

## Evaluation of domestic water measurement error: a case study


Andrés A. Mendoza and Holger Benavides-Muñoz 

### ABSTRACT

This study presents a method to determine the operation of the measuring equipment by analyzing the metrological quality and degradation of accuracy, depending on the accumulated volume and the installation time. Different types of counters at three flow rates were tested to assess the evolution of the relative error and to determine the average error curves and rate of deterioration. The volume of apparent losses caused by the inaccuracies of the meters was also calculated. The results of the investigation establish the sub-accounting errors and the annual degradation rate were  $-15$  and  $-1.88\%$ , respectively for consumption flows below 30 L/h represented by 23% of the subscribers. For flow rates of 120 L/h, the system accounts for a 68% consumption of subscribers and an error of  $-1.8\%$  and a degradation of  $-0.14\%$  were recorded. Finally, for consumption flows of 1,500 L/h, the system has accounted for 9% consumption of the subscribers; over-accounting values were obtained generating an average error of 16% and a degradation of 1.68%. It is concluded that the hydrometric district has a sub-accounting error equal to  $-3.24\%$ , which results in a volume of apparent losses of  $1.21 \text{ m}^3/\text{connection}/\text{month}$ .

**Key words** | apparent losses, domestic water meter, sub-accounting, water meter accuracy, water meter degradation

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### HIGHLIGHT

- This paper proposes a methodology that allows determining the operation of the domestic water meter by analyzing the metrological quality and degradation of accuracy, specifically by the statistical calculation of the weighted measurement error, the annual degradation and the volume of apparent losses of the domiciliary meters installed in urban areas, using a hydraulic bench test.

### INTRODUCTION

Domestic water meters decrease their measurement efficiency over time, affecting sustainability in household water measurement management (Hernández 2018). There are two kinds of error in these meters: the sub-accounting

that generates economic losses for the company for not invoicing a certain volume of water consumed, and the over-accounting that implies a charge higher than the volume actually consumed by the users. These errors in the measurement are given by factors of quality and age of the meters, thus generating uncounted water (Arregui *et al.* 2018). The economic losses due to these errors are important to estimate the reduction of losses. The reduction of losses allows for a better management of the service, reduction

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in the apparent losses of water and in the obtainment of a greater scope of coverage (Arregui *et al.* 2003).

Domestic water meters are the instrument through which municipal water companies control the volume consumed (Szilveszter *et al.* 2015). A permanent control of the metrological quality of these devices will guarantee the sustainability and efficiency of the management of the supply system, that is why determining the deterioration over time and performance based on their accumulated volume will allow acting to make the substitution on time and not to wait for the accountants to fail completely to make the changes (Moahloli *et al.* 2019).

Several investigations have been done to estimate apparent water losses in recent years. Ncube & Taigbenu (2019) assessed the apparent losses caused by the inaccuracy of the water meters, by making a comparison between the traditional method, to determine by evaluating consumption patterns and laboratory tests with a hydraulic bench, and the billing analysis method. Moahloli *et al.* (2019) investigated the optimal period for the replacement of water meters to minimize the loss of income from water. Palau *et al.* (2018) analyzed the influence of time on the measurement error of water meters to assess the deterioration of the equipment.

Arregui *et al.* (2018) studied three models: non-linear degradation from age, totalized volume or both parameters simultaneously; furthermore, Arregui *et al.* (2015) presented an evaluation of the real loss taking into account the consumption characteristics of domestic users. In Ecuador, Szilveszter *et al.* (2015) analyzed the behavior of domiciliary meters in Ibarra city, where they determined the error curve based on the model according to the manufacturer and the totalized volume.

The objective of this research is to propose a methodology that allows determining the weighted measurement error, the annual degradation and the volume of apparent losses of the domiciliary meters installed in urban areas, making the metrological behavior of the water meters prevalent by the statistical calculation of the global error by using a hydraulic bench.

## METHODOLOGY

The methodology, proposed for the estimation of the measurement error and the temporary degradation of

water meters, includes the characterization of the following aspects.

### Selection of test flows

According to Hernández (2018) to select the flow rates of the test, it is necessary to know the different consumption flows that are taken into account in the error curve of the meters; for this reason, the following regulations were met: (a) the standard international ISO 4064-1 (2014), (b) the international recommendation OIML R49-2 (2013) and (c) the Ecuadorian Technical Standard NTE INEN-OIML R49-1 (2009).

### Sample error calculation

Mantilla *et al.* (2018), Palau *et al.* (2018), Ethem Karadirek (2019) and Moahloli *et al.* (2019) define the relative error of the accuracy in the measurement of the domestic meter as the difference between the volume of water recorded by the device and the corresponding test volume that is calculated by the following equation established in ISO 4064-1 (2014):

$$\varepsilon = \left( \frac{(V_f - V_i) - V_r}{V_r} \right) \times 100 \quad (1)$$

where  $\varepsilon$  is the relative error (%);  $V_f$ , volume after the test ( $\text{m}^3$ );  $V_i$ , initial volume ( $\text{m}^3$ ); and  $V_r$ , volume accumulated by the tank ( $\text{m}^3$ ). Therefore, the counter sub-accounting is indicated with a negative error and over-accounting with a positive error (Mantilla *et al.* 2018). Weighted errors have been obtained for a frequency distribution based on the consumption flow rates extracted from a sample of domestic customers. The calculation of the weighted error uses the procedure described in Arregui *et al.* (2006).

### Relative error curve

The error curve of the meters determines the evolution of the precision and the behavior of the measurement at different flows (Arregui *et al.* 2015). As Arregui *et al.* (2018) stated, for very low flow rates between 0 and 15 L/h, the meter does not register consumption because the turbine starts its

proper operation from a certain determined flow rate as the starting flow. Because of this, there is a sub-accounting error of  $-40\%$  that occurs with the starting flow. As the flow increases ( $15\text{--}30\text{ L/h}$ ), the error decreases until positive values are reached with the minimum flow, where an error of  $\pm 5\%$  is expected. Continuing with the increase in flow ( $30\text{--}120\text{ L/h}$ ), the error decreases until it stabilizes in the transient flow with an error of  $\pm 2\%$ . This error remains uniform with small variations until reaching the permanent flow ( $120\text{--}1,500\text{ L/h}$ ). Therefore, for the measurement error of multi-jet water meters with a metrological class model B and diameter of  $15\text{ mm}$ , the permissible measurement error of  $5\%$  in the lower flow range (minimum flow) and  $2\%$  in the upper flow range (transient and permanent flow) are allowed according to [ISO 4064-1 \(2014\)](#) ([Szilveszter et al. 2015](#); [Palau et al. 2018](#)).

### Degradation of the counters

It is the rate of deterioration of the domestic water meter and the increase in measurement error during the operation time ([Hernández 2018](#)). [Mbabazi et al. \(2015\)](#) estimated the degradation of the accuracy of the meters by assessing the evolution of the volume measured against the meter's age and by assuming a linear regression analysis to predict the degradation rate of the accuracy of the counter due to its simplicity and low cost, as expressed in the following equation:

$$D = \frac{\varepsilon}{A} \quad (2)$$

where  $D$  is the degradation of domestic water ( $\%/year$ ) and  $\varepsilon$ , relative counter error, is the measurement error found by the test in the hydraulic bench ( $\%$ ).  $A$ , age, is the estimate that is made by the ratio in the totalized volume in the meter until the date of analysis and the average annual consumption of the meter ([Hernández 2018](#)), this value is provided by the following equation:

$$A = \frac{V_i}{A_c} \quad (3)$$

where  $A$  is the average age of the domestic counter (years);  $V_i$ , initial volume, is the amount of water registered in counter

in units of volume in the meter at the date of the test ( $m^3$ ); this value is provided by Equation (1);  $A_c$ , annual consumption, is the annual record of consumption on each counter, provided by the supplying entity ( $m^3/year$ ) ([Hernández 2018](#)). The speed, at which the domestic meter degrades over time or with volume, is an essential component of any economic calculation and plays a fundamental role in the time to perform the substitution ([Arregui et al. 2018](#)).

### Volume of apparent loss

According to [Moahloli et al. \(2019\)](#), stratified mean volumes were used to determine the volume of apparent loss taking into account the relative measurement errors of the whole sample in relation to the meter's age and total recorded volume:

$$V_{al} = V_m \times E_w \quad (4)$$

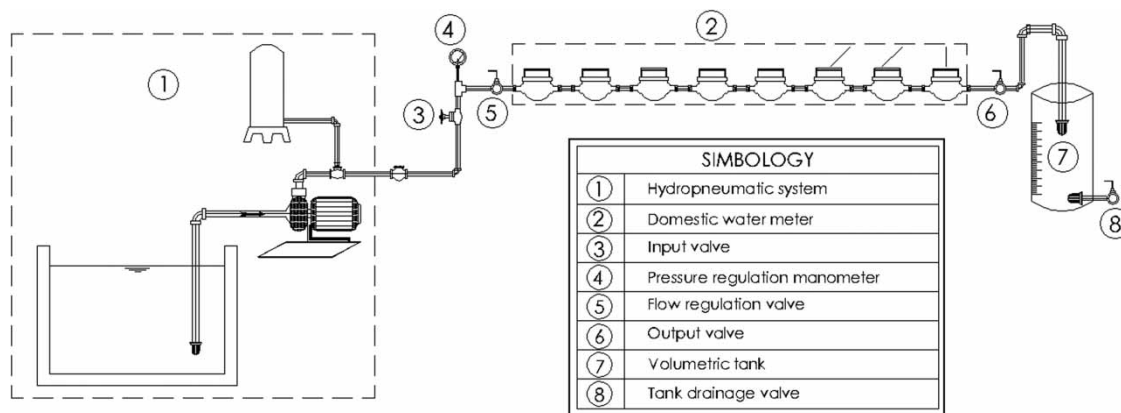
where  $V_{al}$ , volume of apparent loss of counter ( $m^3/month/connection$ );  $V_m$ , average volume consumed by a user in a month ( $m^3/month$ ) obtained from the UMAPAL measurement registry;  $E_w$ , weighted error ( $\%$ ) value of the error taking into account the rate of flows tested and the consumption rate of counter, view [Table 1](#) ([Arregui et al. 2011](#); [Moahloli et al. 2019](#)).

### Hydraulic bench

The metrological behavior of household meters is analyzed by the liquid collection method by the use of a hydraulic test bench, according to [OIML R49-2 \(2013\)](#) and [ISO 4064-1 \(2014\)](#) ([Szilveszter et al. 2015](#); [Mantilla et al. 2018](#); [Palau et al. 2018](#); [Ethem Karadirek 2019](#); [Ncube & Taigbenu 2019](#)). The tests were performed by taking readings with the counters at rest (start/stop test method) according to [Arregui et al. \(2015\)](#). The test procedure is based on the comparison of the volume of the  $200\text{ L}$  calibrated tank (actual volume) with the volume measured by the water meters (indicated volume) ([Arregui et al. 2018](#)), to determine the actual volume that circulates through the meters with a certain flow and time of registration. [Figure 1](#) shows the components of the hydraulic bench ([UMAPAL 2019](#)).

**Table 1** | Weighted error ( $E_w$ ), taking into account the relative error of the meter and the consumption rate

Brands	Sample U	Age		Volume		30 L/h %	120 L/h %	1,500 L/h %	$E_w$ %
		min	max	min	max				
M1	19	2	21	1,072	8,519	-14.57	-0.55	16.25	-2.26
M2	4	1	3	57	1,594	-5.06	-0.57	1.84	-1.38
M3	12	2	22	1,052	9,619	-13.78	-1.15	14.32	-2.66
M4	11	4	24	1,876	9,454	-15.61	-1.34	17.48	-2.92
M5	5	3	11	1,612	6,466	-12.37	0.58	13.54	-1.23
M6	3	13	16	5,137	8,891	-21.13	-7.36	23.16	-7.77
M7	10	8	24	3,083	13,581	-21.36	-2.15	21.63	-4.43
<b>Global weighted error</b>						<b>-14.84</b>	<b>-1.79</b>	<b>15.46</b>	<b>-3.24</b>

**Figure 1** | Simplified scheme of the hydraulic test bench.

To determine the error of the meters, the volume recorded before the test and the actual volume that circulates through the circuit after it, were compared. For this purpose, reference standards were used: flow meters, pressure gauges and a tank with a graduated scale that allow the volume to be determined accurately.

### Experimental design and methodological proposal case study

This research was applied in Loja city (latitude 4°S and longitude 79°W) located in the south of Ecuador, and it has an altitude of 2,100 m above sea level. 'Ruta 46' Hydro-metric District is located in the San Sebastián parish, to the south-east of the city, supplying water to the Zamora Huayco, Las Minas and Estancia citadels. The study area

covers 653 subscribers who have residential category consumption.

### Sampling of domestic water meter accountants

The models of counters that exist in the study area are multi-jet turbine with a nominal diameter of 15 mm, type B class. The main elements of the meter structure are a totalizer, a turbine, the distribution chamber with various openings where water enters and two filters for suspended solids and sediments (Palau 2005). The counters were grouped to facilitate the representation of the average error curve according to the following technical considerations: *Accumulated volume*, to evaluate the meters that have the same totalized volume characteristics were grouped into volume ranges with increments every 1,000 m<sup>3</sup>. *Age*,

counters were classified into six groups, up to 3, 6, 9, 13, 16 and 24 years. To estimate the duration of the meters, the department of UMAPAL (2019) provided information on the cadastre of readings of several months of the hydrometric district under study on the basis of which annual consumption averages were established. Brands, seven different marks were obtained in the sampling of the water meters; they are represented with the following abbreviations: M1, M2, M3, M4, M5, M6 and M7.

### Consumption pattern

Water meters operate with varying flow rates due to temporary changes in water consumption, depending on consumption habits and the climate of the area (Szilveszter *et al.* 2015; Ethem Karadirek 2019). The water consumption pattern represents the frequency distribution of consumption flows, which is constructed as a histogram that stratifies water consumption into various flow ranges (Arregui *et al.* 2006, 2018). The analysis in this study uses a frequency distribution of consumption flows (Figure 2) extracted from 'Route 46' Hydrometric District of one of the water supply systems managed by UMAPAL (2019).

The subscribers' consumption will allow establishing the flow rate range that is most likely to influence the overall system error. For this, the flows tested in the test bench are taken into account and the two variables are related, (i) the percentage of consumption and (ii) the average error in the said consumption (Moahloli *et al.* 2019). The frequency distribution obtained from Figure 2 shows a volume consumed of 23% for flow rates below 30 L/h, for flow rates that reach the transition of 120 L/h, the highest consumption amounts to 68%. Finally, because it is considered a household consumption, the amount of water consumed up to the permanent flow of 1,500 L/h is only 9%.

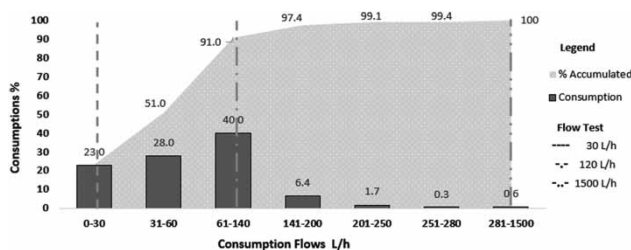


Figure 2 | Evolution of consumption in the Hydrometric District Route 46 (UMAPAL 2019).

## RESULTS AND DISCUSSION

Sixty-four meters was analyzed, representing 10% of the subscribers in the study area. From the statistical analysis, it was determined that the data have a polynomial distribution with values of sub-accounting and over-accounting errors; therefore, the mean was selected to represent the central location of the relative error of the meter (Moahloli *et al.* 2019).

This study found that the relative error of the household counter in the study area has a tendency to sub-accounting with the increase of the totalized volume and the years of operation of the measuring instrument (Table 1). Arregui *et al.* (2015); Ncube & Taigbenu (2015, 2019); Ethem Karadirek (2019) and Moahloli *et al.* (2019) also observed a similar pattern. Studies conducted by Arregui *et al.* (2007) and Fontanazza *et al.* (2013) have shown that the wear of moving parts has a greater impact on the error at low flow rates. Otherwise, the permanent flow (1,500 L/h) tends toward over-accounting values, according to Arregui *et al.* (2018) the reduction of the water passage sections and the accumulation of sediments on the inner surface of the turbine chamber are the main causes of the over-accounting error in the water meters.

Figure 3 shows the variation of the average error of the domestic water meters based on the totalized volume; the polynomial trend line showed a low correlation in the values obtained ( $R^2 = 0.427$ ), due to the negative errors that present at a higher totalized volume, which generates an inclination toward sub-accounting values because the meters have more accumulated volume and more operating time.

The average errors of the water meters were stratified according to the total volume registered in  $m^3$ , the operating

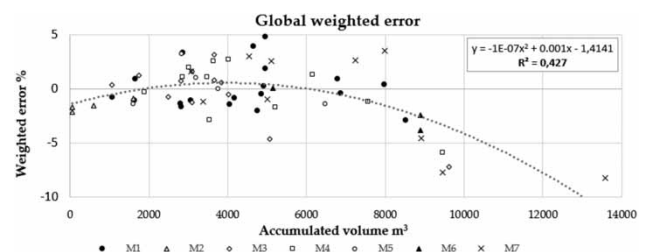
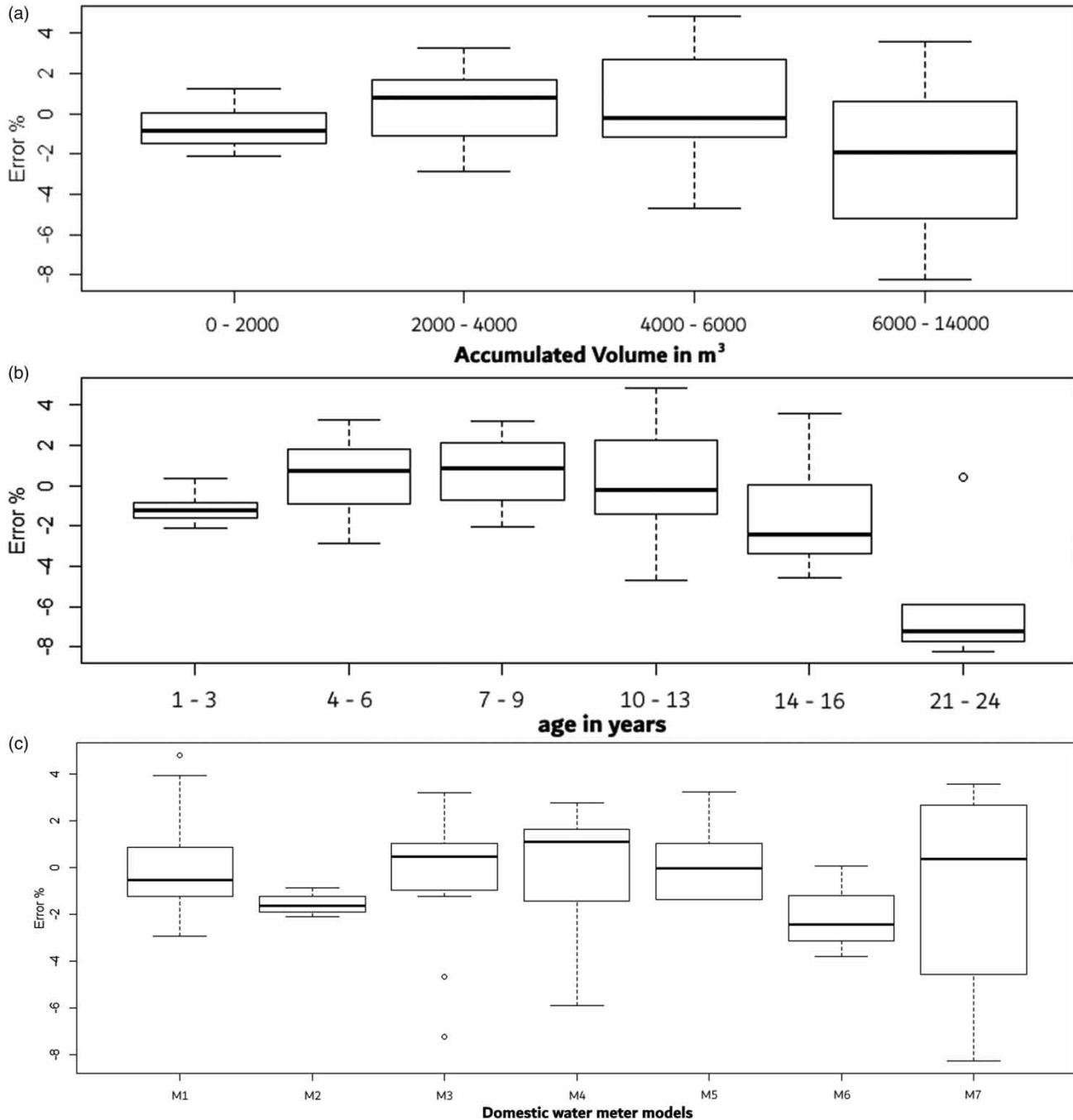


Figure 3 | Global average error according to the totalized volume and the model of the domestic counters.

age in years and brands of manufacturers, as shown in Figure 4; this was estimated to determine the effect on the relative error of the meter and determine trends during the operating time of the device (Moahloli *et al.* 2019). The meter records were classified into four reading ranges

every 2,000 m<sup>3</sup>, except for the last group that covers a larger dimension due to the small sample size. In the same way, the sample was grouped by years of operation, selecting six categories at 2-year intervals. For the last stratification, seven types of manufacturers were chosen.



**Figure 4** | Relative error of counters stratified by (a) accumulated volume, (b) years of operation and (c) manufacturer brands.

### Error curve based on flow rate

The characteristic curve of the average relative error of the hydrometric district is presented in Figure 5 and the curve presents a logarithmic trend line that ranges from sub-accounting values of  $-15\%$  to low consumption rates, to over-accounting values of  $+15\%$  at high flow rates. The data, to generate the curve based on flow rates, have a high correlation of 0.99.

At flow rates lower than  $Q_m$  (30 L/h), the meter does not record the values consumed, there is sub-accounting, so they do not enter the permitted range of  $\pm 5\%$ ; according to the consumptions presented in Figure 2, 23% of users do not record actual consumption. As the flow rate approaches  $Q_t$  (120 L/h), the error is reduced and enters within the theoretically allowed limits  $\pm 5\%$ ; 68% of users have consumption records within this range, so it is considered that the hydrometric district has a normal error. For the flow rate approaching  $Q_p$  (1,500 L/h), the error exceeds the maximum limit  $\pm 2\%$ , so the over-accounting increases. In this area, there are 9% of consumers.

### Degradation of the meter park

The degradation of the error is the rate at which the meter deteriorates (Hernández 2018). During the operating time of the device, deterioration rates vary depending on the flow patterns of user consumption (Arregui *et al.* 2015).

Figure 6 shows the evolution of the error of the three flow rates during all the years of operation, including the annual deterioration rate of all the meters analyzed without grouping them by models. Under the conditions of permanent flow, the analysis showed a gradual over-accounting error with a variation rate of 1.68%/year while during

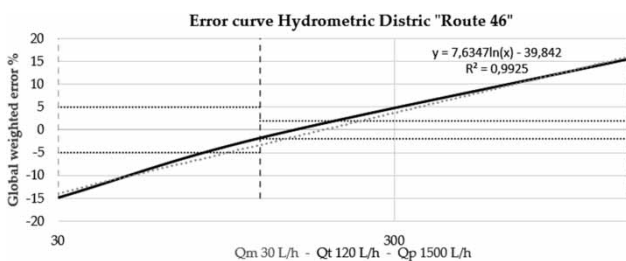


Figure 5 | Average error curve for different test flows.

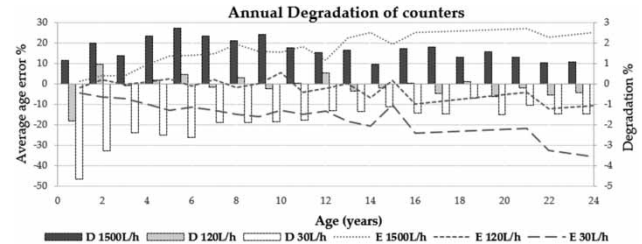


Figure 6 | Degradation through the years of operation, depending on the relative error by accumulated volume.

periods of transient flow, the error ranged over the value 0% (annual average variation  $-0.14\%$ ). Finally, during minimum flows, the variations were more pronounced with an annual degradation of  $-1.88\%$ . The degradation rates obtained were comparable to the degradation rate of 2.1% (Arregui *et al.* 2006), 4.1% (Ncube & Taigbenu 2015) and 1.45–6.67% (Mbabazi *et al.* 2015).

The errors obtained show that the degradation of the metrological performance is more pronounced in low flows where the domiciliary meters have a strong tendency to sub-accounting. In the medium and high flows of 750 L/h and higher, the average errors remain fairly stable. This tendency of some meters to over-accounting water consumption under specific conditions has been reported by Arregui *et al.* (2018). Often, previous studies on the degradation rate consider that the weighted error of the counters degrades linearly from an initial value (Szilveszter *et al.* 2015; Arregui *et al.* 2018; Ethem Karadirek 2019; Moahloli *et al.* 2019; Ncube & Taigbenu 2019). Also, Ethem Karadirek (2019) confirmed that water consumption patterns have significant effects on the inaccuracies of water meters, especially with domestic consumption being the pattern with the highest coverage and with the highest proportion at low flow rates, they generate the most apparent losses to the system (Ncube & Taigbenu 2019).

### The volume of apparent losses

Based on the marketing report provided by UMAPAL (2019), in the study area, there is an average domestic consumption of  $37.45 \text{ m}^3/\text{month}/\text{counter}$ , related to the weighted error ( $E_w$ ) determined in this study (Table 1). Using Equation (4), the volume of losses is obtained per connection equivalent to  $1.21 \text{ m}^3/\text{month}/\text{counter}$ ; by the date of sampling, the

water balance had 653 domestic connections. Therefore, it was determined that the total volume of apparent losses, caused by the sub-accounting of the household meters considering a 10% sample of the 'Route 46' Hydrometric District, amounts to 792.34 m<sup>3</sup>/month.

## CONCLUSIONS

This study develops a method that allows determining the weighted measurement error and the temporary degradation of domiciliary meters installed in urban areas, disaggregating the metrological behavior of water meters. The methodological prototype of this investigation allows developing a statistical calculation of the global error of the domestic water meters, by the use of a hydraulic test bench, providing a better understanding of the relationship between the meters classified according to their manufacturer brand, the totalized volume registered and the operating age. This article reveals the following:

1. The weighted error that represents the current state of the meter park of the hydrometric district, considering the different flow rates analyzed in the hydraulic bank and the percentage of consumption in the study area, obtained a sub-accounting value equivalent to -3.24%, generating losses to the company that supplies the drinking water service.
2. The annual degradation for a permanent flow rate of 1,500 L/h is 1.68%; otherwise, the annual degradation for a minimum flow rate of 30 L/h is -1.88%, for the transient flow of 120 L/h, the average value is -0.14%.
3. The volume of apparent losses caused by the sub-accounting of the domestic meters is 1.21 m<sup>3</sup>/connection/month, considering a sample of 10% of the study area; the total value of the apparent losses for the entire hydrometric district amounts to 792 m<sup>3</sup>/month.

## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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