

Determination of the optimum number of water meter test flow rates in South Africa

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ABSTRACT

Metering errors are one of the main contributors of apparent losses, therefore the determination of the optimum number of flow rates to reproduce the meter error curve is of critical importance. The objective of this study was to determine the optimum number of flow rates suitable for testing water meters in South Africa. This was achieved by accessing data from two local studies that tested 323 used water meters over 10 flow rates. The used water meters had been removed from the field and tested in the laboratory. The data from the laboratory tests were then further analysed by recalculating the weighted error for different flow rate combinations. The optimum number of flow rates, which was found to be 7, was the combination that minimised the weighted error of the tested meters. This study therefore recommends increasing the number of flow rates prescribed by the South African National Standard 1529-1:2019 from three flow rates (q_{min} , q_t and q_p) to 7 flow rates, namely 7, 15, 30, 60, 120, 1500 and 3,000 l/h.

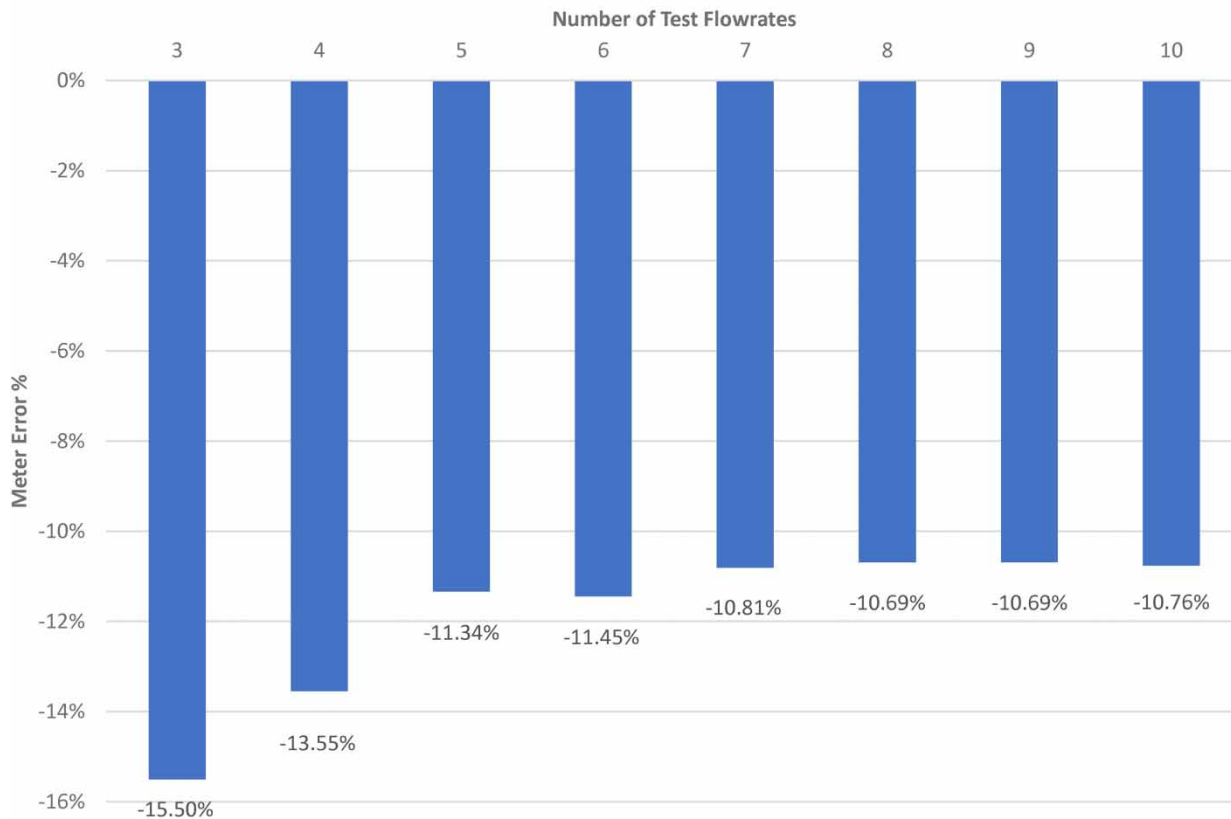
Key words: apparent losses, test flow rates, water meter errors

HIGHLIGHTS

- This study analyses data from two South African studies that had tested 323 used water meters.
- The analysis recalculates weighted error for different flow rate combinations.
- The South African National Standard 1529-1:2019 prescribes three flow rates for the evaluation of metering accuracy. This study recommends increasing to 7.
- This study creates a comprehensive consumption profile for South Africa.

GRAPHICAL ABSTRACT

Weighted meter error with test flow rates (South African Municipality A)



INTRODUCTION

Water meters enable the measurement of water that is conveyed from a water service provider to a consumer, and as such, verification of their accuracy throughout their lifecycle is the subject of legal scrutiny. Such scrutiny is however challenging and limited in many jurisdictions, particularly in the developing world. In the South African context, the Legal Metrology Act 9 of 2014 (Presidency 2014) and its regulations form the basis of such scrutiny. While this Act, and its associated regulations, require all measuring instruments to be the subject of initial and on-going verification, there are limited requirements for water meters when compared to other measuring instruments, especially in the aspect of on-going verification. The prescription and management of on-going verification should be underpinned by the metrological control of water meters, which is a foundational imperative for meter management as it forms the basis for all meter accuracy estimation through meter testing (Arregui *et al.* 2006b). Meter accuracy estimation is a very important aspect in the management of apparent water loss as metering errors have been shown to be the largest contributors to apparent losses (Rizzo & Cilia 2005).

Thornton *et al.* (2008) define apparent losses as the non-physical losses that occur when water is successfully delivered to the consumer but, for several reasons, is not measured or recorded accurately, thereby inducing a degree of error in the customer consumption. The determination and management of metering errors follows a methodology that measures both the accuracy of a meter and the effectiveness of that meter in measuring a particular consumption pattern (Ferréol 2005). This is collectively known as determining the weighted accuracy of a meter and has been implemented by many authors including Noss *et al.* (1987), Yee (1999), Arregui *et al.* (2006a, 2013), Arregui *et al.* (2006b), Mutikanga *et al.* (2011a) and Ncube & Taigbenu (2019a, 2019b).

However, one non-trivial aspect of this methodology is determining the flow rates at which the meters must be tested. This is because meter testing must reconstruct a representative error curve through the testing of a single meter at several selected flow rates. Several representative error curves are presented in Ncube (2019). If adopted testing points are not adequately

representative, the obtained estimates are also erroneous. Generally, determination of the meter error curve requires testing the meter at more than the four flow rates (Q1, Q2, Q3 and Q4) referred to in standards aligned with the International Standards Organisation (ISO) 4064 series, the three flow rates ($q_{\min}$, q_t and q_p) in the South African National Standard (SANS) 1529 (an outdated version of the ISO 4064), or the three flow rates (minimum, intermediate and maximum) prescribed in the American Water Works Association's (AWWA) Manual M6. Studies, such as Allender (1996), Mutikanga *et al.* (2011b) and Yee (1999), that evaluated apparent losses using only three points have several pitfalls and these were demonstrated in Arregui *et al.* (2009) where utilising inadequate testing points introduce substantial errors in the estimation of metering accuracy. In Figure 1, Johnson (2019) graphically demonstrates the impact of the number of test flow rates, as recommended by different guidelines and standards, on meter-weighted error.

In Figure 1, the impact of the application of the four test flow rate requirement of the Australian Standard, AS 3565.4 (Standards Australia 2007) and the six test flow rate requirement of the Australian Guidelines (Water Services Association of Australia 2012) provides an approximation of their underestimation of weighted error when compared with Arregui *et al.*'s (2006a) nine test flow rate requirement. In these studies, the four test flow rate results underestimated the weighted error by approximately -0.8% when compared with the six test flow rate results. To counteract this handicap, Arregui *et al.* (2013) proposed the optimum number of required test flow rates for meters with different permanent flow rates, based on the testing of several meter models at 20 different flow rates. The optimum number of test flow rates that minimised the meter error was found to be eight for the different permanent flow rates considered.

The determination of the error curve using low flow rates where large variations occur requires exceptional care to obtain a precise representation of the actual performance of meters in the field. This is very important for communities that experience high incidences of low flows, such as in the city of Johannesburg, which has an estimated 63% occurrence of leakage and monthly leakage ranging from 11 to 41 m³/month (Lugoma *et al.* 2012; Ncube & Taigbenu 2016). In considering this reality, Ncube & Taigbenu (2019a) slightly modified the recommendation of Arregui *et al.* (2013) to suit meters popularly used in South Africa and incorporated test flow rates employed locally. Similarly, Fourie *et al.* (2020), for a section of the South African province of Gauteng, adopted the 10 flow rates commonly used in South Africa for meter degradation analysis, with slight variations to the flow rates. However, the optimality of the 10 flow rates was not evaluated for local conditions, particularly since limited financial resources limit water meter testing initiatives.

Another obstacle in the determination of weighted accuracy estimates, particularly for studies that did not undertake consumption characterisation studies, is the determination of the consumption profile, at the same level of detail as the test flow

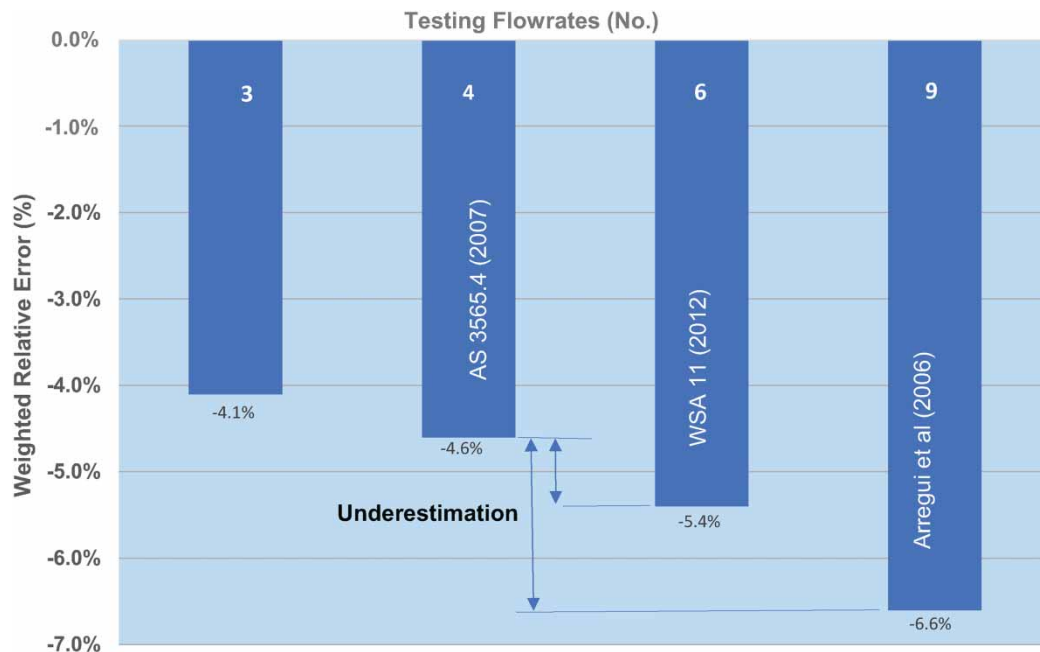


Figure 1 | Influence of the number of test flow rates on meter-weighted error.

rates. Various studies tend to interpolate previous results on consumption profiles while other studies, such as Szilveszter *et al.* (2015), calculate the weighted error using consumption patterns from different locations, which are not without drawbacks, including likely not being representative. In addition to evaluating the optimum number of meter test flow rates appropriate for the South African and similar contexts, this study creates a comprehensive consumption profile that can be adapted for South African and similar locality studies, without the need for extrapolation.

METHODS AND DATA

The original datasets of Ncube & Taigbenu (2019a) and Fourie *et al.* (2020), who estimated weighted meter error in South Africa, were used as the basis of this study. These studies evaluated a total of 323 water meters that were tested at 10 flow rates and these varied slightly from the flow rates derived in the rigorous study by Arregui *et al.* (2013), with adaptations for local requirements.

Ncube & Taigbenu (2019a) tested 123 water meters that were removed from the field using stratified sampling of Municipality A's network. The meters therefore adequately represented both the meter models and the meter readings within Municipality A. Table 1 reproduces the test flow rates employed in the study, together with the generalised equation (last row in Table 1) for use with any meter size.

Fourie *et al.* (2020) tested 200 water meters (2 models from the same manufacturer) from Municipality B. The meters were tested based on consumers' requests (when suspecting a fault) or those that had been flagged for verification through various municipal processes. These meters were therefore not representative of an installed meter fleet but were those that were potentially at the end of their useful life. The effect of this limitation will be highlighted during the discussion of results. The test flow rates applied in the dataset are summarised in Table 2. Significant differences in the test flow rates between Tables 1 and 2 are noted in the low flow (Q3 and Q4) and high flow (Q7, Q8 and Q9) regions. The different values observed for these flows are in the regions where the meter error curve varies the most.

Raw data from each test result in the two studies were collated and the weighted accuracy and error for each test were recalculated while varying the number of test flow rates used to estimate the weighted error. The combinations of flow rates used are summarised in Table 3 for both datasets.

The first of three test flow rates ($q_{\min}$, q_t and q_p) comprise the legislated flow rates largely used in South Africa (SANS 1529-1, 2019) with subsequent combinations covering the gap between the three test flow rates and the measuring range of a meter. The impact of each additional flow rate to the eventual weighted accuracy was recorded to determine the usefulness of the added flow rate. In the comparative weighted error of the SANS 1529-1 (2019), three test flow rates against the 10 flow rates are instructive on the implications of its use for meter error assessments. The calculation of the weighted error was computed

Table 1 | Test flow rates (Municipality A) (Ncube & Taigbenu 2019a)

Size	q_p , ℓ/h	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
15 mm	1,500	7	15	22.5	30	60	120	750	1,500	2,250	3,000
20 mm	2,500	12	25	37.5	50	100	200	1,250	2,500	3,750	5,000
25 mm	3,500	17	35	52.5	70	140	280	1,750	3,500	5,250	7,000
Any other	q_p	$0.5q_{\min C} - 1$	$q_{\min C}$	q_{tC}	$q_{\min B}$	$0.5q_{tB}$	q_{tB}	$0.5q_p$	q_p	$1.5q_p$	$2q_p$

Table 2 | Test flow rates (Municipality B) (Fourie *et al.* 2020)

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
15 mm meter, $q_p = 1,500 \ell/h$	7	15	30	45	60	120	240	750	1,500	3,000
Relationship to key flows	$0.5q_{\min C} - 1$	$q_{\min C}$	$2q_{\min C}$	$2q_{tC}$	$2q_{\min B}$	q_{tB}	$2q_{tB}$	$0.5q_p$	q_p	$2q_p$

Table 3 | Details of test flow rates

Number of test flow rates	3	4	5	6	7	8	9	10
	Included flow rate, Q^a							
Municipality A (Table 1)	2, 3, 8	1, 2, 3, 8	1–4, 8	1–5, 8	1–6, 8	1–8	1–9	1–10
Municipality B (Table 2)	2, 3, 9	1, 2, 3, 9	1–4, 9	1–5, 9	1–6, 9	1–7, 9	1–9	1–10

^aThe postscript relates to the Q values in Tables 1 and 2.

using the adapted formula from [Ncube \(2019\)](#) given by:

$$\bar{\varepsilon}_w = \sum_{q=1}^n \text{PTC}_q * 0.5(\text{GAAL}_q + \text{GAAL}_{q-1})$$

where q refers to the flow rate at which the meter is tested. This is the main parameter obtained from [Ncube & Taigbenu \(2019a\)](#) and [Fourie et al. \(2020\)](#). n is the number of key flow rates used in the testing, and in this case, those adopted for the evaluation exercise. PTC_q is the consumption percentage at each specific flow rate from 1 to n obtained from the consumption profile that was expanded in this study ([Table 4](#)). GAAL_q is the average accuracy of the meter at each specific flow rate from 1 to n . GAAL_0 is the meter accuracy flow at a flow rate of 0 (or where known, the starting flow rate), where it is assumed that the meter is not turning, and therefore, the meter accuracy is assumed to be minus 100%.

In this study, the evaluation of the optimal number of test flow rates was based on finding the least number of test flow rates (that will result in lower costs of meter testing) for the different flow rate combinations with the least difference in the weighted meter accuracy when evaluated against the 10 test flow rates.

The raw consumption characterisation dataset of [Ncube & Taigbenu \(2016\)](#) that produced the consumption profile considered typical of a South African city was evaluated to cover all common test flow rates that have been observed in literature and those used at some of the accredited flow laboratories in South Africa. Following the same methodology of [Ncube & Taigbenu \(2016\)](#), the flow logging data were re-analysed and categorised to the flow rates (ℓ/h) used in the original study i.e. 7.0, 15.0, 22.5, 30.0, 35.0, 45.0, 60.0, 96.0, 120.0, 240.0, 300.0, 750.0, 1,173.0, 1,500.0, 2,500.0, 3,000.0, 3,500.0 and 5,000.0 over the four consumer categories of business, public benefit organisations, residential and multi-purpose. A comprehensive consumption profile covering these flow rates was then developed in this study ([Table 4](#)) and was also used in the further analysis of the [Fourie et al. \(2020\)](#) dataset, since the study previously used interpolation.

RESULTS AND DISCUSSION

[Table 4](#) shows the expanded consumption profile for the City of Johannesburg with the different consumer categories. This profile is useful for evaluating weighted meter error at varying flow rates and would therefore minimise the need to resort to interpolation – the inflection of the meter error curve at certain flow rates makes interpolation unreliable and should therefore not be underestimated. It must also be noted that flow rate of 5,000 ℓ/h has been excluded from the profile as there is no recorded flow at that level.

The variation of the weighted meter error with the number of adopted test flow rates of the representative meter fleet of [Ncube & Taigbenu \(2019a\)](#) is shown in [Figures 1 and 2](#).

The weighted meter accuracy increases with the increasing number of flow rates, or conversely, the error decreases with the increasing number of test flow rates. In all cases, better accuracy is achieved at 10 flow rates, with a 4.74 difference in weighted accuracy when compared with three flow rates ($q_{\min}$, q_t and q_p). The inadequacy of the popularly used three test flow rates for the estimation of meter error and the weighted meter accuracy is clearly demonstrated in this figure.

It is important to note an important distinction in this study from the trend recorded by [Johnson \(2019\)](#) ([Figure 1](#)), where the weighted error increases with more test flow rates. This peculiarity is due to the compounding effect of the South African (City of Johannesburg) consumption profile, which has a high incidence of relatively low flows compared to the profiles for other countries. The net effect is that locally, the use of three test flow rates tends to exaggerate the weighted meter error and this over-estimation is reduced by increasing the number of flow rates. Another notable difference is that in [Figure 2](#), the omission of a certain number of test flow rates (7, 8 and 9 test flow rates) has a minimal difference of between 0.04 and 0.08 with

Table 4 | Expanded consumption profile for the City of Johannesburg

Flow rate in ℓ/h	7	15	22.5	30	35	45	60	96	120	240	300	750	1,173	1,500	2,500	3,000	3,500
Consumption category	Proportion of the investigated flow rate (%)																
Business	2.68	5.48	6.93	10.04	0.56	0.33	21.12	1.97	12.02	13.81	5.31	11.87	6.06	1.33	0.44	0.06	0.05
Public benefit organisation	2.02	3.11	3.33	8.45	0.77	0.21	25.22	0.89	19.89	16.45	4.13	10.21	3.36	1.06	0.86	0.05	0.01
Residential	5.50	9.02	5.89	8.73	0.97	0.60	20.04	1.50	12.14	13.73	2.70	10.71	6.01	1.57	0.83	0.06	0.05
Multi-purpose	1.93	4.22	2.82	6.00	0.87	0.33	18.64	1.70	18.60	13.69	4.30	15.19	8.21	1.96	1.39	0.15	0.08
All	3.05	5.54	4.59	8.17	0.81	0.37	21.24	1.48	15.92	14.45	4.01	11.99	5.90	1.49	0.92	0.08	0.05

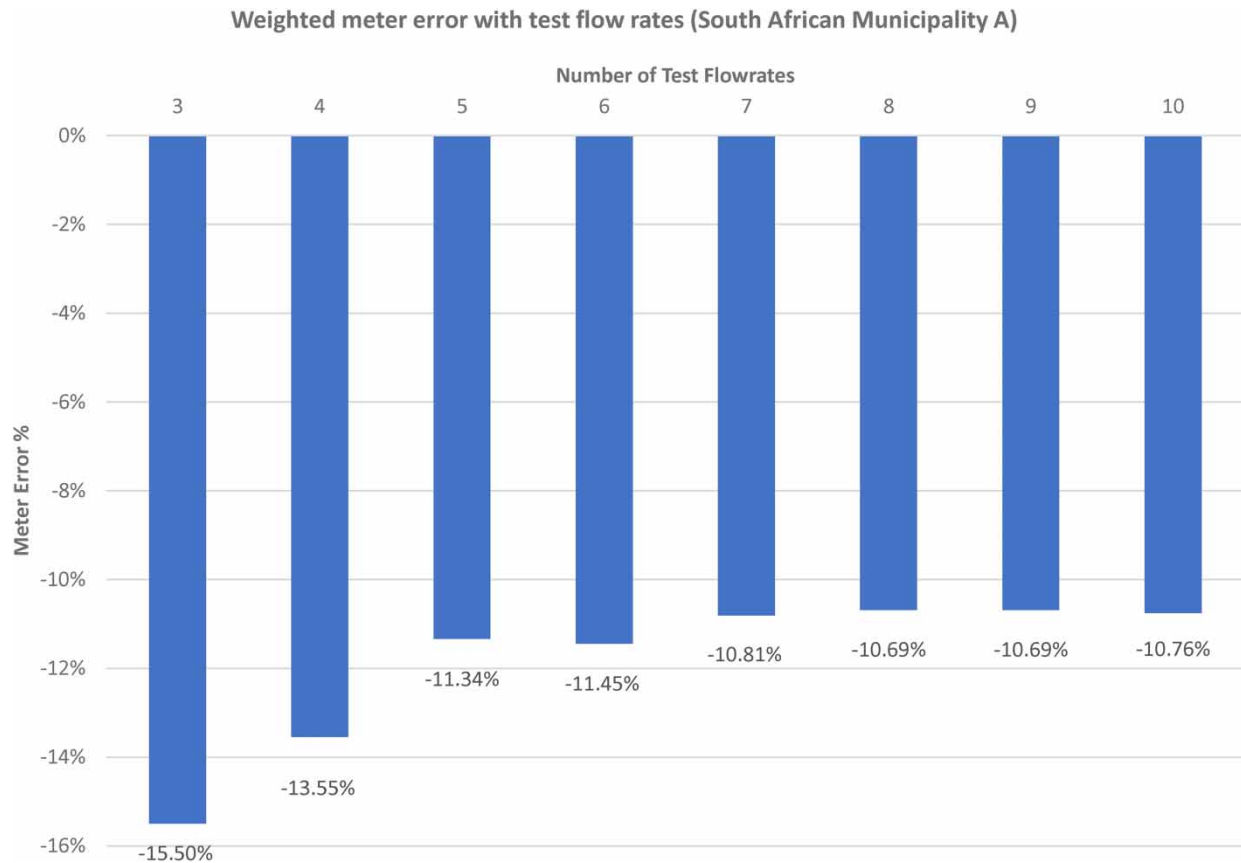


Figure 2 | Impact of number of test flow rates (Municipality A).

the reference 10 test flow rates. While the above are minor differences, it is instructive on the fact that the choice of specific meter test points is not trivial and should therefore be given due consideration.

End of life meters evaluated by [Fourie *et al.* \(2020\)](#) for Municipality B also showed similar trends, albeit with much higher weighted meter errors as would be expected for such meters. [Figure 3](#) shows this variation for the two meter models evaluated.

Reducing the number of test flow rates from 10 to 3 leads to an over-estimation of the weighted meter error by 5.82 and 4.43 for Models 1 and 2, respectively. However, it is clear from the weighted accuracy of these meters that the majority are at the end of their useful life, as would be expected, due to the reason for the test. The focus on only two meter models that are not necessarily representative of the municipality, or any other municipality for that matter, was also not beneficial for deriving generally applicable results. As such, this dataset was excluded from the final determination of the optimum number of test flow rates. Despite the exclusion, it remains clear that the number of flow rates matters, with fewer flow rates tending to over-estimate the weighted meter error.

The relative minimal gain between some combinations of flow rates was also observed and this resulted in additional refinements to the analysis to determine the optimal combination of flow rates. The following constraints were introduced:

- The three flow rates specified in the SANS 1529 standard ($q_{\min}$, q_l and q_p) were retained as the minimum requirement since they define the flow range that a meter can be subjected to in the South African context.
- All flow rates, which when omitted, led to a high variance in weighted error, were included. Conversely, those that did not lead to a high variance were excluded.

Focusing on [Ncube & Taigbenu's \(2019a\)](#) more representative dataset (i.e. 123 m), the omission of Q7 in [Table 3](#) resulted in a weighted error variance of 0.04 when compared to the baseline/best-case option of 10 flow rates. This variance is limited in its impact. The exclusion of Q9 led to a weighted error variance of 0.07, which is also minimal. Another observation made

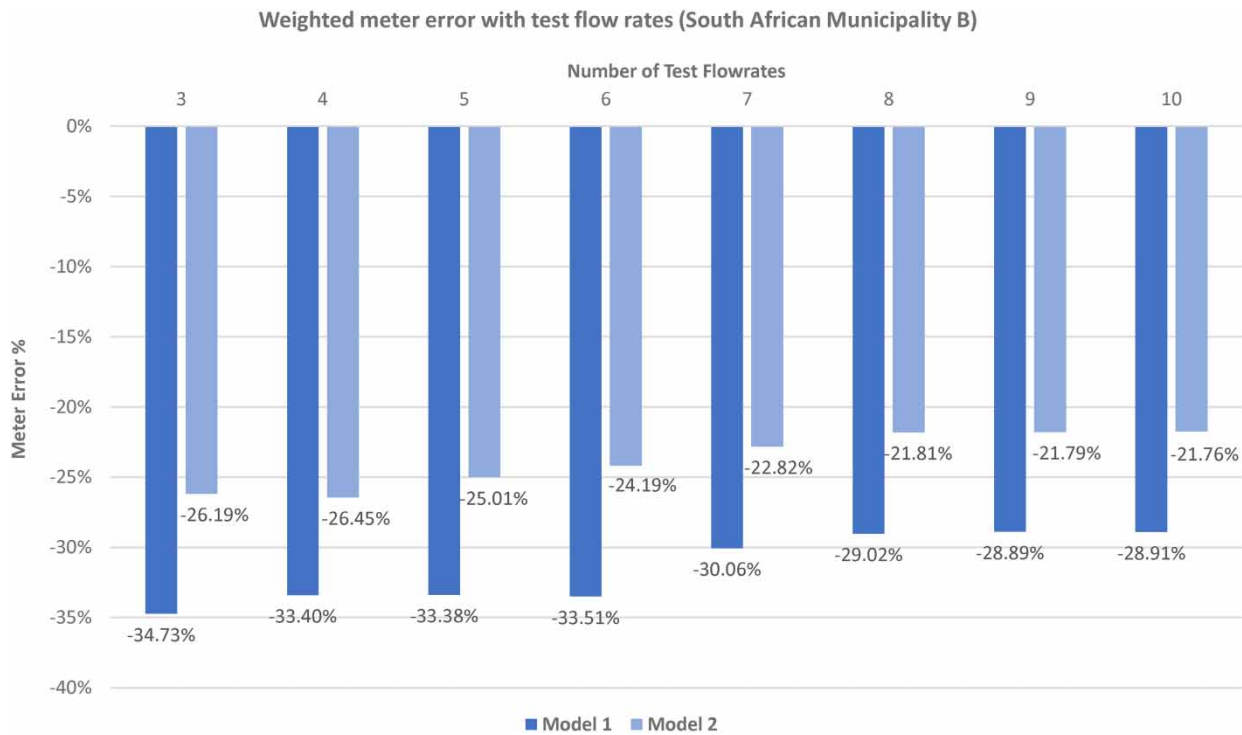


Figure 3 | Impact of number of test flow rates (Municipality B).

was that due to the inflection of the error curve at the transition flow rate, Q6 could also be omitted with limited impact. While the general rule was to ensure that the preceding and succeeding flow rates were included whenever a particular flow rate was omitted, further analysis showed that Q6 and Q7 could be omitted with minimal impact. In total, flow rates Q6, Q7 and Q9 were eliminated. Three additional combinations were introduced, and their results are shown in Table 5.

The three and six test flow rates produced higher variances compared to the baseline option. The seven test flow rate option under-estimates the meter accuracy by only 0.05 and this is impressive considering that Ncube & Taigbenu (2019b) found that meter degradation was about 0.7 per annum. This is, therefore, a superior estimate that also fulfils the requirement of evaluating the meter accuracy over the meter measuring range ($q_{\min}$ – $q_{\max}$) compared to the seven flow rates of Table 3 that over-estimate the error and do not include the permanent and maximum flow rate. In view of the time and the cost of meter testing, the margin of the error is minimal and the use of these seven test flow rates is therefore considered optimum. The adopted meter test flow rates are presented in Table 6 along with the consumption proportion at those flow rates.

Table 5 | Additional variations of test flow rates

No. of flow rates	10 (baseline/best-case option)	3	6	7
Included flow rate, Q^*	1–10	2, 4, 8	1, 2, 4, 5, 8, 10	1, 2, 4, 5, 6, 8, 10
Weighted accuracy	89.24	86.62	89.89	89.19

*The postscript relates to the Q values in Tables 1 and 2.

Table 6 | Recommended water meter test flow rates and consumption profile for South Africa

Seven (7) test flow rates, Q	Q1	Q2	Q4	Q5	Q6	Q8	Q10
Test flow rates, ℓ/h	7	15	30	60	120	1,500	3,000
Consumption proportion at flow rate	5.50	9.01	14.61	21.57	13.64	34.66	0.89

It should be noted that the meter error curves for flow rates beyond the transitional flow rate (120 l/h for Class B meters and 30 l/h for Class C meters) tend to be linear towards the permanent flow rate (1,500 l/h), with minimum variation (Arregui *et al.* 2018; Fourie *et al.* 2020). Therefore, even without any test points between these two flow rates, the results presented in Table 6 are adequate.

CONCLUSIONS

While previous studies in South Africa and internationally have recommended the use of 8–10 test flow rates for the evaluation of metering accuracy, this study has shown that, for a marginal decrease in estimation accuracy, it is possible to use seven test flow rates instead in South Africa. The cost of meter testing in both time and resources involved can therefore be considerably less, as about 30% of the testing requirements can be sacrificed without much loss in outcome. In addition, this study presents an expanded and reconfigured consumption profile (Table 4), for South African and similar locality studies, to allow for the flexibility in applying different testing requirements. As has been demonstrated in this study, the selection of test flow rates is best done through the application of scientific rigour as anything less will be fraught with challenges (such as additional costs with marginal benefits for more flow rates and the unsatisfactory results obtained when using only three test flow rates, as has been adopted in some studies and in practice). The seven test flow rates of Table 6 are therefore recommended as the optimum number of test flow rates for the evaluation of metering accuracy, and in defining and meeting on-going meter verification requirements for South Africa.

ACKNOWLEDGEMENTS

This paper is based on a Water Research Commission (WRC), South Africa funded project C2020-2021-00114 entitled *Water Meter Performance in South Africa*. The funding and support of the WRC is gratefully acknowledged.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 12 May 2023; accepted in revised form 20 December 2023. Available online 2 January 2024