariant WDN parameters in the system (6). In addition, the m days should belong to both off-peak and peak water consumption periods, in order to encompass different and independent WDN working conditions. Moreover, water consumptions usually show day-by-day fluctuation around the mean seasonal value, which usually increases with the size of the population. The joint effect of seasonal and day-by-day fluctuation of water consumptions on leakage estimate is shown in the last part of this work using a synthetic case study.

Finally, for water management purposes, the methodology permits to compare the values of L_N (and K) estimated by applying the methodology on different analysis periods, even within the same year, thus allowing to detect possible variations of leakages over the two analysis periods and/or a change in water usage pattern, thus supporting further application of the same analyses.

It has to be remarked that leakage estimation is based on the global hydraulic behavior of the WDN, thus specific WDN physical data affecting leakages, such as pipe conditions, age, material or surrounding environment, are not required. Nonetheless, if such data were available, they could be used to identify the boundaries of homogeneous WDN sub-portions (DMAs), to install additional flow meters and apply the proposed methodology at higher resolution. Also, with these physical data the results of the proposed methodology could be compared with those of hydraulic modelling integrating them.

Three alternative formulations for a_d.

In system (6), a_d accounts for the difference between day and night average pressure effecting leakages, as discussed above. If pressure measurements are available, a_d can be assessed using models like that in the right-side Eq. (5). Since in real networks pressure monitoring is usually not available and considering that the methodology allows the use of any physically consistent model for a_d, three formulations are proposed below to estimate a_d based only on inlet volume data, which are designated as formulation A, B and C.

They show progressively increasing mathematical complexity and number of parameters to be estimated, while permitting the interpretation and validation from WDN hydraulic perspective.

***Formulation A*.** It holds if WDN pressure is sensibly invariant over time, then:

$$a_d = 1 \quad (8)$$

This formulation does not require pressure input data, and holds for those WDNs where negligible pressure variations occurs over the day. As discussed above, this is the case of oversized WDNs with respect to customer consumptions (e.g. due to firefight requirements) and/or pressure control by RRTC-PCVs.

Formulation B. It is based on the hydraulic consideration that the higher is the average water inflow V_d the lower are the average daily values of pressure P_d and leakage L_d; while lower night inflows averaged over the m days (i.e. V_N^{avg}) is likely to reflect higher average night pressures, related to the assumption of invariant night average leakage volume L_N:

$$a_d = \frac{L_d}{L_N} = \left(\frac{P_d}{P_N^{avg}}\right)^{\gamma} \simeq \left(\frac{V_N^{avg}}{V_d}\right)^{\alpha} \leq 1 \tag{9}$$

where the exponent α>0 in general is different from the parameter γ of Eq. (3), since the relationship between average WDN pressure and inlet volume in not linear. Since Eq. (9) is assumed to be consistent with the global hydraulic behavior of the WDN, the parameter α is an invariant of the hydraulic system to be estimated as an additional unknown of the system (6).

Formulation C. It is a more complex formulation for a_d which is consistent with the condition that $L_d \leq L_N$, while permitting to fall into the case of $L_d = L_N$ (allowed in Eq. (9) only for $\alpha \rightarrow 0$). In this case, the difference between the invariant average night leakage (L_N) and the average daily leakage (L_d) volumes is formulated as a fraction of L_N, which is supposed to change day by day. Similarly as formulation B, such fraction depends on the WDN pressure variations over the day and is proportional to the ratio between daily and night inlet volumes V_d and V_N^{avg} as reported in Eq. (10):

$$L_d = L_N\left[1 - b\left(\frac{V_d}{V_N^{avg}}\right)^{\delta}\right] \quad \rightarrow \quad a_d = 1 - b\left(\frac{V_d}{V_N^{avg}}\right)^{\delta} \tag{10}$$

where the exponent δ is different from parameters α and γ. In addition, $\delta \geq 0$ consistently with the hydraulic observation that the average WDN daily pressure (P_d) increases as V_d decreases, and L_d tends to L_N. Consistently, the coefficient b>0 and large values of b are likely to represent WDNs with large pressure variation over 24 hours giving rise to daytime leakages quite lower than night ones. Vice versa, if b tends to zero, a_d tends to unit value representing WDNs with negligible pressure (and leakage) variation over the day, thus falling into the case of $L_d = L_N$ of formulation A. Assuming $\delta \geq 0$, the physically consistent range for b is obtained by imposing the condition $0 < a_d \leq 1$:

$$b \in \left[0, \left(\frac{V_N^{avg}}{V_d} \right)^{\delta} \right[\tag{11}$$

As in formulation B, δ and b are assumed as system invariants to be estimated as additional unknowns of the system (6).

Therefore, the three proposed formulations result in the following three different equations for each dth day to be used into as many solution runs of the system (6):

$$K \cdot V_d - K \cdot L_N + L_N = V_{N,d} \tag{12a}$$

$$K \cdot V_d - K \cdot \left(\frac{V_N^{avg}}{V_d} \right)^{\alpha} \cdot L_N + L_N = V_{N,d} \tag{12b}$$

$$K \cdot V_d - K \cdot \left[1 - b \left(\frac{V_d}{V_N^{avg}} \right)^{\delta} \right] \cdot L_N + L_N = V_{N,d} \tag{12c}$$

Consequently, solving system (6) with formulation *A*, *B* or *C*, permits to estimate two (K and L_N), three (K, L_N and α) and four (K, L_N, b and δ) unknowns, respectively. All these parameters are supposed to be invariant since they entails the same water consumption daily patterns over the m days, as discussed above.

As discussed, these parameters reflects the global hydraulic behavior of the WDN. Accordingly, they can be used as priors during the estimation phase if the methodology is applied on a WDN sub-portion (i.e. new DMAs within the system) where inflow measurements are collected at its boundary. The larger is the difference of global hydraulic behavior between DMA and WDN (pressure level, asset conditions, etc.) the higher will be the distance between the priors ad the newly estimated parameters.

Cases of study

The proposed methodology for leakage assessment is demonstrated for two different WDNs. The first WDN is a literature case study named Apulian WDN (e.g. Giustolisi, 2010), which adopts two scenarios representing opposite hydraulic operations in terms of pressure (and leakage) variation over time. Thereafter, one of the synthetic Apulian WDN configurations is used to analyze the effect of seasonal and day-by-day fluctuations of water consumptions on leakage estimate. The second WDN is a real network located in Southern Italy.

Apulian Network – synthetic case studies

Using synthetic WDNs permits testing the effectiveness of the methodology, before its application with real flowrate data, while imposing that all hypotheses are verified. Also, such testing neglects the uncertainties related to flow measurement and other real operating conditions. In all synthetic scenarios, the WDN hydraulic behavior is simulated using the hydraulic analysis module of the WDNetXL system (Giustolisi et al., 2011). Indeed, such hydraulic models entails pressure-driven analysis of all demand components. Household water demands are modelled as in Wagner *et al.* (1988), while background leakages are simulated as pressure-dependent outflows distributed along pipes, using the Germanopoulos' leakage model (Germanopoulos, 1985; Germanopoulos and Jowitt, 1989, Giustolisi et al., 2008). In addition, WDNetXL permits the realistic simulation of any control devices, including RRTC-PCVs (Giustolisi et al., 2015), which are assumed to work in one of the following configurations. Figure (2-c) and Tables 1 and 2 report the base Apulian WDN topology along with pipe and node data.

In order to test the applicability of the methodology in a realistic context, the assumed daily demand pattern shows the minimum between 02.00 and 04.00 a.m. (Figure (2-a)). The monthly average demand pattern curves in Figure (2-a) are obtained multiplying the base winter pattern (i.e. from January to March and from October to December) by a seasonal demand coefficient ($s \geq 1$) that changes monthly as in Figure (2-b). The peak value of s is in August, when water demand is assumed to double the base one. Moreover, in order to reproduce the day-by-day fluctuations of the water demand observed in real WDNs, each daily multiplier s is sampled randomly from a uniform distribution in the range $\pm r$, which is assumed to be $\pm$10% of s. This assumption, adopted in both the case studies below, implies that the absolute values of the day-by-day fluctuations increases as s increases, being the largest in August, which is consistent with variations observed in real systems.

As mentioned above, two scenarios are considered here representing opposite hydraulic operations.

Case 1 - The original nodal customer demands reported in Table 2 are multiplied by a factor 0.1, so that the network operates as *oversized*. In addition, a RRTC-PCV is assumed on pipe 34 marked with a circle in Figure (2-c), controlling pressure at node 13 (marked with a triangle in Figure (2-c)) with pressure set at 15 m. Since pipe 34 is the only inlet of the entire WDN, the reduced pressure zone actually matches with the WDN. Such configuration permits sensibly invariant pressure (and leakage) over time since the RRTC-PCV regulates pressure hourly during the 365-day extended period simulation. As a result, the maximum oscillation of pressure is less than 1m. Parameters of the background leakage model (i.e. Giustolisi et al., 2008) are set to have an annual average leakage rate of about 22% of the total inlet volume.

Case 2 - In order to emphasize pressure variations and their effect on leakages, customer demands are 2.5 times larger than *case 1,* the elevation of reservoir 24 is raised to 50 m and no PCV is installed. This configuration avoids pressure deficient conditions, while generating considerable oscillations of pressure (about 20 m at node 23) and leakage volumes daily over each day and among the 365-day extended period simulation. Leakage model parameters are set to have an annual average leakage rate of about 34% of the total inlet volume.

The assumption of proportional demand patterns, as well as the condition that no pressure deficient condition occurs (i.e. pressure is always higher than 10m at all demand nodes), guarantee that the ratio between average night and daily water consumption (i.e. K) is invariant over the year in both case studies. This allows use in both cases of m=365 days, without making distinctions between weekend and working days. In addition, in both case studies it is assumed that *sampling time* Δt=1 hour, which is the time step of the one-year long extended period simulation. Table 3 reports, for both extended period simulations, the annual total inlet volume, the annual background leakage volume and invariant value of K. It is worth noting that in both synthetic cases leakages rates are consistent with average values observed in many real WDNs worldwide. Figure 3 shows the average daily inflow and the ratio $Q_{N,d}/Q_d$ whose trend is consistent with that observed in real WDNs (e.g. see Figure 1). Table 4 summarizes the results of leakage assessment procedure on both synthetic cases, showing the parameters estimated using the three separate formulations. Figure 4 also reports the average daily leakage outflow as simulated by the model (i.e. L) and assessed using formulations *A*, *B* and *C*. Consistently with Eq. (8), the daily average leakage outflow L_d calculated with formulation *A* (L_d(A)) is constant and equal to L_N (shown in Table 4); on the contrary, L_d(B) and L_d(C) change day by day, as per Eqs. (9) and (10).

In the pressure controlled configuration (*Case 1*) the simulated leakage volume is roughly constant over time. Accordingly, the formulation *A* returns the best approximation of actual system behavior in terms of both estimated *K* and leakage rate. Nonetheless, the estimates obtained with formulations *B* and *C* are quite close to *A* due to the low values of estimated parameters α, δ and *b*, as shown by the low difference between the known (i.e. simulated) and estimated leakage rates.

In the pressure variant configuration (*Case 2*), the hypothesis of constant leakage rate (i.e. independent on pressure and water consumptions) is no longer applicable and formulation *A* clearly overestimates the leakage rate of about 3.1%. This result is consistent with the solution of equations (6) with m=2, showing that the solution with a_d =1 (as in formulation *A*) returns leakage rates which are always larger than any solution with a_d <1, under the hypothesis of invariant L_N. Thus, formulation A always overestimates the actual leakage rate of a WDN. On the other hand, Formulation *C,* which is conceived to follow the change of leakages due to the significant pressure variation of *Case 2*, is able to return the best results in terms of predicted values of *K*, leakage rate and seasonal pattern of total leakage volume, with a leakage rate mismatching of only 0.7% . From data assimilation perspective, this result is due to the estimate of one more parameter into a physically consistent formulation, which permits to reproduce more closely the expected WDN hydraulic behaviour.

It is worth noting that, the simpler formulation *B* with just one parameter (α) is not able to reproduce the actual WDN hydraulic operation: the estimated value of α tends towards zero and thus this formulation degenerates into *A*, failing to reproduce the effect of pressure on leakages.

Nonetheless, these results demonstrate the versatility of the methdology in comparing alternative expressions to characterize the effect of pressure changes on leakages in WDNs with no pressure data. Besides, it proves robust with respect to formulations like *B*, which is hydraulically consistent but too simple to reproduce the effect of pressure variations.

Effect of seasonal and hourly fluctuation of water consumptions.

The abovementioned *Case 2* configuration of Apulian WDN is used herein to analyze the robustness of the proposed methodology with regards to different seasonal and day-by-day fluctuations of the water demand.

The seasonal fluctuation is simulated by increasing the peak factor s in August by 10, 20, 50 and 100% of the base demand (in December), as shown in Figure 5. The impact of day-by-day fluctuations is simulated by multiplying the hourly demands by factors r that are sampled in the range 0-20 % around seasonal multiplier s (i.e. $r = 0\%$, $\pm 5\%$, $\pm 10\%$, $\pm 15\%$ and $\pm 20\%$). This way the random fluctuation of hour demand pattern results into a day-by-day demand fluctuation with respect to the seasonal increase. It is worth noting that these scenarios result also into a variations of the ratio K among the analysed days, which allows investigating the effectiveness of the methodology as the first hypothesis is progressively relaxed, as happens in real WDNs.

The leakage assessment methodology has been applied to *Case 2* network under 20 water consumption scenarios, as obtained from combination of the simulated values of four s and five r. The relevant leakage rates ranges from about 34% (for s=100 %) to about 39% (for *s*=10 %) of total annual inlet volume. Since the parameters of the background leakage model do not change over the 20 scenarios, the increase of leakages is consistent with the increase of average WDN pressure (and leakages) due to decreased water demands.

Figure 6 reports the results of the leakage assessment in terms of absolute percentage error with respect to known (simulated) annual leakage volume in every scenarios, using the three proposed formulations. As expected, formulation *C* shows the best results, with the minimum mismatching from the "known" leakage volume, because of its capability to follow pressure and leakage variations over time. This effect is further evident by comparing results of formulations *A* (Fig. 6a) and *C.*

In fact, in *Case 2*, formulation *A* shows an increasing trend of the error with the seasonality (i.e. *s(Aug)*) because it is not able to account for the decrease of pressure due to higher water consumptions. In addition, for each seasonal increase scenario, the rise of random hourly fluctuation range *r* results into increasing error, with the maximum usually for *r*=±20% around *s*. In fact, *r* acts as a noise with respect to the main seasonality trend, and has maximum impact on the lowest seasonal fluctuation (i.e. *s(Aug)* =10%).

About formulation *B*, as with previous results on the base *Case* 2 (see previous section) it keeps on degenerating into *A*.

In the first three seasonal fluctuation scenarios (i.e. *s(Aug)*= 10%, 20% and 50%) the absolute errors returned by applying formulation *C* are lower than 2%. This error increases only for hourly fluctuation range *r*=±20%, consistently with the masking effect of *r* in low seasonality scenarios.

For high seasonality ((i.e. *s(Aug)*= 100%), errors of formulation *C* are not that sensitive to hourly fluctuations *r*, but the error on leakage volume rises to about 4%. Although this error is still low if compared with other formulations, it is likely to indicate that for large seasonality of water consumptions, the effects of pressure on leakages is not completely described by formulation C.

Yet, it is worth noting that such a larger set of cases shows the effectiveness of the methodology since the mismatching between estimated and "known" leakage rate is relatively low, taking into account that the methodology estimates are made without pressure data.

Real case study

This case study concerns a small real WDN in the Apulia region (Southern Italy) with about 4500 inhabitants. An elevated tank feeds the network by gravity with level daily fluctuation usually within 2m. The available data used for this application are the water inlet volume V(t) during the sampling time step $\Delta t = $ 10min for the year 2012 (366 days). Figure 7 plots daily and night (from 2.00 to 4.00 a.m.) average inlet volumes for 356 days resulting from eliminating days with missing/erroneous records.

Based on information provided by the water Utility, consumption is mainly domestic and the summer peak (i.e. from the end of July to the beginning of September) is mainly attributable to the increase of both per-capita water consumption and population, as the town is located in a touristic seaside area. For the same year, the Utility estimated a leakage rate lower than 10% for this system, obtained through a top-down methodology based on the subtraction of metered water consumption and apparent losses from total inlet volume.

Unfortunately, pressure monitoring is not available, thus night and day leakage fluctuation cannot be modelled as a function of the average WDN pressure (e.g. as in the last Eq. 5); thus the three proposed formulations are used.

The methodology is applied on three data partitions that are assumed to correspond to different daily consumption patterns (corresponding to different K values). The first partition (all days) explores the application of the methodology on the entire dataset. The other two partitions refer to working days (from Monday to Friday) and weekend days (Saturday and Sunday). The latter includes the nights between Friday and Saturday and between Saturday and Sunday, consistently with the expected changes of household water consumption. Table 5 reports the leakage assessment results for the three partitions and the three proposed formulations.

In all cases the formulation B degenerate into A due to the low estimated value of α, close to the precision used in the computing environment. This confirms previous findings about formulation B, which is apparently consistent with the WDN hydraulic behavior, although it is not able to catch the effect of pressure variation.

Formulation C returns a slightly lower leakage rate than formulation A, resulting from the low values of coefficient b. The value of the exponent δ is the upper bound assumed for this simulation, although separate analyses, not reported here for the sake of brevity, proved that these results do not change even for wider ranges of δ. This behavior is likely due to the very low leakage rate in this WDN, which results into a minor effect of water consumption seasonality.

Actually, the leakage estimation methodology retuned an average leakage rate higher than 8% considering all days together, which is consistent with the estimate of the Utility based on *top-down* leakage estimate. During the working days, such value slightly increase. *Vice versa,* during the weekend the value of K increases mainly due to the increase of night water consumption, which results into lower night leakages (i.e. L_N) and reduced leakage rate.

Concluding remarks

Controlling and reducing water losses in WDNs is a major management issue worldwide and the reliable assessment of real losses (leakages) is essential to quantify the magnitude of the phenomenon, prioritize investments and plan rehabilitation and operational activities. Actually, in many WDNs worldwide, the leakage assessment is quite a challenging task because of the lack of flow and pressure monitoring within the WDNs.

The *bottom-up* methodology proposed herein entails a data assimilation approach where the system information represented by the WDN inflow data series is accumulated into a model, which is physically consistent with the WDN hydraulics. The methodology descends from the analysis of inflow data patterns recorded in real WDNs, which are characterized by seasonal variation of water inflow and consumption.

The proposed leakage assessment framework allows accounting for pressure-leakage dependence by using pressure records (if available) or by including some formulations entailing physically consistent relationships between pressure (and leakage) variation and water inflow data. Such versatility permits comparisons of different formulations with growing complexity and number of parameters, which are expected to increase the reliability of leakage estimates. In addition, in contrast to other leakage assessment procedures, the methodology does not require any prior assessment of the water demand. Rather, it returns the estimate of night water consumption as the difference between the recorded night inflow and the estimated night leakages. In addition, the methodology returns the total annual volume of real losses, which can be compared with estimates obtained by applying other methodologies that account also for apparent losses.

The results obtained on two synthetic configurations of Apulian WDN, entailing steady PCV-controlled pressure and pressure changing scenarios, demonstrate the consistency of the methodology. The latter scenario have been used to analyze the sensitivity of the procedure with respect to seasonality and random fluctuations of the hourly water demand. Results show that the formulation *C* proposed herein is able to improve the accuracy of the leakage estimate obtained by using simpler formulations *A* and *B*, irrespective of hourly demand fluctuation. This happens due to the increased complexity of Formulation *C*, which involves the estimation of two parameters, allowing a better simulation of leakage changes caused by pressure variations over time than formulation B. Finally, the application on a real WDN further demonstrate the effectiveness and consistency of the proposed methodology.

Although this work demonstrates the methodology on systems fed by gravity from one source only, it can be used when multiple sources feed the network by gravity. In fact, records of outflows from all water sources is a common practice in real networks and data can be summed to get the total network inflow over time. In case one or multiple variable level tanks are installed in the system, inflow/outflow from the tanks are usually measured and can be easily introduced in the main mass balance in Eq. (5). If the system is supplied by pumps with fixed schedule, the applicability of the methodology needs to be investigated. In fact, if the day-by-day pump schedule is invariant and night pressure level is larger than daily one, then the same assumptions reported herein apply. On the contrary, if these hypotheses do not apply further investigation occur.

It is worth noting that the leakage estimate framework introduced here lend itself to further improvements and upgrades. For instance, future research might look at enlarging the range of applicability to WDNs where some of the hypotheses reported in this work do not strictly hold, or might propose different modelling of pressure changes based on inlet flow data.

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Notation

a_d ratio between L_d and L_N

D number of time steps over which inflow measurements $Q(t)$ are sampled in 24 hours

K ratio between night and daily average water consumption in Δt

$L(t)$ leakage volume in Δt at time t

L_d average daily leakage volume in Δt over the dth day

$L_{N,d}$ average night leakage volume in Δt of the dth day

L_N average night leakage volume in Δt

m number of days analyzed

N number of time steps over which inflow measurements $Q(t)$ are sampled during night

$Q(t)$ network inlet flowrate recorded at time t

$P(t)$ average network pressure at time t

P_d average daily network pressure of the dth day

P_N^{avg} average night network pressure over the (m) analyzed days

$P_{N,d}$ average night network pressure of the dth day

V_d average daily network inlet volume in Δt over the dth day

$V_{N,d}$ average night network inlet volume in Δt of the dth day

V_N^{avg} average value of $V_{N,d}$ over the m analyzed days

V_{leak} daily total leakage volume

γ, β parameters of the pressure-leakage model

α, δ, b parameters of expressions for a_d

Δt sampling time interval;

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List of Figures

Table 1. Apulian WDN pipe data

Pipe ID	Length [m]	Diameter [mm]	Unit Hydraulic Resistance [m^6/s^2]
1	348.5	327	0.46
2	955.7	290	0.87
3	483.0	100	265.15
4	400.7	290	0.87
5	791.9	100	265.15
6	404.4	368	0.25
7	390.6	327	0.46
8	482.3	100	265.15
9	934.4	100	265.15
10	431.3	184	9.88
11	513.1	100	265.15
12	428.4	184	9.88
13	419.0	100	265.15
14	1023.1	100	265.15
15	455.1	164	18.56
16	182.6	290	0.87
17	221.3	290	0.87
18	583.9	164	18.56
19	452.0	229	3.07
20	794.7	100	265.15
21	717.7	100	265.15
22	655.6	258	1.64
23	165.5	100	265.15
24	252.1	100	265.15
25	331.5	100	265.15
26	500.0	204	5.63
27	579.9	164	18.56
28	842.8	100	265.15
29	792.6	100	265.15
30	846.3	184	9.88
31	164.0	258	1.64
32	427.9	100	265.15
33	379.2	100	265.15
34	158.2	368	0.25

Table 2. Apulian WDN node data

Node ID	Elevation [m]	Customers' demand [l/s]
1	6.4	10.9
2	7.0	17.1
3	6.0	14.9
4	8.4	14.3
5	7.4	10.1
6	9.0	15.3
7	9.1	9.2
8	9.5	10.6
9	8.4	12.2
10	10.5	14.6
11	9.6	9.0
12	11.7	7.6
13	12.3	15.2
14	10.6	13.6
15	10.1	9.3
16	9.5	11.2
17	10.2	11.5
18	9.6	10.8
19	9.1	14.7
20	13.9	13.4
21	11.1	14.7
22	11.4	12.0
23	10.0	10.4
24	Ho = 46.4	0.0

Table 3. Analysis of Apulian WDN

Case	K	Average annual inflow [m^3/h]	Average annual leakages [m^3/h]	Leakage rate [%]
Case 1	0.154	82.72	18.24	22.06
Case 2	0.154	243.79	82.88	33.94

Table 4. Apulian WDN: leakage assessment results

Case	*Simulated Leakage rate [%]*	*Form.*	*Estimated leakage rate* [%]	K	L_N [m^3/h]	α	δ	b
Case 1	22.06	*A*	22.02	0.153	18.21	-	-	-
		B	21.65	0.153	18.19	1.48×10^{-2}	-	-
		C	22.00	0.153	18.21	-	0.637	4.0×10^{-4}
Case 2	33.94	*A*	37.00	0.160	90.16	-	-	-
		B	37.00	0.160	90.16	2.22×10^{-16}	-	-
		C	33.21	0.153	90.16	-	1.534	3.1×10^{-2}

Table 5. Real WDN: leakage assessment results

Days	*Form.*	*Leakage rate* [%]	K	L_N [L/s]	α	δ	b
All days	(A)	8.56	0.254	0.67	-	-	-
	(B)	8.56	0.254	0.67	2.22×10^{-14}	-	-
	(C)	8.06	0.252	0.67	-	5	1.4×10^{-4}
Working days	(A)	9.28	0.247	0.75	-	-	-
	(B)	9.28	0.247	0.75	2.21×10^{-14}	-	-
	(C)	8.68	0.245	0.75	-	5	1.5×10^{-4}
Weekend days	(A)	6.79	0.269	0.52	-	-	-
	(B)	6.79	0.269	0.52	2.21×10^{-14}	-	-
	(C)	6.52	0.268	0.52	-	5	9.4×10^{-5}

Figure 1. Average night and daily water inflow and their ratio in two real WDNs in Apulia region (Italy)

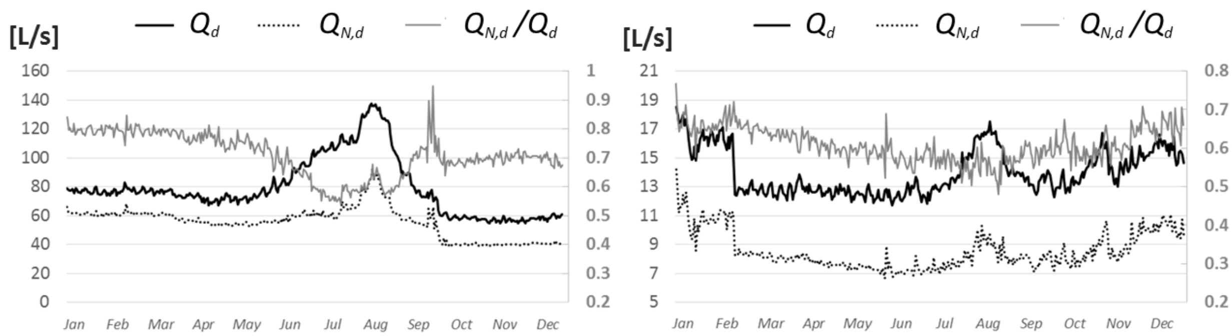

Figure 2. (a) Daily average demand patters for each month; (b) Seasonal demand multipliers; (c) Apulian WDN layout

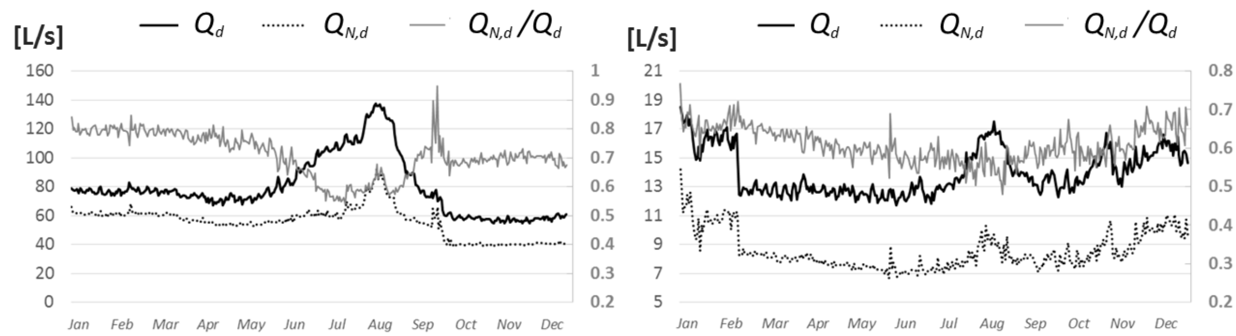

Figure 3. Average daily inflow in Case 1 and Case 2 of Apulian WDN

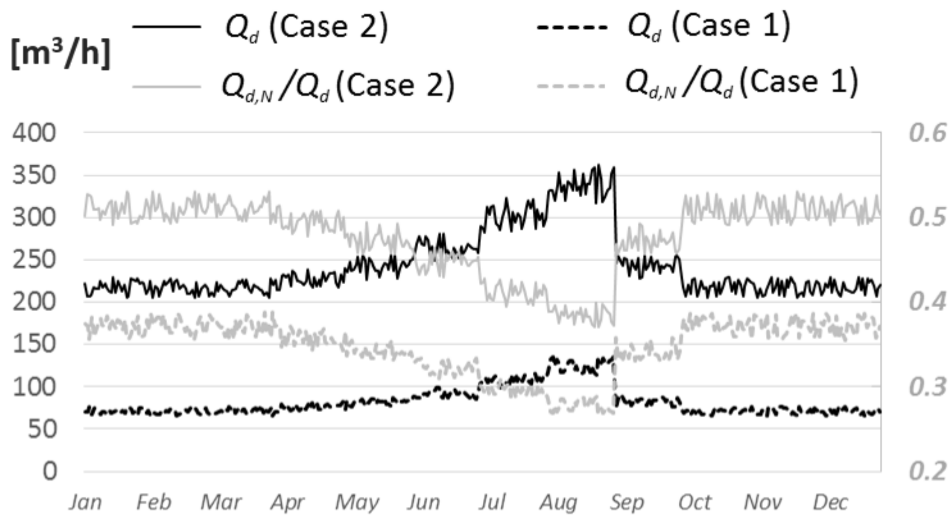

Figure 4. Daily average leakage outflow in Case 1 and Case 2 of Apulian WDN

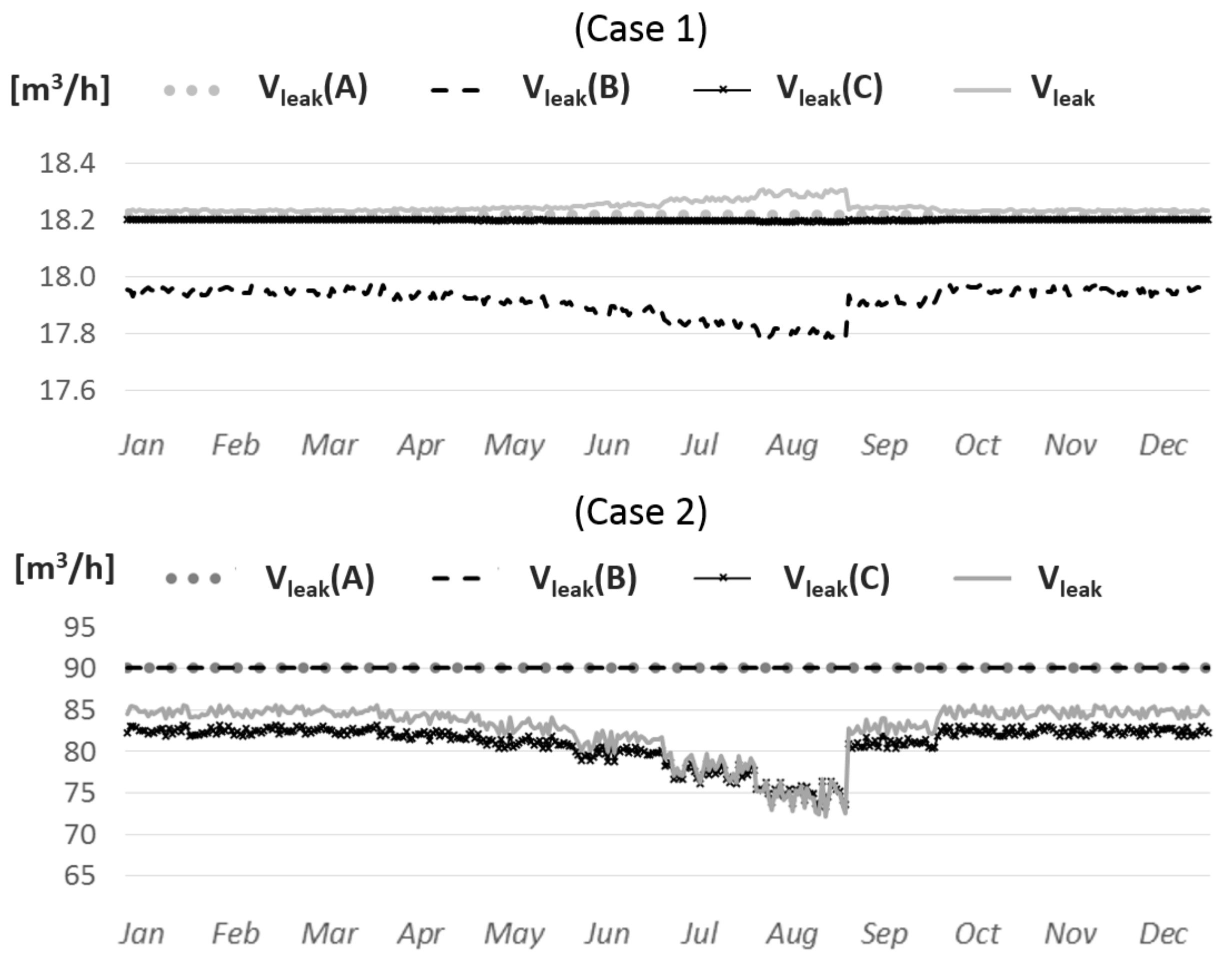

Figure 5. Seasonal multiplying factors

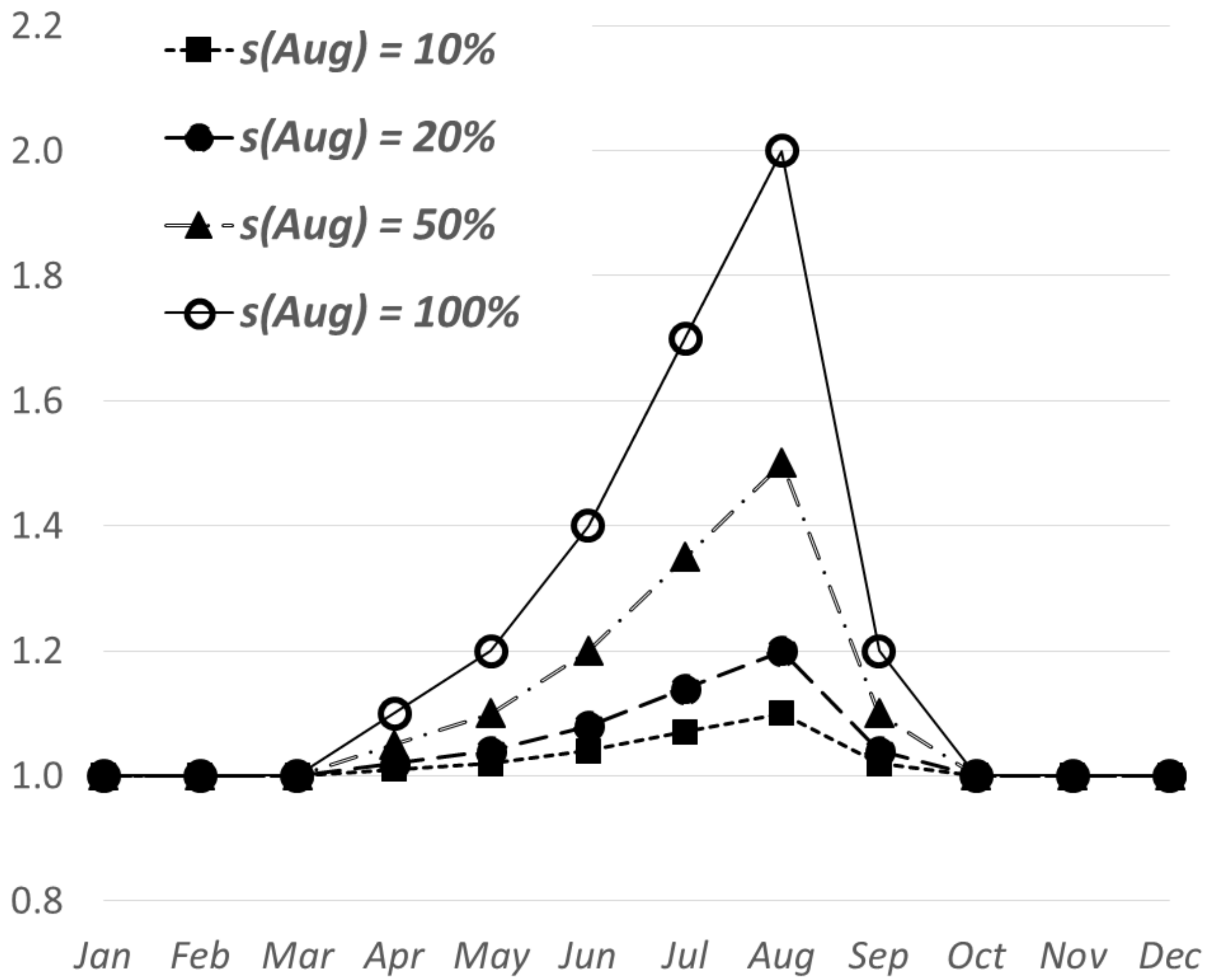

Figure 6. Error on total leakage volume due to seasonality and fluctuation of water requests

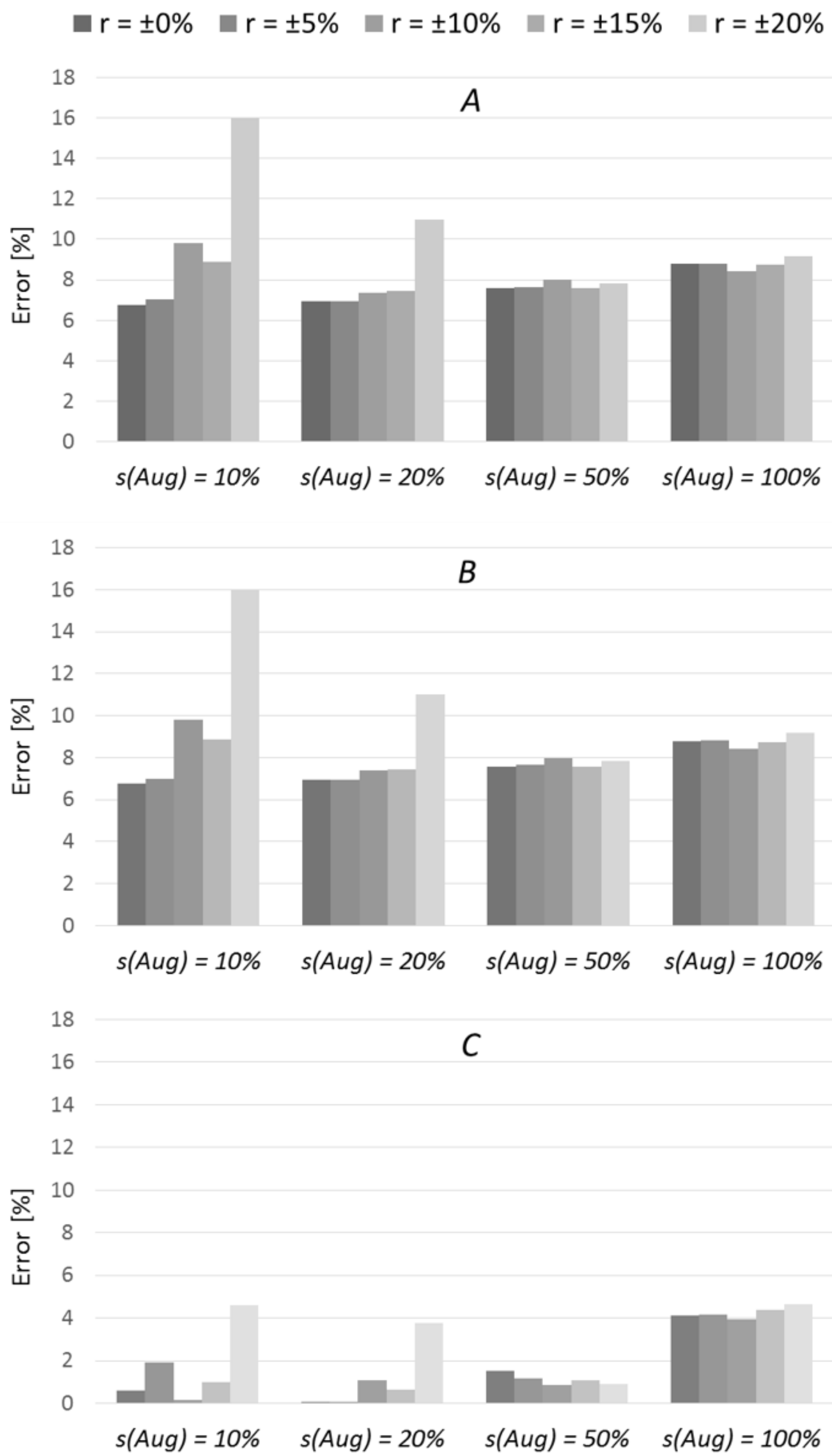

Figure 7. Average daily inflow recorded for the real network