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Effects of network pressure on water meter under-registration: an experimental analysis

C. M. Fontanazza[1], **V. Notaro**[1], **V. Puleo**[2], and **G. Freni**[1]

[1]University "Kore" of Enna, Enna, Italy
[2]University of Palermo, Palermo, Italy

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Correspondence to: C. M. Fontanazza (chiara.fontanazza@unikore.it)

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Abstract

In water supply systems, a considerable amount of apparent loss is caused by meter under-registration. Water meters are subject to intrinsic systemic error depending on the actual flow rates passing through them. Furthermore, the moving parts of the meter are subject to wear and tear that progressively reduce meter accuracy. The increase in systemic error is especially evident at low flow rates because of growing friction in the rotating mechanism, which requires a higher flow to start the meter (starting flow). The aim of this paper is to experimentally investigate metering error in an attempt to find a direct link between meter age, network pressure and apparent losses caused by the inability of the meter to accurately register the volume passing though it at low flow rates. The study was performed through laboratory experiments in which worn-out water meters were tested using a test bench. The results of the laboratory experiments show that ageing and pressure are both relevant parameters for determining meter starting flow. These results were then applied to assess the effects on apparent losses of the age of the meter, varying pressure values upstream of the meter (the pressure in the network where the meter is installed) and different patterns of flow rates passing through the device (the consumption pattern of the user). The presented results are useful for understanding the effects of operating conditions on water meter under-registration, which can aid water managers in implementing effective replacement campaigns.

1 Introduction

In water supply systems, velocity water meters (single-jet and multi-jet) are the most common devices for measuring user consumption. These meters provide indispensable data used by the utilities for issuing bills, computing the system water balance, and identifying network failures, water theft and anomalous user behaviour. Therefore, the utilities rely on these instruments for both the technical and economic management of their water systems.

Despite their importance, water meters are subject to intrinsic errors that are responsible for apparent losses actually caused by meter under-registration. Because of these errors in accounting the water volume consumed by users, the water utility does not receive appropriate compensation for the service provided.

From a technical point of view, intrinsic meter error can produce under- or over-registration of users' water consumption. Expressed as a percentage, the metering error ε is defined by the equation

$$\varepsilon = \frac{V_\mathrm{i} - V_\mathrm{a}}{V_\mathrm{a}} \tag{1}$$

where V_a is the actual volume passing through the meter, and V_i is the volume indicated by the meter that corresponds to the actual volume. The graphical representation of the variation in error with the flow rate is known as the error curve. Figure 1 shows a sample error curve for a new multi-jet water meter.

To evaluate the metrological performance of any type of water meter, the ISO 4064:2005 standard carefully defines the requirements for the error curve using four flow rates: minimum flow rate, Q_1; transitional flow rate, Q_2; permanent flow rate, Q_3; and overload flow rate, Q_4. For flow rates lower than the minimum, the error curve steeply decreases but does not reach the axis of ordinates, which effectively means that there is a flow rate for which the meter does not register any volume. This flow rate is known as the starting flow, defined properly as the flow that can generate motion in the meter when the mechanism is at rest. At this flow rate, the meter begins to measure the passing water volume, even if the accuracy is practically zero (i.e. the metering error is about −100 %). This metrological parameter not only represents the starting point of the error curve but also is indispensable for determining the percentage of volume registered by a meter. Unfortunately, its evaluation is extremely difficult.

As discussed above, metering error depends on the actual flow rate passing through the meter. Therefore, the rate of water consumption recorded by the meter depends on the temporal pattern of end user demand (Male et al., 1985; Ferreol, 2005). For consumption at medium and high flow rates, the error can be very low. For consumption at flow rates lower than the minimum, the error will be negative and very high, reaching −100 % when the flow is lower than the starting flow. As a result, apparent losses due to meter under-registration depend on the percentage of user's consumption that occurs at low and very low flow rates as well as on the ability of the meter to accurately register the water volume consumed.

In countries suffering water shortages (such as those in arid and semi-arid climates), the use of private storage tanks (Rizzo and Cilia, 2005; Criminisi et al., 2009) affects the share of the consumption that occurs at low flow rates. The use of storage tanks is a common practice for coping with water scarcity (Cubillo et al., 2004; Andey and Kelkar, 2009). During periods of water shortage, a discontinuous water supply and water resource rationing are often the primary measures adopted by water utilities to distribute the limited water as efficiently as possible. Users compensate for this intermittent water service by collecting water in a tank during serviced periods and redistributing it when public water service is not available (Fontanazza et al., 2007, 2008). Private tanks are filled using a proportional float valve that opens partially or totally as a function of tank water level and network pressure. While the users are receiving a continuous supply, the tank is usually full, and the float valve opens as soon as the tank's water level falls. During periods of high consumption, the tank's water level drops, the float valve opens completely, and water enters the tank at a high flow rate. During periods of lower consumption, the water level does not fall as much, the valve opens only partially, and the flow rate passing through the meter and entering the tank is very low. The meter is thus forced to work in the lower part of its measuring range where error is very high. Furthermore, the slow closure of the float valve induces flows that are lower than the meter's starting flow and thus are not registered. When the users experience intermittent supply (De Marchis et al., 2010, 2011), water flows into the tank only when the network pressure at the user connection is sufficient to supply the tank. When the network pressure is low, tank water levels drop to meet user needs, with tanks often almost empty by the time the network pressure increases. As a consequence, the float valve is completely open and allows water to pass at a very high flow rate.

The dependency of the apparent losses on the presence of private tanks and the behaviour of their users has been analysed previously (Rizzo and Cilia, 2005; Cobacho et al., 2008; Criminisi et al., 2009). The effect of a tank on consumption flow rates raises the global error of a meter, ranging from approximately −10 % for a new meter to −40 % for a worn-out meter. In terms of apparent losses, experimental evidence shows that the average under-registration of worn-out meters ranges from approximately 10 to 50 % of total household consumption (Criminisi et al., 2009).

Several other factors cause water meters to lose their accuracy. Thornton and Rizzo (2002) identified meter wear and tear, incorrect installation, lack of maintenance or calibration, incorrect meter type and class for the current application, incorrect meter sizing and demand patterns as possible causes of meter inaccuracy. Arregui et al. (2005) presented real field and laboratory data on the impact of several parameters on the accuracy of both domestic and industrial water meters and on different meter technologies (single-jet, multi-jet, oscillating-piston, Woltman and Tangential meters). Incorrect mounting position, wear of moving parts, suspended solids and deposits, leaks and user's storage tanks, and partial blockage of the inlet strainer are all said to influence the error curve of domestic water meters (although this varies with the meter technology). In addition to these factors, velocity profile distortions and proper meter sizing also have an effect on water meter error for industrial applications.

The pressure level of the network is not generally included amongst the causes affecting metrological performance, but such a factor is especially important for systems that include private tanks because the rate that water flows into these tanks is driven in part by network pressure and not only by user demand.

The aim of this paper is to provide an initial basis for analysis of the effect of network pressure on ageing water meters' under-registration and subsequent apparent losses. For this investigation, two coupled experimental studies are required: one based on laboratory analyses aimed at obtaining meter error curves that account for meter age

and network pressure, and another based on field studies aimed at analysing user water demand and how it may be modified by network pressure, water scarcity and the idiosyncrasies of a user's private distribution system. As discussed above, the characteristic shape of the error curve shows that for flow rates higher than the transitional value, metering errors are negligible, but they become extremely important and negative for flow rates ranging from the starting flow to the minimum flow rate. For this reason, in the present study, the error curves of several worn-out water meters were defined for different operational pressure values at lower flow rates only. The laboratory tests were performed using a standard test bench. For each pressure value, measured upstream of the meter, meter error at the selected tested flow rates was interpolated to provide an empirical equation of the error curve. The starting flow of each meter was evaluated using this equation, and the effect of pressure on the starting flow was studied. Finally, three demand profiles were determined using an experimental field campaign to assess apparent losses due to meter under-registration: the first profile is of a user with a private tank subject to intermittent supply; the second is of a user with a private tank subject to continuous supply; and the third is of a user without a tank. Apparent losses were calculated for each pressure value as a percentage of consumption at flow rates lower than the meter's starting flow. The results of the experimental study can be used in the planning process to maximise the effectiveness of selective water meter replacement in reducing apparent losses.

2 Laboratory studies

Laboratory experiments were performed to obtain the error curves at low flow rates of 143 worn-out water meters, replaced with new instruments in 2006 by the local Palermo water utility (AMAP S.p.A.). The meters were installed to monitor residential users, who comprise 85 % of the total Palermo water distribution network. The meters are multi-jet, with a diameter of 15 mm and a permanent flow rate, Q_3, of 1.5 $\text{m}^3\,\text{h}^{-1}$. The meters manufactured before 1997 belong to class B, with the rest belonging to class C, according to the ISO 4064:1993 standard. Their service lives ranged from 0 (new meter) to 45 yr, which was taken into account when considering the wear and tear on each meter. As shown in Table 1, the meters were divided in nine age classes as defined by service life. The service life of the meters in age classes 7, 8, and 9 is very long. Most utilities, including the Palermo utility, replace meters on a run-to-fail basis, and there is not yet a mandatory requirement to replace water meters. As a consequence, residential water meters can be very old. This policy indicates a lack of planning and can result in important economic losses (Fontanazza et al., 2012).

Figure 2 shows the total water volume measured by the meters during their service lives, another relevant factor influencing meter wear and tear. The water volume measured by the meters is understandably proportional to meter age because of the homogeneity of user demand. This pattern effectively represents the relationship between meter wear and tear and the age of the instrument and justifies the meter classification used in this study (Table 1).

The water meter tests were performed using a test bench in the hydraulics laboratory of the Department of Civil, Environmental, Aerospace and Materials Engineering at the University of Palermo. The test bench is a weight calibration device consistent with the ISO 4064:2005 standard. It consists of a water supply system (mains, one unpressurised tank, two pumps); a test section in which the meter is placed; four fluxmeters to establish the approximate flow rates at which the meter is tested; two pneumatic and automatic gate valves; two pressure gauges to measure the pressure upstream and downstream of the tested meter; a vacuum gauge; two calibrated tanks, each placed on a precision electronic balance; a temperature sensor; and a control panel (Fig. 3). The test bench is connected to a computer for test automation, measurement acquisition and result calculation.

The test method applied to determine the measurement error was the “collection” method (ISO 4064:2005). The water passing through the meter is collected in one of the two calibrated tanks, with the quantity determined by weight. Meter error is defined by Eq. (1), where the actual volume is that collected in the tank and measured by the

precision balances. The volume indicated by the meter, corresponding to the actual volume, is determined by reading the meter when its sensor stops.

The error curve of the 143 water meters for low flow rates were defined for four different pressure values, representing the network pressure measured upstream of the instruments: 0.5, 1.0, 1.5 and 2.0 bar. For each test pressure, the meters were tested at four different experimentally determined flow rates: the first being the highest flow rate at which the meter sensor remains at rest, with the other three at increasing intervals of one litre per hour (i.e. the second flow rate is one litre per hour greater than the first, and so on). Therefore, the testing flow rates were different for each meter and changed with test pressure. A total of 31 water meters were not tested because they were blocked or unreadable (Table 1). Nearly all the meters in the last two groups (age classes 8 and 9) worked despite their very long service lives. As a result, at the end of laboratory analysis, the low flow rate error curves for 112 water meters were defined for each of the four tested pressure values.

3 Field studies

To apply the results of the laboratory study to the evaluation of the relationship between apparent losses, meter age and network pressure level, three consumption profiles were developed to represent different types of users:

- Consumption profile A corresponds to users who have a private tank that is filled during the night and emptied during the day. During the monitoring period, the network was managed via intermittent distribution, which is often applied by utilities to cope with water scarcity (Criminisi et al., 2009). When the network is empty, the user’s consumption is guaranteed by the water collected in the tank. During the service period, water entered the tank at flow rates much higher than common consumption pulses and, for this reason, apparent losses were small.

- Consumption profile B corresponds to users who have a private tank that is always full because the user has a continuous water supply. The tank was always full and, once water flowed from the tank to the user, was rapidly replenished through a partially open float valve. The percentage of the volume that entered the tank at low flow rates was higher, and thus also higher was the risk of apparent losses due to under-registration of the meter.
- Consumption profile C corresponds to users without a tank, with the consumption profile determined by actual user demand.

The water consumption profiles were obtained from an experiment performed in 2008 when fifteen residential users in the Palermo distribution network were continuously monitored for approximately 2 months. The flow rates entering the tanks and leaving the tanks for the user's consumption were measured every second for users with tanks. Similarly, for users without tanks, the user's consumption was also measured every second. The three consumption profiles are not presented as typical of users in Palermo because of the small number of monitored users. The profiles are only used here to analyse differences in meter under-registration.

Figure 4 shows the percentage of total volume consumed by the users belonging to profiles A, B, and C at different flow rates. For users corresponding to profiles A and B, the water meter is always installed upstream of the tank. The volume measured by the meter is not connected with the users' actual consumption but rather reflects the filling and emptying of the tank. For profile A, the tank empties during the day and fills during the night. Therefore, most of the water passes through the meter at flows between $30\,\mathrm{l\,h^{-1}}$ and $120\,\mathrm{l\,h^{-1}}$, which reflects the tank filling process (Fig. 4a). For profile B, the private tank is usually full, and it slowly refills after each consumption event because the volume of water entering the tank is controlled by a floating valve. In this case, a significant part of the water volume (approximately 30 %) is supplied at flows lower than $50\,\mathrm{l\,h^{-1}}$ that may be subject to high metering error (Fig. 4b). For profile C, the user is not connected to a private tank, and the flow passing through the meter is completely

dependent on user consumption. In the presented case, the volume of water supplied at flows lower than $50\,\mathrm{l\,h^{-1}}$ is less than 15 % (Fig. 4c).

4 Analysis of results

4.1 Analysis of the relationship between meter starting flow, meter age and network pressure

The laboratory results obtained for each meter and test pressure were interpolated. The following is the empirical equation for the error curve that was determined:

$$Q_{\mathrm{meas}} = Q_{\mathrm{real}} \cdot \left[1 - \left(\frac{Q_{\mathrm{start}}}{Q_{\mathrm{real}}} \right)^{k} \cdot \cos \left(\pi \cdot \frac{Q_{\mathrm{real}} - Q_{\mathrm{start}}}{Per} \right) \right] \tag{2}$$

where Q_{meas} is the flow rate corresponding to the volume indicated by the meter $[\mathrm{l\,h^{-1}}]$, Q_{real} is the flow rate corresponding to the actual volume passing through the meter $[\mathrm{l\,h^{-1}}]$, Q_{start} is the starting flow $[\mathrm{l\,h^{-1}}]$, k is a dimensionless coefficient that takes into account the reduction of metering error with the flow rate Q_{real}, and Per is the semi-period of measurement error oscillation around zero, which accounts for both negative and positive errors depending on passing water flow $[\mathrm{l\,h^{-1}}]$. The formulation of the error curve was determined to be a combination of a co-sinusoid describing the oscillation of the error around zero and a power function controlling the amplitude of the error oscillation. The parameters in Eq. (2) were obtained by fitting the experimental data with the error curve using the least square method: error data for each meter were fitted separately, yielding an error curve for each of the tested meters. Figure 5 shows an example of an error curve obtained during the laboratory study for a sample water meter in age class 3, tested at a pressure of 1.0 bar.

The influence of pressure on the shape parameters k and Per is negligible: for the same meter under different pressure scenarios, Per values remain in a 2 % range around the average without any visible dependency on pressure, while k assumes higher values when the test pressure increases, but with variations in a range of 3 % around the average value. The effect of these parameters can thus be considered negligible (Table 2).

For the different pressure values, the starting flow of each tested meter was calculated using Eq. (2). Estimating Q_{start} from laboratory experiments is difficult because the incipient movement of the mechanism must be noted by the test operator (and so the value is dependent on the operator's experience) and because Q_{start} is affected by the hysteretic behaviour of the initial part of the error curve (Arregui et al., 2006). For this reason, interpolation is more reliable because it is more objective and less dependent on the above-mentioned hysteresis.

Figure 6 illustrates the non-parametric distribution of the starting flow of the meters at each specified test pressure. For each age class plotted in Fig. 6, the points represent the minimum and maximum starting flow registered during the laboratory experiments; the ends of the whiskers represent the 5th and 95th percentiles and the ends of the boxes the 25th and 75th percentiles of meter starting flow, with the thin and thick lines within the boxes representing the median and mean of the empiric distribution, respectively. The short distance between both the maximum and minimum values and between the extremes is typical of age classes in which starting flows are similar for all meters analysed. This behaviour is characteristic of homogeneous classes in which all meters have the same technical features and are often made by the same manufacturer. In contrast, a wide distance between maximum and minimum values and between the extremes, with an overall larger box, is typical of age classes in which meters have different features and manufacturers. The classes in which the median is lower than the mean (e.g. class 3 and class 5) include a few meters with high starting flows and a majority that demonstrate better performance. The oldest classes display the opposite behaviour, with a small number of meters that have retained very good performance with low starting flows, comparable to those of newer meters, and a large majority of meters with high starting flows. In fact, not all meter models deteriorate in

the same manner and therefore respond to past experiences in different ways (Zhen and Tao, 2008). Finally, classes such as class 4 that have small boxes with a wide distance between the extremes reflect the presence of outliers, i.e. single meters with very low or very high starting flows. Analysis of Fig. 6 shows that starting flow, as well as the dispersion of data around the median, tends to increase with age, except for classes 4 and 6. Increasing pressure reduces the starting flow, in terms of both the percentiles and the extremes. This effect appears to be more evident for the older classes, most likely because of the higher absolute values of the starting flows.

To better separate the effects of age and pressure, Fig. 7 shows the average starting flow of each class after interpolation by an exponential law. The exponential regression can be substituted by a linear law (neglecting classes 7, 8 and 9) without reducing the regression R^2. This shows that the increase in starting flow over time can be explained by a linear function of age. With meter ageing, the starting flow begins to increase proportionally more than age, demonstrating the increasing impact of wear and tear. The effect of pressure on the average starting flow gradually becomes less evident as the meter ages.

Figure 8 shows the dependency of the average starting flow on pressure, with the starting flow obtained under a test pressure of 0.5 bar taken as 1.0. The effect of pressure is significant, with Fig. 8 confirming that increasing pressure reduces the starting flow and consequently the potential apparent losses due to meter under-registration. The effect of pressure on the starting flow is essentially linear, most likely because the effect is related to water flowing around the moving parts of the meter at very low velocities, thus maintaining laminar flow. The newer the meter is, the greater the influence of pressure: for class 1 (0–5 yr), the starting flow at 2.0 bar is only 60 % of its value at 0.5 bar, while for class 3, the starting flow is reduced by approximately 15 % for the same increase in pressure. The older age classes have relative reductions in starting flow similar to class 3, thus showing that the effect of pressure weakens with ageing. These results imply that controlling background losses in distribution networks by reducing pressure may cause an increase in meter under-registration. Real losses will decrease, but apparent losses will increase. The choice to intervene in this manner should be based on an understanding of the water losses and the relative magnitudes of the real and apparent components of the loss. A cost-benefit analysis can determine when intervention is necessary.

A predictive equation of starting flow that uses both pressure and meter age was obtained by interpolating all the laboratory results:

$$Q_{\mathrm{start}} = (-0.7405 \cdot P) \cdot e^{(0.0031 \cdot P + 0.00437) \cdot \mathrm{Age}} \tag{3}$$

where P is the pressure [bar] and Age is the meter age [yr]. As discussed above, the effect of pressure on starting flow is essentially linear, while the influence of age is exponential.

The experimental analysis confirms and extends the considerations noted by Arregui et al. (2006). Metering performance at high flows is not greatly affected by meter wear and tear because meters follow the momentum equation principle. This was confirmed in our experimental study by the fact that the parameters k and Per are less variable than the starting flow Q_{start} considering both meter age and pressure. Per is not significantly affected by meter age or pressure; this parameter affects the period of the oscillation of the error around zero, and this aspect seems to be more related to meter construction than to wear or pressure. The variation of k with age is in the range of 30 % (between new and 40-yr-old meters), and its variation with pressure is in the range of 4 %. This parameter controls the shape of the error curve, and its reduction with age is due to the increase in error for higher flows; its dependence on pressure is small and is possibly due to the combined effect of pressure and turbine friction drag.

Both parameters have a greater effect on meter starting flow Q_{start}, which is the main parameter influencing meter performance at low flows. Meter wear and tear increases friction in the meter mechanism thus increasing the resistance to the start of turbine movement; the difference between the pressure on the two sides of the turbine dictates the start of movement, which is contrasted by the turbine static friction.

4.2 Evaluation of apparent losses

As a final step in the presented study, the change in apparent losses due to meter under-registration with meter age at different network pressure levels was assessed for each of the three user types (defined in the previous section). Tables 3, 4 and 5 show the apparent losses as percentages of consumption for the three user types at flow rates lower than the starting flow, for different meter age classes and for each test pressure.

Table 3, which presents consumption profile A, shows minor apparent losses, as water enters the tank at flow rates that are generally higher than the meter starting flow; the only exception is meter age class 9, for which the apparent losses reach an average of 13 %, with almost 20 % at low pressures. The average starting flow of the meters in age class 9 is higher than 30 $\mathrm{l\,h^{-1}}$ at 0.5 bar and decreases to a little less than 30 $\mathrm{l\,h^{-1}}$ at 2.0 bar (see Fig. 7). Profile A's percentage of consumption at flow rates lower than these values is quite high, and thus the apparent losses increases as well (see Fig. 4a). Conversely, the average starting flows of the meters in all other age classes (from 1 to 8) are always lower than 20 $\mathrm{l\,h^{-1}}$ (see Fig. 7), which is a small percentage of profile A consumption (see Fig. 4a). Therefore, passing from meters of age class 8 to those of age class 9 brings a sharp increase in apparent losses. This sharp increase does not happen for the other two types of users (consumption profiles B and C). As shown in Fig. 4b and c, the percentages of consumption at flow rates lower than the average starting flow of the meters of age class 9 are not as low as those of profile A. Therefore, a gradual increase in apparent losses occurs. In summary, for the type of user corresponding to profile A, meter ageing is not a significant issue, as the meter usually operates within a flow range for which measurement error is low. For the same reason, the pressure is also not a significant issue. For meters of age class 9 only, a pressure increase from 0.5 to 2.0 bar results in an increase in apparent losses of almost half.

Table 4 displays the apparent losses when the tank is always full (profile B). Here, water enters the tank at very low flow rates, which depend on the opening of the float valve and not on actual user consumption. Apparent losses are higher and rapidly increase with meter age but decrease with pressure. For meters of age class 1, a pressure increase from 0.5 bar to 2.0 bar results in apparent losses that are almost 4 times lower.

Table 5 shows the apparent losses for an intermediate situation (profile C), in which there is no tank. For this type of user, the loss levels are between the two previous cases. This profile is likely to be the most common in networks that do not suffer water scarcity. The average apparent losses due to meter starting flow increase rapidly with meter age, reaching a maximum value of 14.5 % by age class 9. The effect of pressure is also important, with apparent losses almost halved for class 2 when pressure increases from 0.5 to 2.0 bar.

For profiles B and C, the reduction in apparent losses due to pressure changing from 0.5 to 2.0 bar decreases with an increase in meter age. This statement is justified by the results gathered from the analysis of Figs. 7 and 8. As Fig. 7 shows, an increase in meter age yields an increase in the average starting flow for a given pressure value. Conversely, for a given age class, an increase in pressure yields a decrease in the average starting flow (Fig. 8). The older the meter is, the lower the decrease in the average starting flow. Therefore, a decrease in the average starting flow causes a substantial recovery of apparent losses if the consumption pattern of the user has a relatively high percentage of consumption at lower flow rates (see Fig. 4b and c).

5 Conclusions

This paper has described the results of a laboratory and analytical study of the share of apparent losses caused by the inability of water meters to register flow rates lower than the meter starting flow. This parameter is frequently neglected both because it is often deemed to be of little influence and because quantifying it is complex. A laboratory

procedure was proposed to reliably estimate starting flow through experiments performed on a sample of worn-out water meters.

The results of the laboratory study show that ageing and pressure are both relevant parameters for determining starting flow. The former relates to starting flow in that starting flow progressively and nonlinearly increases with meter age, while the latter has a linear influence on starting flow, with its effect highest for newer meters and progressively masked by wear and tear as the meter ages.

The application of laboratory results to three user consumption profiles illustrated the complexity of the picture and the significance of the apparent losses due to meter under-registration for some user profiles. If the flow entering a user's water system is controlled by a tank, the combined influence of pressure, meter age and tank filling significantly affects apparent losses. These can be negligible if the tank fills and empties cyclically, the water meter is new and the pressure is high; at the opposite end of the loss spectrum, the apparent losses can be equivalent to 1/4 of total consumption if the water meter is old, pressure is low and the tank is always full. Under the most common conditions (users without tanks), apparent losses tend to be in the range of 15 %, demonstrating the importance of correct meter management.

The results of this paper show that pressure control, a common method of reducing background losses in distribution networks, may have the negative side effect of an increase in apparent losses due to meter under-registration. Such an effect should be considered when water loss reduction campaigns are designed by utilities, which are increasingly interested in conserving water by reducing pressure.

Moreover, the information obtained in the experimental study can be used by water managers to prioritise water meter replacement campaigns by integrating this information with other relevant factors such as age, installation, water quality, etc. The study demonstrates that the commonly used parameters for prioritising water meter replacement should be integrated with the discussed considerations of network pressure and the presence of private tanks.

The results of this analysis could be integrated into future studies that could aim to investigate the integration of all the factors affecting the importance of water meter replacement (the cost of replacement or repair; the actual amount of revenue lost; and local conditions, particularly where there is no water storage at the property served) with network water pressure.

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Table 1. Age class divisions of the tested meters with indication of the water meters not tested because they were blocked or unreadable.

Age class	Service life [years]	No. meters	%	Metrological class	No. meters not tested
1	0–5	18	12.6	C	0
2	5–10	16	11.2	C	6
3	10–15	19	13.3	B	5
4	15–20	17	11.9	B	4
5	20–25	15	10.5	B	2
6	25–30	19	13.3	B	8
7	30–35	19	13.3	B	5
8	35–40	10	7.0	B	0
9	40–45	10	7.0	B	1
TOT		143	100		31

Table 2. Variation of the parameters *Per* and *k* with meter age class and pressure.

Age	*Per* [$\mathrm{l\,h^{-1}}$]				*k* [–]			
class	$p = 0.5$ bar	$p = 1.0$ bar	$p = 1.5$ bar	$p = 2.0$ bar	$p = 0.5$ bar	$p = 1.0$ bar	$p = 1.5$ bar	$p = 2.0$ bar
1	25.11	25.27	24.96	24.96	1.92	1.94	1.97	2.00
2	34.26	34.26	34.41	34.41	1.90	1.92	1.95	1.99
3	39.22	39.53	39.37	39.53	1.78	1.81	1.84	1.85
4	49.76	50.53	50.84	49.91	1.71	1.74	1.76	1.79
5	53.01	52.86	52.86	53.17	1.65	1.69	1.71	1.76
6	29.45	29.61	29.61	29.76	1.62	1.63	1.66	1.69
7	39.37	39.99	38.91	38.91	1.60	1.61	1.64	1.66
8	36.43	36.58	36.27	36.12	1.56	1.58	1.60	1.63
9	31.31	31.62	31.16	31.78	1.54	1.56	1.57	1.60

Table 3. Apparent losses for each meter age class and test pressure: profile A.

Age class	Apparent losses [%]				Average [%]
	$P = 0.5$ bar	$P = 1.0$ bar	$P = 1.5$ bar	$P = 2.0$ bar	
1	0.19	0.16	0.14	0.12	0.15
2	0.28	0.25	0.22	0.21	0.24
3	0.56	0.50	0.48	0.46	0.50
4	0.38	0.35	0.32	0.31	0.34
5	2.08	1.66	1.39	1.28	1.60
6	0.60	0.50	0.48	0.46	0.51
7	2.04	1.73	1.56	1.46	1.70
8	2.65	2.16	1.90	1.68	2.10
9	19.34	13.91	11.38	9.95	13.64

Table 4. Apparent losses for each meter age class and test pressure: profile B.

Age class	Apparent losses [%]				Average [%]
	$P = 0.5$ bar	$P = 1.0$ bar	$P = 1.5$ bar	$P = 2.0$ bar	
1	4.29	2.69	1.51	1.22	2.43
2	8.24	7.86	7.11	6.37	7.40
3	11.19	10.80	10.53	10.34	10.72
4	9.41	9.00	8.76	8.58	8.94
5	15.82	14.53	13.72	13.37	14.36
6	11.32	10.74	10.59	10.36	10.75
7	15.69	14.77	14.24	13.92	14.65
8	17.57	16.07	15.28	14.61	15.88
9	27.29	25.45	24.05	23.06	24.97

Table 5. Apparent losses for each meter age class and test pressure: profile C.

Age class	Apparent losses [%]				Average [%]
	$P = 0.5$ bar	$P = 1.0$ bar	$P = 1.5$ bar	$P = 2.0$ bar	
1	4.29	2.69	1.51	1.22	2.43
2	8.24	7.86	7.11	6.37	7.40
3	11.19	10.80	10.53	10.34	10.72
4	9.41	9.00	8.76	8.58	8.94
5	15.82	14.53	13.72	13.37	14.36
6	11.32	10.74	10.59	10.36	10.75
7	15.69	14.77	14.24	13.92	14.65
8	17.57	16.07	15.28	14.61	15.88
9	27.29	25.45	24.05	23.06	24.97

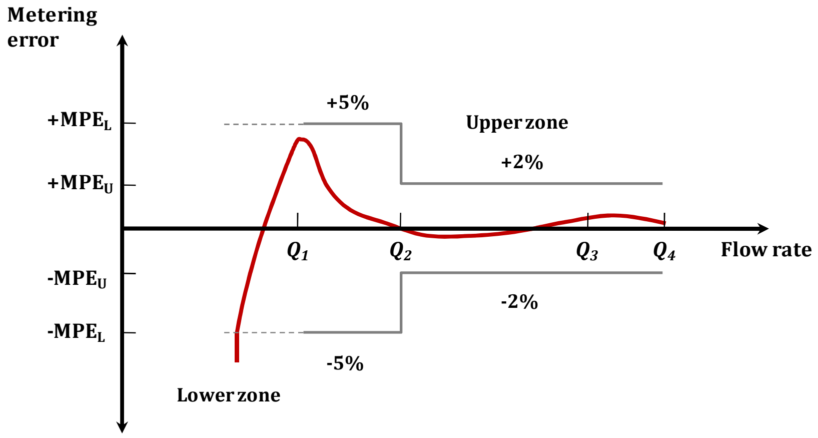

Fig. 1. Sample error curve for a new water meter.

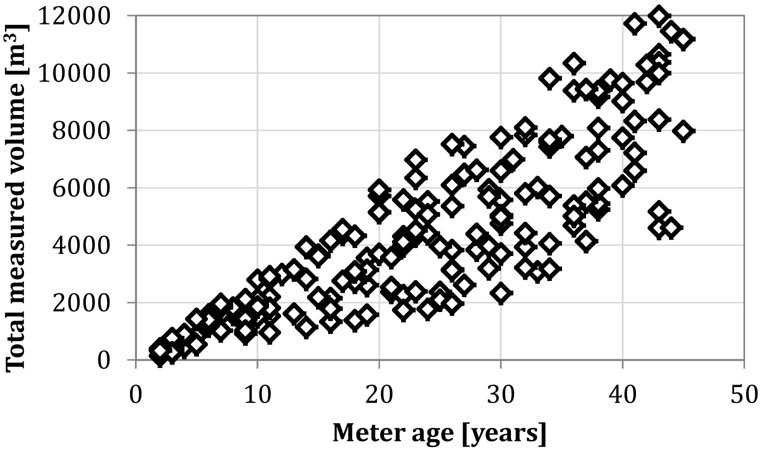

Fig. 2. Total volume measured by the tested meters over their service lives.

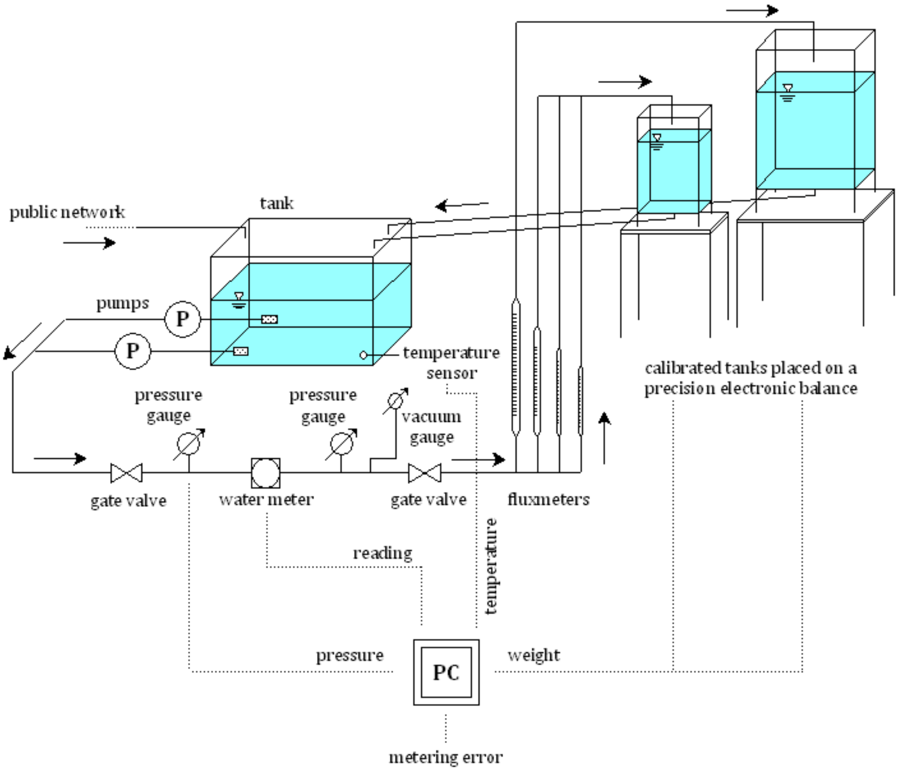

Fig. 3. A schematic of the test bench.

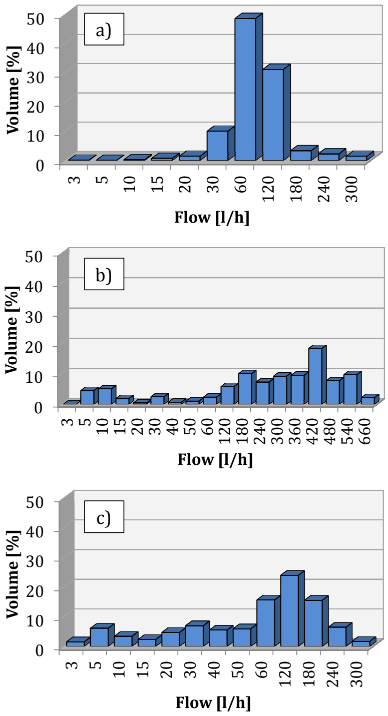

Fig. 4. Consumption profiles used in the study: **(a)** user A; **(b)** user B; **(c)** user C.

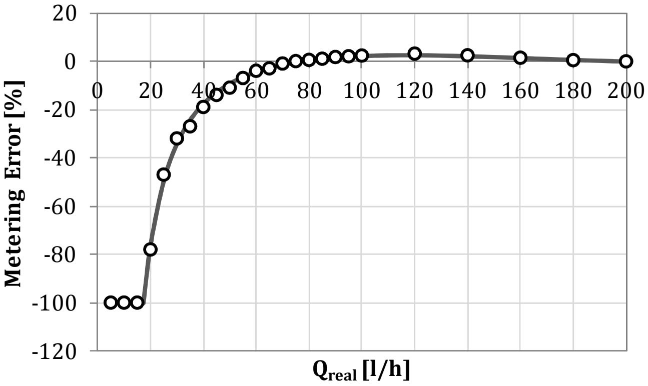

Fig. 5. Example of an error curve for a sample water meter in age class 3 (test pressure $p = 1.0$ bar): $Q_{\mathrm{start}} = 17.20\,\mathrm{l\,h^{-1}}$, $k = 1.84$ and $Per = 38.22\,\mathrm{l\,h^{-1}}$.

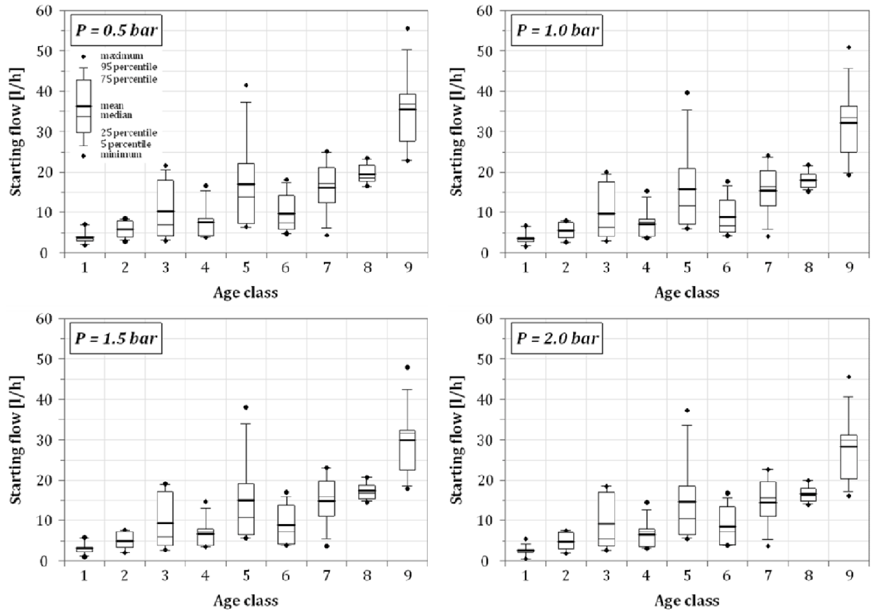

Fig. 6. Box plots summarising the laboratory results.

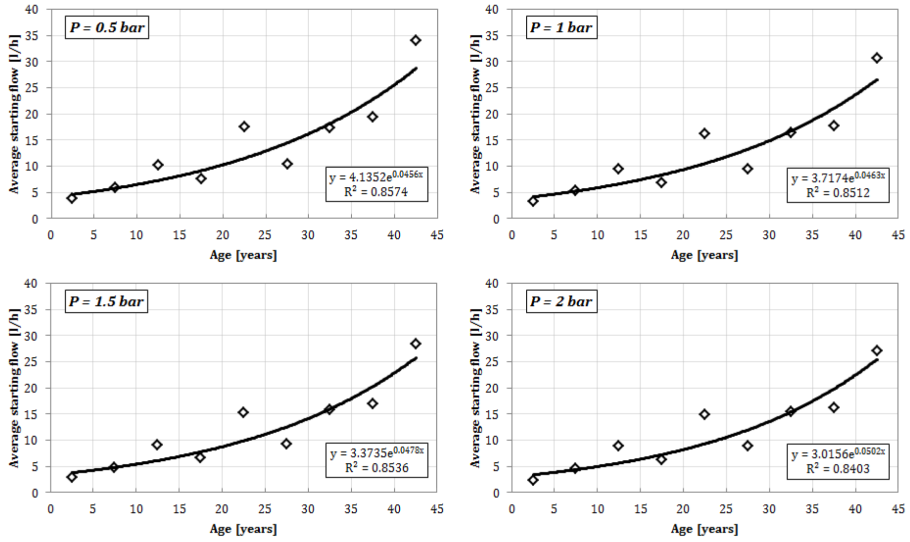

Fig. 7. Relationship between average starting flow and meter age for the four different test pressures.

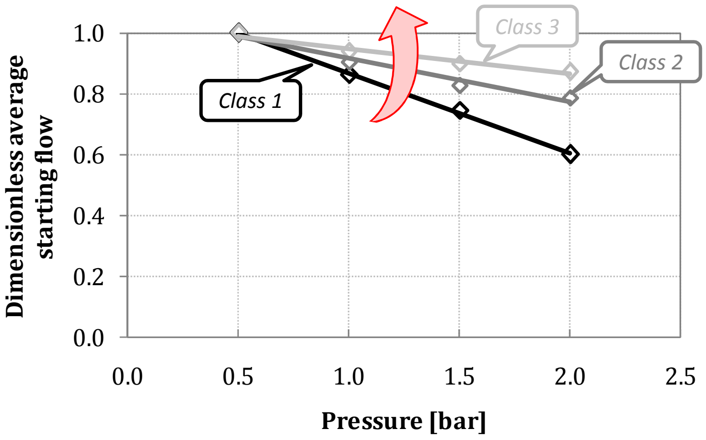

Fig. 8. Relationship between average starting flow and test pressure for the different meter age classes.