UNDERSTANDING NON-REGISTRATION IN DOMESTIC WATER METERS

Implications for meter replacement strategies

P Mukheibir, R Stewart, D Giurco, K O'Halloran

Abstract

Understanding elements of non-revenue water (NRW) has become more critical in an era where urban water has a rapidly increasing value. Meter under- and over-registration of flows has received considerable research attention over the years, but there has been limited focus on non-registration, particularly for domestic water meters over their life cycle. This paper presents empirical estimates on non-registration for typically installed domestic water meters and emphasises that both under- and non-registration should be considered for any meter replacement assessments and associated policies. Economic modelling showed that domestic water meters should be replaced at lower throughput volumes when considering both of these meter inaccuracy categories. The key value of the paper is that it provides a methodology for determining non-registration for a fleet of domestic meters.

Introduction

Most Australian utilities have meter replacement programs, but the criteria for replacement vary. It is argued that different operating conditions, pipe materials, the condition of the network and water quality affect meters differently. However, there is still limited understanding of meter accuracy performance with in-situ age, particularly when considering its starting or minimum registration level (Qs). Theoretically, water with a flow rate less than the Qs flow rate of a meter (< 15L/hr) cannot be measured and represents lost revenue. In this paper the term *non-registration* refers to the failure of the meter to register accurately the volume of water passing at flow rates below the meter's specified minimum registration rate (Qs). The significance of this unread volume is not yet well understood.

In the past, much work has been done on meter accuracy, with utilities testing batches of meters in accordance with the NMI R49-2 (2009b). However, the low flows at which the meters are tested are usually not low enough to measure the actual minimum registration level for each meter. So traditionally *under-registration* at the various standard flow rates has been assumed to be the primary contributor to non-revenue water attributable to meter inaccuracy. The research reported here will show that non-registration could be more significant than under-registration and should be considered together with under-registration when estimating the non-revenue water (or the *unregistered* volume) and for determining replacement intervals for a fleet of meters.

Research has also shown that a fleet of water meters can become less accurate with age and usage (i.e. under-registration of flow) and, as will be shown, non-registration of the meter can also increase with usage, resulting in higher volumes of unaccounted for water (Arregui *et al*., 2005; 2006). This paper provides a summary of the results of analysing the impact of meter usage and age on the starting registration flow of meters, albeit based on a small sample size. It proposes a methodology (based on the available research) for calculating the non-registration volume of a suite of meters and scheduling the replacement of a meter based on non- and under-registration calculations. The study was conducted on a common brand of 20mm meter used in Australia.

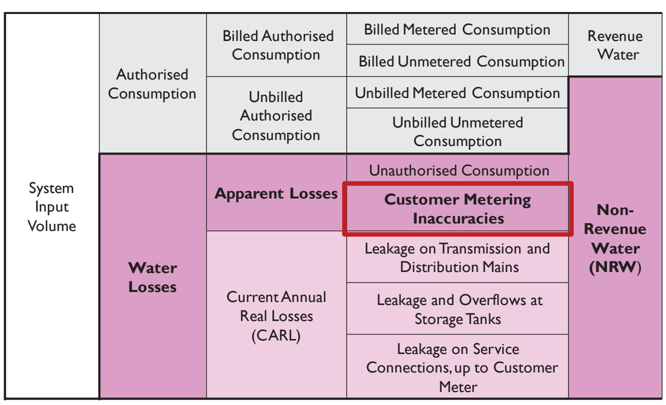


Figure 1. IWA Water Balance (Alegre *et al.*, 2006).

Customer Meter Inaccuracies Component of Non-Revenue Water

As illustrated in Figure 1, customer-metering inaccuracies, together with unauthorised consumption, account for the apparent losses when undertaking a water balance of the system input volume (Alegre *et al*., 2006). Since this value cannot be precisely measured or determined, the Water Services Association of Australia (WSAA) has provided a default value for the purposes of preparing the water balance. The WSAA (2010) default value for average non-revenue water based on an *under-registration* of residential meters is 2.0% of recorded residential metered volume. In earlier versions of the WSAA Handbook (2006), the default value for residential meters was 1.5% for under-registration, with an additional 0.5% being added to the residential meter error to account for meter non-registration. This change results in a simplification of the sources of meter error and, therefore, lacks focus on non-registration as being a key source of non-revenue water, as is demonstrated in this paper.

This paper advocates that the unregistered consumption of domestic customer meters comprises the sum of the non-registered and under-registered volumes and should be expressed as:

unregistered volume = non-registered volume + under-registered volume

The total unregistered volume is significant when estimating apparent losses for a meter, and the fleet of meters should, therefore, be disaggregated into the registration groups when calculating the water loss due to meter error, as will be further shown in this paper.

Understanding Non-Registration of Domestic Water Meters

To gain a better understanding of non-registration of water meters, this research combines three components. The first estimates the extent of non-registered water at low flows for new and aged meters. The second seeks to quantify how prevalent 'low-flow events' are in daily household water use. The third component considers the role that usage has on the Qs and, hence, the non-registration volume. These three pieces of information are then used to estimate non-revenue water attributable to non-registration (rather than under-registration) and are discussed in the next sub-sections.

Table 1. Non-registered water for a new meter as a percentage of the daily consumption.

Interval category (L/hr)	Flow rate interval (L/hr)	Percentage of daily consumption per category (%)	Proportion of interval volume in each category	Recording accuracy of meter per interval	Non-registered water per interval (%)
		A	*B*	*C*	*D=A*B*(1/C - 1)*
	0 to 1		0.05	0.15	0.37
	1 to 2		0.12	0.35	0.30
0 ≤ 5	2 to 3	1.31	0.23	0.60	0.20
	3 to 4		0.30	0.85	0.08
	4 to 5		0.30	0.90	0.04
	5 to 6		0.20	0.95	0.01
	6 to 7		0.20	1.00	0.00
5 ≤ 10	7 to 8	1.29	0.20	1.00	0.00
	8 to 9		0.20	1.00	0.00
	9 to 10		0.20	1.00	0.00
Total percentage non-registered water for a new meter					1.00

Meter testing at low flows

Using a device called an Unmeasured-Flow Reducer (UFR) a study was conducted to show that non-registration below 5L/hr is apparent (CIEM, 2011a). The UFR is designed to reduce the amount of water that flows below the flow meter measurement threshold by changing the flow regime through the meter at low flow rates. For the standard new meter used in this study, the Qs (i.e., minimum flow rate) was specified as 2L/hr (or 0.033L/min). Theoretically, therefore, water with a flow rate less than the Qs flow rate of a meter cannot be measured. Figure 2 details the flow rate recording accuracy for the new Qs = 2L/hr water meter, pre- and post-implementation of a UFR device.

A summary of key findings from the study (CIEM, 2011a) are detailed below and are shown in column C of Table 1:

- The new water meter (DN20) demonstrated a poor water recording accuracy less than 3L/hr.
- The new water meter displayed accurate measurement after 6L/hr, with or without installation of UFR.
- For flow rates from 0–2L/hr, there were significant under-registration of flows without the UFR, with only 14% and 36% recorded from flow rates of 0–1L/hr and 1–2L/hr, respectively; whereas, with the UFR, the measured flows improved to 55% and 85% respectively, indicating that measurement in these lower flow rate intervals improved with the UFR by 41% and 49%.
- From 2–3L/hr, with the UFR, there was almost 95% flow recording accuracy, compared to 61% without the UFR (i.e. 33% more accurate than without UFR);
- From 3–6L/hr, the meter with UFR was considered accurate. The UFR contributed to 5%–11% improvement in the measurement recording accuracy of the new meter.
- The reason for some degree of non- or under-registration at these very low flow rate levels when using the UFR could not be established.
- Based on the recorded accuracy with and without UFR, the average accuracy for flows recorded below 5L/hr was 57%. This inaccuracy was attributed to non-registration.

This phase of the research gave an estimation of the magnitude of non-registration. The next section explores how prevalent low flow rates are, which could give rise to significant non-registered volumes.

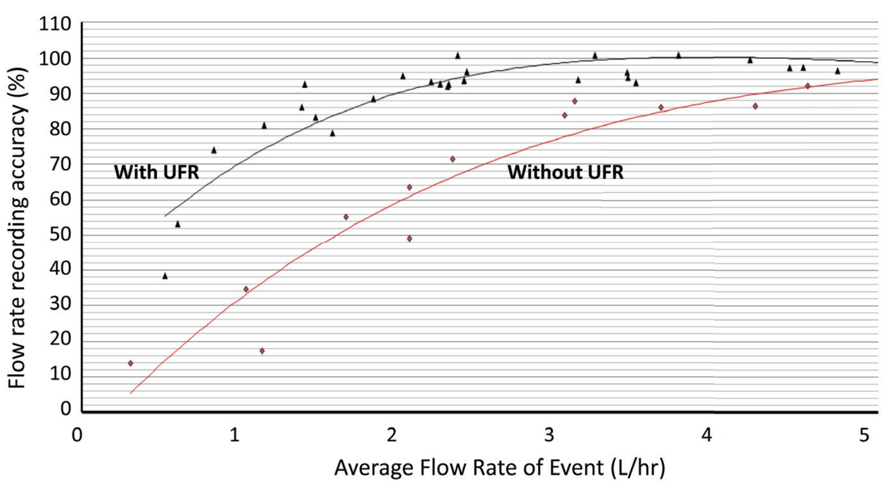
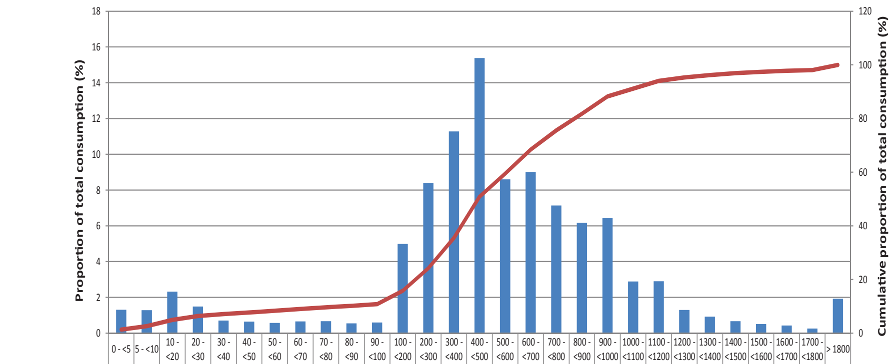


Figure 2. Flow rate registration accuracy for new meter with and without UFR.

Consumption flow rate profile: prevalence of low-flow events

Smart meters enable high-resolution flow data to be captured remotely and used for a range of urban water planning purposes (Stewart *et al*., 2010) such as demand management (Willis *et al*., 2010; Willis *et al*., 2011a), scheme evaluation (Willis *et al*., 2011b; Talebpour *et al*., 2011) and demand forecasting (Makki *et al*., 2011). To determine how often low flow events occur in a day, data was analysed from a sample of smart meters drawn from the South-East Queensland and Melbourne regions. High-resolution smart metering technology (i.e. 0.014L/pulse at 5-second intervals) enabled flow data from over 400 households to be classified into the flow rate categories shown in Figure 3. The results are summarised as follows (CIEM, 2011b):

- The first 11 flow rate categories shown in Figure 3 (i.e., from ≤ 5L/hr up to the 91–100L/hr category) generally showed low flow events. Sources include leaks, internal taps, toilets, dishwashers, and some part of shower and clothes-washer events. Data collection does not include volumes of consumption in flow rates less than 2L/hr, as the minimum registration of a new meter is 2L/hr in



Flow rate category (L/hr)	0 - <5	5 - <10	10 - <20	20 - <30	30 - <40	40 - <50	50 - <60	60 - <70	70 - <80	80 - <90	90 - <100	100 - <200	200 - <300	300 - <400	400 - <500	500 - <600	600 - <700	700 - <800	800 - <900	900 - <1000	1000 - <1100	1100 - <1200	1200 - <1300	1300 - <1400	1400 - <1500	1500 - <1600	1600 - <1700	1700 - <1800	> 1800
Prop of T Con(%)	1.31	1.29	2.32	1.49	0.7	0.64	0.57	0.66	0.67	0.55	0.6	4.99	8.39	11.28	15.38	8.6	9.01	7.14	6.17	6.43	2.89	2.9	1.3	0.92	0.67	0.51	0.43	0.26	1.92
Cum Prop of T Con(%)	1.31	2.6	4.92	6.41	7.11	7.75	8.32	8.98	9.65	10.2	10.8	15.79	24.18	35.46	50.84	59.44	68.45	75.59	81.76	88.19	91.08	93.98	95.28	96.2	96.87	97.38	97.81	98.07	100.00

Figure 3. Proportion and cumulative proportion of total water consumption (%) in each flow rate category (SEQ and Melbourne region combined sample, *n* = 406).

specification and potentially higher in practice, as illustrated above. Therefore, the 0 ≤ 5L/hr category essential has flow recorded in the 2 to 5L/hr range.

- The middle flow rate range made up the majority of total water use (i.e., from 100L/hr to 1200L/hr), especially the 300–600L/hr interval. Sources include showers, clothes washers, irrigation and external taps.
- The rest of the range (i.e., from 1200L/hr to over 1800L/hr) can be attributed to showers, clothes washers, irrigation, external taps and uncommon water usage (e.g., service break leaks).

The first three flow rate categories shown in Figure 3 are the most important for estimating non-registered volumes. Therefore, the following values were applied in conjunction with the above meter-testing results to provide a robust estimate for non-registered flow:

- **0 ≤ 5 flow rate interval category**: 1.31% of total residential consumption;
- **5 ≤ 10 flow rate interval category**: 1.29% of total residential consumption; and
- **10 ≤ 20 flow rate interval category**: 2.32% of total residential consumption.

Impact of usage on non-registration

It is well known that meter ageing, or more correctly meter usage, affects meter accuracy for flow rates above Qs (Arregui *et al*., 2005). To date, there has been little reported on the relationship between non-registration of meters (i.e. below Qs) and age due to the cost of this type of testing and, historically, a low level of concern for this type of water loss. The escalation of water tariffs in the past five years and a heightened expectation of better accounting of system input volumes has emphasised the need to provide sound estimates of citywide non-registration volumes.

To address this knowledge gap a small sample of meters from across the three Melbourne urban water utilities' jurisdictions, with differing registration volumes, were tested to determine their Qs (WBW, 2011). The meters were assembled in batches of three meters in series with similar usage registration. The worst case for each batch was recorded, i.e. the flow at which the last meter in the testing batch started to register water flow. Ideally, individual meter testing should be conducted to obtain a more accurate relationship between meter age and Qs instead of this adopted sampling approach; however, the testing time for each test (i.e. 6–8 hours per test) and the rig's limited availability for research testing activities, meant that this alternative testing approach had to be adopted. Nonetheless, the results and trend established would closely resemble that obtained if the ideal testing procedure was followed and individual meters were tested. The results are illustrated in Figure 4, where it can be seen that older meters (3000+ kL) exhibit a Qs that is more than double the Qs of a newly installed meter – i.e. 7.26L/hr and 3.4L/hr respectively.

Therefore, the decreasing accuracy of the meter not only results in under-registration of usage volume but also results in higher non-registration thresholds. As such, any estimation of non-registered water must take account of a region's meter age and type profile.

Understanding Components of Unregistered Water

Determining under-registered volumes

All meters have specified ranges of accuracy and must comply with the NMI R 49 specifications for maximum permissible error for domestic flow meters, as shown in Table 3 (NMI, 2009a). The under-registration of a fleet of meters is best determined by annual random sample testing of the fleet to take into account the specific network operating conditions, and the registered usage of the meters.

To obtain the average error for a meter across a range of flows, the meters are tested against the flow rates shown in Table 4, and the errors weighted according to the flow profile (similar to the one shown in Figure 3) of an average domestic consumer. The first line of Table 5 provides the average percentage error in the meter registration for a representative sample from two Victorian water utilities of 660 20mm meters of the same brand and model. As can be observed, the results fall well within the NMI specifications. Also, the registration begins as an over-registration when the meter is relatively new and under-registers when the meter has registered greater than 2000kL. This result may vary from utility to utility and between brands and models.

Calculating non-registered volumes

This section combines the above empirical findings to develop an estimate of non-registered water in residential households.

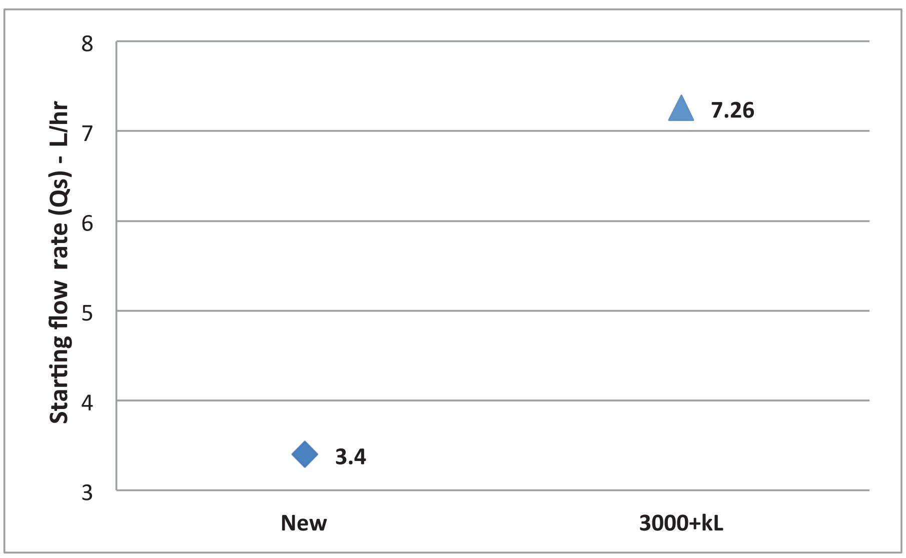


Figure 4. Average starting flow rate (Qs) of tested meters.

The recording accuracy of the meter in column C of Table 1 is based on the non-registration determined by using the UFR device. The allocation of average volume per flow rate interval below 5L/hr is not known; therefore, a distribution for this range has been estimated as shown in column B. For the other ranges, the proportion of flow-per-litre interval has been assumed to be equal. Column A represents the percentage of daily consumption per interval category, eg. 0 ≤ 5L/hr flow rate interval.

In Figure 3 of this paper, it is illustrated that for a meter registering in excess of 3000kL, the Qs can be expected to be no worse than 7.4 L/hr. Given that for a new meter the Qs was 3.4L/hr and this equated to 85% average non-registration (see Figure 2), the same logic was applied to the well-used meter. It was found that 85% average non-registration for the well-used meter was associated with 7.3L/hr, and a similar linear curve was applied back to the flows of less than 1L/hr to assign the percentage of recording accuracy in column C of Table 2.

The non-registered water can be calculated by multiplying columns A and B together with the factor representing the unrecorded volume. Based on the research reported in this paper, the non-registered water is, therefore, calculated to be 1% of the average daily registered consumption. Using the same approach for a well-used meter (of the same brand and type) that had registered in excess of 3000kL, the estimated total non-registered volume is 3.5% of the average daily registered consumption (see Table 2).

Based on the percentage of non-registration for the two ends of the usage spectrum, the percentage of non-registration for the range of registered volumes was linearly interpolated (this is shown in line two of Table 5). When compared with the non-registration, it is clearly demonstrated that, for the chosen brand of flow meter in this study, the under-registration is much less and, hence, both sources of error should be taken into account when considering the effectiveness of the meter – as is shown in the next two sections.

Considering both non- and under-registration

The unregistered volume is made up of both *under-registration* and *non-registration*, as explained previously, and therefore both should be considered when determining the optimum replacement interval of a suite of meters.

According to Table 5, the average non-registration increases threefold from 1.0% for a new meter to 3.5% for an aged (3000+ KL) meter. The average under-registration determined from the sample of meter testing discussed above falls within a range between -0.4% and +0.1% and changes on average from being positive when relatively new to being negative for higher registration volumes. Australian standards (NMI, 2009a) permit new meters to over-register (provided they are within the specified upper and lower limits shown in Table 3) and this now occurs with popular types of new positive displacement meters.

When combined, the over-registration for the new meter slightly offsets the non-registered volume, whereas for older meters the two combine to produce a higher unregistered volume (as shown in the last row of Table 5). This brings into question the focus on under-registration as the indicator for poor performance of the meter and potential loss of revenue, whereas in this study non-registration has been illustrated to be more significant and becomes progressively worse with usage.

Table 2. Non-registered water for a used meter that has registered more than 3000kL, as percentage of the daily consumption.

Interval category (L/hr)	Flow rate interval (L/hr)	Percentage of daily consumption per category (%)	Proportion of interval volume in each category	Recording accuracy of meter per interval	Non-registered water per interval (%)
		A	*B*	*C*	*D=A*B*(1/C - 1)*
0 ≤ 5	0 to 1	1.31	0.05	0.08	0.81
	1 to 2		0.12	0.18	0.74
	2 to 3		0.23	0.29	0.71
	3 to 4		0.30	0.40	0.58
	4 to 5		0.30	0.52	0.37
5 ≤ 10	5 to 6	1.29	0.20	0.63	0.15
	6 to 7		0.20	0.74	0.09
	7 to 8		0.20	0.85	0.05
	8 to 9		0.20	0.90	0.03
	9 to 10		0.20	0.95	0.01
10 ≤ 20	10 to 11	2.32	0.10	1.00	0.00
	11 to 12		0.10	1.00	0.00
	12 to 13		0.10	1.00	0.00
	13 to 14		0.10	1.00	0.00
	14 to 15		0.10	1.00	0.00
Total percentage non-registered water for a used meter					3.54

Table 3. Permissible meter registration error (NMI 2009a).

Class 1	>100kL/hr	Lower range (<32 L/hr)	± 3%
		Upper range (>32 L/hr)	± 1%
Class 2	<100kL/hr	Lower range (<32 L/hr)	± 5%
		Upper range (>32 L/hr)	± 2%

Table 4. Meter testing flow rates and weightings.

Flow rates L/Hr	Weighting %
300	27.0%
600	42.0%
1200	23.0%
2400	8.0%
	100.0%

Informing Better Meter Replacement Policies

Current meter replacement policies

NMI R-49 specifies the maximum permissible error for domestic flow meters and recommends that tested meters falling outside this range should be replaced (see Table 3, NMI, 2009a). There is a wide range of replacement policies within the water industry, which use a combination of the age and the total registration of the meter. Based on the age of the meter, the policies reviewed specify meter replacement within 10 to 15 years, while based on registration volume, the range is from 3500–7000kL.

Table 5. Percentage of non-registration associated with each range of total registered volume.

Meter registration (kL)	0-500	501-1000	1001-1500	1501-2000	2001-2500	2501-3000	3000+
Under/over -registered % *(results from meter testing)*	0.1%	0.1%	0.1%	0.0%	-0.2%	-0.4%	-0.4%
Non-registered % *(extrapolated from Tables 1 & 2)*	-1.0%	-1.4%	-1.8%	-2.3%	-2.7%	-3.1%	-3.5%
Unregistered % *(Combined)*	-0.9%	-1.3%	-1.7%	-2.3%	-2.9%	-3.5%	-3.9%

Implications for meter replacement

As demonstrated, it would be prudent to base meter replacement timing on the combined impacts of both under-registration and non-registration over its life cycle. Economic modelling was conducted to determine the cost-effective time to replace a meter, considering the under-registration and non-registration percentages of total consumption detailed in Table 5. Optimum timing for replacing domestic meters was calculated using the net present value (NPV) of the cumulative value of the lost water to the utility and the meter replacement cost for a range of annual consumption volumes. The analysis was based on:

- A meter replacement cost of $95.00;
- A discount rate of 7%;
- A 20-year analysis period; and
- A rising block tariff structure of the following:

  <440 L/d (<161 kL/yr) = $1.80/kL

  <880 L/d (<321 kL/yr) = $2.10/kL

  >880 L/d (>321 kL/yr) = $3.10/kL

For consumption greater than 3000kL, the annual increase in percentage of unregistered volume was considered to be at the same annual rate used to reach 3000+kL. For example, an annual consumption of 250kL would take 12 years to reach 3000kL, therefore the annual increase in percentage unregistered volume for the combined losses would be calculated as (-4.0 less -0.9)/(12-1) = -0.28%/yr (assuming a linear relationship).

The results indicate that for the unregistered percentages presented in this paper, it is not cost effective to replace domestic meters unless they register more than 250kL/yr. While some utilities base their replacement on age, total registration or a combination thereof, the loss incurred by the utility is a percentage of the annual volume. For example, if a meter registers only 150kL/yr, then even after 20 years and a total registration of 3000kL or 40 years and a total registration of 6000kL, the loss of revenue is less than the cost to replace the meter. By contrast, for an annual consumption of 250kL/yr, the economically optimum time to replace the meter would be in year 11. This is based on the combined effect of the non- and under-registered volume. As seen in Table 6, the two types of unregistered volumes on their own, however, indicate that a better NPV is achieved by not replacing the meter with a lower annual registration.

For even higher consumption volumes between 300kL/year and 400kL/year, the losses resulting from non-registration are high enough to warrant the meter to be replaced, whereas basing the replacement solely on under-registration would indicate that the meters do not need replacing, since it would cost the utility more to replace the meter than the value of the lost revenue through under-registration.

The inclusion of non-registration in the consideration for meter replacement has the effect of bringing forward the replacement date based on registered volume. Depending on the meter replacement cost, batch meter test results and the price of water for a specific water utility, slightly different results will be obtained. By continually updating the replacement policy based on up-to-date meter test data and water demand modelling, a more accurate replacement policy can be developed based on the optimum NPV of the lost revenue.

Recommendations

When considering unregistered metered volumes for domestic meters, it is recommended that both forms be considered together, viz:

unregistered volume = non-registered volume + under-registered volume

This will have implications for both non-revenue water accounting and for setting guidelines and policies for the replacement of domestic meters. The percentages for each registration group will vary for each utility based on meter type, network and operating conditions, and annual volumes passing through the meter.

Utilities wanting to assess the implications of the findings in this paper for their asset management policies and non-revenue calculations should conduct testing on the brands and models in their fleet to determine the relevant percentages of losses.

Non-revenue water considerations

The research presented in this paper, therefore, suggests that non-registration is more significant than under-registration in understanding non-revenue water; i.e. it could account for a larger percentage of the non-revenue water passing through a meter. The additional volume associated with the percentage of non-registration can help further explain the *apparent losses* (*customer metering inaccuracies*) when calculating the water balance and the overall water loss.

In order to fully account for the non-revenue water due to errors in the registration of domestic water consumption, both the non- and under-registration of the meters should be considered. As has been illustrated, the volume of unregistered water increases with increased meter use. Therefore, using an average for a fleet of meters is not reliable enough, and improved estimates can be achieved by assessing the losses per registration group.

Table 6. Outcome of meter replacement analysis.

kL/yr	Year for meter exchange based on NPV		
	Under-registration	Non-registration	Combined
150	*No replacement*	*No replacement*	*No replacement*
200	*No replacement*	*No replacement*	*No replacement*
250	*No replacement*	*No replacement*	Year 11
300	*No replacement*	Year 11	Year 10
350	*No replacement*	Year 10	Year 10
400	*No replacement*	Year 10	Year 9
450	Year 11	Year 9	Year 9
500	Year 11	Year 9	Year 9

Meter replacement guidelines

Based on these loss percentages and the costing assumptions, it would appear that it is not cost effective to replace the meter solely based on the registration age. When preparing a meter replacement policy, consideration of both the non- and under-registration components of the unregistered volume should be made. As has been illustrated with the available data, the percentage of non-registered volume increased more significantly with higher total registered volumes as compared with under-registration. Therefore, non-registration should not be neglected.

The replacement interval will vary between brands and sizes of meters and will also depend on the operating conditions of the meter. Lastly, given that variable water charges are often increasing at rates greater than inflation, thus implying a greater value of non-registered water, there may be greater justification for reducing meter replacement intervals in the future.

Further Research Opportunities

The research in this report is based on a limited sample size. To better understand the implications of non-registration for assessing non-revenue water and developing meter replacement guidelines to assist non-revenue water calculations and meter replacement policies, further work is required to:

1. More rigorously test a statistically relevant sample of meters at very low flows (i.e. flow rates below 5L/hr) for a range of brands with differing levels of registration, to improve the confidence associated with the non-registration percentage losses.
2. Collate and test both non- and under-registration for statistically significant samples of different water meter types in varying water distribution areas in order to provide default values for meter replacement assessments.
3. Apply smart metering technologies and advanced customer demand profiling techniques to improve the present understanding of domestic user profiles.

Acknowledgements

This project was funded by the Victorian Smart Water Fund. Thank you to members of the Steering Committee and Henry Friese from Barwon Water (Geelong) for meter testing. The contributions of other members of the project team are also gratefully acknowledged.

The Authors

Dr Pierre Mukheibir (email: pierre.mukheibir@uts.edu.au) is a Research Director at the Institute for Sustainable Futures at the University of Technology Sydney. His research is focused on Urban Water Planning & Management, Water Supply Demand Strategies and Water Loss Reduction.

Associate Professor Rodney Stewart (email: r.stewart@griffith.edu.au) is the Director of the Centre for Infrastructure Engineering & Management at Griffith University. His research is focused on Urban Water Planning, Smart Metering and Residential End Use Studies.

Associate Professor Damien Giurco (email: Damien.Giurco@uts.edu.au) is a Research Director at the Institute for Sustainable Futures, University of Technology, Sydney. His urban water research focuses on Integrated Resources Planning, Smart Metering and Industrial Ecology.

Kelvin O'Halloran (email: kohalloran@seqwater.com.au) is an Adjunct Associate Professor, Infrastructure Engineering & Management, Griffith University. He has held research positions at UNSW, UQ and UCL (London) and has worked for Gold Coast Water, Thames Water, Wide Bay Water and, currently, Seqwater. He specialises in bringing together universities and industry for mutually beneficial projects.

References

Alegre H, Baptista J, Cabrera E, Cubillo F, Duarte P, Hirner W, Merkel W & Parena R (2006): Performance Indicators for Water Supply Services – 2nd Edition. *IWA Manual of Best Practice*, IWA Publishing.

Arregui F, Cabrera Jr E, Cobacho R & García-Serra J (2005): Key Factors Affecting Water Meter Accuracy, Proceedings of Leakage 2005 Conference, Halifax.

Arregui FJ, Cabrera E, Cobacho R & García-Serra J (2006): Reducing Apparent Losses Caused by Meters' Inaccuracies, in *Water Practice & Technology*, Vol 1, IWA Publishing.

CIEM (2011a): Experimental Study on Meter Registration Accuracy at Low Flow Rates and Benefits of UFR Implementation, Technical Report 2, Understanding Apparent Water Losses Through Non-Registration of Domestic Water Meters [prepared for the Smart Water Fund], Centre for Infrastructure Engineering and Management, Griffith University.

CIEM (2011b): Determining Average Volumes of Residential Water Consumption in Flow Rate Interval Categories, Technical Report 1, Understanding Apparent Water Losses Through Non-Registration of Domestic Water Meters [prepared for the Smart Water Fund], Centre for Infrastructure Engineering and Management, Griffith University.

Makki AA, Stewart RA, Panuwatwanich K & Beal C (2011): Revealing the Determinants of Shower Water End Use Consumption: Enabling Better Targeted Urban Water Conservation Strategies, *Journal of Cleaner Production*, in-press, doi:10.1016/j.jclepro.2011.08.007.

NMI Recommendation R 49-1 (2009a): Water Meters Intended for the Metering of Cold Potable Water and Hot Water, Part 1: Metrological and Technical Requirements, National Measurement Institute, Sydney, April 2009.

NMI Recommendation R 49-2 (2009b): Water Meters Intended for the Metering of Cold Potable Water and Hot Water, Part 2: Test Methods, National Measurement Institute, Sydney, April 2009.

Stewart RA, Willis R, Giurco D, Panuwatwanich K & Capati G (2010): Web-based knowledge management system: linking smart metering to the future of urban water planning. *Australian Planner*, Vol 47, pp 66–74.

Talebpour M, Stewart R, Beal C, Dowling B, Sharma A & Fane S (2011): Rainwater Tank End Usage and Energy Demand: A Pilot Study. *Water Journal,* Vol 38(1): pp 85–89.

Water Services Association of Australia, National Water Commission and the NWI Parties 2006, National Performance Framework: 2005–06 Urban Performance Reporting Indicators and Definitions Handbook.

Water Services Association of Australia, National Water Commission and the NWI Parties 2010, National Performance Framework: 2009–10 Urban Performance Reporting Indicators and Definitions Handbook.

WBW (2009): Understanding Apparent Water Losses Through Non-Registration of Domestic Water Meters [prepared for the Smart Water Fund], Wide Bay Water, November 2009.

WBW (2011): Understanding Apparent Water Losses Through Non-Registration of Domestic Water Meters, Stage 2: Refining the Predictions from Stage 1 [prepared for the Smart Water Fund], Wide Bay Water, July 2011.

Willis RM, Stewart RA, Panuwatwanich K, Jones S & Kyriakides A (2010): Alarming Visual Display Monitors Affecting Shower End Use Water And Energy Conservation in Australian Residential Households. *Resources, Conservation and Recycling*, Vol 54 (12), pp 1117–1127.

Willis RM, Stewart RA, Giurco DP, Talebpour MR (2011a): End Use Water Consumption in Households: Impact of Socio-Demographic Factors and Efficient Devices, *Journal of Cleaner Production*, in-press, doi:10.1016/j.jclepro.2011.08.006.

Willis RM, Stewart RA, Williams P, Hacker C, Emmonds S & Capati G (2011b): Residential Potable and Recycled Water End Uses in a Dual Reticulated Supply System. *Desalination Vol* 272 (1–3), pp 201–211.