An experimental analysis on accuracy of customer water meters under various flow rates and water pressures

I. Ethem Karadirek

ABSTRACT

Apparent losses are mainly due to metering errors in well-managed water supply systems. There are many types of water meters based on mechanisms to measure flow passing through. Therefore, selection of water meter type is important as meter type effects measurement accuracy. In this study, a total of 50 domestic water meters were tested under varying flow rates and different water pressures. Water consumptions of end-users show temporal changes depending on the life style of consumers. Flow rates passing through the water meter and water consumption profiles affect water meter accuracy. Water consumption of a couple of end-users was monitored and consumption patterns were extracted and obtained water consumption patterns were used to determine water meter errors. The collection method was applied for determination of water meter errors. Starting flow rates, error curves and weighted error of water meters were measured in a laboratory setup. Tested volumetric-type water meters have the lowest starting flow rate and the highest accuracy whereas single-jet water meters have the lowest accuracy and the highest starting flow rate. This study aimed to provide insights on the accuracy of water meters under varying flow rates and water pressures, and advantageous information for water meter-type selection.

Key words | apparent losses, water meter accuracy, water meter management, water meter under-registration

I. Ethem Karadirek
Department of Environmental Engineering, Faculty of Engineering,
Akdeniz University,
Antalya,
Turkey
E-mail: *ethemkaradirek@akdeniz.edu.tr*

INTRODUCTION

The problem of excessive water losses in urban water supply services has become more crucial. Water losses are defined as the difference between the amount of water supplied to the system and the amount of authorized water consumption (Lambert *et al.* 1999; Alegre *et al.* 2000). Water losses consist of real (physical) losses and apparent (commercial) losses. Real losses result from leakage in mains, leakage in service connections, and leakage and overflow at storage tanks whereas apparent losses are usually associated with customer water meter inaccuracies, data handling errors and unauthorized consumption (Tabesh & Delavar 2003; McKenzie & Seago 2005). Real losses refer to the water that is physically lost while apparent losses are the sum of losses which are used but not paid for (Al-Washali *et al.* 2016). Reducing apparent losses results in short-term increases in water utility/municipality revenue that leads to better services for water consumers in the long term.

Apparent losses in a well-managed water supply system are mostly due to metering errors (Arregui *et al.* 2018). Metering errors, which might result from meter wear and tear, incorrect installation, insufficient maintenance or calibration, incorrect meter type, class and sizing and demand profile, have a significant effect on apparent losses (Criminisi *et al.* 2009). There are various types of water meters, such as mechanic, electromagnetic, and ultrasonic, which are classified based on the mechanism to

doi: 10.2166/aqua.2019.031

measure the flow passing through. Generally, most installed water meters in water utilities are domestic water meters and about 70–80% of total water consumption is measured by those domestic water meters (Arregui *et al.* 2018). Single-jet, multi-jet and volumetric customer water meters are the most widely installed water meters (Criminisi *et al.* 2009). Varying flow rates and temporal demand patterns affect the accuracy of water meters (Arregui *et al.* 2005, 2006a, 2016; Criminisi *et al.* 2009). Metrological and technical requirements of water meters are specified by ISO4064-1 (2014). Technical requirements of water meters define an error curve using minimum flow rate (Q_1), transitional flow rate (Q_2), permanent flow rate (Q_3) and overload flow rate (Q_4) (Fontanazza *et al.* 2013). Minimum flow rate is the lowest flow rate that the water meter starts to measure within maximum permissible errors (MPEs), whereas overload flow rate is the highest flow rate that the water meter operates for a short time period within MPEs. Permanent flow rate is the highest flow rate within the rated operating conditions at which the meter starts to operate within the MPEs and transitional flow rate divides flow rate range as the upper and lower flow rate zones which are characterized by its own MPEs (ISO4064-1 2014). Accurate metering of water consumption is crucial for socially fair pricing (Kanakoudis 2016) and determination of the accuracy of water meters is important for a proper water balance to control water losses (Lambert & Hirner 2000). Walter *et al.* (2018) studied the inaccuracies of single-jet and multi-jet water meters in an intermittent supply system. Criminisi *et al.* (2009) evaluated the water meter errors due to water meter ageing and the private storage tank effect on water meter accuracy. Consumer water consumption patterns affect water meter accuracy. Arregui *et al.* (2018) examined the performance analysis of ageing single-jet water meters for measuring residential water consumption. Apparent losses resulting from inaccuracies of water meters can be minimized by implementing a nine-step technique including water meter selection and optimal replacement period (Arregui *et al.* 2012). Selection of water meter type is an important issue for water utilities. An optimal water meter selection system that utilizes consumer water consumption patterns with numerous water meter specifications has been developed by Johnson (2001). The system assumes water meter performance as a function of consumer water consumption patterns and selection of a water meter is made through a ranking process (Johnson 2001). Arregui *et al.* (2003) presented management strategies based on utilization of billing data for optimum selection and replacement period of water meters. The strategy relies on the comparison of annual readings of in-service water meters (Arregui *et al.* 2003). This strategy requires a detailed billing database and, furthermore, selection of water meters might be affected by data handling errors and reading errors. Mutikanga (2014) proposed a methodology for water meter selection using an analytical hierarchy process that was applied to select appropriate residential-type water meters in Uganda. However, the proposed methodology has uncertainties such as quantitative performance criteria that should be taken into consideration (Mutikanga 2014). A series of laboratory experiments was carried out to determine the effects of water pressure on water meter accuracies. Tested water pressure levels were 0.5, 1.0, 1.5 and 2.0 bar and the study showed that water pressure and water consumption patterns are relevant parameters for water meter inaccuracies (Fontanazza *et al.* 2013). Mutikanga *et al.* (2011) presented the results of a study investigating water meter performance in Uganda and the study showed that low water pressure affects the performance of water meters. There are no universally accepted water pressure standards for water distribution systems (Ghorbanian *et al.* 2016). However, a minimum water pressure of around 20–25 m is common for many water utilities (Monsef *et al.* 2018), and the advised operating pressure is between 4 and 5.5 bar (60 and 80 psi) (Xu *et al.* 2014). Water utilities are to keep water pressures within certain limits. This study aims to provide an experimental evaluation of water meter accuracy under various flow rates and water pressures. For this purpose, water consumptions of typical residential end-users were monitored to determine flow rates and water consumption patterns were extracted from obtained data. The water pressures that water meters tested were chosen to simulate the effects of desired water pressures on water meter accuracies. Domestic type single-jet with dry chamber, multi-jet with dry chamber and wet chamber, and volumetric water meters were tested to determine the inaccuracies of water meters at determined flow rates of typical end-users under different water pressures.

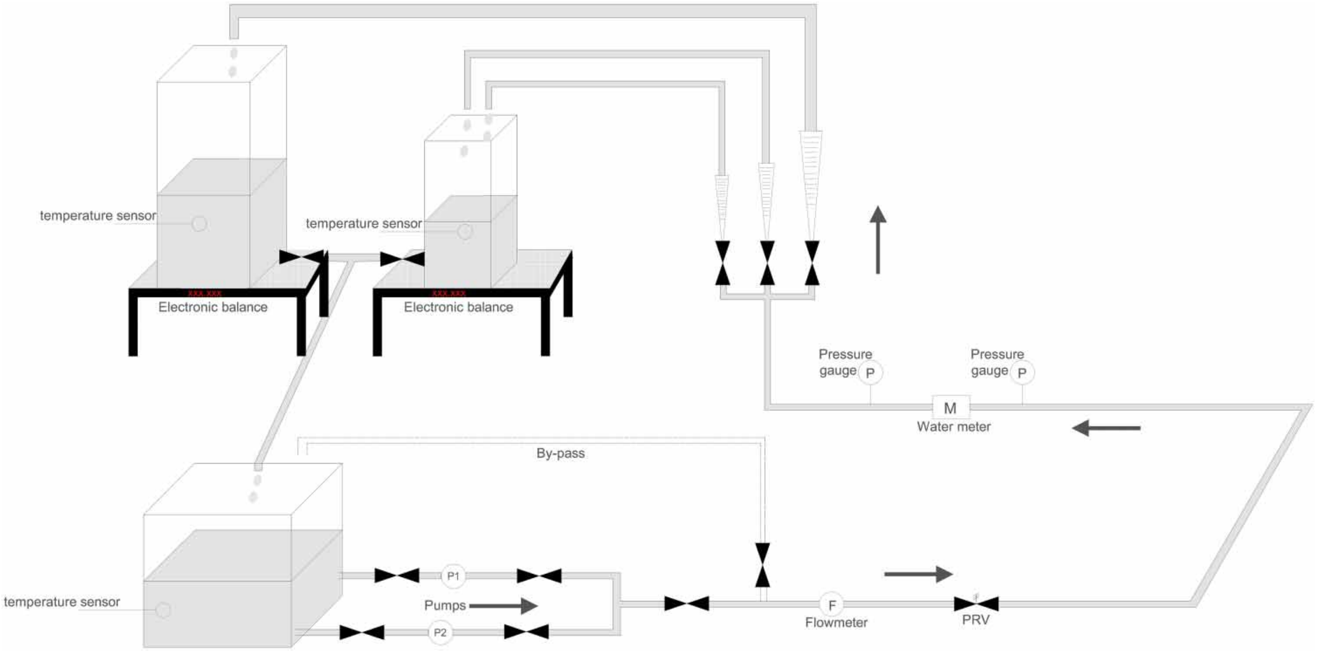

Figure 1 | Experimental setup for determination of water meter inaccuracies.

METHODOLOGY

Test setup

Experiments were performed to evaluate the inaccuracies of water meters at varying flow rates and water pressures. Figure 1 represents the laboratory setup of the experiments. Test setup is weight calibrated in consistence with the ISO4064-2 (2014) standard. Test setup consists of water tanks, pressure gauges, a flowmeter, rotameters that measure the volumetric flow rate of water in a closed tube, temperature sensors, an accurate and calibrated electronic balance, water supply tank, two water pumps for different flow rates, pressure reducing valve (PRV) to control water pressure in the system, air relief valve, filters, gate valves and mains.

A total of 50 new water meters were tested for determination of water meter inaccuracies. Technical and metrological characteristics of the tested water meters are given in Table 1. Water meters are characterized by the permanent flow rate and the ratio R of permanent flow rate (Q_3) to minimum flow rate (Q_1) ($R = Q_3/Q_1$) (ISO4064-1 2014). The R value is used to define the accuracy range of water meters. The register of a water meter can be placed in a dry or wet chamber (water filled). The impeller of water meters with a dry chamber is separated from the water

Table 1 | Technical and metrological characteristics of tested water meters

Type	Technology	Metrological class, R (Q_3/Q_1)	Standard	Q_1 (m^3/h)	Q_2 (m^3/h)	Q_3 (m^3/h)	Q_4 (m^3/h)	Length (mm)	Diameter (mm)	Number of meters
M-1	Single-jet (Dry chamber)	100	ISO4064: 2014	0.025	0.040	2.5	3.125	110	15	10
M-2[a]	Multi-jet (Dry chamber)	100		0.025	0.040	2.5	3.125	190	20	10
M-3[a]	Multi-jet (Dry chamber)	80		0.03125	0.040	2.5	3.125	190	20	10
M-4	Multi-jet (Wet chamber)	100		0.025	0.050	2.5	3.125	190	20	10
M-5	Volumetric	200		0.0125	0.0200	2.5	3.125	190	20	10

[a]Multi-jet water meters with dry chamber were provided from two different water meter suppliers.

chamber and the impeller is coupled with a magnetic element whereas the counter of water meters with a wet chamber is immersed in water (Van Zyl 2011). Domestic water consumption is mostly metered with 15 mm and 20 mm standard sized water meters. Single-jet water meters are usually available with a diameter of 15 mm and a length of 110 mm, while the most common diameter and length of multi-jet and volumetric water meters are 20 mm and 190 mm, respectively. Therefore, laboratory test setup was designed considering the diameters and lengths of tested water meters. In this study, single-jet, multi-jet with dry and wet chamber, and volumetric rotary piston water meters were tested.

Domestic type water meters with different measurement technologies were tested in this study, as most installed water meters in water authorities are domestic meters. The so-called 'collection' method, in which the quantity of water passing through the water meter is collected in one or more collecting tanks and the quantity determined by weighing (ISO4064-2 2014), was applied for determining the meter errors. Each meter was tested individually and metering errors in the weighing method applied in this study were determined by Equation (1):

$$\varepsilon = \frac{V_m - V_a}{V_a} \times 100 \tag{1}$$

where ε is the metering error as a percentage, V_m is the volume of water that is measured by the water meter while V_a is the actual volume of water passing through the meter.

Water consumption patterns

Water meters work under varying flow rates due to temporal changes in water consumption depending on the life style of consumers. Besides flow rates, water pressures also show temporal and spatial changes in urban water distribution systems. Therefore, water meters should be tested under varying flow rates and water pressures. End-use water consumption of different consumers from different countries such as the USA (Buchberger & Wells 1996; Deoreo *et al.* 2016) and Spain (Arregui *et al.* 2006a, 2018) were studied. In this study, water consumption patterns that represent typical residential users were obtained from the water consumption of 12 domestic water consumers (apartment blocks with direct supply from network) in Antalya, Turkey. Water consumption patterns of end-users were monitored by flow meters for a period of 4 weeks in August 2018 and the frequency distribution of water consumption was extracted from obtained data, a methodology described by Arregui *et al.* (2006a, 2006b, 2018). The frequency distribution of water consumption was used to determine the amount of water consumption at each flow rate. Therefore, it was possible to determine water meter inaccuracies under varying flow rates. Water meter inaccuracies were determined at varying flow rates under different water pressure conditions as water pressure in urban water distribution systems showed temporal and spatial changes. Water pressures during maximum water consumption periods might be lower compared to the water pressures during minimum water consumption periods. Therefore, all water meters were tested at two different water pressures, around 2.5 bar and 4.5 bar at which many water distribution systems are operated.

RESULTS AND DISCUSSION

Consumption patterns

The frequency distribution of water consumption extracted in the context of this study is given in Figure 2 and shows that a large amount of water (76.2% of total water consumption) is consumed at flow rates between 120 and 1,200 L/h. Around 21.3% of total water consumption was consumed at flow rates lower than 120 L/h whereas around 2.5% of total water consumption occurred at flow rates higher than 1,200 L/h. Even though the overload flow rate of tested water meters is 3.125 m^3/h, no consumption at overload flow rate was observed. Extracted water consumption patterns were used to test water meters and to calculate the weighted average error of each water meter.

Inaccuracies of water meters

Many types of water meters based on measurement mechanisms are available on the market for residential applications. Velocity-type water meters that measure the velocity of

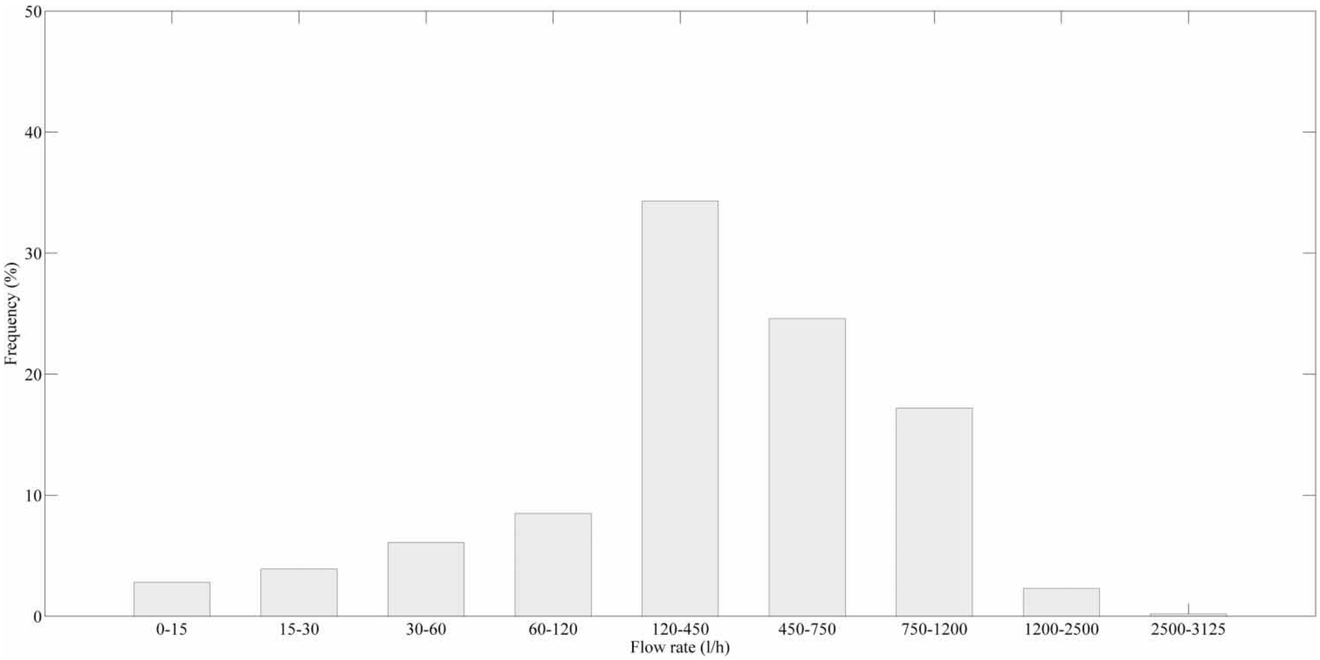

Figure 2 | Frequency distribution of water consumptions.

water passing through and volumetric water meters are used most commonly by water utilities. Selection of the type of water meter is an important issue for water utilities due to fair pricing of water and water loss control. The accuracy of water meters depends on the measurement technology of the meter and the accuracy class of the meter. In this study, a total of 50 new domestic water meters were tested under varying flow rates and water pressures. Observed water consumption patterns within the context of this study were used to simulate water consumptions at varying flow rates passing through the water meters. Average starting flow rate of each water meter and average water meter errors at each flow rate were determined. MPEs, which represent extreme measurement errors permitted by specifications for a given measurement, average measurement errors of water meters at each flow rate, and average starting flow rate of each water meter are summarized in Table 2. According to ISO4064-1 (2014), the MPE for accuracy class 1 water meters is ±3% between minimum and transitional flow rates whereas the MPE is ±1% between transitional and overload flow rates (±1% for temperatures between 0.1 °C and 30 °C; ±2% for temperatures higher than 30 °C). On the other hand, the MPE for accuracy class 2 water meters is ±5% between minimum and transitional flow rates, and ±2% for flow rates between transitional and overload flow rates (±2% for temperatures between 0.1 °C and 30 °C; ±3% for temperatures higher than 30 °C). Tested water meters M-1, M-2, M-3 and M-4 are accuracy class 2 water meters whereas M-5 is an accuracy class 1 water meter, according to ISO4064-1 (2014). The water meter M-5 has the lowest starting flow rate, as it is an accuracy class 1 water meter while the others are accuracy class 2 water meters. M-2, a multi-jet water meter with a dry chamber, has a lower starting flow rate than water meters M-1, M-3 and M-4, although they belong to the same accuracy class. Average starting flow rates for water meters M-1, M-2, M-3, M-4, M-5 are 12.32 L/h, 7.02 L/h, 9.72 L/h, 7.54 L/h, 2.17 L/h, respectively. The water meter M-4, a multi-jet with wet chamber, has relatively higher accuracy compared to M-1, M-2 and M-3 at flow rates higher than 60 L/h. For instance, measurement errors of the water meter M-4 are relatively high at lower flow rates while inaccuracies of M-4 are low at higher flow rates. The impeller of water meters with a wet chamber is directly connected to the counter while the impeller of water meters with a dry chamber is separated from the measurement chamber. Thus, no friction losses or relatively low friction losses occur in water meters with

Table 2 | Average starting flow rates, MPEs and average measurement errors of tested water meters

Flow rate (l/h)		**15**		**30**		**60**		**120**		**450**		**750**		**1,200**		**2,500**		**3,125**	
Pressure (bar)		**≈2.5**	**≈4.5**	**≈2.5**	**≈4.5**	**≈2.5**	**≈4.5**	**≈2.5**	**≈4.5**	**≈2.5**	**≈4.5**	**≈2.5**	**≈4.5**	**≈2.5**	**≈4.5**	**≈2.5**	**≈4.5**	**≈2.5**	**≈4.5**
Water meters	**Starting flow (L/h)**	**Errors (%)**																	
M-1	12.32	−5.18	−4	3.98	3.64	3.1	3.12	3.54	3.59	3.81	4.61	4.79	5.03	4.73	4.8	4.53	4.58	4.38	4.41
M-2	7.02	−4.22	−4.07	1.79	2.26	2.25	2.24	1.51	1.39	1.62	1.38	1.67	1.7	1.44	1.4	2.34	2.3	2.26	2.23
M-3	9.72	−16.51	−14.87	−1.35	−1.19	−2.58	−2.39	−2.5	−2.36	−0.82	−0.82	0.9	0.88	1.138	1.037	0.36	0.34	0.28	0.27
MPE (ISO 4064)		N/A	N/A	±5	±5	±2	±2	±2	±2	±2	±2	±2	±2	±2	±2	±2	±2	±2	±2
M-4	7.54	−7.86	−6.65	−3.83	−3.25	−2.01	−1.78	0.23	0.28	0.3	0.35	0.36	0.29	1.13	1.18	0.77	0.74	0.68	0.65
MPE (ISO 4064)		N/A	N/A	N/A	N/A	±2	±2	±2	±2	±2	±2	±2	±2	±2	±2	±2	±2	±2	±2
M-5	2.17	0.37	0.15	0.96	1	1.32	1.37	1.4	1.39	0.92	0.92	0.62	0.64	0.13	0.11	−1.27	−1.24	−0.56	−0.54
MPE (ISO 4064)		±3	±3	±1	±1	±1	±1	±1	±1	±1	±1	±1	±1	±1	±1	±1	±1	±1	±1

wet chambers, as power transmission from the water chamber to the counter takes place directly. Relatively low measurement errors of the water meter M-4 at higher flow rates might be associated with friction losses. Measurement errors of all tested water meters at flow rate 15 L/h and water pressure ≈2.5 bar are relatively high. Generally, water pressure affects the measurement errors at lower flow rates whereas the effects of water pressure at higher flow rates are negligible. Higher measurement errors at lower water pressures have also been reported (Mutikanga *et al.* 2011; Fontanazza *et al.* 2013). Measurement errors and starting flow rates of tested water meters are given in Figure 3. The results of this study are summarized in Table 2 and Figure 3, and the testing procedure presented in this study can provide insights for the selection of appropriate water meters at different flow rates and water pressures.

Error curves for each water meter at different water pressures were determined and are given in Figure 4. Inaccuracies of water meters for tested water pressures are negligible.

The study showed that around 6.7% of water was consumed at flow rates lower than 30 L/h at which the highest measurement errors occur for water meters M-1, M-2, M-3 and M-4. The water meter M-5 is more appropriate than the water meters M-1, M-2, M-3 and M-4 at flow rates of 15 L/h and 30 L/h. On the other hand, around 8.5% of water was consumed at flow rates between 60 L/h and 120 L/h at which measurement errors of water meters M-1, M-2, M-3 and M-5 are out of range of MPEs, whereas the error of the water meter M-4 is within the limit of MPEs. Measurement errors of M-1 are out of range of MPEs at all tested flow rates. Water meters have different measurement errors at different flow rates, and this should be considered for selection of water meters. The findings of this study confirmed that water consumption patterns have significant effects on the inaccuracies of water meters.

There are many parameters, such as accuracy, size, cost, maintenance requirement, water quality and mounting ease that should be considered for water meter selection. However, selection of water meters is generally based on the initial measurement performance and cost of the water meters. This study showed that some water meters have higher accuracy at lower flow rates whereas others have higher accuracy at higher flow rates, even if they are in the

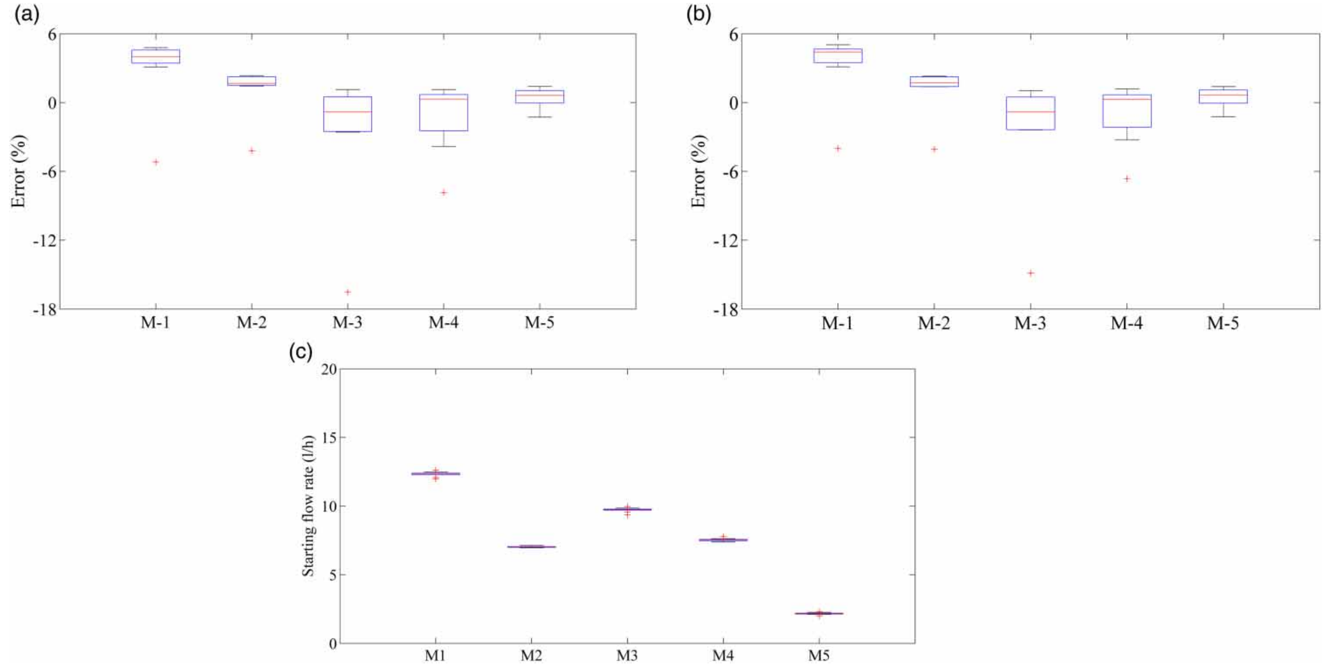

Figure 3 | Box-plots showing measurement errors of tested water meters at different water pressures (a) $P \approx 2.5$ and (b) $P \approx 4.5$ and starting flow rates (c).

same accuracy class. Therefore, the determination of water consumption patterns of consumers is crucial for selection of water meters. In this study, the weighted error of each water meter (Table 3) was calculated based on a combination of error curve of tested water meters and water consumption patterns. The methodology used to calculate the weighted error of each water meter basically depends on multiplying the water consumption percentage and the average measurement error of each water meter, as described in previous studies (Arregui *et al.* 2006b, 2018).

CONCLUSIONS

This paper presents the findings of a laboratory study on the determination of inaccuracies of domestic-type water meters. As there are many types of water meter and water meter type affects the measurement accuracy, the selection of water meter type is an important task for water utilities. The most widely used domestic-type water meters (single-jet, multi-jet and volumetric) were tested to determine the measurement errors under varying flow rates and water pressures. Results show that the effects of tested water pressure on water meter inaccuracies are negligible at higher flow rates whereas water pressure affects the measurement accuracy at lower flow rates. Effects of low water pressure levels on performance of water meters have also been reported in the literature. Despite findings about the effects of water pressure on the accuracy of water meters, more research is needed to determine the accuracy of water meters at extreme water pressure levels that might exist in water distribution systems. On the other hand, flow rates and water consumption patterns have a great impact on water meters' errors. There are many parameters such as water quality, class and size, maintenance requirement and cost that should be taken into consideration in the selection of water meters. This study confirmed that water consumption patterns should be taken into consideration for the selection of water meter types, as reported in the literature. Tested volumetric-type water meters are more accurate for measurements at lower flow rates with the lowest starting flow rate whereas measurement errors of tested multi-jet water meters are lower than tested volumetric-type water meters at maximum flow rates. However, other factors for the selection of appropriate water meters should also be considered. Although

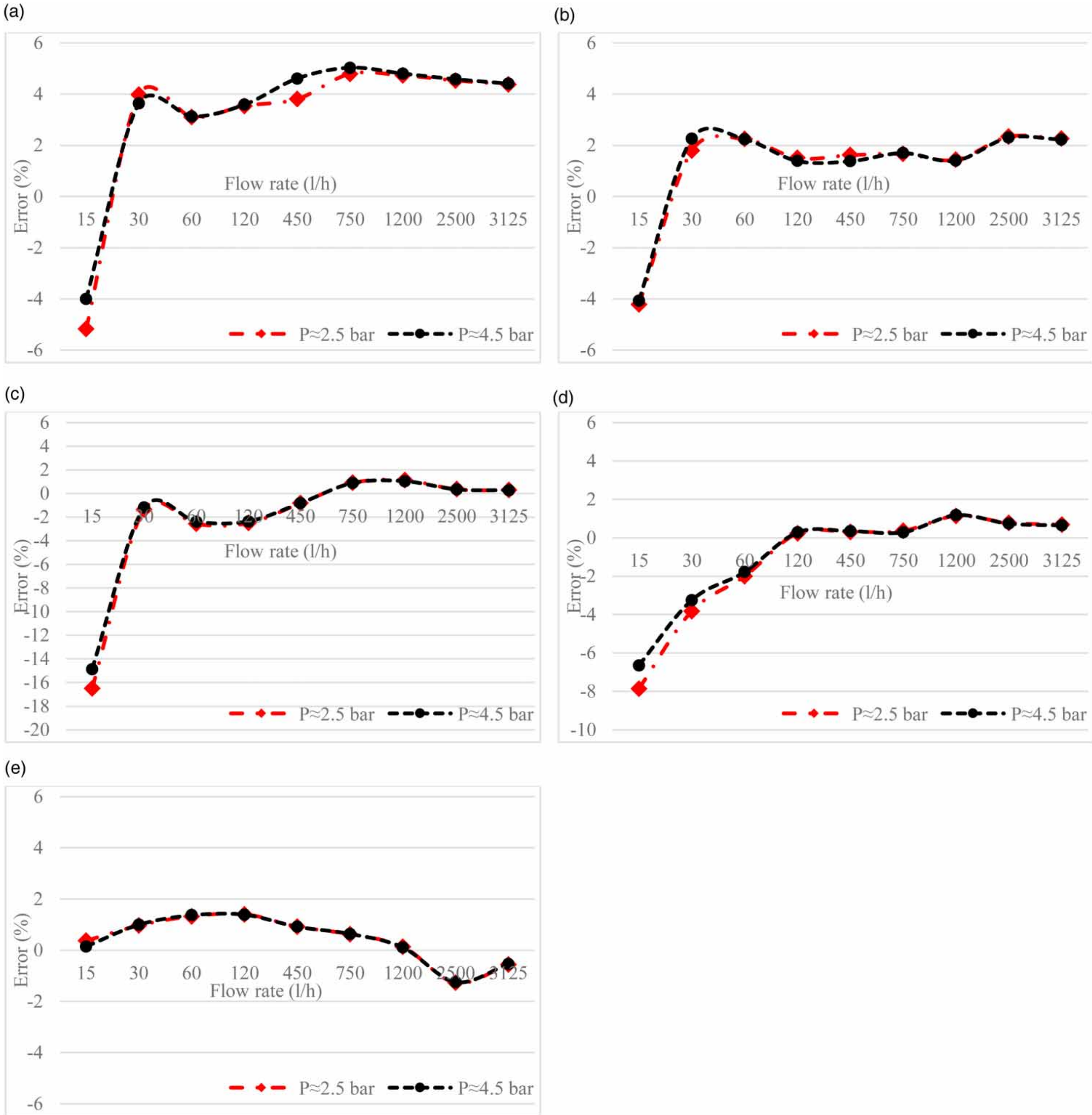

Figure 4 | Error curves of tested water meters at different water pressures: (a) M-1, (b) M-2, (c) M-3, (d) M-4, (e) M-5.

Table 3 | Weighted measurement errors of tested water meters at different water pressures

Water meter	**M-1**		**M-2**		**M-3**		**M-4**		**M-5**	
Water pressure (bar)	≈2.5	≈4.5	≈2.5	≈4.5	≈2.5	≈4.5	≈2.5	≈4.5	≈2.5	≈4.5
Weighted error (%)	−4.17	−4.47	−1.79	−1.72	−1.60	−1.50	−1.08	−1.01	−0.63	−0.64

the tested multi-jet water meters with wet chambers have relatively lower weighted average error than multi-jet water meters with dry chambers, water quality can affect the measurement errors of water meters with wet chambers due to poor resistance against suspended particles. Water meters with dry chambers are more protected against suspended solids as the counter and indicator are not directly in contact with the water, but they might require protection against magnetic fields that might affect the readings. Volumetric-type water meters have better performance at lower flow rates, however, they are also vulnerable against suspended solids and are prone to relatively higher pressure losses. Such factors affecting measurement errors should be considered by water utilities during the selection process of appropriate water meters. The accuracy of water meters from different meter brands, even if they have the same measurement technology, might vary significantly. The results obtained for tested water meters cannot be extrapolated as there are many parameters affecting the measurement errors. However, the findings of this study can provide insights about the inaccuracies of different measurement technologies at varying flow rates and water pressures.

ACKNOWLEDGEMENTS

This study was supported by the Scientific and Technological Research Council of Turkey (Project No.117Y301) and Akdeniz University. The author would like to thank Gamze Akgul and Ediz Kumuk for their support.

REFERENCES

Alegre, H., Hirner, W., Baptista, J. M. & Parena, R. 2000 *Performance Indicators for Water Supply Services*, 1st edn. IWA Publishing, London, UK.

Al-Washali, T. S., Sharma, S. & Kennedy, M. 2016 Methods of assessment of water losses in water supply systems: a review. *Water Resources Management* **30** (14), 4985–5001.

Arregui, F., Cabrera, E., Cobacho, R. & Palau, V. 2003 Management strategies for optimum meter selection and replacement. *Water Science and Technology: Water Supply* **3** (1–2), 143–152.

Arregui, F. J., Cabrera, E. J., Cobacho, R. & Garcia-Serra, J. 2005 Key factors affecting water meter accuracy. In: *Proceedings of the Leakage 2005 Conference*, Halifax, Canada.

Arregui, F. J., Cabrera, E., Cobacho, R. & García-Serra, J. 2006a Reducing apparent losses caused by meters inaccuracies. *Water Practice and Technology* **1** (4), wpt2006093-wpt.

Arregui, F. J., Cabrera, E. J. & Cobacho, R. 2006b *Integrated Water Meter Management*. IWA Publishing, London, UK.

Arregui, F. J., Soriano, J., Cabrera, E. & Cobacho, R. 2012 Nine steps towards a better water meter management. *Water Science and Technology* **65** (7), 1273–1280.

Arregui, F. J., Balaguer, M., Soriano, J. & Garcia-Serra, J. 2016 Quantifying measuring errors of new residential water meters considering different customer consumption patterns. *Urban Water Journal* **13** (5), 463–475.

Arregui, F. J., Gavara, F. J., Soriano, J. & Pastor-Jabaloyes, L. 2018 Performance analysis of ageing single-jet water meters for measuring residential water consumption. *Water* **10** (5), 18.

Buchberger, S. G. & Wells, G. J. 1996 Intensity, duration, and frequency of residential water demands. *Journal of Water Resources Planning and Management-ASCE* **122** (1), 11–19.

Criminisi, A., Fontanazza, C. M., Freni, G. & La Loggia, G. 2009 Evaluation of the apparent losses caused by water meter under-registration in intermittent water supply. *Water Science and Technology* **60** (9), 2373–2782.

Deoreo, W. B., Mayer, P. W., Dziegielewski, B. & Kiefer, J. C. 2016 *Residential End Uses of Water, Version 2*. The Water Research Foundation, Denver, CO, USA.

Fontanazza, C. M., Notaro, V., Puleo, V. & Freni, G. 2013 Effects of network pressure on water meter under-registration: an experimental analysis. *Drinking Water Engineering and Science Discussions* **6**, 119–149.

Ghorbanian, V., Karney, B. & Guo, Y. P. 2016 Pressure standards in water distribution systems: reflection on current practice with consideration of some unresolved issues. *Journal of Water Resources Planning and Management* **142** (8), 8.

ISO4064-1 2014 *Water Meters for Cold Potable Water and Hot Water – Part 1: Metrological and Technical Requirements*. International Organization for Standardization, Geneva, Switzerland.

ISO4064-2 2014 *Water Meters for Cold Potable Water and Hot Water – Part 2: Test Methods*. International Organization for Standardization, Geneva, Switzerland.

Johnson, E. H. 2001 Optimal water meter selection system. *Water SA* **27** (4), 481–488.

Kanakoudis, V. T. S. 2016 Socially fair domestic water pricing: who is going to pay for the non-revenue water? *Desalination and Water Treatment* **57** (25), 11599–11609.

Lambert, A. & Hirner, W. 2000 *Losses From Water Supply Systems: Standard Terminology and Recommended Performance Measures. IWA Blue Pages*. IWA Publishing, London, UK, pp. 1–13.

Lambert, A. O., Brown, T. G., Takizawa, M. & Weimer, D. 1999 A review of performance indicators for real losses from water supply systems. *Journal of Water Services Research and Technology-AQUA* **48** (6), 227–237.

McKenzie, R. & Seago, C. 2005 Assessment of real losses in potable water distribution systems: some recent developments. In: *4th World Water Congress: Innovation in Water Supply – Reuse and Efficiency* (P. Wilderer, ed.). IWA Publishing, London, pp. 33–40.

Monsef, H., Naghashzadegan, M., Farmani, R. & Jamali, A. 2018 Pressure management in water distribution systems in order to reduce energy consumption and background leakage. *Journal of Water Supply Research and Technology-AQUA* **67** (4), 397–403.

Mutikanga, H. E. 2014 Residential water meter selection using the analytical hierarchy process. *Journal of the American Water Works Association* **106** (5), E233–E241.

Mutikanga, H. E., Sharma, S. K. & Vairavamoorthy, K. 2011 Investigating water meter performance in developing countries: a case study of Kampala, Uganda. *Water SA* **37** (4), 567–574.

Tabesh, M. & Delavar, M. R. 2003 *Application of Integrated GIS and Hydraulic Models for Unaccounted for Water Studies in Water Distribution Systems*. A. A. Balkema Publishers, Leiden, The Netherlands.

Van Zyl, J. E. 2011 *Introduction to Integrated Water Meter Management*. Water Research Commission (WRC), Gezina, South Africa.

Walter, D., Mastaller, M. & Klingel, P. 2018 Accuracy of single-jet and multi-jet water meters under the influence of the filling process in intermittently operated pipe networks. *Water Science and Technology-Water Supply* **18** (2), 679–687.

Xu, M. H., Yang, J., Hughes, D. M. & Lechevallier, M. W. 2014 Survey of pressure management in water distribution systems. *Journal of the American Water Works Association* **106** (11), E518–E524.

First received 11 March 2019; accepted in revised form 27 October 2019. Available online 19 November 2019