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Quantifying measuring errors of new residential water meters considering different consumption patterns

F. J. Arregui*[1], M. Balaguer*, J. Soriano* and J. García-Serra*

*Department of Hydraulic and Environmental Engineering. Universitat Politècnica de València.

Camino de Vera s/n, 46022 Valencia, Spain. Tel. +34963879898. [1]farregui@ita.upv.es

Abstract

Water meter measuring errors vary depending on the water flow rate. Therefore, the discrepancy between the amount of water actually consumed and the volume registered by a meter will differ depending on how water consumption is distributed by flow rates. Published studies assessing the residential performance of new meters have only analysed the error curves of the meters – without calculating the influence that consumption patterns have on their field performance. Moreover, in most cases, research has been limited to analysing compliance with published standards and regulations. Such analysis is related to legal metrology and is not designed to obtain the real field performance of meters. In contrast, this work presents an evaluation of the commercial losses to be expected when new residential meters are installed. For this purpose, a comprehensive test program on 11 types of residential meters was conducted – along with an extensive bibliographical review. The error curves obtained have been combined with the consumption patterns measured from monitoring activities carried out by the authors and from available studies on residential water demand. As a result, this paper provides information about the order of magnitude of the initial measuring error as a function of the residential meter model and user characteristics.

Keywords: residential water meters, water meter accuracy, residential meters error curves, residential consumption patterns

1. Introduction

Water meters – in the same way as any measuring device – are imperfect instruments. When installed, they cannot register the exact amount of water consumed by the users. Every water meter, regardless of its technology, has specific measuring limitations (Rizzo and Cilia 2005; Thornton et al. 2008; Lievers et al. 2009; Crimisi et al.,2009; Mutikanga 2011b; Mukheibir 2011). Frequently, a portion of the water consumed is not registered and therefore not charged to the customer. In such cases the meter is said to be under-registering or showing negative error. In contrast, depending on the meter technology, some factors may lead to the opposite result (Yaniv 2012), that is, the meters may register more water than the volume actually consumed. The meter is then said to be over-registering or showing positive error. In either case, as meter inaccuracies are recognised as a critical component of apparent losses (Lambert, 2000; Alegre et al., 2006), it is important to quantify the magnitude of these measuring errors.

The first aspect to be considered is that the error of a water meter is not constant or independent of the flow rate through the meter. For low flow rates, errors are usually larger and more sensitive to external variables; while for medium and high flow rates only small variations appear. Thus, the difference between the amount of water registered by the meters installed in the field and the actual volume consumed is a function of two parameters: a) the water consumption patterns of the users, defined by their consumption flow rate distribution; and b) the characteristic error curve of the meters. The weighted error of a meter, defined as the percentage difference between the actual consumption and the registered volume, can be obtained by combining these two parameters. Therefore, the parameter weighted error is a measure of the real field performance of a water meter when registering the water consumption of a given type of user.

Because of the large number of meters being used to measure domestic water consumption in a network, this calculation can only be approached by a statistical sampling of users and meters. Consequently, the calculation of the weighted error of all installed meters can be extremely complex and requires an enormous investment in human, material, and economic resources (Arregui et al. 2006; Mutikanga et al. 2011a).

The purpose of this paper is not to determine the weighted error of worn meters but to provide information on the real field performance that can be expected from new meters. Many technical papers and reports assume that the initial error of newly installed meters is close to zero (Allender 1996; Yee 1999; Hill and Davis 2005). This conclusion is far from being true in most situations as the sensing devices used by meters cannot measure very low rates of water consumption. Obviously, each meter model achieves different field performance – depending on the technology used, the construction quality of the sensing element, and the type of customer being measured.

To conduct the proposed study on the initial field performance, residential meters have been classified depending on: the compliant standard; the metrological class; the metering technology used in their construction; and the type of user measured. Two procedures were then followed to obtain the error curves of unused meters. For the first procedure, a comprehensive laboratory work was conducted to determine the error curve of 11 different meter models that met the ISO 4064 standard. For the second procedure, a literature review of previous studies (Barfuss et al. 2011; Bowen et al. 1991) provided information about the error curves of AWWA compliant meters. Consumption patterns, which define the consumption flow rates of domestic users, were extracted from previous works by the authors and well known references in the field (Bowen et al. 1993; Arregui et al. 2006; DeOreo and Hayden 2008, Beal and Stewart 2011, DeOreo 2011). In general terms, all these consumption patterns were obtained by continuously measuring the water use of residential customers with high-precision water meters and high-capacity data-loggers.

2. Error curves of new ISO water meters

To evaluate the initial performance of new residential meters, several types of commercially available water meters were tested. In total, a sample of 330 DN15 meters, classified into 11 different types – 4 of which were oscillating piston meters and 7 of which were single-jet meters. A summary of the main metrological characteristics of the meters, including the version of the ISO standard according to which the meter model was approved, is shown in Table 1.

2.1 Testing procedure

Measuring errors of the meters were obtained by means of a volumetric test bench using two calibrated probes of 10 litres and 200 litres. The test bench is located at the laboratory of the ITA research group at the Universitat Politecnica de Valencia. The bench is designed for testing meters ranging from 15 to 40 mm. For the particular case of the meters under study, the bench can fit series of up to 5 meters – and which can be tested from 1 l/h up to 3125 l/h.

Meters were tested taking readings with the meters at rest (standing start and stop test method). The 10-litre probe was used to test the meters for flows up to 120 l/h; while the 200-litre probe was used for flows of between 120 l/h and 3125 l/h. The scale division of the probes was of 0.01 and 0.2 litres respectively.

The flow rate used for the test was adjusted by means of high-precision regulating valves and electromagnetic meters that provided accurate information about the actual flow rate passing through the meters. Two electromagnetic meters were used for visualising the flow: a DN2 for flow rates up to 120 l/h and a DN10 for higher flow rates.

For flow rates lower than 120 l/h the water was supplied to the test bench from a pressurised vessel that provided a constant and pulsation-free hydraulic head of approximately 6 bar.

Larger flow rates were supplied by means of a submersible pump. In this case, hydraulic pulsations generated by the pump that could affect the performance of velocity meters were reduced by a pressurised vessel located between the pump and the test bench.

Before the tests were started several actions were taken to guarantee the accuracy of the results:

- Meters were installed in a completely horizontal position in order to minimise any effect caused by orientation.
- Air was entirely removed from the test section by means of a vacuum pump.
- A flow approximating the nominal (permanent) flow rate was left running through the meters for more than five minutes or approximately 200 litres. This step ensured that all the mechanical parts of the meters were lubricated with water before starting the first test.
- Error determination tests always started from the lowest to the highest flow rate.
- The starting flow rate of the meters was determined after finalising all accuracy tests.

All meter readings were checked twice before starting a new test. To minimise reading errors, meter errors were calculated on-site before starting the next test. The formula used to calculate the relative indicating error of the meters is that defined in the ISO 4064 standard:

$$\varepsilon = \frac{(V_i - V_a)}{V_a} \qquad (1)$$

Where V_i is the indicated volume by the meter and V_a is the actual volume as measured by the volumetric probe. The accumulated volume could be read from the meters with sufficient resolution to reduce the related component of the testing uncertainty to a value of 0.25% or better.

The determination of the error curve at low flow rates, where large variations occur, has been conducted with exceptional care so as to obtain a precise representation of the actual performance of the meters in the field (Richards et al. 2010). For this reason, selected meters have been tested at six flow rates lower than or equal to 120 l/h (Table 2).

2.2 Tests results

Table 2 also summarises the starting flow rate and the average indicating error for each meter model determined during the tests. The average value shown was obtained considering, for each meter model, all 30 meters tested, except in those cases in which some meters were considered to be defective, i.e. when they clearly underperformed at one or several flow rates in relation to the rest of the same meter model. Defective meters were discarded when calculating the average error at each flow rate in order to purge their influence in the error curve shape. In other words, the aim of this study was to establish the metrological limitations of new meters being in normal working order. It is understood that defective meters will cause additional errors and water companies will take all necessary precautions to identify and reject them before they are installed.

For that reason, a clear distinction should be made between what has been considered to be a defective meter and a non-conforming (with respect to the ISO standard) meter. A defective meter will always be a non-conforming meter. The opposite is not necessarily true. Non-conformities have also been classified depending on whether they appear at low flows (Q1) or high flows (Q4). While the first type is caused by an excess of friction on the mechanical components of the meters, the second type can be easily explained in most cases by the weakness of the magnetic coupling between the turbine/piston and the register (Arregui et al., 2006). In total, 20 meters out of 330 were found to be defective, 16 of them at low flows, 2 at high flows, and 2 at both flow rates (Table 3). Although most non-conformities are usually found at low and high flows, in some cases, depending on the shape of the error curve, they can also be found at intermediate flows (M5 at 60 l/h in table 2).

Finding defective meters in a sample of new meters should not come as a surprise to any engineer working in a water meter laboratory. As found by Neilsen et al. (2011), a non-negligible number of new meters did not meet the specifications set in AWWA standards for new water meters. In fact, for the sample analysed in Neilsen's study the percentage of meters not meeting the standard requirements at low flow rates varied, depending on the meter technology, from 0% to 25%, meaning in the latter case that only 75 out of 100 meters successfully passed the error test at low flow.

Additionally, the complementary parameter of the *error variability of the sample tested at a given flow rate*, can be used as a measure of how much control the manufacturer has over production. A large error variability of the sample indicates that each meter is produced very differently from the others and, in general, it can be considered as a sign of poor production quality. meter models having large error variability require stricter quality controls than meter models showing narrower error variations in their production (ISO 3951-5:2006).

All oscillating piston meter models tested in the present study presented small error variability at all flow rates. This result served as evidence that proper testing procedures and equipment were used. On the contrary, velocity meters showed a different behaviour. During the study, several single-jet meter models had large error variations, indicating that production was not properly controlled. Considering this parameter, some of the batches tested should have been rejected even if the average error fell within the maximum permissible error limits.

The error curves of the meters tested at the ITA laboratory have been plotted separately depending on the meter technology and metrological class. Figure 1 shows the error curves of single-jet Class B and R100 meters. As can be seen, large variations in performance are found at low flow rates between different meter models. The errors of Class C and their equivalents, R125 and R200, are plotted in Figure 2. On average, all meter models under test met the ISO requirements with respect to the maximum permissible error. The differences at medium and high flows between meter models were small, and mainly depended on the adjustment of the error curve made at the factory and the specific constructive characteristics of the meters.

Finally, Figure 3 shows the average error curve for the four positive displacement meter models tested in this study. All four types showed a remarkably similar error curves, no matter their metrological class or nominal flow rate, and an exceptional performance at low flow rates.

Moreover, the difference between the shape of the velocity meter error curves (Figure 1) and positive displacement meter curves (Figure 2) is clearly revealed. While the error curve of a velocity meter can show several ups and downs throughout the measuring range, the typical error curve of a residential positive displacement meter is similar to an inverted parabola with a maximum (more positive error) close to a flow rate of 100 l/h. In relation with the error curve shape, it must be kept in mind that in a typical residence most water consumption takes place between 200 l/h and 600 l/h (Bowen et al. 1993; DeOreo and Hayden 2008; Blokker et al. 2010; Beal, and Stewart 2011) where measuring errors of positive displacement meters are always positive.

3. Error curves of unused AWWA water meters

The AWWA Research Foundation published a report in 2001 (Barfuss et al. 2011) about the accuracy of new and used domestic meters. In this study 150 new residential meters of different technologies were comprehensively tested for accuracy. All the meters inspected complied with AWWA standards. The flow rates at which the meters were tested and the number of meters studied for each technology are shown in Table 4. The samples contained six meters for each meter model and were provided by several contributing manufacturers.

Table 4 shows the average error at each flow rate of the samples taken from the different meter technologies considered in the study (results were not presented per meter model separately). As expected, metrological performance at low flows was also meticulously examined. None of the meter technologies tested was able to measure the lowest flow rate, and only the nutating disc showed an acceptable performance at 7.1 l/h (1/32 gpm).

In relation to water meters complying with AWWA standards, the AWWARF published in 1991 a comprehensive report (Bowen et al. 1991) in which several brands of positive displacement meters – nutating disc and oscillating piston – were tested when new and after registering four million gallons of water. The total sample was constituted by 40 unused meters classified into 10 different meter models from five manufacturers. In contrast with the other two studies considered in this paper, meters were not randomly selected and no defective meters were found. Additionally, it should be mentioned that the purpose of the research was not to examine a large sample of new and unused meters but to determine the influence of certain variables in meter accuracy and error variation over time.

The results from this report cannot be analysed by meter model as they were presented by meter technology and in such a way that meter models could not be identified. The average errors from this report by meter technology are presented in Table 4. Obviously, as can be expected from a non-random sample, the error curves obtained for both types of technologies were slightly better than those obtained by Barfuss et al. in 2011.

4. Comparing ISO and AWWA error curves

4.1 Single-jet meters

A substantial difference can be observed at low flow rates when comparing the error curves of AWWA single-jet meters against ISO single-jet meters. The worst ISO meter model tested in the studied sample had an average error at 15 l/h (approx. 1/16 gpm) of -23.9%. At this flow, the average error for the single-jet meters tested in Barfuss et al. (2011), 24 meters from four different manufacturers, was -75.9%. This deficient performance at low flows can also be clearly identified in Figure 1.

The difference in performance at low flows can be partially explained by the fact that AWWA meters have a larger flow capacity than ISO meters for the same size. The maximum flow (overload flow) of an ISO meter is 3125 l/h, 3000 l/h or 2000 l/h depending on the ISO standard version and the permanent flow rate of the meter, while the maximum flow rate of an AWWA residential meter is 4543 l/h (20 gpm). This means that, theoretically, a 5/8”x 3/4” meter can stand a 45% higher flow rate than its equivalent DN15 ISO meter. However, it is worthwhile analysing if domestic water consumption requires such a large flow capacity. From the measurements taken at different types of residences, the conclusion is that very few residential users consume water over the maximum flow rate of an ISO meter (Bowen et al. 1993; DeOreo and Hayden 2008; Beal and Stewart 2011; DeOreo 2011).

Finally, it should be noted that dissimilarities in performance in the medium flow range between AWWA and ISO meters were negligible and these differences only depend on the construction characteristics of the meters and not on the standard specifications.

4.2 Oscillating piston meters

If a similar comparison between AWWA and ISO meters is made with oscillating piston meters the differences are even greater. Barfuss et al. (2011) found that the average error of oscillating piston meters (A1) at a flow of 7.2 l/h and 14.2 l/h was of -97% and -60% respectively. The worst equivalent ISO meter (M8) from among those tested in this study showed errors, at similar flow rates, of -4.5% and -0.25% respectively. At flow rates greater than 100 l/h the differences between AWWA and ISO meters were negligible and can only be due to manufacturing quality.

When the comparison of ISO oscillating piston meters is made with the results extracted from the previous study conducted by the AWWARF (Bowen et al. 1991), the differences in error curves are mostly the same. However, it is important to highlight once more that in this study the meters under test were not selected randomly. Figure 3 presents the differences between the error curves of all three studies.

5. Consumption patterns

As it has been said, real field performance of the meters will depend not only on the error curves of the meters but also on the consumption flow rates of the users. Therefore, the amount of water not registered by a water meter can only be calculated if the consumption pattern of the user is known. Even though the authors have been gathering consumption data of domestic users for the last ten years (Arregui et al. 2006, Cobacho et al. 2008), the collected data is insufficient to provide a reliable consumption pattern for different types of users and countries. The present work aims to assess the initial performance of the meters for different types of users. Consequently, two additional consumption patterns other than the patterns measured by the authors have been included in this research – these patterns being extracted from previous reputable reports. In total, four consumption patterns (Figure 4) were used for the calculations of the weighted error of the meters:

Consumption pattern I: This consumption pattern was published in Arregui et al. (2006). It is associated with apartments in buildings with a direct supply, meaning that the pumps are connected directly to the network. The consumption pattern was obtained after logging 389 apartments located in major Spanish cities for a time lapse of one or two weeks. Data logging activities started in 2003 and finished in 2005.

Consumption pattern II: This consumption pattern was published in Arregui et al. (2006) and corresponds to users having a roof tank in their private facility. It was calculated after logging 58 dwellings in three small to medium sized Spanish cities for two weeks.

AWWA consumption pattern: In 1993 the AWWA Research Foundation published a report (Bowen et al. 1993) in which a large sample of households were monitored (some 706 households in five cities throughout the United States). The sample was classified depending on the type of residence (single family – multifamily); size (greater or smaller than 186 square metres); and the season of the year when the measurements were taken (summer or winter). Unexpectedly, the consumption patterns found for the mentioned variables were quite similar to each other and minimal differences at low and high flows were found for the types of users monitored. Consequently, for the purpose of this study and with the aim of simplifying the calculations, only the water consumption obtained for the complete sample is considered.

As it can be seen in Figure 4, consumption at high flow rates, above the maximum flow rate of an ISO meter (approx. 3000 l/h or 13 gpm), represents a very small percentage of the total consumption. Even when analysing the specific consumption patterns for single families or large residences (greater than 186 square metres), this percentage did not increase significantly and in both cases stayed below 2% (Bowen et al. 1993). Similarly, a sample of 34 single family residences with pool and garden were monitored during the summer period by Arregui et al. (2006). In these measurement activities only 2.7% of the total consumption occurred over the maximum flow rate of the meters and this consumption level occurred in a limited number of users.

SEQREUS consumption pattern: Finally, the final consumption pattern considered was published in 2011 by the Urban Water Security Research Alliance (Beal and Stewart 2011). This pattern was calculated as the average of three monitoring periods, two in summer and one in winter, between June 2010 and June 2011. The number of residences monitored was different for each period, being 213, 219, and 110 households respectively. The residences under study were located in four different cities in south-east Queensland (Australia) and had external (lawn and garden watering) and internal water use. However, garden watering only accounted, on average, for 12.6% of the total water consumption. Consequently, water consumption at high flow rates caused by sprinklers was not observed.

6. Calculating the weighted error of ISO meters

The weighted error of a meter represents the amount of water that is not registered by a meter for every 100 litres of water consumed according to the water consumption pattern of the user (Arregui et al. 2006). This parameter is of much greater meaning than the error curve alone and is the primary contribution of the present work with respect to previous studies that only analysed meter error curves.

All calculations carried out in this study regarding the weighted error have been performed by means of a free software tool, Woltmann, which was specifically designed for this purpose. The calculation procedure used by the software is the same as that described in Arregui et al. (2006). This paper does not address in detail how to calculate the weighted error, but it should be mentioned that the simplified procedure proposed by AWWA and used by several authors (Male et al. 1985; Allender 1996; Yee 1999; Mutikanga et al. 2011b) is not recommended – and may lead to erroneous conclusions (Arregui et al 2009). AWWA procedure reconstructs the meters' error curve at low flows only with the information of a single flow rate. Furthermore, it does not take into account the starting flow rate of the meter.

For this analysis, the four water consumption patterns were combined with the available error curves of the meters to determine their weighted error. As can be inferred from the shape of the error curves, the weighted error strongly depends on the amount of water consumed at low flow rates, where the meter errors are greatest. Taking this into account, the four water consumption patterns used in this study can be organised depending on how difficult it is for a meter to measure each water consumption distribution. The most severe consumption pattern is *consumption pattern II* which defines that 14.9% of the water is used below 36 l/h. The most favourable consumption pattern is *SEQREUS* which defines that approximately only 6.3% of the water is used below 36 l/h. Taking this into consideration, it is apparent that the weighted error of the meters calculated using *consumption pattern II* will be much larger than for other consumption patterns, for which the amount of water used at low flows is significantly smaller.

Additionally, from Figure 5, it is clear that the most unfavourable water consumption patterns increase the differences in the field performance of the meters. For example, taking into account the meter models tested during this study, the difference between the best (M8) and worst (M3) meter is only 3.96% when the consumption pattern considered is the *SEQREUS pattern*. However, this difference in weighted error increases to a value of 10.15% when the consumption pattern used for the calculation is *consumption pattern II*. In such case, the weighted error of the best meter (M10) is -0.60% while the weighted error of the worst meter (M3) is as high as -10.75%. Additionally, this consumption pattern enables a quick visual comparison of the performance of the oscillating piston (M8, M9, M10 and M11) and single-jet meters. The excellent performance of positive displacement meters at low flow rates provides a significant advantage in comparison with single-jet meters. If meters are analysed by technology the following conclusions can be made:

6.1 Single- jet meter's

Single-jet meters always show a weighted error that is more negative than oscillating piston meters. Due to the metrological limitations at low flows the magnitude of the error highly depends on the consumption pattern.

Taking into account the most unfavourable consumption pattern, the worst weighted error found was of -10.75% for meter model M3. This meter is metrological class B. In contrast, the best performing single-jet meter (M7), corresponding to metrological class R200, reached an initial weighted error of -3.68%. At this point, it is important to highlight that these values correspond to the initial performance and in many cases the weighted error has a tendency to increase in value over time or accumulate volume.

Conducting the same analysis for the most favourable water consumption pattern, SEQREUS, the weighted errors noticeably change. Meter model M3, even with its technical limitations, reaches an error of -3.87%; while the error of M7 becomes an extraordinary -0.71%. Once more, these differences highlight the importance of using an adequate water consumption pattern for the calculations.

6.2 Oscillating piston meters

When analysing this technology it has been found that the *AWWA pattern* is more unfavourable than *consumption pattern II*. This conclusion can be justified by the fact that the performance of the oscillating piston meters is extremely good at low flows. Therefore, the percentage of water used in this range has limited importance. Nevertheless, the fact that *AWWA pattern* shows a larger percentage of consumption at high flows also affects the weighted error calculations. It should not be forgotten that the typical error curve of an oscillating piston meter is a decreasing curve after a maximum (more positive) error that is usually located around 100 l/h. For this reason, it is not unusual to find oscillating piston meters showing negative error at maximum flow rate (Table 2). In fact, all four meter models tested during this study showed a negative error at maximum flow rate. This conclusion is also consistent with the results found in both of the AWWARF studies considered (Table 4).

Two additional conclusions can be raised from Figure 5. Firstly, for a given consumption pattern, the dispersion of the weighted error of the oscillating piston meter models tested is almost negligible. The selection of a meter model has to be made based in alternative parameters rather than the initial meter error. Secondly, the initial weighted error of an oscillating piston meter is always better than any velocity meter – and the reason why this meter technology is not the only one in use is related to its sensitivity to suspended particles. In water systems with poor water quality, or water with a high tendency to form scale, or frequent large bursts occurring in mains and service pipes, oscillating piston meters are much more likely to become blocked than single-jet or multi-jet meters. In such cases, velocity meters are a much better option than positive displacement meters (Arregui et al. 2006).

7. Comparing the weighted error of ISO vs AWWA meters

For this comparison, the results of the error curves obtained during this research and the results published by Barfuss et al. (2011) have been used for calculations of the weighted error. As expected, from the error curves plotted in Figures 1 and 3, the weighted error of the meter models in compliance with AWWA standards are, in general, much larger than the errors of the equivalent ISO meters. This is true independently of the meter technology considered.

7.1 Single-jet meters

As shown in Figure 5, the average weighted error calculated for all single-jet meters tested in Barfuss et al. (2011), A5, is almost the same as the weighted error obtained for the worst meter model that complies with ISO tested in this study (M3). The values found were -12.18% and -10.75% respectively. For the most favourable water consumption the average weighted error of the AWWA single-jet meters was -4.56%, while the error found for the worst ISO meter was -3.87%. The best performing meter model (M7) from those tested achieved a weighted error of only -0.71%

7.2 Oscillating piston meters

Surprisingly the average weighted error of the oscillating piston meters tested in Barfuss et al. (2011), A1, did not showed a substantial better performance than the single-jet meters tested in the same study (A5). Consequently, the difference between these meters and the ISO meters tested in this research is important. This difference in performance can be mostly assigned to the deficient sensitivity of AWWA meters at low flows. If the comparison is made with the *AWWA consumption pattern* the differences become significantly smaller.

It should be remembered that AWWA meters have a larger flow rate capacity and so can stand higher flow rates through the meter. Therefore, it can be concluded that AWWA meters are only appropriate for customers with large water consumption flow rates, such as houses with pools and automatic sprinklers for watering. Consumption in a typical apartment will not reach these high flow rates and there is no reason to install meters with such a high flow rate capacity.

7.3 Other technologies (AWWA)

For the other technologies tested in Barfuss et al. (2011) – fluidic, multi-jet and nutating disc meters – the weighted errors found were also higher than for the equivalent ISO meters. Taking into account the *AWWA pattern* the errors obtained were -6.37%, -5.36% and -3.24% respectively. These errors significantly increase when considering *consumption pattern II*, and reach -12.98%, 11.67%, and -6.91%.

Even though the nutating disc meters (A4) show a better performance than oscillating pistons (A1), the weighted error does not approximate the figure attained by ISO oscillating piston meters. AWWA multi-jet meters (A3) achieve a weighted error similar to the worse single-jet meter tested in the present study.

8. Conclusions

The research conducted provides valuable information about what can be expected about residential meter field accuracy. In all cases, ISO meters have been proven to achieve better measuring performance than the equivalent AWWA meters. The explanation for this conclusion can be found in the flow rate capacity of the meters. The maximum flow of AWWA meters is significantly larger than the equivalent ISO meters. As a consequence, low flow sensitivity of AWWA meters is reduced. Since consumption in most households, even those in the USA, rarely exceeds 3000 l/h, there is no advantage in having such a large flow capacity that in most cases remains unused. In contrast, the lower flow rate sensitivity prevents AWWA meters from detecting the leaks that will inevitably occur.

In relation to the different tested metering technologies, unused oscillating piston meters have clearly out-performed single-jet meters in all the considered situations. Unfortunately, this metrological advantage is not universally exploitable as positive displacement meters are very sensitive to water quality and their use is not recommended for utilities with water quality problems. In any case, it has been proven that this meter technology can be very adequate for certain systems supplying water of sufficient quality – and so reduce commercial losses from residential customers.

Finally, it has been shown that the expected initial error of ISO velocity meters, under the most favourable working conditions (Beal and Stewart 2011), ranges from an excellent -0.71% (M7) down to -3.87% (M3), depending on the ISO meter considered. This initial error, under favourable working conditions, becomes -4.56% for the AWWA single-jet meters and -4.46% for the AWWA multi-jet meters tested by Barfuss et al. 2011.

Measuring errors significantly increase when measuring the water consumption of users with a roof tank. In such cases, ISO velocity meters have shown errors of between -3.68% and -10.75%. For the same type of user, the calculated initial error for single-jet and multi-jet AWWA meters was as high as -10.84% and -12.21%.

ISO oscillating piston meters in all cases have shown errors of between 0% and -1% independently of the type of user. The performance of AWWA oscillating piston meters was much worse and for the most unfavourable water consumption the error went down to -11.37%. AWWA nutating disc meters performed much better than oscillating pistons.

Finally, it should be noted that the test flow rates suggested by the AWWA standards may not be appropriate for conducting a proper quality control over new meters because meters are becoming more sensitive. The accuracy test at the lowest flow rate of 57 l/h (1/4 gpm) is too high to validate performance at low flow rates. Moreover, in the opinion of the authors, a lower capacity meter for accurately measuring residential water consumption should be considered in the AWWA standards. The smallest water meter defined in the standard is significantly oversized if the real water consumption needs of most residential users are considered.

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Table 1. Characteristics of the residential meters tested at ITA laboratory

Id	Number of meters tested	Register resolution (x 10^{-5} m^3)	Technology	Q1 (l/h)	Q2 (l/h)	Q3 (l/h)	Q4 (l/h)	Metrological Class	Standard
M1	30	5	Sj*	30	120	1500	3000	B	ISO 4064:1993
M2	30	5	Sj*	30	120	1500	3000	B	ISO 4064:1993
M3	30	5	Sj*	30	120	1500	3000	B	ISO 4064:1993
M4	30	5	Sj*	25	40	2500	3125	R100	ISO 4064:2005
M5	30	5	Sj*	20	32	2500	3125	R125	ISO 4064:2005
M6	30	2	Sj*	15	22.5	1500	3000	C	ISO 4064:1993
M7	30	5	Sj*	12.5	20	2500	3125	R200	ISO 4064:2005
M8	30	2	Op**	12.5	20	2500	3125	R200	ISO 4064:2005
M9	30	2	Op**	15	22.5	1500	3000	C	ISO 4064:1993
M10	30	2	Op**	7.9	12.7	2500	3125	R315	ISO 4064:2006
M11	30	5	Op**	5.1	8.1	1600	2000	R315	ISO 4064:2005

*SJ = Single jet   ** OP = Oscillating piston

Table 2. Average starting flow rate and indicating error for each meter model

			Test Flow (l/h)	6	10	15	30	60	120	600	1500	2500	3000
M1	Avg. Q_{start} (l/h)	8.77	Avg. Error (%)	-100	-36.51	-8.92	3.84	2.13	1.49	1.06	0.52	0.32	0.3
	Std. Dev. (l/h)	0.47	Std. Dev.(%)	0.00	9.71	2.78	0.76	0.98	0.66	0.39	0.49	0.51	0.55
			Test Flow (l/h)	6	10	15	30	60	120	600	1500	2500	3000
M2	Avg. Q_{start} (l/h)	9.68	Avg. Error (%)	-100	-67.08	-17.49	-0.29	1.09	0.07	-0.33	-1.22	-1.38	-1.38
	Std. Dev. (l/h)	1.46	Std. Dev.(%)	0.00	29.11	7.19	18.25	2.89	0.58	0.67	0.65	0.57	0.53
			Test Flow (l/h)	6	10	15	30	60	120	600	1500	2500	3000
M3	Avg. Q_{start} (l/h)	12.36	Avg. Error (%)	-100	-88.26	-23.87	2.47	2.39	0.77	-1.25	-0.50	0.13	0.3
	Std. Dev. (l/h)	2.13	Std. Dev.(%)	0.00	22.35	8.14	2.38	0.68	1.28	0.59	0.53	0.56	0.62
			Test Flow (l/h)	6	10	15	25	60	120	600	1500	2500	3000
M4	Avg. Qstart (l/h)	8.60	Avg. Error (%)	-100	-34.60	-11.15	-1.05	-0.44	-0.80	0.23	0.55	0.73	0.76
	Std. Dev. (l/h)	0.74	Std. Dev.(%)	0.00	9.74	2.77	1.21	1.02	0.75	0.80	0.95	1.17	1.20
			Test Flow (l/h)	6	10	20	60	120	600	1500	2500	3000	
M5	Avg. Q_{start} (l/h)	5.05	Avg. Error (%)	-39.89	-6.84	-0.93	-2.61	-0.58	0.39	0.42	0.35	0.2	
	Std. Dev. (l/h)	0.84	Std. Dev.(%)	23.10	8.13	1.07	1.00	0.75	0.53	0.42	0.44	0.45	
			Test Flow (l/h)	6	10	15	22.5	60	120	600	1500	2500	3000
M6	Avg. Q_{start} (l/h)	4.63	Avg. Error (%)	-38.55	-7.77	-1.90	-0.60	1.30	1.14	-0.62	-1.14	-1.50	-1.69
	Std. Dev. (l/h)	0.42	Std. Dev.(%)	19.33	2.14	1.29	1.01	0.48	0.42	0.34	0.34	0.40	0.42
			Test Flow (l/h)	6	12.5	20	60	120	600	1500	2500	3000	
M7	Avg. Q_{start} (l/h)	4.04	Avg. Error (%)	-15.76	0.24	1.40	-1.34	0.27	0.91	0.61	0.31	0.08	
	Std. Dev. (l/h)	0.41	Std. Dev.(%)	7.11	1.04	1.13	0.51	0.36	0.32	0.27	0.29	0.38	
			Test Flow (l/h)	6	12.5	20	60	120	600	1500	2500	3000	
M8	Avg. Q_{start} (l/h)	1.54	Avg. Error (%)	-4.53	-1.41	-0.26	1.20	1.77	0.92	0.11	-0.55	-0.99	
	Std. Dev. (l/h)	0.22	Std. Dev.(%)	1.31	0.32	0.19	0.24	0.37	0.26	0.16	0.19	2.27	
			Test Flow (l/h)	6	10	15	22.5	60	120	600	1500	2500	3000
M9	Avg. Q_{start} (l/h)	1.77	Avg. Error (%)	-3.00	-1.48	-0.22	0.65	1.45	1.51	0.83	0.10	-0.34	-0.39
	Std. Dev. (l/h)	0.40	Std. Dev.(%)	1.01	0.64	0.37	0.22	0.18	0.19	0.14	0.13	0.15	0.16
			Test Flow (l/h)	5	13	25	60	120	600	1500	2500	3000	
M10	Avg. Q_{start} (l/h)	1.14	Avg. Error (%)	-2.32	0.30	1.14	1.58	1.46	0.36	-0.53	-1.16	-1.29	
	Std. Dev. (l/h)	0.43	Std. Dev.(%)	0.60	0.22	0.14	0.34	0.20	0.16	0.15	0.18	0.18	
			Test Flow (l/h)	5	8	15	30	60	120	600	1600	2000	
M11	Avg. Q_{start} (l/h)	1.59	Avg. Error (%)	-2.95	-1.01	0.39	1.21	1.62	1.47	0.75	-0.20	-0.53	
	Std. Dev. (l/h)	0.19	Std. Dev.(%)	1.03	0.72	0.43	0.33	0.25	0.20	0.29	0.31	0.39	

Table 3. Defective meters and non-conformities found during the tests

Meter model	Total	Defective Low flow	Defective High flow	Non-conformities Low flow	Non-conformities High flow
M1	30	0	0	2	0
M2	30	1	0	1	0
M3	30	5	0	4	0
M4	30	3	1	2	4
M5	30	3	1	3	3
M6	30	3	0	3	6
M7	30	1	0	0	0
M8	30	0	2	0	3
M9	30	0	0	0	0
M10	30	2	0	1	0
M11	30	2	0	1	0
A1	48	1	1	11	0
A2	6	0	0	0	0
A3	42	3	0	10	4
A4	30	0	0	0	0
A5	24	0	0	6	6
B1	20	0	0	0	0
B2	20	0	0	0	0

Table 4. Average error for several meter technologies (Barfuss et al. 2011)

Id	Meter models	Nº	Test Flow (gpm)	1/64		1/16	1/8	1/4	1/2	1	2	15	20
			Test Flow (l/h)	3.5	7.1	14	28	57	114	227	454	3407	4543
A1*	8	48	Oscillating piston	-99.97	-97.17	-59.98	14.03	-2.90	-0.26	0.64	0.71	-0.03	-0.18
A2*	1	6	Fluidic oscillator	-100.00	-100.00	-89.95	-3.55	-3.16	-1.62	-0.62	-0.50	-0.75	-0.73
A3*	7	42	Multi-jet	-99.99	-99.95	-70.83	13.22	-2.77	0.67	0.60	0.23	0.15	-0.04
A4*	5	30	Nutating disc	-97.62	-55.90	-12.99	-3.64	-0.71	0.81	0.95	0.81	-0.59	-0.71
A5*	4	24	Single-jet	-100.00	-99.11	-75.88	12.84	0.24	-0.81	-0.48	0.07	0.19	0.14
B1**	10	20	Nutating disc			-6.5	-2.4	0.0	1.1	1.4	0.7	0.2	0.2
B2**	10	20	Oscillating piston			-32.1	-9.2	-2.1	-0.3	0.6	1.0	-0.1	-1.0

* Barfuss et al. 2011 ** Bowen et al. 1991

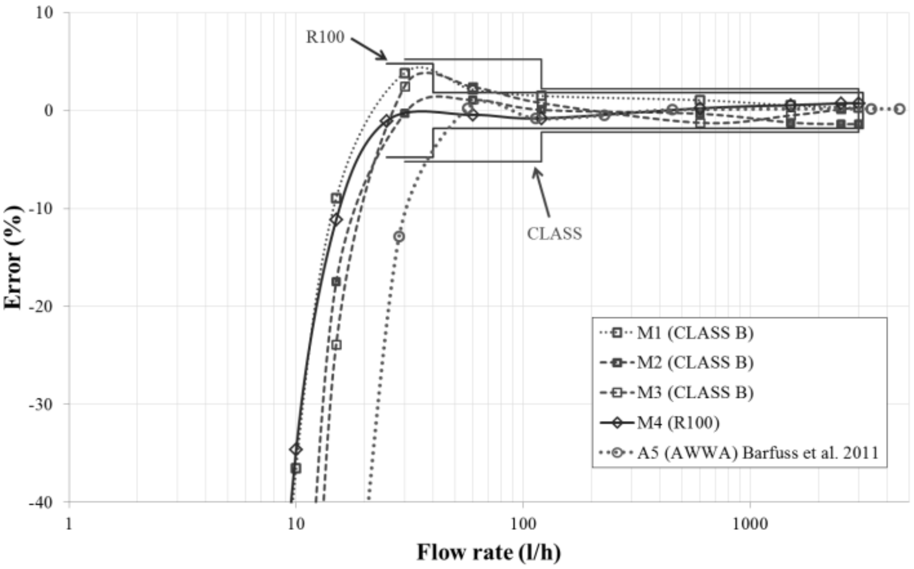

Figure 1. Average error of Class B and R100 single-jet meters

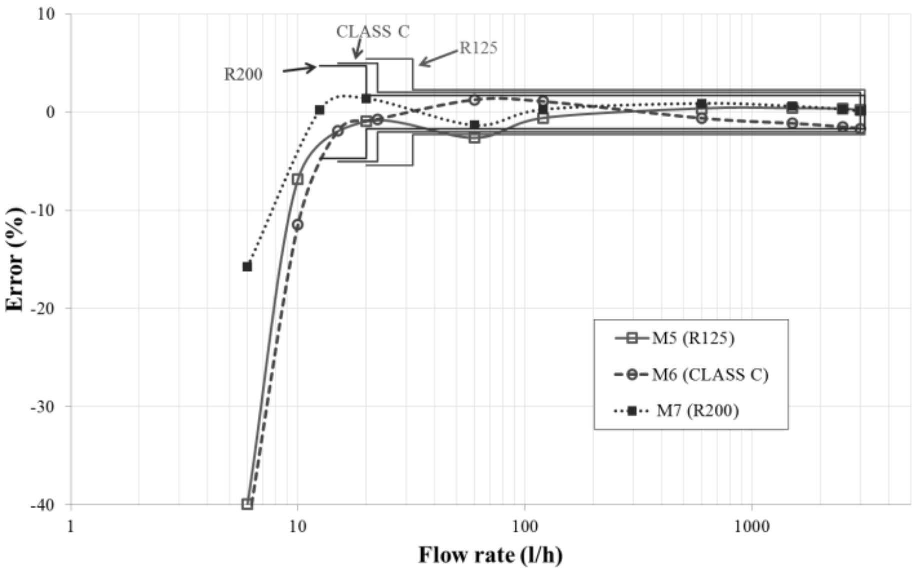

Figure 2. Average error of Class C and R>125 single-jet meters

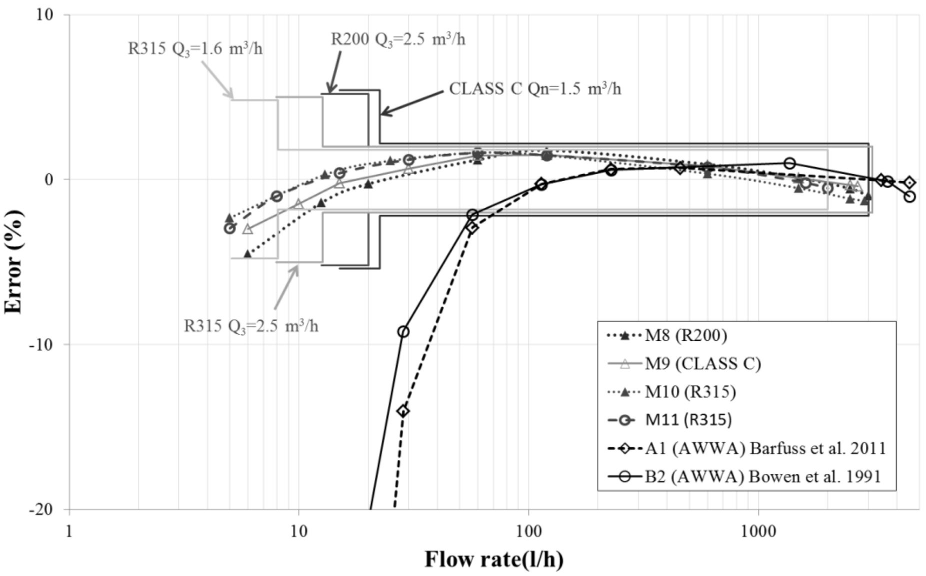

Figure 3. Average error of oscillating piston meters

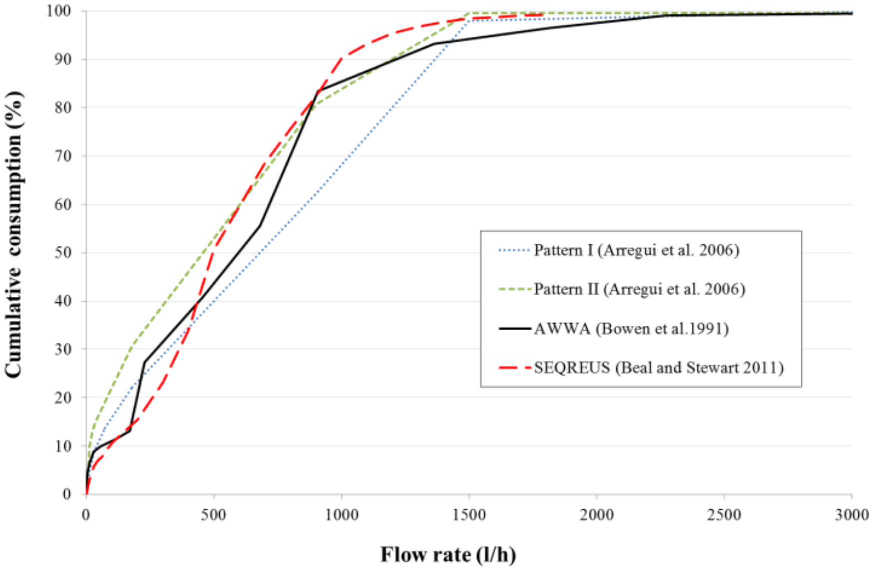

Figure 4. Cumulative proportion of total consumption (%)

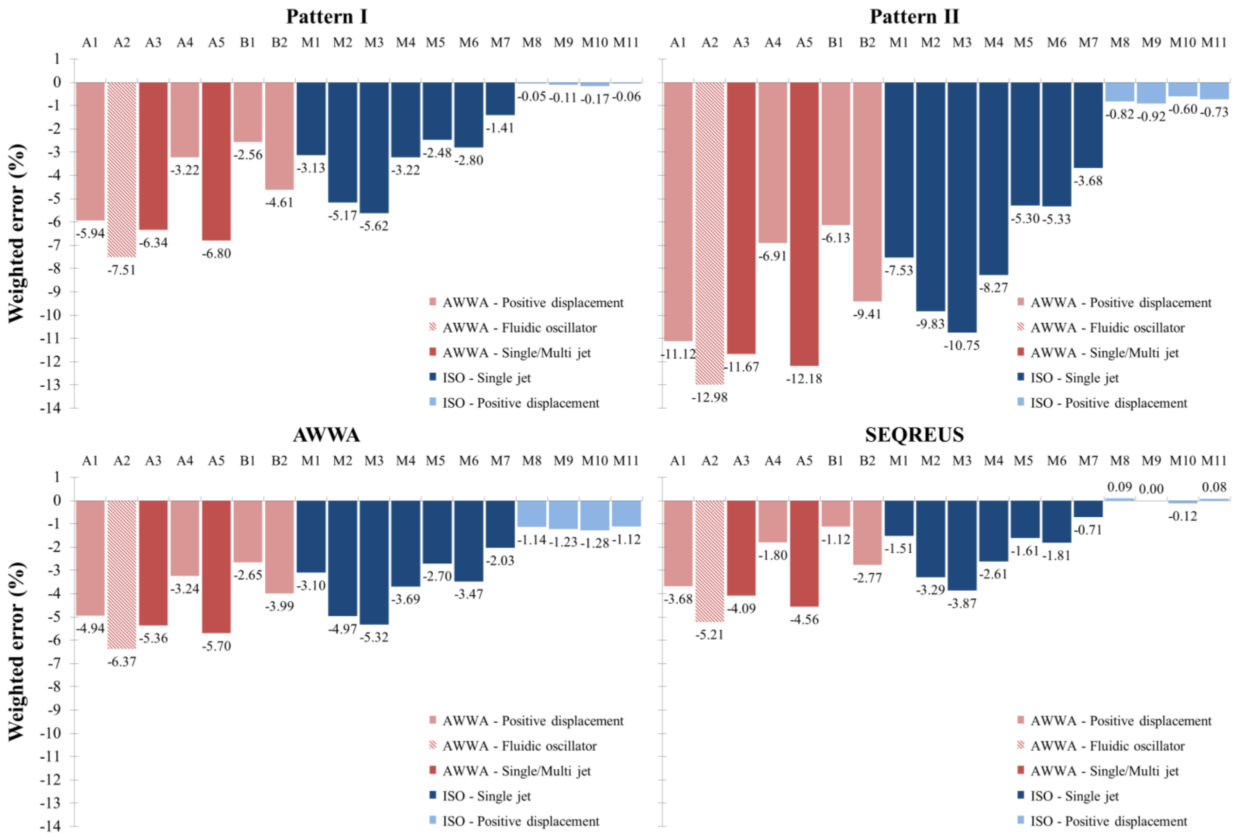

Figure 5. Weighted error of new meters for different domestic consumption patterns