Customer Metering Inaccuracies

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This paper acts as Appendix 3 of the free Guidance Notes on Apparent Losses and Water Loss Reduction Planning by Vermersch, Carteado, Rizzo, Johnson, Arregui and Lambert at http://www.leakssuite.com/guidance-notes-app-loss/

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1 Introduction

Real and apparent (commercial) losses, although different in nature, are both components of what is known as non-revenue water (Figure 1). While real losses are easily recognised and accepted by utilities engineers and managers, apparent losses are not so well understood. This is probably because apparent losses cannot be physically seen – like a burst in a main - and are mostly related to economic losses. A cubic meter of apparent losses is not something material that a poorly trained engineer or manager can touch. However, apparent losses have a major impact in the revenue of the water utilities. Quite often the cost for the utility of a cubic meter of real losses is much less than the cost of a cubic meter of apparent losses.

The logical question to ask is where apparent losses come from? It is commonly accepted that in systems where all customers are metered, apparent losses come from three major components (Figure 2): systematic data handling errors, unauthorised consumption and customer metering inaccuracies. While the first two are more related to the utility management, the last one is more of a 'technical' component. The purpose of this document is to make a brief conceptual approach to this last component. The other two apparent losses components are described in other documents within this manual.

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Figure 1. IWA Water Balance showing Customer Metering Errors

How important can water meter inaccuracies be in a water supply? We can start by saying that it is impossible to perfectly register all water consumed by every customer, even if the most advanced meter in the market is installed at each customer connection. Meters, as any other measuring instrument, have technical limitations and under different circumstances they cannot measure all water consumption from customers. Furthermore, in practice, metering water consumption represents additional difficulties, some of them technical and some other related to local constraints of the water utility, as it will be seen throughout the document. The most important of them is that water meters' metrological performance degrades over time. Frequently meters tend to register, as time goes by, less and less consumption from customers.

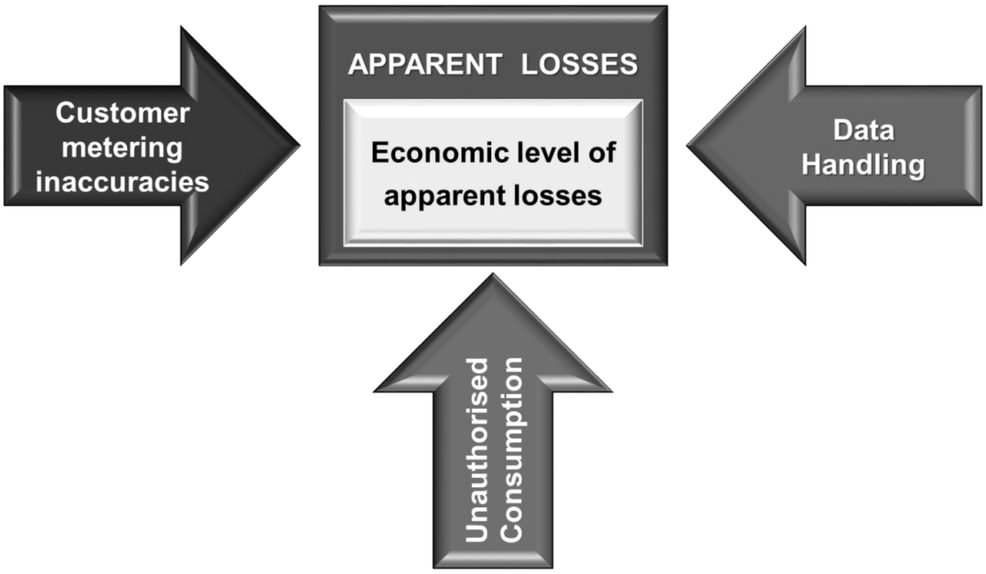


Figure 2. The three major apparent losses components for fully metered systems

The objective of this document is to highlight the most common and important aspects related to customer metering inaccuracies. This document is not intended to be a comprehensive training course on water metering and it is assumed that the reader has basic knowledge on water meters technologies, standards, and other related concepts. The bibliography provided at the end should be taken as a source of additional information.

2 Basic concepts and definitions

2.1 Measuring errors: the error curve of a meter

The measuring error of a meter at a given flow rate is defined as the difference between the volume registered by the water meter and the actual volume consumed. The error is usually expressed as a percentage of the actual volume passed through the meter:

$$\varepsilon_Q(\%) = \frac{Vol_{registered} - Vol_{actual}}{Vol_{actual}} \cdot 100$$

Measuring errors are something of concern for water utilities because meters cannot achieve a perfect metrological performance under the varying working conditions usually found in the field. In fact, there are flow rates for which the sensor of the meter will not even move or detect any flow, implying that the meter has an error of -100%. At some other flows the measuring errors of the meter may become negligible. This variability of performance throughout the measuring range leads to a situation in which water meters do not register the exact volume of water consumed (it is extremely difficult establishing what that quantity that could exactly be). Sometimes water meters register more water than the amount of water used by a customer. At other times they register less water than the volume actually used. The error curve (Figure 3) is the parameter defining how the measuring errors vary with the flow rate. Information about this parameter is needed to calculate how much water is not registered or is registered in excess.

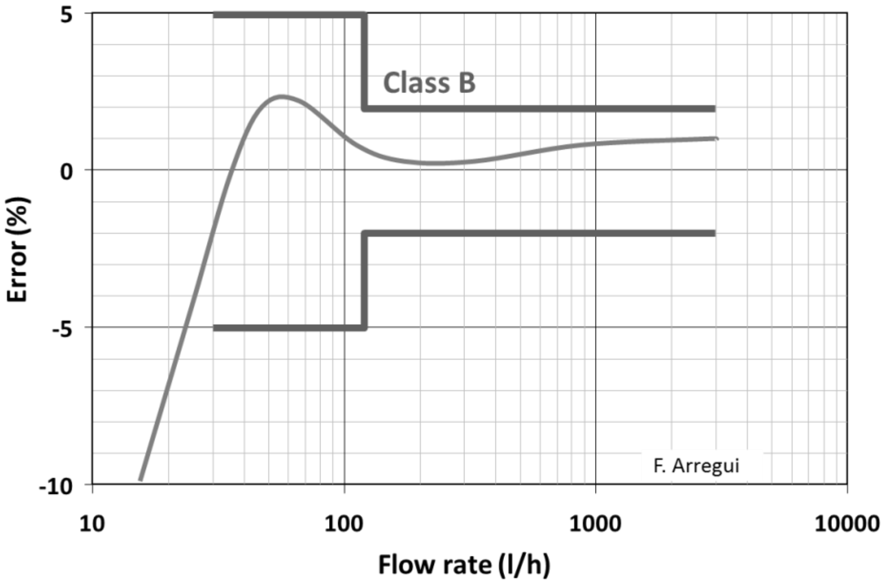


Figure 3. Error curve of a brand new single jet Class B domestic meter

The detailed shape of the error curve of every meter is not known and the information about the error is limited to very specific flow rates, typically associated to the metrological parameters defined in the Standards described in Section 3 below.

As seen in Figure 3 the metrological performance of a new meter is not uniform throughout the measuring range, and the errors depend on the flow rate passing through the meter. This is true even for new meters. When meters age, the way the error curve evolves with time (Figure 8) and/or with the totalised volume will depend on the working conditions of the meter, its measuring technology and water quality going through the meter. The large number of parameters affecting water meter aging is one of the main reasons why it is impossible to make a reliable prediction without testing meters in laboratory or in the field. In fact, it is not unusual to find the same model of meter behaving completely different in two water utilities.

Also, another important concept to keep in mind is that the actual error of a meter is not the same as the maximum permissible error defined in most Standards for water meters. Typically the Standards divide the measuring range of water meters into two zones: the upper and the lower zone (Figure 3). Each Standard uses different criteria to define these two zones. For example, ISO 4064 and OIML R49 divide the measuring range using a reference flow rate (the transitional flow rate or Q_2). The maximum permissible error in the lower zone, between the minimum and the transitional flow, is ±5%; while the maximum error allowed in the upper zone between the transitional and the overload (maximum) flow is ±2%. The definition of a maximum permissible error does not mean that the error of the meter working within that range matches that maximum permissible error. So it would be incorrect to say that the error of a meter is -5% if it measures flow rates between minimum and transitional and -2% if it measures flow rates between transitional and the maximum flow rate. The actual error of that meter at different flow rates will be defined by its error curve (Figure 3).

2.2 Water consumption pattern

Due to the varying errors throughout the measuring range an additional parameter is needed to obtain the real measuring performance of the meter: the consumption profile of the user being measured (Figure 4). This parameter, defines how much water is used at each flow rate range and is distinctive for each user or type of user.

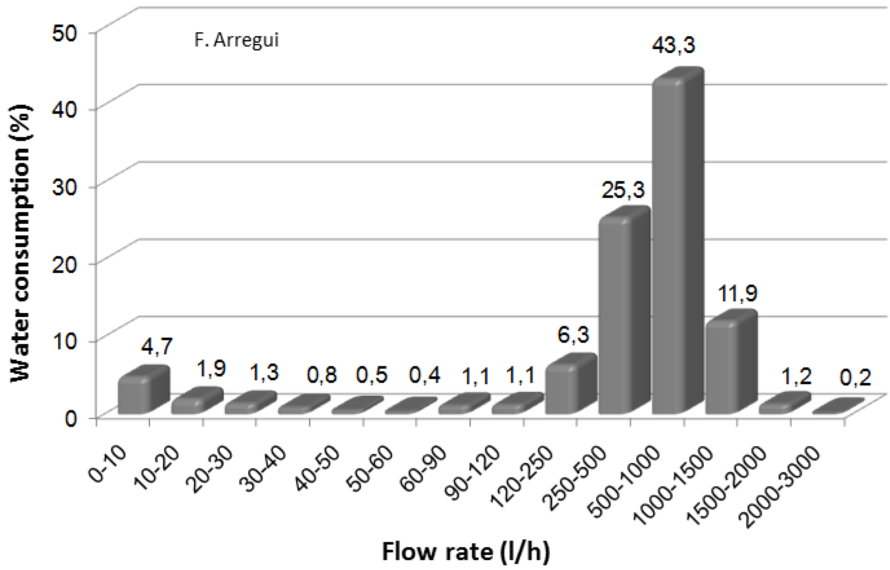


Figure 4. Example of a water consumption profile of a user

The weighted error of the meter is calculated combining the information about the error of the meter at each flow rate with the information about how much water is used in that flow rate range. This way, the weighted error of a meter defines, in a single parameter, what percentage of water is not registered or registered in excess by the meter. A negative value indicates that the meter is measuring less water than the amount being consumed, i.e. the meter is under-registering water consumption. A positive figure means that the meter is registering more water than the volume that has gone through it.

Obviously, this procedure for calculating the performance of a water meter leads to an important conclusion: the same meter measuring water consumption of two different users may show different weighted error figures. The weighted error of meter is related to both its error curve and the water consumption profile of the user being metered. Therefore, the weighted error of a meter cannot be calculated if information of either the error curve or the consumption profile of the user is not available.

3 Standards for water meters

Standards are a keystone when dealing with water meters, for they are closely related to regulations and requirements that the utilities must follow. It is however difficult to present a section on standards that will remain updated for a long period of time as these documents are of a changing nature.

Water meters are used for trade as the volume measured serves as the reference for billing purposes between customers and water companies. Standards are developed to protect the rights of the customers and to assure an adequate quality of water volume measurements. They define how meters have to be designed, manufactured and tested, and the metrological and technical characteristics that they have to meet.

Most measuring principles used by water meters have been unchanged for many years. However, technology advances make possible the introduction of new techniques that improve how consumed water is measured. As a result, most standards have to be periodically updated when these new technologies and technical requirements have received major revisions.

The most common technical parameters to be considered in a water meter are the working pressure and temperature, flow capacity, indicating device, electromagnetic compatibility, dimensions, and designation.

The metrological characteristics are related to the primary function of a meter, i.e. to adequately measure the volume of water that has circulated through it. They define the maximum permissible errors within the working flow range and its amplitude.

The latest water meters standards published up to July 2016 are the following:

3.1 ISO-4064

Issued by: International Organization for Standardization
Year: 2014
Parts:

- ISO 4064-1:2014 Water meters for cold potable water and hot water -- Part 1: Metrological and technical requirements
- ISO 4064-2:2014 Water meters for cold potable water and hot water -- Part 2: Test methods
- ISO 4064-3:2014 Water meters for cold potable water and hot water -- Part 3: Test report format
- ISO 4064-4:2014 Water meters for cold potable water and hot water -- Part 4: Non-metrological requirements not covered in ISO 4064-1
- ISO 4064-5:2014 Water meters for cold potable water and hot water -- Part 5: Installation requirements

Description: ISO 4064-1:2014 specifies metrological and technical requirements of water meters for cold potable water and hot water flowing through a fully charged, closed conduit. These water meters incorporate devices which indicate the integrated volume.

In addition to water meters based on mechanical principles, ISO 4064-1:2014 applies to devices based on electrical or electronic principles, and mechanical principles incorporating electronic devices, used to measure the volume of cold potable water and hot water.

ISO 4064-1:2014 also applies to electronic ancillary devices. Ancillary devices are optional. However, it is possible for national or regional regulations to make some ancillary devices mandatory in relation to the utilization of water meters.

3.2 OIML R49

Issued by: International Organization of Legal Metrology

Date: 2013

Parts:

- OIML R 49-1:2013 Water meters for cold potable water and hot water -- Part 1: Metrological and technical requirements
- OIML R 49-2:2013 Water meters for cold potable water and hot water -- Part 2: Test methods
- OIML R 49-3:2013 Water meters for cold potable water and hot water -- Part 3: Test report format

Description: Same as ISO 4064 documents.

3.3 EN 14154

Issued by: European Committee for Standardization

Year: 2014

Parts:

- EN ISO 4064-1:2014 Water meters for cold potable water and hot water - Part 1: Metrological and technical requirements (ISO 4064-1:2014)
- EN ISO 4064-2:2014 Water meters for cold potable water and hot water - Part 2: Test methods (ISO 4064-2:2014)
- EN ISO 4064-3:2014 Water meters for cold potable water and hot water - Part 3: Test report format (ISO 4064-3:2014)

- EN ISO 4064-4:2014 Water meters for cold potable water and hot water - Part 4: Non-metrological requirements not covered in ISO 4064-1 (ISO 4064-4:2014)
- EN 14154-4:2014 Water meters - Part 4: Additional functionalities
- EN ISO 4064-5:2014 Water meters for cold potable water and hot water - Part 5: Installation requirements (ISO 4064-5:2014)

Description: Same as ISO 4064 documents.

3.4 AWWA recommendations

Issued by: American Water Works Association

Year: 2015

Parts:

a. C700-15 Cold-Water Meters, Displacement Type, Bronze Main Case
b. C701-15 Cold-Water Meters–Turbine Type
c. C702-15 Cold-Water Meters–Compound Type
d. C703-15 Cold-Water Meters–Fire Service Type
e. C704-15 Propeller-Type Meters for Waterworks Applications
f. C708-15 Cold-Water Meters–Multijet Type
g. C710-15 Cold-Water Meters–Displacement Type, Plastic Main Case
h. C712-15 Cold-Water Meters–Single jet Type
i. C713-15 Cold-Water Meters–Fluidic-Oscillator Type
j. C750-16 Transit-Time Flowmeters in Full Closed Conduits

Description: These standards describe the technical and metrological characteristics of the various types of instruments used as customer meters in North America. One important difference in comparison with other international standards is that metrological requirements are not exactly the same for all meter types. Each meter technology has its own particular requirements and constrictions.

4 Calculating the actual field performance of a meter

4.1 The error curve of a meter: the test bench

The actual measuring performance of installed water meters are strongly related to the shape of their error curve. Each meter, depending on its technology and operating conditions, will have a different error curve (Figure 5). This characteristic error curve will not stay invariant for long periods of time. It will evolve with time and other influencing parameters.

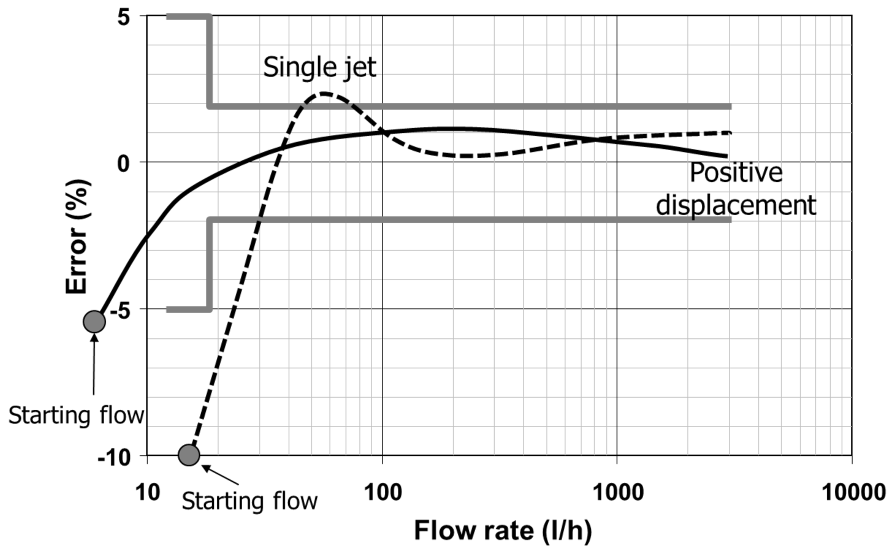


Figure 5. Comparison between the typical error curve of a single jet and a positive displacement meter

From an economic perspective, a close study of the error curve of a domestic meter is not feasible. The amount of human and technical resources required to determine in detail the error curve of each meter is extremely high. Consequently, domestic meters can only be studied by sampling a number of units and extrapolating the results to the complete population of meters. In order to obtain significant results, sampling has to be conducted following well established statistical procedures.

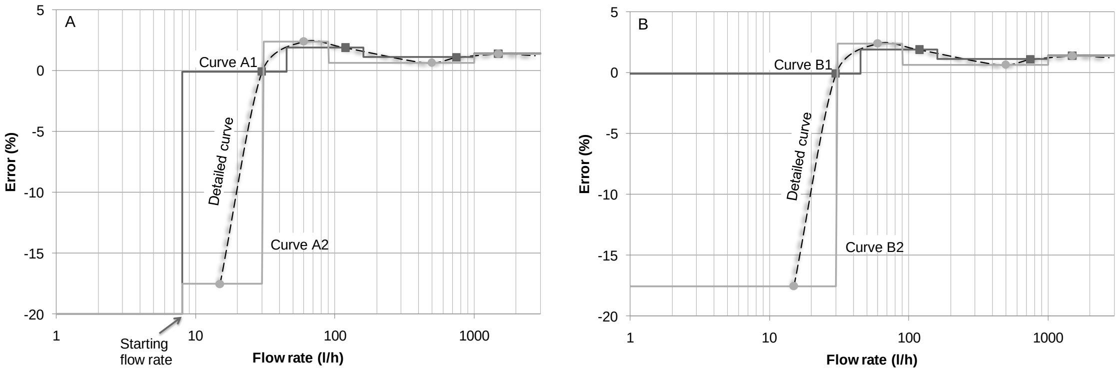
Conversely, because of their importance, non-domestic meters of larger diameters can be studied individually if required. In such cases, the amount of water billed is high enough to make an individual error test for each meter profitable.

Consequently, testing water meters can be one of the most important activities in water meter management. It requires knowing not only how good or bad a meter is before it is installed in the field but also estimating how fast its metrological characteristics degrade with time, or how it will perform under specific working conditions.

Despite its importance it is also well known that testing meters is a time-consuming and costly activity. It requires highly trained personnel and expensive equipment to conduct the testing of the meters and to obtain meaningful results. This is why it does not come as a surprise that not many water utilities own a suitable test bench where conducting appropriate metrological tests. The real situation is even worse as many of the companies that own a test bench mostly use it to solve customers' complains and not to study the average metrological performance of their installed meters.

When analysing the metrological performance of a meter it should be highlighted that there is no possibility of obtaining its complete error curve which has to be reconstructed from a limited amount of information. Most of the time water companies only test meters at three flow rates, some others testing procedures are not defined and other water utilities test meters only at one flow rate (typically nominal flow rate).

Arregui et al. (2009) showed how different testing flow rates and the consideration or not of the starting flow rate could lead to significantly different results. The differences in the weighted error calculation obtained by different testing procedures could be as high as 8%. Figure 6 shows an example of how an error curve of a meter can be reconstructed in different ways depending on the flow rates at which the meter was tested and the consideration (or absence of consideration) of a starting flow rate.



Tested Flow rate	Curve A1	Curve B1
Starting flow	8 l/h	-
30 l/h	-0.10%	-0.10%
120 l/h	1.87%	1.87%
750 l/h	1.08%	1.08%
1500 l/h	1.38%	1.38%

Tested Flow rate	Curve A2	Curve B2
Starting flow	8 l/h	-
15 l/h	-17.54%	-17.54%
60 l/h	2.38%	2.38%
500 l/h	0.65%	0.65%
1500 l/h	1.38%	1.38%

Figure 6. Reconstruction of the error curve from the information available at four flow rates

Consequently, an adequate selection of the test flow rates has to take into consideration how much information will be lost. If meters are not tested at low flow rates, where abrupt changes in the error curve appear, or testing flow rates are not properly selected, there is a significant risk of an inaccurate reconstruction of the curve. The immediate consequence of this is that the metering error obtained from this reconstructed curve will be for sure unreliable.

Additionally to the comments made above, it should also be noted that the combined uncertainty of the test shall be low enough, in the order of 1/5th of the maximum permissible errors. Otherwise, the results of the tests will be meaningless and will have no metrological validity. The calculation of the combined uncertainty is extensively explained in the document ISO/IEC Guide 98-1:2009, and it considers the total test volume, the volume reading resolution of the meter under test, the uncertainty of the reference volume used to calculate the error, and many other factors.

Table 1 presents a proposal for testing flow rates for meters of different permanent flow rates. This table has been constructed based on a specific study in which several models were tested at 20 different flow rates. Using this detailed information on the error curve, a reference value for the weighted error was obtained for each meter. This reference value of the weighted error was compared to the weighted error calculated when fewer test flow rates were selected. The number of test flow rates is selected in such a way that the discrepancies between the reference and the calculated weighted errors are not unreasonably large. For example, if the number of test flow rates is too small there is a high risk that the errors at the selected flows do not represent the average error of the meter.

Since Table 1 has been built with the sole purpose of calculating the weighted meter error, test flow rates do not necessarily have to be the same as the corresponding minimal, transition, permanent or overload flow rates for its metrological class, as defined in the standards. Additionally, it could also be argued that the selected number of flow rates for testing the meters is too large. However, apart from the clear advantage of obtaining a more accurate figure for the weighted error, the selection of a large number of test flow rates has an additional advantage: it is easier to identify anomalous results (typically coming from the fact that the readings of the meters when being tested are taken manually) or meter behaviour.

Table 1. Proposal of test flow rates for different permanent (Q_3) flow rates

Permanent flow rate (m^3/h)	Q_{T1} (L/h)	Q_{T2} (L/h)	Q_{T3} (L/h)	Q_{T4} (L/h)	Q_{T5} (L/h)	Q_{T6} (L/h)	Q_{T7} (L/h)	Q_{T8} (L/h)
1.6	8	16	32	64	128	800	1600	2000
2.5	13	25	50	100	200	1250	2500	3125
4	20	40	80	160	320	2000	4000	5000
6.3	32	63	126	252	504	3150	6300	7875
10	50	100	200	400	800	5000	10000	12500
16	80	160	320	640	1280	8000	16000	20000
25	125	250	500	1000	2000	12500	25000	31250
40	200	400	800	1600	3200	20000	40000	50000
63	315	630	1260	2520	5040	31500	63000	78750
100	500	1000	2000	4000	8000	50000	100000	125000

4.2 Consumption patterns of users

Most of the time water companies are not interested in the water meter error curves but in the percentage of water, with respect the total volume consumed, that is not registered by their meters. It is important to note, once more, that the error curve alone cannot provide such information. Metering errors can only be calculated when both, the error curve of the meters and the water consumption profiles of the users are available. Meters inaccuracies are obtained by a proper combination of these two parameters.

4.2.1 Consumption profiles of domestic users

Water consumption profiles of domestic users have to be obtained by means of statistical analysis and data sampling. For such purposes, a significant sample for each different consumption group (which have to be previously defined) has to be selected and monitored.

The cost of such activity is even higher than the cost of testing meters in the laboratory. The necessary equipment is expensive and field work is always considerable in terms of labour hours and materials. If this was not enough, the meaning of "significant sample" is always uncertain and difficult to estimate and define (mainly because it depends on the acceptable uncertainty on the determination of the weighted error).

Fortunately, experience has proved that it is possible to use, as a first approximation to the problem, without introducing an unacceptable level of uncertainty, standard water consumption profiles for typical domestic users depending on their characteristics. Certainly, the real consumption profile of the users will not correspond exactly to the standard profiles proposed in this document but, as a first approximation, for a preliminary study, they should produce figures of the weighted error accurate enough for the purpose. In later stages of the study, and once the methodology has been established, it will be possible to substitute these profiles with more accurate ones obtained from real measuring campaigns. Furthermore, the availability of standard consumption profiles, independently of its correctness, will allow water companies to analyse the performance of new and used meters with respect a standard user. This will also permit a more reliable comparison between water companies by calculating metering error using the same parameters and calculation techniques.

A proposal of water consumption profiles for domestic users is shown in Table 2. As it can be seen, the recommended profiles only shows how water is distributed on different flow rate ranges but it does not provide information on the total consumed volume. Profile I corresponds to a flat in an apartment building or a house (having no garden or swimming pool) without a private storage tank. Profile II corresponds to an apartment or a house (having no garden or swimming pool) supplied from a private roof tank. Profile III corresponds to a house with garden and/or swimming pool and not having a private storage tank.

Table 2. Proposal of domestic consumption profiles

Flow rate (l/h)	Profile I	Profile II	Profile III
0-12	4.7%	10%	2.5%
12-24	2.8%	3.1%	1.1%
24-36	1.9%	1.8%	0.8%
36-72	4.3%	4.2%	2.3%
72-200	8.5%	11.6%	7.5%
200-900	40%	50%	25.3%
900-1500	35.7%	19.3%	41.2%
1500-3000	1.9%	0%	16.2%
3000-4500	0.2%	0%	2.3%
>4500	0%	0%	0.8%

4.2.2 Consumption profiles of non-domestic users

On the other hand, quite frequently, water consumption profiles of non-domestic users cannot be treated by means of a statistical approach. Consumption characteristics are completely different from one user to another even if they belong to the same user group (for example hotels, restaurants, schools, hospitals, etc.). Therefore, except for very specific cases, water consumption profiles of non-domestic users have to be studied individually. Consequently, it is not possible to establish a standard consumption profile that could be used for a typical customer.

For establishing non-domestic users' consumption patterns there are several options (from the simplest to the more complex):

a. To mount a data logger in the currently installed meter.
b. To substitute the meter by a high-end meter with an electronic register with some water consumption processing capabilities. An example of water meter that can be used for this purpose is an electromagnetic or ultrasonic meter with sufficient low flow sensitivity (having a reduced bore).
c. To substitute the meter by a high precision meter and mount a logger for a limited period of time.

4.3 Weighted error of a meter

For the weighted error calculation, a free EXCEL worksheet *MeterErrorCalculator* that combines both data, the error curve and the consumption pattern, can be used. Also, a free evaluation version of the software (http://www.woltmann.es/woltmann-en.php) allows for this calculation. The calculation is made according to the procedure comprehensively explained in Arregui et al. (2006). Additionally, Arregui (2009) shows how different weighting procedures can lead to different values for the weighted error. For this reason it is proposed that the calculation of the weighted error is standardized by the use of freeware software.

However, the interpretation of the weighted error should always take into account the uncertainties related to water consumption profiles and error curves determination. By doing this a final result of an estimated weighted error with an associated uncertainty can be given. It is always important to keep in mind that the weighted error of a meter is not a single figure (because of the way it is obtained) but an interval in which, with a certain probability, the real error is expected to lay. This uncertainty has to be considered when planning future replacement scenarios to calculate the risks associated to the decisions taken.

4.3.1 Approximate figures for the initial weighted error of domestic meters

Table 3 summarises the estimated initial error, when properly installed, of brand new domestic meters for different meter technologies, metrological classes and types of users. It is important to note that the figures presented do not correspond to the apparent losses as other terms have also to be considered (unauthorised consumption and data handling-errors) and the weighted error of a water meter will change with time and/or accumulated volume. Therefore, this table only provides an indication of which could be the minimum figure for the weighted error of domestic water meters if all of them were completely new and were properly installed.

Table 3. Typical values of the initial weighted error of properly installed brand new domestic meters

Consumption profile	Meter type	Single jet /Multi jet	Positive displacement
I	Class B or Q_3/Q_1 equal or lower than 125	-8% ÷ -3%	-
	Class C or Q_3/Q_1 greater than 125	-4% ÷ -1%	0% ÷ -1%
II	Class B or Q_3/Q_1 equal or lower than 125	-15% ÷ -8%	-
	Class C or Q_3/Q_1 greater than 125	-10% ÷ -4%	-1% ÷ -3%
III	Class B or Q_3/Q_1 equal or lower than 125	-7% ÷ -3%	-
	Class C or Q_3/Q_1 greater than 125	-3% ÷ -0%	-0% ÷ -1%

As previously stated, the weighted error of any water meter will change with time. The way it varies in time and/or with accumulated volume is unpredictable and the only way of obtaining a proper estimation is by: a) testing the meters and b) obtaining the real consumption patterns of the different types of users.

In any case, it can be affirmed that the weighted error of a positive displacement meter will for sure become more negative than the initial value. In other words, if the initial weighted error of a positive displacement meter is -1%, after several years it will become more negative than –1%.

However, this is not true for a velocity meter. The weighted error of single jet and multi-jet meters can evolve in many different forms depending on multiple factors. It is not unusual to find single jet and multi-jet meters over-registering water consumption. Obviously, this over-registration will not happen to every installed meter but it may affect how the weighted error of the meters evolves in time.

4.3.2 Approximate figures for the weighted error of non-domestic meters

Non-domestic customers may account for a significant percentage of water consumption. Unfortunately, predicting the real performance of these meters is a much more difficult task than for domestic customers:

- Very few water utilities own a large capacity test-bench for non-domestic meters (40 mm and above). Therefore, it is impossible to implement a strict control on the initial performance of procured meters and/or to conduct a proper research on how the error curves of installed meters degrade with time.
- Typically non-domestic meters are much more affected by installation conditions and flow profile distortions than domestic meters. The actual effect that these parameters will have on the measuring performance of the meter is, in most cases, unpredictable.

Therefore, it cannot be stated that if meters are not properly installed the weighted error will increase in a given percentage as this may not be true at all. In fact, some velocity profile distortions may cause over-registration while some others will lead to under-registration of water consumption.

- Water consumption profiles also play an important role in the calculation of the weighted error. Unlikely domestic users, non-domestic users do not have a similar consumption profile and they must be studied individually.

Consequently, this figure can only be roughly estimated unless first-hand information about water meters error curves and water consumption profiles of the users are available. Otherwise, a rough estimation can be made based on the:

- Age/accumulated volume of the meters.
- Expected quality of the meters.
- Existing quality control procedures of procured meters.
- Installation conditions.
- Quality of sizing procedures in the utility.
- Measuring technology of the meters.

5 Factors affecting water meters' accuracy

Even though there is a tendency of not thinking of water meters as high precision instruments, they are measuring devices incorporating in their design a great deal of technology and practical (field) experience. However, because of their complexity, there are a number of factors that can affect how well water consumption is measured. The influence of each one of these factors depends on the design of the meter and its actual working conditions in the field. Therefore, it is not possible to establish in advance how well the meter will perform when first installed and maintain its accuracy over time.

In this section, a brief description of some of these 'influence factors' is given.

5.1 Improper installation of water meters

Meter's manufacturers always send together with the instruments the required installation conditions. These instructions typically refer to the length of straight pipe that needs to be present before and after the meter and the orientation of the meter.

5.1.1 Velocity profile distortions

Most water meters measure or estimate flow velocity at limited portions inside the pipe section. However, current technologies are unable to obtain a perfect estimation of the average velocity independently of the flow velocity distribution inside the pipe (Johnson 2001). In other words, when the velocity distribution in the pipe, at the section where the sensor is located, changes with respect an undistorted velocity distribution (used during the design stage), the metering error changes with respect to the original one. A general rule for the magnitude and sign of these changes cannot be elaborated. However, for some particular cases it is possible to establish in advance, in qualitative terms, how the error will be modified. In Albaina (2016) a comprehensive set of accuracy tests conducted in an independent laboratory to several types of meters is described.

Table 4, shows from a qualitative perspective how different metering technology currently available in the market influences sensitivity to flow distortions.

Table 4. Flow distortion sensitivity

Meter type	Sensitivity
Single jet	Low
Multijet	None
Woltmann horizontal	Low - Medium
Woltmann vertical	Low
Electromagnetic – full bore	Medium
Electromagnetic – reduced bore	Low
Ultrasonic – full bore	Medium – High
Ultrasonic – reduced bore	Low
Oscillating piston	None
Nutating disc	None
Tangential	High
Proportional	High
Insertion probes	High
Vortex	Low
Fluidic	None

As has been already mentioned, most often profile distortions are thought to be caused by some element located upstream of the meter. However, a flow profile distortion can also be produced by an element or an atmospheric water discharge located downstream of the meter.

All in all, it is always advisable to strictly follow manufacturers recommendations for each specific meter regarding the need of straight pipes lengths upstream and downstream the meter.

5.1.2 Orientation of the meter

This factor mainly affects specific meter designs which use a mechanical sensor to determine the flow velocity through the pipe: single jet and multi-jet. In such cases, the velocity is measured by a rotating device (paddle wheel or turbine) which is held at the correct position by means of one or two bearings. The rotational friction at the bearings increases when the orientation of the meter is not as specified by the manufacturer (typically with the rotation axis perpendicular to the pipe and the register facing up).

At low flows, for example those caused by a leak inside a house, the energy transferred by the water to the sensing device it is extremely low. Therefore, the increase of friction cause by an improper orientation of the meter has a significant effect. The influence of the orientation decreases as the energy transferred by the water to the turbine increase, i.e. the flow rate increases. At certain level, the influence of the orientation becomes negligible. In other words, this factor only affects accuracy of velocity meters (single jet and multi-jet) at low flows, below 1/10th - 1/20th of the permanent flow. For example, a DN15 – Q3 2.5 m^3/h, orientation of the meter will only affect flow rates below 100 L/h.

5.2 Water meters wear and tear

Moving parts of mechanical meters are subject to wear. This means that their original shapes and dimensions may change over time. There may be different outcomes from deterioration of the meter's components:

- Friction between moving parts increases. In this case the low flow performance of the meter will degrade. Typically, errors in the lower part of the range will become more negative while errors in the rest of the range will remain quite stable.
- Wear deforms or changes the original dimensions of the specific components of the meters. This may have unpredictable consequences. For example, in a single jet meter the clearance between the tip of the paddle wheel and the wall of the measuring chamber increases. This leads to a reduction of the energy transfer to the impeller by the water jet and, therefore, to an under-registration of the meter. In other cases, the pivot holding the impeller may wear off allowing the impeller to hit the wall of the measuring chamber. This frequent contact of the impeller and the wall of the measuring chamber can also reduce the length of the paddles, also leading to an under-registration of water consumption.

As a general rule, it is reasonable to accept that mechanical meters which have worn down, tend to under-register water consumption. This under-registration is typically more noticeable at low flows, and usually at medium and high flows changes in accuracy are moderate.

5.3 Low pressure

There are not many published studies which relate working pressure and accuracy. However, it would be safe to state that as long as pressure inside the meter is above vapour pressure of water at any point inside the meter, the metrological performance will not be affected. To guarantee this requirement, at any flow rate and for most meters, it is advisable to have a water pressure of more than 1 bar (100 kPa) at the inlet of the meter.

In case, of having low pressure inside the meter, water can form water vapour bubbles that can reduce the accuracy and increase the wearing of certain parts of the meter.

5.4 Water quality

This is probably one of the influencing factors that can have the largest long term impact on the overall accuracy of a meter. Also, its effects are quite likely the most difficult to predict in the long term as they cannot be easily reproduced in the laboratory. In fact, all endurance tests, as defined in the standards, only account for the mechanical robustness of the meters. These tests cannot be used to have an indication on how well a meter will degrade in the field.

As water quality is a general statement, it has been divided into three different components.

5.4.1 Presence of suspended solids and particles

Depending on the nature of the solids, particles or fibres that are moving with the flow, the results on the accuracy of the meters may be different. Basically there are two effects that can take place. The suspended solids erode critical components of the meter - for example the impeller, turbine, etc. - altering their geometry. Typically, this effect will lead to an under-registration of the meter. The second effect has to do with the accumulation of particles in certain locations inside the meter. In this case, there is a partial blockage of the available section through which the water can flow, increasing the local velocity. If this is the case, some velocity meters can tend to over-register water consumption. However, if the accumulation is so significant that it interferes with the movement of the sensor, then it will cause under-registration. In the most severe cases the accumulation will completely stop the meter. In the case of organic particles or fibres, the accumulation at the bearing may cause premature wear , the slow down or the complete blocking of the water meter.

Obviously, it is impossible to generalise the effect on the metrology of all different type of particles. Therefore, it is important to conduct an analysis about the nature of the particles present in the water supply in order to predict what will be their influence in the different meters used in the system.

5.4.2 Scaling built-up. Tuberculation in pipes

Scaling built-up is one of the mayor problems faced by water meters. The amount of scaling not only depends on the quality of water but also on the specific composition and surface finishing of the materials in contact with water. Consequently, it is possible to find the same type of water meter with different levels of scaling problem severity.

The use of plastic or composite materials reduces the probability of scaling and prevents suspended solid from adhering to the internal surface of the meters.

Scaling can initially lead to over-registration of single and multi-jet meters. However, as scaling becomes more and more severe it is likely that at some point the meter stops. On the other hand, positive displacement meters are adversely affected by scaling (under-registration of water consumption).

Non-mechanical meters can also be affected by scaling processes. For example, the electrodes of an electromagnetic meter can be isolated from water, leaving the meter out of service. A similar effect can happen with the transducers of an ultrasonic meter. In these cases, the removal of the scale can be achieved by vibrating the electrode or transducer of the meter.

5.4.3 Presence of air bubbles / pockets

All commercial water meters are designed to work in fully pressurized systems. The presence of a two-phase fluid, like the one formed by the mixture of water and air, can lead to significant measuring errors. The magnitude of the error depends, among other factors, on the proportions between the liquid and the gaseous phases, especially considering that the use of a water meter is only intended to measure water volumes.

Under the presence of large air pockets or a great number of small air bubbles, a mechanical meter still counts a volume of fluid passing through it. However, non-mechanical meters tend not to register any volume at all when a certain proportion of the measured fluid is gaseous. For example, an electromagnetic meter cannot measure air flows because air is not a conductive fluid. Also, an ultrasonic water meter cannot measure an air flow or a flow with a large number of gas bubbles because the sound velocity in air is much different from the sound velocity in water and bubbles interrupt the signal between transducers.

As a conclusion, it can be stated that under the presence of air bubbles/pockets mechanical meters tend to register larger water volumes than those actually consumed. On the other hand, non-mechanical meters, under the same conditions, usually register less water volume than the volume flowing though the meter.

5.5 Transmission defects

Modern mechanical meters use magnetic transmission to transfer the rotational movement of the sensor (impeller, turbine, piston, disc…) to the register. This transmission technique prevents debris or suspended solids and particles from entering the register and being trapped between gears, stopping the meter.

The main disadvantage with respect to mechanical transmission is that its coupling strength is not as good. Therefore, depending on the quality of the magnets and the space between them, it is possible than the register does not turn at the same speed as the sensor (there is some slippage between them) or, in the worst case, that the register remains still while the sensor is turning.

Another significant disadvantage of magnetic transmission is that it can be affected by external magnetic fields. In other words, an external magnet producing a high intensity magnetic field can stop or slow down the register of the meter even if there is a water flow through the meter.

On the contrary, mechanical transmissions have as a main disadvantage that at least one of the gears of the register is in contact with water. This can be a weak point for the long term accuracy as water quality can increase the friction between moving parts in contact with water.

In summary, uncoupling of the turbine/piston magnet and the register magnet can occur:

- After a sudden start of the meter
- At high flows
- Under the influence of external magnetic fields.

5.6 Environmental working conditions

As with any other instrument, environmental working conditions can affect not only the initial but also the long term metrological performance of a meter. On the one hand, rough environmental conditions may accelerate the degradation of some components of the meter. For example: high temperature can deform plastic parts of the register, frosting may break or enlarge the body of the meter, direct sun light can make plastic component brittle and meter register unreadable, also high humidity environments can make the reading of the meter impossible, etc..

Solid state meters incorporating electronic components which are powered by a lithium or Li-ion battery can also be affected by high and low temperatures. The charge of these batteries can decrease if temperature rises, or falls below a given threshold. Humidity is also a factor that can affect the working life of electronic components. Condensed water is extremely corrosive and can corrode the electric connections.

Most of the time, undesirable environmental conditions cannot be prevented. The best strategy to mitigate their effect is to protect the meter as much as possible given the local circumstances and economic constraints. Also, a proper selection of the meter specifications can help in reducing the influence of this parameter.

5.7 Electronics components failures and firmware bugs

The use of electronic components has brought a number of significant advantages to water metering. However, it is important to keep in mind that these components are not 100% reliable. Most people understand right away that a mechanical meter with moving parts may fail after some period of use. It is more difficult to understand that electronic components also have an expected life cycle and they will not keep on working for ever.

Moreover, meters using electronic components need a firmware (i.e. an operating system). As with any other software, meters' firmware cannot be guaranteed to work under all circumstances. A specific combination of factors can cause the software crash or "make mistakes". Furthermore, having a firmware makes electronic meters vulnerable to a potential hacker.

At this stage the experience gained in the last few years it is not enough to fully guarantee that modern solid state meters (non-mechanical) can remain working 10 years after installation. This does not mean that they will not last for 10 years or more. What it means is that this working life cycle cannot be guaranteed with the present knowledge.

5.8 Meter sizing

Water meters have a measuring range defined between the minimum (Qmin) and the overload (Qmax) flow rates. The standards specify the maximum permissible metering errors within the measuring range. In theory, any meter sold by a manufacturer should have an error in the measuring range smaller than the one defined by the standards. Above and below the maximum and minimum flow rate of the measuring range the metrological behaviour of the meter is unknown. Typically, below the minimum flow rate of the measuring range the errors of a mechanical meter become more and more negative (Figure 7). This happens down to a limit in which water flow is not capable of moving the sensing element. This threshold is called starting flow rate of the meter. Once a meter starts, measuring errors of velocity meters are typically close to -50%. The initial error at a flow rate slightly larger than the starting flow of a positive displacement meter is close to -20%.

One important thing to note about the starting error of a mechanical meter is that for a given meter:

- The starting error is not the same as the stopping error.
- It does not correspond to a unique flow rate. The starting flow rate may change depending on several factors. Therefore, it may happen that the values obtained in consecutive tests are different from each other.
-

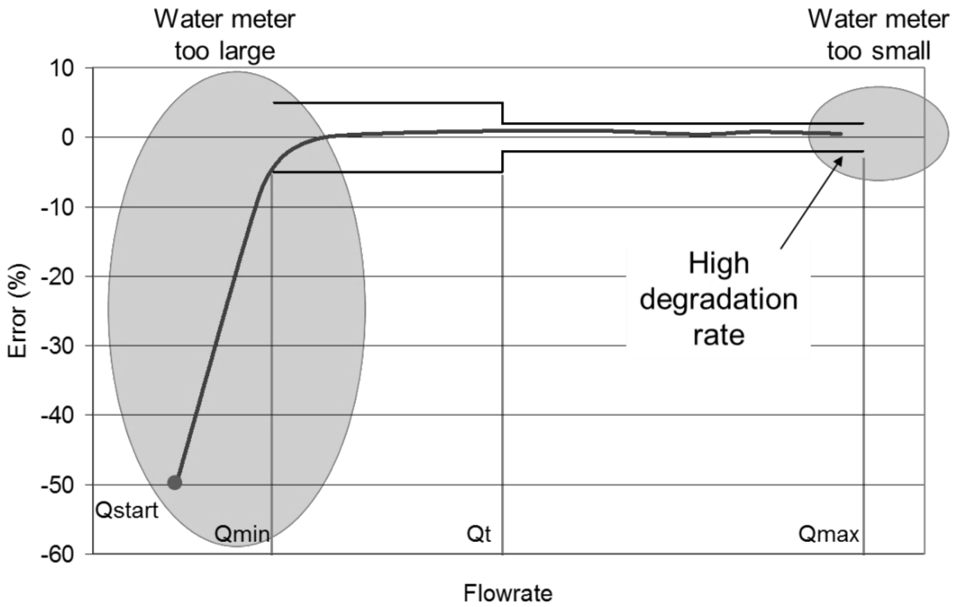


Figure 7. Water meter sizing of a velocity mechanical meter

Sizing is important to make sure that the meter is working in within in the range where measuring errors are known. If the meter is too large (the nominal flow rate is too big for the consumption flows), the meter will always be working in the lower part of the range. It could happen that some consumption is not measured at all because it occurs at a flow rate smaller than the starting flow rate. If the meter is too large, the meter will be working in the upper part of the range, close to or above the maximum flow; this means that moving parts will be spinning at maximum velocity and degradation processes will for sure be faster than normal.

Also, another important thing to consider when sizing a meter is that the error curve always degrades faster in the lower part of the range. This can be seen in Figure 8, showing the typical evolution of the error curve of a single jet domestic meter. At low flow the error becomes more negative and the starting flow increases. At medium and high flows the error can become more negative or positive depending on the circumstances. For this reason, if a meter which is too large is selected and it frequently works in the lower part of the range, the overall accuracy of the meter will be compromised as the meter will have difficulties registering low flows. These difficulties will increase over time as the error curve will evolve as shown in Figure 8: the starting flow will increase and the error at low flow will become more negative.

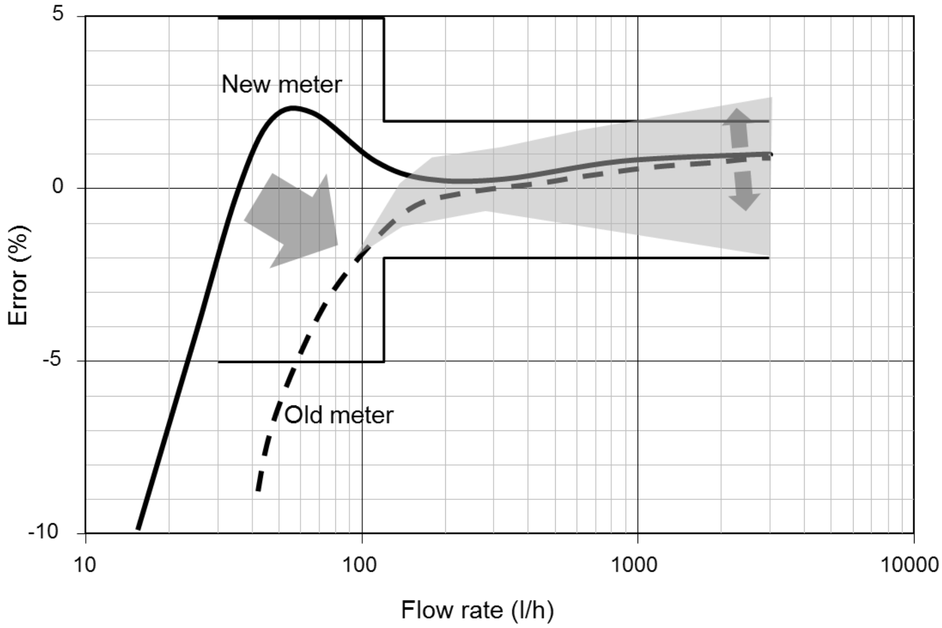


Figure 8. Typical degradation of the error curve of a single jet residential meter

However, sizing is not only about making the meter work in the measuring range. Sometimes, a meter can work most of the time close to the nominal flow and suffer a quick degradation of the error curve (as if it was undersized). Customers having sudden variations in flow, even if the consumption flow rate does not exceed the maximum flow rate of the meter, can produce extremely severe working conditions for the meters to the point of breaking the sensor (Figure 9).

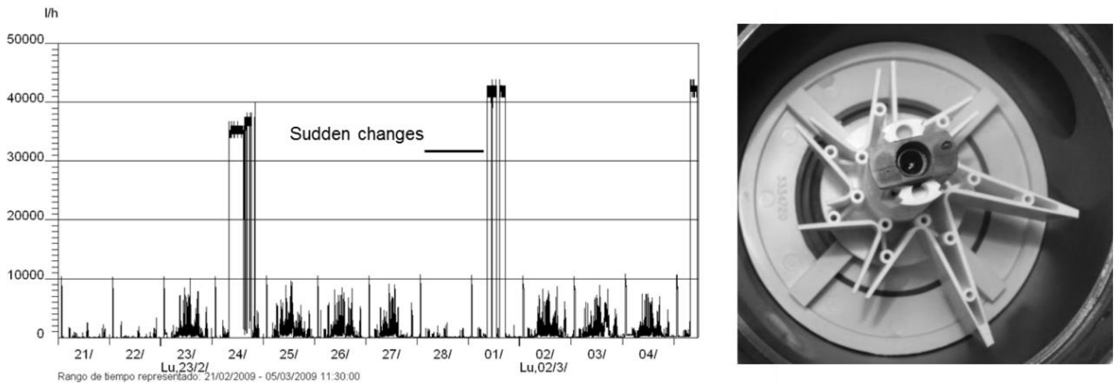


Figure 9. Single jet meter failure because of sudden flow variations

Details on meter sizing strategies can be found in Arregui et al 2006, AWWA M22- Sizing Water Service Lines and Meters (2014), and other documents.

6 Calculating the combined weighted error of installed meters

To calculate the global water meter accuracy of installed meters it is necessary to know the weighted error of the different types of meters used in the system. Each meter type measuring consumption of a particular type of customer constitutes a group (or cluster) within the water supply. The average weighted error of each meter group needs also to be weighted by a coefficient which should take into account the importance of each group.

This weighting coefficient that takes into account how important each particular group (meter type measuring water consumption of a specific type of customer) is within the water system can be obtained using various approaches:

- Considering the number of meters belonging to each group
- Considering the amount of volume registered by each group of meters in a given interval of time.
- Considering the actual consumption (estimated from the registered volume and the weighted error) of the customers measured by each group of meters in a given interval of time.

The first approach will not properly consider large/medium size meters and customers. The third one introduces the complexity of having to correct meter readings to obtain the real consumption. For this reason, the recommended approach to obtain the weights of each group is the second one. This approach will be more accurate when there are no groups having significant measuring errors significantly larger than other groups.

A free EXCEL worksheet *Meter Stock Analysis* allows for a quick estimation of the meter stock combined error. Obviously, as this software tool uses estimations, the result provided is only a first approximation to the real figure, but can be accurate enough to improve the results of a water balance.

Appendix I, describes a simplified example of how to conduct the calculation of the combined weighted error of the meter stock using the free EXCEL worksheet.

7 Apparent losses indicators

Water utilities need tools that allow them to identify how well the strategies adopted are helping in the reduction of apparent losses. Performance indicators are of great help when monitoring the improvement achieved by the various measures and action plans followed to improve the overall efficiency of the system. Under some circumstances, they also allow for a performance comparison between similar water utilities.

IWA performance indicators for Water Supply Services - Second Edition (Alegre et al 2006) defines a comprehensive set of indicators in various areas. Unfortunately, these indicators provide limited information when establishing the amount of apparent losses in the system. This paper on Customer Metering Inaccuracies forms a stand-alone Appendix 3 to the Guidance Notes on Apparent Losses and Water Loss Reduction Planning (Vermersch, Carteado, Rizzo, Johnson, Arregui and Lambert, 2016), and readers are referred to the discussion of Apparent Loss Indicators in Section 3 of that Guidance Note. The performance indicators from Alegre et al (2006) which specifically related to metering are listed below.

Operational indicators
- OP7 – System flow meters calibration
- OP8 – Number un flow meters replaced per year
- OP36 – Customer meter reading efficiency
- OP37 – Domestic customers meter reading efficiency
- OP38 – Percentage of active meters
- OP39 – Percentage of non-metered water

Financial indicators:
- Fi21 – Meter management cost (%)

Physical indicators:
- Ph10 – District meter density (nº/connection)
- Ph11 – Customer meters density (nº/connection)
- Ph12 – Number of metered customers (nº/customer)
- Ph13 – Number of domestic metered customers (nº/residential customer)

Quality of service indicators:
- QS24 – Time to install a customer meter (days)

Personal requirements indicators:
- Pe4 - Meter management personnel

8 Strategies to reduce Metering Errors

8.1 Auditing customers and meters databases

Prior to any other analysis, a detailed evaluation of the system needs to be conducted to prevent any unnecessary estimations that may distort the final results before obtaining an overview of the current water-metering situation. The free EXCEL worksheet *MeterStockAnalysis* can also be used as a support tool for this initial audit.

In any case, after the audit is conducted the following questions should be able to be answered:
- What percentage of customers is being metered?
- How many meters are registering a null monthly consumption?
- How likely is water theft in the utility? / Are there any procedures to prevent customers from tampering with meters or establishing illegal connections?
- How many customers are not being billed? / How many customers do not pay their bills?
- What is the tariff structure for the different type of users?
- How many meters are registering monthly volumes too high or too low considering their connection size?

- What is the estimated optimum replacement period of installed meters? / How are meters selected for replacement?
- How are water meters procured and selected? / How is the quality of the meters controlled?
- How is the metrological performance of the installed meters controlled?
- Who is conducting the installation of the meters? / Is there any control over the installation conditions?

The information gathered during this initial audit will serve as a starting point to all other steps described in the integrated water meter management cycle.

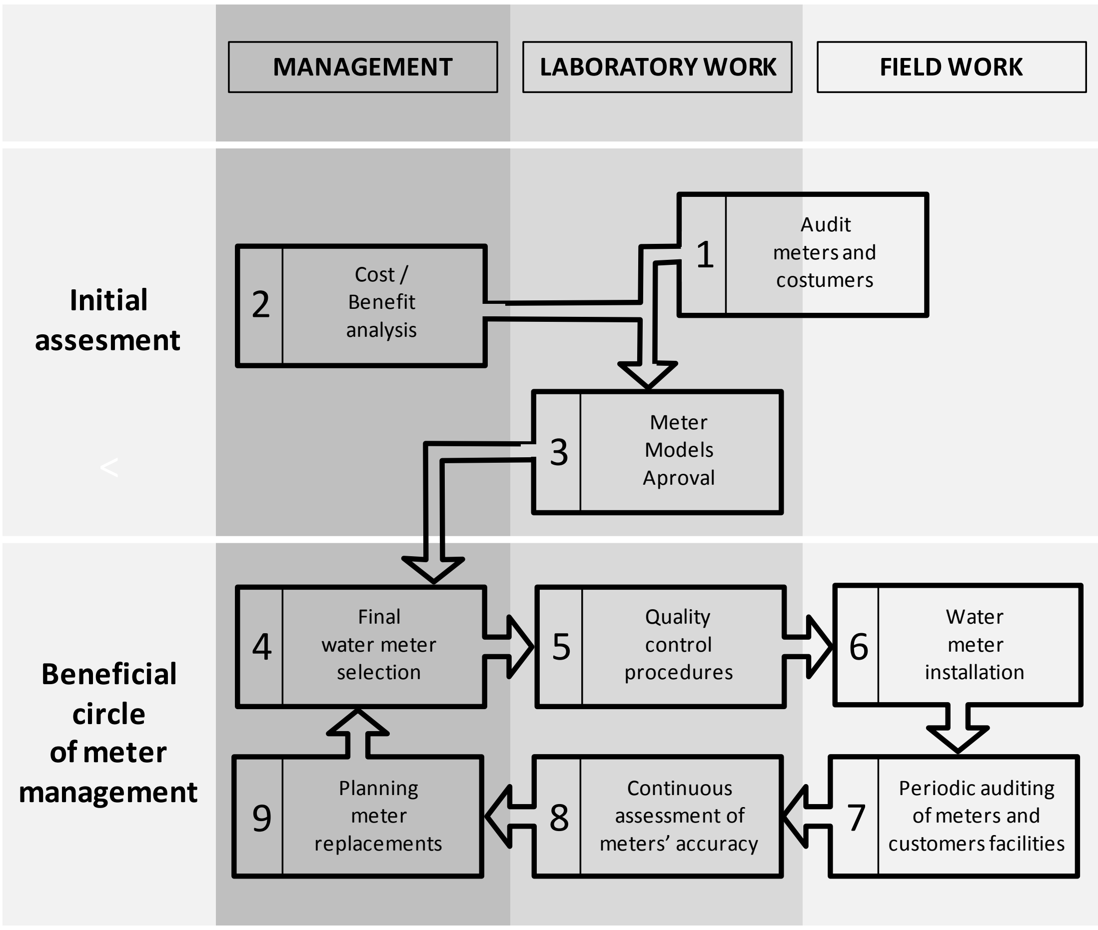


Figure 10. The nine steps (From Arregui et al 2012)

The second step consists of a straightforward cost/benefit analysis that will, at this initial stage, allow for the rejection of any option that is clearly unsuitable for the utility. It will provide an initial guess of the theoretical replacement period depending on the cost of the water meter, the selling price of water and an estimation of the degradation rate of the weighted error of the meters (Arregui et al. 2011). However, since this study is conducted before any real data is available, results should only be taken as what they really are: estimates.

This initial study will also allow for an estimation of what is the maximum price that can be paid for a water meter depending on the water tariff. This sensitivity analysis is explained in detail in Arregui et al (2006). Obviously, a low price of water will make more difficult the recovery of the additional money invested in a high-end water meter. In these cases the most expensive water meters should have a better initial metrology which remains more stable over a longer time period.

During the initial assessment stage, the water company should also consider what are the desirable (required) technical characteristics of the meters to be selected. These requirements can be derived from the initial audit (Step 1) and can be fine-tuned in the future with additional data and a wider experience. Other authors proposed similar approaches (Lievers and Barendregt, 2009). The following issues should be considered:

- *Meter design* to assure a proper performance in adverse installation sites: high temperatures, direct sun light exposure, high humidity, tight spaces (reading), installation at an angle, etc.…
- *Frequency of meter tampering*. Generally speaking, when meters are manipulated, buying cheaper meters and replacing them more frequently becomes a better option than choosing expensive meters and maintaining them for a longer period of time.
- Also, anti-tampering devices and seals should be incorporated in the design of the meters to prevent customers from dismounting or disassembling the meters.
- *Water storage tanks* at the customers' facilities. This will affect the sizing of the meters and the metrological class and starting flow required for accurate measurements.
- *Service interruptions* and the discharge of air flows through the meters once the service is restored.
- *Water quality.* Systems with a high number of pipe repairs are not suitable for positive displacement meters or wet totalizers. Also, water hardness may play an important role in the long term performance of water meters.
- *Legal restrictions.* In most places water meters are under the supervision of national metrological agencies. In Europe, for instance, all water meters used for custody transfer should comply with the European Measuring Instruments Directive 2004/22/EC (MID). In other parts of the world meters are only required to meet ISO 4064:2005 standard or OIML R49:2006 Recommendation.

This list of minimum technical requirements will be more or less comprehensive depending on the in-house experience with respect to metering devices management. In any case, it can be completed in the future as more information about the working performance of different meter designs is gathered from the field.

8.2 Water meter approval

In principle, all water meters models in conformity with local legislation on water metering can be used for metering customer's water consumption. However, some water companies have their own meter approval procedures that restrict the type of meters that can be procured by the company. At this point it is important to make a clear distinction between a legal approval of a meter model and the utility's approval. The legal metrological approval will depend on local regulations. For instance, in Europe meters in conformity with the European Directives can be used for custody transfer. However, a utility may only select few of those meters, from the ones available in the market in conformity with the European directives, for internal use. A meter can be approved for acquisition in that utility only after it has been satisfactorily tested by the company according to their internal testing procedures. The tests conducted by the utility do not necessarily have to match those defined by the European Directive or other international standards.

This way of proceeding will prevent the massive use and acquisition of water meters that have not been comprehensively tested (avoiding significant technical problems in the future). It is not uncommon that a manufacturer finds out about a design problem in a meter model once they have been installed in the field. By that time it is usually too late for the water company to fix the problem and a generalized meter failure may take place leading to huge economic losses.

Furthermore, internal meter approval procedures will avoid one of the most commons pitfalls in water meter management: the purchase of a large number of meters of a single model at once (typically the cheapest one). Managers should always keep in mind that the savings deriving from the purchase may be negligible when compared with the amount of money that a difference in registered volume can generate throughout the meters' life, especially when the selling price of water is high.

To illustrate this point the following example can be considered: Two domestic meters are priced 18€ and 21€ respectively. A typical domestic customer uses 200 m^3 per year. The average water selling price is 1€/m^3. With a difference in weighted error of 1% the price difference would be recovered in only 1.5 years. The payback period could be even shorter period if the weighted error degrades differently in the two meters considered (due to different qualities in design and manufacturing). In the previous example, if the lifespan of a meter is assumed to be about 10 years, the initial difference would be recovered at least six fold.

As a general rule, testing procedures for water meter approval within a water utility should comprise two stages. The first one should be conducted in the laboratory with a second phase in the field, at selected representative sites.

The laboratory tests should be designed to verify the real metrology of the meters and other functioning characteristics that are not considered in the standards, for example:

- *Strength of the magnetic coupling*. The error curve should be tested under the influence of an external magnetic field of a given intensity. Also, the magnetic coupling should be checked against suddenly occurring high flows of (e.g. the maximum flow rate).

- The real value of the *starting flow of the meters* (Richards et al. 2010). This parameter is not defined in any standard and therefore is not officially tested by any manufacturer or metrological institution.
- The *shape of the error curve*. A standard approval procedure may require, for example, that meters achieve a weighted error higher than 0% for a specific water consumption pattern defined by the utility.
- *Mechanical strength* of the totalizer, pipe connections, meter casing or any other component that can be tampered with. The mechanical strength tests are particularly important for plastic (composite) meters.
- *Anti-tampering protection*. In some areas tampering with meters is an extremely important issue. It is crucial to understand how customers are manipulating installed water meters to define which characteristics best protect the meters against customers.

The second stage will consist of field tests. Contrary to laboratory tests, field tests require that the meters remain installed in the field for at least a year or two before they can really provide any useful information. These tests should be carefully planned to identify any possible defect in the design of the meters. Therefore, tested meters should always be installed at premises with adverse conditions and in locations where they may have functioning problems.

Although some conclusions about the degradation rate of the weighted error may be obtained from these field tests, it is important to keep in mind that the main objective is not determining how fast meters degrade but identifying design defects or other factors that may cause meter failures. Examples of potential installation sites for field tests are sites with:
- Extremely high or low temperatures
- Direct exposure to sun light
- High humidity
- Frequent high flow rates or sudden changes in flow
- Large water volumes consumed at low flows (private storage tanks)
- Frequent low pressure
- Poor water quality (suspended solids, high content of calcium, etc.)
- Conflicting customers

Only meter models that successfully pass laboratory and field tests should obtain the approval certificate by the water company. Future water meter procurements should be strictly restricted to meters meeting both national legal requirements and the utility's approval standards.

Obviously, this methodology will only be applicable if new meter models are continuously tested and the water company has a sufficient number of meters types approved for each diameter. In other words, utility managers must have a sufficient range of meter models to choose from. Otherwise, a limited number of approved meters could lead to water meter shortages and quality problems.

8.3 Water meter selection criteria

The final meter selection should be conducted with a detailed cost/benefit analysis only for those meters approved by the utility. This analysis should also include other parameters that may be of importance for the water utility. For example, one of the criteria to be considered is the ability of the meter manufacturer to produce meters with similar quality and to supply enough quality instruments in a specified time. Some manufacturers are not prepared to supply large batches of meters while maintaining the desired quality levels. Quite often the average quality of large batches is significantly lower than the quality of smaller lots. For this reason it is desirable to distribute meter replacement over time and to have a more or less uniform replacement rate every year.

Additionally, previous experience with a manufacturer or, with the same or similar water meter model, should be taken into consideration for meter selection. Some meters' designs may simply prove not adequate for the utility's local conditions.

A good strategy to reduce the risk involved in the use of a single meter model is to select several manufacturers and meters. This should be enough to reduce the risk of a widespread meter failure, but not too many so the benefits of procuring large quantities of meters are maintained. The ideal number of meter models to be selected would be between two and four depending on the amount of customers and meters which need to be purchased every year.

Each customer type should have an ideal meter model that should be selected from those meters approved by the utility. A meter model can obtain the approval from the utility but only be suitable for users that match certain constraints. There are meters that can only be installed in a fully horizontal position, others which cannot stand high pressures, low temperatures, high or low flows, suspended solids, or cannot be exposed to direct sunlight. All those factors need to be considered to make the right meter selection and maximize the benefit from the meter.

In any case, it is important to highlight, again, that the selection of a meter type should never be conducted solely on the basis of the acquisition price since the total cost of a meter is composed of two terms. The first is the initial acquisition and installation costs. The second is the cost of the unregistered water (throughout the meter's life). Usually the magnitude of the second term is considerably larger than the difference in acquisition and installation costs of two meter models.

8.4 Quality control of procured meters

Just like any other metering device (intended for custody transfer), procured meters should be checked for compliance with the theoretical technical specifications, the most important of which are the metrological requirements which have a direct impact on the amount of water to be billed. International standards and recommendations like OIML R49 and ISO 4064 and also some international legislation (European Directives) define a set verification tests to be conducted before a meter is sent to a water utility. These tests (usually called initial tests) are conducted at the manufacturer's facilities prior to the shipment of the meters.

Considering that most water meters are built from high precision mechanical or electronic components that can be easily damaged during transportation, it is highly advisable to re-check a sample of the meters received. This can be done, if available, at the testing facilities of the water utility. Otherwise, an independent external laboratory can also be selected to conduct these tests. Verification activities are extremely important in situations in which manufacturers are under great pressure to produce a large number of water meters in a short period of time at very low price. For this reason it is highly advisable to conduct these verification tests when procuring large batches of meters.

Additionally, it should be taken into account that water meter manufacturing procedures are always subject to improvements. The design and composition of different components can also change over time. Such modifications may lead to alterations in the quality or the performance of the meters, and how the meter's accuracy will degrade with time. These changes are not necessarily notified to customers (the water utilities) who will think that they are still buying the same product they started to buy a few years before.

Therefore, quality control procedures should be designed to ensure that procured meters perform according not only to the legal specifications but also to their expected behaviour, i.e. the behaviour that made the utility approve the acquisition of the meter. In other words, if a meter is selected for having a low weighted error (as a result of the shape of its error curve) it should be assured that all meters bought in the future have the same error curve that leads to such an initial weighted error. In this context, all tests should be defined so the quality control procedure is reliable and meaningful. Additionally, all materials, equipment and methods should be traceable. Otherwise the results of the test will be meaningless, could easily be contested by the supplier and will not be useful in any action against it. For this reason it is extremely important that the all parties know and agree in advance about the quality control procedures at the reception of the batches.

Parameters that can be checked during these quality control tests are:

- Weighted error of the meter according to a predefined formula or procedure.
- Starting flow rate of the meter. Even though this is not a metrological parameter considered in the standards, the starting flow rate of a meter gives reliable information about the low flow metrological performance.
- Magnetic coupling strength. This is one of the weak points of modern water meters. If magnets are not strong enough the register and the turbine may slip at high flows, producing a significant under-registration. Also, weak magnets are more sensitive to external magnetic fields.
- Anti-tampering protection.

For each one of these tests acceptance and rejection criteria should be defined using statistical methods. An example on how to define a quality control test for the weighted error of a meter can be found in Arregui et al. (2006). Also standards like the ISO 2859 and ISO 3951 can help in defining the sampling plans and the acceptance/rejection criteria for the tests.

For example, conformance criteria will depend on the minimum acceptable quality level of the batch (defined as the maximum percentage of nonconforming meters), the inspection type (Normal, tightened, reduced) and level (determines the relation between the batch size and sample size).

However, and since only a limited number of meters can be tested, all decisions are subject to errors. There is a certain probability of accepting a defective batch of meters and a certain chance of rejecting a shipment of meters which conforms to the required quality standards. The probability of acceptance of a defective shipment is called a type I or α error, and may be considered a risk on the buyer's side. The probability of rejection of a correct shipment is known as a type II or β error, and defines the seller's risk. Defining a sampling plan implies selecting a value for type I and II errors. Suppliers will obviously try to minimize type I probabilities while water utilities will try to reduce type II. There are several possibilities to define the sampling plans which are widely covered by the literature and international standards (for example ISO 3951).

Conducting quality control procedures will certainly increase the average quality of newly installed meters. A failure in the production system will be detected before it can produce high economic losses to the water utility. They will also allow the analysis of the initial metrological performance of the meters and will provide valuable data on which characteristics are undesirable in procured meters. This information can be used to improved approval meter procedures within the water utility. In Gavara (2015) the results of quality control procedures over time were presented for a water utility having around 500,000 meters. These tests showed that approximately 5% of the meters delivered to this particular utility (over a period of 5 years) had some type of defect. This percentage (given as a reference) corresponded to a water utility conducting quality control tests before the study was started.

Also, an additional advantage of conducting quality control tests is related to the supplier's perception of the customer. A manufacturer selling meters to a water utility which systematically conducts quality control tests will for sure deliver much higher quality meters.

8.5 Controlling water meter installation

Water meters will not perform as expected if they are not installed properly or if the working conditions are not suitable for a particular meter technology. As a result, water meter installation sites should be correctly designed in order to preserve, in the long run, the metrological performance of the meters.

Designing a standard/reference installation site for each water meter technology, size and type of customer will greatly improve the quality of the resulting installations. The most significant factors that should be considered are:

- Probably the most important thing to control, to check if a meter is properly installed or selected, is its sizing. Meter capacity has to be adequate for the typical consumption flow rates of the customer. Section 5.8 briefly describes the issues to be considered. Details on how to size a meter can be found in other international references and the instructions given by the manufacturer.
- Most velocity water meters are sensitive to flow profile distortions. Therefore the length of straight pipe between the meter and any distorting element should be big enough to ensure a minimum "quality" of the velocity profile distribution (and hence of the measurement).
- Water meters are designed to measure a one-phase fluid: water. The presence of air bubbles will affect the metrological performance of the meter and can contribute to degrade its mechanical components. The installation of an air-valve upstream will only remove the air that is trapped close to the meter when no flow is passing. The air valve will not prevent large pockets of air passing through the meter under normal operating conditions. For a complete removal of air volumes, they have to be discharged from the pipe before arrival at the meter. Unfortunately, in some water utilities with service interruptions, this is not possible. Therefore, it has to be accepted that during some times of the day air volumes will go through the meter, with all the consequences associated with such situations. The way the air volumes affect the meter will depend on the technology. In some cases, mostly for solid state meters, air will lead to under-registration (in the case of ultrasonic and electromagnetic meters). In some other cases air will produce over-registration of water volumes (as air volumes will be registered as if they were water volumes).
- To obtain the actual field performance of various types of meters they need to be tested on-site. This is especially true for small and medium calibre meters. The installation of a verification tap downstream of the meter will allow such tests. This tap will also provide a fast method to identify clogged meters.
- The measuring errors of mechanical meters under forward and reverse flow conditions are often different (Arregui et al., 2006). The installation of good quality non-return valves should be required. One common example of this problem is the over-registration of mechanical meters installed in apartments (located in buildings). Pressure variations produced by pumps and water consumption within the building and the elasticity of the system, may produce frequent water flows in forward and reverse directions. Non-return valves will also protect the utility from any intrusion of uncontrolled water in the network and will also assure a proper metrology of the meters.
- Quite often the space left around the meter is not enough to facilitate maintenance or replacement operations. This will greatly increase the replacement costs of meters. Also, the lack of space may limit in the future the type of meter that might be installed. It is not unusual to find small residential meters, usually those installed on the walls, rotated around the pipe axis in order to be able to take the reading. As mentioned in Arregui et al. (2006) this will cause a loss of accuracy as well as a faster degradation

rate of the metering performance. A general modification of the installation sites to fix this problem may not be economical. However, this is a factor to take into account when planning new installation sites or when selecting the meters (not all meters degrade their performance by the same amount when not installed in a completely horizontal position).

- Measuring errors can also be caused by manipulation of the meters. This is why meters should be installed in such a way that protection against tampering and theft is maximized, while still allowing reading of the instrument. Installation of meters inside households should be avoided when possible.
- All meters contain pieces or components that can suffer unfavourable environmental conditions, such as direct sunlight exposure, high temperature or humidity, vibrations, low temperatures below freezing point, etc. Installation sites should be designed to avoid these harmful environments.
- As has been already mentioned, mechanical meters can be seriously damaged by suspended solids or debris transported by water. The installation and proper maintenance of a strainer upstream from the meter is highly recommended, especially for medium and large meters and in networks with a high burst frequency. Nonetheless it should be highlighted that an improper maintenance of a strainer installed too close to a meter can cause significant measuring errors.
- Finally, a frequent cause for mechanical meters failure is the existence of unexpected high flows (above the maximum flow of the meter). Utility staff should avoid under-sizing mechanical meters. In case of doubt, an acceptable solution would be to increase the replacement frequency of meters that are suspected of being under-sized or to replace them by non-mechanical options available.

A desirable good practice for the water utility is to record the key facts from each installation site to be used in future meter selection processes. This information will not only provide a support for decision making in meter acquisition but also valuable data for the analysis of factors that can contribute to the degradation rate of the meters' accuracy.

8.6 Control the performance over time/accumulated volume of installed brands and types of meters

Any of the economic models proposed in technical literatures that are used to assess the optimal replacement period of a meter (Arregui et al. 2011; Johnson, 2011; Ferreol, 2005; Johnson, 2001; Yee, 1999; Allender, 1996) need to be fed with reliable data about the degradation rate of the weighted error of installed meters. The only way to obtain the necessary data consists in periodically testing (in the laboratory and/or in the field) the meters that are being currently used in the water supply. The alternative of using "standard" figures or "typical" values for the degradation rates of water meters will only provide approximate figures.

The problem comes because gathering data from a significant sample of meters' errors requires testing meters periodically. Otherwise the amount of available data will not be sufficient to obtain definitive conclusions about the degradation rate, and the uncertainty associated to the results will be too large. It is important that managers realize that a snapshot of the meters' errors at one specific moment in time is not the same as a continuous film about how meter errors evolve as they age. The latter provides a significantly larger amount of useful information, not only about the errors but also about the parameters that affect how these errors change over time.

Meter testing procedures should be defined to provide information about the real behaviour of the meter in the field. Quite often these procedures are not properly designed and they distort the metrological behaviour of the meters. A clear example is when a positive displacement meter is tested initially at a very high flow rate (which has never occurred in the field) and then tested at low flows. In such cases, the errors at low flows obtained in laboratory will probably be much better than the errors of the meters in the field. Also, it is quite likely that a different result would have been obtained in the laboratory if the accuracy tests had started at the lowest flow (instead the highest) and then finished at maximum flow.

Additionally, testing procedures for used meters should be designed so that the error curve of the meters can be properly reconstructed from the results of the test (Arregui et al. 2009). The aim of these tests is completely different from initial verification tests in which meters are checked for legal requirements about errors at different flow rates. The needs for both tests are different and consequently the number and magnitude of testing flow rates will also be different. However, since the tests for used meters need a larger quantity of data, a good practice is to include in such tests the flow rates of the initial verification procedures as well. Section 4.1 (Table 1) in this document provides a proposal of flow rates at which meters can be tested to obtain a reliable figure for the weighted error.

As mentioned before, testing procedures should be carefully designed and agreed with meter suppliers. Frequent metrological comparisons between laboratories (the one from the manufacturer and the one from the water utility) need to be conducted to assure that the utility's lab - or the external independent laboratory chosen for the purpose - is properly operating and results match those obtained in other accredited laboratories.

Finally, it is necessary to consider the collection of complementary data during field tests. Otherwise, it will be impossible in the future to establish the effect of different parameters in the metrological behaviour of the meter. For instance, it is always interesting to gather data about the characteristics (hydraulic, sociological, etc.…) of the customer the meter was serving, the installation site and network conditions in the surrounding area, meter characteristics (length, type, model version, year of production, thread size) water quality, etc.

When a meter fails, in order to find the reason for failure, it is highly advisable to disassemble the meter to find the cause of failure. Sometimes, the failure may be the result of external manipulation. Other times a design or manufacturing defect will be found. This kind of data, together with the results of the tests, need to be recorded and will help in the future in the development of the procurement requirements. Unfortunately test bench manufacturers do not usually provide, together with the test bench, a database capable of managing both types of data. The authors have developed Woltmann, a commercial software developed at ITA (Arregui et al., 2010) designed to store and analyse these data.

8.7 Optimize the replacement schedule for the meters.

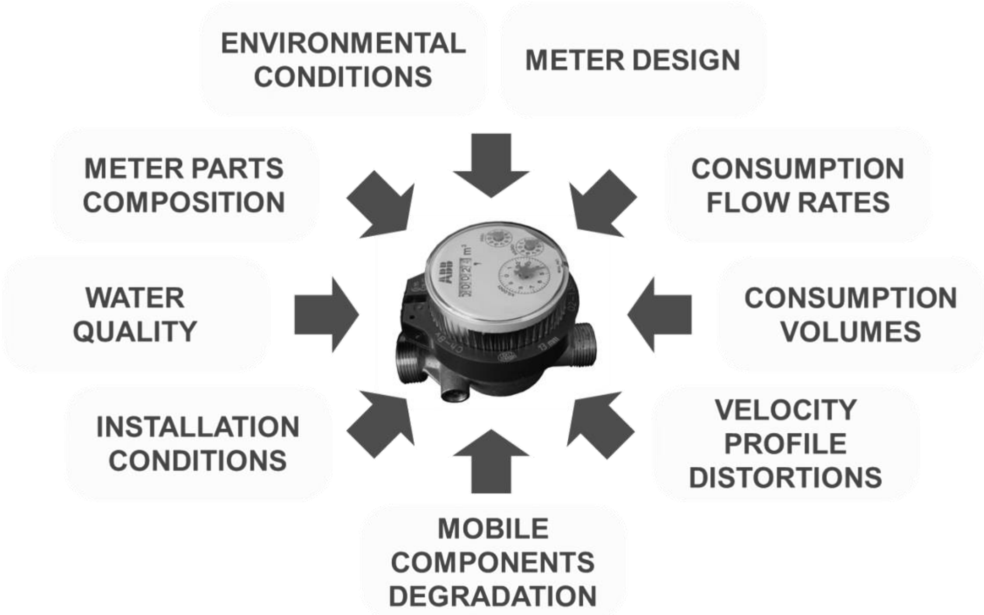


Figure 11. Factors affecting water meter accuracy

Replacement frequency of a meter depends on many factors that cannot be easily controlled (Arregui et al. 2006, Hill and Davis 2005). Especially, as it has already been mentioned in a previous section, the degradation rate of the metrological performance of a meter depends on a number of factors which do not equally affect all meters - not even the ones belonging to the same type (Figure 11). As a consequence, the economic model used to determine when meters should be replaced is subject to a certain degree of uncertainty that should be acknowledged when planning meter substitutions. Meters with a higher risk of malfunctioning or assigned to users with a higher consumption potential should always be replaced first. It is obvious that the average bill of a customer is a key priority for meter replacements. On the contrary, quite often, the best economic option is to leave customers with subsidized tariffs with the oldest and lowest cost meters.

During meter testing activities it is likely that at some point, when degradation rates of meters are updated with more reliable figures, the utility finds it advisable to recalculate the lifespan of a meter. For example, this can happen when the metrological performance in the field of a specific version of a meter model does not meet the expectations, and specific factors are found to negatively affect the degradation rate of the error. In such cases, the replacement period should be recalculated with the latest available information.

In Arregui et al. (2006) Arregui et al. (2011) a graphical method to calculate the optimum replacement frequency of a meter is given (Figure 12). The method uses the following parameters:

- V is the ratio between the initial cost of the meter and the revenue it generates over a year. The initial cost of the meter should include the acquisition, installation and other administrative costs. The revenue is calculated as the product of the average yearly consumption and tariff paid by the user.

$$V = \frac{Acquisition + Installation + Administrative}{(yearly\ consumption) \cdot (m3\ cost)}$$

- The 'a' parameter is defined as the average yearly degradation rate of the weighted error of a meter. Five values are considered ranging from 0.1 %/year to 0.9 %/year. The first one corresponds to a meter which degrades very slowly. The higher one is associated to a meter degrading very fast. It should also be noted that if very low quality meters are bought, their degradation rate can be significantly larger than the maximum degradation rate considered in the figure. Experience has shown that certain models have a degradation rate larger than 1 %/year.
- The discount rate 'r' represents how much return is expected from the investment in water meters. Usually, as the installation of water meters is compulsory, the discount rate should be selected close to zero. This is so because there is no option. Each customer should have a water meter.

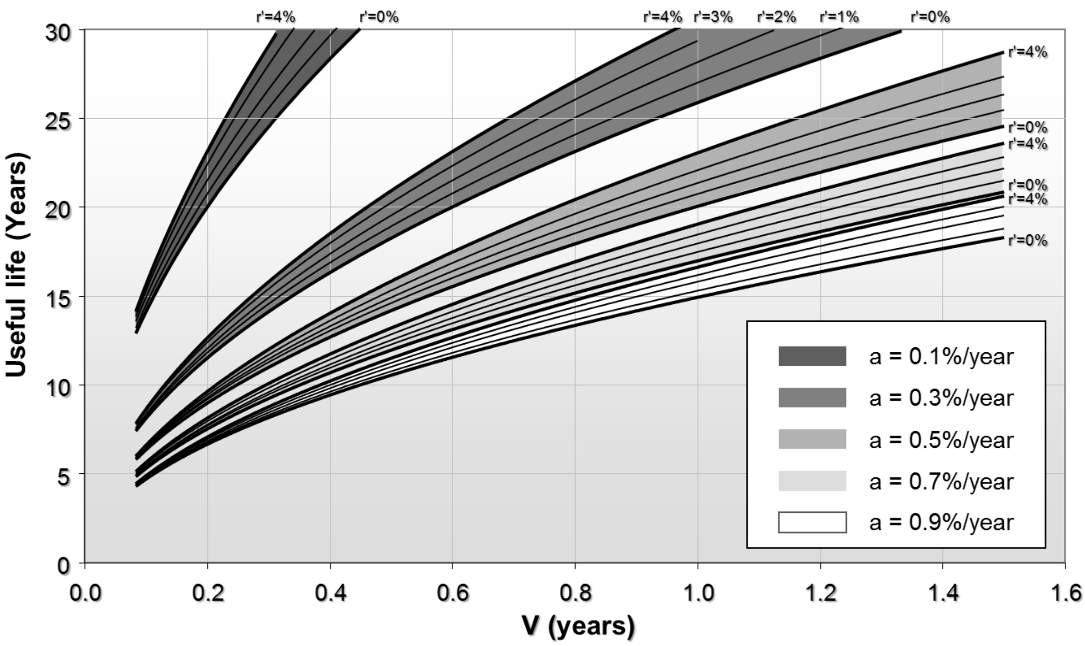


Figure 12. Calculating the optimum replacement period of a meter

The calculation of the replacement frequency of the meters gives as a result a time span that can be longer or shorter depending mostly on the price of water. In those utilities in which the revenue for the utility for each cubic meter is low, the cost curve is usually quite flat. This means that the metering costs around the minimum do not differ too much and replacing the meters one or two years before or after the optimum time does not increase cost significantly. However, higher prices imply a cost curve with a sharper minimum. In other words, replacing the meter one year sooner or later than the optimum implies a significant additional cost. This is the reason why utilities with higher tariffs really need to accurately determine which is the optimum replacement period of the different meters used. On the other hand, water utilities with a low selling price do not need to be so precise in the calculation of the optimum replacement period and can work with rougher estimates.

Meter replacement campaigns should be evenly distributed throughout the year. As has been mentioned, it is not a good idea to concentrate meter substitution activities in a few months after each procurement. A well-trained team is the key to ensure that meters are properly installed and to keep management informed about any irregularity in the installation sites. This team should also uninstall meters in such a way that they are still valid for testing and obtaining reliable conclusions about the influence of different parameters. In other words, they should treat meters as what they really are: precision instruments.

During meter replacement activities any sign of tampering in the meter or the customer facility should be investigated. Meter replacement activities are a good time to identify how meters are manipulated and how illegal connections are made. The experience gained from these findings can always be incorporated in future meter procurement procedures.

Planning a proper replacement campaign implies a sufficient stock of new meters, which implies having completed all previous steps. It is not uncommon to find water companies that cannot install new meters because they have no new stock. The lack of stock can be caused by a combination of factors: there are not approved meters types due to the fact that approval procedures are very slow, laboratory tests have proved that approved meters are actually failing, manufacturers do not have the production capacity to serve the meters on time, procured meter batches have been rejected because of quality problems, etc.…

The only real solution to this final problem is careful planning and an integrated meter management system working on a continuous basis and not just a set of isolated initiatives. Trying to rush things by skipping steps may produce undesired results. For instance, pressing meter manufacturers to supply large batches of meters in a reduced time frame may lead to meters below the desired quality levels being supplied.

8.8 Identifying stopped/blocked meters

Finally, a special mention has to be made of those meters which have completely stopped. Even though it seems a trivial problem, practice has shown that identifying stopped meters is a more complex task that one might think. Firstly, the identification of stopped meters requires reliable readings (actual readings) from the meters. If the water utility makes frequent estimates of readings it will be almost impossible to identify those meters. Secondly, if the consumption of a customer is zero, it does not necessarily mean that the meter is stopped or blocked. It may just simply mean that the customer is not living in that house.

Therefore, the problem has to be approached as a statistical problem. The identification should involve different factors that may increase the probability of a meter being stopped.

These factors should be considered before targeting a meter and, even so, there is a chance of making a mistake and replacing meters which were not stopped. The following list of some of these factors is presented:

- Meter model: positive displacement, velocity meter, specific meter model, etc.
- Network area: end of a branch, high or low pressure zone, water coming from a low quality source, etc.
- Customer type: income, probability of tampering,
- Installation conditions: inside the customer's premises, ground installation,

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