Ambiente & Água - An Interdisciplinary Journal of Applied Science
ISSN 1980-993X – doi:10.4136/1980-993X
www.ambi-agua.net
E-mail: ambi.agua@gmail.com

Metrological performance of single-jet water meters over time

ARTICLES doi:10.4136/ambi-agua.2205

Received: 28 Oct. 2017; Accepted: 20 Aug. 2018

Carmen Virginia Palau[1]; Juan Manzano[1]; Iban Balbastre Peralta[1]; Benito Moreira de Azevedo[2]; Guilherme Vieira do Bomfim[2*]

[1]Universitat Politècnica de València (UPV), Valencia, Spain
Departamento de Ingeniería Rural y Agroalimentaria (DIRA). E-mail: virpaes@agf.upv.es, juamanju@agf.upv.es, ibbalpe@agf.upv.es
[2]Universidade Federal do Ceará (UFC), Fortaleza, CE, Brasil
Departamento de Engenharia Agrícola (DENA). E-mail: benitoazevedo@hotmail.com, guile2007@gmail.com
[*]Corresponding author

ABSTRACT

To maintain quality measurement of water consumption, it is necessary to know the metrology of single-jet water meters over time. Knowing the accuracy of these instruments over time allows establishing a metrological operation period for different flow rates. This will aid water companies to optimize management and reduce economic losses due to unaccounted water consumption. This study analyzed the influence of time on the measurement error of single-jet water meters to evaluate the deterioration of the equipment and, with that, launch the metrological operation period. According to standards 8316 and 4064 of the International Organization for Standardization (ISO), 808 meters of metrological Class B were evaluated in six water supplies, with age ranges of 3.7 to 16.4 years of use. The measurement error was estimated by comparing the volume measured in a calibrated tank with the volume registered by the meters at flow rates of 30, 120, 750 and 1,500 L h^{-1}. The metrological operation period of the meters was obtained for each flow rate by the relation between error of measurement and time of use (simple linear regression). According to the results, the majority of the equipment presents increasing under-registration errors over time, more pronounced at low flow rates and with less favorable operating conditions. The metrological operation period for flow rates of 30, 120, 750 and 1,500 L h^{-1} is estimated at approximately 3, 8, 14 and 13 years. This operation period combined with consumption patterns of users will establish the best time to replace the meters.

Keywords: hydrometry, measurement error, water consumption.

Desempenho metrológico de hidrômetros unijato com o tempo de uso

RESUMO

Para manter a qualidade de medição do consumo de água, é necessário conhecer a metrologia de hidrômetros unijato ao longo do tempo. Conhecer a metrologia desses instrumentos com o tempo permite estabelecer um período de operação metrológica para diferentes vazões. Isso ajudará as empresas de água a otimizar a gestão e a reduzir as perdas econômicas devido ao consumo do volume de água não contabilizado. Neste estudo, a

This is an Open Access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

influência do fator tempo sobre o erro de medição de hidrômetros unijato foi analisada com o objetivo de estimar sua deterioração e, com isso, o período de operação metrológica. Conforme as normas 8316 e 4064 da Organização Internacional de Normalização (ISO), foram avaliados em seis abastecimentos 808 hidrômetros de classe metrológica B, com uma faixa de idade de 3,7 a 16,4 anos de uso. O erro de medição foi calculado pela comparação entre o volume de um depósito calibrado e o volume medido pelos hidrômetros, nas vazões de 30, 120, 750 e 1.500 L h^{-1}. O período de operação metrológica dos medidores foi estimado para cada vazão, por meio da relação entre erro de medição e tempo de uso (regressão linear simples). De acordo com os resultados, a maioria dos hidrômetros apresenta erros crescentes de submedição com o tempo, sendo mais pronunciados nas vazões reduzidas e nas condições de funcionamento menos favoráveis. O período de operação metrológica para as vazões de 30, 120, 750 e 1.500 L h^{-1} é estimado em aproximadamente 3, 8, 14 y 13 anos. Este período de operação, combinado com os padrões de consumo dos usuários, estabelecerá o melhor momento para substituir os hidrômetros.

Palavras-chave: consumo de água, erro de medição, hidrometria.

1. INTRODUCTION

Single-jet water meters are the most widely used velocity meters for quantifying domestic water consumption (Szilveszter et al., 2017), mainly due to their low cost and high reliability (Arregui et al., 2007). This technology is used in residential areas (Arregui et al., 2016) and in small areas of pressurized irrigation systems (Daneshnia et al., 2015).

These water meters are composed of a totalizer incorporated by mechanical or magnetic coupling to a turbine inside a measuring chamber. The incidence of a tangential water jet on the turbine generates the rotation of this element. The rotation speed is directly proportional to the flow rate and to the volume registered (Arregui et al., 2007).

Over time, like any mechanical instrument, these water meters present a natural deterioration of their mobile elements that can cause significant measurement errors. The problem is more serious when this wear is accelerated by external factors, such as inadequate mounting position, reduced pressure in the network (Arregui et al., 2007), poor water quality (Buck et al., 2012), water freezing (Cichoń and Królikowska, 2016), on-site leakage (Couvelis and van Zyl, 2015), storage tanks (Mutikanga et al., 2011), partial blockage of the inlet strainer, water consumption patterns (Arregui et al., 2005), different manufacturers (Shields et al., 2012), and intermittently operated pipe networks (Walter et al., 2018).

Studies show that the degradation of single-jet meters over time, especially when associated with low flows rates, causes increasing errors of under-registration (Criminisi et al., 2009; Mutikanga et al., 2011, Puleo et al., 2014). The magnitude of these errors varies according to the manufacturer and materials used, the quality of water and the installation conditions of each water meter.

The lack of knowledge of the metrological evolution of these instruments over time can produce economic losses due to unregistered consumption. This study therefore evaluated this deterioration over time. This is fundamental to estimate the metrological operational period to achieve adequate water meter management.

2. MATERIALS AND METHODS

The tests were carried out in the laboratory of the ITA (Sustainable Urban Water Management), located in the Universitat Politècnica de València, Valencia, Spain.

The metrological behavior of the single-jet water meters was analyzed by the method of collecting liquid in a volumetric tank, according to ISO 8316 (1987). To meet the requirements of this standard, a test bench with two calibrated tanks and three independent flow lines was installed in the laboratory (Figure 1A).

Figure 1. Test bench (A), calibrated volumetric tanks (B) and accurate volumetric water meters and rotameter (C).

The calibrated tanks of 10 and 200 L had resolutions of 0.01 and 0.2 L, respectively, and an accuracy of 0.2% as percentage of span for both probes. Each tank contained a capacitive level switch that stopped the water flow at nominal volume and allowed measurement of the exact volume by a graduated scale (Figure 1B).

The first two flow lines had highly accurate volumetric meters with pulse emitters of 20 mm (0.1 L pulse^{-1}) and 40 mm (1 L pulse^{-1}). The frequency of pulses was received by a converter that regulated the test flow, showing it on a digital display. The third line had a rotameter that allowed the adjustment of flow rates between 10 and 100 L h^{-1} (Figure 1C).

The test procedure was based on comparing the volume of the calibrated tank (actual volume) with the volume measured by the single-jet water meters (indicated volume) at four flow rates: 30 L h^{-1} (minimum flow rate); 120 L h^{-1} (transitional flow rate); 750 L h^{-1} (permanent flow rate); and 1,500 L h^{-1} (maximum or overload flow rate).

In the first two flow rates, the volumes were compared using the tank of 10 L. In the last two flow rates, the volumes were compared using the tank of 200 L. Meters were tested by a volumetric standing-start-and-finish method (Paton, 2005). Volume readings were taken at the beginning and at the end of the test period to compare water meter measurement with calibrated volume.

The measurement error of the single-jet water meters was calculated by the volume difference in litres, by Equation 1, as referred to in ISO 4064 (2014).

$$Measurement\ error\ (\%) = \left(\frac{indicated\ volume - actual\ volume}{actual\ volume}\right) 100 \qquad (1)$$

Samples of 808 single-jet meters of metrological Class B, randomly selected by the water supply company, were tested. This metrological class must guarantee ±2% accuracy for flow rates between the minimum and the transition, and ±5% for flow rates between the transition and the maximum, according to withdrawal standard ISO 4064 (1993). In the current standard ISO 4064 (2014), the corresponding metrological class would be accuracy Class 2 with the same requirements.

Nine models ('a', 'b', 'c', 'd', 'e', 'f', 'g', 'h' and 'i') belonging to different manufacturers (Figure 2) were chosen for testing from six water supplies (Table 1).

Figure 2. Sample of the evaluated single-jet meters.

Generally, water meters of analyzed supplies are similar in terms of the initial metrological class and measurement technology. The evaluated supplies have a number of users ranging from 1,500 to 200,000 homes. The differences are found in the conditions of installation and in the company management. Factors such as water quality, position of installation, topology of the dwelling or the period that the meters remain in service are variables that affect their deterioration.

Table 1. Description of the samples of single-jet water meters in service, by water supply company and by water meter model.

Model	Water supply						Total	NSM	NMD
	1	2	3	4	5	6			
a	81	-	5	35	-	272	393	7	24
b	-	-	-	-	-	66	66	2	1
c	-	17	-	40	-	11	68	0	0
d	3	-	11	39	-	3	56	0	0
e	12	-	-	11	-	1	24	0	2
f	34	-	20	-	-	-	54	16	13
g	-	4	-	-	110	7	121	34	2
h	-	1	-	-	-	2	3	0	0
i	-	-	1	-	-	22	23	0	0
Total	130	22	37	125	110	384	808	59	42
Subscriber	5,500	750	4,000	200,000	4,500	7,500	-	-	-

NSM: number of stopped water meters; NMD: number of water meters deteriorated.

Only the water meters samples in operation were evaluated in all water supplies. In this sense, the stopped and deteriorated equipment was not considered in the study. Stopped water meters were considered those with a measurement error of -100% at all tested flow rates and deteriorated meters showed -100% error at 30 and 120 L h^{-1} flow rates.

The results were analyzed by water supply and by water meter model. The discussion was based mainly on the most representative groups, which had the highest number of suitable samples. The 95% confidence interval was estimated with samples that had a minimum of ten meters per supply to enable comparison between systems studied.

The metrological operational period of the meters was estimated for the most representative model (Model 'a'), by means of a simple linear regression graph between measurement error and time of use. This chart, using new and used water meters, was created by measuring the errors at regular intervals of two years. In the regression graph, the operation period was the time of use obtained with the measurement errors of ±2% for the flow rates of 30 and 120 L h^{-1}, and of ±5% for the flow rates of 750 and 1,500 L h^{-1}.

3. RESULTS AND DISCUSSION

3.1. Analysis by water supply

The average errors of the samples of each population are shown in Table 2.

In general, the water meters have more accentuated under-registration of volumes at lower flow rates, which decreases potentially when the instrument operates at higher flow rates. High under-registered errors at low flow rates can be explained by increasing friction in the rotary drive, which requires a higher flow rate to begin the movement. This friction wears moving parts and progressively reduces the accuracy of the meter (Fontanazza et al., 2013), which does not register lower than starting flow rates.

In water supply 1, Models 'a' and 'f' show the most severe under-registration errors operating at low flow rate, in addition to the greater number of stopped and deteriorated equipment. In Models 'e' and 'f', under-registration errors greater than -2% also occur at higher flow rates (750 and 1,500 L h^{-1}). In this case, the deterioration of the equipment can cause a great economic problem to the water company due to the unaccounted volume of water not registered.

In water supplies 2, 3 and 4, sample size was not considered representative of the population of instruments. Therefore, results are only valid to study the performance of water meters by model.

In water supply 5, with only Model 'g' tested, the percentage of damaged water meters was high (35 instruments) and very significant. This may indicate that a defective lot of meters has been installed which can lead to significant economic losses for the company or that the sample tested is biased and not randomly selected.

Sample in water supply 6 is considered the most representative of meter population. For this reason, it is possible to carry out a detailed study of performance of water meters over time.

In general, most of the models studied have high under-registered errors, especially at low flow rates (30 and 120 L h^{-1}). One parameter that may accelerate deterioration is the installation position. Inclined installation of the meter usually causes under-registered errors due to the reduction of the turbine's rotation and the rise of starting flow rate (Arregui et al., 2007). According to the mentioned authors, the turbine rotation decreases because of the inadequate position of the turbine shaft. This wrong position increases the friction and wear of the measurement zones. Furthermore, this deterioration reduces sensitivity to low flow rates and single-jet meter are not able to measure reduced flow rates.

The optimum performance of a single-jet meter is in horizontal position because the turbine shaft rests in only one point. This reduces friction and, consequently, measurement error at low flow rates are lower (Silva et al., 2012). In this position, deterioration of the turbine and the turbine shaft is smaller due to the hard and resistant materials used in manufacturing (Arregui et al., 2007).

Error curves of most representative models of the water supply 6 are shown in Figure 3.

Table 2. Measurement errors of the single-jet water meters in service, organized by water supply.

Water supply	Model	NMT	CV (m^3)	Measurement error (%)				NSM	NDM
				(30 L h^{-1})	(120 L h^{-1})	(750 L h^{-1})	(1,500 L h^{-1})		
1	a	70	1,308.4	-42.7 ±10.1	-3.0 ±2.7	-0.9 ±0.9	-0.4 ±0.8	2	8
	d	3	2,007.5	-34.5	-5.2	-3.1	-2.7	0	0
	e	11	3,396.2	-14.2 ±9.2	-2.9 ±2.6	-3.1 ±1.6	-2.6 ±2.0	0	1
	f	26	3,164.6	-43.0 ±15.2	-4.9 ±1.7	-3.9 ±2.2	-3.1 ±0.8	4	11
2	c	17	222.9	-24.3 ±18.2	-1.3 ±1.7	-0.8 ±0.5	-0.7 ±0.4	0	0
	g	3	1,456.7	-42.5	-4.3	0.5	-0.7	0	1
	h	1	95.2	-8.4	-0.9	0.7	-1.8	0	0
3	a	4	1,022.3	-57.0	-0.5	0.2	0.3	1	0
	d	11	1,420.6	-30.3 ±26.6	1.3 ±3.2	0.6 ±2.1	2.0 ±2.2	0	0
	f	6	2,121.4	-74.2	-7.9	-5.5	-6.0	12	2
	i	1	1,601.6	-100.0	1.4	-9.4	-8.3	0	0
4	a	32	-	-19.8 ±11.9	0.0 ±0.9	-0.6 ±0.7	-0.2 ±0.8	0	3
	c	40	-	-17.3 ±10.1	0.9 ±1.6	1.2 ±1.6	1.3 ±1.6	0	0
	d	39	-	-5.3 ±5.0	-0.7 ±0.4	-0.2 ±0.4	0.3 ±0.4	0	0
	e	10	-	-62.5 ±21.5	3.0 ±2.4	4.9 ±2.4	5.0 ±2.3	0	1
5	g	64	892.9	-14.8 ±6.5	-2.1 ±1.4	-0.1 ±0.7	0.9 ±0.4	34	1
6	a	253	893.3	-52.5 ±5.1	-6.8 ±1.6	-1.8 ±0.3	-1.1 ±0.3	4	13
	b	62	1,737.6	-11.0 ±8.9	0.0 ±1.3	-0.2 ±1.7	2.4 ±1.6	2	1
	c	11	352.8	-29.8 ±22.6	-0.2 ±0.9	-1.4 ±1.1	-0.9 ±0.4	0	0
	d	3	1,110.1	-20.7	-2.2	-1.6	-1.8	0	0
	e	1	485.6	-100.0	-1.3	0.8	1.2	0	0
	g	7	3,588.3	-0.5	-0.9	-1.2	-0.6	0	0
	h	2	237.0	-1.0	0.7	-1.4	-0.8	0	0
	i	22	2,152.5	-60.2 ±19.0	-3.5 ±3.5	-1.2 ±1.8	-1.6 ±1.9	0	0

NMT: number of water meters tested; CV: cumulative volume; NSM: number of stopped water meters; NDM: number of water meters deteriorated. The 95% confidence interval was estimated with samples that had a minimum of ten meters per supply to enable comparison between the studied systems.

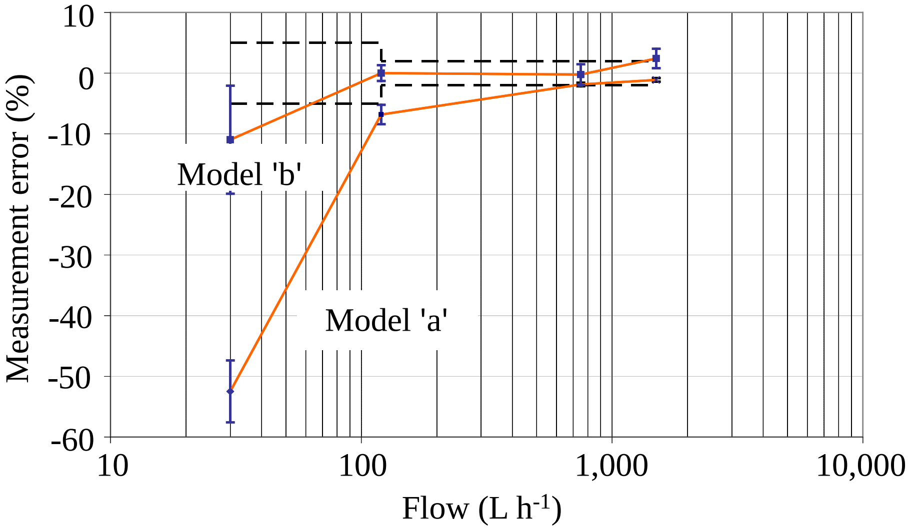

Figure 3. Error curve of the single-jet water meters Models 'a' and 'b', installed in water supply 6.

The determination of error curve in Model 'a' indicates that water meters are damaged. Therefore, average errors are outside the limits established by ISO 4064 (2014) at flow rates of 30 and 120 L h^{-1} (error of ±5%). In addition, a high percentage of equipment, approximately 7%, were stopped or failed at 30 and 120 L h^{-1}, or they had under-registered errors greater than -50%.

The error curve of Model 'b' indicates a better performance than Model 'a'. Also, this model shows slight over-registered errors at flow rates close to 1,500 L h^{-1}. This can be caused by the by-pass regulation system of this model, which generates positive errors at medium and high flow rates (Silva et al., 2012). The bypass circuit is partially obstructed over time and water passes through a restricted area. This causes higher fluid velocity and turbine rotation speed increases, generating over-registration measures. According to Arregui et al. (2007), the reduction of water passing sections or sediment accumulation on the inner surface of the turbine chamber are the main causes of over-registration error in single-jet water meters.

The parameter that may have had an influence on the rapid deterioration of all models was the inclination in which many of them were installed in this water supply (Figure 4).

Figure 4. Inadequate mounting position of some evaluated single-jet meters.

The inappropriate installation of water meters increases the friction of the moving parts and leads to a higher degradation rate of the equipment (Figure 3). This effect is even more visible at low flows rates (Arregui et al., 2005).

3.2. Analysis by water meter model

In general, comparing the errors of the main models of each water supply shows that their performance is quite similar. Age is the parameter that most affects their deterioration (Table 3).

Table 3. Measurement errors of the single-jet water meters in service, organized by model.

Model	Water supply	NMT	AA (year)	Measurement error (%)			
				(30 L h^{-1})	(120 L h^{-1})	(750 L h^{-1})	(1,500 L h^{-1})
a	1	70	8.20	-42.7 ±10.1	-3.0 ±2.7	-0.9 ±0.9	-0.4 ±0.8
	3	7	10.10	-62.80	-0.60	0.30	0.30
	4	35	7.20	-26.8 ±13.2	-0.4 ±0.9	-0.8 ±0.8	-0.3 ±0.8
	6	251	9.80	-52.2 ±5.1	-6.9 ±1.6	-1.9 ±0.3	-1.1 ±0.3
c	2	17	3.90	-24.3 ±18.2	-1.3 ±1.7	-0.8 ±0.5	-0.7 ±0.4
	4	40	3.70	-17.3 ±10.1	-0.8 ±1.6	-1.2 ±1.6	1.3 ±1.6
	6	11	5.80	-29.8 ±22.6	-0.5 ±1.1	-1.4 ±1.1	-0.9 ±0.4
d	1	3	7.00	-34.40	-5.20	-3.10	-2.70
	3	11	16.40	-30.3 ±26.6	1.3 ±3.2	0.6 ±2.1	2.0 ±2.2
	4	39	6.80	-5.3 ±5.0	-0.6 ±0.4	-0.2 ±0.4	0.3 ±0.4
	6	3	13.00	-20.70	2.20	-1.60	-1.80
g	2	3	5.30	-42.50	-4.40	-0.50	-0.70
	5	64	4.70	-14.8 ±6.5	-2.1 ±1.4	-0.1 ±0.7	1.0 ±0.4
	6	7	8.40	-30.30	1.30	0.60	1.90

NMT: number of water meters tested; AA: average age.

In the same way as in the supply analysis, the models investigated have similar measurement errors. Mostly negative errors, decreasing as the flow rate increases, with accused values at lower flow rates. Main models performance clearly show, considering the low flow rates, that measurement error increases with the time of use.

Similar results were found in Kampala, Uganda. Residential water meters with 10 and 20 years of use and low pressures in water network were the main cause of under-registration (Mutikanga et al., 2011). In Palermo, Italy, in the same way, meters with 0 to 45 years of use had negative errors that increased rapidly with age (Criminisi et al., 2009).

Fontanazza et al. (2013) indicates that age and pressure are relevant factors to determine the starting flow rate of the meter, considered the main parameter that influences operation. The wear caused by age increases the meter mechanism friction, increasing the resistance to begin the movement of the turbine, especially when the pressure is reduced. In this situation, the water meter considerably increases the unregistered volume of water by not recording consumption or by doing so improperly.

The comparison of similar models with the same age in different supplies shows that the variability between them can be explained by the different operating conditions: installation conditions, water quality, hydraulic parameters of the network, etc. (Arregui et al., 2005, 2018; Buck et al., 2012; Mbabazi et al., 2015).

In Model 'a', meters installed in supplies 1 and 6 had certain characteristics that accentuates their deterioration with respect to supply 4. In these cases, meters presented a wrong installation in the majority of the samples. In Models 'c' and 'd', operating conditions in supply 4 were more favorable than in supplies 1 or 2 for the period of use from 4 up to 7 years, respectively. In Model 'g', similar to other models, supply conditions in 5 were more favorable than supply conditions 2.

The comparison between different models can be done in supply 4 that permits comparison to models with similar ages. In this case, Model 'a' presents higher deterioration than Model 'd', especially at low flow rates. This wear can be attributed to manufacturing differences that normally affect metering (Sumrak et al., 2016).

The Figure 5 shows Model 'a' water meters by age groups to obtain the error evolution over time for each flow rate tested.

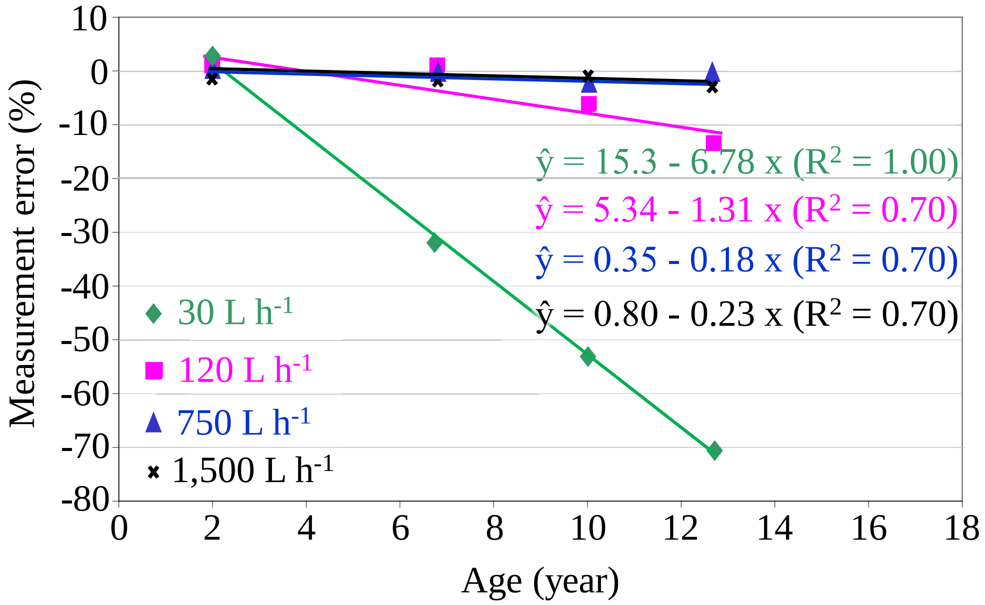

Figure 5. Measurement error of the single-jet water Model 'a' meters, depending on the time of use.

According to Figure 5, measuring errors for meters up to 2 years in service remain within the recommended limit of ±5% at all flow rate tested.

Over time of use, the rates of deterioration vary depending on the consumption flow rate patterns of the users. Regarding consumption at higher flow rates of 750 and 1,500 L h^{-1}, errors are repeated during the study period, ranging from -0.5 to -1.5% per year and within the limit of ±2%. Only after about 13 and 12 years of use, respectively, would deterioration be considerable. Working at low flow rates of 120 L h^{-1} and, especially, 30 L h^{-1}, the errors exceed the limit of ±5%, suggesting the substitution in approximately 8 and 3 years, respectively. Therefore, water meters working at low flow rates during long periods will worsen easily.

It should be noted that age is one of the crucial parameters for the renewal decision-making process. However, in recent strategies to replace water meters, in addition to age, factors such as total volume passing through the meter and the network pressure are considered (Puleo et al., 2014). Also, the price of water, the consumption volume or the cost of acquiring and installing the meter can help to make the decision (Arregui et al., 2011).

Single-jet water meters in service tends to shift the error curve to the right, registering water consumption inadequately over time. As already mentioned, improper installation resulting in increased turbine friction, particle accumulation causing partial obstructions and other factors can accelerate the deterioration of the equipment. Particularly, this phenomenon is enlarged at low flow rates. For example, at 30 L h^{-1}, where water driving forces are lower and the greater friction caused by the wear of internal parts is more appreciable in meter accuracy.

However, as the instrument ages, the deterioration can appear in higher flow rates as verified in the 120, 750 and 1,500 L h^{-1}.

4. CONCLUSIONS

The study of metrological performance of several models of single-jet water meters in service shows that most equipment has increased under-registration errors over time. These measuring errors are greater at low flow rates and under less favorable operating conditions. In addition, the study allows estimating the measurement error with the service time to evaluate the metrological operation period of the equipment. This period, for the tested flow rates of 30, 120, 750 and 1,500 L h^{-1}, is estimated at approximately 3, 8, 14 and 13 years, respectively.

Unaccounted volume of water depends on the consumption pattern of users. If percentage of consumption is higher at high flow rates, the volume not registered will be less. On the contrary, if the percentage of user consumption at low flow rates is higher, unaccounted water volume will also be high.

5. REFERENCES

ARREGUI, F.; CABRERA JUNIOR, E.; COBACHO, R.; GARCIA-SERRA, J. Key factors affecting water meter accuracy. In: IWA SPECIAL CONFERENCE - LEAKAGE, 2005, Halifax. **Procedings…** Halifax: IWA, 2005. p. 1-10.

ARREGUI, F. J.; CABRERA JUNIOR, E.; COBACHO, R. **Integrated water meter management**. London: International Water Association, 2007. 272 p.

ARREGUI, F. J.; COBACHO, R.; CABRERA JUNIOR, E.; ESPERT, V. Graphical method to calculate the optimum replacement period for water meters. **Journal of Water Resources Planning and Management**, v. 137, n. 1 p. 143-146, 2011. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000100

BUCK, B. S.; JOHNSON, M. C.; BARFUSS, S. L. Effects of particulates on water meter accuracy through expected life. **Journal of the American Water Works Association**, v. 104, n. 4, p. 231-242, 2012. https://doi.org/10.5942/jawwa.2012.104.0054

CICHOŃ, T.; KRÓLIKOWSKA, J. The impact of some external factors on the metrological properties of a water meter. **Czasopismo Techniczne**, v. 3, n. 1, p. 3-11, 2016. https://doi.org/10.4467/2353737XCT.15.355.4820

COUVELIS, F. A.; VAN ZYL, J. E. Apparent losses due to domestic water meter under-registration in South Africa. **Water SA**, v. 41, n. 5, p. 698-704, 2015. https://doi.org/10.4314/wsa.v41i5.13

CRIMINISI, A.; FONTANAZZA, C. M.; FRENI, G.; LA LOGGIA, G. Evaluation of the apparent losses caused by water meter under-registration in intermittent water supply. **Water Science and Technology**, v. 60, n. 9, p. 2373-2382, 2009. https://doi.org/10.2166/wst.2009.423

DANESHNIA, F.; AMINI, A.; CHAICHI, M. R. Berseem clover quality and basil essential oil yield in intercropping system under limited irrigation treatments with surfactant. **Agricultural Water Management**, v. 164, p. 331-339, 2015. https://doi.org/10.1016/j.agwat.2015.10.036

FONTANAZZA, C. M.; NOTARO, V.; PULEO, V.; FRENI, G. Effects of network pressure on water meter under-registration: an experimental analysis. **Drinking Water Engineering and Science Discussions**, v. 6, n. 1, p. 119-149, 2013. https://doi.org/10.5194/dwesd-6-119-2013

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. **ISO 8316**. **Measurement of liquid flow in closed conduits -- Method by collection of the liquid in a volumetric tank.** Geneva, 1987. 21 p.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. **ISO 4064**. **Measurement of water flow in closed conduits -- Meters for cold potable water -- Part 1:** Specifications. Geneva, 1993. 6 p.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. **ISO 4064. Water meters for cold potable water and hot water -- Part 1:** Metrological and technical requirements. Geneva, 2014. 38 p.

MBABAZI, D.; BANADDA, N.; KIGGUNDU, N.; MUTIKANGA, H.; BABU, M. Determination of domestic water meter accuracy degradation rates in Uganda. **Journal of Water Supply: Research and Technology-AQUA**, v. 64, n. 4, p. 486-492, 2015. https://doi.org/10.2166/aqua.2015.083

MUTIKANGA, H. E.; SHARMA, S. K.; VAIRAVAMOORTHY, K. Investigating water meter performance in developing countries: a case study of Kampala, Uganda. **Water SA**, v. 37, n. 4, p. 567-574, 2011. https://doi.org/10.4314/wsa.v37i4.18

PANTON, R. Calibration and standards in flow measurement. In: SYDENHAM, P. H.; THORN, R. (Eds.). **Handbook of measuring system design**. Nova Jersey: Wiley, 2005. p. 1-5.

PULEO, V.; FONTANAZZA, C. M.; NOTARO, V.; DE MARCHIS, M.; LA LOGGIA, G.; FRENI, G. Definition of water meter substitution plans based on a composite indicator. **Procedia Engineering**, v. 70, n. 1, p. 1369-1377, 2014. https://doi.org/10.1016/j.proeng.2014.02.151

SHIELDS, D. J.; BARFUSS, S. L.; JOHNSON, M. C. Revenue recovery through meter replacement. **American Water Works Association**, v. 104, p. 252-259, 2012. https://doi.org/10.5942/jawwa.2012.104.0056

SILVA, D. G. M.; ERAZO, J. G.; CRUZ, A. M. O. Eficiencia en el consumo de agua de uso residencial. **Revista Ingenierías Universidad de Medellín**, v. 11, n. 21, p. 23-38, 2012.

SUMRAK, M. L.; JOHNSON, M. C.; BARFUSS, S. L. Comparing low flow accuracy of mechanical and electronic meters. **Journal of the American Water Works Association**, v. 108, n. 1, p. E327-E334, 2016. https://doi.org/10.5942/jawwa.2016.108.0069

SZILVESZTER, S.; BELTRAN, R.; FUENTES, A. Performance analysis of the domestic water meter park in water supply network of Ibarra, Ecuador. **Urban Water Journal**, v. 14, n. 1, p. 85-96, 2017. https://dx.doi.org/10.1080/1573062X.2015.1057181

WALTER, D.; MASTALLER, M.; KLINGEL, P. Accuracy of single-jet and multi-jet water meters under the influence of the filling process in intermittently operated pipe networks. **American Water Works Association**, v. 18, n. 2, p. 679-687, 2018. https://doi.org/10.2166/ws.2017.149