Water Resources Management manuscript No.
(will be inserted by the editor)

Techno-economic analysis of residential water meters: a practical example

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Received: date / Accepted: date

Abstract As water is a scarce natural resource, one of the most crucial aspects influencing its management is the measurement of user consumptions. There are many studies which set out to analyze issues related to water meter accuracy from either a technical or economical point of view. This investigation proposes an approach that integrates both technical and economic studies to advise in the error evaluation and the units renewal decisions. The technical study includes a methodology for measuring the error produced at different flow rates and an analysis of the results obtained. In the economic study three methods – linked to different management strategies – have been outlined to make an adequate appraisal of the water meter replacement time. The procedure was applied to the water meter park of a medium-sized Spanish city. Results indicate that both measured volume and age contribute to the error evolution, and that there was no noticeable influence regarding either the transmission type or the brand. In the economic study, specific results related to the water replacement were obtained, and a sensibility analysis revealed the influence of the price of water, water meter cost and the cost of capital.

Keywords Water meter · Meter accuracy · Replacement · Techno-economic analysis

1 Introduction

The World Bank study estimates the global water losses at 32 billion cubic meters each year, half of which occur in developing countries [19]. These losses can be real (water leaks) or apparent, those related to the water consumed, but not a paid consequence of water meters errors, water theft or billing errors [6].

The accurate measurement of the water consumed by water meters is a pivotal factor in reducing any uncertainty affecting the water balance and has significant

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technical and economic implications. Moreover, it forms the basis for evaluating the efficiency of water management policies [15] and analyzing the influence of a number of factors in the demand for water [17].

Water measurement will become an even more critical aspect in any future scenarios: the world's water supplies are set to increase due to population growth which will be reflected in an important stress in the water management mainly due to the competition among the different forms of water consumption (agriculture, industry and residential).

Maintaining high levels of accuracy in a water meter park will guarantee a more efficient technical water management as well as generating increased revenue from the sale of water. However, this involves more substantial investments (elevated accuracy meters and more frequent replacements). Therefore, such investment decisions need to be carefully weighed up in the light of a combination of both financial and technical factors.

In the case of residential water meters there are many parameters which affect water meter accuracy including the wear and tear of the moving parts, water quality, etc. [1, 18]. Many studies technically analyze which factor most influences the measurement error of a water meter park by testing a sample of meters and they all point to two main tendencies: those that consider the meter's age as the critical factor [4] or its accumulated registered volume [11]. Other studies have proposed different financial frameworks to assess water distribution companies in their decision making concerning water meter replacement time (which is dependent on their particular management strategy) for example: the Pay-back period to calculate the time required to recoup the investment of a new water meter, used in a strategy based on maintaining the water meter park as upgraded as possible without economical losses [5]; indicators as Net Present Value [10, 14] or new synthetic ones [12, 2] to calculate the age of renewal in a strategy of maximize the profits from the sale of the water.

In this case, to study the accuracy of a water meter park and to evaluate the decision making governing the unit renewal, a procedure with an integrative character including both a technical and economic study is proposed.

From a selected sample of water meters, the technical study defines the process of measuring errors on a laboratory test bench and analyzing the results: detecting how a series of factors influence the magnitude of the errors and finding trend patters. The economic study includes the definition of different methodologies (Pay-back, Net Present Value of a replacement Chain and Accumulated volume) applied depending on the operation strategy followed and the water consumption characteristics. In order to provide an example, the proposed procedure has been applied to a medium-size city in Spain.

2 Materials and methods

2.1 Technical study

The testing process has been performed in a laboratory test bench a water recirculating system. This is a typical infrastructure designed for this application with rotameters, two tanks one calibrated for measuring the volume, a regulation valve for water flow adjustment, and a recirculation pump. The test bench ensures that the meter is tested under constant water flow rates, measuring its measurement error comparing the volume of the calibrated tank and the volume registered in a defined time. Thus, the error is calculated as,

$$e_i = \frac{V_i - V_a}{V_a} \cdot 100 \tag{1}$$

Where, e_i (%) is the error corresponding to a flow rate tested i, Vi is the volume indicated in the meter and Va is the real value measured in the calibrated tank (both volumes with the same units).

To obtain the total error of the water meter, it also necessary to consider the water consumption patter of the demand where the meter is installed, which defines the fraction of the volume consumed in different flow rates ranges.

The total error of a water meter tested is calculated as,

$$E = C_a + \sum_{i=1}^{n} C_i \cdot e_i \tag{2}$$

Where, $E(\%)$ is the value of total error, C_a and C_i are the fractions of the consumption, derived from the water consumption pattern, at flow rates lower than start-flow or each flow rate tested respectively.

In the tests, the total error values are in all cases negative, if a positive value is obtained the meter tested is not considered as it deemed to be damaged.

The process is divided into two stages: the first stage to determine the start-flow measure and the second stage where the errors at different flow rates are obtained.

2.1.1 Start-flow measures

The procedure for each water meter consists of increasing the flow rate from a very low value, not detected by the water meter, up to a minimum or start-flow value that can be measured by the meter. It is done in successive steps, increasing the flow rate and keeping it steady over a long time.

2.1.2 Obtaining error at different flow rates

To determine the total error of a water meter, it is tested with seven flow rates as suggested in the European Standard EN14154:2005+A2:2011 [9]– four reference flow rates of the meter and three intermediate values – and then applying the procedure proposed in the standard. The reference flow rates define different water meter measurement conditions: minimum water flow rate (Q_1) the lowest flow rate that can be measured; permanent flow rate (Q_3), the highest flow rate that can be measured in continuous; overload flow rate (Q_4), the highest flow rate that can be measured only at short periods of time without adversely affecting the accuracy of the meter; and the transitional flow rate (Q_2) a value between the permanent and minimum flow rate.

2.2 Economic study

The economic study is focused on identifying the optimum period of renewal (renewal age or volume registered) of the water meter. It includes three different approaches that can be used depending on the strategy selected.

2.2.1 Pay-Back

The economic concept of the pay-back period (T_{PB}) represents the time interval when the monetary savings obtained with the replacement of an old water meter with a new one, reach the needed investment. For its calculation, it is supposed that the renewal take place at the beginning of each (T_{PB}) interval, and the savings are obtained comparing with an old unit installed at the beginning of the previous interval.

Its use corresponds to a renewal strategy based on maintaining the water meter park as upgraded as possible without economical losses, rather than a policy of maximising profits from the sale of water. It is a fast and easy approximation, as it does not require data of neither income nor discount rate.

This approach considers that the water meters errors are consequence of the water meter age, and that the annual water consumption is similar in all years and meters of the park.

Equation 3 represents the mathematical formulation associated with the T_{PB}.

$$-I + \sum_{i=1}^{i=T_{PB}} S_i = 0 \tag{3}$$

Where, T_{PB} (years) is the pay-back period, I (€) is the initial investment, S_i (€) is the annual economic savings corresponding to the difference of income (derived from the error) at year i after the water renewal. For this specific case,

- $I = C_C$
- $S_i = V_m \cdot (E_n(i) - E_0(i)) \cdot Cw$

Where, C_c (€) is the cost of the water meter, V_m (m^3/year) is the annual water consumption, C_w (€/m^3) is the price of water, $E_n(i)$ is the total error of new water meter installed i years ago and $E_0(i)$ total error of the old water meter installed $i + T_{PB}$ years ago. $E(i)$ values are calculated from the tendency of the water meters errors (found in the tests) against age,

$$E(t) = m_1 \cdot t + n_1 \tag{4}$$

Where, t are the years of use, m_1 and n_1 are regression adjustment coefficients. Therefore,

- $E_0(i) = m_1 \cdot (i + T_{PB}) + n_1$
- $E_n(i) = m_1 \cdot i + n_1$

Obtaining a constant cash-flow value,

- $CF_i = V_m \cdot (-m_1 \cdot T_{PB}) \cdot C_w$

With this data and 3 the T_{PB} can be determined as follows,

$$T_{PB} = \sqrt{\frac{-C_C}{V_m \cdot C_w \cdot m_1}} \tag{5}$$

2.2.2 Net Present Value of a replacement Chain

The Net Present Value (NPV) calculates the actual value of an investment considering investment, cash flows, and discount rate. However, in its primitive form it is applicable to a single investment. When the economic activity requires successive investments to maintain the production indefinitely, a variation of this method called Net Present Value of a replacement Chain ($NPVC$) is used. It calculates the global net present value at the starting date of a sequence of investment projects with an identical time frame (called replacement projects), in which the initial investment (I) is replaced at the end of each project life (see 1 to maintain the activity [13].

The renovation of water meters can be considered as a succession in perpetuity of replacement projects. This method calculates the renewal period T_R as the project duration that maximizes the value of $NPVC$.

Its use corresponds to a renewal strategy based in the maximization of the profits from the sale of water (including incomes and costs).

As the Pay-back, this approach considers that the water meters errors are result of their age, and an uniform annual water consumption in all years and meters of the park.

For a chain of k replacement projects with a duration of n years each, the $NPVC$ is calculated with the equation 6,

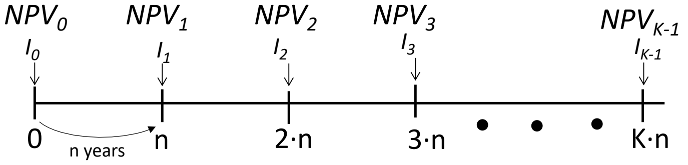

Fig. 1: NPVC conceptual diagram.

$$NPVC_k = \sum_{j=0}^{j=k=1} \frac{NPV_j}{(1+f)^{j \cdot n}} \tag{6}$$

With, $NPVC_k$ (€) is the result obtained, and f (as a decimal) is the nominal discount rate that considers both inflation and investment risk. The value of NPV_j for the project corresponding to replacement j can be calculated as,

$$NPV_j = -I + \sum_{i=1}^{i=n} \frac{CF_i}{(1+f)^i} \tag{7}$$

Where i are the years from year j. The value of the rate f can be expressed using the s inflation rate and r real discount rate that represents the interest requested by the investor. From now on we will refer to the real discount rate as the capital cost.

Therefore, separating both effects,

- $(1 + f) = (1 + r) \cdot (1 + s)$

On several occasions, only the factor $(1 + r)$ is used in the equation 6 because the factor $(1 + s)$ is simplified, however in this case it has been included for a more detail description.

And in our case of study,

- $I_j = C_C \cdot (1 + s)^{j \cdot n}$
- $V_m \cdot (1 + E(i)) \cdot C_w \cdot (1 + s)^{j \cdot n + i}$

Where $E(i)$ is the total error in year i after renewal, and V_m (m^3) is the annual water consumption.

Substituting in equation 6,

$$NPV_j = -C_C \cdot (1 + s)^{j \cdot n} + \sum_{i=1}^{i=n} \frac{V_m \cdot (1 + E(i) \cdot C_w \cdot (1 + s)^{j \cdot n + i}))}{(1 + r)^i \cdot (1 + s)^i} =$$

$$= -C_C \cdot (1 + s)^{j \cdot n} + \sum_{i=1}^{i=n} \frac{V_m \cdot (1 + E(i)) \cdot C_w \cdot (1 + s)^{j \cdot n}}{(1 + r)^i}$$

Substituting in equation 5 and simplifying,

$$NPVC_k = \left(-C_C + \sum_{i=1}^{i=n} \frac{V_m \cdot (1 + E(i)) \cdot C_w}{(1 + r)^i} \right) \cdot \sum_{j=0}^{j=k-1} \frac{1}{(1 + r)^{j \cdot n}} \tag{8}$$

For an infinite number of k replacement projects, $\sum_{i=0}^{i=inf} \frac{1}{(1+r)^{j \cdot n}}$, is a sum of a geometric progression with infinite terms and a common ratio of $\frac{1}{(1+r)^n} < 1$ and therefore equation 9 can be obtained,

$$NPVC = \left(-C_C + \sum_{i=1}^{i=n} \frac{V_m \cdot (1 + E(i)) \cdot C_w}{(1 + r)^i} \right) \cdot \frac{(1 + r)^n}{(1 + r)^n - 1} \tag{9}$$

$E(i)$ values are obtained from the results of water meters tests (applying the methodology described in 2.1, specifically for a linear regression adjustment.

As $NPVC$ is a discrete function and therefore the value of T_R is obtained by progressive iterations.

2.2.3 Acumulated volume method

The accumulated volume method is based on that a water meter must be changed when the registered (accumulated) volume reach to a certain value, called replacement volume V_R. This approach considers that is more correct to suppose the errors of the water meters as a consequence of the volume registered instead of the meter age.

This method corresponds also to a renewal strategy based in maximization profits from the sale of water, but in this case obtaining the volume measured that minimizes the cost per cubic meter registered. Unlike the $NPVC$ method that assumes a uniform annual water consumption, this method could also be more suitable if the volume measured changes significantly from year to year or from one meter to another in the park.

Equation 10 represents the cost per cubic meter associated to the sale of water,

$$C(V) = \frac{1}{V} \cdot \left(C_C + C_w \cdot \int_0^V -E(V) \cdot dV \right) \tag{10}$$

Where, $C(V)$ is the cost per cubic meter corresponding to a total V registered volume,and $E(V)$ is the function of the error against the registered volume, obtained with the tests results.

$$E(V) = m_2 \cdot V + n_2 \tag{11}$$

Where, m_2 and n_2 were the regression adjustment coefficients.

Substituting this error adjustment in equation 10 and with the derivative of the obtained function it is possible to determine the measured volume that minimizes the water cost per m^3, V_R (m^3),

$$V_R = \sqrt{\frac{-2 \cdot C_C}{C_w \cdot m_2}} \tag{12}$$

3 Practical example

The methodology described has been applied to the water meter park of a medium-sized Spanish city with around three hundred thousand inhabitants, located in the north of the country.

The water meters selected were those with DN13 nominal diameter, the size with the greatest number of installed units, with a higher degree of consumption, also some of them had been in operation for more than 50 years.

A sample of 128 water meters have been tested, in order to analyse how four different factors, influence the total error: type of transmission, brand, measured volume and age (years of use). The water meters correspond to two brands, (whose names had changed several times throughout the period of study) Tavira and CdC. Those installed before 1984 have a direct mechanical link between the turbine and the display, the ones after that date have a magnetic transmission reducing friction forces.

The sample is representative of the water meter park, and it has been divided in groups to distinguish the trends and effects of the different factors in the errors produced.

- Group A: 22 water meters installed from 1966 to 1984 that represent the oldest water meters, of the two brands.
- Group B: 32 water meters installed from 1984 to 2013, all with similar annual water consumption - around 100 m^3/year - of the two brands.
- Group C: 46 water meters installed from 1973 to 2013 corresponding to different ages and volumes registered, all Tavira brand.
- Group D: 28 water meters installed from 1984 to 2013 with similar total measured volume (around 1750 m^3), all Tavira brand.

The flow rates selected for the test were:

- Reference flow rates: 30 (minimum), 120 (transition), 1,500 (permanent) and 3,000 (overload) L/h.
- Intermediate flow rates: 75, 600 and 1200 L/h.

The consumption patter used has been obtained by performing an average of the three different models considered as the most recent and significant: the one proposed by Bowen et al [3] for the American Water Works Association; the obtained for different locations in the Community of Valencia, Spain during years 1999 and 2000 [16]; and the found for the Community of Madrid, Spain [7]. The flow rates of consumption patter obtained are: 15, 30, 75, 120, 600, 1,200, 1,500 and 3,000 L/h that correspond to percentages of consumptions of 5, 3, 14, 31, 26, 12 and 2%.

4 Results and discussion

4.1 Technical study

The results of the errors weighted with the proposed water consumption pattern are shown in Table 1. The maximum error allowed (defined by the European Directive 2004/22/CE [8] is ± 6% for low flow rates (30 L/h ≤ Q < 120 L/h) and ± 2,5% for higher flow rates (120 L/h ≤ Q ≤ 3000 L/h). Shaded values in the table indicate errors which exceed the limits.

Errors are mainly within limits, with the exceptions of:

- All flow meters at 30 L/h test (minimum flow rate).
- Many of Group A flow meters (all of Subgroup A2), the oldest ones.
- Subgroup C1 meters in the cases of flow rates of 30 L/h, 75 L/h and 3000 L/h.

The average values of start-flow and error obtained were 22 L/h and -8.4% respectively (excluding Group A old meter series).

Fig. 2 shows, as an example the results obtained with water meters of subgroup C3 and A2. Each point corresponds to an error value defining error lines per water meter tested; the limits are represented in the figure as thick horizontal lines. A2 water

Table 1: Description of the sample, average start-flow and total error for each subgroup of water meters.

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]							[10]
								30	75	120	600	1200	1500	3000	
A	A1	1966-1984	2300-7300	Tavira	Mechanical	13	37	-46.8	-12.9	-0.8	0.6	1.0	0.9	0.6	-9.8
	A2	1966-1984	750-8300	CdC	Mechanical	9	44	-67.5	-21.1	-7.4	-5.7	-2.7	-2.7	-2.6	-14.9
B	B1	1984-2013	100/year	Tavira	Magnetic	23	20	-15.7	-1.2	-.07	-0.3	-0.5	-0.2	0.1	-8.2
	B2	1984-2013	100//year	CdC	Magnetic	9	23	-17.6	-2.1	-0.6	-0.4	-1.6	0.2	0.3	-8.5
C	C1	1973-1989	500-9500	Tavira	Mechanical	10	32	-36.9	-6.7	-2.9	-0.7	-1.6	-1.8	-2.5	-10.3
	C2	1994	500-9500	Tavira	Magnetic	15	22	-16.4	-2.7	-1.4	0.1	0.4	0.5	0.9	-7.9
	C3	2004	100-5700	Tavira	Magnetic	13	18	-17.3	-0.8	-0.5	0.1	-0.2	-0.3	0.0	-8.0
	C4	2012-2013	50-2200	Tavira	Magnetic	8	21	-20.3	-0.5	-0.4	0.3	-0.1	-0.1	0.1	-8.1
D	D1	1984-2013	1000-2200	Tavira	Magnetic	28	24	-30.1	-4.7	-1.3	0.0	0.1	0.3	0.6	-8.8

Where [1] is Group, [2] Subgroup, [3] Period, [4] Volume m^3, [5] Brand, [6] Transmission, [7] Number of meters, [8] Qstart [L/h], [9] Error [%] at different flow rates [L/h] and [10] Total average error.

meters errors are out of the limits in most of the units tested for the different flow rates. C3 water meters errors are in many cases out of limits with low flow rates (around the minimum), but within the limits for higher flow rates (with the only exception of one unit).

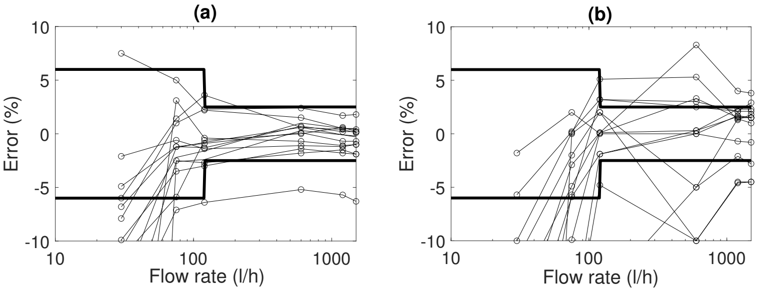

Fig. 2: Error vs Flow rate C3 (a) and A2 (b).

Even though the distribution in groups was very useful to choose a significant sample, the trends are clear if all the counters are taken as a whole, since the number of units for each group is not very high.

Fig. 3 shows the evolution of the error against the age (a) and against the registered volume (b). The error values obtained are dispersed but their magnitude have a clear tendency to increase (negative values) with both age and registered volume. Using a linear regression adjustment on the data, although with a low adjustment (R^2 around 10%) a pattern can be established,

$$E(t) = (-0.0896 \cdot 7.1734) \cdot 10^{-2} \tag{13}$$

$$E(V) = (-0.0005966 \cdot V - 7.57778) \cdot 10^{-2} \tag{14}$$

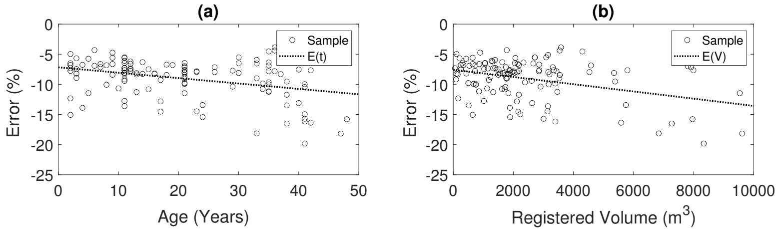

Fig. 3: Errors vs Age (a) and Registered volume (b).

Fig. 4 shows the error results obtained depending on type of transmission (a) and the brand (b). In general, the meters with mechanic transmission present higher errors than those with magnetic transmission, however the mechanic ones are also the oldest (DN13 water meters have magnetic transmission since 90´s) and therefore we cannot conclude that there is a clear influence of the type of transmission in the error magnitude. Additionally, there are not significant differences between both brands, only a slight tendency for older CdC meters to have poorer error values than those of Tavira.

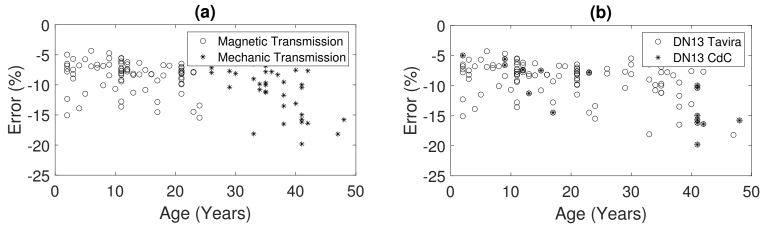

Fig. 4: Error vs Age-Transmission (a) and Age - Brand (b).

4.2 Economic study

For the economic study, the three methods described earlier were applied to the experimental results obtained. The input data of cost of water meter, price of water and the value of annual water consumption (similar in all years and meters) were supplied by the local water management company: C_c= 30.00 €, V_m= 80 m^3/year, C_w= 0.50 €/m^3.

- *Pay-Back*

As it was commented before, this methodology is suitable for the strategy based on maintaining the water meter park as upgraded as possible without economical losses.

In this case, with the error data obtained, the Pay Back Period is T_{PB}= 40.8 years. This may seem as a very long period, but it is a consequence of the low water price and that the meters degradation is quite slow. As commented previously, it is only an approximation without considering the income and the capital cost.

- *Net Present Value of replacement Chain*

$NPVC$ methodology has been applied to the case of study with a capital cost of r = 10% obtaining a T_R=94 years (Fig.5). Even though it is a long time, the $NPVC$ reaches a value close to the maximum at about 30 years, with a very small subsequent increase. So, also taking into consideration the further advantage of high accuracy, the renewal age can be anticipated without bearing too many financial losses.

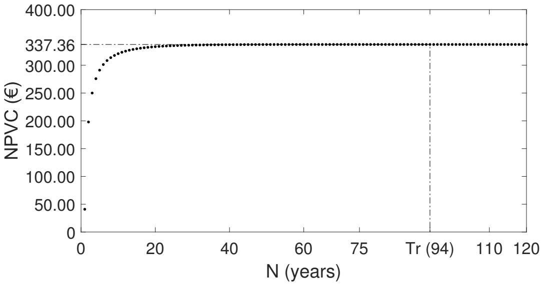

Fig. 5: NPVC vs Renewal Age.

Fig. 6 shows the results of renewal age against the water price for different water meter costs with a constant capital rate (r = 10%) (a), and capital costs with a constant water meter cost (C_C=30.00 €) (b). The functions decrease with the water prices in both cases, characterized by an elevated dependency (and value) of the renewal time in low prices scenarios (C_w <1.00 €/m^3), and low dependency (and smaller renewal times) in high prices scenarios (C_w >2.50 €/m^3).

The increment in the water meter cost (Fig. 6 (a)) or cost of capital (Fig. 6 (b)) leads, in both cases, to greater renewal times, more pronounced in low cost scenarios.

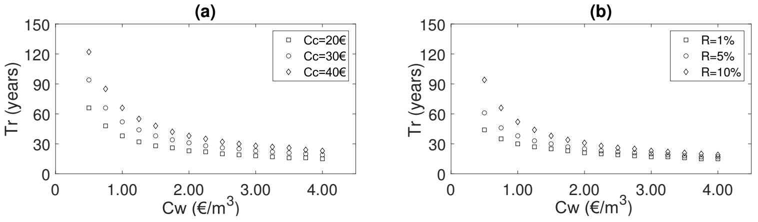

Fig. 6: Renewal period vs Water price. Water meter cost sensibility (a) and Capital cost sensibility(b).

Fig.7 shows the resulting effect of the water meter cost and capital costs, highlighting the importance of the water price. For high prices scenarios, the change of renewal time with meter and capital cost, is much less pronounced that in low prices scenarios.

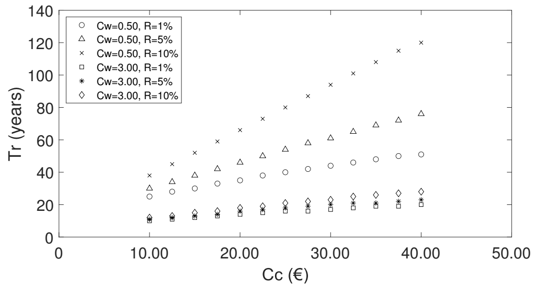

Fig. 7: Renewal period vs Water meter cost. Capital cost and Water price sensibility.

- *Accumulated volume*

The Accumulated volume method have been applied to the case of study obtaining a minimum cost value with V_R= 4485 m^3 (Fig.8). Most of the cost reduction occurs in the first 3000 m^3, therefore, if we want to limit the error increment, the meter can be changed earlier without substantial losses.

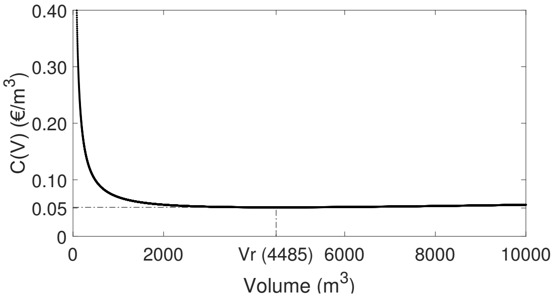

Fig. 8: Cost vs Registered volume.

Like with the $NPVC$ with the renewal time, the renewal volume V_R is a decreasing function of the water price (Fig. 9 (a)) with an important dependency with water prices in low prices scenarios and reduced in high ones. Also, the increment of the water meter costs rises the renewal volumes, effect that is amplified in low prices scenarios (Fig. 9 (b)).

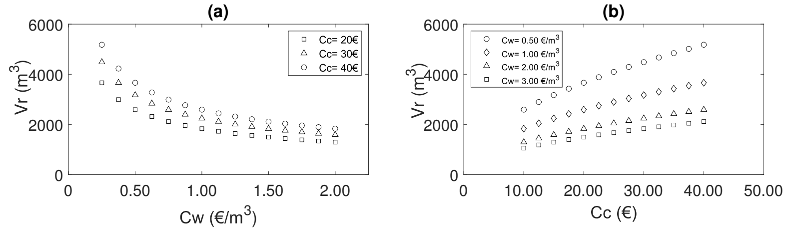

Fig. 9: Replacement volume vs Water price (a) Replacement volume vs Water meter cost (b).

5 Conclusions

A procedure is proposed including both technical and economic studies to evaluate the accuracy of a water meters park and to assist in the units renewal decision. The technical study defines a procedure to calculate and analyze the water meter errors. The economic study proposes three methodologies –Pay-back, Net Present Value of replacement Chain and Accumulated volume– corresponding to the application of two water meter renewal strategies (maintain the water meter park as upgraded as possible without economical losses, or maximize the profits).

The procedure has been applied to the water meter park of a medium-sized Spanish city. The results indicate that the error is influenced by the measured volume and age, but neither the type of transmission nor the brand made any substantial difference. The different economic methodologies were applied with the calculated meter errors and the actual costs and prices of this city. The pay-back period obtained is about 40 years and the renewal period ($NPVC$ method) about 94 years, however after 30 years of installation the increment of the profits is very reduced. The replacement volume (Accumulated Volume method) for minimum costs was about 4500 cubic meters.

The sensibility analysis shows that the renewal period is a decreasing function with the water prices, characterized by rather lengthy renewal periods for low water prices and a tendency to stabilize for higher prices. Increasing the water meter cost or cost of capital, increase renewal periods and amplifies dependencies in low price scenarios with a very attenuated effect for high prices. Similar qualitative results of tendency and dependency in function of the water prices are found with the replacement volume function.

Acknowledgements The authors want to thank the collaboration of the “Empresa Municipal de Aguas de Gijón (EMA)”. This work has been carried out in the framework of the Research Grants 2018-2020 (reference FC-GRUPIN-IDI/2018-000205), funded by the Govern of the Principality of Asturias (Spain) and co-funded by ERDF.

Conflict of interest

The authors declare that they have no conflict of interest.

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