



Article

# Performance Analysis of Ageing Single-Jet Water Meters for Measuring Residential Water Consumption

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**Abstract:** Single-jet meters are one of the most frequently used domestic meters that can be found in water distribution systems. Like any other water meter technology, they have significant metrological limitations that prevent them, even if recently installed, from measuring all water consumption of a domestic customer. After installation, their metrological characteristics evolve depending on the particular design of the meters and their actual working conditions in the field. This work presents a comprehensive set of tests to determine the initial and after installation weighted error of two types of domestic single-jet water meters. Three non-linear degradation models have been derived from the tests results. These models consider age, totalised volume, or both parameters simultaneously as drivers of the weighted error. The results show that even though the construction of the two examined meters is similar, they have been working under comparable operational conditions and measuring water of the same quality, there is a significant difference in the performance between both types. This result highlights the need to conduct individual analyses for each meter type and the impossibility of generalizing conclusions on how the weighted error could evolve over time.

**Keywords:** water meter accuracy; apparent losses; single-jet water meters performance; water metering errors; domestic water meter replacement

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## 1. Introduction

Water losses have been identified as one of the leading problems common to any water utility in the world. High levels of losses can significantly affect future water resources availability, energy consumption associated to water production and distribution, overall quality of service to customers, water quality levels and operational costs and life of the assets. Depending on their nature, the International Water Association (IWA, London, UK) categorises water losses in two components [1]: real losses and apparent losses. Real losses are mainly caused by leakage in pipes, valves, tanks, and other elements in the network. Apparent losses include the volume of water stolen by the users, the measuring errors of the meters and data handling errors. While apparent losses volumes are typically smaller than real losses, these two components become almost equal when making the comparison in terms of revenue loss caused by the utility. This is because a cubic meter of water lost in a leak in the network has a cost to the utility equal to the production cost. On the contrary, a cubic meter supplied to a customer that is not measured by the water meter has a cost to the utility equal to the retail price of the last cubic meter of water sold to that customer. In addition, in a properly managed water supply system, apparent losses are mainly caused by water meter inaccuracies. Consequently, the water utility's revenue strongly relies on the actual measuring performance of installed water meters.

While the published International Standards on water meters [2,3] mostly specify the metrological and technical requirements of new meters, there is a lack of international standards defining how the metrological performance of the meters should be after installation. Only very few countries have specific legislation or standards in relation to the metrological requirements of used meters. In addition to this, the number of parameters that can affect the actual accuracy of a water meter in the field is not small. Thus, it is reasonable to assume that the metrological performance evolves over time—or with the amount of volume measured—depending on the working conditions, water quality, and design of the instrument itself [4,5]. Apart from that, there is not a standardised or widely accepted international procedure to calculate the overall metrological performance of the meters under real working conditions. Even more, studies related to the performance of installed meters are extremely difficult to find and frequently water companies keep them as confidential documents. All these factors in combination, make it difficult for water utility managers to estimate the actual impact of meters errors in their water balances and decide when is the optimal time to replace them [6–9].

By far, from all meters' types used by water utilities, the most common ones are the ones employed to measure household consumption [10]. Typically, around 90–95% of installed meters in a water utility are small diameter domestic meters and they measure around 70–80% of the total water consumption. Because of technical design limitations, domestic meters are not capable of registering the exact amount of water consumed by a customer. Depending on its construction technology [11,12], diameter, consumption characteristics of the customer, or type of water distribution system [13,14], each water meter has specific measuring limitations [15,16]. This means that a percentage of the water actually consumed by a customer may not be registered. If this is the case, the meter is said to be under-registering water consumption or have a negative error. Other times, some meter technologies, under certain working conditions, may show the opposite behaviour, that is, to register more water than the volume actually passed through the meter. Then, the meter is said to over-register water consumption or have a positive error. In either case, it is important to quantify the magnitude of these measuring errors to calculate the total amount of apparent losses.

For this analysis, a critical aspect to be considered is that the error of a water meter, despite the working principle used, varies with the flow rate passing through it. Typically, at low flow rates, measuring errors are more negative and sensitive to external variables [17]. For medium and high flow rates, error variations are smaller and less sensitive to the magnitude of the flow [16,18,19]. Thus, the difference between the amount of water registered by a meter and the actual volume used by the customer is also dependent on the consumption flow rates. The weighted error of a meter, defined as the relative difference between the actual consumption and the registered volume, can be obtained by combining the error curve of a meter and the consumption flow rates of the customer [16,20,21]. Consequently, the weighted error is an indicator of the real, in the field, the overall metrological performance of a water meter when registering water consumption of a given user.

The main objective of this paper is to determine the weighted error of new and in-service single-jet domestic meters in order to provide information on the real field performance that can be expected from the meters installed in several water supply systems in the Spanish East Coast. More specifically, the study has focused on the analysis of two type of common single-jet domestic meters. The work has been conducted in collaboration between ITA-UPV (Universitat Politècnica de València, Valencia, Spain) and FACSA (Sociedad de Fomento Agrícola Castellonense, Castellón, Spain), one of the largest water supply companies in Spain.

Although the results cannot be directly extrapolated to other water utilities—due to the numerous factors affecting meters accuracy degradation—this work provides water meter managers with a reference of the methodology to be used in the estimation of the measuring errors. It can also provide a sense for an order of magnitude of the accuracy degradation rate of single-jet domestic meters and the procedure to identify the best approach for modelling their actual weighted error degradation. For the particular case of the water systems analysed, the results will be used in the future by FACSA to improve meter selection and to obtain a more accurate estimation of the actual level of apparent losses, revenue decay and calculation of the optimal replacement frequency of the meters [20–25].

## 2. Materials and Methods

### 2.1. General Approach

For the determination of the initial weighted error of the meters under study, a comprehensive test program was conducted between 2008 and 2014, in which a sample of 3762 new water meters has been tested to determine the performance of the initial meters. These tests have been used by FACSA to decide the most adequate meter to be utilised in each water supply system. In addition, the ongoing quality control tests have guaranteed the performance of procured meters before they were installed in the field. Therefore, they provide a valuable information about the capability of the manufacturers to produce and deliver, on the long and medium term, meters with the expected metrological quality.

The work presented provides real figures of the initial weighted error of two common domestic single-jet water meter types. The weighted errors have been obtained for a frequency distribution function of the consumption flow rates extracted from a sample of domestic customers monitored in a water supply managed by FACSA [26]. The calculation of the weighted error was done by means of a dedicated EXCEL© tool [27] that utilizes the procedure described in Arregui et al. in Reference [16]. The tool is freely available for download and allows for the calculation of the weighted error of any meter by introducing its error curve and the associated frequency distribution function of consumption flow rates.

Although the initial weighted error figure was primarily used by the water utility to make a preliminary selection of the most suitable domestic water meter, it is important to remark that the most profitable water meter for the utility is not necessarily the one with the lowest initial weighted error. The rate at which this error degrades with time or with volume is an essential component of any economic calculation and it plays a critical role not only in the selection but also in the replacement policies to be implemented [23–25,28].

Consequently, the work conducted also comprised a detailed analysis on how the weighted error of these two meter types changes over time and/or with the totalised volume. For this purpose, a sample of 1210 ageing water meters of the two meter types were removed from the field and tested in a laboratory. Three mathematical degradation models have been developed for each one of the meter types. The first one relates the degradation of the weighted error to age, the second relates it to the totalised volume, and the third one accounts for the impact of both parameters simultaneously.

For a better understanding of the methodology followed and the amount of data used, Figure 1 shows the different stages comprising the analysis carried out and the relevant information associated with each one of them.

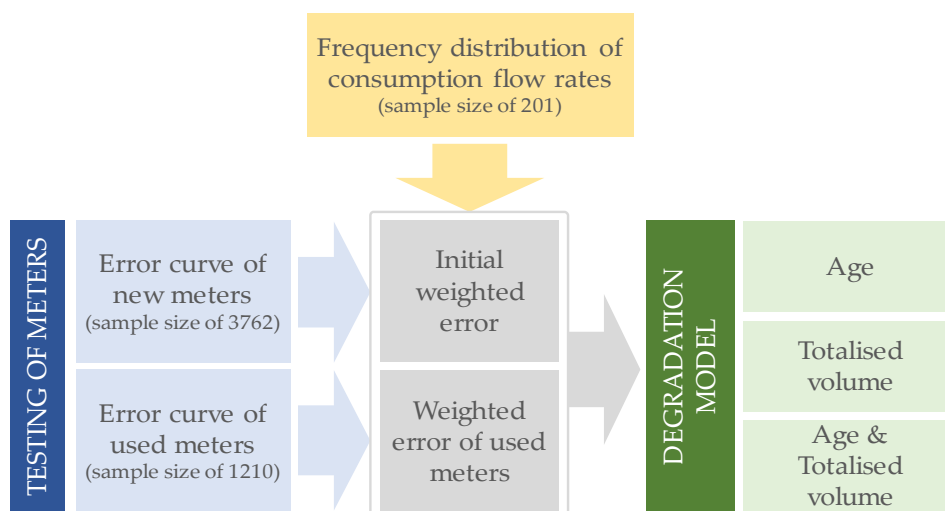
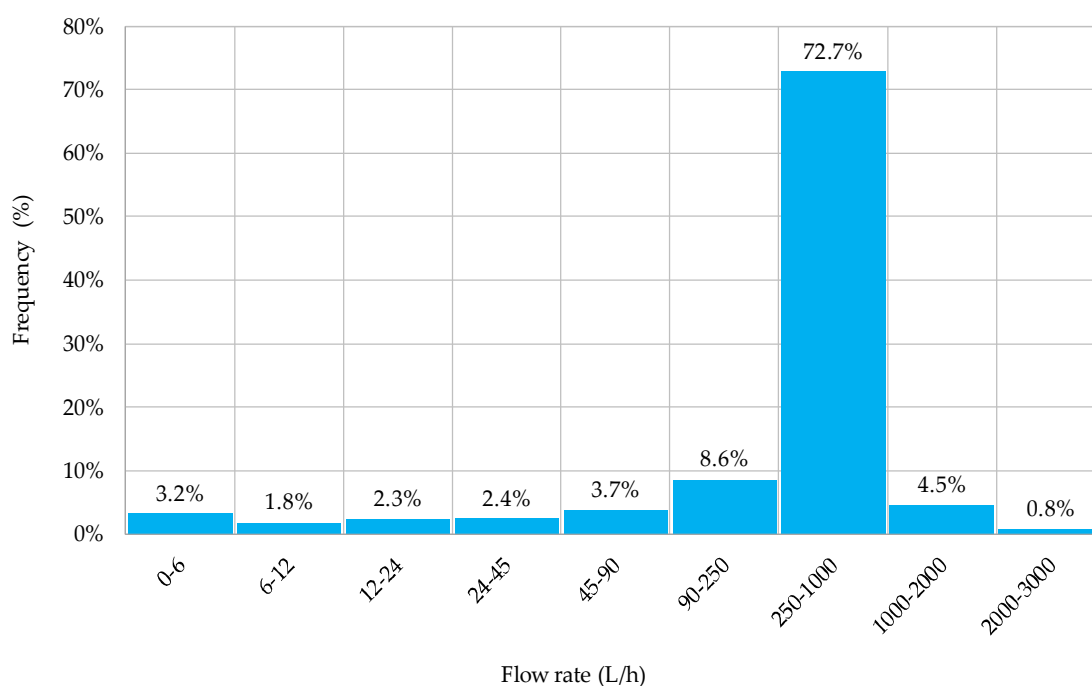


Figure 1. The diagram of the methodology used.

## 2.2. Water Consumption Flow Rates of Domestic Users

Water consumption flow rates from customers are not uniform throughout the day. Depending on the number and characteristic of the water appliances being used at each specific time, the flow rate passing through the meter may change. Therefore, when measuring water consumption from any user, water meters work under varying flow conditions. As defined by the error curve, the measuring errors of any water meter change depending on the flow rate passing through it. Consequently, two parameters are needed to calculate how much water is not registered by a meter when measuring the consumption of a specific user: (1) statistics about how much water is consumed at each flow rate (2) details on the error curve that provides information about the measuring errors at different flow rates. Information about the first parameter is summarized in the so-called water consumption pattern (a frequency distribution function of the consumption flow rates), which is built as a histogram that stratifies water consumption into several flow rate ranges. Examples of actual domestic consumption patterns in different countries can be found in Bowen et al. [29] and DeOreo et al. [30] in the USA, Beal and Stewart [31] in Australia, and Arregui et al. [10,16] in Spain. Other frequency distribution functions for particular types of customers can be found in Arregui et al. [32].

For the particular analysis conducted in this study, a frequency distribution of consumption flow rates (Figure 2) extracted from residential customers of one of the water supply systems managed by FACSA is used [26]. This frequency distribution was obtained by measuring, for a period of approximately two weeks, the water consumption of 201 domestic customers with a resolution of 0.1 L. The consumption data were recorded with a time resolution of 0.02 s. The oscillating piston water meters employed in the monitoring campaign were produced by ITRON (Aquadis) and the data-loggers used were manufactured by Sensus (Cosmos Data Logger). The fieldwork took place between November 2005 and April 2006. The methodology followed in this study is the same as described in Arregui et al. [16].



**Figure 2.** The frequency distribution for the consumption flow rates of the monitored residential users.

The obtained frequency distribution did not show a large percentage of volume consumed at low flows. In fact, on average, only 7.3% of the consumption took place at flow rates lower than 24 L/h, where domestic single-jet water meters may have most problems for measuring water volumes [13,19]. At higher flows, this percentage decreases and the amount of water consumed between 24 and 45 L/h represents only 2.4% of total consumption. According to the frequency distribution, most of the water usage, up to 72.7%, takes place between 250 and 1000 L/h. Finally, because of the characteristics of the households—mainly apartments located in residential buildings—the amount of water consumed above 2000 L/h is negligible, only 0.8%. The reason for this can be found in the sporadic overlapping of uses within the household and the limited consumption flow rate of the water appliances. Considering that according to the ISO 4064:2014-1, the overload flow rate of a typical domestic meter (with a permanent flow rate of 2.5 m<sup>3</sup>/h) is 3125 L/h, it is clear that most water consumption of the monitored users is well below the maximum capacity of any domestic meter. In other words, the meters typically installed for measuring water consumption in apartments are oversized considering the actual consumption flow rates of the users.

### 2.3. Testing Equipment and Procedures

Measuring errors of new and used meters were obtained by means of two different volumetric test benches, both having two calibrated probes of 10 L and 200 L and located in the laboratories of ITA and FACSA. For the particular case of domestic meters, the benches can fit up to 5 and 6 m respectively—which can be tested from 1 L/h up to 3125 L/h. The errors of the meters were obtained with the standing start and stop test method [33–35]. The 10 L probe was used to test the meters for flows up to 120 L/h; while the 200 L probe was used for flows higher than 120 L/h. The scale division of the probes was of 0.01 and 0.2 L, respectively, which represents 0.1% of the tested volume.

This means that the expanded uncertainty of the error tests conducted in this work was mainly driven by the resolution of the volume readings of the meters. For both meter types the smallest volume that could be read from the register was 0.05 L. This represents 0.5% when the test volume was 10 L and 0.025% when it was 200 L. All in all, the estimated test uncertainty was less than 0.2% for flow rates larger than 120 L/h and approximately 0.8% for tests equal or below 120 L/h.

When selecting the flow rates at which the meters should be tested, it is crucial to make a distinction between legal metrology tests and tests designed to establish the actual performance of the meters in the field, that is, the weighted error. In both cases, the criteria are completely different. For legal metrology, testing is mainly conducted to determine if the meters meet the metrological requirements at the flow rates specified by the standards. If the accuracy tests are limited to these flow rates it is extremely difficult to make a proper reconstruction of the error curve in the whole measuring range [32,36]. For this reason, and considering that the tests were conducted to establish the weighted error of the meters, the selection of flow rates had to take into consideration the need of obtaining an accurate representation of the performance at low flows [18,37–39]. This is the only scientific methodology that allows for a proper calculation of the weighted error of the meters. Considering this, the meters under analysis were tested at seven flow rates, four of which were at a flow rate equal or lower than 120 L/h. Also, both meter types underwent two slightly different sets of tests; one aimed at obtaining the initial metering performance before installation (Table 2) and the other conducted to verify the actual performance of the meters removed from the field (Tables 3–6). The main difference between both testing procedures was related to the order in which the meters were tested at the selected flow rates, the determination of the starting flow rate, and the magnitude of the largest flow rate.

### 2.4. Water Meter Sample Description

The presented work focused on two types of single-jet domestic water meters from different manufacturers (hereinafter called M\_1 and M\_2). Both types have an extra-dry register and a magnetic coupling between the turbine and the register. Other relevant technical and metrological characteristics

of these meter types are described in Table 1. The initial weighted error of both types was calculated analysing a sample of 3762 new meters: 1068 corresponded to type M\_1 and 2694 to M\_2. The accuracy tests of new meters took place between 2008 and 2014. In addition to the extensive analysis conducted to the new meters, a stratified sample of 1210 m of the same two meter types under study was taken from the field. A total of 406 m of type M\_1 and 804 m of type M\_2 with different ages and volumes were analysed. The accuracy tests of the ageing meters were conducted between 2010 and 2015. A detailed stratification of meters by type, age and totalised volume can be found in Tables 3–6. In total, the research carried out has analysed the error curves at seven flow rates of 4972 m.

**Table 1.** The technical and metrological characteristics of the meters sample.

Meter Type	Tech.	Class	Standard	Q <sub>permanent</sub> (m <sup>3</sup> /h)	Length (mm)	Sample—New Meters	Sample—Used Meters
M_1	Single-Jet	B	ISO4064:1993	1.5	115	1068	406
M_2	Single-Jet	B	ISO4064:1993	1.5	115	2694	804

### 3. Results and Discussion

#### 3.1. Error Curves

##### 3.1.1. Error Curves of New Meters

Table 2 presents the average results of the accuracy tests conducted on the sample of new meters stratified by type. Except for a few exceptions, the errors obtained for both brands fall within the maximum permissible error tolerances allowed for their metrological class [2,40]. However, M\_1 showed a poor metrological performance at the highest flow rates. This can be explained by the weakness of the magnetic coupling between the turbine and the register [16]. Some of the tested units presented an error greater than  $-60\%$  at 3000 L/h. Nonetheless, this undesirable performance at the overload flow rate had a limited practical impact on the weighted error of the meters since the amount of water consumed around this flow is almost negligible (as defined by the frequency distribution of consumption flow rates in Figure 2). In this particular case, assuming a measuring error of 0% instead of  $-3.6\%$  at 3000 L/h, the weighted error becomes 0.3% more positive.

**Table 2.** The average starting flow rate and error tolerance (%) of indication for each meter type.

Meter	Sample Size	Q <sub>start</sub> (L/h)	15 L/h	30 L/h	60 L/h	120 L/h	600 L/h	1500 L/h	3000 L/h
M_1	1068	5.3	$-8.9$	1.5	1.3	1.5	1.5	1.3	$-3.6$
M_2	2694	5.3	$-8.4$	3.3	2.7	0.9	0.8	0.6	0.5
ISO 4064 Error tolerance			N/A	$\pm 5$	$\pm 5$	$\pm 2$	$\pm 2$	$\pm 2$	$\pm 2$

The minimum flow rate of a Class B meter with a permanent flow rate of 1.5 m<sup>3</sup>/h is 30 L/h and the transitional flow rate is 120 L/h [40]. This means that for flow rates between 30 L/h and 120 L/h, the maximum permissible error is  $\pm 5\%$  and for flow rates equal or above 120 L/h, the maximum allowable error is  $\pm 2\%$ . In both cases, the average error of the sample within the measuring range, between 30 L/h and 3000 L/h, is positive except at the maximum flow rate of M\_1 when some meters had a marked underperformance. In addition, the results presented in Table 2 show that the error curve of M\_1 is slightly more positive than the error curve of M\_2.

##### 3.1.2. Error Curves of Ageing Meters

The average metering errors for different flow rates and ages are shown in Tables 3 and 4. From these tables, it is clear that at medium and high flows, 750 L/h and above, the error variation is almost negligible for meter M\_1 and small for M\_2. However, at low flows, the measuring errors

significantly increase (become more negative) with age. On the other hand, even though the starting flow rate of used meters was not tested in this study, the magnitude of the error at the lowest flow rate is negatively correlated with the value of the flow rate at which the impeller starts to move [41] and it can be used to estimate the starting flow. In other words, when meters become older, the starting flow rate is larger and the amount of water consumed below the starting flow rate rises. This implies that the rate at which the starting flow rate of a meter increases is strongly related to the rate at which the weighted error of a meter evolves with time.

**Table 3.** The average error of indication (%) of meter type M\_1 classified by age.

Age (years)	Meters Tested	15 L/h	30 L/h	60 L/h	120 L/h	750 L/h	1500 L/h	2750 L/h
1–2	79	−12.2	0.9	1.3	1.4	1.1	0.9	0.3
3–4	96	−22.3	−0.8	1.3	1.2	0.9	0.7	0.1
5–6	114	−49.1	−14.3	−4.7	−1.2	−0.4	0.3	−0.2
>7	117	−35.2	−8.1	−2.5	−0.7	−0.3	−0.4	−1.0

**Table 4.** The average error of indication (%) of meter type M\_2 classified by age.

Age (years)	Meters Tested	15 L/h	30 L/h	60 L/h	120 L/h	750 L/h	1500 L/h	2750 L/h
3	62	−73.0	−24.5	−8.1	−4.5	−1.8	−1.7	−1.4
4	37	−87.5	−39.4	−10.6	−4.3	−1.7	−1.5	−1.2
5	161	−53.0	−22.0	−8.8	−4.7	−2.3	−2.1	−1.4
6	16	−68.9	−16.3	−4.6	−3.1	−1.7	−1.2	−6.4
7	133	−53.4	−17.8	−8.0	−6.0	−3.8	−3.4	−5.4
8–9	162	−61.2	−20.8	−9.0	−5.5	−2.7	−2.3	−6.2
>10	233	−55.7	−14.6	−5.4	−3.8	−2.1	−4.0	−7.4

Additional to this analysis, the average error curves were calculated by stratifying both meter types according to their totalised volume. The resulting errors for each flow rate and totalised volume group are shown in Tables 5 and 6.

**Table 5.** The average error of indication (%) of meter type M\_1 classified by totalised volume.

Total. Volume (m <sup>3</sup> )	Meters Tested	15 L/h	30 L/h	60 L/h	120 L/h	750 L/h	1500 L/h	2750 L/h
0–500	206	−19.3	−0.5	0.7	1.3	0.8	0.7	0.1
500–1000	89	−30.6	−5.4	−0.7	0.5	0.4	0.1	−0.4
1000–2000	67	−40.8	−10.2	−3.3	−0.5	0.1	−0.2	−0.7
2000–3000	23	−69.9	−14.7	−2.5	−0.9	−0.3	−0.4	−0.8
3000–5000	14	−87.7	−44.7	−19.0	−15.2	−7.7	0.2	−1.0
>5000	7	−77.1	−42.8	−21.3	−5.9	−1.3	−1.4	−1.4

**Table 6.** The average error of indication (%) of meter type M\_2 classified by totalised volume.

Total. Volume (m <sup>3</sup> )	Meters Tested	15 L/h	30 L/h	60 L/h	120 L/h	750 L/h	1500 L/h	2750 L/h
0–500	201	−35.8	−11.4	−4.6	−2.6	0.3	0.4	−0.7
500–1000	190	−50.8	−10.9	−4.1	−2.5	−1.6	−1.2	−1.2
1000–2000	262	−64.3	−15.9	−4.0	−2.5	−1.4	−2.2	−3.9
2000–3000	106	−82.8	−32.1	−10.4	−4.5	−1.7	−2.9	−8.0
3000–5000	35	−94.4	−65.8	−26.9	−12.6	−3.9	−3.7	−20.5
>5000	10	−97.6	−62.7	−29.4	−15.0	−4.5	−11.8	−21.4

The errors obtained manifestly show that metrological performance degradation is more pronounced at low flows where single-jet meters have a strong tendency to under-register water consumption. At medium and high flows, 750 L/h and above, the average errors remain quite stable, especially for meter type M\_1. The reason for this is that a number of units, 14 out of 406 of meter type M\_1 and 40 out of 804 of meter type M\_2, showed an over-registration greater than +3% at flows 750 L/h and above. Moreover, three meters of each type presented an error of indication greater than +10%. This tendency of some single-jet meters to over-register water consumption under specific conditions has been reported by References [42,43] and partly compensates the negative errors that may appear in some units.

Finally, it was observed that the strength of the magnetic coupling of the older units of meter type M\_2 (more than 5 years old) has significantly degraded and there is some slipping between the impeller and the register at high flows (Tables 4 and 6). This behaviour can be easily identified in meters being more than 6 years old and having a large totalised volume, more than 3000 m<sup>3</sup>. The breakage of the magnetic coupling at high flows can produce a significant under-registration when measuring the water consumption of large water consumers. However, this is not significant for the type of domestic customer present in the water supply area (apartment located in residential buildings) which sporadically consumes water above 2000 L/h as shown in Figure 2.

### 3.2. Weighted Error of New Meters

The data obtained from the accuracy tests of the meters cannot be properly used unless the errors are combined with the associated consumption flow rates of the users (Figure 2) to calculate the weighted error. This indicator can be used as the initial reference to derive the degradation rate of the accuracy as a function of age or the totalised volume.

For both meter types and the used frequency distribution function of the consumption flow rates (Figure 2), the initial weighted error of the tested meters is close to −4%. This means that a newly installed single-jet water meter, of the tested types, is capable of registering approximately 96 out of 100 L consumed. This conclusion is in line with the results obtained from other researchers and clashes with the preconceived idea of some utility managers that a brand new meter can register 100% of the water consumed by the customers [23,25]. The inability of the meters studied to measure 100% of the water consumed by domestic users is mainly due to their limited performance at low flows. The starting flow rate, in both cases around 5 L/h (Table 2), is the threshold below which the meters do not register any consumption, that is, have a measuring error of −100%. Above this flow rate, the errors are negative and rapidly increase to values close to −5%. Measuring errors of the meters for flow rates above 30 L/h are close to 0% and produce a limited impact on the weighted error. More precisely, the initial weighted error obtained for M\_1 was −3.5% while for M\_2 the resulting weighted error was −3.9%. As expected, the differences in weighted errors between them are almost negligible and mainly driven by the slightly more positive error curve of M\_1.

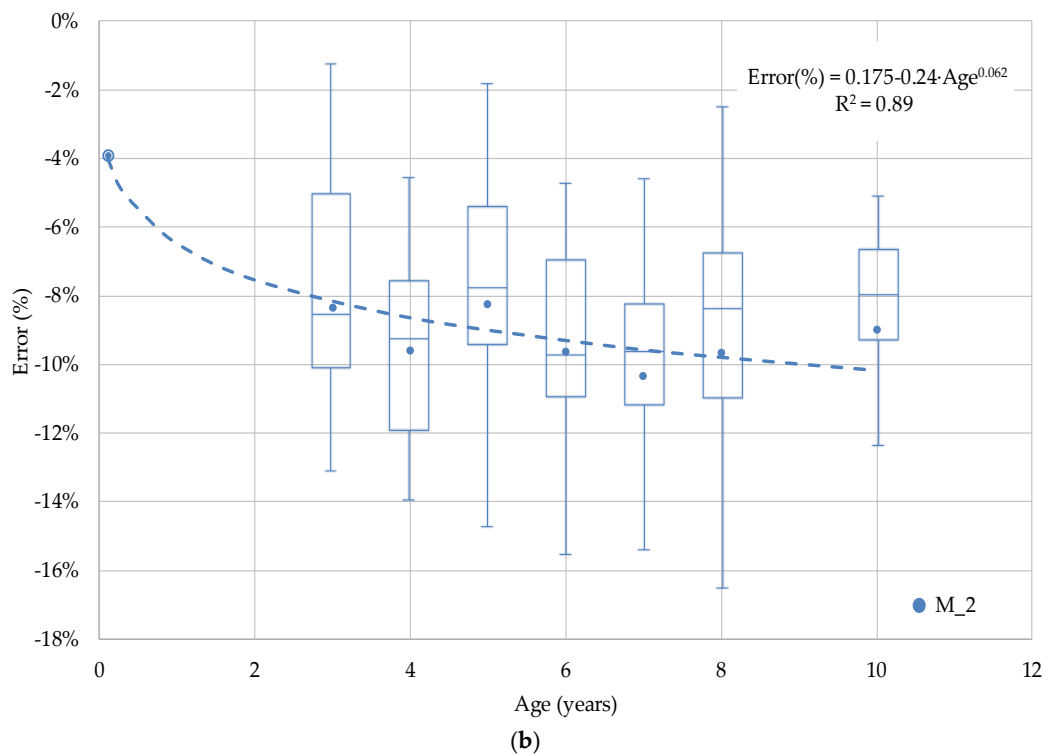
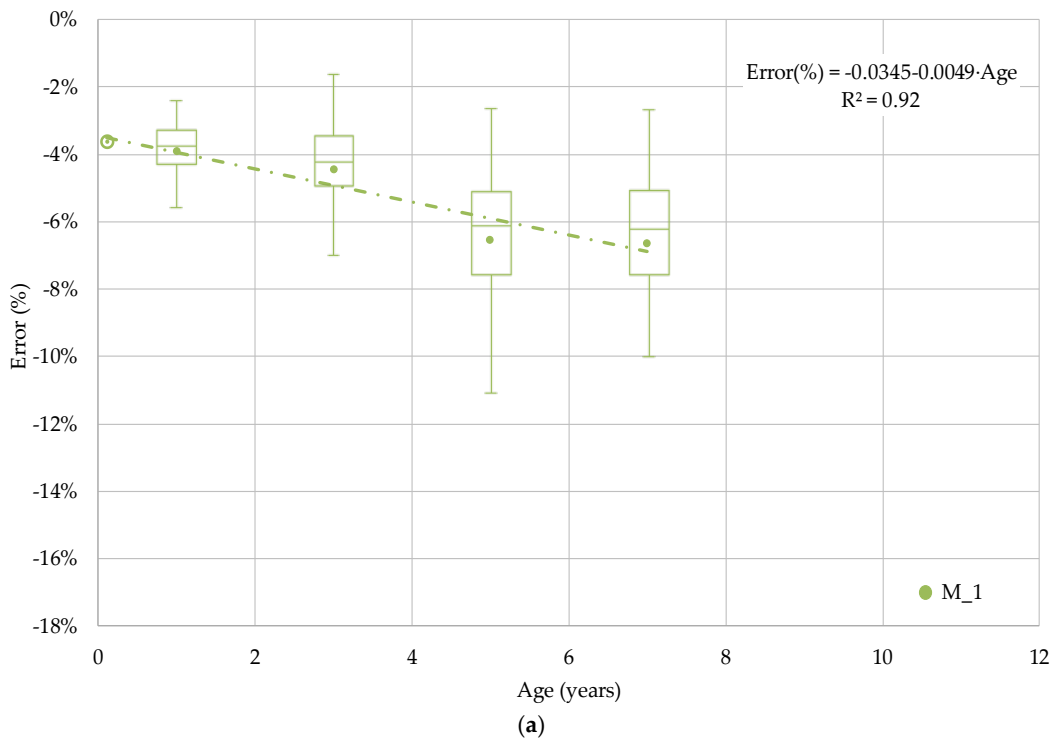
Following this calculation, the analysis described in the succeeding subsections refers to the evolution of the calculated weighted errors with age, totalised volume, or both parameters simultaneously.

### 3.3. Degradation Rate of the Weighted Error

#### 3.3.1. Degradation Rate with Age

Figure 3 shows the degradation rate of the weighted error for both types against age. The number of meters tested of each one by age group is shown in Tables 3 and 4.





**Figure 3.** The degradation rate of the weighted error with age: (a) meter M\_1; (b) meter M\_2.

Frequently, previous studies on meter degradation consider that the weighted error of domestic meters degrades linearly from an initial value [16,23,25,28,44,45]. Conversely, from the results presented in Figure 3, it is not obvious that a linear trend adequately represents the evolution of the weighted error with time. In the particular case of M\_2, it seems that there is a quick initial degradation rate and after a few years, the weighted error tends to evolve at a much slower rate or even remain constant. On the contrary, the behaviour of meter type M\_1 can be accurately described by

a linear trend. In any case, from this graph, it is obvious that the measuring performance of meter M\_2 is worse than the one obtained for M\_1 at any age (except for brand new meters when the performance of both types are quite similar).

Additionally, when analysing the results presented in Figure 3, it should be noted that even though all units belonging to a specific meter type are considered to be the same, they can show significant manufacturing changes over time, not visible from the outside, that may have caused considerable behaviour discrepancies. At the time the study was conducted, more detailed information about these potential manufacturing changes was not available.

Overall, a regression model in the following form can describe how the weighted error, W. Error (%), evolves with age:

$$W.Error (\%) = E_0(\%) + A \cdot Age^B \tag{1}$$

where age is expressed in years,  $E_0(\%)$  is the initial error, and the parameters A and B can be obtained by a regression analysis of the data. In the particular case of the linear regression commonly used by other authors in References [4,5,16,44], the parameter B would adopt a value of 1.

### 3.3.2. Degradation Rate with Totalised Volume

Figure 4 presents the weighted error trends of both meter types with respect the totalised volume. In this case, the  $R^2$  coefficients obtained are closer to 1 and the models proposed better explain the variability of the results. For both meter types, the mathematical regression that provided the best fitting to the data was not linear. Similarly, to what has been observed with the age of the meters, the average rate at which the meters degrades slow down as the meters register more water. Additionally, in this graph, it can be observed that the average performance of meter type M\_2 is significantly worse than for M\_1 for any totalised volume. This reinforces the idea that the initial error is not an appropriate parameter to select the most profitable water meter for the utility.

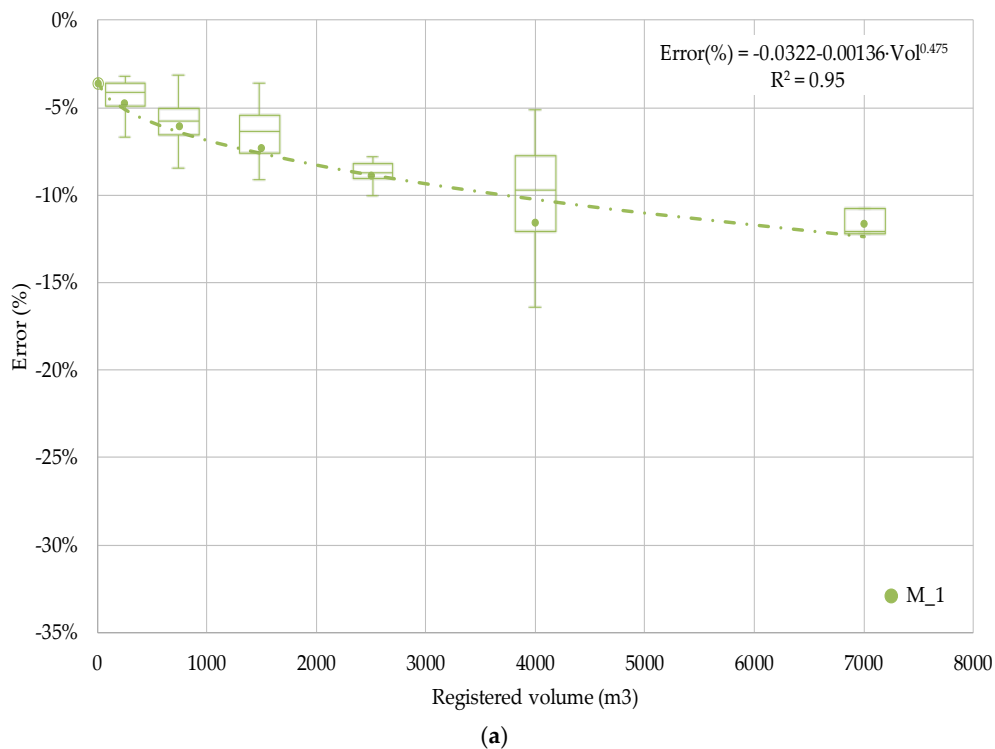
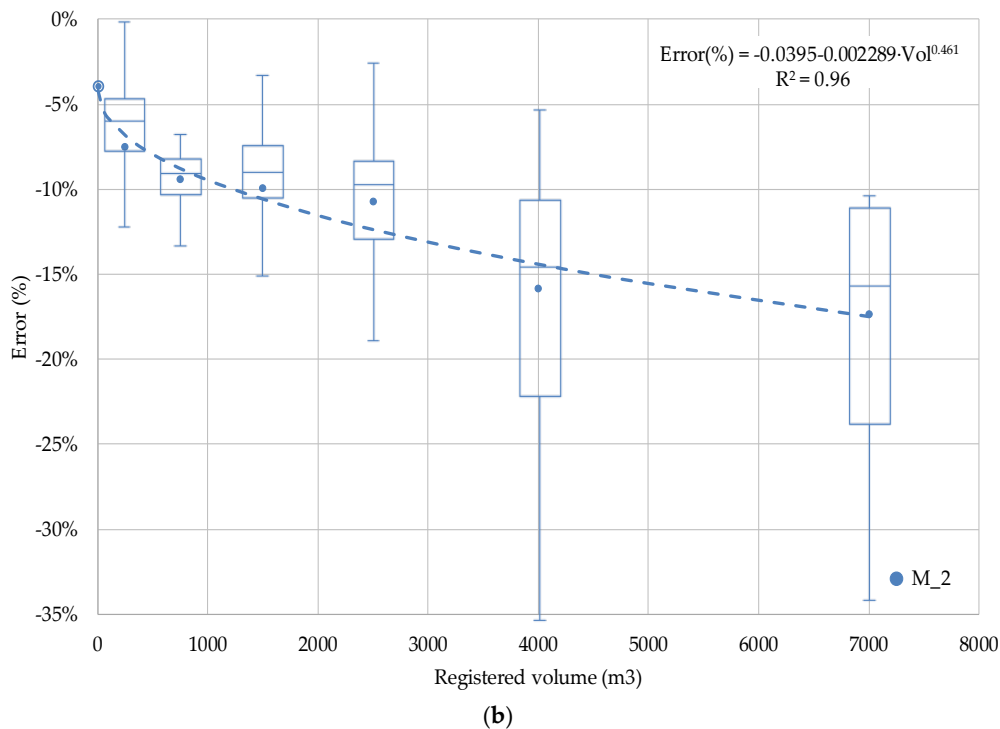


Figure 4. Cont.



**Figure 4.** The degradation rate of the weighted error with totalised volume: (a) meter M\_1; (b) meter M\_2.

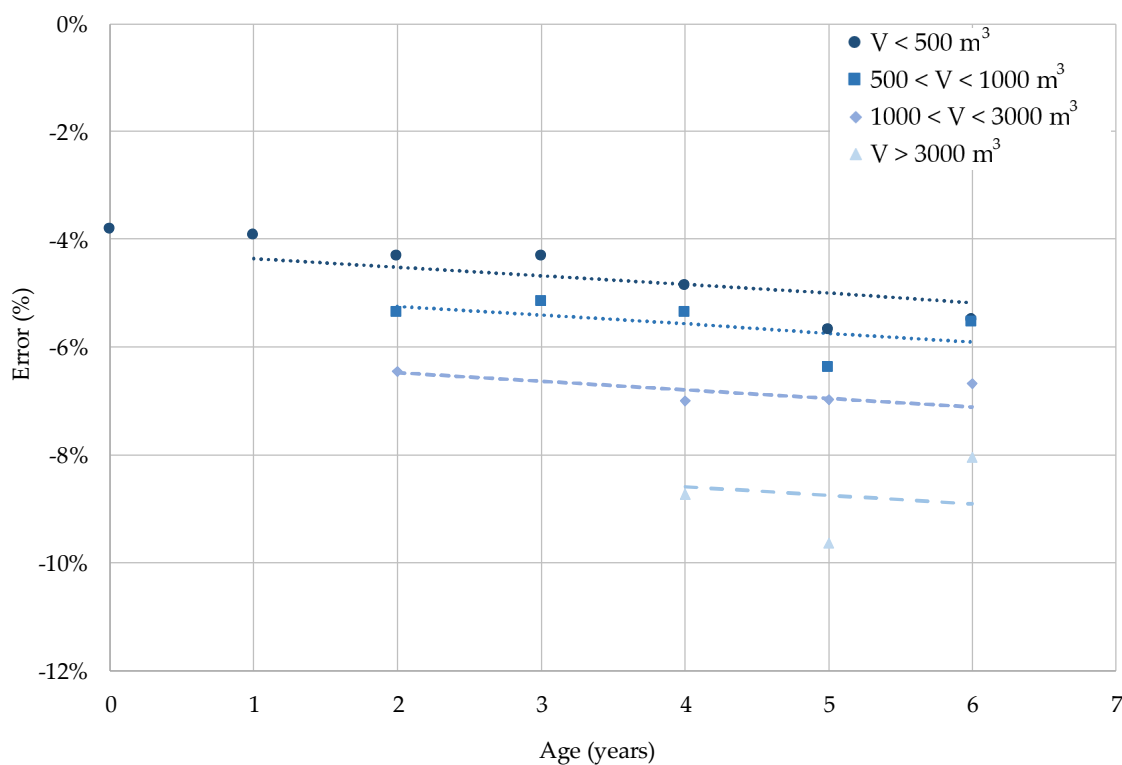
From the above, it has been concluded that a regression model in the form of

$$\text{Error}(\%) = E_0(\%) + A \cdot \text{Volume}^B \tag{2}$$

which can describe how the weighted error is related to the totalised volume of the meters (expressed in cubic meters).

### 3.3.3. Degradation Rate with Age and Totalised Volume

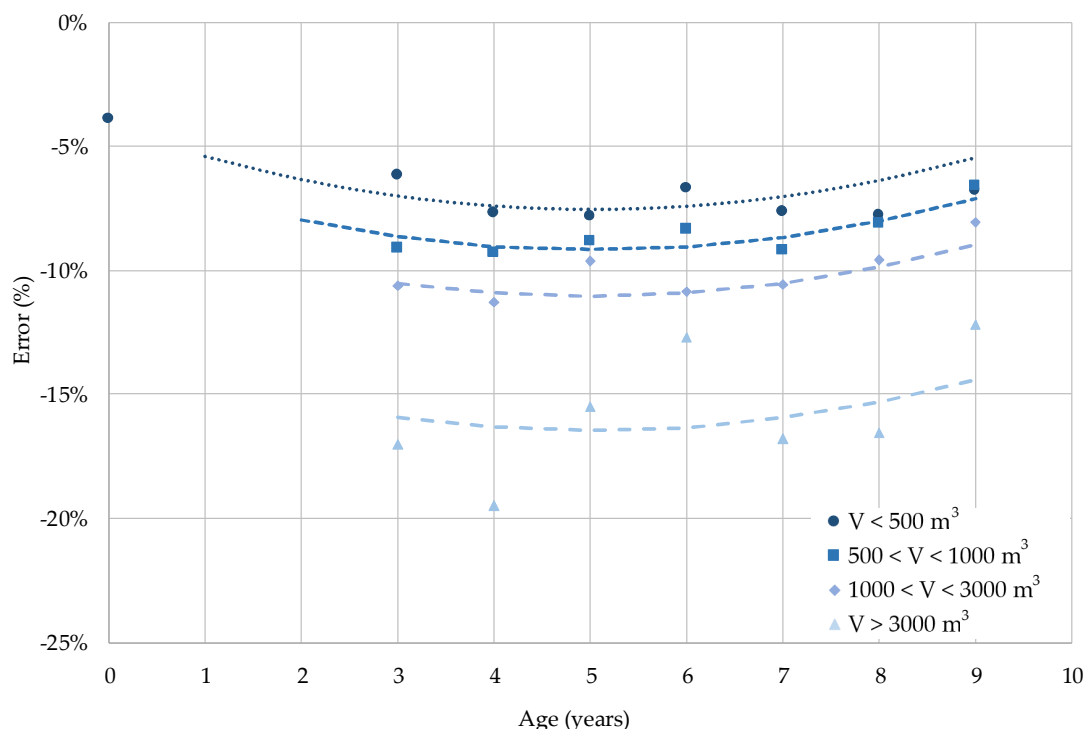
Figure 5 shows the weighted error plotted against age and totalised volume for meter type M\_1. This figure allows for a better understanding of how age and totalised volume can affect the weighted error of a particular meter type. As can be seen, the dispersion of the error increases with the age and totalised volume of the meters. The overall tendency is that the meter error becomes more negative with both age and totalised volume. In the case of M\_1, it was found that a linear regression could represent the degradation of the weighted errors with age for all the totalised volume ranges.



**Figure 5.** The degradation rate of the weighted error with age and totalised volume (meter M\_1).

A similar analysis was conducted for meter type M\_2. For this meter type, the sample size was larger (Table 1) and the evolution of the error with age and totalised volume did not follow a linear trend (Figure 6). For M\_2 it was observed that older meters (more than 6 years old), independently of the totalised volume group, have slightly more positive errors than meters being between 2 and 5 years of age. This behaviour can be explained by the working principle of single-jet meters. Some of these meters have a slight tendency to over-register water consumption with the appearance of moderate calcium depositions [16,46]. Generally speaking, these depositions grow as meters become older but there are other parameters that can affect how fast they evolve, such as water quality, brass composition, working conditions, and so forth.

Consequently, this particular single-jet meter type seems to have a tendency to slightly improve its overall performance as it becomes older. In any case, the weighted error is considerably larger, for any age and totalised volume range, than for meter type M\_1. In addition, it should be remarked that the oldest meter tested of M\_1 type was only 7 years old and the improvement of meter type M\_2 only became significant after this age.



**Figure 6.** The degradation rate of the weighted error with age and totalised volume (meter M\_2).

### 3.3.4. Mathematical Degradation Model

A combined mathematical model that simultaneously takes into account age and totalised volume can be built using the results of the weighted error calculations made for the two meter types. The proposed degradation model should account simultaneously for both effects while maintaining a relative simplicity that makes it usable in practice. For this reason, the proposed non-linear combined degradation model adds (1) the initial weighted error of the meter type,  $E_0(\%)$ , (2) a polynomial term accounting for the error due to age, and (3) a term accounting for the supplementary error due to the totalised volume. This theoretical model can be mathematically written in the following form:

$$\text{Error (\%)} = E_0(\%) + A \cdot \text{Age} + B \cdot \text{Age}^2 + C \cdot \text{Volume}^D \tag{3}$$

where the age is expressed in years, the totalised volume in cubic meters and the parameters—A, B, C and D—can be obtained by conducting a non-linear regression of the available data (Statgraphics 9.0). A reliable figure for the initial error of the meter type,  $E_0(\%)$ , can be derived from the results of the quality control tests conducted on new meters prior to installation. The regression parameters obtained for the two meter types under study are detailed in Table 7.

**Table 7.** The regression parameters values of the proposed equation for the two meter types under study.

Parameter	Meter M_1	Meter M_2
$E_0$	-3.49	-3.91
A	-0.152	-1.313
B	-0.00149	0.131
C	-0.0174	-0.00291
D	0.657	0.959

Figures 7 and 8 present the expected evolution of the weighted error of both meter types, according to the degradation models obtained from the tests, for different ages and annual consumption rates.

For example, from Table 7 and Equation (3) it is possible to obtain the estimated error of a meter M\_1 or M\_2 being 6 years old and measuring water consumption of a customer using an average of 250 m<sup>3</sup>/year. In this case, the totalised volume after 6 years would be 1500 m<sup>3</sup> and the resulting weighted errors are -6.6% for meter type M\_1 and -10.3% for meter type M\_2. The same results can be obtained using Figures 7 and 8.

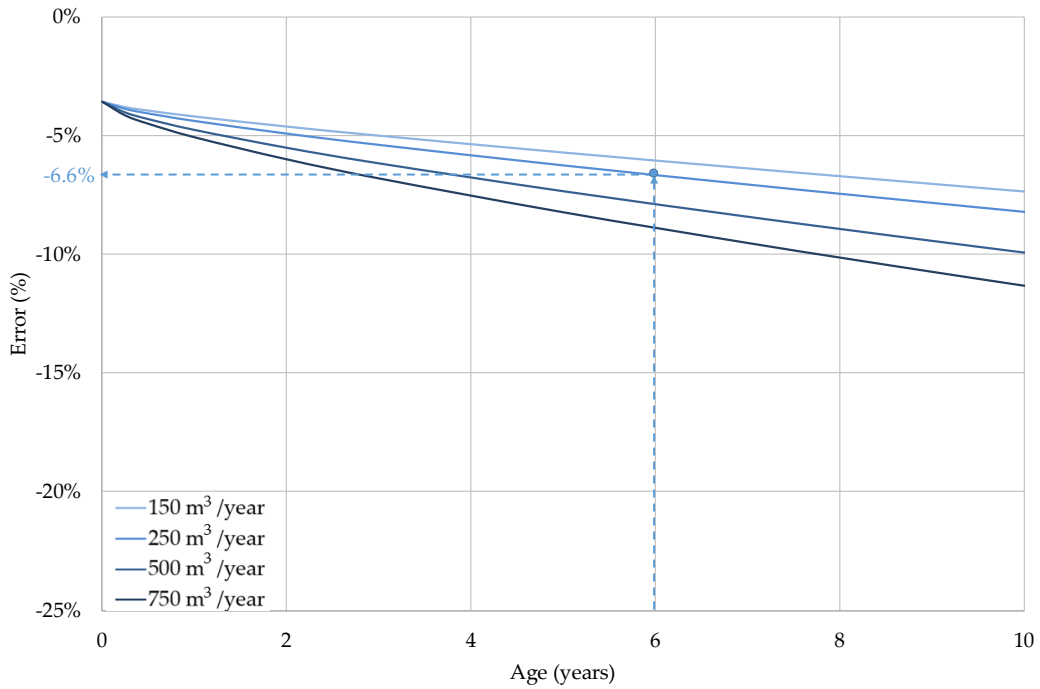


Figure 7. The degradation of the weighted error with age for different annual consumption rates (meter M\_1).

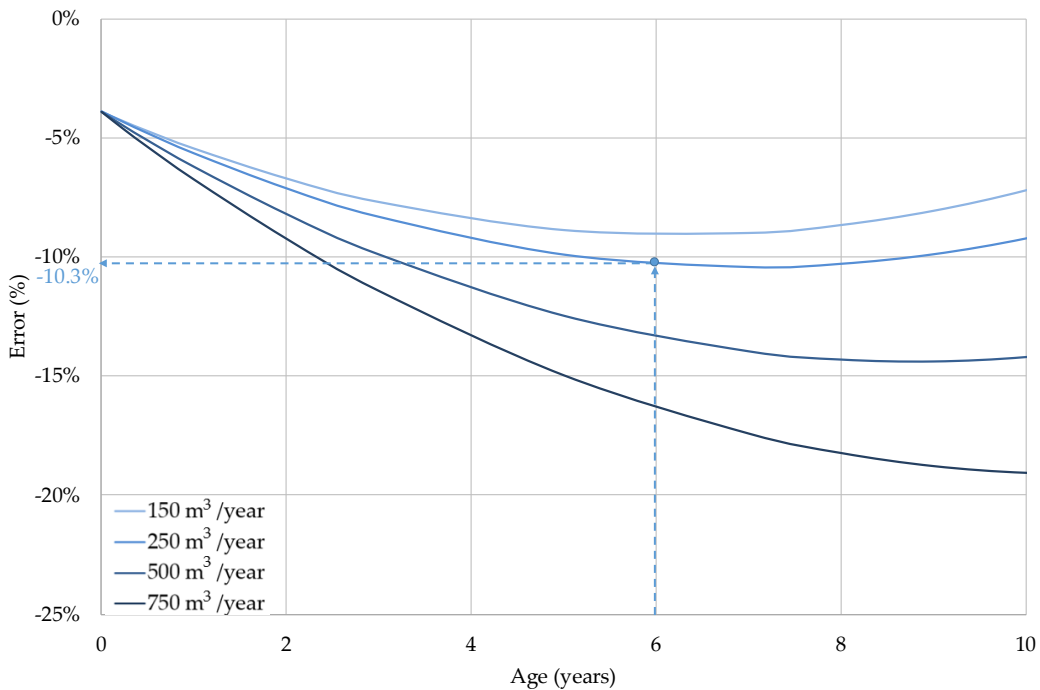


Figure 8. The degradation of the weighted error with age for different annual consumption rates (meter M\_2).

Table 8 compares the weighted errors, calculated for meters of being 6 years old, using the three degradation models proposed. The improvement in the estimation of the weighted error derived from using a combined multivariate model, in comparison with simpler univariate models, is more significant for M\_2 than for M\_1. The reason for this can be found in the fact that totalised volume seems to have a more limited effect on M\_1 (Figure 5 versus Figure 6). Also, the results obtained from the model using the totalised volume are significantly closer to the ones calculated from the multivariate model than the ones derived from the model using age as the driver for the weighted error degradation.

**Table 8.** The comparison of the three degradation models proposed for meters being 6 years old.

Model	Meter M_1 Totalised Volume			Meter M_2 Totalised Volume		
	900 m <sup>3</sup>	1500 m <sup>3</sup>	4500 m <sup>3</sup>	900 m <sup>3</sup>	1500 m <sup>3</sup>	4500 m <sup>3</sup>
Age	−6.4%	−6.4%	−6.4%	−9.3%	−9.3%	−9.3%
Totalised volume	−6.7%	−7.6%	−10.6%	−9.2%	−10.6%	−15.0%
Age & Totalised volume	−6.0%	−6.6%	−8.6%	−9.0%	−10.3%	−16.3%

#### 4. Conclusions

This paper describes the results obtained from a work that was conducted during the past years in coordination with a water utility in Spain. The purpose of the study was to obtain the real degradation rates of the weighted error for two types of single-jet domestic water meters that are being used by FACSA in several water distribution systems and shows if a procurement selection procedure should not be mainly based on the initial errors of the meters.

The analysis of the weighted error of the meters tested shows that the usual assumption, which considers a linear degradation with age or totalised volume, is only acceptable in some cases. In other cases, like for one of the meters under study, this simplification is not acceptable. This work proposes a modified regression model to estimate more accurately the evolution of the weighted error with age and totalised volume as single drivers.

Another frequent simplification when estimating the measuring error of installed meters is to carry out a univariate regression analysis, using age or totalised volume, of the degradation of the weighted error. These models consider only one variable as the drivers of the weighted error. However, univariate regression models may not be accurate enough to establish the real performance of ageing meters. For example, a degradation model that only takes into account age will provide the exact same estimation for the weighted error of meters installed in customers with different consumption rates. However, the presented work has found that there are significant differences in the weighted error of meters having the same age and different totalised volume.

To improve the estimation of the actual performance of the meters this paper has presented a multivariate analysis of the weighted error degradation rates. The aim is to quantify the combined effect of age and totalised volume on the weighted error of the meters. For this purpose, a non-linear model—applicable to the meter types under analysis—that takes into account the initial error of the meters and the simultaneous impact of age and totalised volume has been derived. The proposed degradation model calculates more accurately the weighted error of the meters measuring the consumption of those customers having extremely low or large consumption rates.

It has been found that, for the meters under study, the differences between the proposed multivariate model and the model using the totalised volume are smaller than the ones found for the model using the age of the meters as the driver for the weighted error degradation. Following this, it can be concluded that for the meters analysed, the totalised volume can provide a better approximation than age.

Finally, it is important to highlight that the results obtained for the particular meter types tested cannot be extrapolated to other water utilities as the parameters that may affect the weighted error of ageing meters may differ from those present in the water supply studied. In addition, in order to obtain an accurate approximation of the measuring errors of installed meters, all meter types need to be tested and analysed. Two meter types can behave completely different in a specific water system and the same meter type can present dissimilar ageing processes in two different water systems.

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