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Impact of float-valves on water meter performance under intermittent and continuous supply conditions

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ABSTRACT

Intermittent supply is common worldwide. It triggers households with piped connection to adjust the supply scheme by the use of a water tank with a float valve (FV) at the entrance, which has a major influence on the water meter accuracy. This study investigated the impact of the water tank with a FV on the performance of water meters under intermittent and continuous supply conditions, using laboratory experiments, field measurements, and hydraulic modeling. Results revealed that the inflow rates into the water tank are consistently lower than the outflow rates of the tank. This will always be the case owing to the balancing mechanism of the tank. The flows that pass through the water meter represent the inflows into the tank. Therefore, higher metering errors and more apparent losses are expected for a combination of a water tank, FV, and continuous supply. Besides, different FV types have different hydraulic characteristics. Larger FVs with higher discharge rates tend to maintain the water level close to the full level in the tank and conferred longer periods of low flows, worse meter performance, and more apparent losses. For intermittent supply, results confirmed that higher intermittency levels lead to improved performance of water meters and reduce the apparent losses. This points to the complication in transformation from intermittent to continuous supply worldwide. In this case, water utilities should expect higher meter errors and more revenue losses unless the meter replacement policy recognises lower flows passing through the meter.

1. Introduction

The water meter is a cash register, a system management tool, and a conservation instrument. Yet, water meters are not absolutely accurate measuring instruments. All water meters, including new ones, have drawbacks. Varied measuring limitations exist for different meters, depending on the metering technology and the meter class (Arregui et al., 2006; Van Zyl 2011). Mechanical meters are commonly used to measure the water consumption for customers of water utilities. They are either volumetric meters that measure pockets of water directly such as rotating piston meters, or inferential (or velocity) meters that infer the volumetric flow rate from the velocity of the water, such as Woltmann, Single, and Multi-Jet meters. Electromagnetic and ultrasonic meters are marginal technologies that are used in limited, specific cases because of their high cost and power requirements. They detect water velocity using electromagnetic principles and ultrasound waves. To evaluate the performance of new meters, several standards and guidelines exist (ISO 2014a; ISO 2014b; OIML 2013a; OIML 2013b). Each new meter has to be tested at four main flows (ISO 2014a; OIML 2013a): the minimum flow rate (q_1 or q_{min}), the transitional flow rate (q_2 or q_t), the permanent flow rate (q_3 or q_p), and the overloaded flow rate (q_4 or q_{max}). Recommendations on the selection of the appropriate meter type are proposed based on the consumption data (Johnson 2001) and criteria that include low flow accuracy, ability to pass particulates, and accuracy degradation rate (Mutikanga 2014).

Once the meter is installed in the field, its performance starts to decline. The field meter accuracy is determined by several factors (Arregui et al., 2005; Criminisi et al., 2009; Thornton and Rizzo 2002) including meter wear and tear, blockage of the meter inlet or strainer, depositions of the meter components, incorrect sizing, incorrect mounting position, and incorrect flow profile. While volumetric meters such as the oscillating piston and nutating disk are sensitive to water quality and suspended particles, velocity meters such as single and

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multiple jet meters are more sensitive to low flows and drag torque on the sensor element. There are ample studies in the literature on the field performance of the meter (Arregui et al., 2006; Couvelis and Van Zyl 2015; Ethem Karadirek 2019; Mantilla-Peña et al., 2018; Moahloli et al., 2019; Ncube and Taigbenu 2019; Stoker et al., 2012; Walter et al., 2018; Yazdandoost and Izadi 2018). The inaccuracy level of the used meters depends on the metrological performance of the meter at each flow rate. The share of the flow rate that passes through the meter is, therefore, a governing factor of the meter accuracy (Arregui et al., 2006; Fontanazza et al., 2015; Male et al., 1985). Obviously, the meter performance at low flows is critical (Arregui et al., 2015; De Marchis et al. 2014; Richards et al., 2010). Of the total flow passing through the meter, the higher the proportion of the low flows, the higher the meter inaccuracy. This shows the effect of the consumption profile on the meter accuracy. For this reason, the weighted error of the meter is proposed (Arregui et al., 2006; Shields et al., 2012) to relate the demand consumption flows to the error level of the meter. The weighted error considers the consumption flows that pass through the meter, therefore, it is a good indicator of the meter's field metrological performance. However, this should not be the case in intermittent supply where a water tank with an attached float-valve (FV) exists (De Marchis et al. 2014; De Marchis et al. 2015; Tamari and Ploquet 2012). A network affected by intermittency is stressed by repetitive pressure transients (with entrapped air), causing network deterioration, more leaks and breaks and contamination risks. Once a network affected by intermittency is restored to continuous supply, leakage level increases significantly in the network (Kanakoudis et al., 2016), due to higher pressures during off-peak hours and longer periods of the leaks' run time. In an intermittent supply regime, depending upon the location of the water meter and water tanks, the meter accuracy is affected by the iterative filling and emptying process of the water tank. Rizzo and Cilia (2005) tested and compared the accuracy of a meter installed at the inlet of a water tank with a meter installed at the outlet of the water tank associated with a FV, and found that the inlet meter constantly under-recorded between 5 and 9% of the water measured by the outlet meter. This was due to the effect of the FV and the filling process in the tank. Criminisi et al. (2009) developed a mathematical model to simulate the same arrangement of water tank, FV, water meter, and user consumption. The tank filling process depends on the network pressure, FV characteristics, and tank water level. However, some of the model parameters required laboratory characterization and cannot be generalised for all systems. De Marchis et al. (2013) implemented a mathematical model to assess apparent losses caused by meter under-registration based on a hydraulic network model, a pressure-reducing valve model, a pressure-driven demand, and an apparent losses model, considering the complexity of private tanks yet with constant valve characteristics. The combined influence of pressure reduction and tank filling on the meter error was highlighted by De Marchis et al. (2014) who implemented the model developed by Criminisi et al. (2009). In a specific FV and tank arrangement, they found that meter inaccuracy tends to be over-registration for conditions of intermittent supply where the tank is subjected to cyclical emptying and filling. When the tank is always nearly full, they found that meter inaccuracy tends to be over-registration. The study recommended more investigation with other FV and tank characteristics. This paper presents the results of a study carried out to investigate the impacts of different water supply intermittency and continuity conditions and different tank and FV characteristics on the customer meter performance and level of apparent losses. The influence of intermittent supply level on the apparent loss level was investigated and impact of transforming from intermittent to continuous supply was highlighted for customers whose supply system contains a water tank and FV arrangement. The effects of the characteristics of different FVs and tank sizes were also analysed. The results of this study will aid water utilities to understand the impact of critical factors affecting apparent losses and will assist them in managing apparent losses in distribution networks where intermittent supply and private water tanks with FVs are common.

2. Research methodology

In principle, the meter accuracy is affected by the FV flow rate, which is affected by the water level in the tank, which is affected by the water consumption during the day. Therefore, the methodology of this study started by first defining the meter error—flow relationship, based on bench test experiments for a sample of used meters. Second, the hydraulic characteristics of the FV were experimented to obtain the FV resistance coefficient (K) for each corresponding water level in the tank (h). Non-linear regression analysis was used to empirically model the relationship between K of the FV and the water level in the tank, h. Third, the inflow into the tank varies based on the FV closure level, which depends on the water level in the tank. The water level in the tank and the corresponding inflows are, in particular, modelled hydraulically using a spreadsheet hydraulic model developed for this purpose. The hydraulic model has specific key inputs: field consumption measurements, K—h relationship, and other hydraulic parameters including: inlet pressure, tank elevation, tank size, and friction and roughness of the service connection between the water meter and the water tank. Using the flow—error relationship of the meter, K—h relationship of the FV, and the hydraulic model, the error of the meter can be computed in the model during the course of the day. Afterward, different sensitivity analyses for different intermittency degrees and tank sizes were conducted by changing the model inputs. Finally, to recognize the effect of the FV type, the above steps were carried out for three different types of FVs. The following parts elaborate on the study's methods and experiments.

2.1. Determination of meter errors for extended flow range

Laboratory experiments were conducted during December 2018 at the Bandung Metrology Center (Indonesia) to determine the errors in customer water meters for extended flow range. Thirteen used meters were collected from the field in Bandung city and replaced with new meters. The meters were class B, multi-jet mechanical meters, with a diameter of ½" (15 mm), representing five types of different manufacturers, and with different ages that ranged between 7 and 19 years. The meters were tested using a standard water meter test bench that includes a water pump, stop valves, flow regulating valves, three flow meters (rotameters, viscosity and gravity type), and a standard water tank. The tests were carried out at pressures up to 400 kPa and a temperature of 28 °C. The testing procedures were in accordance with EN 14,154–3 and other recommendations (Arregui et al., 2006; ISO 2014b; OIML 2013b), where the reading of the meters were taken at rest. The error of each meter was then calculated using Eq. 1.

$$\varepsilon = \frac{(V_i - V_{i-1}) - V_a}{V_a} \times 100 \tag{1}$$

where ε is the error of the meter (%), V_i is the reading of the meter when the test stopped (m^3), V_{i-1} is the reading of the meter just before the test starts (m^3), and V_a is the total volume in the standard tank (m^3). The meters were tested at five critical flows of the meters: q_{start} (10 l/h), q_{min} (30 l/h), q_t (120 l/h), q_p (1500 l/h), and q_{max} (3000 l/h). However, to enhance the accuracy of the established error curve, the meters were further tested at 10 other flows. These flows were: 15, 20, 35, 40, 200, 300, 400, 500, 600, and 1000 l/h. In total, there were 15 test flow rates, to establish a more detailed and reliable error curve that incorporates all range of expected flows in this study under continuous and intermittent supply conditions.

2.2. Investigating the FV characteristics

A laboratory experiment was also carried out during January 2019 at the Bandung Metrology Center (Indonesia) to assess the hydraulic characteristics of different FV types (mainly the FV resistance coefficient K but also the distance of the FV movement trajectory, commonly known as the modulation range). To simulate the intermittent supply scheme in the lab, additional equipment was required. Three different brands of FVs with two common sizes ½" (15 mm) and ¾" (20 mm) were obtained from the local market and attached to a small water tank with a capacity of 100 l and a cross-sectional area of 2692.3 cm^2. This equipment was connected to a portable ultrasonic flow meter ($q_{start} = 6$ l/h and $q_{min} = 10$ l/h) and a pressure regulating valve.

The inflow into the tank is, in principle, the same flow that passes through the flow meter. When the water level in the tank rises to the FV level, the FV starts to close, and simultaneously the flow starts to lower. The data obtained from this process is the flow rate and the volume and time of each flow. The ratio of the water volume to the cross-sectional area of the tank gives the water level in the tank, h (mm). The difference between h when the FV starts to move and h when the FV is at a complete stop is the modulation range of the FV. Based on the flow data and water level in the tank during different times, the K of the FV can be calculated using Eq. (2) (Crane_Co. 1957; Mckenzie and Langenhoven 2001).

$$K_i = \frac{P}{Q^2} \tag{2}$$

where K_i is the FV flow resistance coefficient (m.(l/s)$^{-2}$) at a specific water level in the tank h_i (mm), P is the pressure (kPa) before the FV, and Q is the inflow into the tank (l/s). Once the FV characteristics are known, they can be used to simulate the filling process for other hydraulic conditions and tank sizes. The pressure of the experiment was set to 210 kPa when the FV was fully closed. When the FV was fully opened, an inflow of 0.11 l/s occurred with a pressure of 50 kPa. These settings were determined based on preliminary field measurements of flows and pressures at water meters of 30 customers in Bandung city. Field network pressures and flows were measured between November 2018 and January 2019. Measurements were obtained upstream the water meter using calibrated portable ultrasonic meter. The meter (Linflow PF20A) has a size of 15 mm, resolution of 0.01 l, maximum error of ± 1% at 10 l/h, maximum pressure of 1000 kPa, and maximum flow of 1500 l/h.

The resulting K_i values (58, 52, and 19 K_i values for FV1, FV2, and FV3 respectively) for each corresponding water level in the tank h_i were then studied. A regression analysis was conducted to determine the relationship between the water level in the tank h_i (mm) and the FV coefficient K (m.(l/s)$^{-2}$). To obtain a h—K_i relationship, a non-linear regression analysis was conducted using a specific software tool (CurveExpert Pro 2.6.5). The software library contains several data fitting models including the Bleasdale Model, Hoerl Model, and Logistic Model. The Bleasdale Model presented in Eq. (3) was selected to model the experimental data.

$$K = (\alpha + \beta h)^{\frac{-1}{\gamma}} \tag{3}$$

where K is the FV resistance coefficient (m.(l/s)$^{-2}$), h is the water level in the tank (mm), and α, β,and γ are the fitting factors of the equation. The values of the α, β, and γ factors were further optimised using the Microsoft Excel Solver, where the total value of the residual sum of squares (*RSS*) was minimised. After defining the model that fits the experimental data including its factors, k can be determined at any water level in the tank and for different tank sizes and hydraulic conditions.

2.3. Modeling the water level in the tank

The water level in the tank can be modelled using the tank continuity equation (Eq. (4)) based on the inflow and outflow of the tank, as follows:

$$Q_i - Q_{out} = A\frac{dh}{dt} \tag{4}$$

where Q_i is the inflow into the tank, Q_{out} is the discharge out of the tank, and A is the cross-sectional area of the tank. Q_i At any specific time, can be determined based on the Bernoulli and Darcy-Weisbach equations, as shown in Equation 5.

$$Q_i = \sqrt{\frac{\frac{P}{\gamma} - (Z_2 - Z_1)}{K_p + K}} \tag{5}$$

where Q_i is the inflow into the tank (l/s), $\frac{P}{\gamma}$ is the network pressure at the water meter (mwc), $Z_2 - Z_1$ is the elevation difference between the inlet of the tank and the water meter (m), K is the FV coefficient, and K_p is the pipe headloss coefficient between the water meter and the inlet of the tank, which can be calculated using Eq. (6).

$$K_p = \frac{8fL}{\pi^2 g D^5} \times 10^{-6} \tag{6}$$

where K_p is the pipe headloss coefficient (m.(l/s)$^{-2}$) that also considers minor losses, L is the length of the pipe between the water meter and the FV (m), D is the pipe diameter (m), g is the acceleration of gravity (m/s^2), and f is the Darcy-Weisbach friction factor (unit-less) which is calculated by iteratively solving the Colebrook-White equation that is presented in Eq. (7) (Colebrook and White 1937; Colebrook 1939).

$$\frac{1}{\sqrt{f}} = -2log\left(\frac{\varepsilon}{3.7\ D} + \frac{2.51}{Re\ \sqrt{f}}\right) \tag{7}$$

where ε/D is the relative pipe roughness and R_e is the Reynolds number.

In contrast, measuring or estimating Q_{out} is crucial in the modeling of the filling and emptying process of the tank. The resolution of the Q_{out} data should fit the resolution of the model. In this study, a high-resolution model was built with a time step of 5 s. To incorporate proper data in this model, high-resolution logged measurements were obtained. The measurements of a domestic customer consumption were logged by the water company in Castellon, Spain for one week, from March 18 to March 25, 2008. The aim was to model the water level and inflows into the tank using a real high-resolution consumption profile. Any other consumption pattern might amend the calculated weighted error in the model, but will not significantly change the trends of the results. The consumption flows were measured using an oscillating piston meter (Aquadis+ from ITRON). The meter is Class C with size of DN15, q_{start} of 1 l/h, q_{min} of 15 l/h, volume resolution of 0.1 l, and time resolution of 0.02 s. The measurements were logged using Sensus loggers with pulses event times recorded with a resolution of 0.02 s and memory capacity of 256,000 registers. The data was then processed by coding a macro in Microsoft Excel using Visual Basic. The flow data was re-generated every 5 s in the course of the day, to fit the model time step. The instantaneous demand consumption flows during the day were then inserted in the model. The tank size was initially set to a small water tank with a capacity of 500 l and typical dimensions of 1110 mm height, 923.7 mm maximum water level in the tank, and 830 mm diameter. Afterwards, different tank sizes were modelled to analyze the sensitivity of the model to the tank size. Based on all of the above input, the water level in the tank can be modelled at a time step of 5 s and with high-resolution instantaneous consumption.

2.4. Analysis of meter inaccuracies

The accuracy of the water meter is a function of the flow rate that passes through the meter. Therefore, the meter accuracy varies according to the different flows that pass through the meter during the day. In fact, the flows that go through the water meter are the consumption flows. However, for intermittent supply with a water tank and FV arrangement, the flows that go through the meter are not the consumption that discharges out of the tank, rather, they are the inflows into the tank. These inflows are influenced by the instantaneous consumption discharges, network pressure, and the water level in the tank.

In order to obtain a meaningful meter accuracy that describes the actual field condition, the water volume that is actually consumed at each flow rate should be multiplied by the meter error at this flow rate. The summation of this process for all the flows during the day should be divided by the volume of the total water consumption of the day, to give the meter weighted error (Arregui et al., 2006; Shields et al., 2012). In this study, the error curve of the tested meters was established based on the extended range of 15 test flow rates. The error-flow relation was analysed by non-linear regression analysis using CurveExpert Pro 2.6.5. The best fit model in the tool library was the Rational Model which is presented in Eq. (8). The factors of the model were optimised, and then the meter error can be determined at any flow.

$$\varepsilon = \frac{a + bQ_i}{1 + cQ_i + dQ_i^2} \tag{8}$$

where ε is the error of the meter (%); *a, b, c*, and *d* are the equation fitting factors; and Q_i is the inflow rate (l/h). After the flow—error relation is well established, the meter weighted error can be calculated based on the instantaneous inflows into the tank.

The impact of different flow profiles on meter errors was recognised in this study. A comparison was conducted between the continuous water supply without a water tank and continuous supply with a water tank and FV. This was done by calculating the meter errors for the histogram of the consumption flows (discharges out of the tank) and for another histogram of the inflows into the tank. The results were also compared to the meter errors that were generated considering two other typical flow profiles in the literature (Arregui et al., 2015; Arregui et al., 2006).

2.5. *Investigation of the impact of intermittency*

The impact of intermittency on the meter performance was investigated by imposing different intermittency levels in the model and then analysing the inflows and the meter errors. Some systems are intermittent supply with one or two full supply days during the week. In this case, the supply becomes continuous supply for one or two days. Other assigned supply scenarios included very short supply time: 2 h/d; short supply time: 4 h/d; average supply time: 8 h/d; long supply time: 20 h/d; and continuous supply: 24 h/d. These intermittency levels are similar to realistic intermittent supplies (IBN 2020). The 20 h/d supply scenario was assumed to occur from 00:00 AM to 12:00 PM and then from 16:00 PM to 00:00 AM. Thus, the intermittency in this scenario occurred for four hours between 12:00 PM and 16:00 PM. The inflows into the tanks were studied in this scenario and the meter error was calculated at a time step of 5 s. This approach was implemented for the supply scenario of 8 h occurring between 8:00 AM and 16:00 PM, the supply scenario of 4 h/d occurring between 8:00 AM and 12:00 PM, and the supply scenario of 2 h/d occurring between 10:00 AM and 12:00 PM. After the different intermittency scenarios were analysed, the impact of the intermittency on the meter performance can be concluded and compared to the situation of continuous water supply.

2.6. *Sensitivity analysis - different tank sizes*

Finally, the impact of various water tank sizes with FV on the performance of the water meter was assessed. This was conducted by simply altering the tank capacity in the model and analysing the resulting inflows into the tank.

3. Results and discussion

3.1. *Meter error curves*

Fig. 1 shows the error curves of the tested meters: Fig. 1a shows the individual error curves for each meter, Fig. 1b shows the average error curve for each meter type where the same type of meters was grouped, and Fig. 1c shows the average error curve of all the tested meters. The meter performance clearly varies, with high error at low flows and a better accuracy at higher flows. At a certain threshold in the lower zone, the meter starts to slightly over-register the passing flow, and this becomes the trend for the permanent flow in the upper zone. Figs. 1a and 1b show that the performance of the water meter varies because each individual meter differs in terms of age, type, and operating conditions. The tested meters were, therefore, grouped based on their age, size, and type, to minimize the variance and propose a sound meter replacement policy. These groups of the tested meters based on their age and model are presented in Annex 1 in the supplementary material. Fig. 1c shows the errors at different flow rates. The average errors for q_{start}, q_{min}, q_t, q_p, and q_{max} and the standard deviations, shown in brackets, are −85.06% (19.74%), −11.7% (30.27%), 2.21% (2.75%), 0.96% (2.61%), and 1.99% (3.54%), respectively. The average curve error in Fig. 1c was used in the subsequent analyses because the focus of

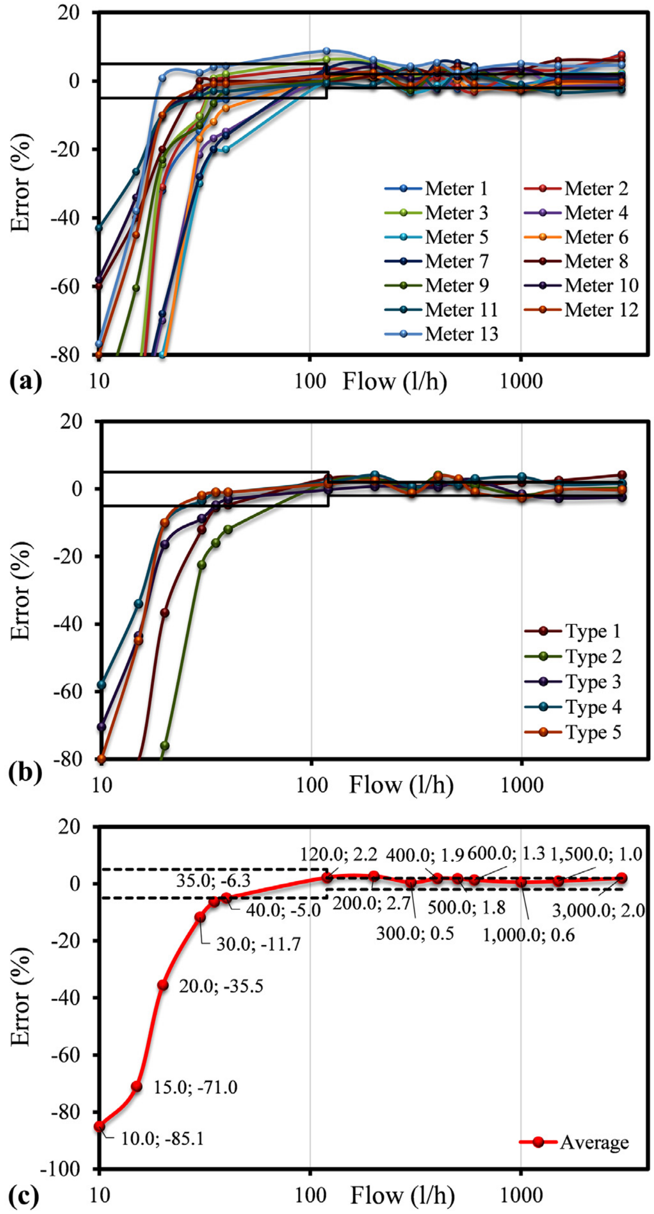

Fig. 1. Error curves of tested meters: a) individual error curves, b) error curves by meter type, and c) average error curve.

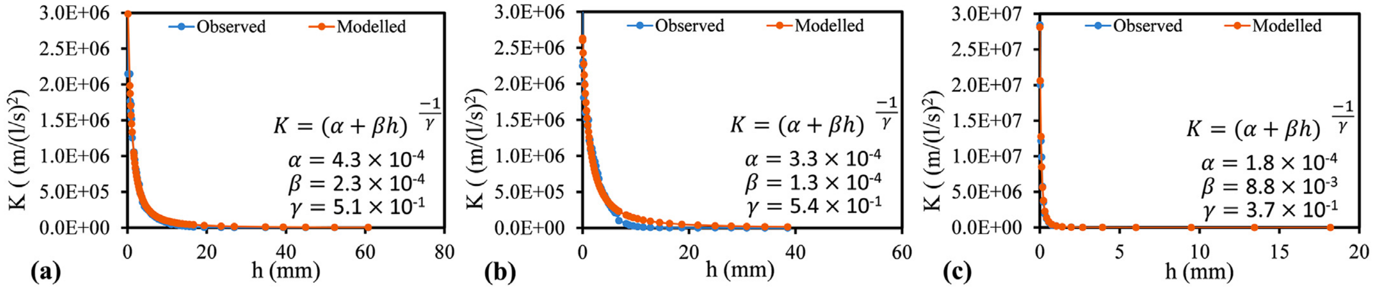

Fig. 2. Experimental and modelled FV coefficients at different openings of the valves: (a) FV1, (b) FV2, and (c) FV3.

this research was not to propose a meter management policy but to figure out the impact of the FV on the meter performance.

3.2. FV characteristics

The detailed characteristics of the FVs are presented in Annex 2. The valves have different sizes and modulation ranges. The modulation ranges are 60.74 mm, 38.50 mm, and 18.19 mm and the sizes are ½" (15 mm), ¾" (20 mm), and ¾" (20 mm) respectively for FV1, FV2, and FV3. However, as the nozzle and washer of the FVs can differ in size and discharge, the hydraulic characteristics of the FVs can be expressed in the form of the K values of the FV. Fig. 2 shows a plot of the K values of the three FVs as a function of the valve openings. The non-linear regression model that gave the best fit for this data was the Bleasdale Model (Eq. (3)), with R^2 of 0.97, 0.94, and 0.99 for FV1, FV2, and FV3, respectively. R^2 is, in fact, not sufficient to indicate the fitting of the experimental data. Fig. 2 shows the difference between the modelled and experimental K values of the FVs. Deviations occurred between the modelled and experimental K values toward the fully open status of FV2, and to a lesser extent, of FV1. The impact of the K deviations on the hydraulic model is not critical. For the purpose of this study, the Bleasdale model can be used to determine the K value of each FV at any height of the tank, which is important in determining the inflow into the tank as shown in Eq. (5). The α, β, and γ fitting parameters of the Bleasdale Model are also presented in Fig. 2.

3.3. Impact of different consumption patterns

Fig. 3 shows different consumption patterns of domestic water usage. The water volume (l) for each flow range (l/h) was summed up and divided by the total consumption volume. Fig. 3a shows a typical consumption pattern for urban households (Arregui et al., 2006), Fig. 3b presents an example of a consumption pattern for a household with a water tank (Arregui et al., 2015), and Fig. 3c presents a histogram of the field consumption measurements in Spain that were obtained for this study. The meter performance varies when the flow that passes through the meter varies. For this reason, the weighted error according to the consumption is crucial in indicating the performance of the meter in the field (Arregui et al., 2006; Shields et al., 2012). Based on the used meter experiments and the established average error curve, the weighted errors of FV1 were −4.2%, −8.7%, and −0.7% for consumption patterns a, b, and c, respectively. The consumption pattern in Fig. 3c has a significantly lower proportion of the lowest flow range, and thus a lower error level. Calculating several metering errors for the same meter sample confirms the significance of the weighted error methodology in indicating the performance of the meter. Furthermore, the consumption pattern in Fig. 3c represents the consumption pattern after the tank, at the outlet of the tank, which is used by the customer. However, once this consumption pattern is modelled instantaneously for the water tank and FV model, the critical flows will not be the consumption flows, but the corresponding inflows into the tank which are, in this case, the flows that pass through the meter. Interestingly, these tank inflow rates are generally lower than the consumption flow rates. The low flow rates in Fig. 3d are more significant as in the flow rate ranges of 12–24 l/h, 24–36 l/h, and 36–72 l/h. Therefore, the flow pattern in Fig. 3d has a higher weighted meter error (−1.24%), as elaborated further in the following section.

3.4. Modeling the water level, FV, meter error, and continuous supply

The left panels of Fig. 4 show the modelled water level in the tank, while the right panels show the modelled inflow into the tank with its corresponding meter error for each FV. The instantaneous consumption lowers the water level in the tank, and immediately thereafter, the FV opens and a refill process begins. The refilling process differs between the FVs depending on the hydraulic characteristics (K) of the FVs. The difference between the inflow and the outflow of the tank causes the water level in the tank to fluctuate. Interestingly, Fig. 4 also confirms that the inflow rates in the tank are constantly less than the consumption discharge rates out of the tank. Thus, for the same consumption pattern, the water tank and FV reduce the flows that pass through the water meter, resulting in higher meter errors.

Different FVs have different hydraulic characteristics which influence the inflow rates and water level in the tank, ultimately influencing the water meter performance. Fig. 4a shows the water level and meter error with FV1 (size ½" [15 mm], modulation range 60.74 mm) in a typical tank with a net height of 923.7 mm. The error of the water meter oscillates in accordance with the inflow into the tank, yet with an average error of −7.47% (for 76% of the time, when there is an inflow into the tank) and a weighted error of −1.24%. Fig. 4b shows the water level and meter error with FV2 (size ¾" [20 mm], modulation range 38.50 mm); the average error was −6.88% and weighted error was −1.12%. Fig. 4c shows the water level and meter error with FV3 (size ¾" [20 mm], modulation range 18.19 mm); the average error at −9.77% and weighted error at −1.74%. Although FV1 and FV2 are different in size and modulation range within the tank, they have close hydraulic characteristics and error levels. This is because the size and modulation range of the FV, in addition to the sizes of the nozzle and washer inside the FV, influence the discharge rate of the FV, as illustrated in Annex 2.

Conversely, FV2 and FV3 are the same size. However, FV3 allows higher inflows, refills the tank faster, and introduces higher flows. As a result, the water level remains close to the full level in the tank. Typically, the water meter performance improves with higher flow rates and worsens at low flow rates. Nonetheless, FV3 has higher flows than FV1 and FV2, but interestingly FV3 has higher errors, as shown in Fig. 4c. To explain this, when an instantaneous consumption is imposed, for every instantaneous consumption a flow immediately comes in and fill the tank to its full level. Thus, the inflow into the tank grows from zero to a certain value and then falls back to zero. In the case of FV3, this process is fast and the cycle is completed before the next instantaneous consumption occurs. On the contrary, the discharge rate of FV1 and FV2 is lower, resulting in lower inflow rates and a slower filling process. The inflow to the tank grows from zero to a certain level

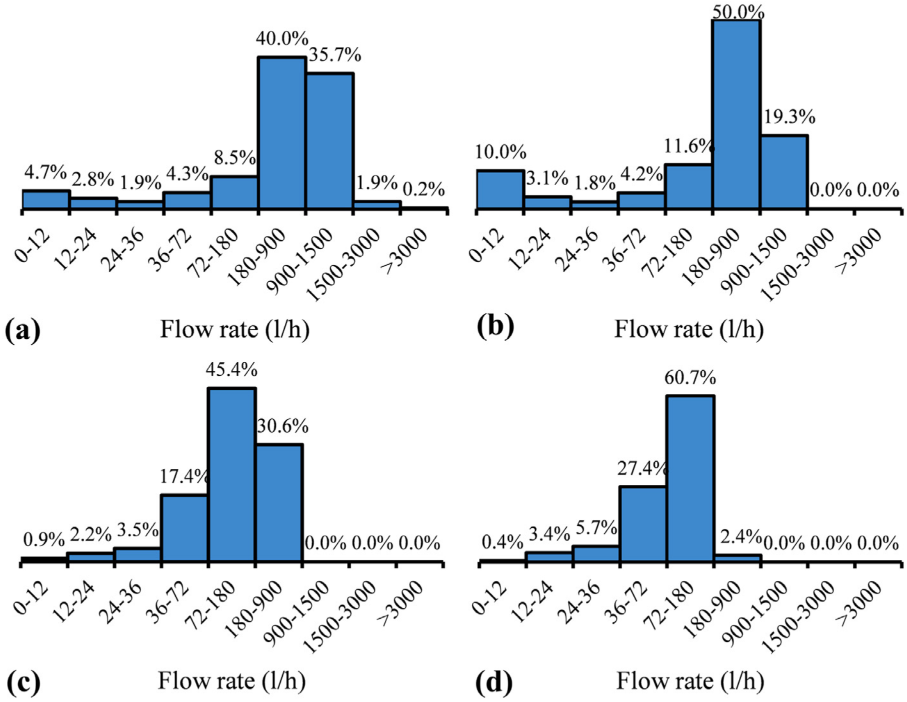

Fig. 3. Histogram of three consumption patterns: (a) typical consumption profile (Arregui et al., 2006), (b) typical consumption profile for premises with water tanks (Arregui et al., 2015), (c) histogram of field measurements, and (d) histogram of modelled inflows into the tank corresponding to consumption outflows of the tank.

and then falls back, but the next instantaneous consumption occurs before the inflow returns to zero, increasing again the inflows and causing further drops in the water level in the tank. This process, in the case of FV1 and FV2, causes the ultimate low flows (0 – 24 l/h) to occur less frequently during the day. As a result, the low flows of FV1 and FV2 occurring during the day are larger in value and for shorter durations than the low flows of FV3, and therefore, the error level of FV3 is higher than the error levels of FV1 and FV2.

To conclude, for the case of combining continuous water supply with an arrangement of water tank and FV, the performance of the water meter improves when the FV discharge rate is lower. This implies that the use of smaller FVs results in better water meter performance and bigger FVs accommodate larger flows but cause higher meter errors. The influence of the length of the modulation range of the FV on the discharge rate of the FV should be investigated. If FVs with a shorter modulation range have higher discharge rates, then a longer modulation range of the FV should trigger better meter performance.

3.5. *Impact of intermittency on the meter performance*

Fig. 5 presents the water level in the tank and meter error within a supply time of 8 h/d with three different FVs. In this scenario, water is supplied between 8:00 AM and 16:00 PM. Although the supply time is only 8 h/d, the timing of the supply corresponds to the consumption pattern that discharges out of the tank, such that the water level in the tank remains above zero. Thus, there is always water for consumption during the course of the day. Other supply time scenarios have been analysed, too. Annex 3 shows the meter error and water level in the tank with a supply time of 2 h/d, 4 h/d, and 20 h/d, where the water level in the tank drops to zero and the consumption in this case was loaded uniformly during the following supply time. As shown in Fig. 5, when the water level drops in the tank, the FV opens fully and higher inflows occur. The higher the intermittency level, the longer the FV remains open, and the higher will be the inflows into the tank. Expectedly, the meter performance improves in intermittent supply, and the lower the number of supply hours, the lower the under-registration level of the meter. Moreover, when the system regime is intermittent supply, the entrapped air in the network discharges through the water meters, causing further over-registration of the mechanical meters.

Table 1 shows the water meter errors under different intermittency levels, for the three FVs, and without considering the over-registration caused by the air pockets travelling through the meters. The trend is nearly consistent; less under-registration was observed when more intermittency was imposed. At a certain degree of intermittency, the average error of the water meter becomes higher than zero, and the meter error is on average not under-registered but over-registered. Even though this is profitable for the water utility, it is important to consider that supply intermittency has other severe consequences on the network, e.g. meter damage, more transients, higher burst rates, more network fatigue, water quality deterioration, and poorer service level.

3.6. *Impact of the tank size on the meter performance*

Fig. 6 shows the water level, consumption, and inflow into the tank with FV1 and four different tank sizes: 500 l, 1000 l, 2000 l, and 5000 l. This analysis is conducted for the continuous supply scenario. These tank sizes have the same height (923.7 mm), and thus the tank size is changed by adjusting the surface area of the tank through increasing the diameter of the tank. When the tank size increases, the consumption event causes a lower decrease in the water level in the tank, and thus lower FV inflow into the tank. The instantaneous consumption is the same for the four tanks, yet the inflow and the water level in the tank is smoother and with less spikes as the tank size becomes larger. This is because the balancing effect of the tank is more significant when the tank size is bigger. The instantaneous consumption has less impact on the water level, and therefore, the water level falls slightly in the tank, and the water level curve in Fig. 6 becomes more uniform. When the inflows into the tank are more uniform and with less spikes, the range of flows shrinks and the ultimately low flows occur less during the day.

Fig. 7 shows the inflow and the corresponding meter errors with FV1 and different tank sizes. The inflow values (l/s) for each time step of the model (5 s) are very low, and therefore converted to (l/h) by simply multiplying these values with 3600. Annex 4 shows the water level, inflows, and meter errors for the tank arrangements with FV2,

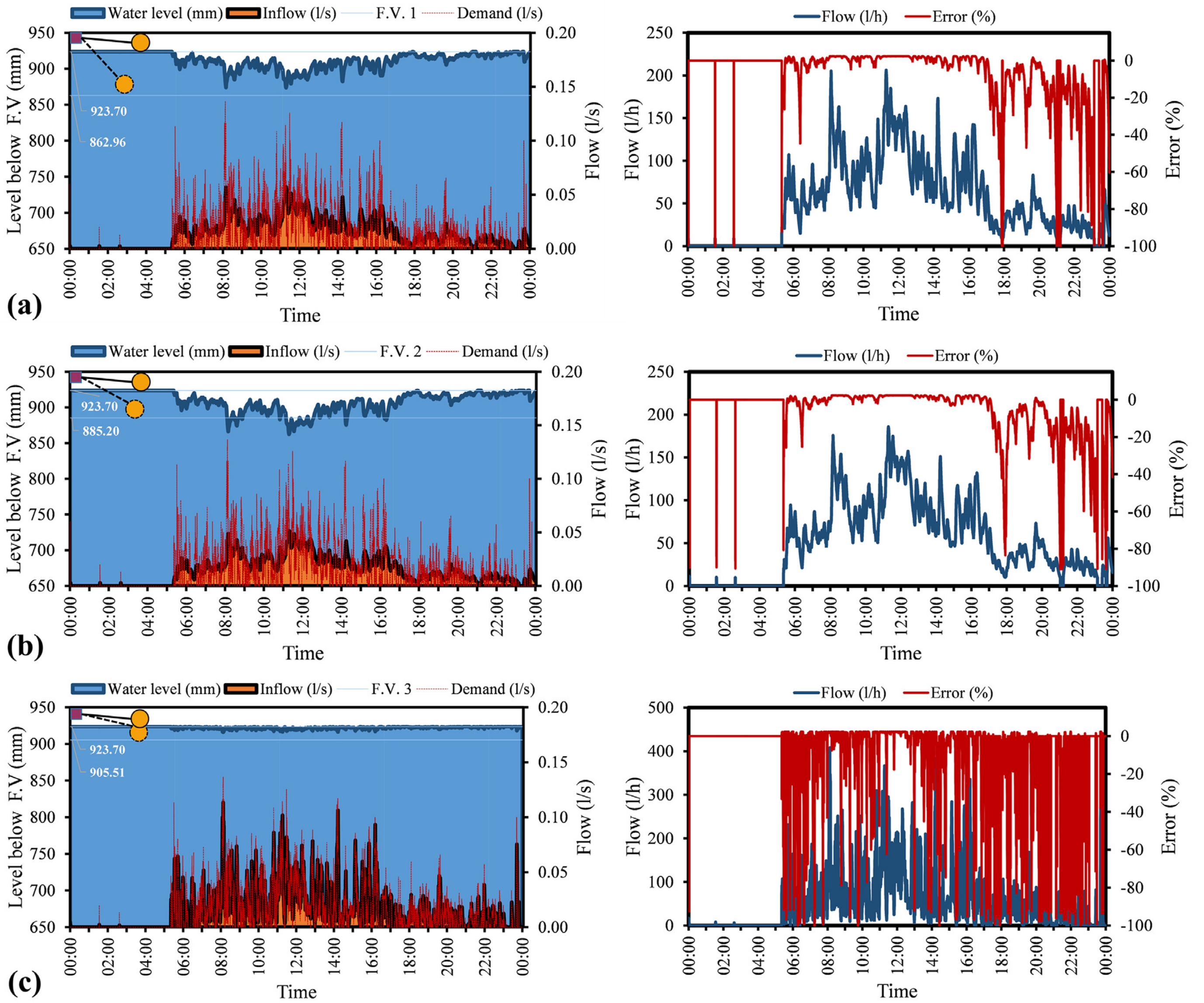

Fig. 4. Water level in the tank (left) and meter error corresponding to the inflow (right) according to the type of FV: (a) FV1, (b) FV2, and (c) FV3. (Continuous supply, 24 h/d).

FV3 and different tank sizes. The trend remains the same. The larger the tank size, the more time is required to fill the tank back to its full level, and the more uniform its inflows become. With FV1, the average errors of the meter were −7.64%, −7.46%, −6.60%, and −4.75% with tank sizes of 500 l, 1000 l, 2000 l, and 5000 l, respectively. Similarly, the weighted errors with FV1 were −1.24%, −1.33%, −1.26%, and −1.03% with tank sizes of 500 l, 1000 l, 2000 l, and 5000 l, respectively. Annex 4 presents the same results for the tank arrangements with FV2 and FV3.

Unexpectedly, these results suggest that larger tank sizes confer better meter performance and less error levels because the inflows into the tank is more uniform. The governing factor in this specific problem is not the size of the tank, but the time required to refill the tank and bring the water level in the tank back to its full level. With larger tank sizes, the water level drops slightly in the tank and the FV opens slightly, causing a lower inflow rate that requires a longer time to refill the tank. If this ‘filling time’ is shorter than the time difference between the first instantaneous consumption and the next instantaneous consumption, then more metering errors will occur with bigger tank sizes. To clarify this point further, Fig. 8 shows the inflow range that discharges into the tank for two tank sizes with FV3 during two hours in the day. The frequency and depth of encroachment into the poor performance zone is greater for the smaller tank size than for the larger tank size. This phenomenon is the reason for the better meter performance of the bigger tank size. Annex 4 represents the full spectrum of inflows for the different arrangements of FVs and tank sizes. Fig. 8 and Annex 4 suggest the same conclusion; the maximum inflow is lower when the tank size is larger, and the minimum inflow is greater because the time required to reach the full tank level is longer with larger tank sizes. In this situation, the next instantaneous consumption occurs before the tank is completely full, causing the inflow to rise again. This process influences the range of inflows into the tank which, in turn, influences the meter performance. In this case, the meter performance improves when the tank size is larger.

To summarize this discussion, the impact of the tank size on the meter performance depends on the time required to refill the tank and the time difference between the consumption events during the day. If the refilling time is longer than the time difference between consumption events, then bigger tank sizes will allow for less low flows, and thus less errors and apparent losses occur, and vice versa. Finally,

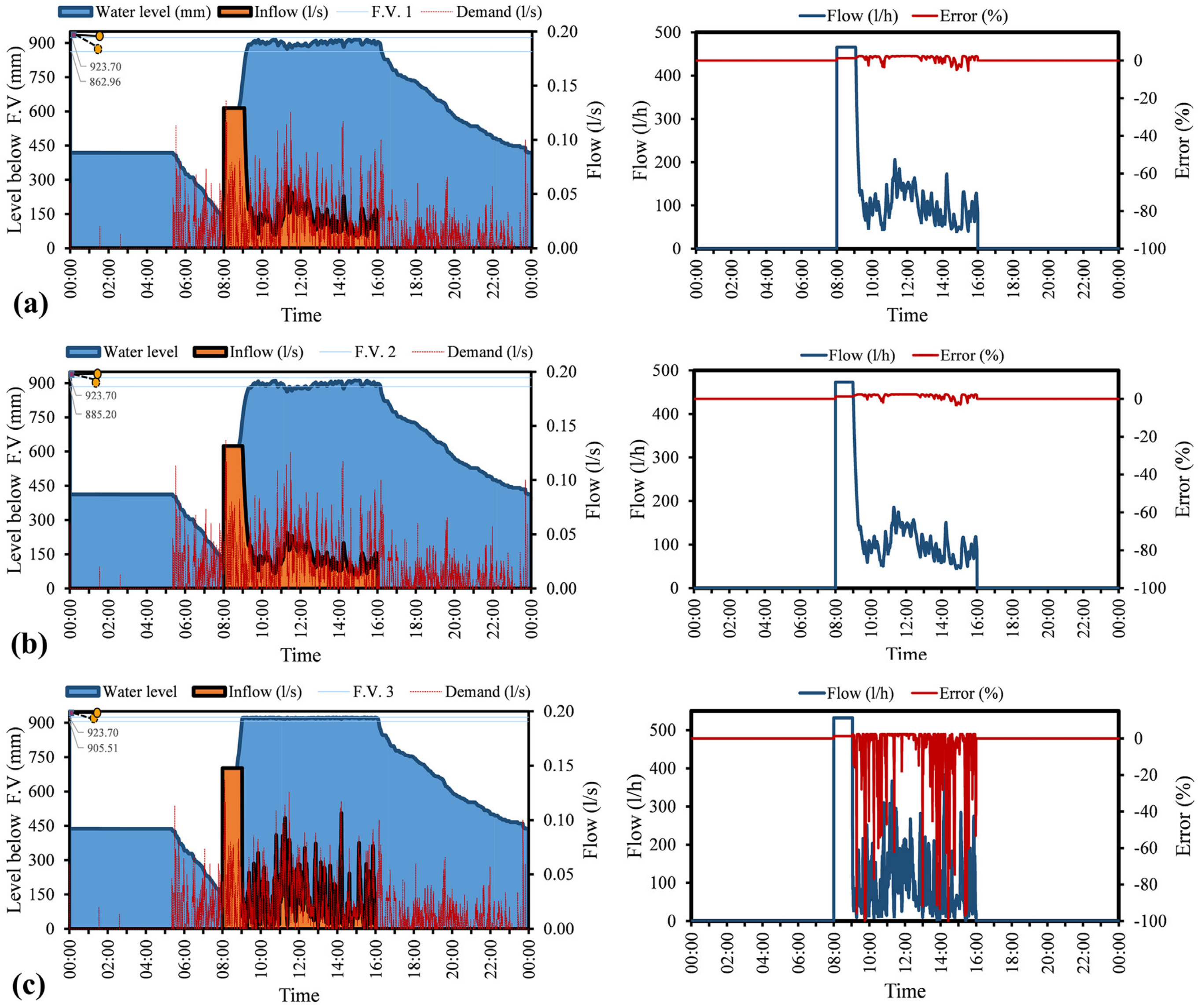

Fig. 5. Water level in the tank (left) and meter error (right) for a supply of 8 h/d according to the type of FV: (a) FV1, (b) FV2, and (c) FV3. (Intermittent supply, 8 h/d).

Table 1
Meter error with different FVs for different intermittency levels.

Supply	Tank Size	FV1 Average Error	Weighted Error	FV2 Average Error	Weighted Error	FV3 Average Error	Weighted Error
2 h/d	500 l	1.3	1.3	1.3	1.3	1.3	1.2
4 h/d	500 l	2.0	1.7	2.0	1.8	1.4	1.5
8 h/d	500 l	1.3	1.6	1.5	1.6	−4.5	0.7
20 h/d	500 l	−4.3	0.7	−3.8	0.8	−2.6	0.8
24 h/d	500 l	−7.6	−1.2	−7.0	−1.1	−9.8	−1.7

the shape of the tank is also important. A tank with the same size can have different surface areas. For example, a tank of 2 m^3 capacity can be with 1 meter in height and 2 m^2 in surface area or 1 m^2 in surface area and 2 m in height. The latter shape is vividly better in terms of meter performance because the surface area is smaller, and thus the consumption event causes higher drops in the water level inside the tank and higher inflow rates. Hence, a cylindrical tank installed in a horizontal position will result in fewer errors than a vertical position or a square tank.

4. Conclusions

This study analysed the impact of the water tank and FV arrangement on the performance of water meter under intermittent and continuous water supply conditions. The error curve of a sample of used water meters was established, the FV characteristics were experimentally determined, and the water level in a water tank with a FV was hydraulically modelled. Typically, water meter accuracy declines as the flow rate that passes through the meter decreases, and decays rapidly when the flow rate is less than the minimum flow of the meter. The

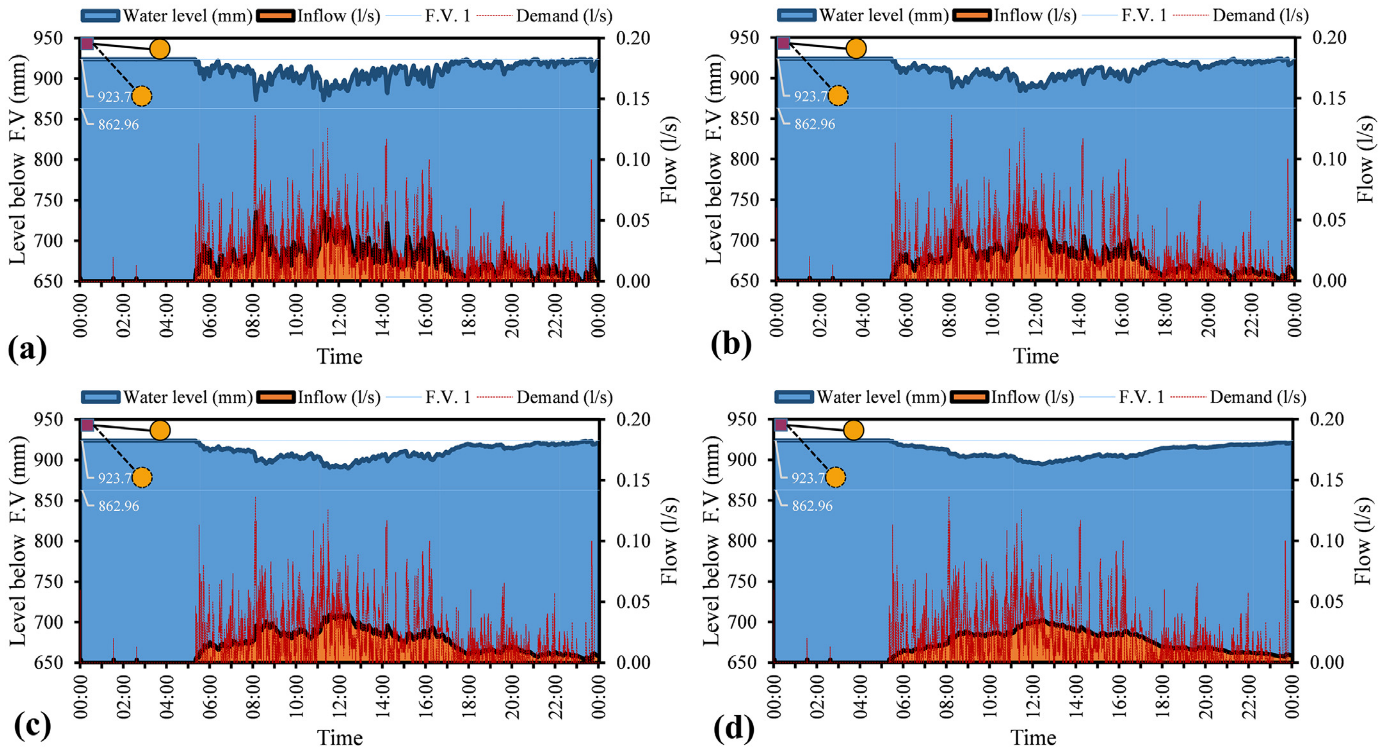

Fig. 6. Water level in the water tank with FV1 and different tank sizes: (a) 500 l, (b) 1000 l, (c) 2000 l, and (d) 5000 l. (Continuous supply, 24 h/d).

water consumption pattern of a user is, therefore, a critical factor influencing the meter performance. The proportion of water consumption at low flows (0–36 l/h) out of the total consumption substantially affects the meter accuracy, confirming the significance of the weighted error as an indicator of the actual field performance of a water meter. Considering the sensitivity of the low flows, the effect of the FV and water tank arrangement on the meter performance should be recognised.

Once the arrangement of water tank and FV is in place downstream of the water meter, under continuous supply condition, the flows that

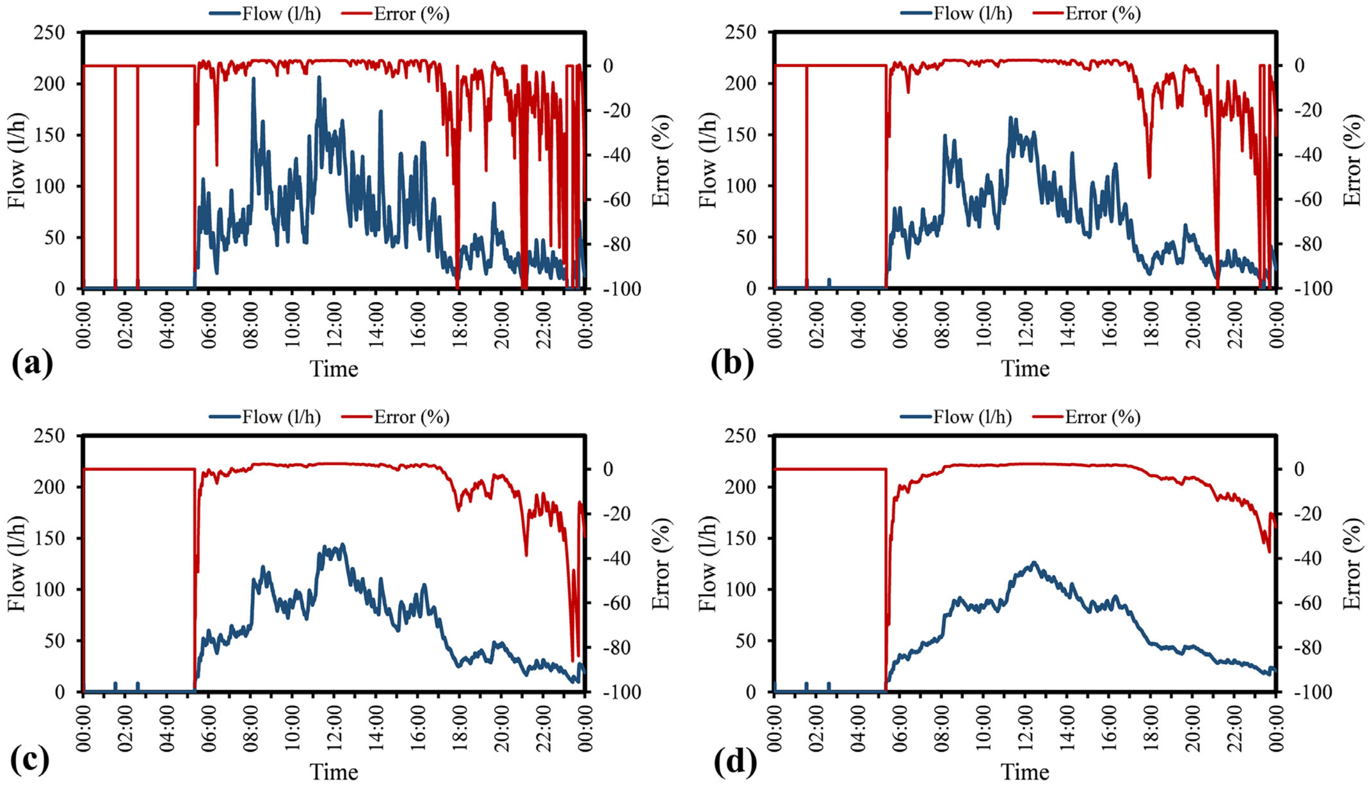

Fig. 7. Meter error with FV1 and different tank sizes: (a) 500 l, (b) 1000 l, (c) 2000 l, and (d) 5000 l. (Continuous supply, 24 h/d). .

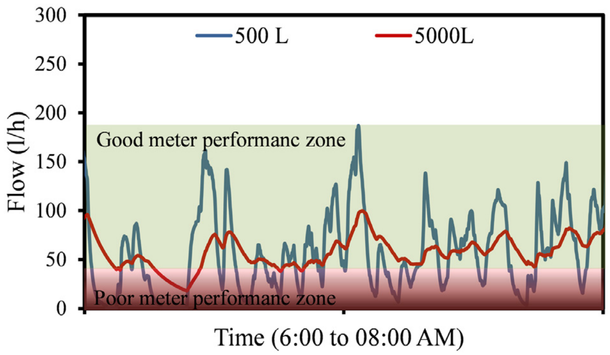

Fig. 8. Inflows with FV3 and two different tank sizes during two hours in the day. (Continuous supply, 24 h/d).

pass the water meter are not the consumption flows that discharge out of the water tank, but the inflows into the tank pass through the meter. The inflows into the tank are consistently lower than the outflows due to the balancing nature of the tank. This result suggests that the arrangement of water tank and FV, when combined with continuous supply, worsens the water meter performance and causes higher metering errors and higher apparent losses. In addition, different types of FVs have different hydraulic characteristics which influence the range of the inflow rates into the tank, the water level in the tank, and ultimately influence the water meter performance. This effect applies in continuous supply. The performance of the water meter improves once the FV discharge rate is lower. With higher FV discharge rates, the water level remains close to the full level in the tank causing only slight FV opening and generating more ultimately low inflows during the day. This implies that smaller FV sizes are advantageous to improve water meter performance and bigger FV sizes cause more metering errors.

For a continuous supply system combined with a water tank and FV arrangement, the sensitivity of the meter accuracy to the size of the water tank is variable. The critical factor is the time required to refill the tank and the time between the instantaneous consumption events. If the refilling process of the tank finishes before the next consumption starts, then, in this case, bigger tanks cause more and longer low flows and produce larger metering errors, and vice versa. Furthermore, the shape of the tank is also important. A cylindrical tank installed in a horizontal position will result in fewer errors than a cylindrical tank in vertical position or a square tank. If the tank is almost full, the water surface area at the beginning of the filling process is very small, causing the water level to drop quickly and increasing the FV inflows.

The impact of supply intermittency on the water meter performance is central. The FV in intermittent supply drops down in the water tank and does not remain within the modulation range of the FV, as in the case of continuous supply. Four different intermittency levels were assessed: 2 h/d, 4 h/d, 8 h/d, and 20 h/d. The results are consistent across these levels. Higher intermittency levels improve the meter performance and reduce metering under-registration. This is because the higher the intermittency level, the longer the FV remains completely open, and the higher will be the inflows into the tank. With high intermittencies, the average error of the water meter becomes greater than zero, which means that the meter error is on average not under-registration but over-registration. Therefore, it is important for water utilities to consider in their meter replacement policy higher metering errors and more apparent losses when transforming from intermittent to continuous supply, to keep the transformation to 24/7 system feasible and efficient.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2020.105091.

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