APPARENT WATER LOSSES RELATED TO MUNICIPAL METERING IN SOUTH AFRICA

Report to the
WATER RESEARCH COMMISSION

by

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Executive Summary

Apparent losses consist of water that is delivered to consumers, but look like losses to a municipality. It consists of two main components: water meter under-registration and unauthorised consumption. Meter reading and data errors may also contribute to apparent losses.

Water meters under-register more as they age, especially at lower flow rates. The purpose of this study was to estimate the extent of apparent losses due to water meter under-registration in South Africa. This was achieved through the following actions:

- An international literature review.
- A field investigation into leakage on consumer properties.
- An analysis of water metering databases.
- Field logging of domestic consumption patterns.
- A review of bulk consumer meter audits.

Apparent losses are normally valued at the retail rate charged to customers thereby making its financial impact much greater than that of real losses which are valued at production costs. If increasing block tariffs are used, apparent losses are valued at the highest block rate paid by the consumer.

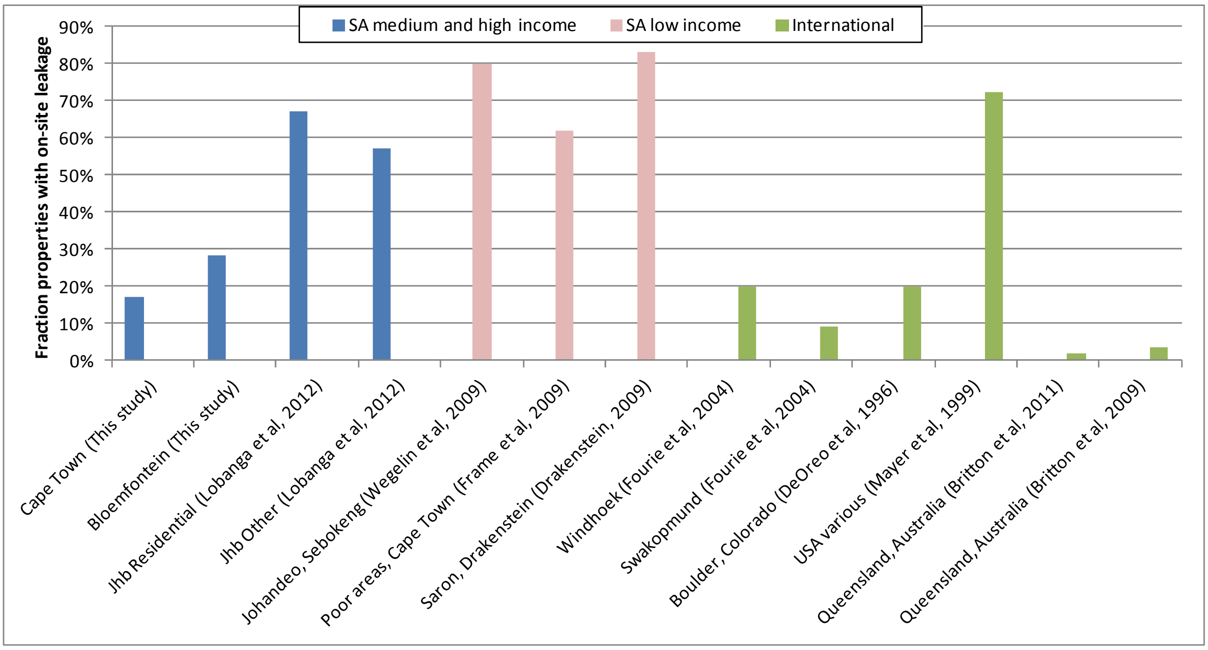
To date default values have been used in Australia, New Zealand, USA and Canada to estimate apparent losses. In South Africa, Seago et al. developed a table to give a water utility suggested values of meter under-registration, illegal connections and data transfer errors as shown below.

Apparent Losses as a Fraction of Total Losses						
Illegal Connections		**Meter age and accuracy**			**Data transfer**	
			Water quality			
Level of illegal connections	**Losses**	**Meter age**	**Good**	**Poor**	**Process quality**	**Losses**
Very high	10%	Poor > 10 years	8%	10%	Poor	8%
High	8%	Average 5-10 years	4%	8%	Average	5%
Average	6%					
Low	4%	Good < 5 years	2%	4%	Good	2%
Very low	2%					

On-site leakage study

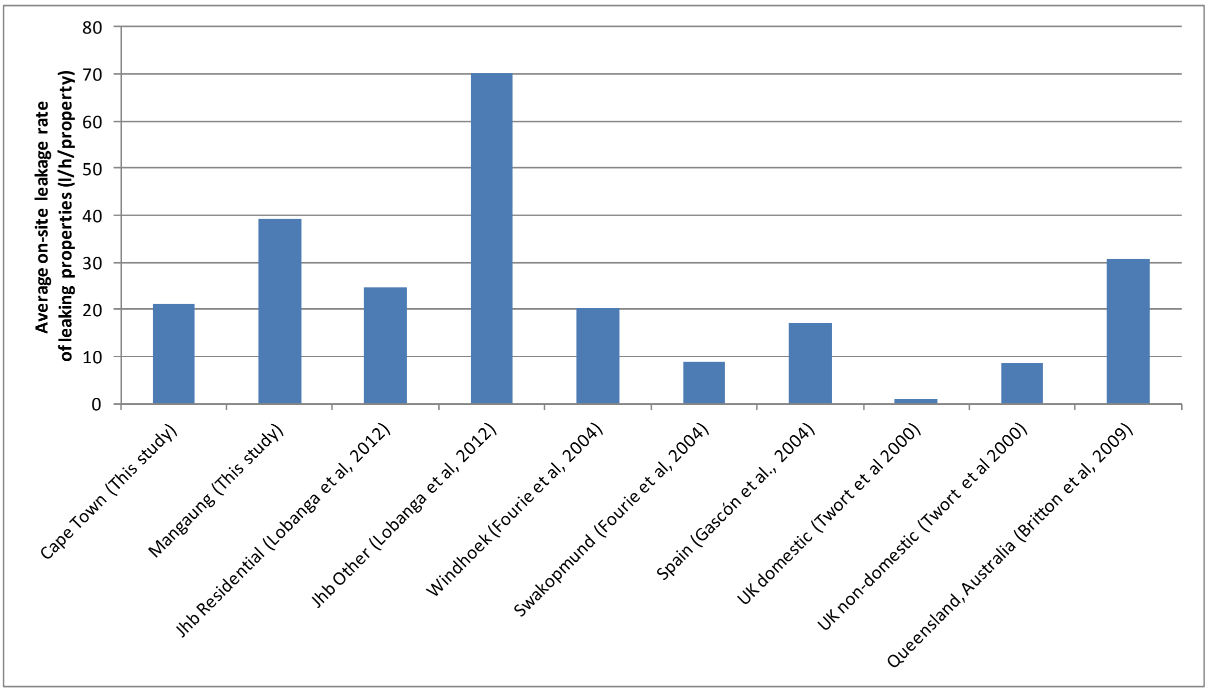
From a municipality's perspective, leakage on consumer properties is considered as consumption and not a loss. However, since on-site leakage typically occurs at low flow rates where water meters under-register, it contributes significantly to apparent losses.

The incidence and flow rates of on-site leakage in suburban properties were measured in Cape Town, Mangaung and Johannesburg, and compared to the results of other studies. It was found that the incidence of on-site leakage varies a great deal, not only in South Africa, but also in international studies as shown in the figure below. On-site leakage was found to occur on 17%, 28% and 67% of middle and high income properties in Cape Town, Mangaung and Johannesburg respectively. Low income areas showed the highest incidence of on-site leakage.



Comparison of on-site leakage incidence studies

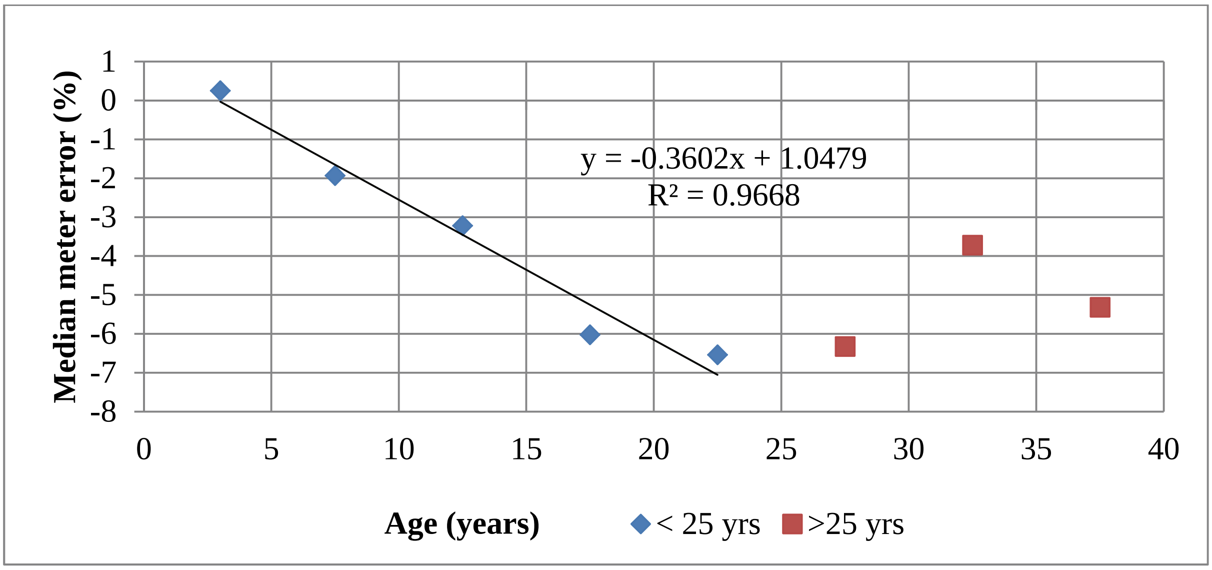
Another finding was that most on-site leakage occurs at low flow rates, with the number of properties decreasing rapidly as the leakage rate increases. A few properties with large on-site leaks typically contribute a significant proportion of the total on-site leakage. The average on-site leakage rates in South African medium and high income residential areas were found to vary between 20 and 39 L/h/property. These correspond to monthly on-site losses between 14 and 29 kl, representing a substantial proportion of normal consumption. Average on-site leakage rates found in this and other studies are shown in the figure below.



Comparison of the leakage rates of properties with on-site leakage

Meter database analyses

Meter under-registration was found to be a strong linear function of both the volume through the meter and meter age. While the former is a better measure of meter deterioration, meter age is a more practical measure to estimate the state of meters in South Africa. The deterioration of domestic meter accuracy with age found in eThekwini is shown below.



Median meter error versus age for 15 mm positive displacement meters in eThekwini

Further database analyses showed that meters in South Africa are replaced at an average age of 20 years, meaning that the average meter has an age of 10 years.

Based on the above the average meter under-registration error can be estimated as 2.6% of consumption. This excludes the error of new meters.

Review of bulk consumer meter reports

A number of bulk consumer meter audits were obtained from various municipalities and evaluated to obtain a wider picture of apparent losses at these users. The results showed that bulk meters are often not sized correctly or in good condition. Meter audits in Tshwane and Ekurhuleni found apparent losses through bulk meters to be around 20%. This is a critical problem since bulk users contribute disproportionally to water consumption, and thus to the income of municipalities.

Discussion and Conclusions

The results of this study showed a strong linear relationship between meter age and under-registration. This relationship was used, in combination with the average meter age of 10 years, to estimate apparent losses due to meter aging as 2.6% of consumption. This excludes the error of new meters.

New meters under-register at low flow rates, but tends to over-register at the higher flow rates where most demand occurs. Thus it is likely that a new meter will have a negligible under-registration of demand. However, on-site leakage normally occurs at lower flow rates where meters under-register. Based on on-site leakage investigations in Cape Town, Mangaung and Johannesburg it is estimated that the meter under-registration error for on-site leakage will be 15% of the registered leakage rate. This is equal to roughly 2.2% of demand.

The total meter under-registration error in middle to high income areas is thus estimated to be 4.8% (say 5%) of consumption. Since this water is lost at the higher block tariff rates, the financial loss to the municipality will be significantly more than 5%. In low income areas, on-site leakage occurs at much higher incidence and thus meter under-registration can be expected to be higher.

A review of meter audits done on bulk consumers showed that a lot more needs to be done to ensure that these meters are correctly sized, installed and in good condition.

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The Reference Group responsible for this project consisted of the following persons:

- JN Bhagwan — Water Research Commission (Chair)
- KV Bailey — Elster Kent Metering
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- C Tsatsi — DWAF
- D van Eeden — Sensus Metering
- TF Westman — City of Tshwane

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1 INTRODUCTION

1.1 Background

There is renewed international awareness that water distribution systems world-wide are aging and deteriorating, while the demands on these systems, and thus on our natural water resources, are ever increasing. Water losses from water distribution systems are reaching alarming levels in many towns and cities throughout the world. The Government has taken a strategic stance in tackling the problem of water supply in South Africa, which is already classified as water-stressed (Rand Water, 2003). The Government's National Water Resource Strategy states that "we cannot afford simply to react to problems of water quality and water scarcity as they arise. We need a systematic, long-term plan to meet these challenges" (DWAF, 2002).

The International Water Association has done pioneering work on water loss classification and reduction. It has developed a table in which the water entering a distribution system is first classified as Authorised Consumption and Water Losses. Water losses, in turn, are classified as Apparent Losses and Real Losses. As the name implies, Real Losses consists of physical leaks from the distribution system up to consumer connections. Apparent Losses, on the other hand, consists of water that is delivered to users, but looks like losses to the municipality. Apparent losses consist of two main components, i.e. water meter under-registration and unauthorised consumption, but meter reading and data errors are also contributing factors (Farley & Trow 2003).

New municipal water meters are sized to be accurate at the normal flow rates estimated for different consumers. While the metering error at these flow rates will typically be small (less than 2%), the meter accuracy can be substantially lower at low flow rates. In addition meter accuracy reduces with time, and thus the under-registration error increases if flow meters are not replaced at regular intervals.

Under-registration of consumption is worst at very low consumption rates, for example when slowly filling a toilet cistern. On-site leakage is a particular problem, since a small leak in a pipe or toilet cistern seal on a property will produce a constant, low flow rate that is likely to be under-registered by the flow meter (or may even not be picked up at all). Since the leak flow is constant, significant volumes of water can be lost by the municipality in this way.

In a recent WRC research project (Van Zyl et al., 2008), it was found that significant on-site losses occur in different areas in South Africa. For instance, of 182 randomly selected properties in suburbs in Johannesburg, 64% had measurable on-site leakage. The average on-site water losses were found to be in the order of 25% of total consumption (Lugoma 2012). It was estimated that the average under-registration of leakage in single stand residential areas was 1.7 l/h, or 1.2 kl/month per property. This is significant, and in the order of 5% of total consumption. For other users (non-domestic and bulk domestic), the average meter under-registration was found to be 4.6 l/h or 3.3 kl/month per property. The results indicated that apparent losses are significant, and recommended further work to investigate this in more detail.

The purpose of this study was to estimate the extent of apparent losses due to meter under-registration in South Africa.

1.2 Aims and Deliverables

The project Reference Group recommended that:

- The project focuses on domestic consumers, and adds other consumers only when the information is readily available.
- Unauthorised consumption not a major part of the project and is only included where information is readily available.
- The project focuses on on-site losses and apparent losses in suburbs (areas with higher income and first-world supply systems).

This was done due to the size and complexity of the problem, and the practical difficulty of identifying unauthorised consumption. In addition, it was recognised that the greatest financial losses due to meter under-registration are likely to occur in suburban areas where consumers use relatively large quantities of water (and thus apparent losses are valued at higher block tariffs) and levels of payment for water are likely to be high.

Thus, the detailed aims and that were addressed by the project can be described as follows:

- Perform an international literature review on apparent losses due to meter inaccuracy.

- Measure on-site leakage on residential properties in the City of Cape Town and Bloemfontein and, in combination with the Johannesburg study, estimate the contribution of on-site leakage to meter under-registration.
- Estimate the meter error versus age and registered volume relationship by analyzing a meter database
- Test water meters in the field to obtain both consumption patterns and meter error of brand new meters installed in the field in selected suburbs in the City of Cape Town
- Review reports on bulk water meter audits performed by municipalities

1.3 Methodology and Layout of This Document

The study approached the problem of estimating apparent losses from a number of different perspectives, and used these findings to obtain an overall picture of the levels of apparent losses due to water meter under-registration in South Africa. The results and findings of the different approaches are presented in separate chapters as follows:

- Chapter 2: Literature review. A detailed review of published literature on apparent losses, including financial impacts, performance indicators, influencing factors and on-site leakage.
- Chapter 3: On-site leakage field study. The occurrence and flow rate distributions of on-site leakage were measured in Cape Town and Mangaung using the same methodology as the earlier Johannesburg study (Van Zyl et al., 2008).
- Chapter 4: Meter database analyses. Two water meter databases, a meter replacement database from eThekwini and the National Water Consumption Archive, were used to i) estimate water meter under-registration by comparing consumption one year before and after replacement and ii) estimate water meter replacement rates in South Africa.
- Chapter 5: Logging of domestic consumption. The consumption of a few properties in Cape Town was logged using accurate master meters installed in series with the consumer meters. Unmetered flow reducers were installed in some of these properties to investigate the impact of these devices on the measured consumption pattern.
- Chapter 6: Review of bulk consumer meter audits. A number of bulk consumer meter audits were obtained from different municipalities and evaluated to obtain a wider picture of apparent losses at these users.

- Chapter 7: Discussion and Conclusions. The results of the different chapters were summarised and integrated, and recommendations for managing apparent losses due to meter under-registration are made.

2 LITERATURE REVIEW

2.1 Introduction

Since the 1990s the International Water Association (IWA) has been at work developing a standardized water audit methodology and water loss performance indicators (Thornton et al., 2008). The IWA Water Balance was developed to be used as an accounting approach that records and displays how treated water entering the system is distributed. It is an important starting point for any Non-Revenue Water reduction strategy, which requires the following questions to be answered (Farley & Liemberger, 2005):

- **"How much** water is being lost?
- **Where** is it being lost from?
- **Why** is it being lost?
- **What strategies** can be introduced to **reduce** losses and **improve** performance?
- **How** can the strategy be **maintained** and the achievements **sustained**?"

One of the important aspects of the water balance is the need to have clear and precise definitions for each category. The following Table 2.1 describes how the IWA have categorized the water balance:

<table>
<tr><td rowspan="9">System Input Volume</td><td rowspan="4">Authorised Consumption</td><td rowspan="2">Billed Authorized Consumption</td><td>Billed Metered Consumption (including water exported)</td><td rowspan="2">Revenue Water</td></tr>
<tr><td>Billed Unmetered Consumption</td></tr>
<tr><td rowspan="2">Unbilled Authorized Consumption</td><td>Unbilled Metered Consumption</td><td rowspan="7">Non-Revenue Water</td></tr>
<tr><td>Unbilled Unmetered Consumption</td></tr>
<tr><td rowspan="5">Water Losses</td><td rowspan="2">Apparent Losses</td><td>Unauthorized Consumption</td></tr>
<tr><td>Metering Inaccuracies</td></tr>
<tr><td rowspan="3">Real Losses</td><td>Leakage on Transmission and/ or Distribution Mains</td></tr>
<tr><td>Leakage and Overflows at Utility's Storage Tanks</td></tr>
<tr><td>Leakage on Service Connections up to point of Customer metering</td></tr>
</table>

Figure 2.1: The Standard IWA Water Balance (Lambert & Hirner, 2000)

The following defines some of the relevant categories of the water balance (Lambert & Hirner, 2000):

- System input. Is defined as the total volume of water entering a distribution system.
- Authorized Consumption. Is all water that is consumed by registered customers whether this consumption is metered or not.
- Water Losses. Is defined as the System Input Volume minus Authorized Consumption. Water Losses are composed of Real and Apparent Losses.
- Real Losses. The physical loss of water from a pressurized distribution network up to the point of the customer's meter.
- Apparent Losses. The non-physical loss of water that reaches the consumer but is not recorded by the water utility. This includes meter under-registration, unauthorized consumption and accounting errors from the billing or metering reading process.
- Non-Revenue Water. It is the sum of Authorized Unbilled Consumption and Water Losses. It is water that the water utility does not receive any income for.

A considerable amount of work and focus has been placed on Real Losses and still much needs to be done in understanding Apparent Losses, its extent in water utilities and finding practical ways of minimising it cost effectively. The IWA Task Force on Apparent Loss is currently doing work in this regard (Johnson & Vermersch, 2011).

An International Water Association draft report on apparent losses was included in the literature review. Since this report made it clear that it should not be used as a reference until finalised, the primary sources used in the report were used whenever possible.

2.2 Financial impacts of apparent losses

Ignoring the contribution of on-site leakage, apparent loss is not a physical loss of water and thus does not have the same operating problems that are associated with real losses in terms of technical and environmental issues. The loss of water from apparent losses is essentially a financial problem of the utility. Apparent losses also distort water consumption data that is important for planning and management.

Apparent losses are normally valued at the retail rate charged to customers thereby making its financial impact much greater than that of real losses which are valued at variable production costs (Thornton et al., 2008). If increasing block tariffs are used, apparent losses are valued at the highest block rate paid by the consumer, and may even push the consumer into the next higher block tariff. Depending on the utility, wastewater charges may be billed from the volume of water consumed by the consumer, thereby increasing the financial impact of apparent losses. The unit retail cost of water can be as much as 10 to 40 times that of the production cost for delivery and treatment (Thornton et al., 2008).

It has been reported in water utilities in Switzerland and the United States that although apparent losses only make up for a small amount of water loss in volumetric terms, they are significantly more costly than real losses. For instance, in a study in Geneva, Switzerland by Guibentif et al. (2007), it was found that apparent losses accounted for 26% of Non-Revenue Water (NRW) in terms of volume of water in 2004, yet accounted for 69% of NRW in terms of financial loss to the utility

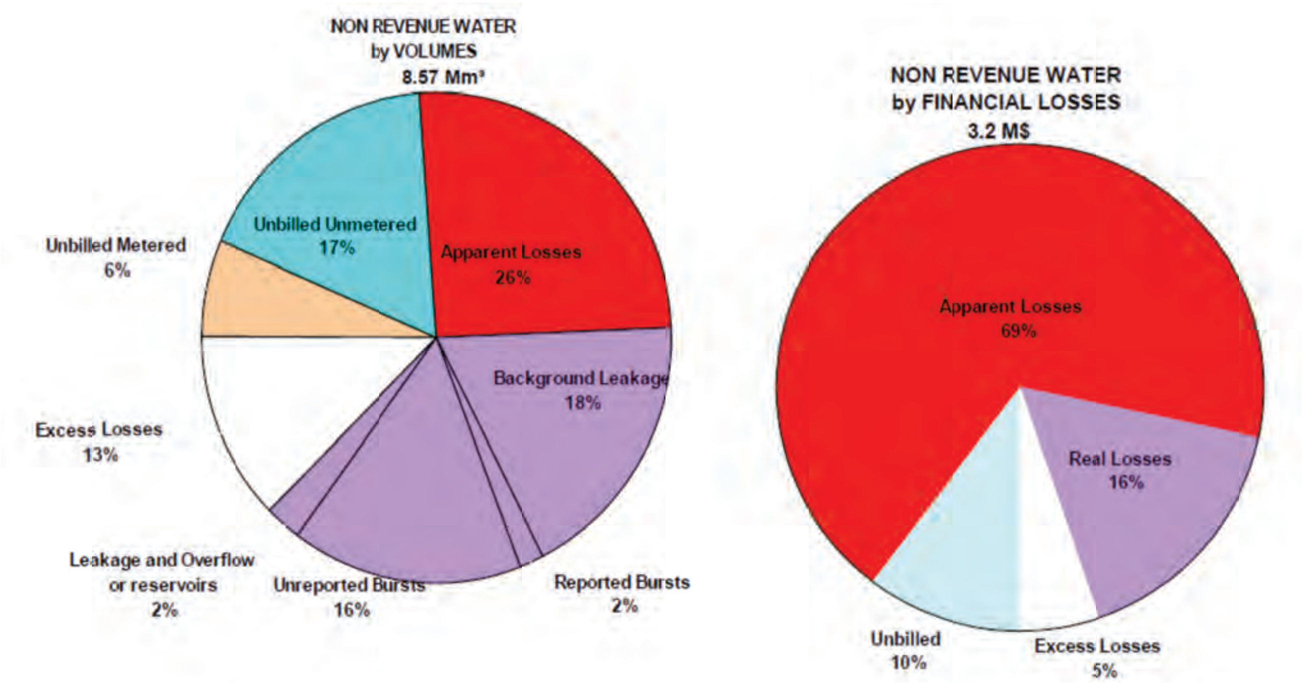

Figure 2.2: Water losses estimated in Geneva, Switzerland, in 2004 and comparing contribution of volumetric and financial impacts (Guibentif et al., 2007)

In Philadelphia, United States, apparent losses cost the city US$ 30.8 million compared to US$ 5.1 million in real losses, but only represented a third of the volume of real losses in the 2006 water audit (Thornton et al., 2008).

In Tampa Bay, United States, apparent losses accounted for 37% of water loss volume, but cost the utility 68% of the total cost of water losses in the 2005 fiscal year (Pickard et al., 2008). Customer meter under-registration accounted for 48% of the total cost of water losses with unauthorized consumption and data handling errors accounting for 12% and 8% respectively.

According to the American Water Works Association (AWWA) (2009), consumer meter under-registration is the main cause for apparent losses in distribution systems.

2.3 Reducing apparent losses

It would be ideal to remove all apparent losses from a water distribution network, however as one attempts to achieve this, so does the task become more costly. This is understood by the law of diminishing returns, whereby as one tries to achieve zero apparent loss the marginal costs begin to exceed the marginal benefit. Therefore, just as is done with real losses, it is understood that there will always be apparent losses and one should seek to achieve the economic level where the marginal cost of apparent loss reduction initiatives is equal to the marginal benefit of potential revenue gain from decreased apparent losses (Figure 2.3).

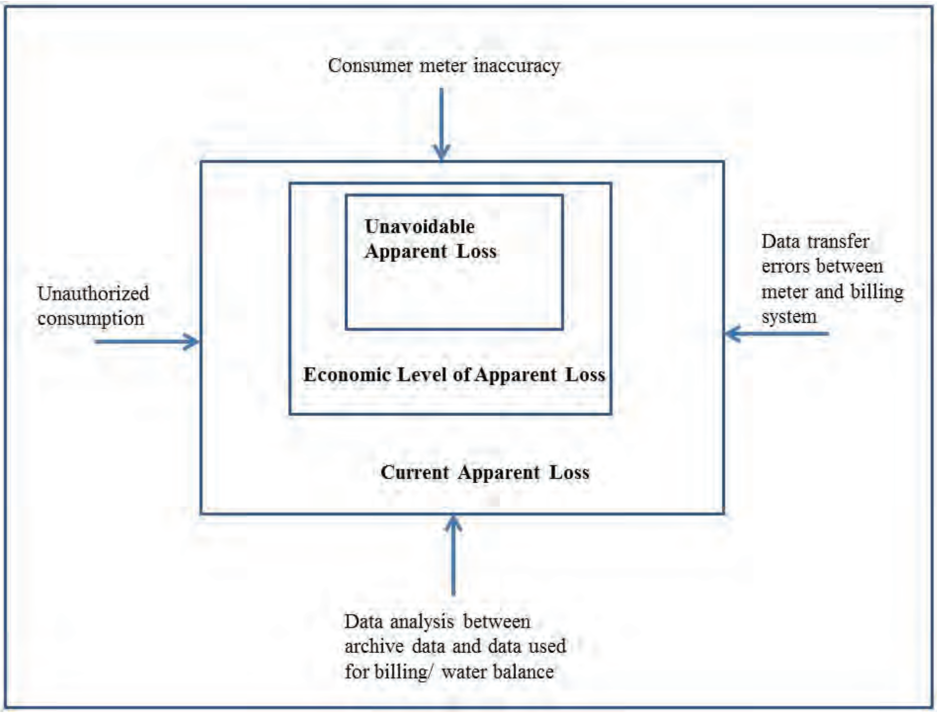

Figure 2.3: The apparent water loss control methodology (Rizzo et al., 2004)

Apparent loss reduction interventions may have other unintended consequences due to the multi-dimensionality of apparent losses. Rizzo et al. (2007) states that the four components of apparent losses ‘can act and interact interchangeably’. This means that a water meter may be over-registering and decreasing apparent losses, but its effects may be reduced due to the theft of water. Another case may be that the meter reader may overstate the actual reading of a meter, but the effects of this error could be not realised in the total apparent loss quantity, due to under-estimating of the actual consumed volume during estimations in the billing system for that year.

Rizzo et al. (2007) point out that apparent losses are also ‘dynamic in nature’ and that removing water meters that are over say 5 years old does reduce meter under-registration, but one must keep in mind that the other remaining meters would have aged as well. Also, increasing discipline of meters readers will not only improve meter readings but may also reduce water theft.

Rizzo et al. (2007) state that an ‘Integrated Apparent Loss Strategy’ is required to deal with these complexities of the multi-dimensionality and dynamics of reducing apparent losses. Adopting an Integrated Apparent Loss Strategy is seen as a change management process. Pocas Martins (2009) specifically addresses change management in a water company aiming to reduce water losses.

When presented with the problem of apparent losses, utilities should focus on those activities that give the greatest return for the least amount of effort and cost. A good example of this is replacing the meters of large consumers first that are old or over-sized to ensure a quick return on investment. The income generated from a large meter replacement programme could then be used to finance the implementation of a more comprehensive meter replacement programme for smaller consumers and other apparent loss reduction projects.

The following diagram developed by Rizzo et al. (2007) presents the actions and approaches that define an Integrated Apparent Loss Strategy.

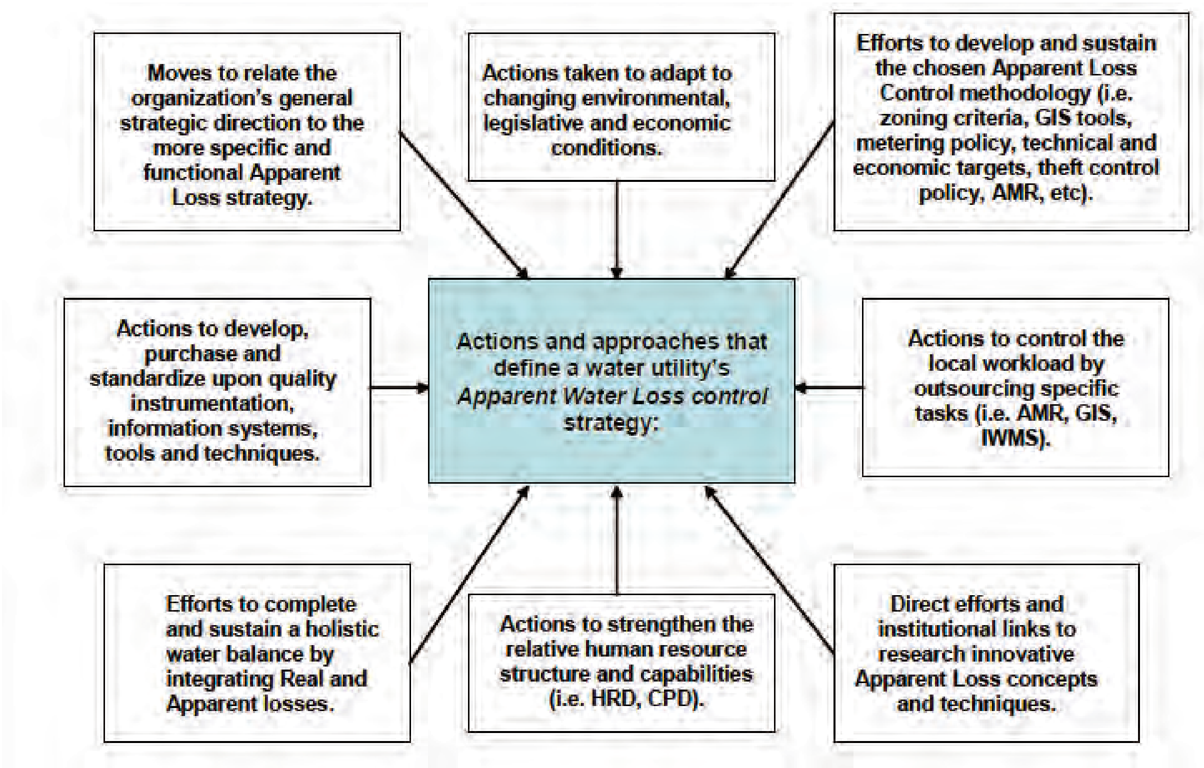

Figure 2.4: An integrated apparent water loss strategy (Rizzo et al., 2007)

2.4 Performance Indicators

Performance indicators are necessary to compare the performance of one utility to another, how the same utility is performing from year to year and for setting performance targets.

The IWA Task Force's Apparent Loss Team is developing a recommendation that the performance indicator for apparent losses should not be represented by a percentage of the water supplied, but rather calculated in the same way as that done for Real Losses and the Infrastructure Leakage Index (ILI) (Rizzo et al., 2007). The Task Force is proposing that a value of 5% of water sales should be used as the Unavoidable Annual Apparent Loss (UAAL) for the moment until further investigation, and should be calculated as follows (Rizzo et al., 2007):

$$Apparent\ Loss\ Index\ (ALI) = \frac{Current\ Annual\ Apparent\ Loss\ (CAAL)}{Unavoidable\ Annual\ Apparent\ Loss\ (UAAL)}$$

Thornton et al. (2008) state that a UAAL of 5% may be high for developed countries where they have good customer meter management, buildings do not have roof tanks and low unauthorized consumption due to good policies and safeguards. They believe that 5% is reasonable for developing countries.

2.5 Current practices for quantifying apparent losses

The level of apparent losses for many water utilities is relatively unknown due to either a lack of data or no standard methodology to measure apparent losses (Mutikanga et al., 2010). Therefore many water utilities use default values or rules of thumb to quantify the level of apparent losses (Mutikanga et al., 2010).

Default values have been used in Australia, New Zealand, USA and Canada to estimate apparent losses (Seago & McKenzie, 2007). Table 2.1 shows the suggested default values that these countries use.

Table 2.1: Suggested apparent loss default values for developed countries (Seago & McKenzie, 2007)

Unauthorized Consumption	**Domestic Meter Under-registration**	**Non-domestic Meter Under-registration**
0.1% of Total System Input	2% of metered consumption	2% of metered consumption

In South Africa, a study was done by (Seago et al., 2004) whereby they developed a table to give a water utility suggested values of meter under-registration, illegal connections and data transfer errors (Table 2.2). Their motivation was to shift away from the 20% lump sum value of total water losses used in the past to calculate apparent losses in the BENCHLEAK model (software that estimates real losses). Only meter age and water quality were considered in the study as indicators of meter under-registration to simplify the table. Each municipality in their study was asked to provide information with regard to their meter accuracy and age, illegal connections and data transfer errors. The values for meter under-registration were estimated by the fact that Europe has a compulsory meter replacement programme every 5 years and the assumption that domestic meters used in South Africa are very similar to those used in Europe.

Table 2.2: Suggested default values for Apparent Losses in South Africa (Seago et al., 2004)

Apparent Losses as a Fraction of Total Losses						
Illegal Connections		**Meter age and accuracy**			**Data transfer**	
		Meter age	**Water quality**			
Level of illegal connections	**Losses**		**Good**	**Poor**	**Process quality**	**Losses**
Very high	10%	Poor > 10 years	8%	10%	Poor	8%
High	8%	Average 5-10 years	4%	8%	Average	5%
Average	6%					
Low	4%	Good < 5 years	2%	4%	Good	2%
Very low	2%					

Mutikanga et al. (2010) developed a similar table as Seago et al. (2004) for Kampala City in Uganda, which can be used as default values for developing countries. The difference lays mainly in the method, as Mutikanga et al. (2010) sought to measure the actual metering errors, obtain actual illegal consumption data and did a meter reading and billing system audit. The following Table 2.3 shows the results of the study.

Table 2.3: Default values proposed for developing countries (Mutikanga et al., 2010)

Apparent Losses as a Fraction of Water Sales						
Unauthorized Consumption		**Meter age and error**			**Meter reading, data handling and billing errors**	
			Losses			
City size	**Losses**	**Meter age**	**With household storage tanks**	**Direct supply**	**Quality of processes**	**Losses**
City (> 100 000 service connections)	10%	Poor (> 10 y)	-28%	-10%	Poor [a]	10%
Municipality (50 000-100 000 connections)	3%	Average (5-10 y)	-20%	-8%	Average [b]	6%
Medium towns (5000-50 000 connections)	2%	Good (< 5 y)	-15%	-5%	Good [c]	2%
Small towns (< 5000 connections)	0.5%					

[a] No management controls in place, employees are poorly remunerated and inefficient billing system
[b] Management controls in place, fairly remunerated employees and good billing system
[c] Well functioning utility with good customer billing system
Percentages represent percentages of water sales

2.6 Factors affecting consumer meter error

2.6.1 Introduction

Consumer water meters serve the purpose of recording the volume of water that is consumed by a consumer. Like any measuring instrument a water meter is not 100% accurate. Therefore, water meters may under-register or over-register the total volume of water passing through it.

The most common water meter is the mechanical type, which has a sensor element that is rotated as water passes the meter chamber. The sensor element has a rotational inertia and friction that the flow of water needs to overcome so that it can rotate and register the water passing through it. This property of the meters sensor element means that the meter tends toward under-registration at low flows and over-registration at high flows in new meters.

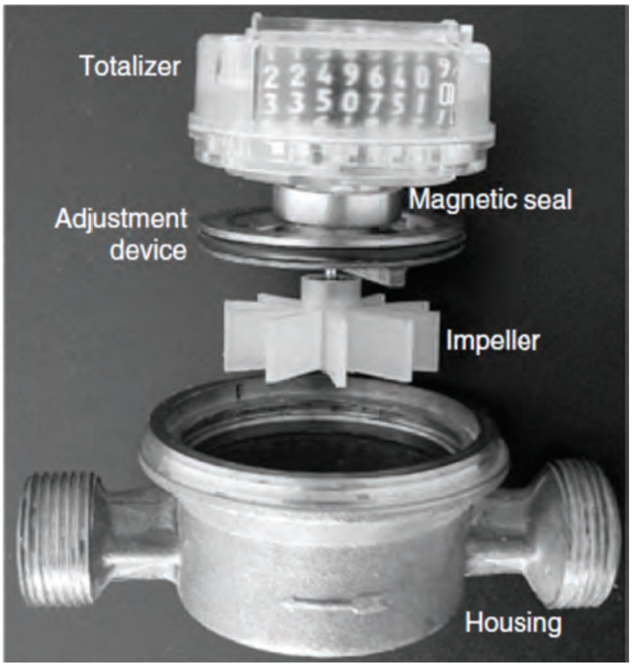

Figure 2.5: Components of a single-jet meter (Arregui et al., 2006 b)

The accuracy of a water meter population is dependent on a number of factors related to the consumer meter, the consumer's consumption behaviour and the distribution system as listed in Table 2.4. These factors are discussed in more detail below.

Table 2.4: Factors affecting meter accuracy

Consumer meter	Consumer consumption behaviour	Distribution system
Error curve Type Size Installation Age	Consumption pattern Seasonal water demand	Water quality Spinning Network pressure Environment

2.6.2 Error curve

The South African Bureau of Standards (SABS) have published the SANS 1529 specification that groups the accuracy of meters into four different meter accuracy classes. There are several internationally published standards that define meter classes in a new way, including OIML R49, ISO 4064, EN 14154 publications.

Water meters do not measure different flow rates at the same accuracy across its measuring range. Therefore, there are certain flow rates that characterize the measuring range and accuracy of the meter. These flow rates are termed as the starting flow rate (q_{start}), the minimum flow rate (q_{min}), the transitional flow rate (q_t), the permanent flow rate (q_p) and the overload flow rate (q_s) as shown in Figure 2.6.

Mechanical meters have a sensor that requires a certain amount of momentum created by the flow of water passing through the meter chamber to rotate the sensor. The minimum flow rate required to just get the sensor moving and registering flow is defined as the starting flow rate (q_{start}). Consumption at flow rates below the starting flow rate is not registered at all by the meter.

Requirements for meter error curves are defined by the three flow rates in the SANS 1529 document: the minimum flow rate (q_{min}), transitional flow rate (q_t) and overload flow rate (q_s). The minimum flow rate is the flow rate where the meter must have a maximum permissible error of 5% up to the transitional flow rate. The transitional flow rate is the flow rate where the meter error changes from below 5% to 2% error. For all flow rates between the transitional and overload flow rates the meter must have an error of below 2%.

The permanent flow rate (q_p) is the design flow rate of the meter, where the meter can measure consumption without any appreciable deterioration than what is expected under normal operating conditions. The permanent flow rate is also sometimes termed in literature as the nominal flow rate.

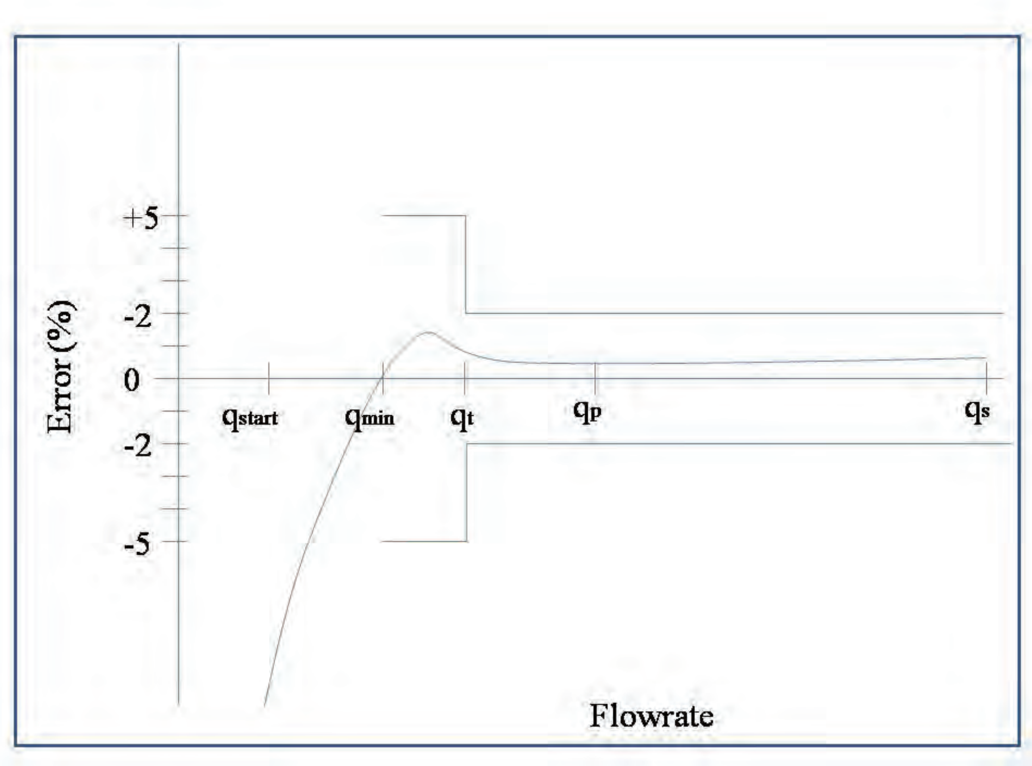

Figure 2.6: Typical meter error curve for a new multi-jet meter, showing defined flow rates

The SANS 1529 document divides the ability of meters to measure flow accurately into groups called classes. These classes are defined by the minimum and transitional flow rates, which are expressed in terms of the permanent flow rate of the meter.

Table 2.5: Meter classes defined for permanent flow rates up to 10 m^3/h (SANS 1529-1, 2006)

Meter class	Minimum flow rate (q_{min})	Transitional flow rate (q_t)
A (least accurate)	0.04 q_p	0.10 q_p
B	0.02 q_p	0.08 q_p
C	0.01 q_p	0.015 q_p
D (most accurate)	0.0075 q_p	0.0115 q_p

Table 2.6: Meter classes defined for permanent flow rates exceeding 10 m^3/h (SANS 1529-1, 2006)

Meter Class	Minimum flow rate (q_p)	Transitional flow rate (q_t)
A (least accurate)	0.08 q_p	0.3 q_p
B	0.03 q_p	0.2 q_p
C (most accurate)	0.006 q_p	0.015 q_p

The meter classes represent the ability of the meter to measure accurately in the lower flow rates. Therefore a Class D meter will measure more accurately at lower flow rates than a Class C, B and A meter. Class D meters are the most and Class A the least accurate. According to SANS 1529-1, Class A meters are not allowed for custody transfer.

Meter error curves deteriorate with time as the meter ages. In particular the starting flow rate tends to increase and the meter accuracy at lower flow rates tend to decrease with time.

2.6.3 Type

There are many different types of water meters, but can be divided into two groups that either measure consumption through the meter inferentially or volumetrically. Water meters are named according to the type of sensor inside the meter chamber. The sensor is the device that picks up the flow of water passing through the meter.

Inferential water meters are also known as velocity meters. They infer the volume of water passing through the meter by the velocity of the water passing through the meter. Some common examples of inferential meters which are mechanically driven are single-jet, multi-jet and Woltmann meters. Inferential meters that are not mechanically driven either are electromagnetic meters which use Faradays law to infer volumes or are Ultrasonic meters that use the Doppler Effect or the Single-Transit Time Effect to infer volumes from water flow velocities. Ultrasonic and Electromagnetic meters are expensive and are commonly used for bulk transfer and bulk consumer metering where large volumes are measured.

Volumetric meters are also known as positive displacement meters. The volume of water passing the meter is measured by each fixed volume of water per rotation of the sensor. The rotary piston and nutating disc meters are positive displacement meters.

Compound meters are two meters put together in one unit. The objective is to have a large meter that can measure high flow rates and a smaller meter that can measure low flow rates at the required accuracy.

Every meter type has different characteristics and is selected based on site conditions and application.

2.6.4 Size

Typically a meter is least accurate at low flow rates (below the transitional flow rate) and most accurate between the transitional and overload flow rates. Therefore, the performance of a particular size meter to measure consumption is dependent on the flow rate demand pattern of the consumer. Water meters that are too large will operate mainly below the meter's transitional flow rate and will under-register a large portion of the water passing through it compared to a correctly sized meter. Meters that are too small will operate mostly above the meters permanent flow rate and may exceed the overload flow rate, thereby initially achieving better accuracy in measuring flows, but will deteriorate faster (Arregui et al., 2011). High pressure loss caused by meter under-sizing may also be a concern.

In Sao Paulo, Brazil, a massive bulk meter change out programme was implemented in 1997 as these meters were experiencing a progressive decay in their performance (Wilson, 2003). In the initial pilot study, 354 bulk meters were selected to be replaced or refurbished and if necessary resized. It was found that 248 (about 70%) of those meters were in fact oversized and only six were undersized. The payback period for the investment was at an average of 2 months, with 83 of the meters having a payback of just one month. By January 2002 a total of 16 809 meters were replaced, with 85% of them being oversized and only 4% undersized.

In the United States, City of Anderson, a meter change-out programme was initiated. Meters were investigated for their applicability of some of the meter types installed and their sizing (Hannah, 2008). The results of the meter replacement programme yielded a 45.5% increase in billed consumption for apartment complexes and a 43.4% increase at schools, motels and retail stores.

Water meters are often sized as the same diameter of the pipe it is installed at, resulting in over sizing (Wilson, 2003). Wilson (2003) claims that over-sizing of water meters, in general, is the major contributor to apparent losses.

2.6.5 Installation

Most water meters are designed to operate in specific orientations such as vertical, horizontal or an incline position. In general, single-jet and multiple jet meters are only designed for horizontal positions, whereas positive displacement meters can operate in virtually any position. When a meter is placed in an incorrect orientation, a higher meter error can be expected. Arregui et al. (2011) states that as a general rule that meters installed in incorrect positions under-register more at low flow rates but maintain their accuracy above the transitional flow rate. However, the mechanical parts of the meter will degrade faster as the impellor bearings are not operating efficiently due to the increase in friction of the moving parts caused by the incorrect orientation (Arregui et al., 2011).

The velocity profile distortions caused by disturbances upstream of the meter affect the measuring accuracy of the meter (also referred to as jetting), but once again the degree of impact on accuracy is dependent on the type of meter. Positive displacement meters are relatively insensitive to velocity profile distortions, but velocity meters are affected to varying degrees for different meter types. When the pipe upstream of a meter passes through two perpendicular planes, a swirl velocity profile develops which may cause more severe meter inaccuracy (Arregui et al., 2011). Manufacturers typically specify the length of straight pipe required upstream and downstream of the meter to mitigate the effect of velocity profile distortions on the meter.

2.6.6 Age

As water meters age they tend to reduce their metrological performance and in general tend to under-register more. Therefore, the longer a meter stays in operation the higher the potential meter under-registration and consequent financial loss.

Provided the correct size and type of meter was selected and correctly installed according to manufacturer specifications, the deterioration of the meter’s performance should be related purely on the design life of the meter. The age of the meter is either defined as the length of time in operation or accumulated consumption volume registered on the meter dial.

In Arizona, United States, it was found in the initial stages of a residential meter replacement programme that the variance of cumulated volume of 10 year old meters ranged from a total of 1 100 to 11 000 m^3 (Davis, 2005). In the Arizona case, it was determined that an accumulated consumption volume based meter replacement programme was more suitable. Using accumulated consumption as the indicator for meter replacement prevents meters from being replaced too early or too late, as might be the case in some instances when using time as an indication of age.

The meter replacement roll-out included testing of 1 297 positive displacement meters that were all 10 years old to determine the deterioration of meters with increasing cumulative consumption (Davis, 2005). This was done to determine the optimal replacement period of meters as a function of cumulative volume. Meters were tested at low (0.25 gpm or 57 l/h), medium (2 gpm or 454 l/h), fast (15 gpm or 3 407 l/h) flow rates. Figure 2.7 shows the results of the study. It was observed that data was more scattered for low flow rates and the decrease in accuracy for medium flow rates were the least. The linear rates of deterioration are 1.9, 0.23 and 0.12 percentage points per 1000 kl of water registered for low, medium and high flows respectively.

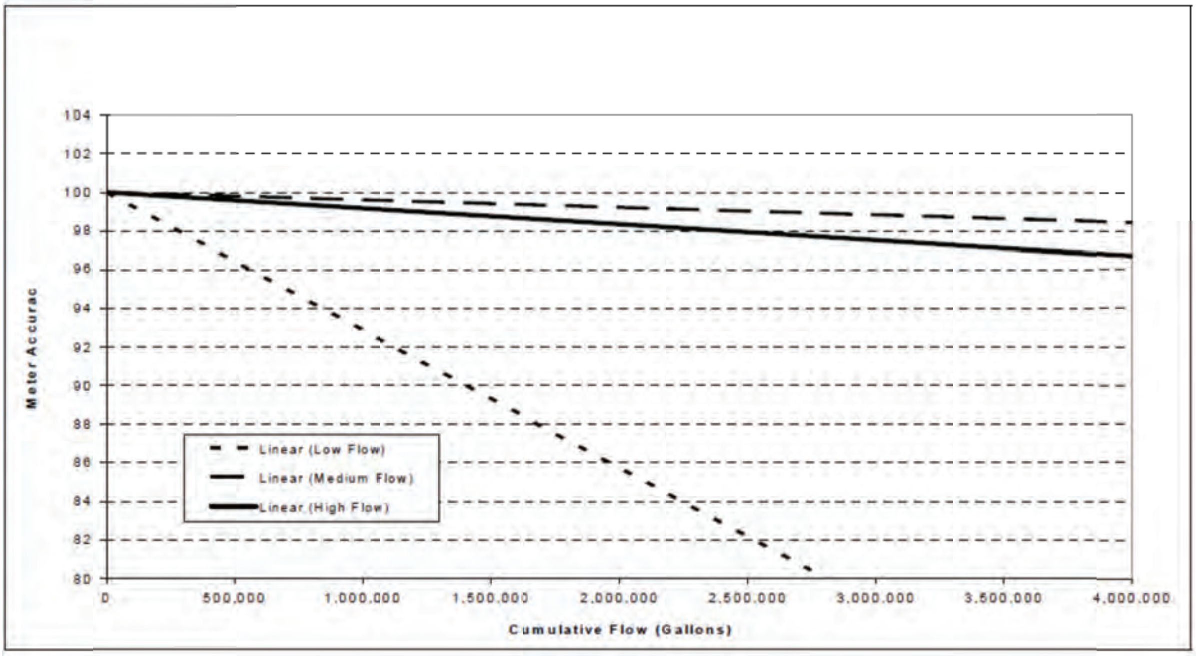

Figure 2.7: Meter accuracy versus cumulative flow for 10 year old meters, tested at low, medium and high flow rates (Davis, 2005)

Arregui et al. (2003) shows a similar trend in Davis's (2005) study, that meters degrade the fastest at low flow rates as they age over time. Arregui et al. (2003) tested 238 Class B single-jet meters with permanent flow rates of 1.5 m^3/h of two different manufacturers in a laboratory. The meters were tested at the 30 l/h, 120 l/h, 750 l/h and 1500 l/h and their starting flow rates.

Arregui et al. (2011) performed fatigue tests on four Class C single-jet meters in the laboratory, to determine how the meter error curve is affected with usage. A volume of water was passed through each meter at an intermittent flow rate of 2 250 l/h for periods of 15 seconds, until a total volume of 1 500 kl was registered. The error curve was then estimated at 0, 600, 1000 and 1500 m^3/h. It was found in the study that the errors at medium and high flow rates were practically unchanged and only the low flow rates were generally affected negatively.

2.6.7 Consumption pattern

The daily consumption pattern of the consumer is the main factor that affects the meters ability to register consumption accurately. To achieve the greatest economic performance of the meter, it is important that the greatest proportion of the consumer's consumption flow rates is between the minimum and permanent flow rates of the meter, and never exceeds the meter's overload flow rate.

There are a number of technical papers available that give information on standard domestic consumption profiles, for example Arregui et al. (2006 b). Arregui et al. (2006 a) logged the consumption profiles of three different types of consumers in South America and Spain (Figure 2.8). The following defines the consumer types shown in Figure 2.8.

- Type 1. Apartment blocks with a direct supply from the network or pump. A total of 389 households were logged for approximately one week.
- Type 2. Apartment blocks supplied from an elevated tank at the top of the building, with the meter installed upstream of the tank. A total of 58 households were logged for a period of one week.
- Type 3. Single houses with a garden. The summer consumption of 34 households was logged for a period of four weeks.

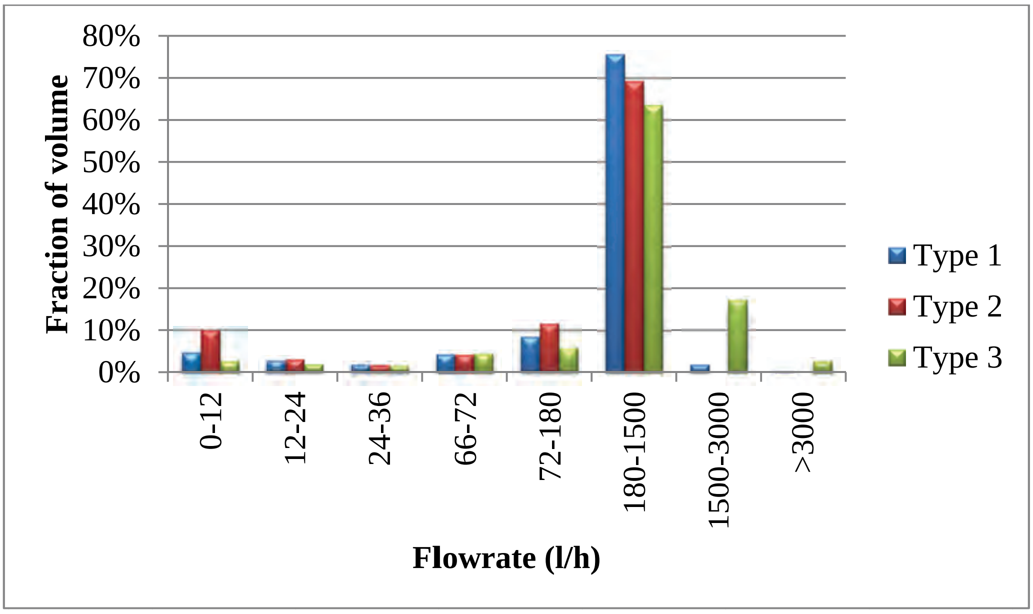

Figure 2.8: Typical consumption flow rates for different household types in Spain and South America (Arregui et al., 2006 a)

In Kampala City, Uganda, many residential customers have storage tanks installed on their premises due to an unreliable water supply (Mutikanga et al., 2010). As part of a study performed by Mutikanga et al. (2010) the accuracy of water meters less than 5 years old were tested for houses with and without storage tanks. Water meters were found to under-register by 15% at houses with storage tanks compared to 5% for houses without storage tanks.

2.6.8 Seasonal water demand

Water demand varies with seasons and the meter error may thus also vary. Davis (2005) logged the consumption patterns of residential consumers in Arizona (United States) over a week during the four different seasons. It was found that there was relatively little change in the percentage of time of low consumption flow rates between the seasons. The medium and high flow rates were the most sensitive to seasonal variation. This study showed that the meter accuracy for the same meter can change over the seasons. In Table 2.7, a summary of the data is shown with the number of samples used.

Table 2.7: Seasonal variation in consumption patterns (Davis, 2005)

Seasons	**Percentage of consumption**			**Number of meter logged**
	Low Flow	**Medium Flow**	**Fast Flow**	
	0-68 l/h	**68-546 l/h**	**546-4095 l/h**	
Spring	13.9%	19.0%	67.1%	27
Summer	10.5%	16.0%	73.4%	48
Autumn	11.5%	25.3%	63.3%	30
Winter	7.8%	33.6%	58.6%	27
Annual Weighted Average	10.87%	22.31%	66.81%	132

Arregui et al. (2006 a) found that meters of holiday homes only occupied in summer vacation periods exhibit a particular problem for meter accuracy. According to the authors this may be due to lime-scale build-up and biological growth accumulating inside the meter when it is stagnant, which affect the efficiency of its moving parts.

2.6.9 Water quality

The quality of the water in the form of suspended solids and depositions also has an impact on the accuracy of the meter. Meter types have different sensing elements and therefore deal with poor water quality differently. Mechanical velocity meters tend to over-register more due to lime-scale build-up on the impellor at medium to high flow rates and under-register greater at low flow rates (Arregui et al., 2011). Positive displacement meters run the risk of being blocked by either chemical build-up or a small stone passing the strainer.

In Kampala City, Uganda, about 76% of meters in the distribution system are of the volumetric type and was found to be unsuitable due to poor water quality (Mutikanga et al., 2010). As a result of poor repair practices in the distribution system, many new volumetric meters would be blocked, and the evidence of this showed in the meter workshop during servicing where suspended solids were found in meter strainers. Mutikanga et al. (2010) concluded that velocity type meters should be installed in the system in future, as this type of meter has greater resistance to poor water quality.

Seago et al. (2004) claim a large impact of water quality on metering accuracy (see Table 2.2) without providing evidence or strong motivation for these values. While such a large impact of water quality on a meter’s accuracy may be expected for positive displacement meters, it is less likely to be the case for inferential meters.

2.6.10 Spinning

Spinning is the rapid oscillation of the meters sensing element, which occurs when air pockets pass a meter, as a result of a poorly designed distribution network (Rizzo et al., 2004). Air also enters the distribution system during repairs and installations of pipes, and is a major problem in intermittent supply systems. All mechanical water meters are susceptible to spinning.

Spinning may case the meter to operate well past its overload flow rate and thus cause permanent damage. It is recommended that valves are opened slowly when new meters are installed, and that air valves are installed upstream of meters to counteract this problem.

2.6.11 Network pressure

It is well known that pipe carrying water under high pressure has a greater probability to leak than a pipe under low pressure. The magnitude of a flow rate of a leaking pipe or through an open tap is a function of the system pressure. Therefore distribution systems with different network pressures will exhibit different on-site leakage characteristics on consumer properties, which in turn affect the consumer consumption patterns. Higher leakage and repair rates increase the probability that suspended solids will enter the system and cause damage to meters.

The network pressure also affects the end use demand profile and the maximum flow rate a consumer can experience when opening their tap fully. Both of these factors can affect the performance and deterioration rate of water meters.

2.6.12 Environment

Environmental factors such as high temperatures and exposure to sunlight may deform or weaken plastic components of the meter and freezing temperatures may increase the operating pressures inside the meter (Arregui et al., 2006 a), all of which may cause deterioration in meter performance. According to SANS 1529, plastic water meters may not be exposed to sunlight and have to be installed inside meter boxes.

2.7 Estimating consumer meter error

2.7.1 Introduction

The objective of testing is to quantify the level of consumer meter under-registration in a supply area. The two parameters of interest are the error curve of the water meter and the consumption pattern of the consumer. Once these parameters are known the level of meter under-registration can be calculated.

The common method of determining the level of meter under-registration is to physically test the meter either in the field or in a laboratory and then determine the customer's consumption flow rate profile. There have been a number of different methods used for testing meter error and flow rate profiles due to either local conditions or financial reasons.

Industrial, Commercial and Institutional (ICI) consumers have a heterogeneous water demand and therefore each customer stand needs to be tested individually. Whereas for residential consumers at the local level the water demand pattern is more homogenous and depending on the population size, representative samples can be used (Arregui et al., 2006 a). The testing methodology of bulk consumers is the same as that for residential consumers except that the lager consumptions and smaller numbers require these meters to be tested individually.

There have been alternative testing methodologies presented in the literature other than the traditional testing of meter error curves in the field or laboratory and logging consumption profiles:

- A zone water balance can be performed to measure meter under-registration (Fantozzi et al., 2008; Rizzo et al., 2007). This is done by removing or quantifying all real losses, on-site leakages and other apparent loss components. For example, real losses can be removed physically or the Minimum Night Flow (subtracting on-site leakage and night consumption) at the zone inflow meter can be measured (Rizzo et al., 2007). This method is more accurate using Automatic Meter Reading (AMR) technology, to reduce the time delay between measuring the zone inflow meter and consumer meters.
- A new meter can be installed in series with the old meter for a sample of customers and the difference registered volume of the new meter and old meter can be calculated (Arregui et al., 2006 b).

- Billing records can be analyzed, whereby the consumption records of old meters that have been replaced can be compared with the newer meters to obtain the level of meter under-registration for the old meter (Arregui et al., 2006 b). The comparison period should cover a period of a year so that seasonal changes and changes in water demand patterns can be taken into account.

This section will discuss the issues and literature related to estimating meter accuracy curves, customer consumption patterns and the weighted meter error.

2.7.2 Meter error curves

The accuracy of a water meter is dependent on the flow rate passing it (Arregui et al., 2006 b). Therefore, to obtain this curve the meter needs to be tested for error at a number of selected flow rates to draw the error curve.

To reduce variability in meter error test results, the population of meters are stratified according to characteristics that affect metering performance into homogenous groups (Arregui et al., 2006 a).

Arregui et al. (2007) state that there are a number of variables that may affect the accuracy of a meter related to the meter characteristics and the consumer characteristics. These meter characteristics include the technology, model, brand, age etc. The consumer characteristics include water consumption patterns, water quality, number of pipe repairs in the network, weather conditions etc. To achieve the most accurate tests results all these variables would need to be considered. However, the numbers of meters that need to be removed from the field become too large and costly. A trade-off between the level of accuracy desired and the number of variables considered needs to be done to achieve the most optimal set of data. Therefore, only those variables that are considered to have the most influence on the metrological performance of the meter should be considered.

The following meter characteristics that affect meter performance have been used to some extent to separate meters into homogenous groups in various case studies. In Switzerland Guibentif et al. (2007) categorized meters by age, annual volumes, diameters, manufacturers and type of customer amongst others, in Italy Fantozzi (2009) removed meters from four water utilities and divided meters according to brand, mark, age, consumption and water quality, in Spain Arregui et al. (2007) tested meters of different models and ages and in

Uganda Mutikanga et al. (2010) categorized meters according to age groups only, as only positive displacement meters were tested.

After the meters have been ordered into homogeneous groups and samples have been selected from the field using a random sampling technique, the meters need to be tested to construct the meter accuracy curve for each meter. To construct the meter accuracy curve, the meter is tested at a number of flow rates. The more flow rates the meter is tested at, the more accurate the constructed curve would be to the actual accuracy curve of the meter, but this comes at increased testing time and cost. Arregui et al. (2006 a) argues that the AWWA method of measuring the accuracy at slow, medium and high flow rates is not accurate enough for the purpose of testing for meter under-registration.

Arregui et al. (2006 a) recommends that the meters starting flow rate should be found and the meter be tested at the minimum flow rate, another flow rate between the minimum and transitional values, the transitional flow rate and the overload flow rate. In Italy, Fantozzi et al. (2009) used a similar method of that described by Arregui et al. (2006 a). The meters were tested at q_p, 30% of q_p, q_t, q_{min} and the starting flow rate q_{start}. Mutikanga et al. (2010) also agree that the standard ISO 4064 three flow rates (q_{min}, q_t and q_s) are inadequate to obtain a defined meter error curve. They performed their tests at 11 different flow rates that as closely as possible resemble the customer consumption profiles.

Water meters can be tested in the laboratory or in the field to estimate its error curve. In the laboratory or in the field, meters are tested by comparing the actual volume of water passing the meter and the registered volume at a specific selected flow rate. The flow rate used for testing is usually measured by a calibrated master meter. The tests vary in how the actual volume of water passing the meter is measured. In the laboratory, the actual volume can be determined by using a calibrated master meter, calibrated volumetric tank or a calibrated weighing scale (Arregui et al., 2006 b). In the field, the actual volume and test flow rate is usually measured by a calibrated master meter. Ross-Jordan (2006) suggests that the actual volume and flow rate can be measured by filling a 25 litre bucket and using a stopwatch. The method presented by Ross-Jordan (2006) is not very accurate, but is useful if the previous more accurate methods are not possible.

2.7.3 Consumption patterns

The user's consumption pattern influences the ability of a water meter to accurately measure the volume of water passing through it. The consumption pattern of the consumer can be determined by either using standard consumption profiles from literature or from tests carried out in the field (Fantozzi, 2009; Arregui et al., 2006 a).

Using standard consumption profiles from literature is subject to error, and should only be used as a reference when no better information is available (Arregui et al., 2006 a). It is advised by Arregui et al. (2006 a) to rather measure the consumption profiles of consumers in the field. It is also stated by Arregui et al. (2006 a) that the local consumer characteristics need to be defined and not blindly use the stratification defined in literature. Characteristics such as monthly volume of consumers can be used to stratify households (Arregui et al., 2006 a).

When measuring the consumption patterns of domestic consumers, the following needs to be done (Arregui et al., 2006 a).

- The population of consumer's needs to be stratified according to variables that have the most influence on the measuring error of the meter. Specifically, variables that affect consumption at low and high flows need to be identified. Households must be selected randomly and depending on the homogeneity of the samples, a sample size of say 50 for each category is usually sufficient to achieve results within a reasonable uncertainty.
- The proper instrumentation needs to be used. Calibrated water meters need to be installed with sufficient accuracy to measure low flows such as leakages. The calibrated meter also needs to have a pulse emitter with a preferable minimum resolution of 0.1 l/pulse. Data loggers with sufficient memory capacity are required. Data loggers are devices which are capable of recording and storing information obtained from the meter regarding the consumer's consumption flow rates during the day.
- It is recommended that the minimum time period that flow consumption needs to be recorded, is one week, to pick up the full range of the consumption flow rates used.

In a Ugandan case study, Mutikanga et al. (2010) logged the consumption flow rates of 90 consumers in Kampala City. A similar methodology was used as that described by Arregui et al. (2006 a). They used Class D positive displacement meters with sufficient sensitivity to detect low flows, the meters were equipped with pulse emitters (0.1 l/pulse) and data loggers were used to record the consumption flow rates for a week.

The uncertainty associated to the estimation of the consumption patterns are caused by different factors like (Arregui et al., 2007):

- Erroneous stratification of the population. The objective of stratifying consumers is to create homogenous groups which have similar consumption characteristics to decrease variability in results. However, if users are stratified improperly a heterogeneous group can be created where consumers have different consumption characteristics, and a large variability in results can be expected.
- Incorrect selection of the sample. In some cases, the sample selected for a defined stratum can be incorrect. This could be due to an improperly updated commercial database where user characteristics are inaccurate or the consumer itself could have changed its consumption characteristics without notifying the utility.
- Variability in the water consumption. Water consumption with regard to quantity and flow rate intensity change not only throughout the day, but also throughout the week and seasons. Therefore, when measuring the water consumption pattern, at least a week or two of data logging needs to be performed to minimize uncertainty.
- Distortions caused by the measuring and data logging equipment. When analyzing data stored from a data logger, the consumption pattern stored in the data logger is not 100% representative of the actual consumption pattern. This is due to the non-linear error curve of the calibrated meter and due to the data processing of the data logger. The resolution of the pulse emitter also has bearing on the uncertainty of the data obtained.

2.7.4 Average Weighted Error

The average weighted error is the percentage of water that is not registered by the consumer meter. The average weighted error of a water meter in operation is affected by two parameters: the error curve of the meter and the consumption pattern of the consumer. The calculation of the average weighted error is performed by multiplying the percentage error of the meter and the percentage of consumption at each defined flow interval, then adding all the percentage errors of each flow interval. The following Table 2.8 is a sample calculation of the average weighted error (Arregui et al., 2006 a).

Table 2.8: Calculation of average weighted meter error for a meter (Arregui et al., 2006 a)

Flow rates (l/h)	Consumption Profile (%)	Meter error (%)	Registered Volume (%)
0-12	4.7	-100	0.00
12-22	2.3	-100	0.00
22-24	0.5	-68	0.16
24-36	1.9	-52	0.91
36-72	4.3	-11	3.83
72-180	8.5	0	8.50
180-1500	75.7	-0.8	75.09
1500-3000	1.9	-0.8	1.88
> 3000	0.2	-0.8	0.2
Total registered volume (%)			90.6
Weighted meter error (%)			-9.4

2.8 On-site leakage

On-site leakages are defined as the leakage occurring on the downstream of the consumer meter. The flow rate and occurrence of on-site leakages are a function of the age and condition of the consumers plumbing system and the network pressure. These leakages can occur from pipes, plumbing fittings, toilets, geysers, taps and other household appliances.

On-site leakages constitute both an apparent loss and demand management problem. However, high flow rate leakages with respect to the meter accuracy curve do not represent a problem in terms of apparent losses i.e. the meter measures most of the leakage in its higher accuracy range. It is the low flow rate leakages that represent a problem for apparent losses, as more of the flow is not registered by the meter.

The importance of understanding the situation and reducing on-site losses has resulted in a number of studies. In Johannesburg, a study was done to investigate the level of on-site leakage on residential and non-residential properties (Van Zyl et al, 2008; Lugoma et al., 2012). On-site leakages were measured by manually reading the consumer meter when there was no consumption during the day time at 5 min intervals. To ensure that there was no consumption during the manual reading process, the consumer was notified about a week before the visit and if at home asked to stop all consumption. A second visit was made to verify the leakage. It was found that 67% of 128 domestic properties had on-site leaks with an average leakage rate (including both leaking and non-leaking properties) of 16.5

l/property/h. For other (bulk domestic and non-domestic) properties, they found that 57% of 54 properties had on-site leaks with an average leakage rate (including both leaking and non-leaking properties) of 40 l/property/h. Most leaks had low flow rates and the number of properties declined rapidly with increasing flow rate as shown in Figures 2.9 and 2.10. The estimated distribution of water delivered to properties in Johannesburg is shown in Figure 2.11.

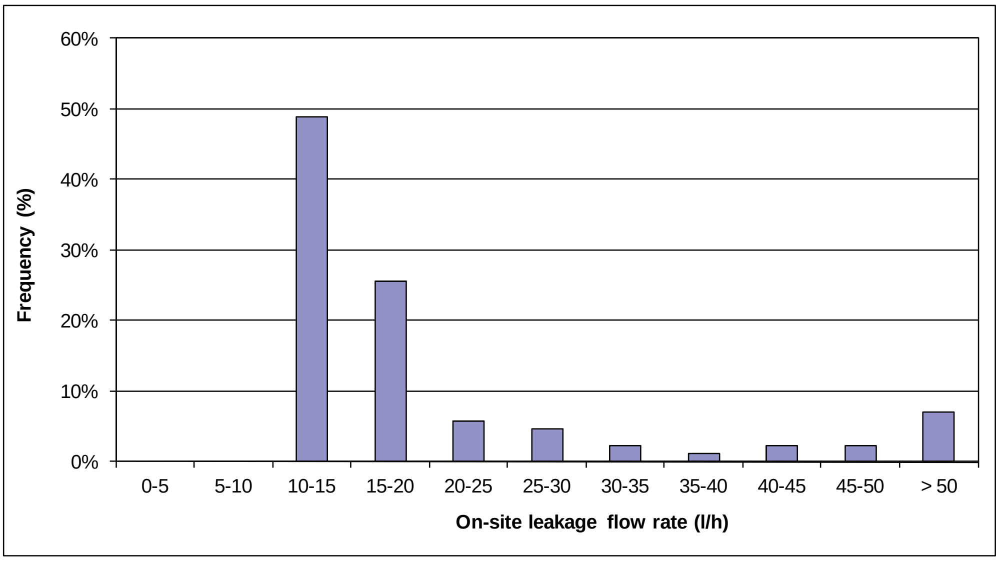

Figure 2.9: Flow rate distribution of on-site leakage at leaking residential properties in Johannesburg (Van Zyl et al, 2008)

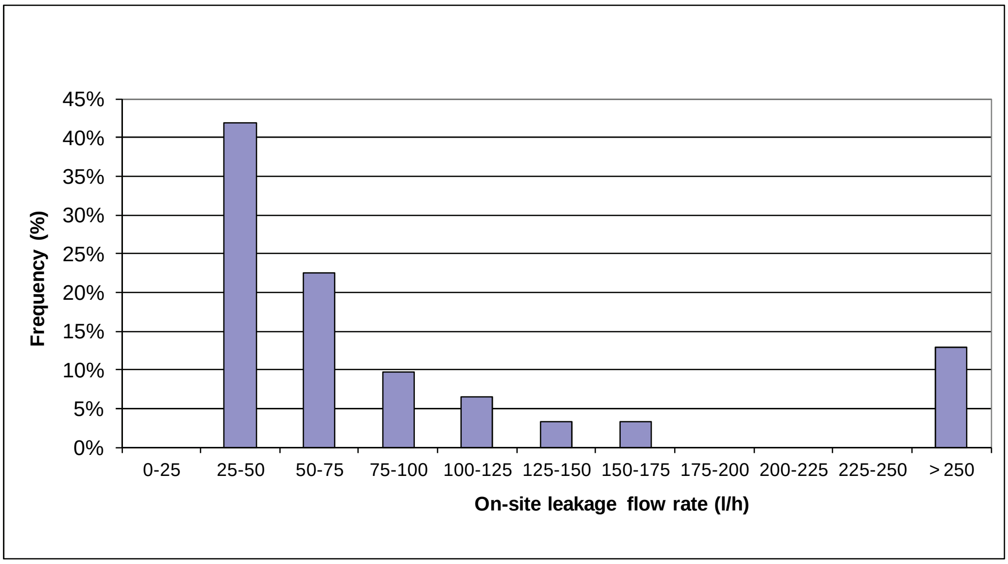

Figure 2.10: Flow rate distribution of on-site leakage at leaking bulk domestic and non-domestic properties in Johannesburg (Van Zyl et al, 2008)

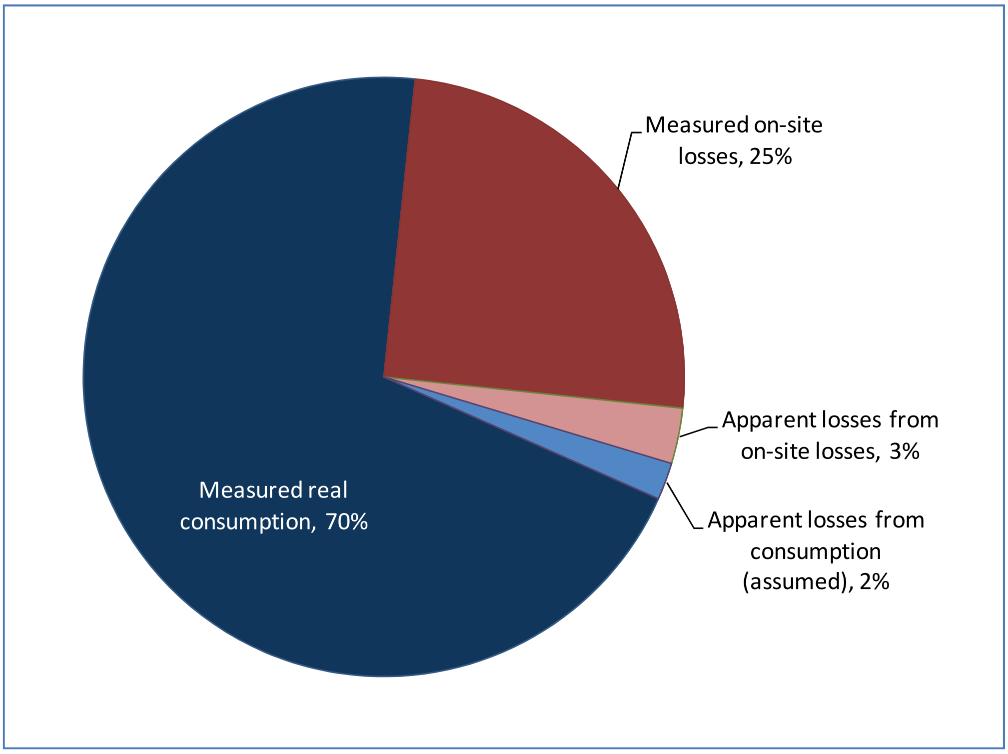

Figure 2.11: Estimated distribution water delivered to properties in Johannesburg. (Lugoma, 2012)

In Johandeo located in Sebokeng (southern Gauteng-Emfuleni Local Municipality), during a community awareness intervention programme, 80% of 2 100 households were found to have on-site leakages during household visits which involved inspection of internal plumbing fixtures (Wegelin et al., 2009 b).

It was found in the 'Water Leak Repair Program in Poor Areas in the City of Cape Town' that 62% of 8 000 properties had leaks by inspecting internal plumbing fixtures and fixing them, with 77% of these leaks from toilet cisterns (Frame et al., 2009). The project reduced monthly household consumption from 19 to 11.5kL.

In the Drakenstein Municipality as part of their leak repair programme, repaired the leaks of over 1 413 households in the Saron area (Drakensberg Municipality, 2009). It was found that 83.4% of the properties had on-site leakages, with 30.9% of properties having cistern leaks and 64.2% having leaks on their pipes.

In Australia, a pilot study was performed in a selected District Metered Area (DMA) in Queensland to measure household leakages in residential properties using Automatic Meter Reading (AMR) technology (Britton et al., 2011). Using the AMR drive-by technology, 2%

of 2 359 households were identified to have leaks. Several leaks were identified in these households of which 46% of the total leaks were due to leaking toilets. Dual flush toilets with a cistern size of 9/4.5 litres were found to have leakage flow rates of between 13.33 to 34.56 litres per hour. Single toilets with a cistern size of 11-15 litres were found to have leakage flow rates of between 12.2 to 38.89 litres per hour. Britton et al. (2011) discovered that the cause of the majority of leaking toilets were as a result of the failure of the 'top valve' in the cylindrical control unit inside the cistern. Leaks from pipes and taps were the other main leak types after the toilet.

In UK, a test was developed for the assessment of on-site leakage (UK Water Industry, 1994). It consists of two nightly readings on the municipal water meter around 2 hours apart. If the meter indicated flow at the times of both readings, these readings were used to estimate the on-site leakage. Any measured consumption greater than this estimate is considered as legitimate consumption. In a study of night-time consumption and on-site losses of 2 929 non-domestic consumers, an average night flow of 8.4 l/property/h was found. The average night-time consumption flow use of non-households was found to be greatly influenced by a tiny proportion of high night flow users as well as by the numbers of properties in different non-household categories having different night use (Twort, et al. 2000).

In addition, Twort et al. (2000) estimated the average background supply pipe losses for households at night as the difference between an average night flow delivered of 2.5 l/prop/h and an average household night use of 1.7 l/prop/h – i.e. 0.8 l/prop/h. The above average night flow delivered was determined on 30 groups of households from Companies, covering 6,207 homes.

Another UK study Burnell and Race (2004) logged the consumption of 2000 properties with new water meters. The largest on-site leakage rate found was 900 l/h. The authors concluded that there is no standard loss-rate for supply pipe leaks and it might be misleading to speak in terms of average rates. They found most on-site leakage rates were small, and that a few properties contributed most of the on-site leakage.

DeOreo et al. (1996) investigated household water demand of sixteen households in Boulder Colorado. They found that 20% of the households had on-site leakage.

Mayer et al. (1999) logged the consumption of 1 188 households in 12 study sites across the USA. They found that a small number of houses were responsible for the majority of the leakage: 67% of the households logged had measurable leaks 1.6 l/h or less, whilst 5.5% of the households lost an average of 15.8 l/h. They found the on-site leakage to be 14% of consumption.

Another study was conducted in Spain on 64 residential houses by Arregui et al. (2006). It was found that most measurable on-site leakage rates ranked between 2 and 40 l/h, with some leaks being as high as 100 l/h. Also in Spain, Gascón et al. (2004) found an average residential leakage rate of 17 l/h per property in studying water consumption patterns in four different cities. There on-site leaks represented 8.9% of the average daily consumption.

In Namibia, Fourie (2004) investigated water use and leakage patterns on private and government in the cities of Windhoek and Swakopmund. The study found on-site leakage on 20% of properties in Windhoek, and 9% of properties in Swakopmund, with average on-site leakage rates of 20.3 and 9 l/h respectively.

Finally, Britton et al. (2009) reports the results of a study of on-site leakage using smart metering in Hervey Bay in Queensland, Australia, which give a ‘trickle alert’ when continuous flow is measured for more than 48 hours. They found on-site leakage on only 3.5% of 23 631 meters investigated. Presumably, the low incidence of on-site leakage is a consequence of home owners being informed of trickle alerts on a regular basis. The average leakage rate of leaking residential properties was found to be 30.8 l/h.

2.9 Unmeasured Flow Reducers

Unmeasured Flow Reducers (UFRs) are devices aimed at reducing apparent losses due to meter under-registration. It consists of a valve that requires a certain pressure difference across the device to open (Yaniv, 2009). On a property with no on-site leakage, the UFR stays closed during periods of zero consumption. When water is used on the property, the UFR remains closed until the pressure difference over it reaches 0.4 bar. Once open, only a 0.1 bar pressure difference is required to keep the UFR open.

In the case of an on-site leakage or consumption at a low flow rate, the pressure over the UFR will equalise quickly after it opened, causing it to close again. This process is repeated, leading to the constant low flow rate being converted into a batched higher flow rate that can be measured more accurately by the meter. Figure 2.12 illustrates this graphically.

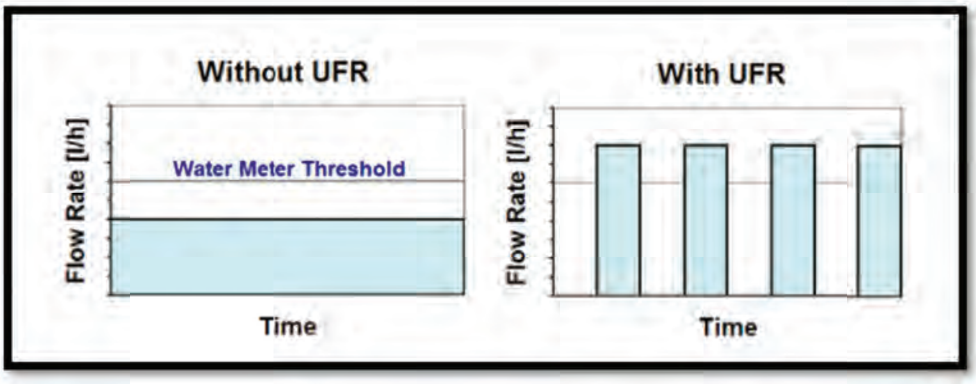

Figure 2.12: Comparison of flow rate curves for a meter with and without a UFR installed (Yaniv, 2009)

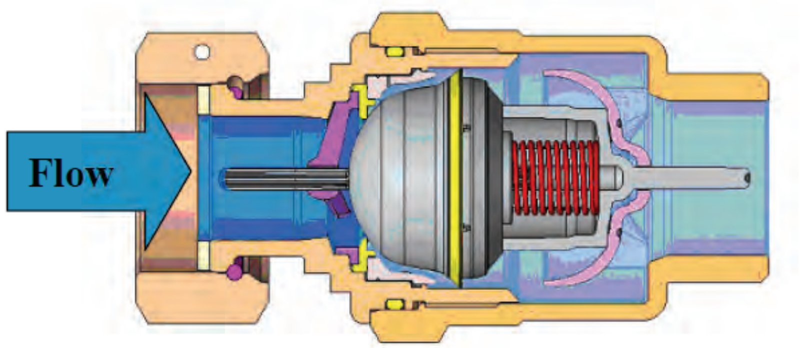

Figure 2.13: Illustration of the UFRs internal components when it is closed (Yaniv, 2009)

A number of studies have been performed to determine the effectiveness of the UFR (Figure 2.13) in reducing meter under-registration internationally and one being done in South Africa. The following studies described are mostly from conference papers and not peer-reviewed journals and the degree of involvement of the supplier in these studies are not clear.

Recently, in 2007, UFRs were tested in the Mangaung Local Municipality on 50 households in Batho near the Bloemfontein CBD (Webster, 2011). The tests were carried out by installing UFRs on each of the properties and reading the registered volume on the meter for six minutes between the middle of the interval of two batches when there is no consumption by the owner. The recorded consumption is then converted to an hourly flow rate, which represents the flow rate of the on-site leakage. It was found that the UFRs were allowing the meter to register an additional 2.1 kl/month.

In Udine, Italy, a sample of 33 meters from the Acegas APS utility was removed from the field to be tested in the Maddalena Meter testing laboratory, with and without a UFR (Fantozzi, 2009). The meters were 20 mm Class C turbine meters with ages ranging from 1 to 7 years. It was found that meters with the UFR installed registered 94%, 31.8% and 14.4% more water passing the meter at flow rates below the starting flow rate, starting flow rate and the minimum flow rate respectively.

Another study was performed in Italy in Palermo City to determine the effectiveness of UFR's three different ways (Fantozzi et al., 2011). The first method was to compare the registration of meters with and without a UFR on two households which have a storage tank installed. The UFR reduced the meter error from -45% to -7% for the one household and -12% to -1% for the other. The first method indicated that there is an improvement in the meters accuracy and motivated the second method. The second method involved testing the UFRs in the laboratory using the consumption pattern shown in Figure 2.14 (typical for the area) and comparing meters removed from the field (with and without the UFR installed) on the test bench.

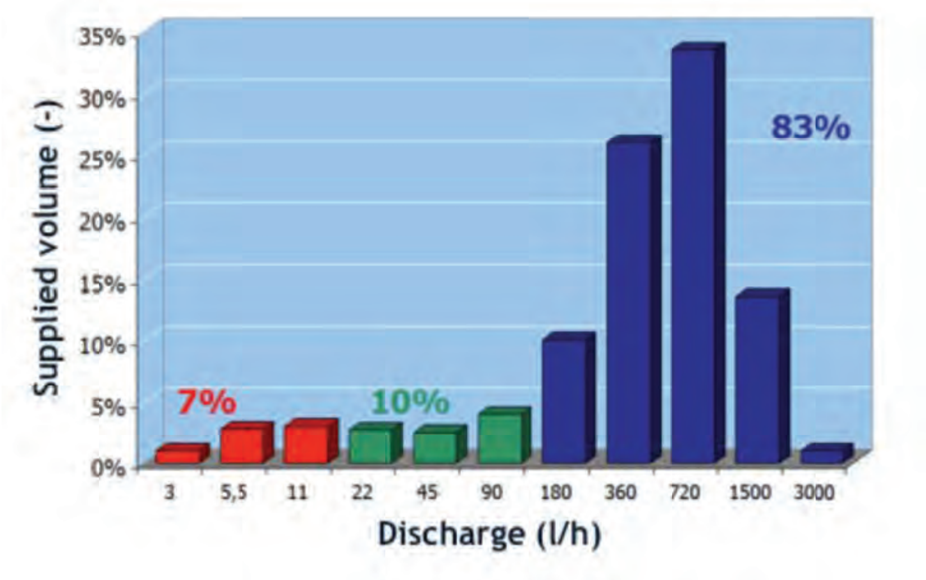

Figure 2.14: Water consumption pattern used for laboratory testing of UFR performance by Fantozzi et al. (2011)

Table 2.9 illustrates the results obtained from the laboratory testing, which shows clear improvement in the meters accuracy to measure consumption.

Table 2.9: Results of meter testing in the laboratory in Italy (Fantozzi et al., 2011)

Meter age* (years)	No. of meters tested	Average starting flow rate (l/h)	Error without UFR (%)	Error with UFR (%)
0-5	22	5.69	-2.60	-0.38
5-10	24	6.69	-5.80	-0.78
10-15	26	12.31	-9.30	-1.37
15-20	24	11.48	-7.90	-1.24
20-25	22	16.43	-11.30	-4.87
25-30	18	9.92	-6.80	-1.49
30-35	16	16.48	-11.80	-5.10
35-40	14	18.74	-13.20	-7.27
40-45	10	33.40	-16.80	-11.52
* Meters younger than 10 years are Class B and the rest are Class C				

The third method was a zonal water balance of a Small District Metered Area (SDMA) and the accuracy of the meters without a UFR and with a UFR installed was compared. The SDMA consisted of 52 consumers having 33 Class C meters less than 11 years old, 17 Class B meters and 2 Class A meters which are older than 11 years. All the meters are of the turbine type and most of the consumers have storage tanks on their properties. The meter under-registration was 28.06% and 18.91% without and with the UFR installed respectively.

In Cyprus, a similar zonal water balance was performed on a hydraulically encapsulated zone of 69 consumers (Charalambous et al., 2007). All the consumers have a storage tank installed with a positive displacement meter to measure consumption. A total of 43 and 26 of the meters are Class D and Class C respectively. With a total 26, 7, 16, and 20 were 1-3, 4-7, 8-11 and greater than 11 years old respectively. A meter under-registration of 6.79% and 2.12% without and with the UFR respectively were estimated. Additionally, the study concluded that UFRs do not induce pressure surges into a distribution network, by measuring the pressures at an appropriate fire hydrant location before and after the UFRs were installed.

In Malta, a zonal water balance was performed on a small hydraulically encapsulated zone with an average meter age of 5 years old (Rizzo et al., 2007). The zone had 26 consumers with Class D positive displacement meters with a 1m^3/h permanent flow rate (Yaniv, 2009). The UFRs were installed with a bypass valve so that the meters registration could be compared for a total of three tests with and without the UFR. A decrease of 5.5% to 6% of meter under-registration was estimated.

In two separate District Metered Areas (DMAs) in Jerusalem, Israel, the meter under-registrations were estimated using a zonal water balance before and after UFRs were installed

(Davidesko, 2007). The DMAs all have Class B multi-jet meters with a permanent flow rate of 2.5 m^3/h. It was estimated that the DMA with 120 consumers had an under-registration of 16% and 6.1% without and with a UFR installed respectively. The other DMA with 360 consumers had an under-registration of 26% and 18.8% without and with a UFR installed respectively.

It is clear from the number of studies done both in South Africa and internationally that UFRs can be effective in reducing apparent losses due to meter under-registration, especially where on-site leakage are common or consumers feed into a storage tank on their properties.

3 ON-SITE LEAKAGE FIELD STUDY

3.1 Introduction

On-site leaks are defined as leaks that occur on the downstream side of the consumer's water meter. Therefore these leakages are not classified as real losses, but as authorised consumption. On-site leakage therefore contribute to additional consumer water demand, but can also contribute significantly to apparent losses due to the constant low flow rates caused by on-site leaks. It is important to quantify the level of on-site leakages in terms of both occurrence and flow rate, to identify the extent of the problem and determine whether it is economical to put measures in place to reduce it or try to measure them better through improved metering.

It is mainly the low flow rate leakages that present an apparent loss problem, as they occur below the transitional flow rate of the meter. It is a legal requirement stipulated in the *SANS1529-1: Water Meters for Cold Potable Water* standard that meters taken out of the field and tested in a laboratory must have a relative error of less than 8% on the lower accuracy band of the meter error curve, therefore meters in the field can be expected to have at most that amount of relative error in legal terms. However, consumer meters in South Africa are often left in the field well past their design lives and can be exposed to poor field conditions, therefore even greater relative errors can be expected. As a meter ages and is exposed to poor field conditions, so does its accuracy decrease, particularly below the transitional flow rate (Davis, 2005).

In the Johannesburg area, a study was performed on middle to high income properties to investigate the level of on-site leakage on domestic and non-domestic consumer properties, which discovered a high incidence of on-site leakage in both domestic and other properties (Lugoma et al., 2012). It was found that 67% of 128 domestic properties had on-site leaks with an average leakage rate (including both leaking and non-leaking properties) of 16.5 l/property/h. For other (bulk domestic and non-domestic) properties, it was found that 57% of 54 properties had on-site leaks with an average leakage rate (including both leaking and non-leaking properties) of 40 l/property/h.

Due to the potential impact of on-site leakage on apparent losses, this study aimed to expand the Johannesburg study by repeating it residential properties in the cities of Cape Town and Mangaung. This study used the same methodology followed in the Johannesburg study. Only consumer meters less than 3 years old are considered in this study, as these meters are most likely to still have a good accuracy at the lower flow rates to be able to register on-site leakage. Since even new water meters can't register leakage flow rates below their starting flow rates, the results are considered conservative.

3.2 Meter database

The consumer meter database for the City of Cape Town was collected from GLS Consulting Engineers from the Swift archive at their offices and the meter database for Mangaung was collected from JOAT consulting and sales at their offices.

The meter databases had no meter information category to identify the type, size, class and manufacturer of the meters in the field. This made it important that this information was collected from the field to assess the accuracy of the meter models found.

The databases only had meters of younger than 10 years old with the following information given as shown and described in Table 3.1.

Table 3.1: Data fields in metering databases

Field name	**Description**
Serial_No	Meter serial number
Stand_ID	Stand's ID consisting of Town, Suburb, Stand, Portion and Sub portion. The format is defined according to the treasury system
Unit_No	Additional Stand ID number to make record unique
GIS_Code	GIS Code (as supplied by the treasury)
Town	Town
Suburb	Suburb
Suburb_Category	The user specified suburb category to which the suburb code is mapped
Stand_No	Stand number
Address	Address
Stand_Owner	Stand owner
Consumer	Consumer
Water_Tariff	Water consumption tariff code
Land_Category	The land use category determined from the land use, water tariff, availability code and tax tariff code
Zone_Category	The zoning category determined from the zoning code and the land use category
Stand_Area	Area of the stand
Measurement_Unit	Water meter measurement unit
Meter_Installation	Date when meter was installed
Units	Calculated Number of living units on the stand
Adjust	Adjustment code indicating anomalies in the readings

3.3 Methodology

3.3.1 Introduction

An identical procedure was followed as in Lugoma et al. (2012) study in determining on-site leakages by inspecting new water meters in the Johannesburg area.

3.3.2 Selection of study area

The City of Cape Town and Mangaung were the municipalities under investigation and a total of 15 and 6 suburbs respectively were selected. A total of 405 new meters in the City of Cape Town (Table 3.2) and 166 new meters in Mangaung (Table 3.3) were investigated from the 01 July to the 22 October 2011 and 13 December 2011 to 11 January 2012 respectively.

Table 3.2: List of suburbs investigated in Cape Town

No.	Suburb	Number of samples	Period of investigation
1	Camps Bay	27	27/09/11-29/09/11
2	Claremont	29	16/07/11-31/09/11
3	Green Point	22	27/09/11-29/09/11
4	Lakeside	27	20/09/11-21/09/11
5	Langa	27	08/09/11-26/09/11
6	Mandela Park	29	13/09/11-27/09/11
7	Mowbray	26	01/07/11-14/10/11
8	Newlands	29	22/09/11-22/10/11
9	Observatory	27	13/07/11-20/09/11
10	Pinelands	29	14/09/11-16/09/11
11	Rosebank	17	04/07/11-15/09/11
12	Salt River	30	11/07/11-30/09/11
13	Thornton	30	21/09/11-22/09/11
14	Tokai	30	14/09/11-19/09/11
15	Woodstock	26	07/07/11-16/09/11
Sum		405	01/07/11-22/10/11

Table 3.3: List of suburbs investigated in Mangaung

No.	Suburb	Number of samples	Period of investigation
1	Botshabelo G	30	13/12/11-14/12/11
2	Mandela View	25	16/12/11-17/12/11
3	Vista Park	30	20/12/11-21/12/11
4	Brandwag	25	28/12/11-29/12/11
5	Freedom Square	26	03/01/12-05/01/12
6	Motlatla	30	10/01/12-11/01/12
Sum		166	13/12/11-11/01/12

3.3.3 Procedure for inspecting consumer meter

The following describes the procedure used in interrogating the new meters selected from the database:

1. Select properties
    a. Only new domestic residential consumer's that are younger than three years old were selected from the database and listed.
    b. From the list of properties, the consumers were selected based on two factors. The first factor required that the properties to be selected were of reasonable walking distance from each other, but not all in the same street. The second factor required that the meter on the consumer's property can be found and is accessible.
    c. Each property selected in the study was given a Reference ID to remove confidential data of the consumer in the analysis part of the study.
2. Notify the consumer
    a. The consumer is made aware of the study by placing a letter in their mailbox about a week before the scheduled visit.
    b. On the day of the visit, the consumer's door bell is rung, and if home, is kindly requested to stop all water consumption.
3. Collect field meter information
    a. The meter is located and identifiable meter information is recorded. This meter information includes the manufacturer's name, the meter's permanent flow rate and the accuracy class of the meter, which are recorded on a field sheet (Appendix B). Additionally a photo of the meter is taken to help identify the meter.
    b. The condition of the meter installation is also recorded and any other useful information found on the consumer's property.
4. Read the meter's dial
    a. The initial reading of the meter is recorded on the field sheet to the lowest fraction of a cubic metre and the stop watch is started simultaneously.
    b. After each five minute interval, the reading on the meter dial was recorded in the field sheet for a total of three intervals.

c. If after ten minutes, there is no registered consumption on the meter's dial, it is assumed that there is no measurable on-site leakage on that property and no further readings were taken.

5. Confirm if there is an on-site leakage from the first visit.
   a. If there was a registered volume found on the first visit, a second visit at a different time was made to confirm the presence of a probable on-site leakage.
   b. The same meter reading procedure used in the first visit was repeated.

3.3.4 Water meter manufacturer catalogues

With the aid of the pictures of the meters taken and identifiable meter information in the field, the meters could be identified within the relevant manufacturer catalogues (Table 3.4). These catalogues contain additional information about the meters starting, minimum and transitional flow rates which are important to describe the accuracy of the meters in the field. All the meters in Table 3.4 have a lowest indicated volume of 0.1 litres.

Table 3.4: Meter information obtained from manufacturer catalogues

Manufacturer	**Type**	**Size (mm)**	**Class**	**q_p (m^3/h)**	**q_t (l/h)**	**q_{min} (l/h)**	**q_{start} (l/h)**
1	Positive displacement	15	C	1.5	22.5	15	5.7
1	Positive displacement	20	C	2.5	37.5	25	9.5
1	Positive displacement	25	C	3.5	52.5	35	13.2
1	Multi-jet	15	C	1.5	22.5	15	6
1	Multi-jet	20	C	2.5	37.5	25	6
1	Multi-jet	25	C	3.5	52.5	35	10
2	Multi-jet	15	B	1.5	120	30	12*
2	Multi-jet	20	C	2.5	37.5	25	10*
3	Multi-jet	15	B	1.5	120	30	10
3	Multi-jet	15	C	1.5	22.5	15	7
3	Multi-jet	20	B	2.5	200	50	18
3	Multi-jet	20	C	2.5	37.5	25	12
4	Multi-jet	15	B	1.5	120	30	12*
4	Multi-jet	20	B	2.5	200	50	20*

Note: * There was no q_{start} available in the manufacturer's catalogue, therefore a q_{start} of 40% of the q_{min} was assumed.

3.3.5 Calculating and verifying on-site leakages and their flow rates

The flow rate of the leakage found on a consumer's property was calculated by:

- Subtracting the final registered volume reading from the initial registered volume reading for each five minute interval.
- The leakage volume of each interval was then converted to an hourly flow rate in litres.
- The leakage flow rate was then taken as the mean of the six values.

Water meter samples that had no measureable on-site leakage after the second visit were deemed not to have any measurable on-site leakage, despite the first visits results. Where it was clear from the data that consumption occurred during the meter reading process in the field, affected records were removed from the data set. The following Table 3.5 lists these records that were removed in this way.

Table 3.5: Records removed from the data set in this study

Ref. ID	**Q_1 (l/h)**	**Q_2 (l/h)**	**Q_3 (l/h)**	**Q_4 l/h)**	**Q_5 (l/h)**	**Q_6 (l/h)**	**Reason**
To4	0.7	0.8	0.7	0	0.4	0	Owner consumed water despite being asked kindly no to during the visit. Based on investigator's observation.
Wo27	68.4	117.6	116.4	30	34.8	33.6	Owner consumed water despite being asked kindly not to, during the visit. Based on investigator's observation.
Lg33	33.6	9.6	9.6	33.6	34.8	33.6	Owner consumed water despite being asked kindly no to during the visit. Based on investigator's observation
Cl2	2.4	6	2.4	2.4	2.4	2.4	Only Q_2 was removed. Very likely consumption based on the flow rates read on other data points.
Gp1	1330.3	0.4	0.2	0.4	0.2	0.4	Only Q_1 was removed. Concern of washing machine being on at the start of meter reading process and validated by comparing Q_1 to the other flow rates read.
FS26	33.6	8.4	8.4	9.6	9.6	9.6	Only Q_1 was removed. Very likely consumption based on the flow rates of other data points.
BG10	80.4	97.2	75.6	55.2	56.4	57.6	The first three data points were removed. Likely consumption based on the flow rates of second visit.

Ref. ID	Q_1 (l/h)	Q_2 (l/h)	Q_3 (l/h)	Q_4 l/h)	Q_5 (l/h)	Q_6 (l/h)	Reason
BW23	26.4	105.6	26.4	26.4	26.4	25.2	Only Q_2 was removed. Likely consumption based on the flow rates of other data points.
BG29	72.0	25.2	22.8	15.6	16.8	16.8	Only Q_1 is purged. Likely consumption based on the flow rates of other data points.
BW19	68.4	69.6	69.6	70.8	69.6	129.6	It was found that a water feature was running consistently throughout the reading process. Therefore all the data on this property was purged.

3.3.6 Correcting for meter error

The volume of water registered on a meter's dial is not the actual volume of water passing through the meter. Due to the error curve of the meter, the meter can under-register or over-register consumption, depending on the flow rate of water passing through the meter. The registered consumption visible on the meter's dial is defined as the indicated volume (V_i). The aim here is to correct for the meters error by drawing the meter's error curve and adjusting the indicated volumes (and thus flow rates) measured in the field to obtain the actual Volumes ($V_{a)}$ that passed through the meter.

The meter error curves were estimated in the following way: The permanent, transitional, minimum and starting flow rates of the different meter models were found in manufacturer catalogues and their corresponding relative errors were conservatively guessed. The transitional flow rate error was assumed to be +2% and the minimum flow rate error to be 0%. A 2nd order polynomial was drawn through the transitional and minimum flow rate, such that it never exceeds +2%, to find the relative error at the starting flow rate and draw the error curve. The following Equation 3.1 describes the 2nd order polynomial:

$$Relative\ error\ (\%) = a(\ln Q_{actual})^2 + b(\ln Q_{actual}) + c \qquad (3.1)$$

Figure 3.1 gives an example of typical error curves used.

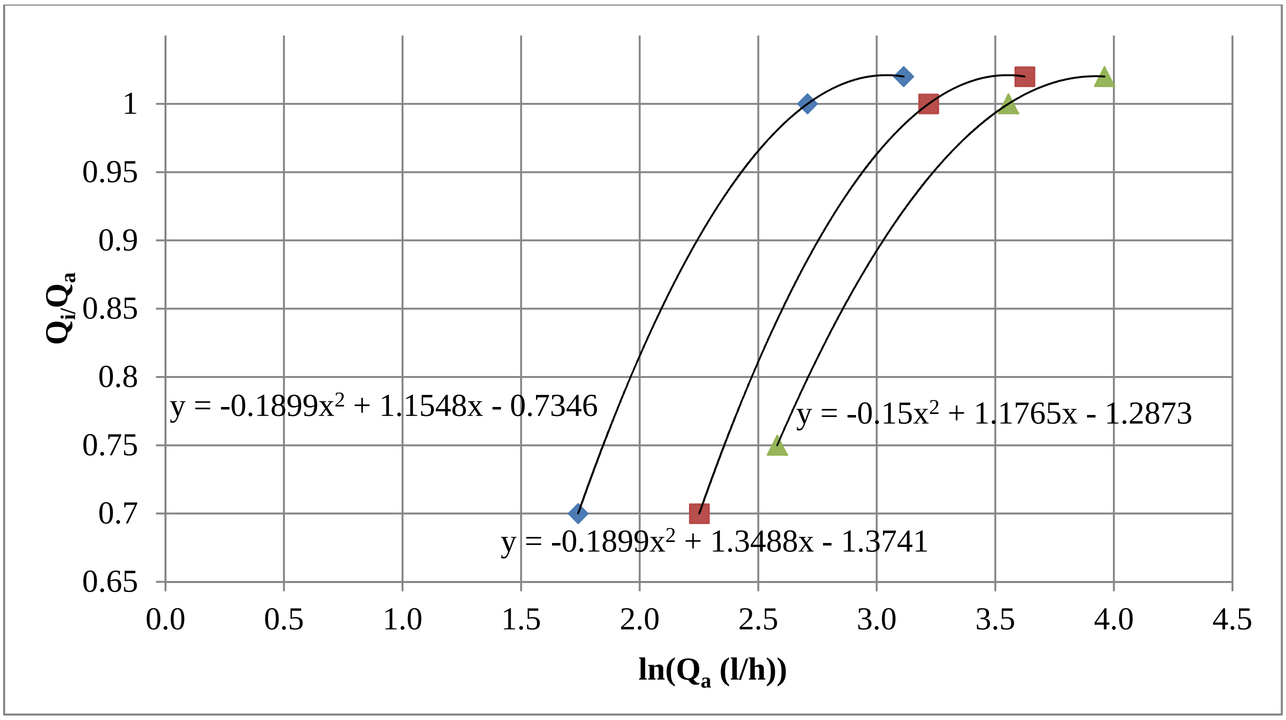

Figure 3.1: Meter error curves of class C positive displacement meters of 15, 20, 25mm meters from Manufacturer 1.

The next step was to develop an expression that can convert the indicated flow rate on the meter dial to an actual flow rate passing through the meter using the error curve. A 3rd order polynomial was used to do this between the starting and transitional flow rates:

$$Q_{actual} = aQ_{indicated}{}^3 + bQ_{indicated}{}^2 + cQ_{indicated} + d \quad \text{...} (3.2)$$

Measured flow rates less than the indicated q_{start} were assumed to equal to the meter's actual q_{start}. Errors in measured flow rates greater than q_t were ignored.

Figure 3.2 provides an example of typical indicated flow rate conversion curve for a meter.

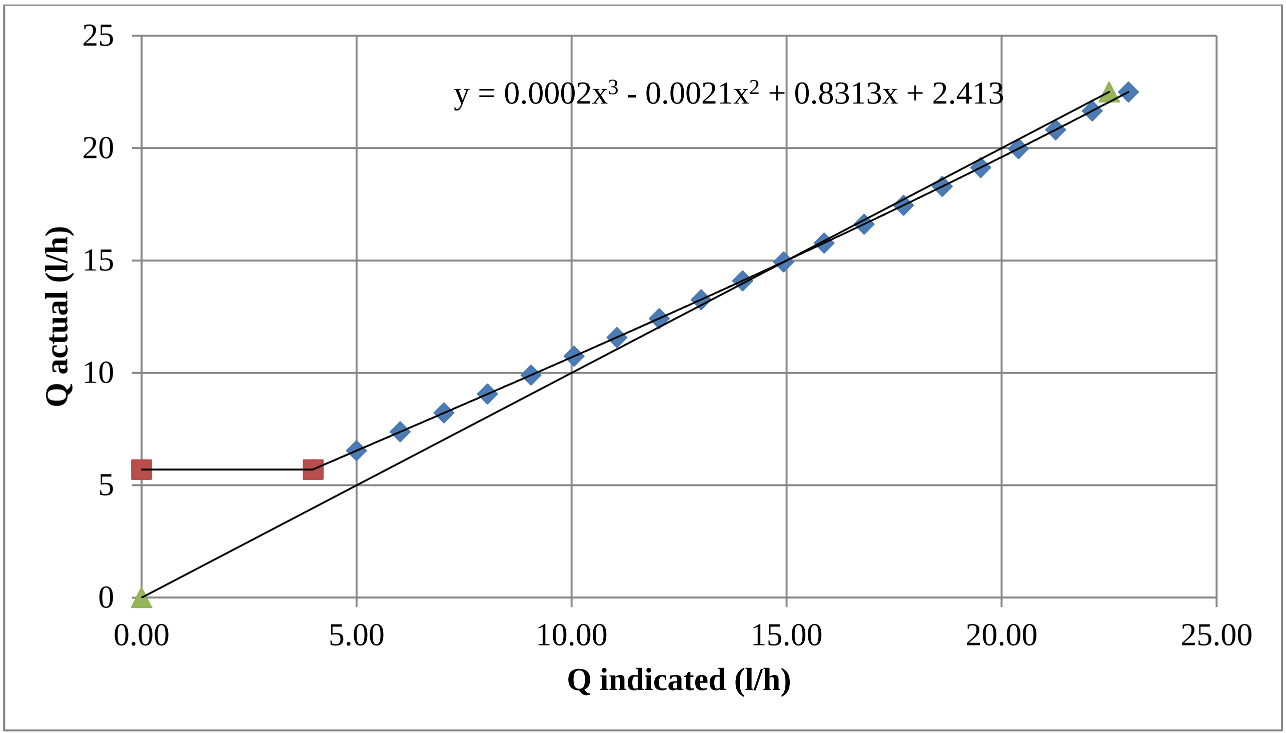

Figure 3.2: Indicated flow rate conversion curve, for a 15mm Class C positive displacement meter

Table 3.6 describes the coefficients used to convert indicated flow rates to actual flow rates.

Table 3.6: Estimated coefficients for Equation 3.2

Meter information					Coefficient			
Manufacturer	Type	Size (mm)	Class	Q_p (m^3/h)	a	b	c	d
1	Positive displacement	15	C	1.5	2.00E-04	-0.0021	0.8313	2.413
1	Positive displacement	20	C	2.5	6.00E-05	-0.0013	0.8314	4.0219
1	Positive displacement	25	C	3.5	3.00E-05	-0.0008	0.8614	4.7482
1	Multi-jet	15	C	1.5	2.00E-04	-0.0017	0.8429	2.2345
1	Multi-jet	20	C	2.5	8.00E-05	-0.0026	0.8665	3.7278
1	Multi-jet	25	C	3.5	3.00E-05	-0.0014	0.869	4.872
2	Multi-jet	15	B	1.5	9.00E-07	-1.00E-04	0.9751	0.8156
2	Multi-jet	20	C	2.5	5.00E-05	-1.00E-03	0.8431	3.7243
3	Multi-jet	15	B	1.5	1.00E-06	-2.00E-04	0.9771	0.7724
3	Multi-jet	15	C	1.5	2.00E-04	-0.0013	0.8251	2.3956
3	Multi-jet	20	B	2.5	3.00E-07	-9.00E-05	0.9811	1.136
3	Multi-jet	20	C	2.5	4.00E-05	-5.00E-04	0.8587	3.262
4	Multi-jet	15	B	1.5	9.00E-07	-1.00E-04	0.9751	0.8156
4	Multi-jet	20	B	2.5	3.00E-07	-7.00E-05	0.9753	1.3579

3.4 Results and discussion

In this section the characteristics of meters found in Cape Town and Mangaung are first described. This is followed by discussion and comparison of the incidence and flow rate distribution of on-site leaks respectively.

3.4.1 Cape Town meters investigated

Figures 3.3 and 3.4 show the proportion of meter manufacturing dates and registered volumes of the 405 Cape Town meters included in this study. It was found that 90% of the meters were less than 2 years old and 79% of the meters had a registered volume of less than 1000 kl.

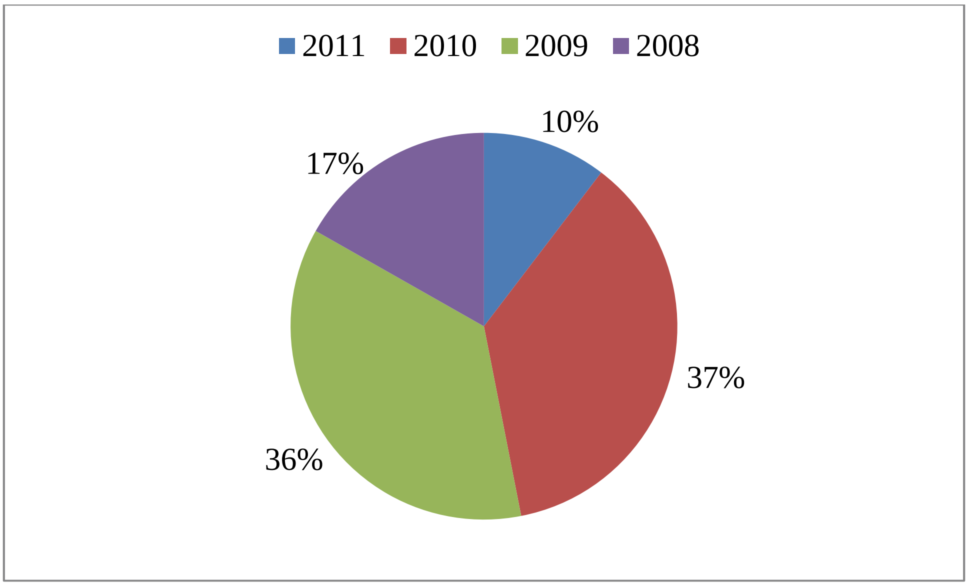

Figure 3.3: Distribution of Cape Town of meter manufacturing dates

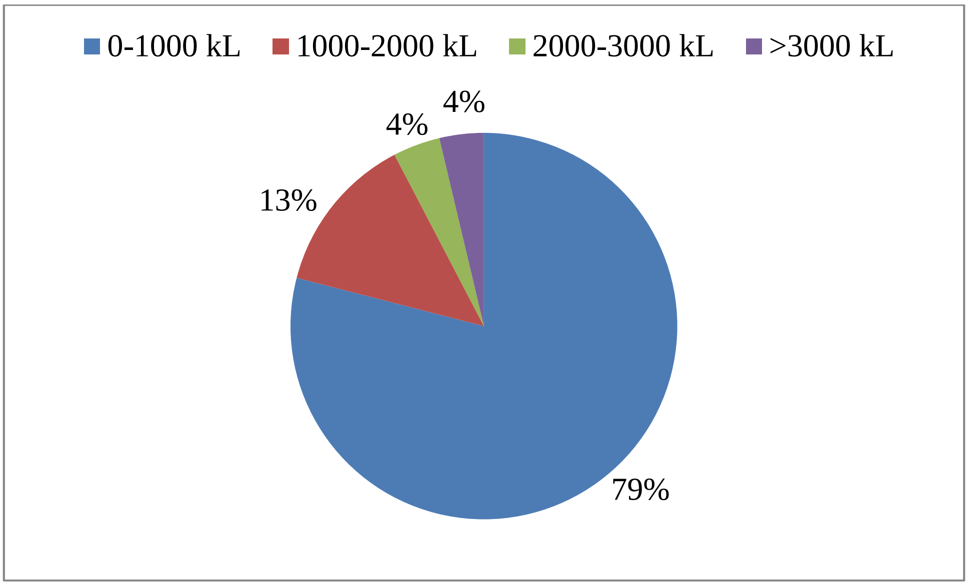

Figure 3.4: Distribution of registered volumes on Cape Town meters

The distribution of meter manufacturer, type, permanent flow rate and class encountered in Cape Town are shown graphically in Figures 3.5, 3.6, 3.7 and 3.8 respectively. The figures show that:

- Manufacturer 1 dominated the market, representing 79% of the meters studied.
- 58% of the meters were multi-jet and 41% of meters positive displacement type meters.
- Most of the meter sizes were found to be 15 mm (39%), followed by 20 mm (37%) and 25 mm (3%).
- 92% of the meters were Class C and only 5% Class B.

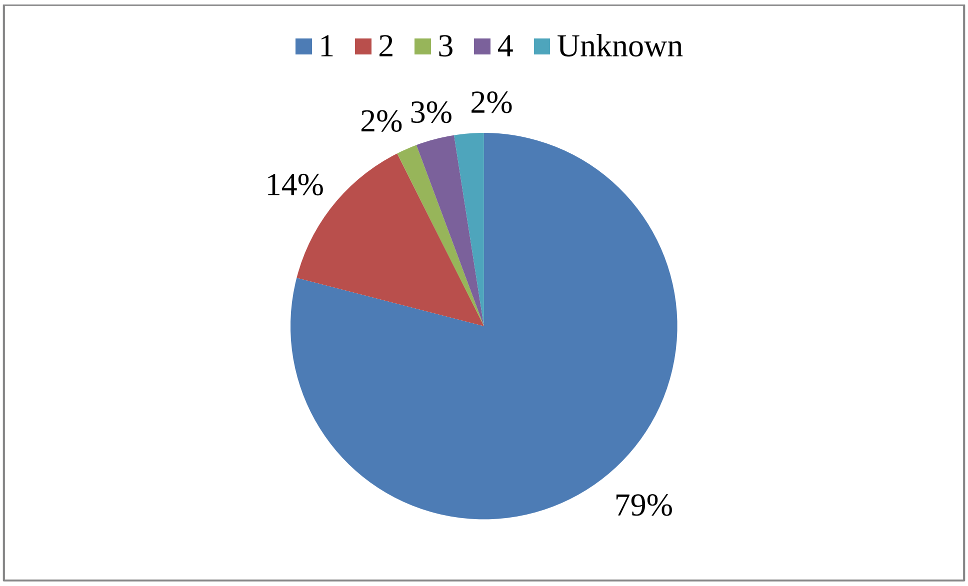

Figure 3.5: Proportion of manufacturer's encountered in Cape Town

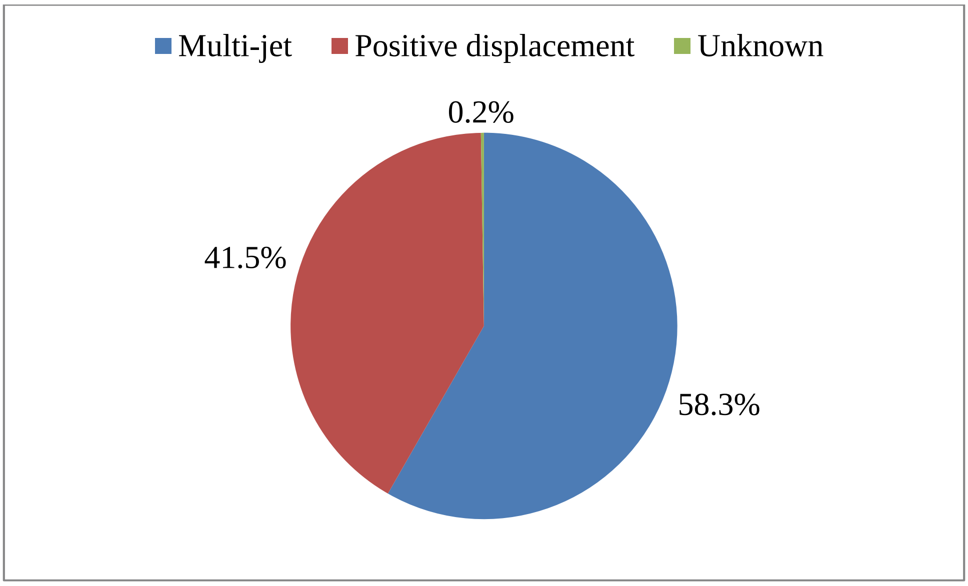

Figure 3.6: Proportion of meter types encountered in Cape Town

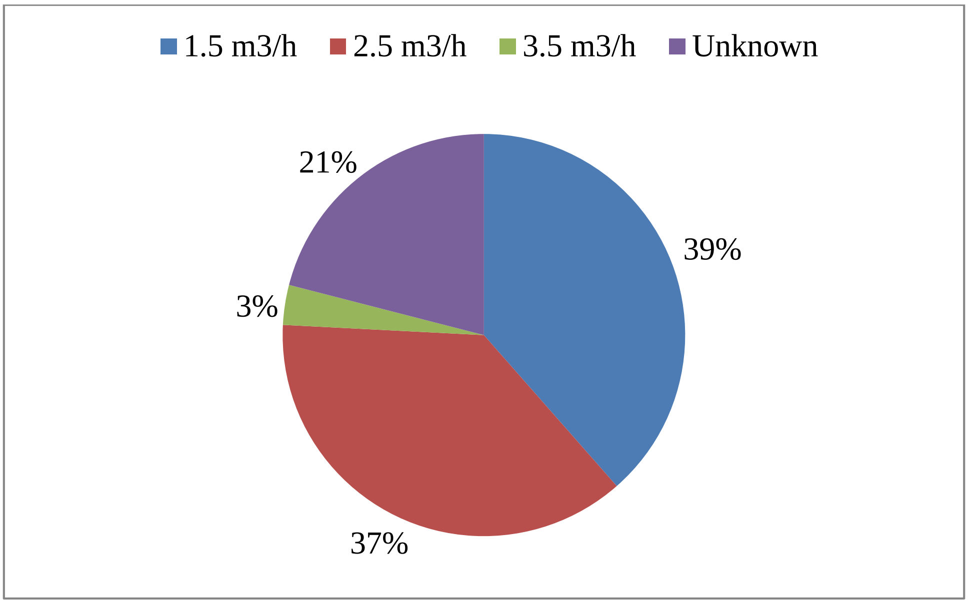

Figure 3.7: Proportion of meter permanent flow rates encountered in Cape Town

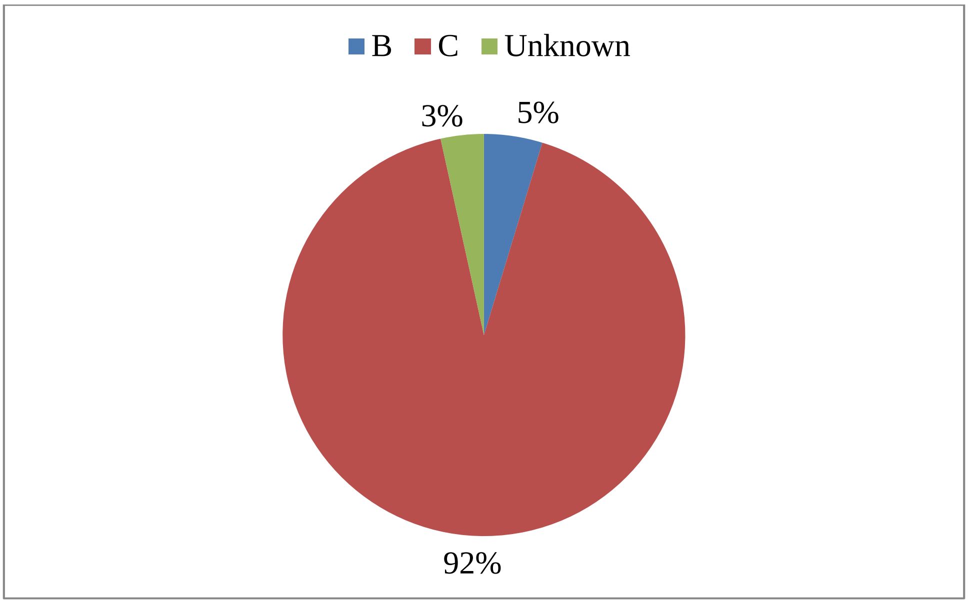

Figure 3.8: Proportion of meter classes encountered in Cape Town

3.4.2 Mangaung meters investigated

In Mangaung a total 166 meters were investigated. All the meters encountered in Mangaung were positive displacement meters (except for one multi-jet meter) from Manufacturer 1 with permanent flow rates of 1.5 m^3/h. A quarter of the meters were Class B and the remainder Class C. A total 33% of the meters were installed in 2011, 30% in 2010, 14% in 2009 and

23% in 2008. Finally, 88% of the meters had a registered volume of less than 1000 kl, 8% between 1000 and 2000 kl, 2% between 2000 and 3000 kl and 1% greater than 3000 kl.

3.4.3 Incidence of on-site leakage

3.4.3.1 Cape Town

A total of 405 properties were investigated in Cape Town with three of these removed from the data set due to inconsistencies in the data (as described earlier). A total of 16.4% of the 402 properties were found to have measurable on-site leakage. However, a large differences between suburbs were observed with Langa having the highest occurrence of 42.3% and Mowbray the lowest of 3.8%. On-site leakage incidence by suburb is given in Table 3.7 and shown graphically in Figure 3.9.

Table 3.7: Incidence of on-site leakage in suburbs of Cape Town

Suburb	**Number of properties**	**Number of leaks**	**% Leaks**
Langa	26	11	42.3
Salt River	30	10	33.3
Woodstock	25	6	24.0
Rosebank	17	3	17.6
Newlands	29	5	17.2
Pinelands	29	5	17.2
Mandela Park	29	5	17.2
Observatory	27	4	14.8
Claremont	29	4	13.8
Thornton	30	4	13.3
Lakeside	27	3	11.1
Camps Bay	27	2	7.4
Tokai	29	2	6.9
Green Point	22	1	4.5
Mowbray	26	1	3.8
Sum	402	66	16.4

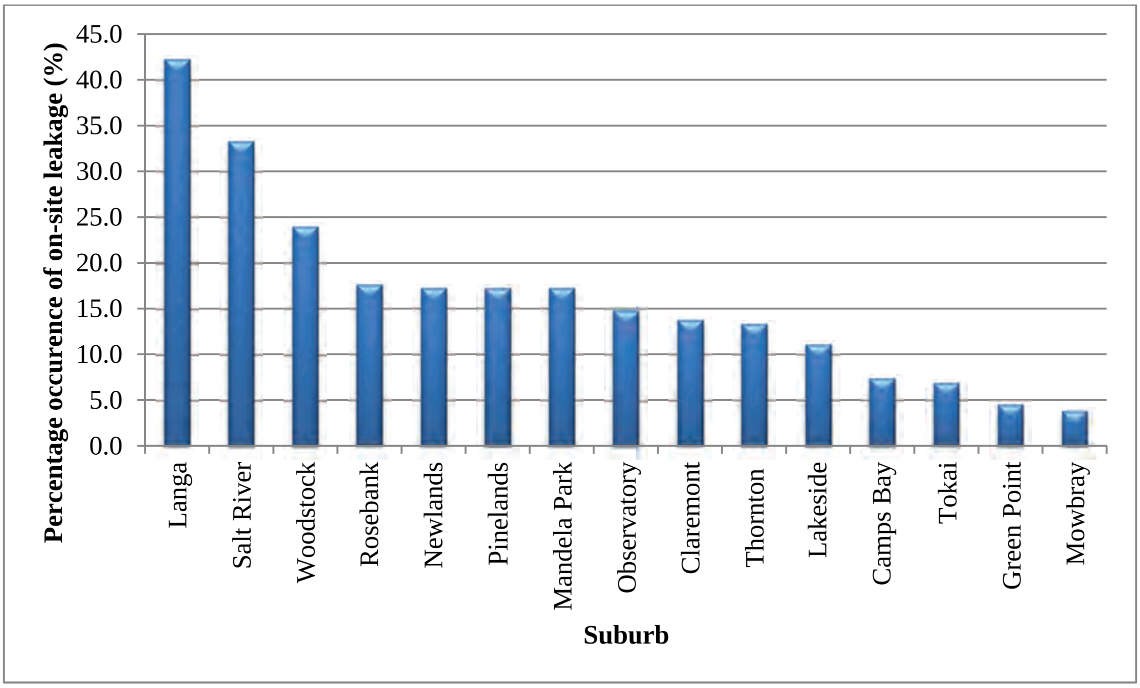

Figure 3.9: Incidence of on-site leakage in suburbs of Cape Town

3.4.3.2 Mangaung

In Mangaung, a total of 167 properties were investigated with one property was removed from the data set due to suspected consumption. It was found that 28.3% the remaining properties had measureable on-site leaks. The suburb of Freedom Square had the highest occurrence of on-site leakages of 61.5% with Motlatla and Vista Park having the lowest of 3.3%. On-site leakage incidence by suburb is given in Table 3.8 and shown graphically in Figure 3.10.

Table 3.8: Incidence of on-site leakage found in suburbs of Mangaung

Suburb	Number of properties	Number of leaks	% Leaks
Botshabelo G	30	14	46.7
Mandela View	25	3	12.0
Vista Park	30	1	3.3
Brandwag	25	12	48.0
Freedom Square	26	16	61.5
Motlatla	30	1	3.3
Sum	166	47	28.3

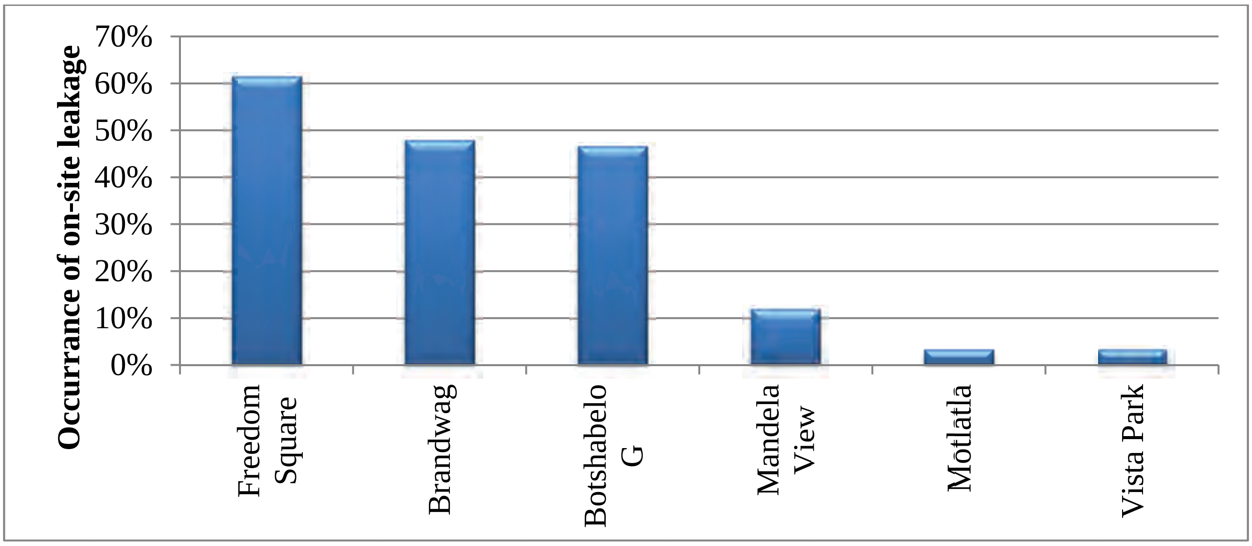

Figure 3.10: Incidence of on-site leakage in suburbs of Mangaung

3.4.3.3 Discussion

The incidence of on-site leakage in suburbs of Cape Town (17.1%) and Mangaung (28.3%) were found to be considerably lower than the 64% found in Johannesburg. The reasons for such a large variation in on-site leakage incidence are not immediately clear. However, However, when these results are compared to other studies, it is clear that a large variation in the incidence of on-site leakage can occur.

Figure 3.11 compares the incidence of on-site leakage in medium and high income areas of South Africa with those of low income areas in South Africa and international studies. It is clear that the incidence of on-site leakage in low income areas is generally very high. International studies generally indicate a low incidence of on-site leakage, with the notable exception of Mayer et al. (1999), who found an on-site leakage incidence in various areas of the USA that is comparable with the Johannesburg finding.

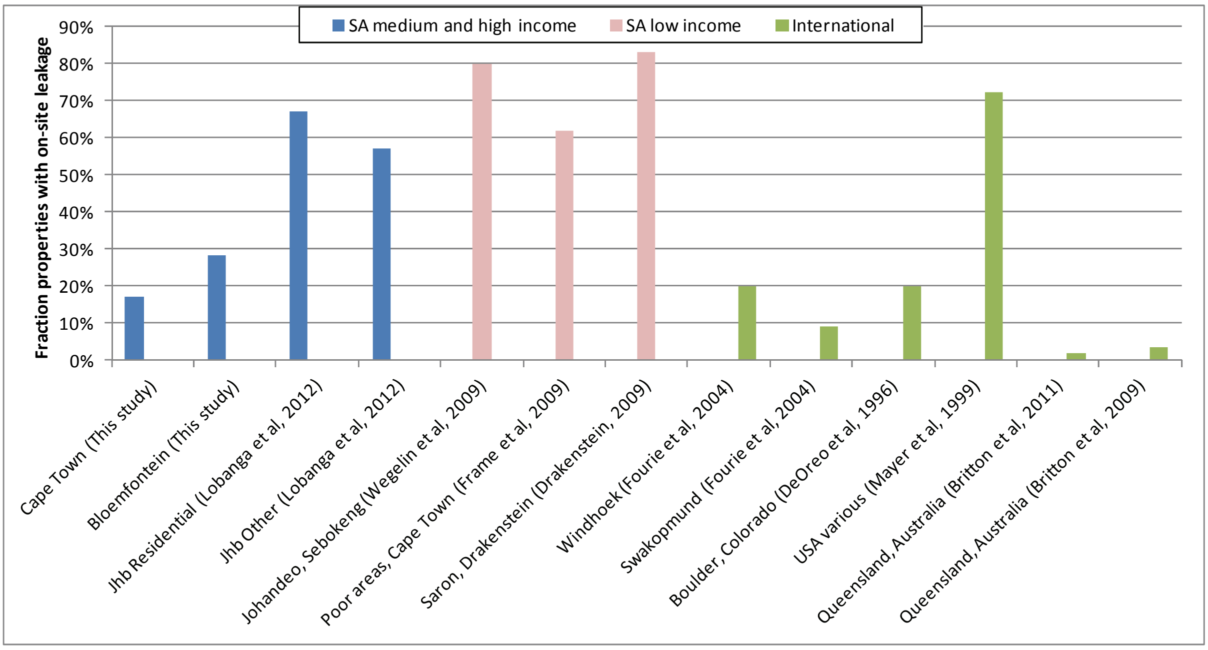

Figure 3.11: Comparison of on-site leakage incidence studies

3.4.4 Distribution of on-site leakage

The statistical parameters of the leakage rates found in Cape Town and Mangaung are given in Table 3.9 with the findings of the Johannesburg study. When considering leaking properties only, the average on-site leakage rates for Cape Town and Mangaung were 21.2 and 39.1 l/h respectively. This is in the same order size as the Johannesburg residential properties (23.4 l/h), but significantly lower than other (bulk domestic and non-domestic) properties in Johannesburg, which had an average 69.6 l/h. In all cases the median leakage rate is significantly lower than the average, showing that the distributions of the leakage rates are skewed towards lower values.

The minimum on-site leakage rate was limited by the lowest starting flow rate of the meters used, and thus has an identical values of 5.7 l/h. Interestingly, the maximum on-site leakage rates determined are similar, varying between 411 and 458 l/h.

When both leaking and non-leaking properties are considered, the monthly loss rates of residential properties in Cape Town, Mangaung and Johannesburg are 2.6, 8 and 11 kl per month per property.

Table 3.9: Descriptive statistics of on-site leakage data corrected for meter error

Description	**Cape Town Residential**	**Mangaung Residential**	**Johannesburg Residential**	**Johannesburg Other**
No of properties investigated	402	166	128	54
No. of properties with leaks	69	47	86	31
On-site leakage incidence	17.1%	28.3%	67%	57%
Properties with on-site leakage				
Mean leakage rate (l/h)	21.2	39.1	23.4	69.6
Median leakage rate (l/h)	10.0	20.0	8.6	30.7
Minimum leakage rate (l/h)	5.7	5.7	5.7	5.7
Maximum leakage rate (l/h)	449	411	411	458
All properties (with and without on-site leakage)				
Mean leakage rate (l/h)	3.6	11.1	15.7	40.0
Ave monthly losses (kl)	2.6	8	11	29

The distribution of residential on-site leakage rates in Cape Town, Mangaung and Johannesburg are compared in Figure 3.12, and the cumulative distributions compared in Figure 3.13. In all three cases the highest occurrence of leakage flow rates occurs between 5 and 10 l/h which are around the starting flow rate of the meter. The trends are similar with the frequency of leakage reducing steeply with increasing flow rate. Following the trend to the left, it seems likely that many properties have on-site leakage below the starting flow rate of the meter, which is thus not picked up.

Figure 3.13 shows that it is found that almost 90% of the leakage flow rates in Cape Town is below 20 l/h, compared to and 50% for Mangaung and 80% in Johannesburg. While Mangaung has a lower incidence of on-site leakage, it has larger leakage flow rates.

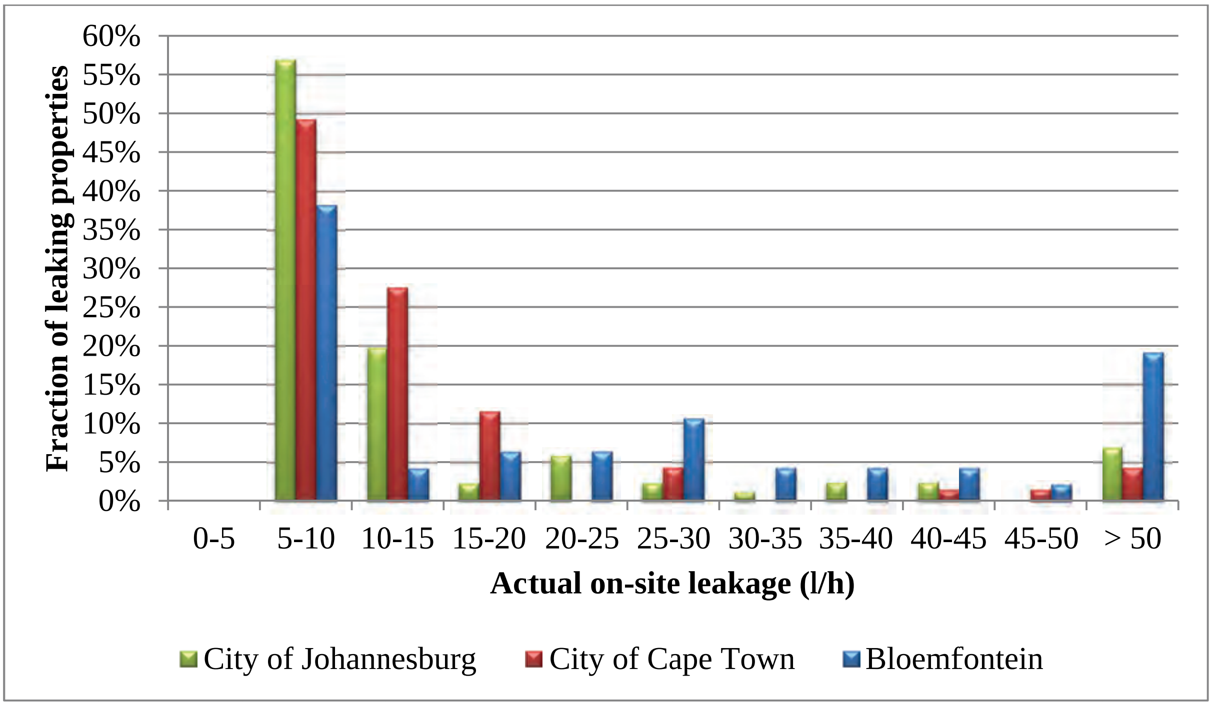

Figure 3.12: Histogram of on-site leakage flow rates measured on leaking properties corrected for meter error

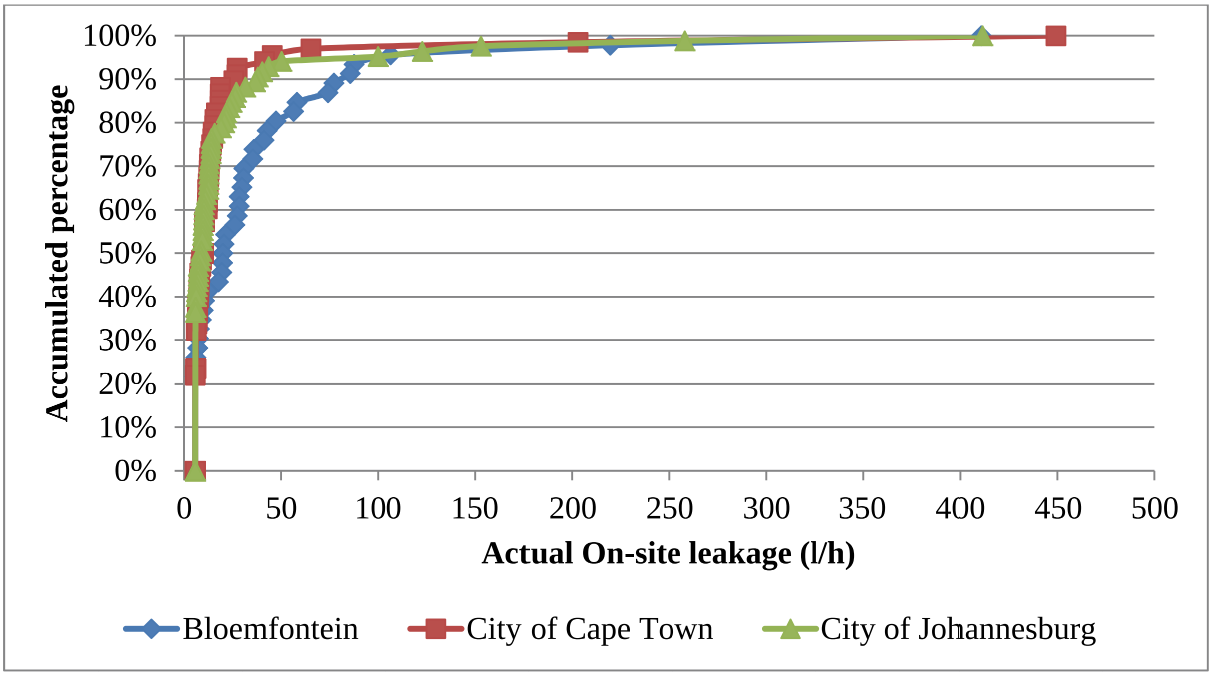

Figure 3.13: Cumulative frequency distribution of measurable on-site leakages found on leaking properties corrected for meter error

In Figure 3.14 the average leakage rate of properties with on-site leakage from various studies is compared. It shows that Johannesburg Other (bulk domestic and non-domestic) have the highest average leakage rates of all the studies, followed by Mangaung.

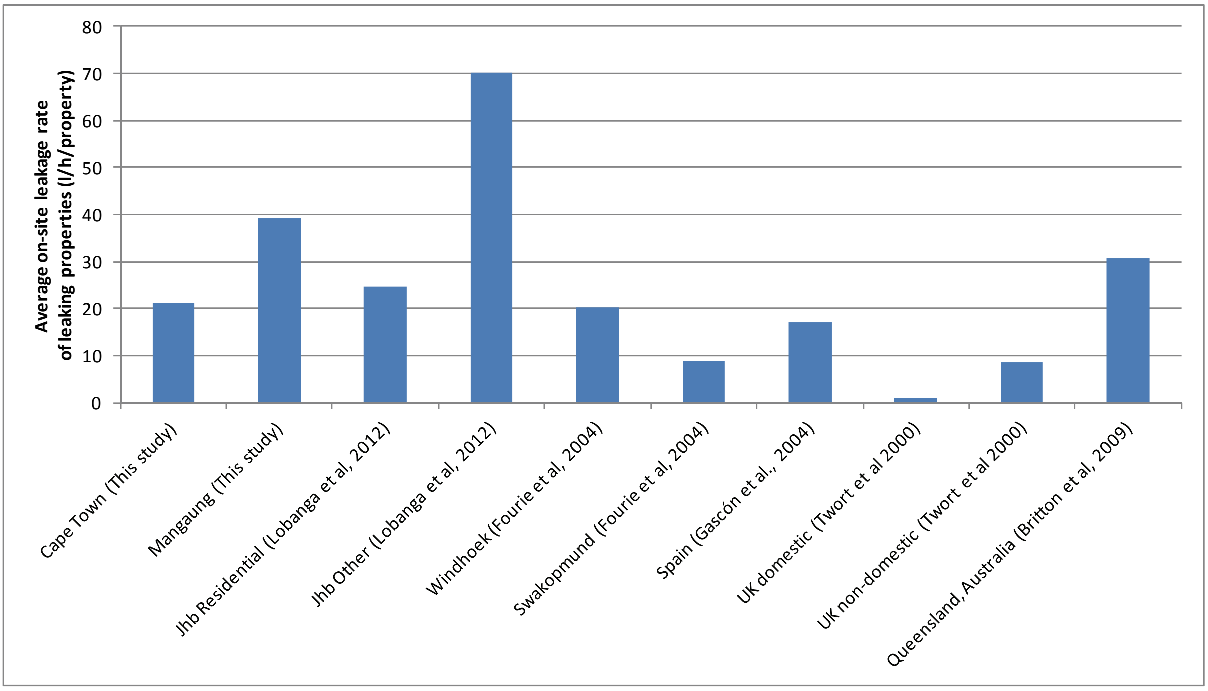

Figure 3.14: Comparison of the leakage rates of properties with on-site leakage

3.4.5 Contribution of on-site leakage to apparent loss

By summing up the metered and actual volume of consumption of each leaking property, the apparent loss due to on-site leakage can be calculated. It was found that in Cape Town, 13.1% (2.8 l/h/leaking property) of the on-site leakage is unmetered for new meters, while in Mangaung this number is 2.7% (1.1 l/h/leaking property). The reason Mangaung has such a low fraction is that its leakage rates were higher and thus less in the low accuracy range of the meters.

The Johannesburg study found that the average under registration of on-site leakage for all ‘Residential’ and ‘Other’ properties was 1.7 and 4.6 ℓ/h, respectively, which is equivalent to an under-registration of 10% of the on-site leakage.

It should be stressed that the findings of these studies exclude leakage that occurred at flow rates below the starting flow rates of the meters, which varies between 5.7 and 20 l/h (See Table 3.4), and thus can be considered as conservative.

As a general rule it seems reasonable to assume that 10 to 15% of measured on-site leakage is under-registered due to meter under-registration. The higher end of this scale is recommended for the following reasons:

- Registered or measured on-site leakage excludes the meter under-registration error. A given error based on the actual leakage, will thus be higher when estimated as a percentage of the registered leakage.
- The on-site leakage values obtained in this study exclude any leakage flow rate below the starting flow rate of the meter. Since the fraction of properties increases with decreasing leakage rate down to the starting flow rate, it is likely that a significant proportion of the properties where no leakage was measured, did have leaks below the starting flow rate of the meters.

It is thus recommended that 15% of on-site leakage measured with relatively new meters is allocated to apparent losses.

4 METER DATABASE ANALYSES

4.1 Introduction

There have been a number of meter testing methods and variations of each method used and described in literature to estimate the error of a water meter installed in the field. The consumer's meter is either removed from the field and tested in the laboratory or is tested in-situ in the field. Both of these methods can become very expensive and time consuming exercises and as a result restricted to small sample sizes that may not appropriately represent the meter population.

The above drawbacks of meter testing stated above makes the possible use of meter databases to estimate meter error an attractive option. The benefit of meter database analysis is that it makes use of a very large quantity of data that is already available in the municipalities meter reading database.

The following list the objectives of this study:

- Estimate metering error based on meter age and volume. This was done for 15 mm positive displacement meters.
- Estimate meter replacement rates.

4.2 Data

4.2.1 Introduction

Two databases were used in this part of the study:

- The meter replacement database collected from the eThekwini Water and Sanitation (EWS). The database included 158 409 domestic and non-domestic consumers that had their meter replaced at least once between June 2004 and February 2011.
- The National Water Demand Archive (Van Zyl & Geustyn 2006), last updated in 2009. The archive contains water demand data for approximately 1.5 million stands in four metros (Johannesburg, Tshwane, Ekurhuleni and Cape Town) and other 151 cities or towns.

The eThekwini database proved to be an excellent resource due to the consistency and accuracy of its data. eThekwini's metering policy is to read every meter on a monthly basis. This means very few readings are estimated, and consistent and reliable results could be obtained from the data. This allowed for the apparent losses of 15 mm positive displacement meters to be estimated by comparing the consumptions for the years before and after replacement for a large number of users.

The same analysis was done on the water demand archive data, but this was not effective since the archive did not include the same level of detail on the water meters, and it was clear that in many cases meters are not read every month and that readings are often estimated. Of the approximately 1.5 million active consumers in the Archive, less than 16 000 meter replacements qualified for further analyses. This is a small number compared to the more than 150 000 meter replacements in the eThekwini database. As a result, meter errors were not investigated using the Archive, although it was useful in estimating the replacement rate of meters.

The National Water Demand Archive is discussed in detail in Van Zyl and Geustyn (2006), and thus only the eThekwini database is described here.

4.2.2 eThekwini meter database

The meter replacement database provided by the eThekwini Water and Sanitation unit has the required minimum fields to perform an analysis for meter error, as shown in Table 3.1.

The EThekwini Water and Sanitation unit has a policy that all their consumer meters in their supply area are read on a monthly basis (Scruton, 2011). Therefore, meter readings are not often estimated.

Table 4.1: Data fields found in meter replacement database

Field name	**Description**
CONN_NO	Connection number
USAGE_TYPE	Domestic user, Flats, Commercial, Industrial, Education etc.
TYPE	Standard meter connection, Cap n Tap, Water dispenser etc.
CON_SIZE	Connection size
METER_SIZE	Nominal bore diameter of the meter
PROPERTKEY	Property key
STR_NUM	Street number
STR_NAME	Street name
SUBURB	Suburb

Field name	**Description**
TOWN	Town
CONSUMER	Consumer
DATE_INSTL	Installation date of first meter
M_YYYYMMDD	Meter number and date the meter was read
C_YYYYMMDD	Monthly consumption in kl/day and date it was read
Date of (1^{st}) Meter Change	Date of first meter change
No. of Meter Changes	Number of meter changes since first installation date

The database includes meters that have been replaced due to a number of reasons:

- Meter stopped.
- Meter dial damaged or unreadable.
- Replacement due to replacement policy.
- Meter replaced and the connection moved from inside consumer property to the outside boundary.
- Meter removed for testing due to consumer complaint for various billing issue queries.

Unfortunately the database did not include the actual meter readings, and thus the total volume through the meter had to be estimated. This was done by multiplying the registered consumption of one year after replacement by the age of the meter.

4.3 Methodology

4.3.1 Introduction

This section describes the processes used for data cleaning, the stratification of meter data and computing meter error.

The database includes many meters that have been replaced due to meter failure and have zero consumption monthly data before or after replacement. This data was removed from the database to ensure that the results reflect meter deterioration and are not biased by meters stopping completely.

The data in the database was cleaned and stratified into homogeneous groups according to factors that affect the accuracy of a meter, so that the data could be used to estimate meter error as a function of age and registered volume.

The meter error of each replaced meter in the database is computed by subtracting the registered consumption before and after the replacement of the consumer's meter. A period of 12 months of registered consumption before and after replacement was used to account for seasonal variation in consumption.

Due to the large number of data points required to reduce variability and the impact of erroneous data, only the 15mm positive displacement meters for domestic users could be analyzed in this study.

4.3.2 Data cleaning

It was important for accurate results that the meter records include at least the following fields:

- Meter information i.e. manufacturer, type, size, class
- Consumer information i.e. user type, location
- Installation date of the replaced meter (to allow its age to be calculated)
- Installation date of the new meter
- At least 12 months of monthly billed consumption data before and after the installation date of the new meter.

If any one of the above fields is missing, it is not possible to use meter database analysis as a method of estimating meter error. Thus a data cleaning procedure removed meters from the database based on the following rules:

- Meters without 12 months of consumption data before and after replacement. This is required to comply with the 12 months consumption before and after rule to ensure that seasonal variations in consumption do not bias the results.
- Meters that has been replaced more than once. This was done as some of the meters were replaced within 12 months of the latest replacement.
- Meters with any zero consumption months the year before and after replacement.
- Meters that did not have installation dates.

4.3.3 Stratifying meter data

One of the important features of analyzing meter inaccuracy is to stratify meters into homogenous groups according to factors that affect the meter's accuracy and to track trends in the data.

The consumer meters were stratified according to manufacturer, meter type, meter size, connection size, age, registered volume and type of consumer. Age groups of 5 year increments and 1000 kl increments were chosen for the age and registered volume groups respectively. The meter accuracy is analyzed for all the meters in their respective groups for the whole eThekwini municipal supply area and again for each town.

It is important to separate meter groups into different towns as they each have their own characteristic network pressure, system pipe burst frequencies and consumption patterns which affect a meter's accuracy:

- Towns with a high network pressure will experience a higher occurrence of on-site leakages with higher flow rates compared to areas with lower network pressures.
- Pipe burst frequency in an area increases the chance of sediment such as sand particles to enter the consumer meters and reduce the efficiency of their sensors. Therefore, it is intuitively expected that meters will degrade faster in areas with high pipe burst frequencies opposed to areas with lower pipe burst frequencies.
- Consumers in different towns will have different consumption patterns according to the characteristics of their plumbing and financial standing.

It is assumed that over a large sample of meters (greater than 1000), that on average the network pressures, pipe burst frequencies and consumption patterns fluctuate around a fixed average.

4.3.4 Calculating meter error

When testing a water meter, the meter error is calculated by subtracting the indicated volume (V_i) of a meter from the actual volume (V_a) passing through the meter and dividing the difference by the actual volume. The fraction is then converted to a percentage, with a negative value representing an under-registration and a positive value an over-registration of the actual volume.

In the database analysis, the indicated volume refers to the 12 months of consumption registered by the old meter before it is replaced. The actual volume refers to the actual 12 months of consumption registered before the old meter is replaced. As the actual consumption before the old meter is replaced is unknown, it is estimated by the new meter installed with 12 months of registered consumption after replacement. The following assumptions need to be made and are discussed and verified in the next section:

- The actual consumption one year before and after replacement is equal when viewed over a large number of meters replaced at random times.
- The new meter is assumed to have negligible error compared to the replaced meter.

4.4 Analyzing factors that may affect meter error

4.4.1 Introduction

The biggest concern of the reliability of using database analysis to estimate meter error is that it assumes that the actual consumption between any two consecutive years are equal over a large sample of consumers. The validity of this assumption depends on the impact of climate variations and local factors such as demand management programmes, consumer behaviour, metering accuracy and the selling price of water on consumption patterns. The main objective of this section is to check the validity of this assumption. It is assumed in this analysis that new meters have negligible error.

4.4.2 Change in consumer annual consumption

There is a clear seasonal variation in consumption visible in Figure 4.1 and an increase in total domestic consumption each year. In conjunction with the increase total consumption, there is an increase in total domestic connections each year, see Figure 4.2.

In order to determine the impact of factors that may change consumer demand, the average consumption per connection needs to be analyzed. In Figure 4.3, there is a clear decrease in average consumption per domestic connection. This decrease could be due to two reasons:

1. The individual consumers are actually using less water due to demand management programmes.
2. A significant fraction of new consumers have low consumption, for instance low income consumers.

The first reason has an impact on the meter error calculation, whereas the second reason does not. The second reason may imply a decrease in the consumption per connection in Figure 4.3, but is in fact not a true decrease or change in the consumer's consumption for the supply area.

The weighting of the impact of the above reasons on Figure 4.3 is unknown. Figure 4.1 shows no clear evidence of change in consumer demand due to climate or local factors, which implies that the 2nd reason is most likely the reason for the change in annual average consumption per domestic connection.

Therefore, with the aid of Figure 4.1, 4.2 and 4.3, it is concluded that the actual consumption between any two consecutive years are equal is an acceptable assumption.

The law of averages also assist with the validity of this assumption over a large sample, in that it is probable that there will be an equal amount of individual consumers having an increased demand as there are having a decreased demand between any two consecutive years.

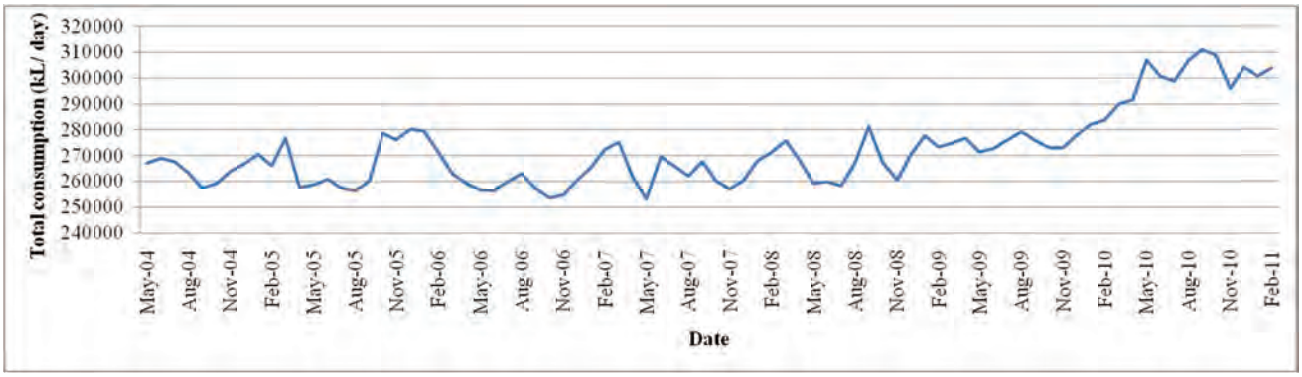

Figure 4.1: Total consumption of domestic consumers in the eThekwini supply area

(Scruton, 2011)

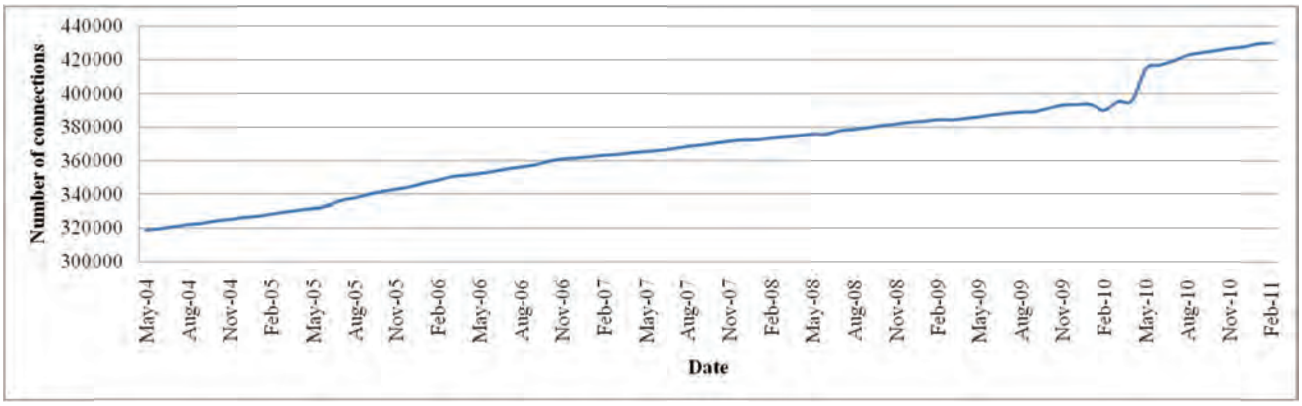

Figure 4.2: Total number of domestic connections in the eThekwini supply area (Scruton, 2011)

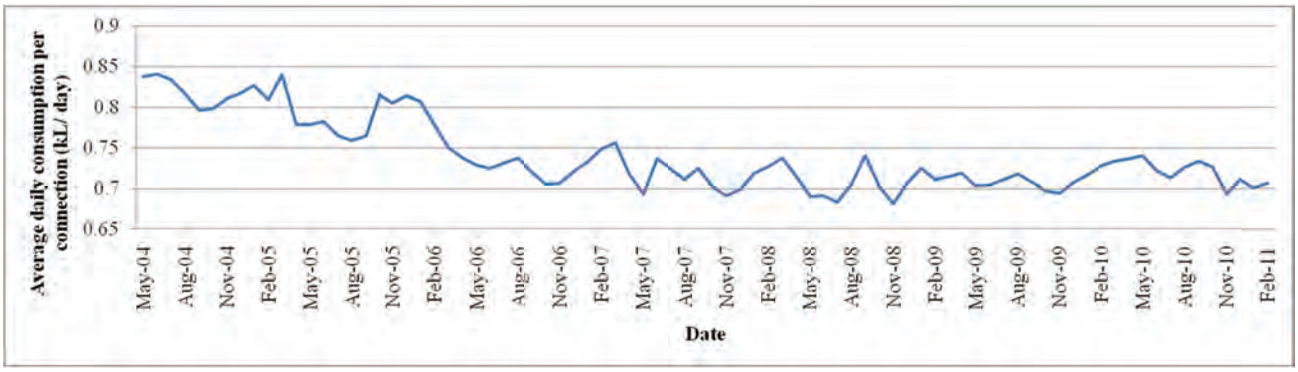

Figure 4.3: Average daily consumption per domestic connection in the eThekwini supply area (Scruton, 2011)

4.5 Results and discussion

4.5.1 Introduction

This section provides the results of the analysis of the data derived from the meter database by:

- Describing the composition of the data after the data cleaning and stratifying processes.
- Presenting the results of the analysis for meter error versus age and registered volume for the municipality as a whole.
- The results of the analysis are then discussed within the relevant sections.

4.5.2 Data

Of the 142 858 positive displacement 15mm domestic meters of the same manufacturer represented 90.2% of the total connections in the EWS meter replacement database. Only 65 067 survived the data cleaning process, see Table 4.2.

Table 4.2: Description of data cleaning

Data	**Number**	**Percentage (%)**
15mm positive displacement domestic meters with standard connection	142 858	100
Meters without installation dates	32	0.0
Meters replaced more than once in sample period	26553	18.6
Meters with replacement dates younger than 20050606 and older than 20100328	33262	23.3
Meters less than a year old	785	0.5
Meters older than 40 years	12	0.0
Meters with zero consumption months before or after replacement	17147	12.0
Meters surviving data cleaning process	65067	45.5

The meters were categorized into both 5 year increments for age and 1000 kl increments for consumption volume registered. Table 4.3 depicts the number of meters in their respective age groups with their corresponding registered volume group, with cells in grey highlighting the highest number of meters in each age group.

Table 4.3: Meter age versus volume registered evaluation

	Number of meters								
Volume (ML)	**1 to 5 yrs**	**5 to 10 yrs**	**10 to 15 yrs**	**15 to 20 yrs**	**20 to 25 yrs**	**25to 30 yrs**	**30 to 35 yrs**	**35 to 40 yrs**	**Sum**
0 to 1	4983	7537	1073	190	16	2	1	1	13803
1 to 2	2065	7762	2470	876	73	20	12	7	13285
2 to 3	523	3965	2423	1704	119	66	18	14	8832
3 to 4	136	1789	1878	2141	174	114	47	27	6306
4 to 5	56	783	1347	2186	258	162	63	39	4894
5 to 6	21	336	854	2003	262	222	72	32	3802
6 to 7	10	184	571	1577	257	253	88	56	2996
7 to 8	7	99	339	1253	216	275	109	73	2371
8 to 9	3	62	238	955	162	241	106	85	1852
9 to 10	4	48	150	697	156	213	101	86	1455
10 to 11	1	32	105	456	103	182	84	87	1050
> 11	6	65	288	1254	359	774	647	1028	4421
Sum	7815	22662	11736	15292	2155	2524	1348	1535	65067

4.5.3 Meter error versus age

The descriptive statistics table (Table 4.4), frequency distribution diagram (Figure 4.4 and 4.5), cumulative frequencies diagram (Figure 4.6 and 4.7) show that: the data tends toward a central location, but is bounded to an under-registration of -100% and unbounded for over-registration. This behaviour of the data regarding the frequency distribution diagrams and cumulative frequency diagrams are evident in all the age groups (Appendix C and D respectively). The median as a result is the preferred measure of central location to that of mean.

Table 4.4: Descriptive statistics for meter error versus age

	Meter error (%)							
Statistic	**0 to 5 yrs**	**5 to 10 yrs**	**10 to 15 yrs**	**15 to 20 yrs**	**20 to 25 yrs**	**25 to 30 yrs**	**30 to 35 yrs**	**35 to 40 yrs**
Mean	25.05	20.21	13.27	8.00	2.76	-1.53	0.71	-1.21
Standard Error	1.84	1.00	2.01	0.96	1.53	0.84	1.50	1.04
Median	0.25	-3.85	-5.12	-7.86	-8.37	-8.16	-5.60	-7.17
Standard Deviation	162.78	151.29	217.95	118.80	70.90	41.98	55.20	40.63
Kurtosis	1004.32	2075.93	5824.42	1033.41	137.96	37.61	247.14	22.79
Skewness	24.59	32.19	68.84	25.70	9.27	4.46	12.19	3.42
Minimum	-99.11	-98.60	-99.76	-99.75	-96.89	-84.96	-94.75	-85.84
Maximum	8035.94	12114.98	19581.32	5807.14	1337.04	559.11	1301.28	404.18
Samples (number)	7815	22662	11736	15292	2155	2524	1348	1535

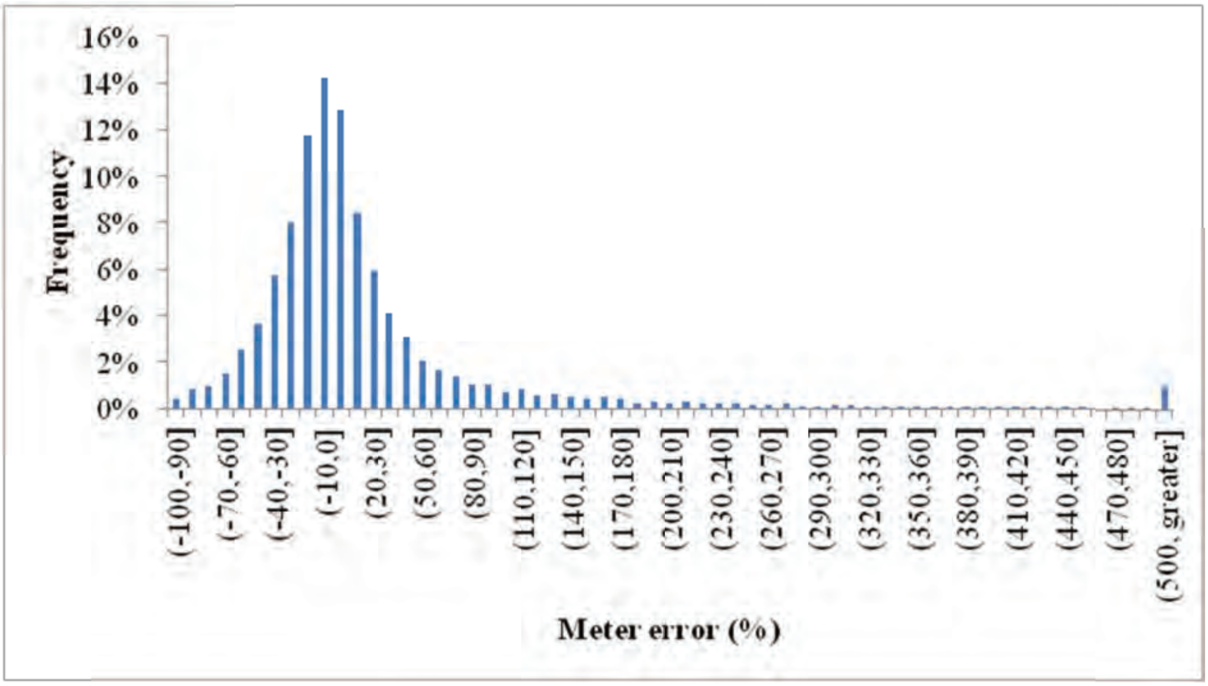

Figure 4.4: Frequency distribution diagram for the 1-5 meter age group

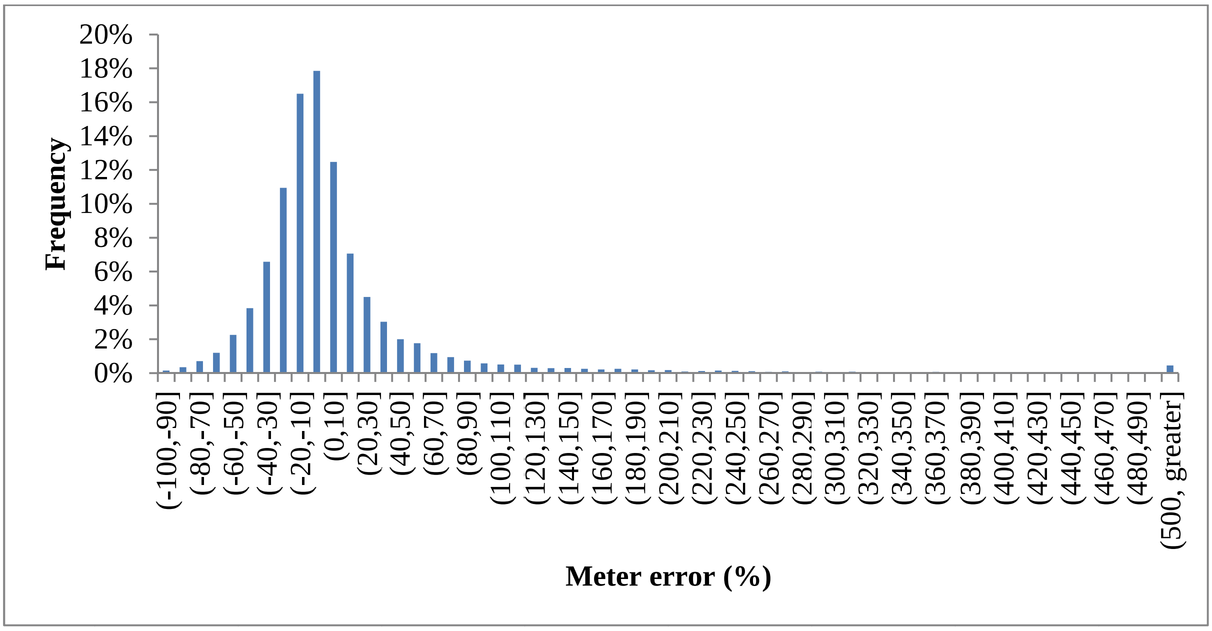

Figure 4.5: Frequency distribution diagram for the 15-20 meter age group

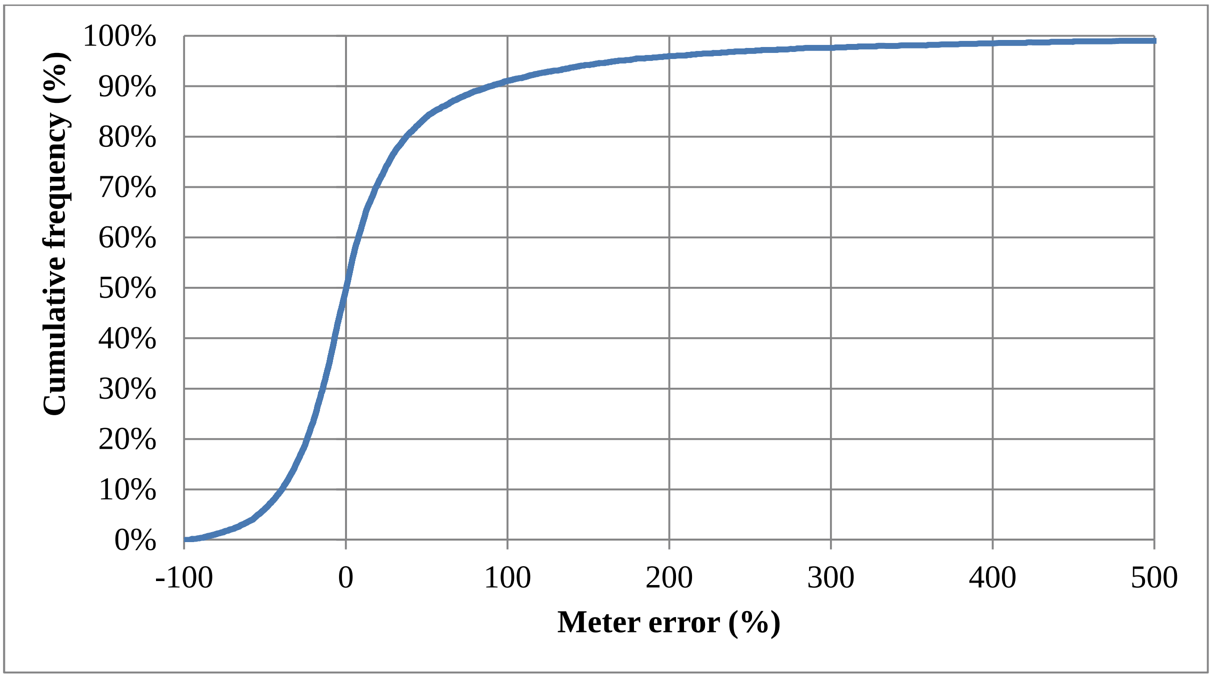

Figure 4.6: Cumulative frequency distribution diagram for the 1-5 meter age group

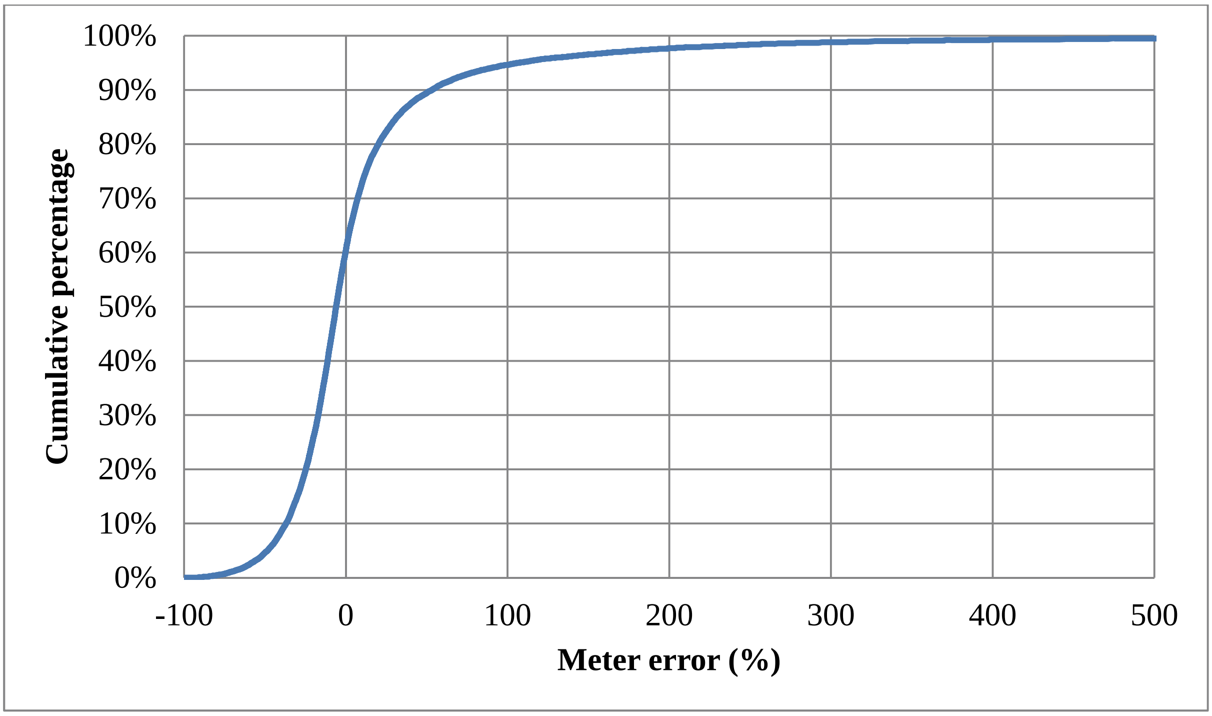

Figure 4.7: Cumulative frequency distribution diagram for the 15-20 meter age group

The median meter error in Table 4.4 was plotted against age in Figure 4.6. It can be seen that the data has a linear fit for meters younger than 25 years, with 0.36%-points deterioration in the meter's accuracy per year. The meters older than 25 years do not fit the linear trend, which could be due to the following reasons:

- These meters may be of better quality than the younger meters, which could be the reason why they stayed in service for so long.
- These meters could be generally on consumer properties that may be from a specific area that have low on-site leakages, consumption patterns skewed to high flow rates, low network pressures and low burst frequencies.
- In Table 4.3, it can be seen that these meters have fewer samples to that of the younger groups, with the 20 to 25 group being the exception.

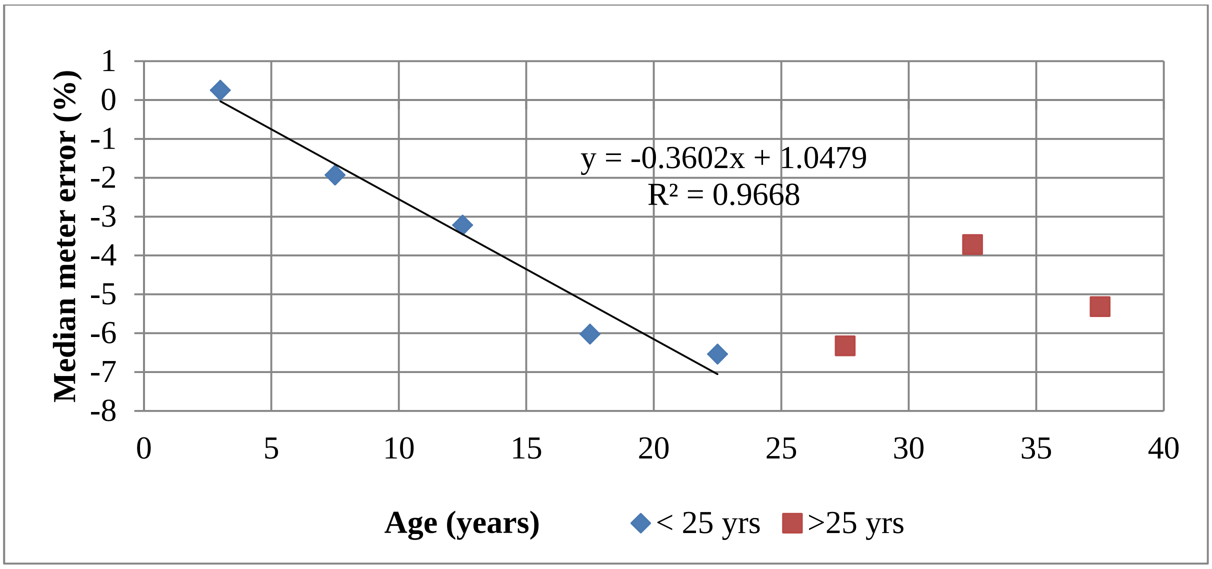

Figure 4.8: Median meter error versus age

4.5.4 Meter error versus registered volume

The descriptive statistics table (Table 4.5), frequency distribution diagram (Figure 4.9 and 4.10), cumulative frequencies diagram (Figure 4.11 and 4.12) show that, as with the meter age analysis: the data tends toward a central location and is bounded by an under-registration of -100% and unbounded for over-registration. This behaviour of the data regarding the frequency distribution diagrams and cumulative frequency diagrams are evident in all the registered volume groups (Appendix C and D respectively). The median as a result is the preferred measure of central location to that of mean.

Table 4.5: Descriptive statistics for meter error versus registered volume (uncorrected for new meter error)

	Meter error (%)										
Statistic	**0 to 1 ML**	**1 to 2 ML**	**2 to 3 ML**	**3 to 4 ML**	**4 to 5 ML**	**5 to 6 ML**	**6 to 7 ML**	**7 to 8 ML**	**8 to 9 ML**	**9 to 10 ML**	**10 to 11 ML**
Mean	54.4	19.6	8.5	4.8	4.5	-0.7	-1.7	-4.8	-4.8	-6.4	-6.2
Standard Error	1.9	1.4	0.8	0.8	4.1	0.9	1.0	0.8	1.0	1.0	1.3
Median	8.3	-1.3	-3.5	-4.5	-7.5	-7.1	-8.2	-8.7	-8.5	-9.7	-9.5
Standard Deviation	223.7	157.4	73.6	65.9	285.1	54.5	55.7	39.0	41.7	38.8	41.1
Kurtosis	914.5	1428.5	153.5	215.3	4547.0	270.8	189.1	32.0	57.0	33.3	64.3
Skewness	22.2	30.6	9.0	10.5	66.2	11.0	10.2	3.7	5.3	3.9	5.5
Minimum	-98.9	-98.3	-99.1	-96.6	-97.2	-96.2	-96.0	-98.6	-96.9	-93.7	-95.7
Maximum	12359.3	9518.8	1779.0	1909.4	19581.3	1697.8	1329.3	483.3	615.0	467.5	605.8
Samples (number)	13803	13285	8832	6306	4894	3802	2996	2371	1852	1455	1050

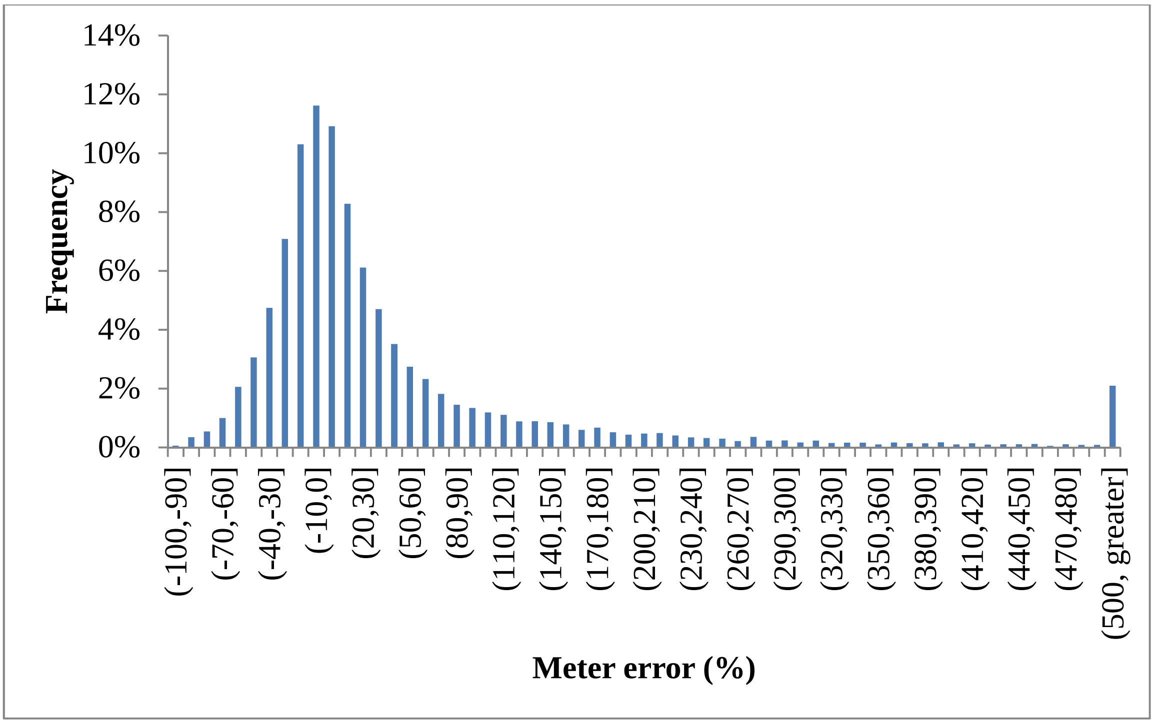

Figure 4.9: Frequency distribution diagram for 0-1000 kl meter registered volume group

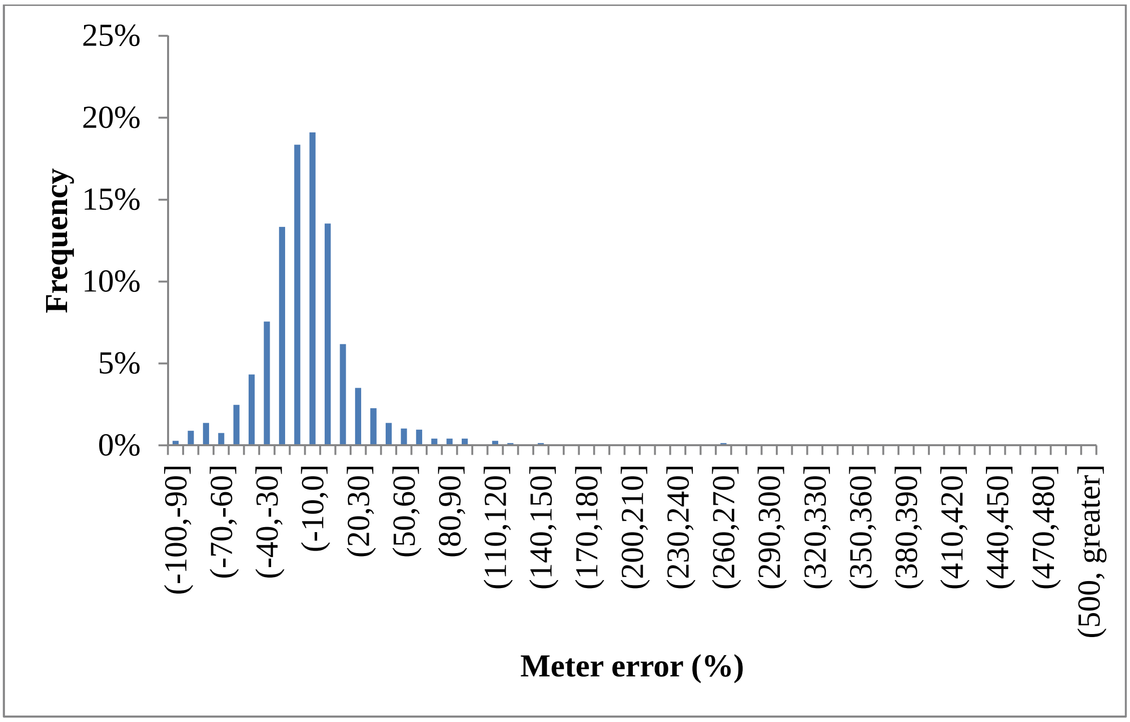

Figure 4.10: Frequency distribution diagram for 9 000-10 000 kl meter registered volume group

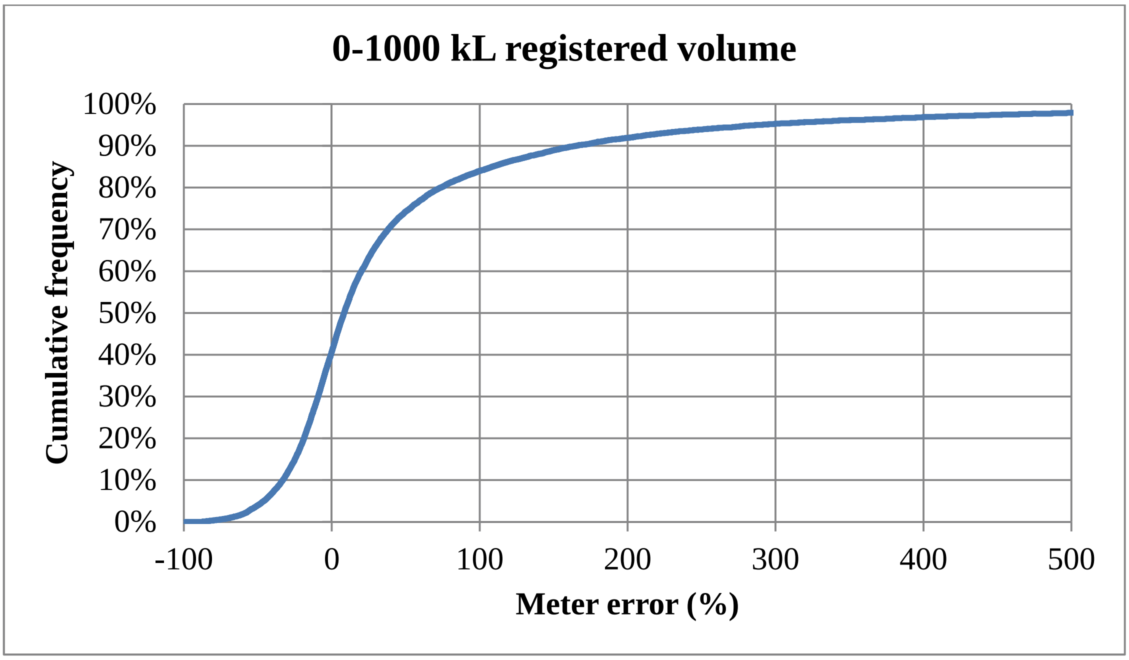

Figure 4.11: Cumulative frequency distribution diagram for 0-1000 kl meter registered volume group

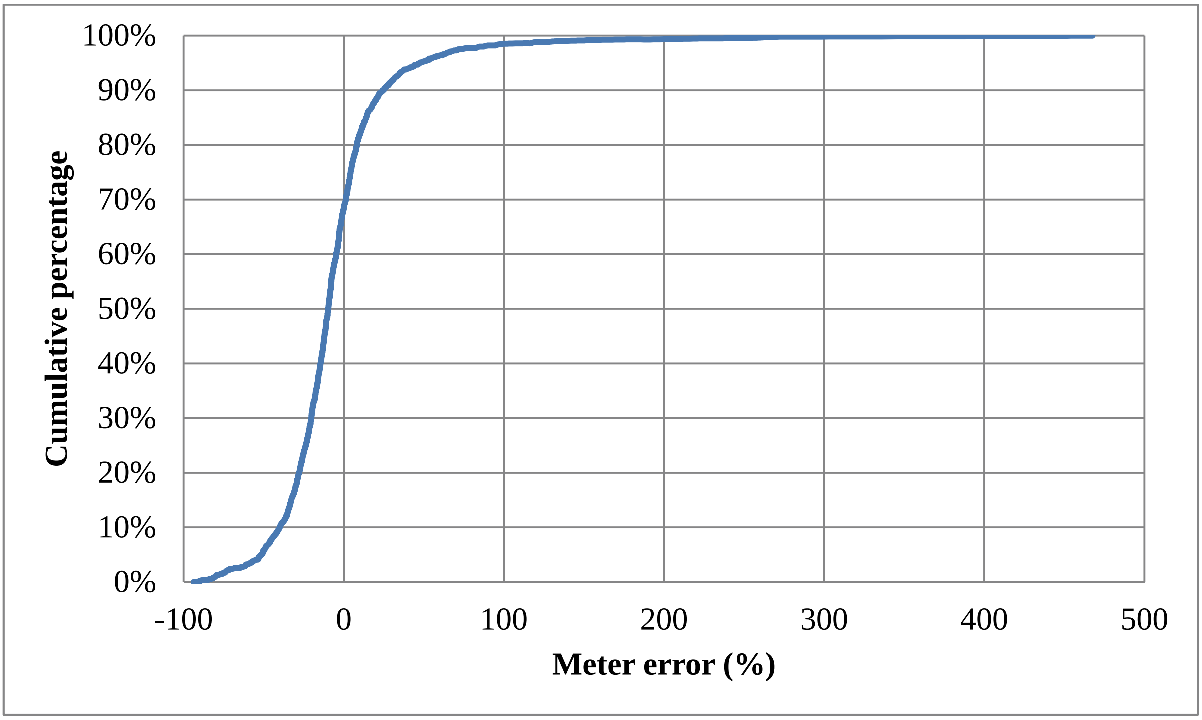

Figure 4.12: Cumulative frequency distribution diagram for 9000-10 000 kl meter registered volume group

The median meter error in Table 4.6 was plotted against registered volume in Figure 4.10. It can be seen that the data has a linear fit for meters with registered volumes greater than 1000 kl, with 0.9%-points deterioration in the meter's accuracy per 1000 kl registered. This value is in line with the deterioration rate

The meters with registered volumes less than 1000 kl do not fit the linear trend. This could be attributed to these meters being of poor quality from the meter supplier and over-registering in the field. Other unknown site conditions could play a part in these meters over-registering as well. The methodology of estimating the registered volume of these meters, already described in Section 4.2.3, may also play a considerable part. All the meters which have decreased their consumption the year after replacement get picked up with this method and results in meters with high over-registrations being pooled in this group. The over-registration therefore may be due to an actual change in consumption rather than a meter error.

The meters with registered volumes greater than 11 000 kl were not considered in the analysis, as they did not have the required 1000 data points.

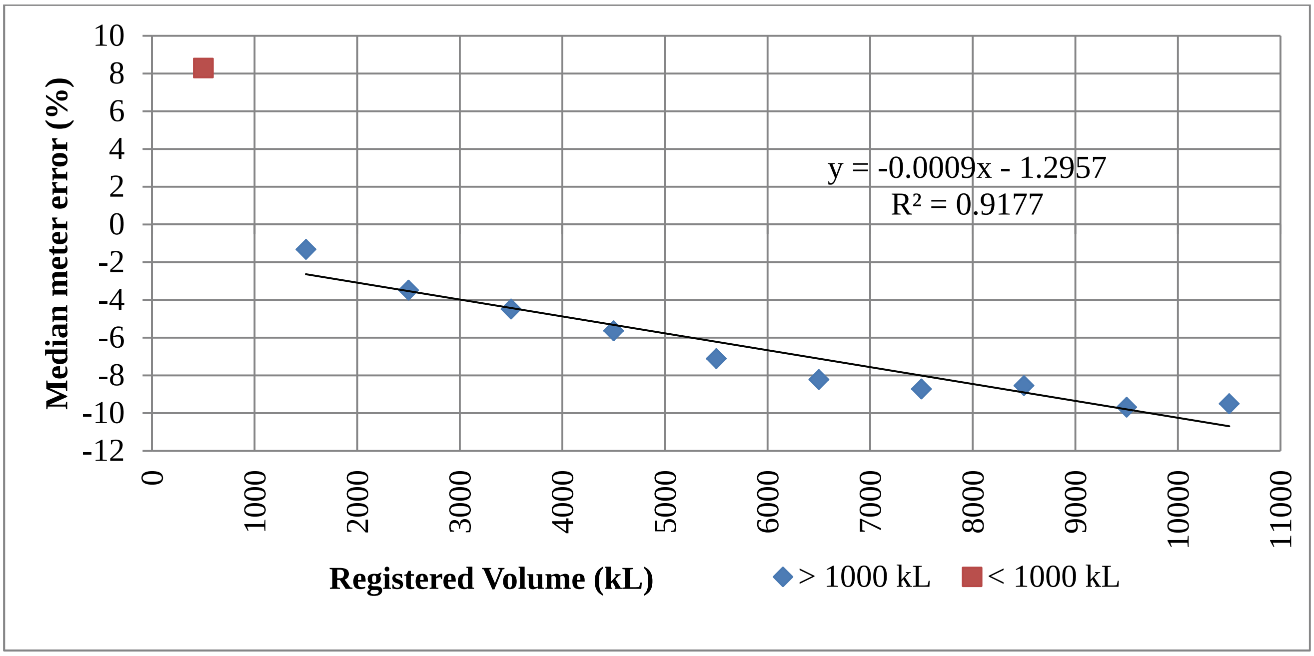

Figure 4.13: Median meter error versus registered volume

4.6 Meter age distribution

The National Water Demand Archive (Van Zyl & Geustyn, 2006) data allowed the age of meters in South Africa to be investigated. The Archive includes a value for the installation date of the meter, which was used as basis for the study. However, when the data was analysed it became clear that, while newer meter installation dates seem realistic, the data was clearly lacking for older meters.

The approach adopted in this study was thus to estimate the average replacement rate over the last three years of available data. Cities without any meter replacements, with less than 5 000 meter replacements or obvious erroneous or erratic data were excluded. The fraction of meters replaced in each of the remaining cities (or areas) is shown in Figure 4.14.

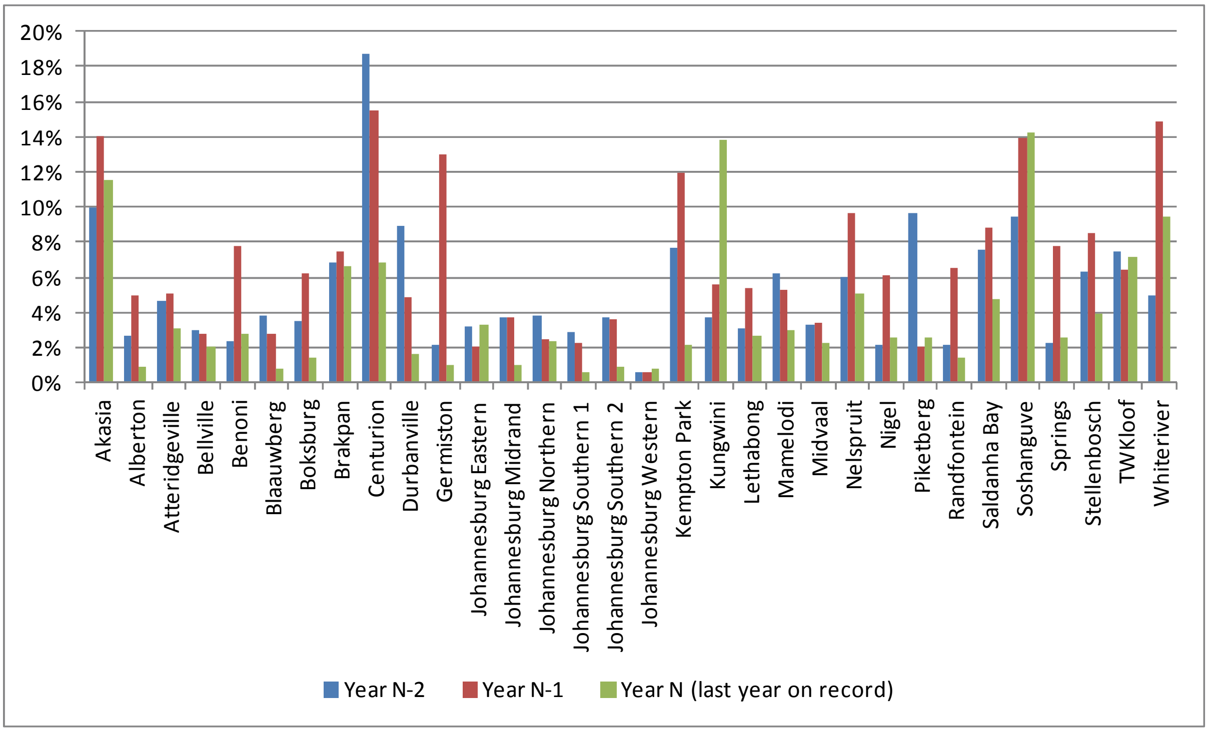

Figure 4.14: Fraction of meters replaced over the last three years of recorded data

The figure shows that meter replacement rates vary greatly between cities, but less so within different years for a given city. The mean replacement rates over the last three years on record are shown in Figure 4.15.

Figure 4.15: Mean meter meters replacement rate for selected cities.

The mean meter replacement rate, weighed by the number of records for each city, was found to be 5%. This implies that, on average, meters are replaced at an age of 20 years, and that the mean age of meters in the system can be estimated as 10 years.

4.7 Conclusion

A methodology was developed to use data recorded in a meter database to estimate meter error in this study. The main drawback was that a minimum of 1000 meter samples per age or volume group were required to obtain data that fits the expected linear trend of deterioration of the meter error curve. This meant that meter error for only the 15mm positive displacement meters could be estimated with this methodology, as they accounted for 90.2% of the 158 409 meter connections in the database. Data cleaning meant that 45.5% of the 90.2% could be used in the analysis.

This study showed that meter database analysis as an alternative method of quantifying meter error to that of meter testing, is both practical and a useful to understanding the performance of meters in the distribution network.

The meter error curves for both the age and registered volume groups showed remarkably good linear fits. The deterioration of meter error was 0.36%-points per year and 0.9%-points per 1000 kl registered for age and registered volume respectively. Volume showed a better relationship than age, but in estimating meter under-registration error age is a more practical measure.

Since the relationship between meter age and error is linear, the under-registration error of a whole area can be made by using the average age of the meter. In a simplified form, the percentage median error of a network can be calculated as 1-0.36 x the average meter age in years.

While this measure is based on 15 mm positive displacement metres in eThekwini data, and thus may not be equally valid for all areas, it provides the first and only known quantitative link between meter error and age. The equation also includes the impact of on-site leakage in the eThekwini area. It should be noted that the curve is based on the median error and not average error.

Data on meter replacement shows that on average meters in South Africa are being replaced at a rate of 5% per year. This means that on average meters are replaced every 20 years and that the average age of meters in South Africa is around 10 years. Based on Figure 4.8, the average meter under-registration error can be estimated as 2.6% excluding the error of new meters.

5 FLOW LOGGING OF DOMESTIC CONSUMER METERS

5.1 Introduction

The Average Weighted Error is calculated by multiplying the error curve of the meter by the flow rate distribution passing through it, which is weighted according to the volume of water used at each actual flow rate. This chapter investigates the consumption profile domestic properties in Cape Town, as well as the impact of unmetered flow reducers (UFRs) on the measured demand distribution.

The objective of this study was to:

- Test master meters to be used for flow logging in a laboratory at a number of selected flow rates.
- Log the consumption profile of domestic consumers using a master meter installed in-line with the consumer meter.
- Log the consumption profile of domestic consumers with a UFR fitted in-line with the master meter to determine its impact.

The study was performed on consumer meters in the City of Cape Town which commenced on 12 January 2012 and ended on 8 March 2012. There were many problems encountered in the field regarding consumers giving permission for logging of their meter as well as practical installation issues. In the end it was only possible to log 8 meters.

Only 15 mm positive displacement consumer meters were tested in the field as positive displacement master meters were used. Positive displacement meters measure packets of water when consumption occurs and pulses the flow, which changes the flow profile and may impact the accuracy of velocity meters.

Despite the small data set, some interesting observations are made by inspection of the consumption patterns and impacts of UFRs.

5.2 Methodology

5.2.1 Introduction

The same meter database used in the on-site leakage study (Chapter 3) was used to select properties. Properties were randomly selected in a spreadsheet to reduce bias error.

An experienced plumbing contractor was employed to carry out all flow logging of consumer meters in the field and notifying them of the test. A number of problems were encountered in the field relating to getting permission from consumers to allow for their meter to be logged, as well as practical problems. In the end only 8 meters were logged.

The master meters were tested in a laboratory under a number of flow rates to estimate its error curve. This was done to correct the flow rate data recorded by the data logger in the field to correct the data for meter error and estimate the actual consumption.

Data loggers with a 1 litre pulse output were used and 15 mm Class C positive displacement meters.

5.2.2 Laboratory testing of master meter

A total of fifteen Class C positive displacement master meters were tested at the manufacturer's laboratory at 7 flow rates of 5, 15, 22.5, 375, 750, 1500 and 2700 litres/hour. See Appendix E for individual meter error curves of each master meter tested in the laboratory. Table 5.1 tabulates the results of the meter error tested at each flow rate in the laboratory for each master meter and Figure 5.1 plots the average error curve from the lab tests.

Table 5.1: Meter error tested at each flow rate in the laboratory

Meter serial number	**Actual flow rate used for testing (l/h)**						
	2700	**1500**	**750**	**375**	**22.5**	**15**	**5**
DA11BA042035	0.07%	0.27%	0.65%	1.12%	1.24%	0.92%	-1.93%
DA11BA042036	0.04%	0.37%	0.78%	1.10%	1.64%	1.25%	-1.39%
DA11BA042037	0.07%	0.26%	0.64%	1.13%	1.56%	1.30%	-1.20%
DA11BA042038	0.16%	0.35%	0.83%	1.17%	1.61%	1.15%	-1.55%
DA11BA042039	0.01%	0.19%	0.70%	1.08%	1.37%	0.92%	-2.29%
DA11BA042040	0.10%	0.29%	0.65%	1.18%	1.41%	1.07%	-1.89%
DA11BA042041	0.11%	0.35%	0.86%	1.14%	1.63%	1.33%	-0.95%
DA11BA042042	0.12%	0.36%	0.72%	1.12%	1.46%	1.02%	-2.04%
DA11BA042043	0.03%	0.22%	0.79%	1.15%	1.50%	1.05%	-2.24%

Meter serial number	**Actual flow rate used for testing (l/h)**						
	2700	**1500**	**750**	**375**	**22.5**	**15**	**5**
DA11BA042044	0.14%	0.41%	0.93%	1.13%	1.5%	1.06%	-2.00%
DA11BA042045	0.24%	0.48%	1.00%	1.24%	1.46%	1.09%	-2.09%
DA11BA042046	0.13%	0.36%	0.76%	1.11%	1.39%	0.84%	-2.81%
DA11BA042047	0.17%	0.29%	0.79%	1.19%	1.63%	1.17%	-1.56%
DA11BA042048	-0.97%	-0.12%	0.51%	1.03%	1.37%	1.05%	-1.60%
DA11BA042049	-0.06%	0.27%	0.64%	1.01%	1.45%	1.18%	-1.41%
Average	0.02%	0.29%	0.75%	1.13%	1.48%	1.09%	-1.80%

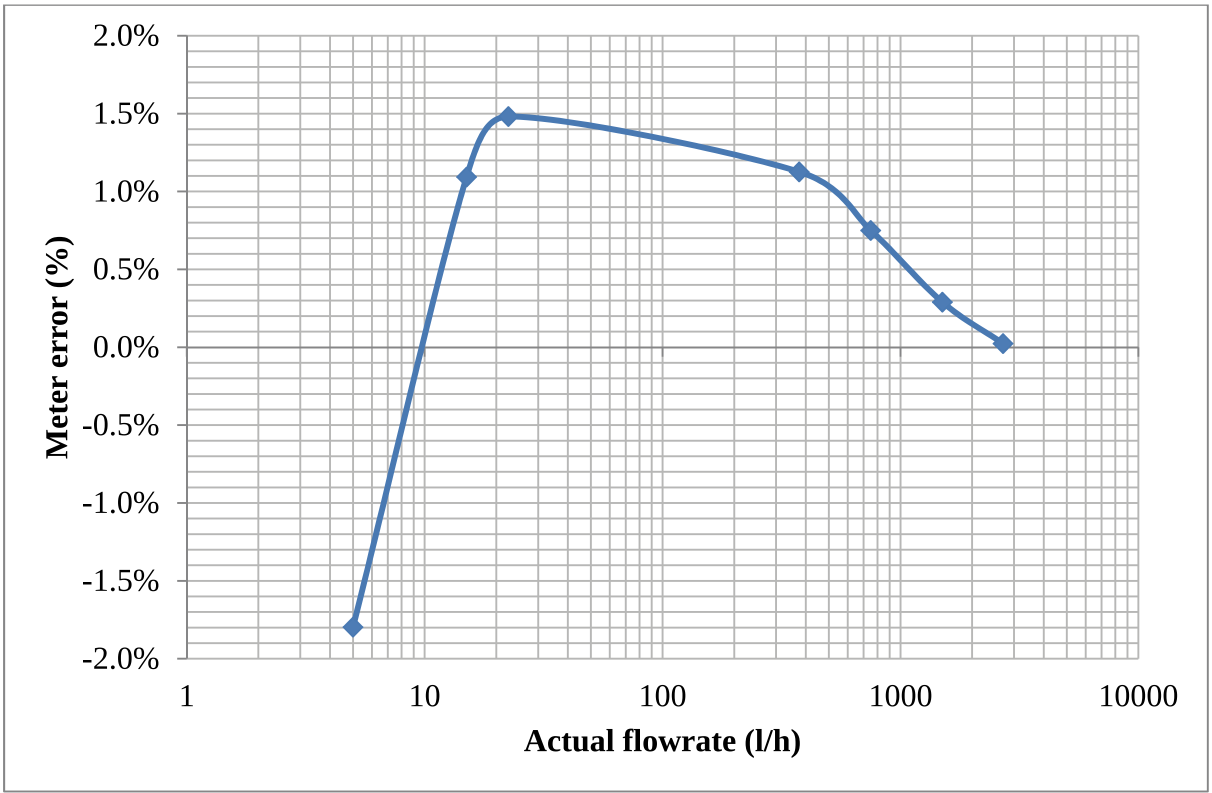

Figure 5.1: Average error curve of fifteen master meters tested in the laboratory

5.2.3 Procedure for flow logging meters and UFRs in the field

The following describes the procedure of testing consumer meters and UFRs in the field:

1. Select consumer meters
    a. Consumer meters were selected randomly from the Swift database described in Table 4.2.
2. Notify consumer

a. The consumer is made aware of the study by placing a letter in their mailbox about a week before the scheduled visit.
b. On the day of the visit, the consumer's door bell is rung, and if home, is kindly made aware of the scheduled test and asked for permission to access their meter for testing.

3. Testing the consumer meter
   a. The consumer's water supply is shut-off for a few minutes so that the master meter can be installed.
   b. The master meter with data logger inside a locked meter box is installed in-line with the consumer meter. The data logger is programmed to measure each 1 litre pulse of the meter's sensor.
   c. The consumer's water supply is then opened and the master meter is then left installed in-line with the consumer's meter for a minimum of a week.
   d. If given permission, a UFR is installed in-line with the master meter for a minimum of a week.

5.2.4 Master meter error

To correct the consumption patterns for error by the master meter, a function of the actual flow rate in terms of the indicated flow rate needs to be found. Firstly, using the error curve in Figure 5.1, the ratio Indicated Flow rate/Actual Flow rate is plotted against the Actual Flow rate to obtain a 3rd order polynomial in Figure 5.2.

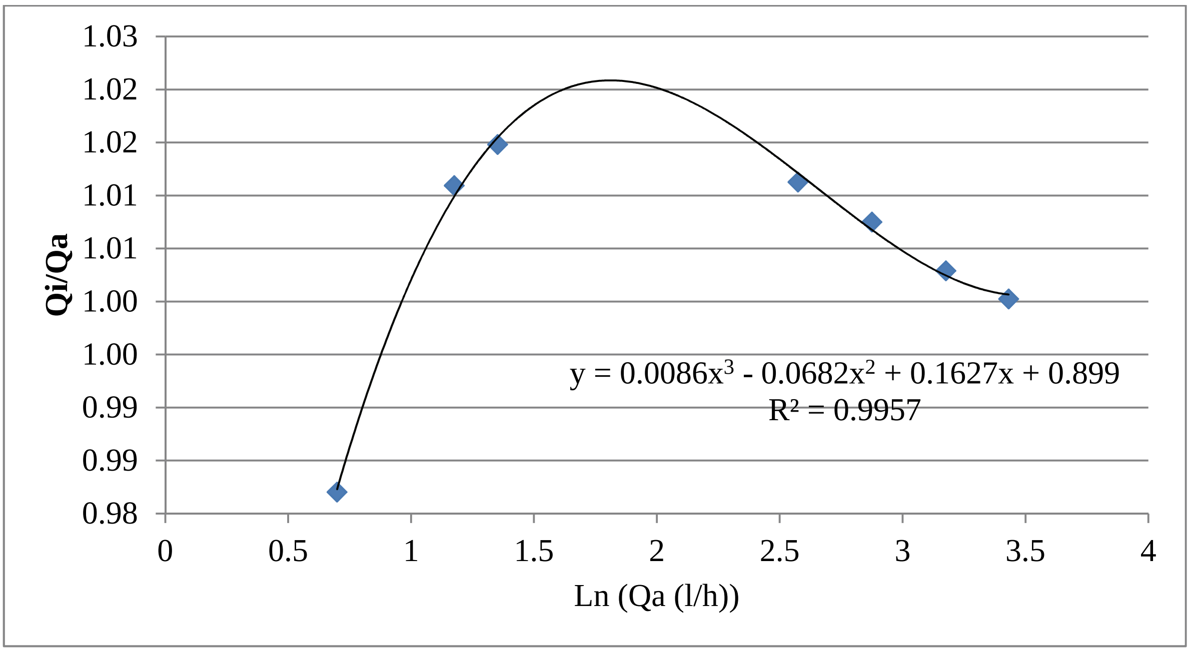

Figure 5.2: Ratio of Indicated and Actual Flow rate versus the Actual Flow rate

Using the 3rd order polynomial in Figure 5.2, a table of Indicated Flow rates and associated Actual Flow rates can be calculated. As this could not be plotted accurately with the regression formulae made available in Excel, the table was used with the aid of the VLOOKUP function to find associated actual flow rates for indicated flow rates. Any flow rates smaller than the starting indicated flow rate was assumed to be the actual starting flow rate.

The error of each master meter was calculated by summing all of the 1 litre pulse flow rates of the indicated flow rates and subtracting it from the sum of actual flow rates, then dividing the difference by the summed actual flow rates.

5.3 Results and discussion

5.3.1 Introduction

This section provides the results and analysis of the flow logging of domestic meters with and without UFRs by:

- Showing the consumption patterns with respect to fraction of time and fraction of volume.
- Comparing the consumption patterns in this study with one performed in Spain and South America.
- Comparing the consumption patterns of domestic consumers with and without UFRs installed in-line with their meter.

5.3.2 Domestic consumer consumption patterns

The results showed that 79.4% of the time the consumption was in the range 0-12 l/h (Table 5.2 and Figure 5.3), although this only accounts for 6.2% of the total volume consumed (Table 5.3 and Figure 5.4). A total of 75.0% of the volume consumed is at flow rates between 180-1500 l/h at 4.5% of the time. The histograms of individual properties are given in Appendixes F and G.

In Figure 5.5, the average consumption patterns in this study are compared with those found in Spain and South America (Arregui, Cabrera, Cobacho, & Garcia-Serra, 2006 a). The consumption pattern in Spain and South America were determined by logging 34 single households during the summer. The largest difference between the demand profiles is that in Spain and South America, 17% of the fraction of volume used is at 1500-3000 l/h compared to just 1% in Cape Town. Besides this factor, the demand flow rate distributions are remarkably similar.

Table 5.2: Fraction of time demand used by domestic consumers in Cape Town

Flow rate (l/h)	**Fraction of time (%)**					
	CL1	**CL3**	**LD1**	**LD3**	**LD4**	**Mean**
0-12	92.7	97.2	77.8	66.8	62.7	79.4
12-24	1.8	0.8	9.8	3.4	10.5	5.3
24-36	0.8	0.3	3.5	1.3	6.2	2.4
36-72	0.8	0.3	2.6	12.7	9.7	5.2
72-180	0.7	0.1	1.6	9.2	4.0	3.1
180-1500	3.2	1.3	4.7	6.4	7.0	4.5
1500-3000	0.0	0.0	0.0	0.1	0.0	0.0
> 3000	0.0	0.0	0.0	0.0	0.0	0.0

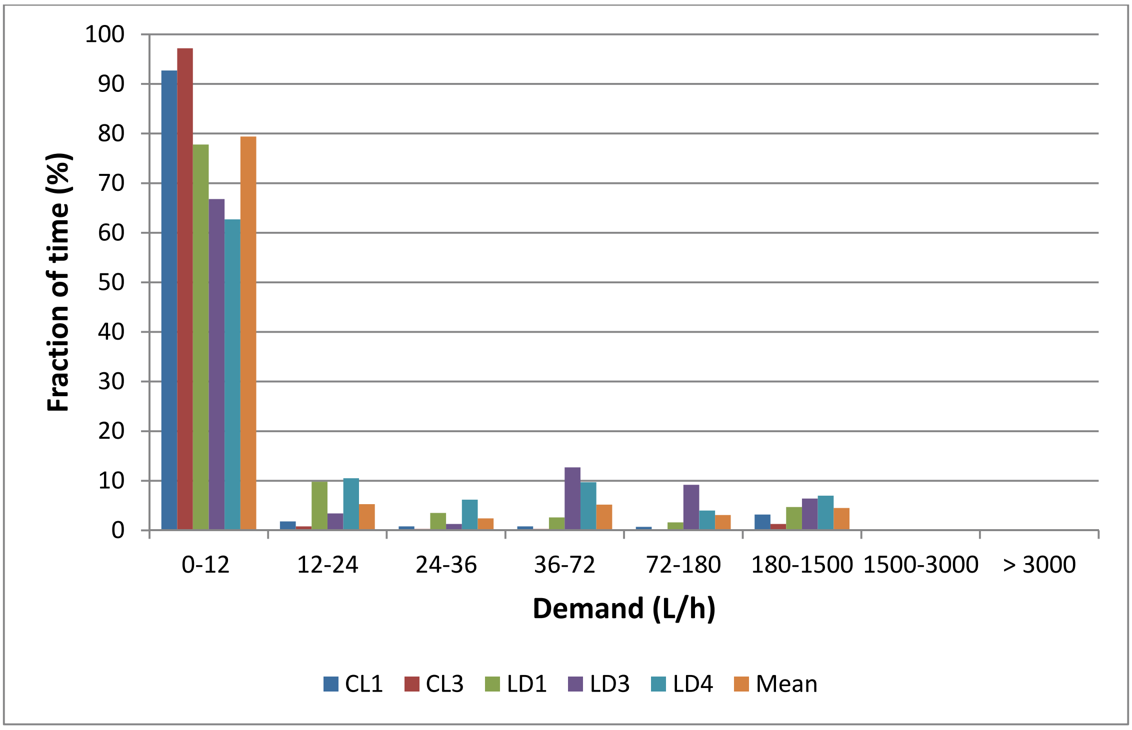

Figure 5.3: Fraction of time demand used of domestic consumers

Table 5.3: Fraction of volume used at each demand by domestic consumers in Cape Town

Flow rate (l/h)	**Fraction of volume (%)**					
	CL1	**CL3**	**LD1**	**LD3**	**LD4**	**Mean**
0-12	4.4	6.9	12.5	3.2	4.1	6.2
12-24	1.0	1.3	4.1	1.2	3.6	2.2
24-36	0.8	0.8	2.6	0.8	3.7	1.7
36-72	1.3	1.3	3.3	13.2	9.6	5.7
72-180	2.9	1.3	4.6	23.0	8.6	8.1
180-1500	89.4	86.5	72.9	56.3	69.7	75.0
1500-3000	0.1	1.9	0.0	2.3	0.8	1.0
> 3000	0	0.0	0.0	0.0	0.0	0.0

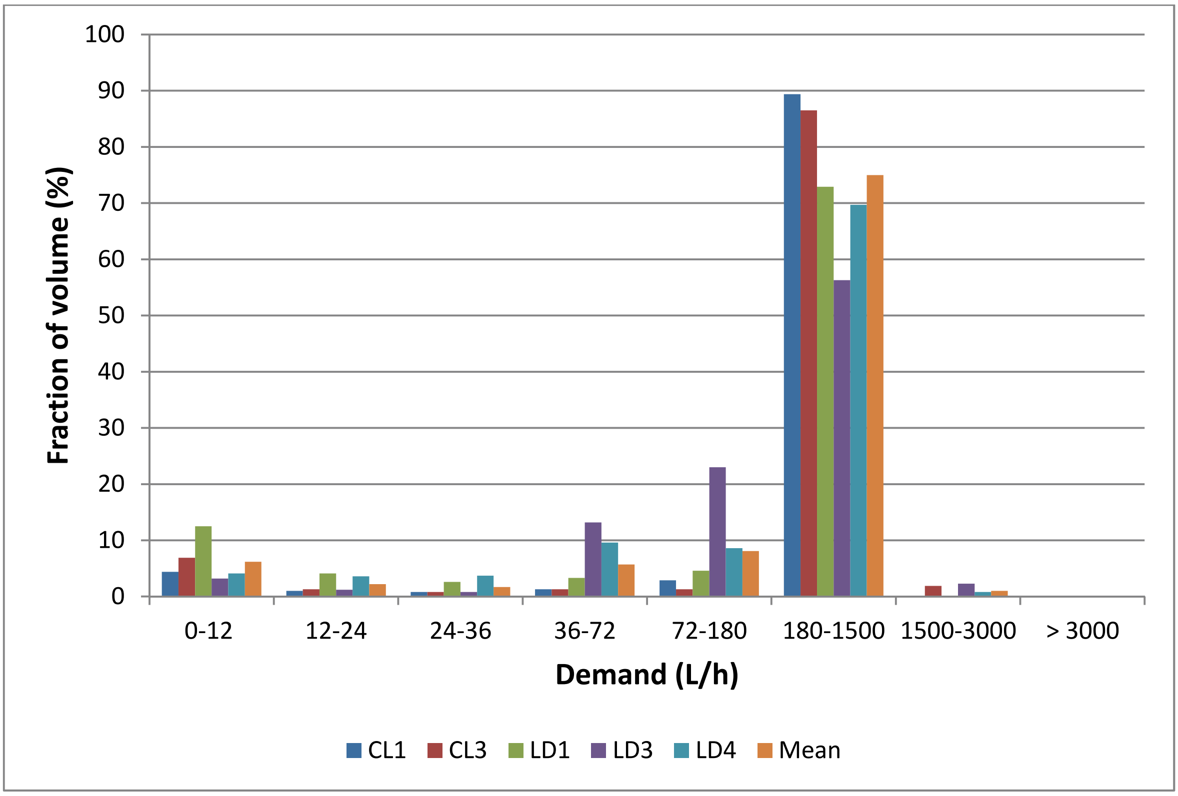

Figure 5.4: Fraction of volume used at each demand period for domestic consumers

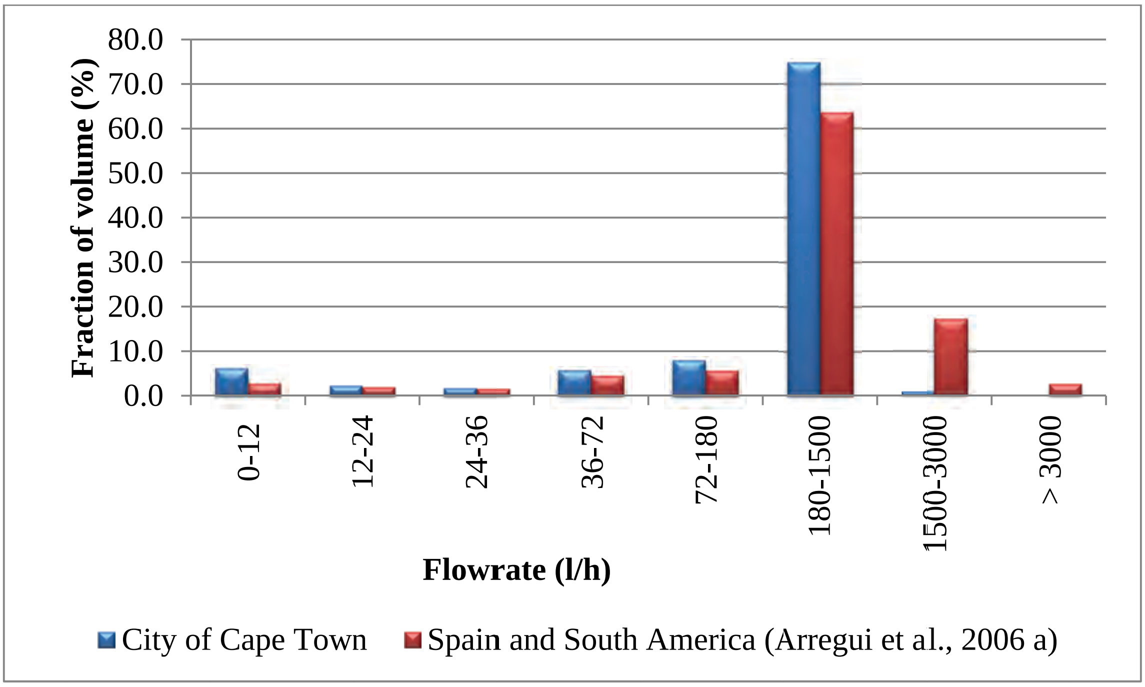

Figure 5.5: Comparison of consumption patterns in Cape Town with Spain and South America

5.3.3 Domestic consumer consumption patterns with UFR

Comparing the results obtained from the master meter with and without a UFR installed, there appears to be no reduction in low flow rates less than 24 l/h from passing the consumer meter. This is most likely due to the fact that the logged properties had no on-site leakage, and did not feed into roof tanks and thus that these properties were not the ideal applications for UFR devices.

Table 5.4: Fraction of time demand used per domestic consumer with UFR installed

Flow rate (l/h)	Fraction of time (%)			
	AT1	CL2	LD2	Mean
0-12	89.5	93.0	91.8	91.4
12-24	4.5	3.2	2.3	3.3
24-36	1.2	0.7	1.5	1.1
36-72	1.2	0.8	1.6	1.2
72-180	0.7	0.7	1.3	0.9
180-1500	3.0	1.6	1.4	2.0
1500-3000	0.0	0.0	0.0	0.0
> 3000	0.0	0.0	0.0	0.0

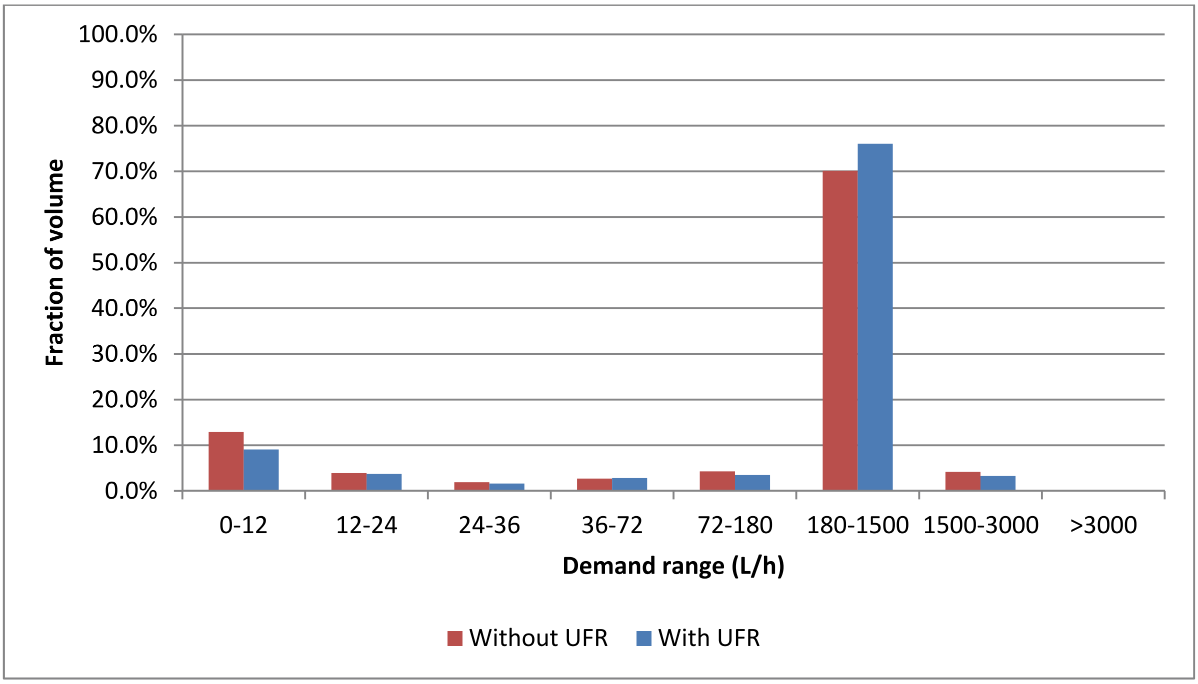

Figure 5.6: Average fraction of volume used at each demand period for domestic consumers with a UFR installed

6 REVIEW OF BULK CONSUMER METER AUDITS

6.1 Introduction

The non-domestic consumers in the industrial, commercial and institutional (ICI) sectors and domestic consumers usually in large flats or complexes fall under this category of bulk consumers.

Non-domestic consumers are usually associated with largest consumers in a municipal supply area. The City of Tshwane’s, which is the largest metropolitan in South Africa, industrial and commercial consumers account for only 3% of the total number of consumers in the City, yet account for 30% of the total consumption (City of Tshwane, 2011).

The characteristic large consumption of these consumers, signify the importance of accurate water metering to mitigate apparent losses. Small errors in meter registration, meter reading and data acquisition can constitute to a large impact on the apparent losses for a municipal supply area. The importance of ensuring that meters are replaced at regular short intervals, motivated by an economic analysis, and is read accurately and stored in the financial database without error is vital to ensure that apparent losses are economically minimized. The extent of unauthorized connections needs to be minimized as effectively as possible, especially for non-domestic users which use large quantities of water.

The major impact that bulk consumers can have on apparent losses, means that any good programme to reduce apparent losses should begin with these consumers to acquire the quickest return for the least amount of effort. This fact has prompted municipalities around the country to do audits on their bulk users. The chapter will review a number of these reports as well as other literature on meter audits of bulk meters.

A meter audit involves the collecting and recording of meter and consumer information in the field to identify metering problems and comparing information in the field to existing information in the billing database of the municipality. A meter audit can provide a host of valuable information that can help direct an apparent loss programme to critical areas where small improvements can result in substantial returns. The following is typical information that is targeted in an audit:

- Un-metered or unauthorized connections
- Meters installed with incorrect orientation
- Meter location
- Meters damaged externally and illegible
- Erratic meters i.e. the register of the dial is not moving smoothly
- Stopped meters
- Old meters
- Leaks at or near meters
- Incorrectly sized meters
- Connections with incorrect meter type
- Meter reading to compare to financial database, which indicates meter reading and acquisition error
- Consumer and account details to compare to financial database
- Accuracy of meter to register consumption

Reports from the following municipalities were included in the study:

- City of Tshwane
- Ekurhuleni Metropolitan Municipality
- Emfuleni Local Municipality
- eThekwini Municipality
- Pietermaritzburg-Msunduzi Transitional Local Council
- City of Cape Town

6.2 Reports and conference papers reviewed

Most of the information in this chapter were sourced from conference papers and unpublished reports made available by municipalities. Table 6.1 lists the sources used.

Table 6.1: List of unpublished reports and conference papers on bulk meter audits performed on municipalities reviewed

Municipality	Contractor/Consultant	Title	Unpublished report/ Conference paper	Reference
City of Tshwane	WRP Consulting Engineers	Tshwane Water Loss Project, Task: Meter Audit of Industrial Consumers	Unpublished report	(City of Tshwane, 2011)
Ekurhuleni Metropolitan Municipality	WRP Consulting Engineers	The Benefits of non-Domestic Consumer Meter Audits and Retrofitting – The Ekurhuleni Case Study	Conference paper	(Wegelin et al., 2009 a)
Emfuleni Municipality	WRP Consulting Engineers	The Emfuleni Water Loss Project – A Major Challenge	Conference paper	(Wegelin et al., 2009 b)
eThekwini Municipality	JOAT sales and service	Detailed meter audit and sizing analysis of top 200 consumers in the eThekwini municipal area	Unpublished report	(eThekwini Water Services, 2006)
Pietermaritzburg-Msunduzi Transitional Local Council	BKS	Water Leakage Management Project, Top 40 Consumer Analysis Report	Unpublished report	(PMLTC, 2001)
City of Cape Town	WRP Consulting Engineers	Pilot Meter Audit in Parow Industrial, City of Cape Town	Unpublished report	(City of Cape Town, 2009)
City of Cape Town	Sohlala Civil Projects	Parow Industrial Area Meter Audit	Unpublished report	(City of Cape Town, 2010)

6.2.1 City of Tshwane

As part of the Tshwane Water Loss Project, large consumer meter audits of industrial consumers were undertaken between 2006 and 2009 (City of Tshwane, 2011). The audit covered 2 497 consumers in 15 industrial and commercial areas, which amongst other tasks covered such as collecting consumer and meter information, performed:

- Water supply shut-downs to identify un-metered connections. These tests are done by closing all metered connections on the consumer's property and then opening the end-use points to check if there is any flow. If there is flow, then the test is positive for an un-metered connection being present and vice versa.
- An economic impact of the audit for each area. Meters that were of poor condition were replaced and un-metered connections were metered. As a result, the economic impact was deduced by comparing monthly consumption data before and after the meter replacement period.

6.2.2 Ekurhuleni Metropolitan Municipality

A pilot Automatic Meter Reading (AMR) project was ensued in the Benoni South area, to determine the impact proper metering and billing would have on revenue flows from industrial consumers, which account for a large portion of the total water consumption in the municipal supply area (Wegelin et al., 2009 a).

A water meter audit of the 176 selected small and large industrial consumers in the project was performed before the commencement of the AMR project.

The meter audit included collecting consumer information, meter information, identifying un-metered connections through water supply shut-downs similar to that explained in the Tshwane case study and an economic impact assessment was done after the installation of the AMR system. Consumer meters that were of poor condition were replaced and un-metered connections were installed with a meter. Only the top 10 largest industrial consumers of the 176 were installed with the AMR system. The AMR system was installed into service from January 2008.

6.2.3 Emfuleni Local Municipality

As part of the Emfuleni water loss project, the meters of non-domestic consumers were audited in an effort to increase revenue flows to the municipality (Wegelin et al., 2009 b). A total of 350 meters were audited in the Tshepiso, Sharpeville, Bophelong, Boipatong, Sebokeng and Evaton areas. The primary focus of the audit was placed on schools, clinics, formal businesses and governmental buildings. Meter and consumer information were collected from the field and un-metered connections were located, however no economic impact after the audit was reported.

6.2.4 eThekwini Municipality

As part of eThekwini Municipality's water loss management programme, a water meter audit of the top 200 consumers was undertaken. The meter audit in this study is similar yet different to the others in that the municipality logged the flow rates for one week before and after recommended meters from the audit were replaced. The accuracy of the meters was then assessed by looking at the consumption from the week before and after the installed meter was replaced.

It was noted in the report that as the meters are monitored over a longer period of time, the results of the impact of the replacements will become more reliable. The accuracy of the logged data was confirmed with the billing database and all logged data that didn't conform within a reasonable range was removed from the data set according to the EWS report (eThekwini Water Services, 2006).

The data logging exercise also allowed for an accurate sizing assessment of the meters.

6.2.5 Pietermaritzburg-Msunduzi Transitional Local Council

The Pietermaritzburg Water Leakage Management Project involved auditing the meters of the top 40 consumers in the Pietermaritzburg-Msunduzi Transitional Local Council (PMTLC) (PMLTC, 2001). The meter audit started in March 2000 and ended in November that year.

The meter audit included collecting information in the field and logging the meters for about a period of two days to check the sizing and performance of each meter.

6.2.6 City of Cape Town

The City of Cape Town initiated a pilot meter audit in a section of the Parow Industrial area. The pilot only audited 40 of the total 280 consumers in the area, to determine if it was economically viable to audit the rest of the consumers (City of Cape Town, 2009). Water supply shut-downs were performed on only some of the consumer properties. The result of the pilot was that the whole area should be audited and that water supply shut-downs should be done to find un-metered connections.

The results of the meter audit of 122 of the remaining consumers to be audited were reported on the 15 December 2011 (City of Cape Town, 2010).

6.3 Results and discussion

6.3.1 Introduction

This section integrates the results from all the case studies to meet the objective of this research by:

- Comparing the condition and accuracy data of each case study where possible.
- Comparing unauthorized and meter reading error data of each case study where possible.
- Comparing the extent of apparent losses from bulk water meters between each applicable case study from the actions taken from recommendation of the meter audit.

6.3.2 Meter condition and accuracy

The data regarding meter condition and age assessments from the different studies are integrated in Table 6.2, with the following main findings:

- There are many bulk meters in the field that are very old and need to be replaced.
- There are a number of meters in the field that have stopped working and not registering any consumption.
- A number of meters are incorrectly sized.
- There are a number of meters with illegible dials.

Table 6.2: Comparison of results from meter audit case studies regarding meter condition

Municipality	**Audited connections**	**Age of meters**	**Condition of meters**
City of Tshwane	2497	Not stated	Illegible, broken, stolen or erratic: - Sub-meter of combination meter (3.6%) - Main meter of combination meter (6.2%) Connections with leaks at meter (1.6%)
Ekurhuleni Metropolitan Municipality	207	A significant number > 15 yrs	Illegible or stopped (23.7%) A number of leaking meters were found
Emfuleni Local Municipality	350	Not stated	Stopped (14%)
eThekwini Municipality	200	Unknown (7.5%) 0-2 yrs (13%) 3-5yrs (76%) 6-10 yrs (3.5%)	Incorrect size (2%) Unloggable (12%) Damaged (0.5%)
Pietermaritzburg-Msunduzi Transitional Local Council	40	0-5 yrs (5%) 5-10 yrs (60%) > 15 yrs (35%)	Unloggable (52.5%) Damaged (5%) Most meters appeared to be over-sized Some connections were installed with the incorrect meter type
City of Cape Town (Pilot audit)	47	> 20 yrs (48.9%), with some over 30 yrs	Stopped (2.1%)
City of Cape Town (Full Audit – in progress)	122	Not stated	Stopped (4.9%) Illegible (2.5%)

The accuracy of the top 200 bulk consumers in the eThekwini Municipal were investigated by comparing the logged flow rates recorded a week before the installed meter was replaced with the week after when the new meter was installed. The analysis could only be performed on a 109 of the 138 meters that were replaced from recommendations made in the audit, as the remaining 29 replaced meters were unloggable. All the meters that were logged were of the Woltmann type.

Table 6.3 presents the data collected from the meter accuracy assessments conducted by the eThekwini municipality and the meter error is calculated using Equation 1 in Chapter 2.

Table 6.3: Meter error versus age according to meter size in the eThekwini Municipality

(Scruton, 2011)

Diameter (mm)	**Age (yrs)**	**Before replacement (m^3/day)**	**After replacement (m^3/day)**	**Meter error (%)**	**No. of meters**	**Apparent loss (m^3/month/connection)**
50	1	626.64	626.40	0.04	1	-7.2
50	3	3373.68	3960.19	-14.8	25	703.8
50	4	2957.28	3643.68	-18.8	23	895.3
50	6	108.24	36.48	196.7	1	-2152.8
50	None	167.28	212.64	-21.3	2	680.4
50	Overall	7233.12	8479.392	-14.7	52	719.0
80	2	65.52	65.52	0	1	0.0
80	3	1704.72	1567.92	8.7	4	-1026.0
80	4	3781.68	3263.76	15.9	15	-1035.8
80	5	1672.56	1616.64	3.5	3	-559.2
80	Overall	7224.48	6513.84	10.9	23	-926.9
100	3	1264.56	1167.84	8.3	3	-967.2
100	4	4397.45	4875.84	-9.8	5	2870.3
100	5	325.92	365.04	-10.7	1	1173.6
100	Overall	5987.93	6408.72	-6.6	9	1402.6
150	2	562.56	418.56	34.4	1	-4320.0
150	3	140.64	110.88	26.8	2	-446.4
150	4	3313.44	3280.80	1.0	2	-489.6
150	5	5298.96	5451.36	-2.8	3	1524.0
150	7	1226.64	1200.72	2.2	1	-777.6
150	Overall	10542.24	10462.32	0.8	9	-266.4
200	5	2264.64	6201.84	-63.5	1	118116.0
200	Overall	2264.64	6201.84	-63.5	1	118116.0
No diameter	No age	4022.40	4099.44	-1.9	15	154.1
No diameter	Overall	4022.40	4099.44	-1.9	15	154.1
Overall		33252.41	38066.11	-12.6	109	1324.9
Overall (excl. 200mm)		30987.77	31864.27	-2.8	108	243.5

Due to the small sample captured in Table 6.3, it is not possible to make any concrete conclusions regarding the ‘error versus age’ for meters with different diameters. However, the 3 and 4 year old 50 mm diameter meters have 25 and 23 samples respectively. It was found that the 3 and 4 year old 50 mm diameter meters have an under-registration of 14.8% and 18.8% respectively with an increase in error of -4% from the 3rd to 4th year. This reaffirms the general rule that these meters need to be replaced frequently (according to an economic analysis) and require routine maintenance to ensure quality performance and extend the meter's life.

By further inspection of the data set, it was found that 51 of the 109 meters were in fact over-registering, which reduces the impact of under-registration and subsequent apparent losses. However, as the logging of consumption only occurred for one week each for the old and new meter, this could just be indicating that approximately half the consumers in fact consumed less water the week after replacement and the other half consumed more.

The meter error of all the 109 meters was -12.6%, but when disregarding the 200 mm meter the meter error dropped to -2.8%. This illustrates the importance of such audits, which finds meters that are grossly under-registering large volumes of water being consumed.

6.3.3 Unauthorized connections and meter reading error

The occurrence of un-metered connections and meter reading error assessments of each case study is presented in Table 6.4. The following issues were identified in the field:

- A number of properties have un-metered connections used for daily operations.
- A number of meters are billed according to historical billed consumption data.
- A number of meters are buried or located inside the consumer's property and therefore difficult to access.
- Some consumers did not receive a bill.
- Some consumers did not have an account number.
- A number of meters could not be located in the field.
- A number of discrepancies between meter readings found in the field and the readings found in the billing database.

Table 6.4: Comparison between case studies regarding unauthorized connections and meter reading error

Municipality	**Audited connections**	**Un-metered connections (%)**	**Meter reading error**
City of Tshwane	2497	5.1	Not stated
Ekurhuleni Metropolitan Municipality	207	12.1	A significant number of consumers are billed according to historical billed consumption. Most meters were located below ground and buried making access difficult for meter reading.
Emfuleni Local Municipality	350	40	Most consumers reported that they do not receive a bill. Consumers that do not have account numbers (62.9%)
eThekwini Municipality	200	0	Not stated
Pietermaritzburg-Msunduzi Transitional Local Council	40	5	Number of the meters could not be located (5%) Number of inconsistencies between meter reading and billing database (5%)
City of Cape Town (Pilot audit)	47	6.4	Meters buried (17.02%) Number of meter readings on site 1000kL more than database reading (23.4%) Number of meter readings in database more than on-site (17.02%) Number of meters located inside the property
City of Cape Town (Full audit – in progress)	122	Not stated	Number of inconsistencies between meter reading and billing database (5.7%)

6.3.4 to apparent losses

The City of Tshwane did an economic analysis of the impact the water meter audit had on its revenue collected. The audit involved the replacement of meters that were not working, old and illegible. Meters were also installed on unmetered connections. The analysis gives an indication of apparent losses caused by such metering inefficiencies (meter error, unauthorized consumption and meter reading errors). This analysis has only been performed on 4 out of the 15 audited areas to date in Table 6.5. Table 6.6 shows the monthly apparent loss volume per connection for each industrial area, by dividing the increase in consumption by the number of connections investigated.

Table 6.5: Apparent loss after meter audit in the City of Tshwane (City of Tshwane, 2011)

Industrial area	**Connections investigated/ Total connections**	**Period before replacement**	**Period after replacement**	**Before replacement (m^3/month)**	**After replacement (m^3/month)**	**Apparent loss (%)**
Rosslyn North	73/ 138	Mar – Aug 06	Jan – Jun 07	18 900	23 900	20.9
Rosslyn South	78/ 236	Feb – May 07	Sep – Dec 07	31 000	34 000	8.8
Pretoria Industrial	56/ 144	Aug 06 - Mar 07	Jul 07 - Feb 08	22 600	29 900	24.4
Waltloo/ Silvertondale	175/ 550	Aug 07 - May 08	Oct – Dec 08	8 441	12 055	30.0
Overall	382/1068			80941	99855	18.9

Table 6.6: Apparent loss per stand after meter audit in the City of Tshwane (City of Tshwane, 2011)

Industrial area	**Apparent loss/connection (m^3/month)**
Rosslyn North	68
Rosslyn South	38
Pretoria Industrial	130
Waltloo/Silvertondale	21
Overall	50

At the completion of the bulk meter audit in Ekurhuleni (Wegelin et al., 2009 a), the top 10 consumers that were installed with the AMR system had an apparent loss of 17.8% which coincides with the -18.9% found in Tshwane.

6.4 Conclusion

It is quite clear from the meter audits researched that asset management regarding bulk consumer meters is not optimal and there is great scope for the implementation of interventions to reduce these losses. There are a large number of bulk consumers with:

- unauthorized connections
- meters that are in poor condition with some not even working.
- meters not being read as they are either buried or located inside the consumer's property and difficult to access. In some cases the meter could not even be found.

Based on the increase in revenue investigations after the meter audits performed in Tshwane and Ekurhuleni, it seems that apparent losses of bulk consumers are potentially around 20%. This gives huge incentive that meter audits should be performed in other municipalities and illustrates the importance of good metering practices.

7 DISCUSSION AND CONCLUSIONS

7.1 Introduction

This study investigated the apparent water loss situation focusing on meter under-registration in South Africa in a number of different ways by:

- Performing an international literature review on the topic of apparent losses due to meter inaccuracy.
- Interrogating new domestic consumer meters for on-site leakage.
- Using a consumer meter database to estimate meter error for different meter ages and registered volumes.
- Testing consumer meters in the field with a logged in-line master meter and the impact of unmeasured flow reducers on meter accuracy.
- Reviewing reports of bulk consumer meter audits.

7.2 Main findings

7.2.1 Under-registration of small meters due to meter aging

The results of this study showed a strong linear relationship between meter age and under-registration. While the relationship was determined for a specific meter model (15 mm positive displacement meter), this relationship represents a first for South Africa and is recommended as a basis for apparent loss calculations.

Since it is a linear relationship, it can be used in combination with the average age of water meters in a system to estimate the meter under-registration. The relationship is given by:

Average meter error percentage = 1-0.36 x average age of meters in years.

A study of meter replacement rates found that meters are replaced at an average rate of 5% per year in South Africa. This means that on average meters are replaced at the age of 20 years, and that the average age of a meter in the system is around 10 years. The average meter under-registration error can now be estimated from the above equation as 2.6% of consumption.

However, this error was based on the difference in consumption between an old and new meter, and thus excluding the error of new meters.

7.2.2 Under-registration of new small meters

Estimate in previous paragraph excludes metering error of new replacement meters. New meters tend to under-register at low flow rates, but over-register at high flow rates. Thus it is likely that a new meter will have a negligible under-registration or even over-register the demand.

The main problem with new meters is likely to be under-registration errors due to on-site leakage. This study showed a high incidence (17-67%) of on-site leakage in medium to high income suburban areas. From a literature review it is clear that the problem is worse in low income areas, with the incidence of on-site leakage in the order of 60 to 80% of properties.

It is recommended that meter under-registration error due to on-site leakage is taken as 15% of the measured on-site leakage in an area.

Assuming a leakage incidence of 30% and an average leakage rate of 20 l/hour at these properties, the average leakage rate over all properties can be calculated as 6 l/hour/property. Based on the 15% rule, this results in an average meter under-registration rate of 0.9 l/hour/property, or 22 l/day/property. Based on a typical consumption of 1000 l/day, this results in a typical meter under-registration of 2.2%.

Combining this number with the age related meter under-registration of 2.6% of consumption, it is possible to estimate the total apparent losses due to meter under-registration in South Africa as 4.8%, say 5% of consumption.

7.2.3 Under-registration of large meters

A review of meter audits done on bulk consumers showed that a lot more needs to be done to ensure that these meters are correctly sized, installed and in good condition. Based on the increase in revenue investigations after the meter audits performed in Tshwane and Ekurhuleni, it seems that apparent losses of bulk consumers are potentially around 20%. Given the fact that bulk meters measure a disproportionally large fraction of municipal consumption (and thus income), it is imperative that municipalities do more to ensure that these meters accurate.

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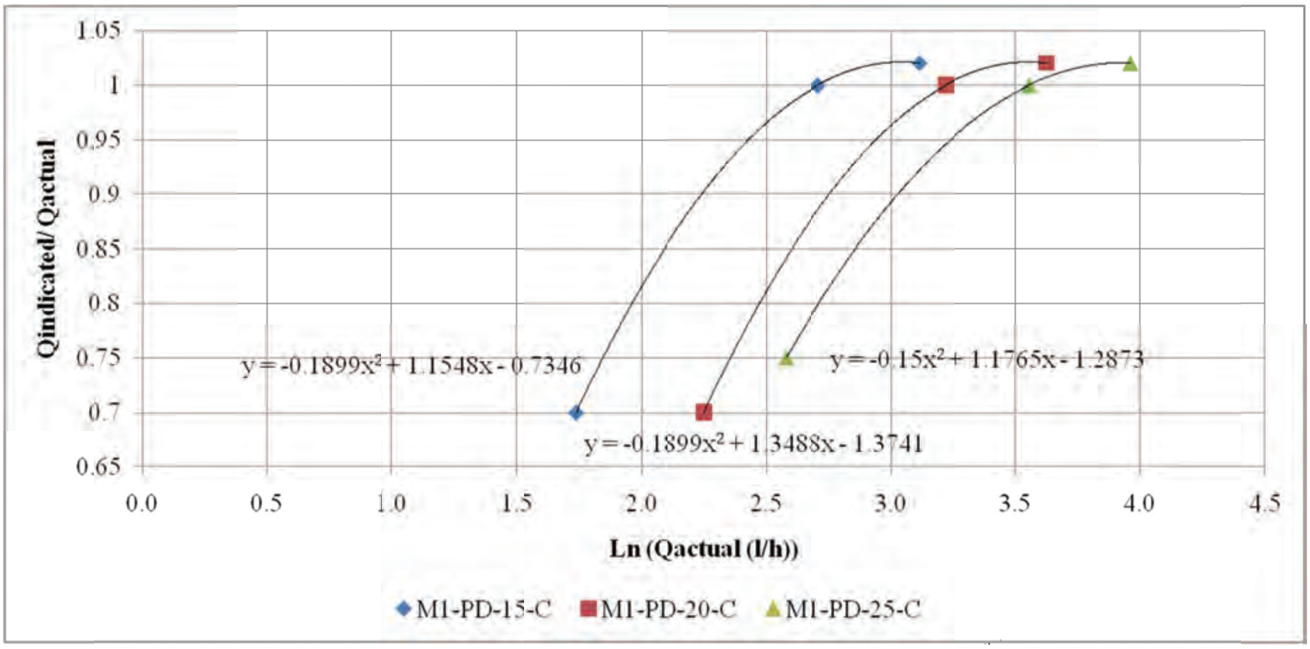
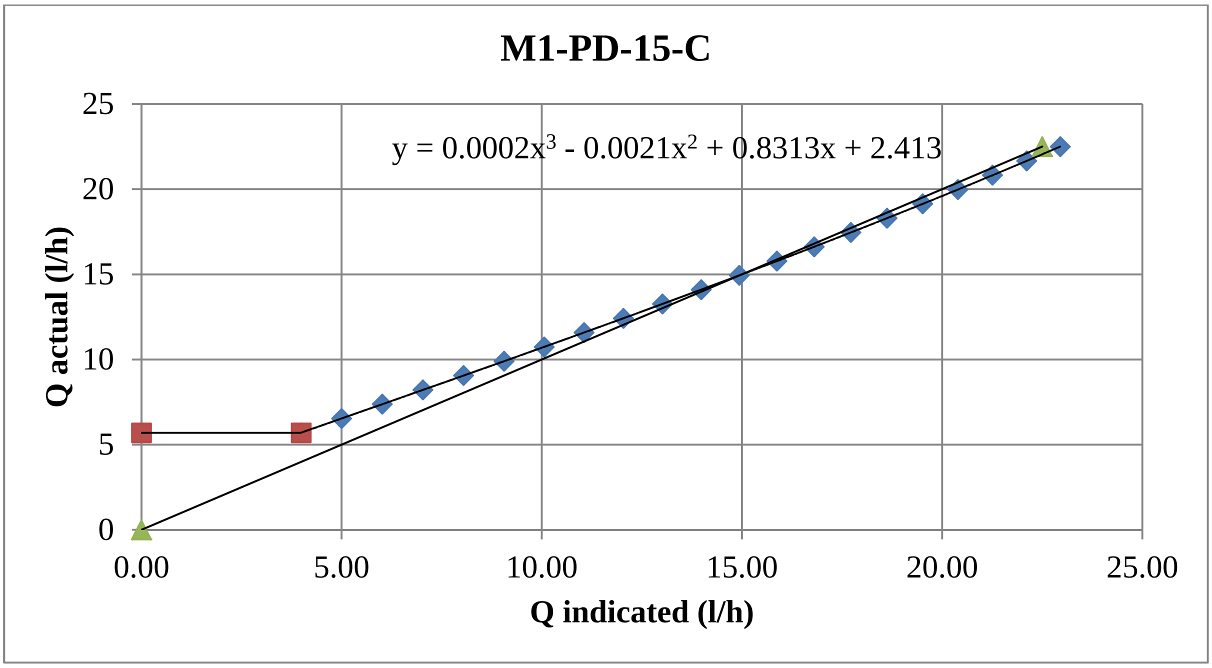
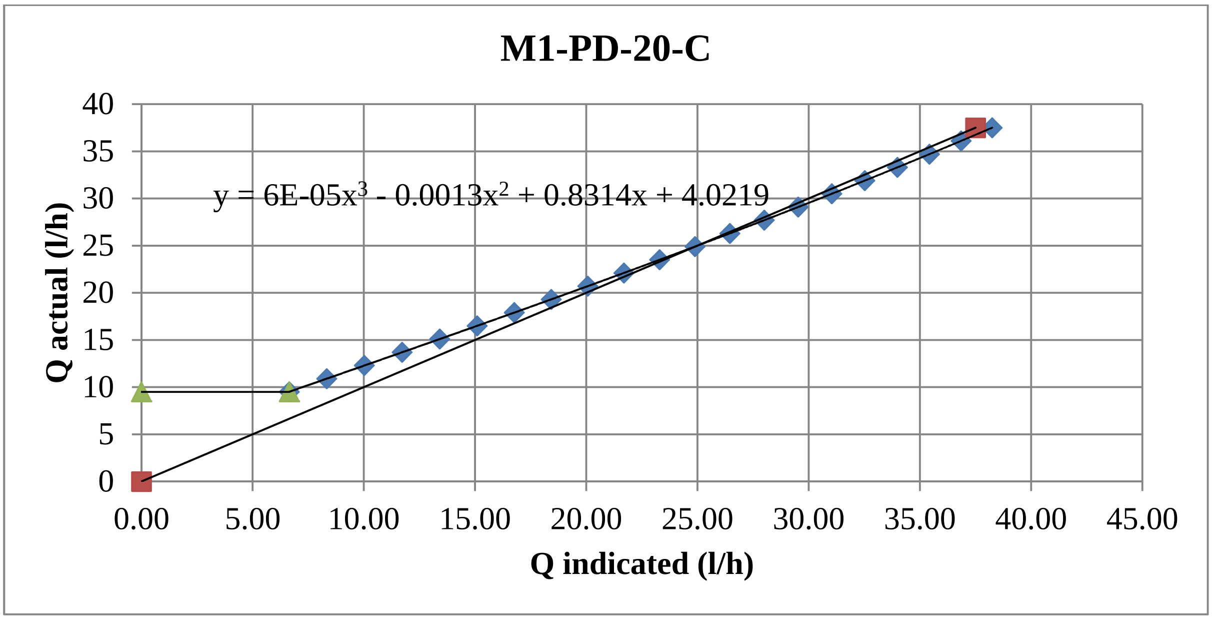
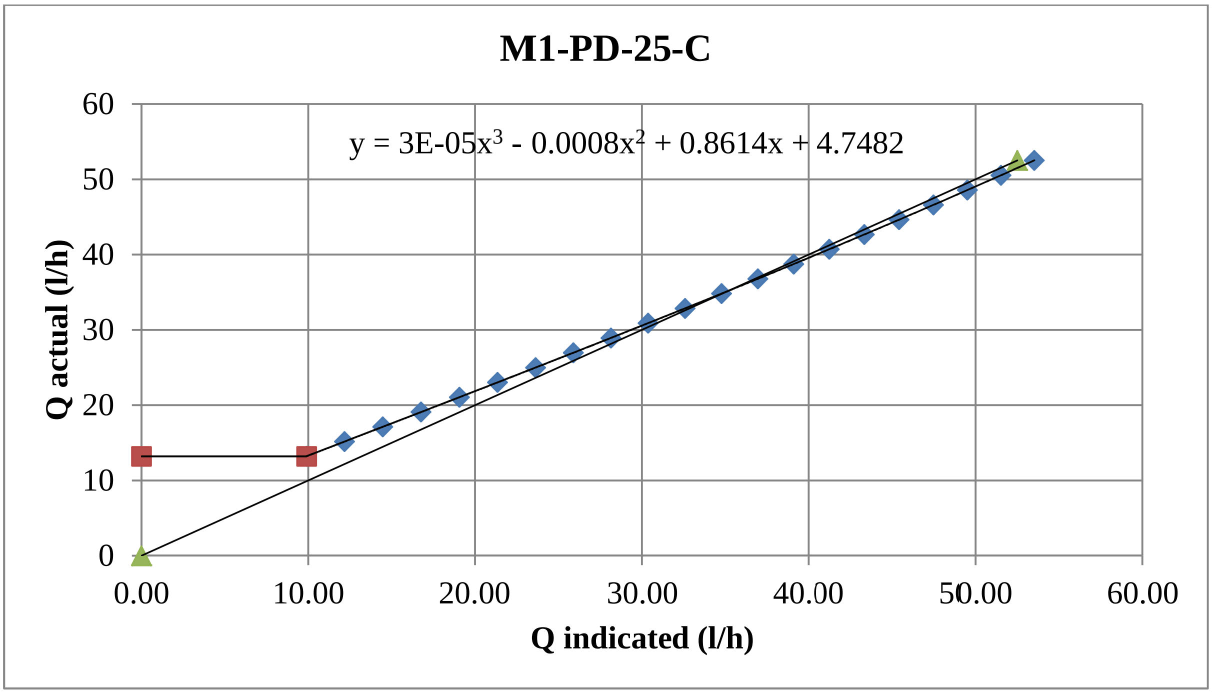
APPENDIX A: ON-SITE LEAKAGE METER ERROR CURVES

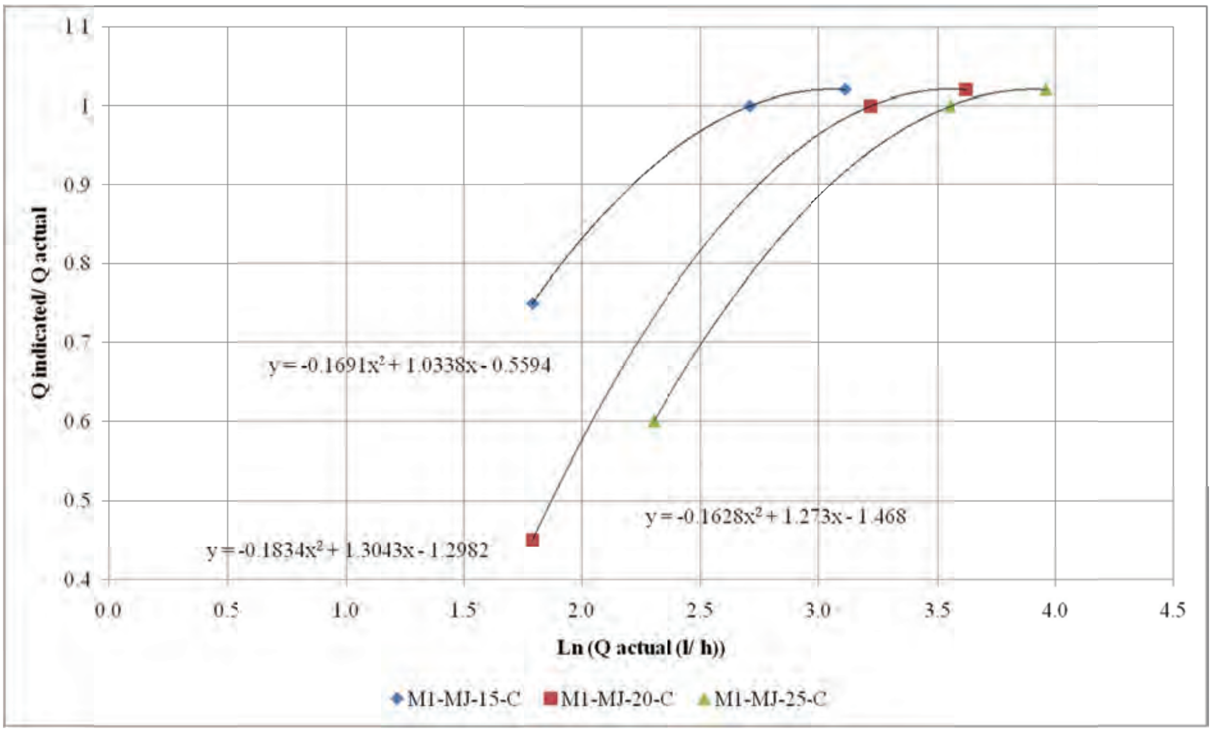
<u>Note</u>: M – Manufacturer PD – Positive displacement meter MJ – Multi-jet Number – meter size in mm Letter – Class

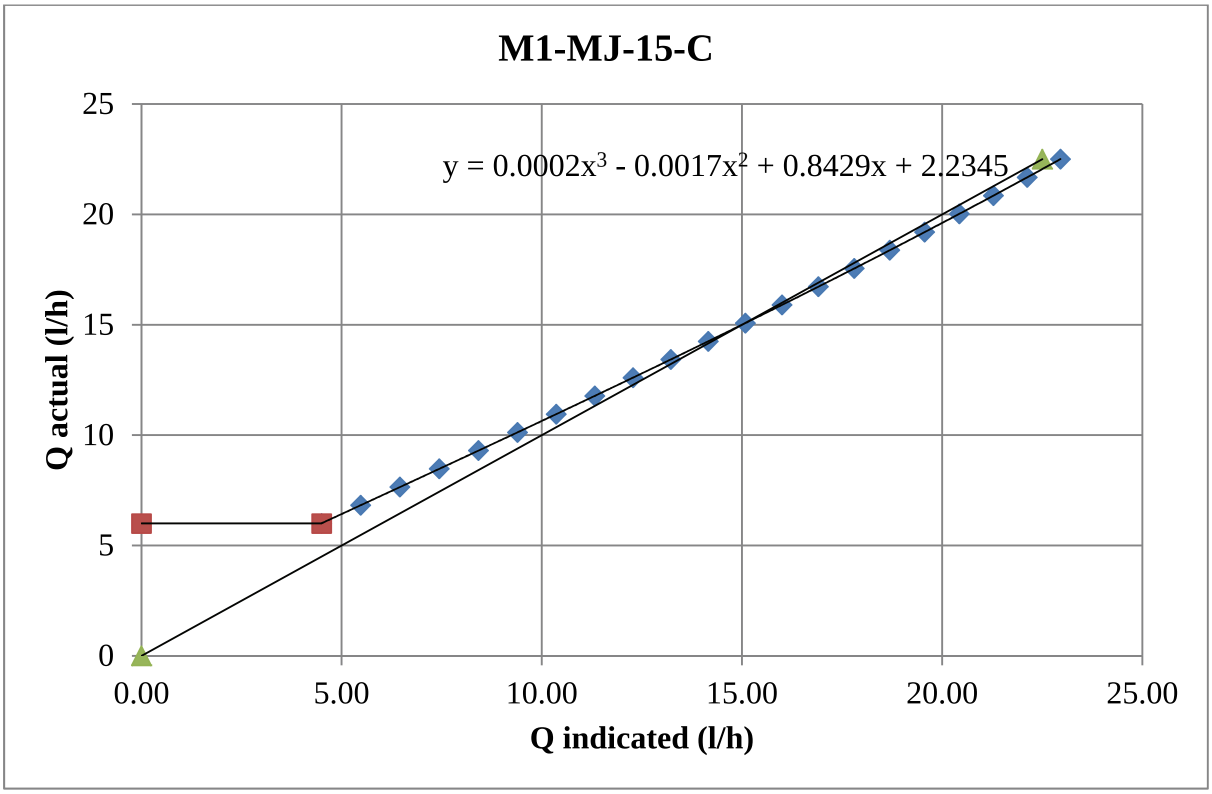


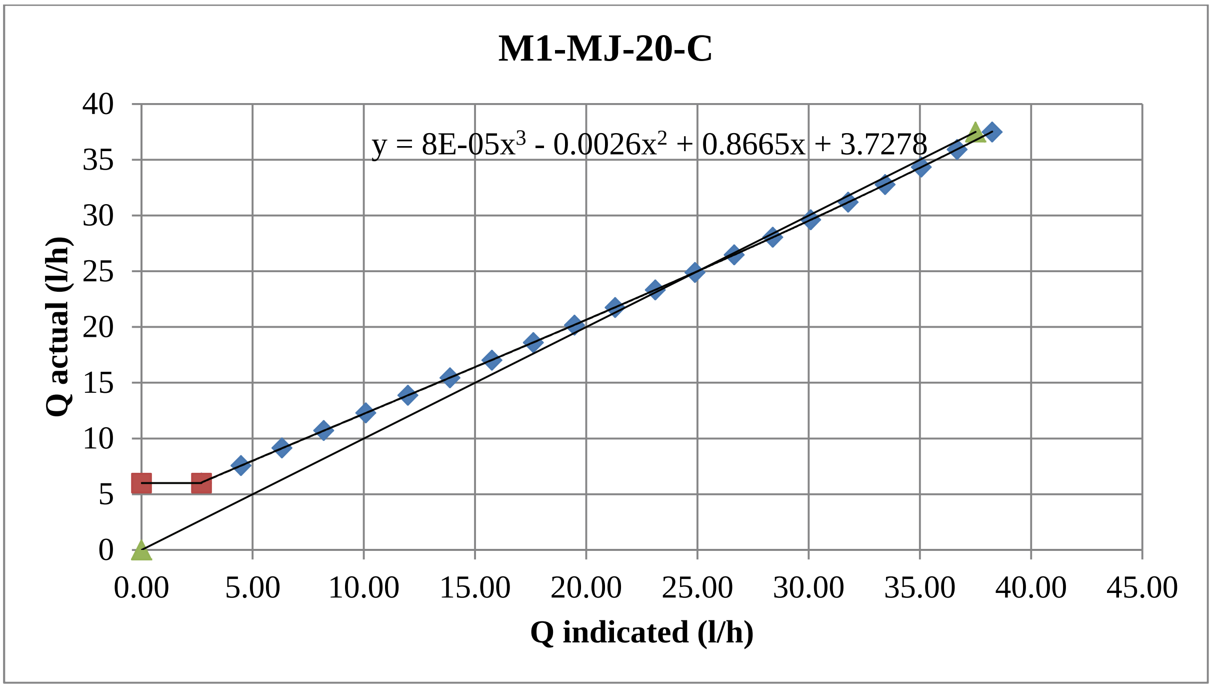

M1-PD-15-C
y = 0.0002x3 - 0.0021x2 + 0.8313x + 2.413
Q actual (l/h)
Q indicated (l/h)
0
5
10
15
20
25
0.00
5.00
10.00
15.00
20.00
25.00

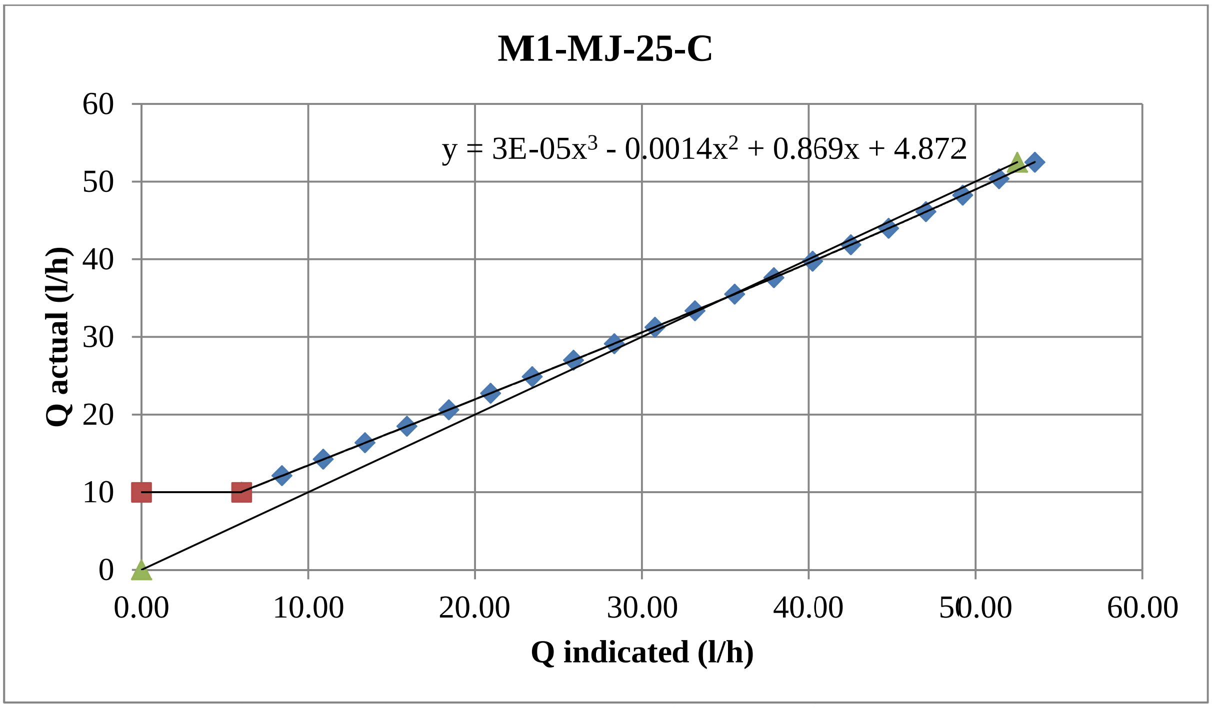

M1-PD-20-C
y = 6E-05x3 - 0.0013x2 + 0.8314x + 4.0219
Q actual (l/h)
Q indicated (l/h)
0
5
10
15
20
25
30
35
40
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00

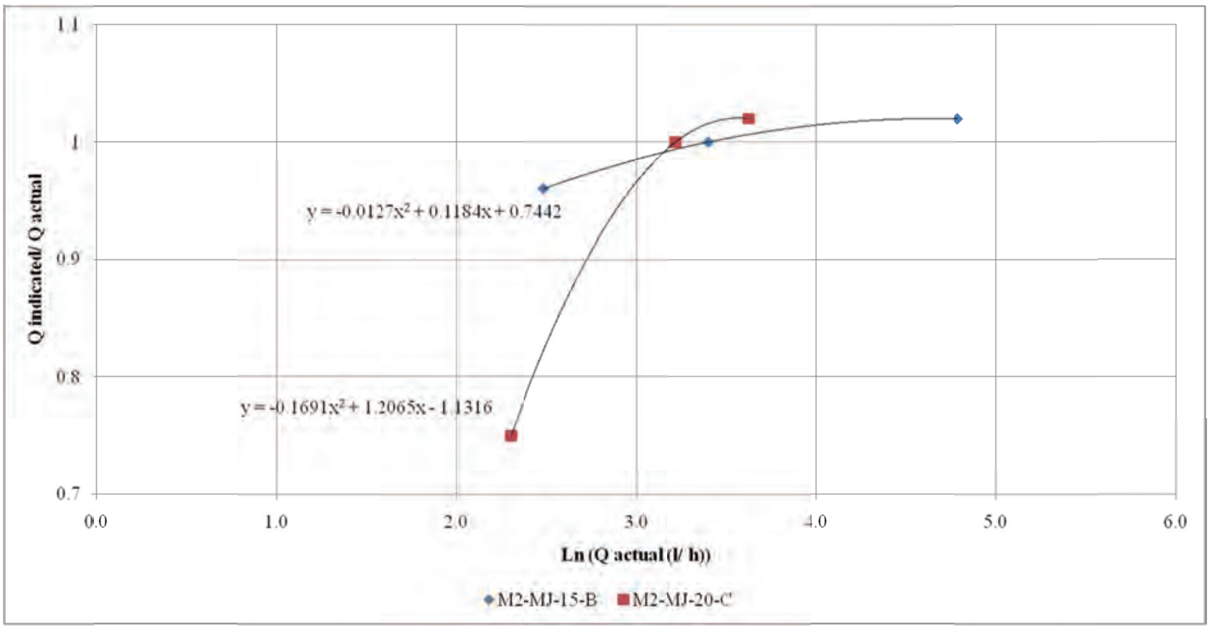

M1-PD-25-C
y = 3E-05x³ - 0.0008x² + 0.8614x + 4.7482
Q actual (l/h)
Q indicated (l/h)
0
10
20
30
40
50
60
0.00
10.00
20.00
30.00
40.00
50.00
60.00

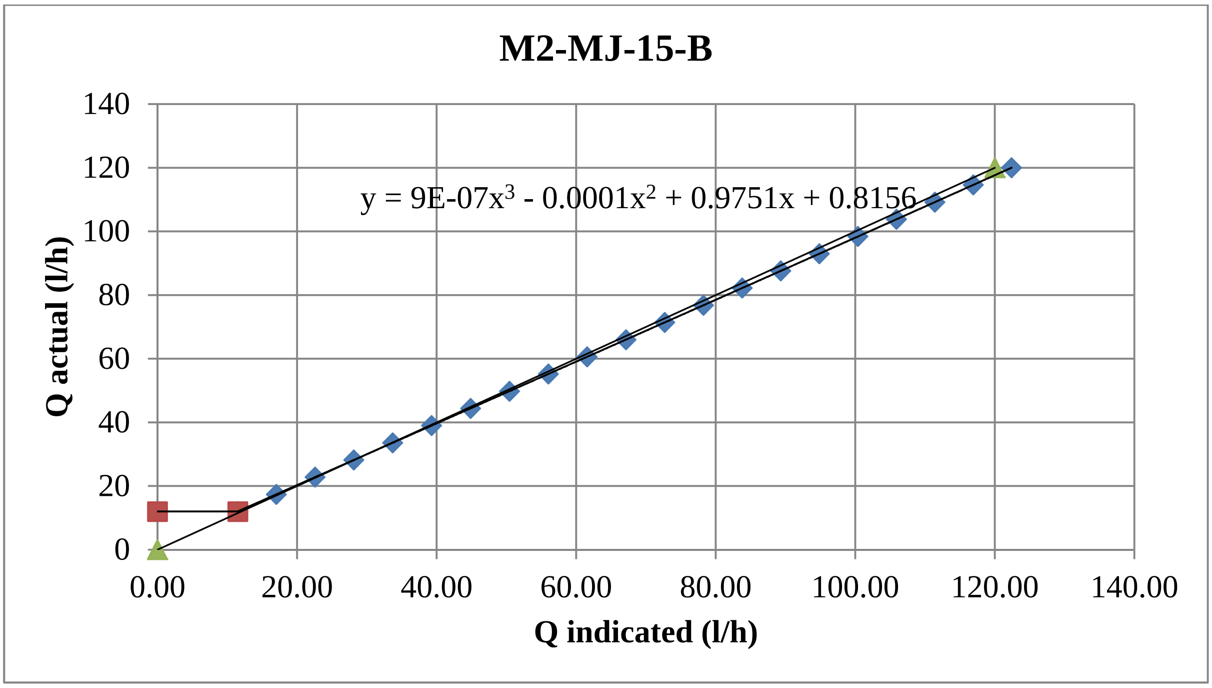

Q indicated/ Q actual
Ln (Q actual (l/ h))
y = -0.1691x² + 1.0338x - 0.5594
y = -0.1834x² + 1.3043x - 1.2982
y = -0.1628x² + 1.273x - 1.468
M1-MJ-15-C
M1-MJ-20-C
M1-MJ-25-C

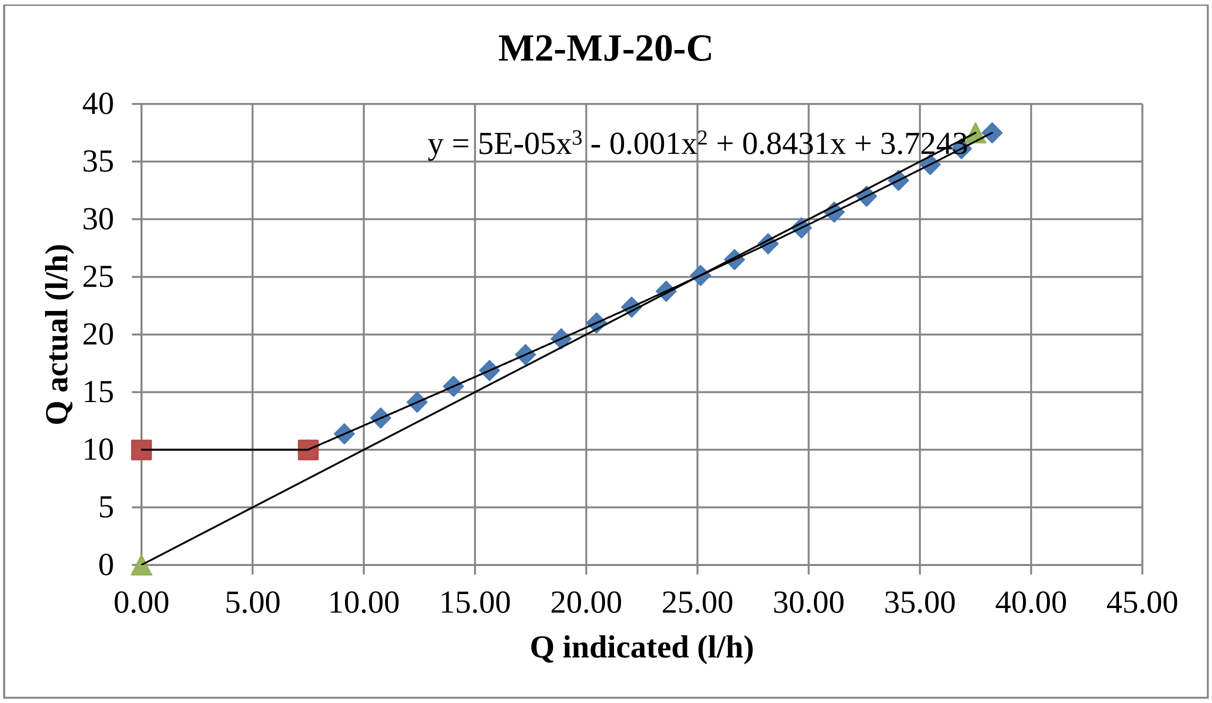

M1-MJ-15-C
y = 0.0002x³ - 0.0017x² + 0.8429x + 2.2345
Q actual (l/h)
Q indicated (l/h)
0
5
10
15
20
25
0.00
5.00
10.00
15.00
20.00
25.00

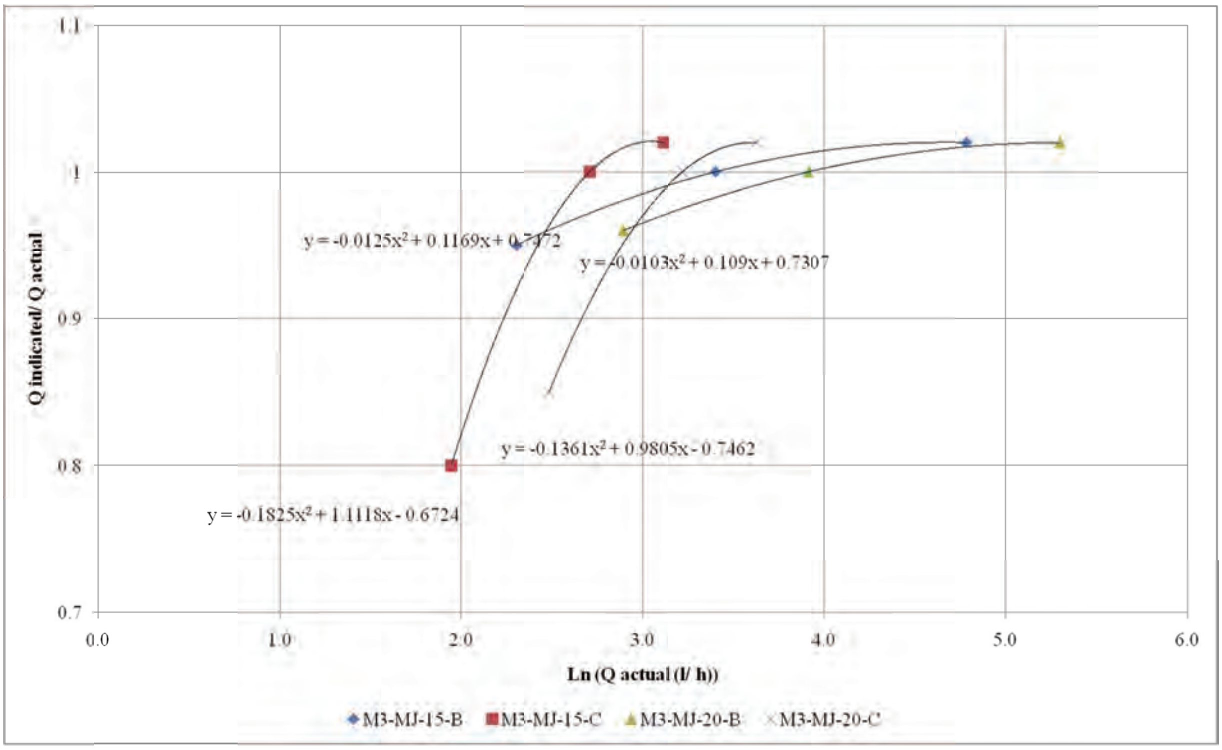

M1-MJ-20-C
y = 8E-05x³ - 0.0026x² + 0.8665x + 3.7278
Q actual (l/h)
Q indicated (l/h)
0
5
10
15
20
25
30
35
40
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00

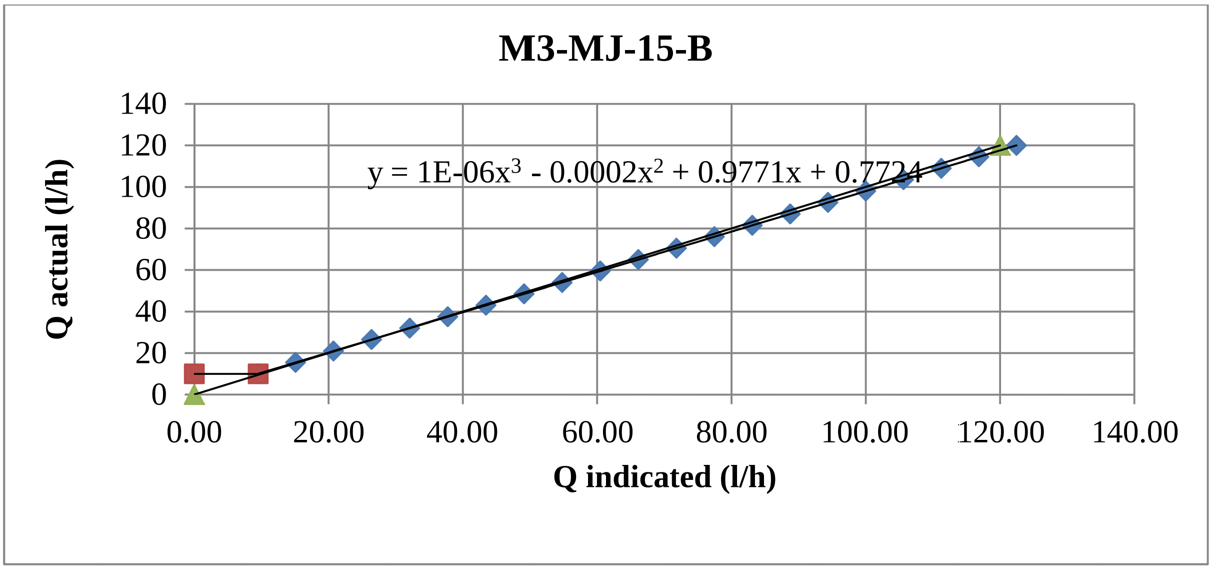

M1-MJ-25-C
y = 3E-05x³ - 0.0014x² + 0.869x + 4.872
Q actual (l/h)
Q indicated (l/h)
0
10
20
30
40
50
60
0.00
10.00
20.00
30.00
40.00
50.00
60.00

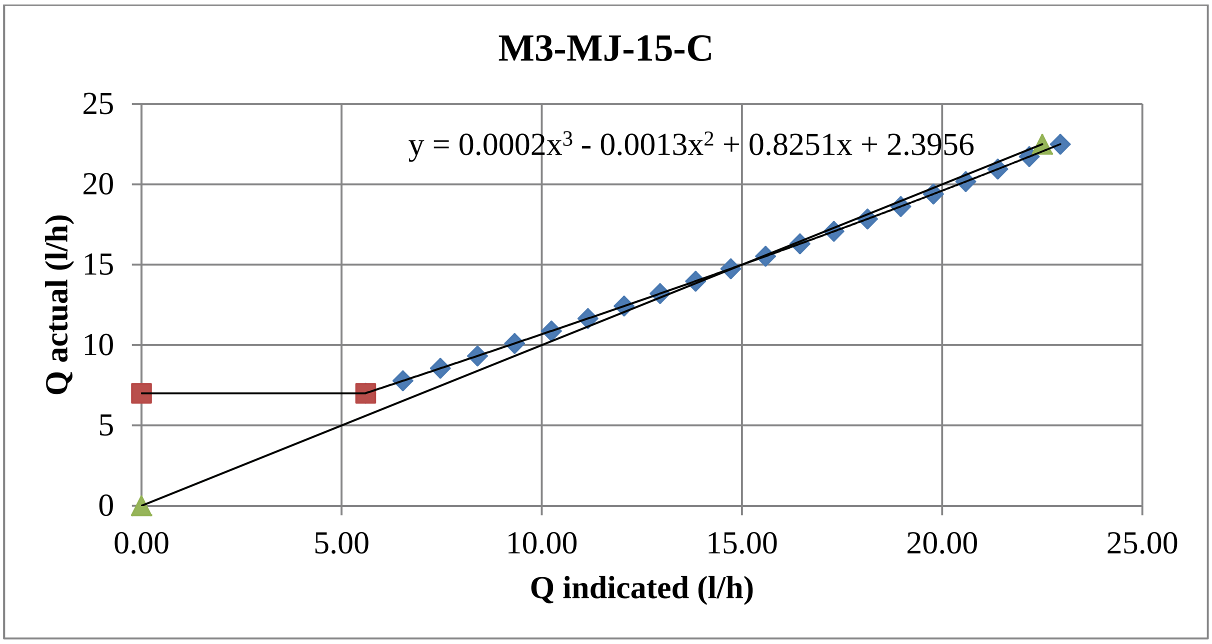

y = -0.0127x² + 0.1184x + 0.7442
y = -0.1691x² + 1.2065x - 1.1316
Q indicated/ Q actual
Ln (Q actual (l/ h))
M2-MJ-15-B
M2-MJ-20-C
0.7
0.8
0.9
1
1.1
0.0
1.0
2.0
3.0
4.0
5.0
6.0

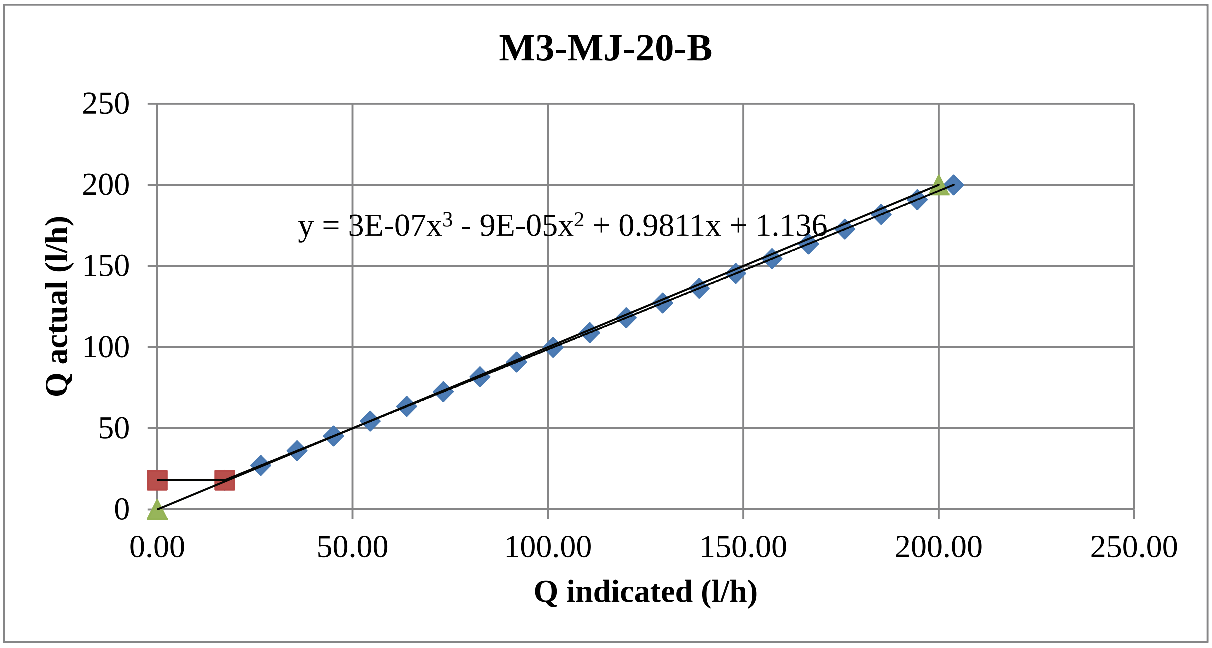

M2-MJ-15-B
y = 9E-07x³ - 0.0001x² + 0.9751x + 0.8156
Q actual (l/h)
Q indicated (l/h)
0
20
40
60
80
100
120
140
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00

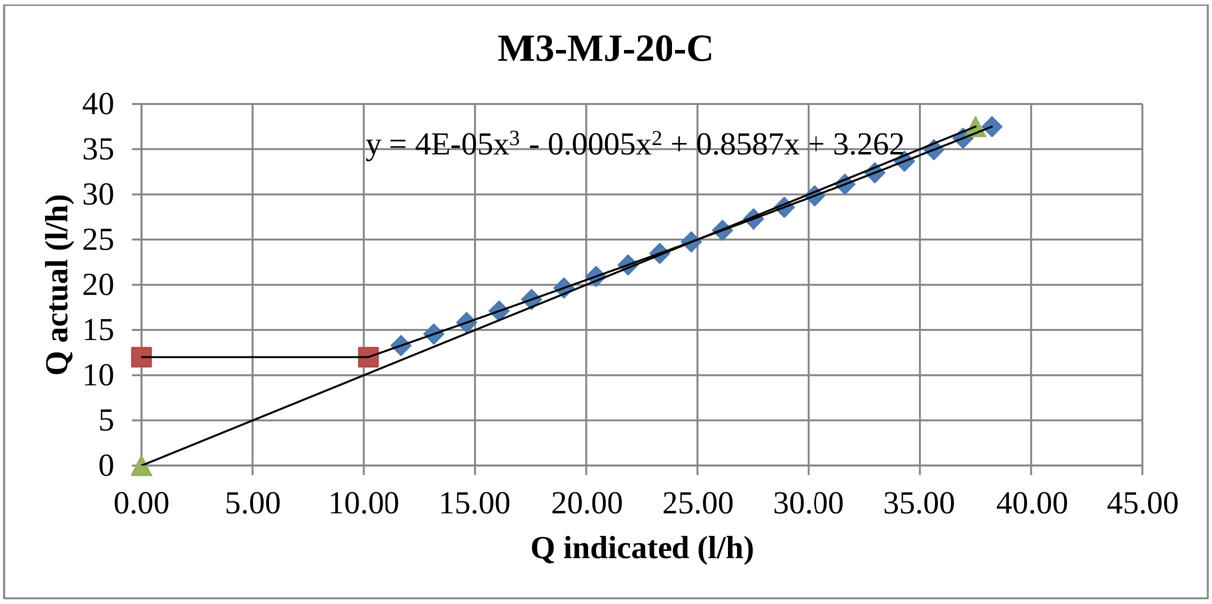

M2-MJ-20-C
y = 5E-05x³ - 0.001x² + 0.8431x + 3.7243
Q actual (l/h)
Q indicated (l/h)
0
5
10
15
20
25
30
35
40
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00

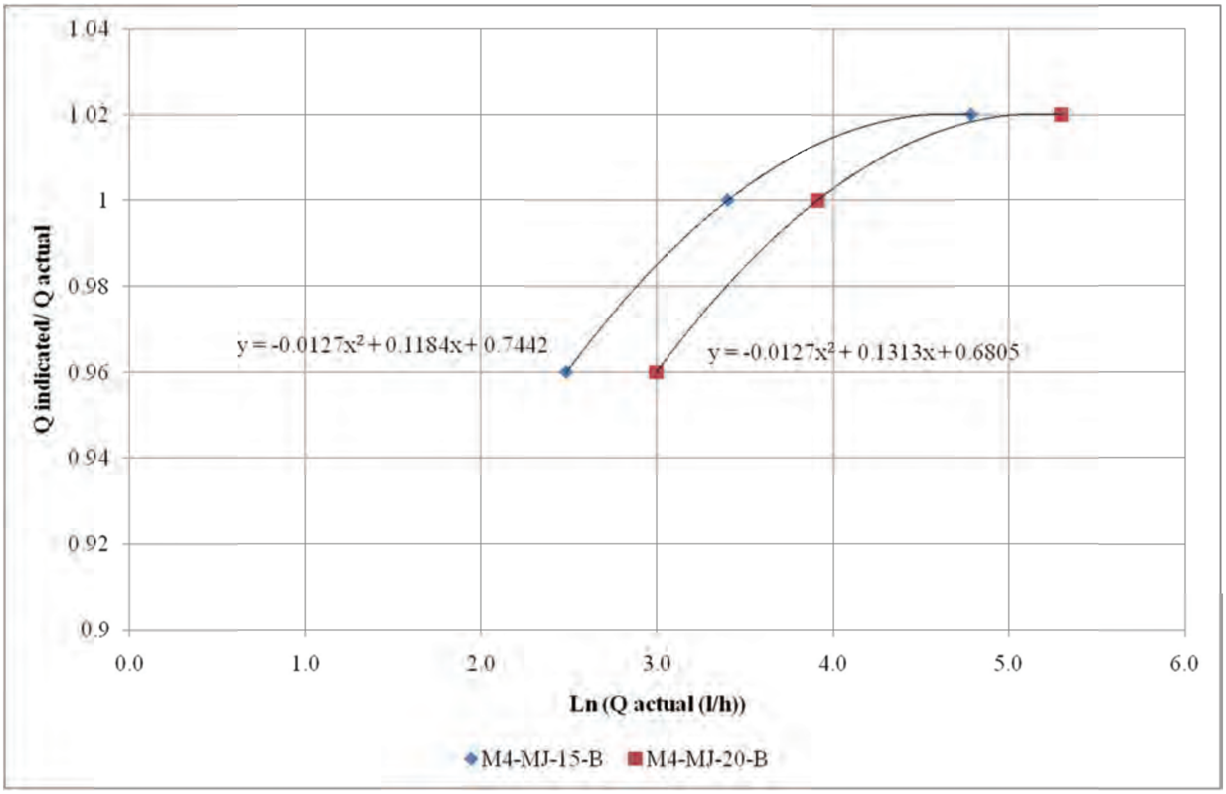

Q indicated/ Q actual
Ln (Q actual (l/ h))
y = -0.0125x² + 0.1169x + 0.7472
y = -0.0103x² + 0.109x + 0.7307
y = -0.1361x² + 0.9805x - 0.7462
y = -0.1825x² + 1.1118x - 0.6724
M3-MJ-15-B
M3-MJ-15-C
M3-MJ-20-B
M3-MJ-20-C

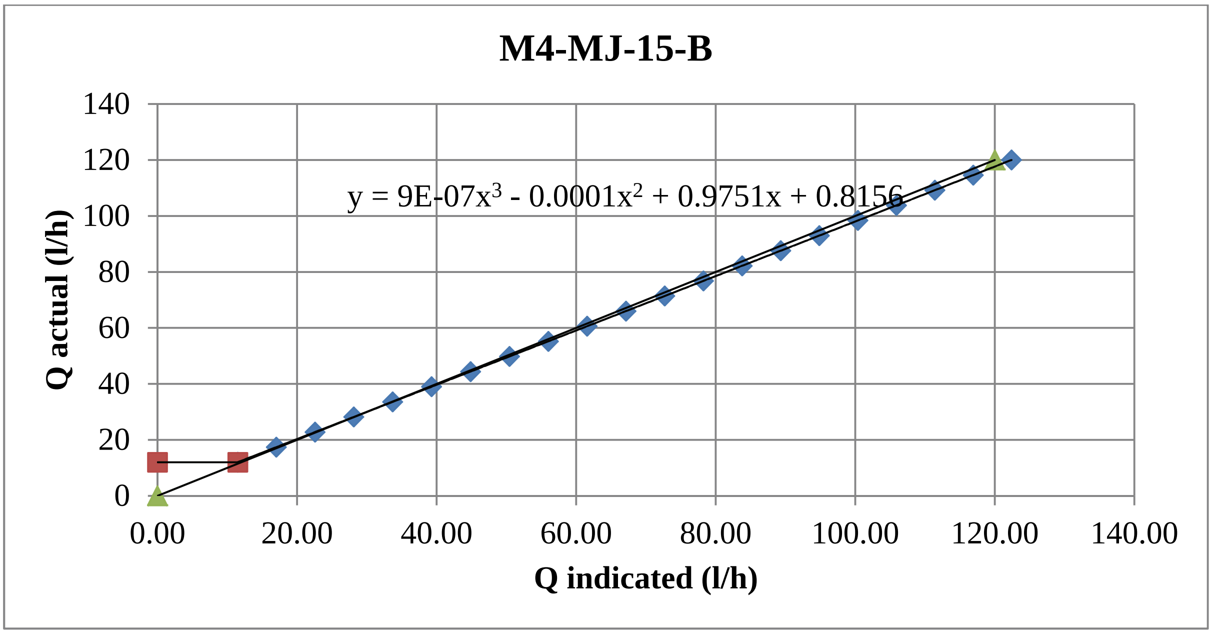

M3-MJ-15-B
Q actual (l/h)
Q indicated (l/h)
y = 1E-06x³ - 0.0002x² + 0.9771x + 0.7724

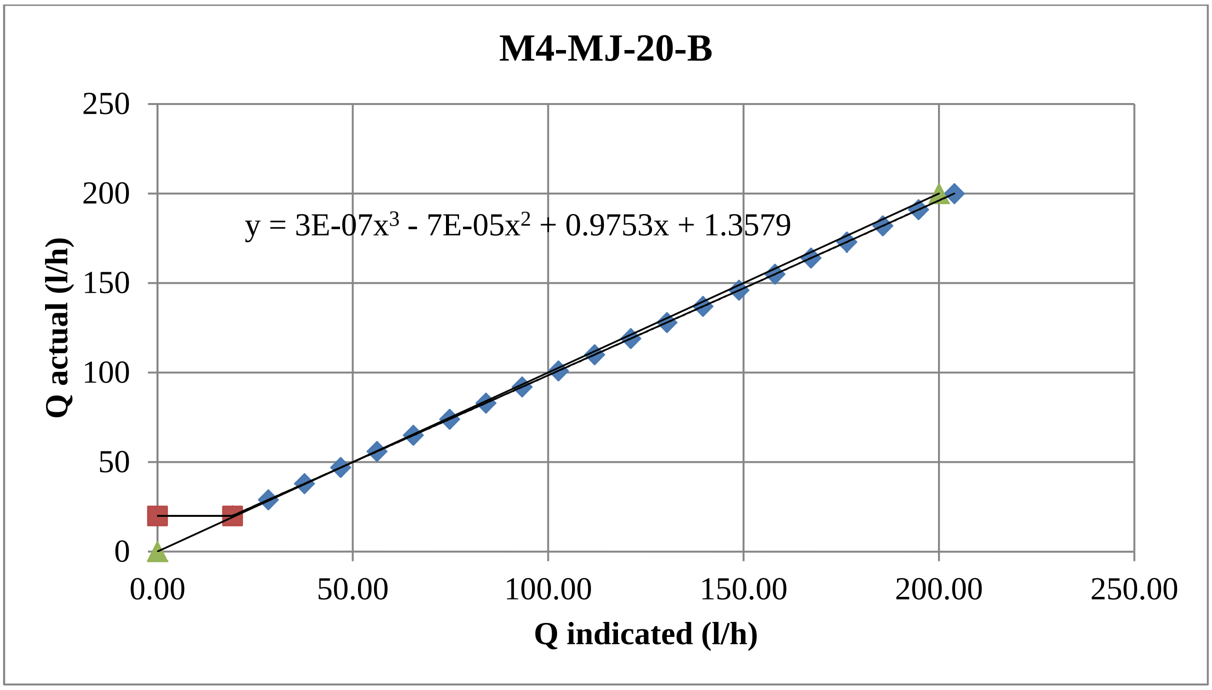

M3-MJ-15-C
y = 0.0002x³ - 0.0013x² + 0.8251x + 2.3956
Q actual (l/h)
Q indicated (l/h)
0
5
10
15
20
25
0.00
5.00
10.00
15.00
20.00
25.00


M3-MJ-20-B
y = 3E-07x³ - 9E-05x² + 0.9811x + 1.136
Q actual (l/h)
Q indicated (l/h)
0
50
100
150
200
250
0.00
50.00
100.00
150.00
200.00
250.00


M3-MJ-20-C
y = 4E-05x³ - 0.0005x² + 0.8587x + 3.262
Q actual (l/h)
Q indicated (l/h)
0
5
10
15
20
25
30
35
40
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00


y = -0.0127x² + 0.1184x + 0.7442
y = -0.0127x² + 0.1313x + 0.6805
Q indicated/ Q actual
Ln (Q actual (l/h))
0.9
0.92
0.94
0.96
0.98
1
1.02
1.04
0.0
1.0
2.0
3.0
4.0
5.0
6.0
M4-MJ-15-B
M4-MJ-20-B


M4-MJ-15-B
y = 9E-07x³ - 0.0001x² + 0.9751x + 0.8156
Q actual (l/h)
Q indicated (l/h)
0
20
40
60
80
100
120
140
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00


M4-MJ-20-B
y = 3E-07x³ - 7E-05x² + 0.9753x + 1.3579
Q actual (l/h)
Q indicated (l/h)
0
50
100
150
200
250
0.00
50.00
100.00
150.00
200.00
250.00

APPENDIX B: ON-SITE LEAKAGE DATA COLLECTION FIELD SHEET

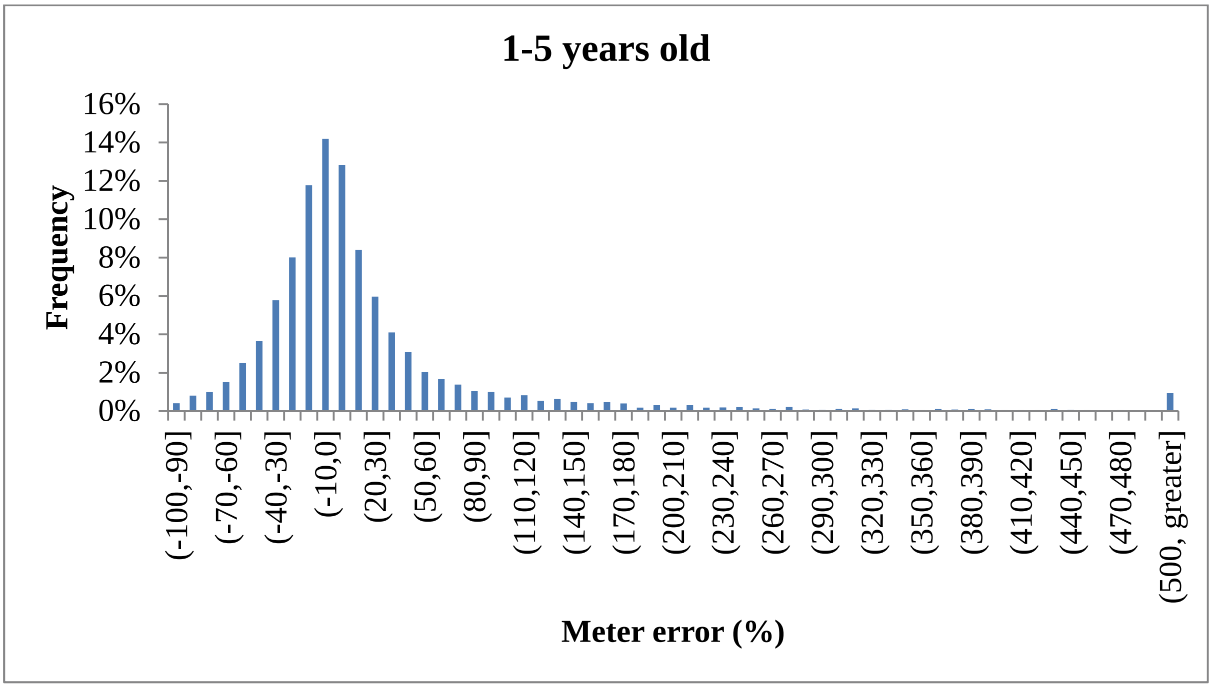
GENERAL INFORMATION (IDENTIFICATION)		OBSERVATION
SUBURB:		
STREET NAME:		
HOUSE NUMBER:		
STAND NUMBER		
METER NUMBER		

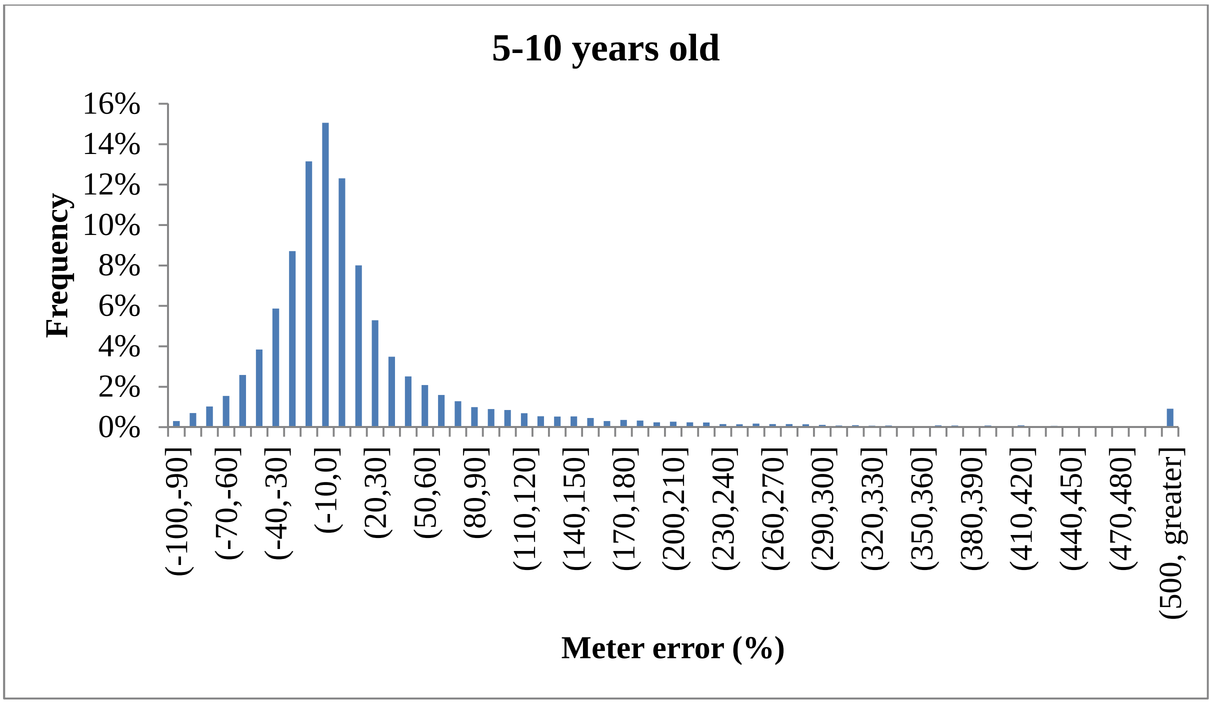
CATEGORIE&TYPE		DOMESTIC		NON DOMESTIC
		HOUSE		OFFICE
		BLOCK OF FLATS		SHOP
		TOWN HOUSE		RESTAURANT
		OTHER		HOTEL&GUEST
				SCHOOL
				HOSPITAL
				CHURCH
				OTHER

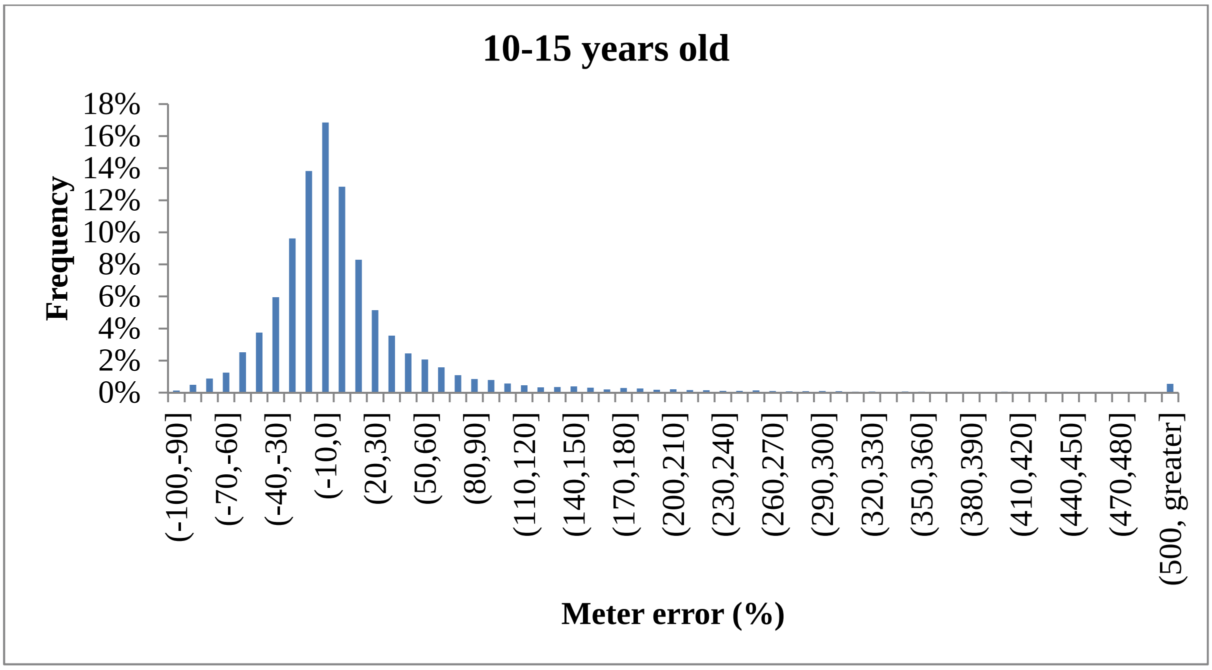
MEASUREMENTS INFORMATION		VISIT# 1	VISIT# 2
DATE/HOUR			
INITIAL METER READING			
READING AFTER 5 MIN	1		
10 MIN	2		
15 MIN	3		
20 MIN	4		
VOLUME AFTER 5 MIN	1		
10 MIN	2		
15 MIN	3		
20 MIN	4		
FLOW RATE (Litres/Hour)	1		
	2		
	3		
	4		
FINAL FLOW RATE (Litres/Hour)			
OBS :LEAK OR NO-LEAK			

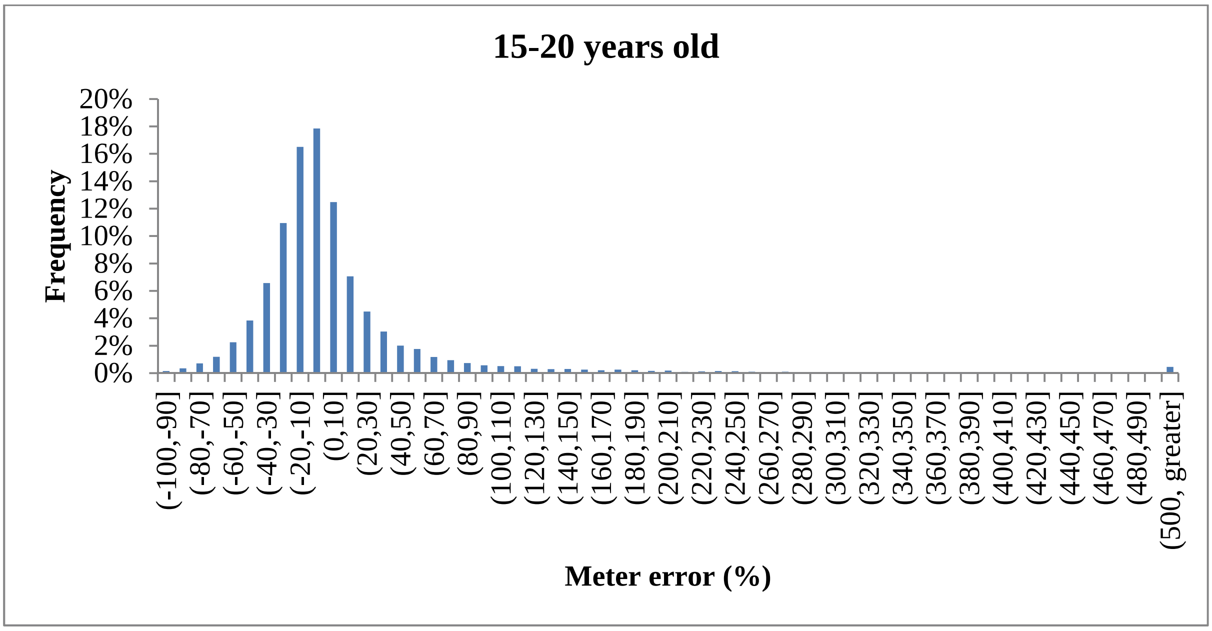
COMMENTS AND OBSERVATIONS:	Y/N		
meter were buried underground			
meter box could not be opened			
meter could not be located			
meter dials were illegible			
meter without box cover			
meter were leaking			
customer at home - not at home			
washing machine			

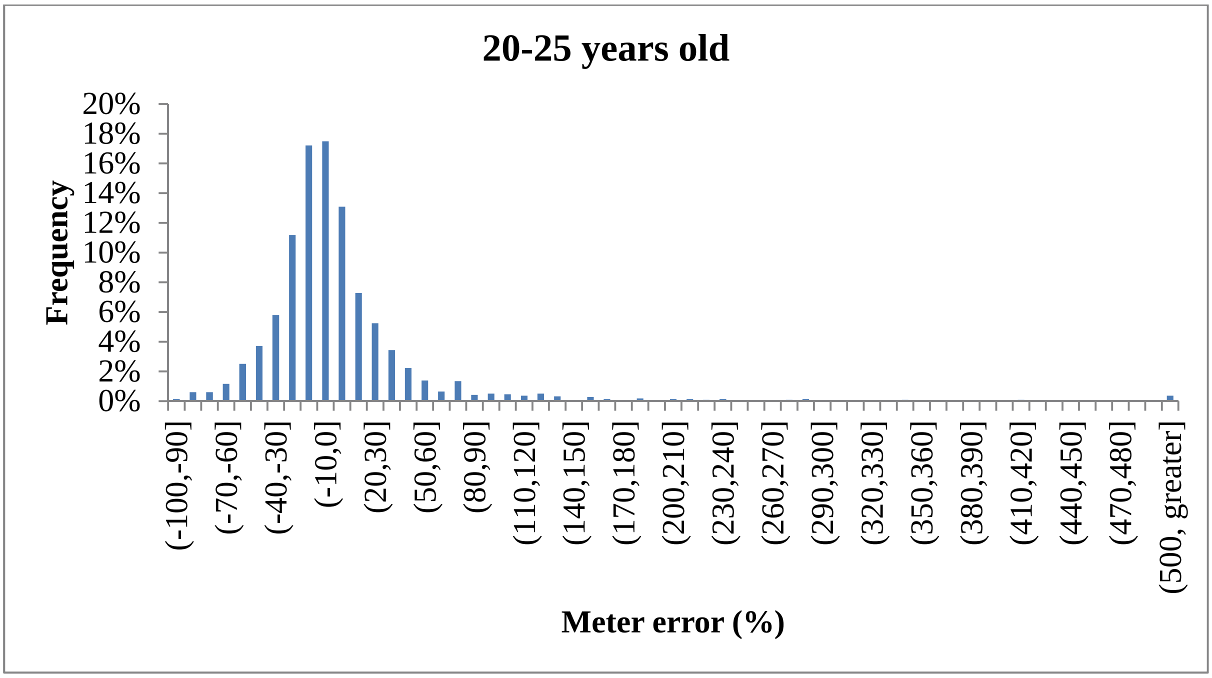
APPENDIX C: DATABASE ANALYSIS HISTOGRAMS

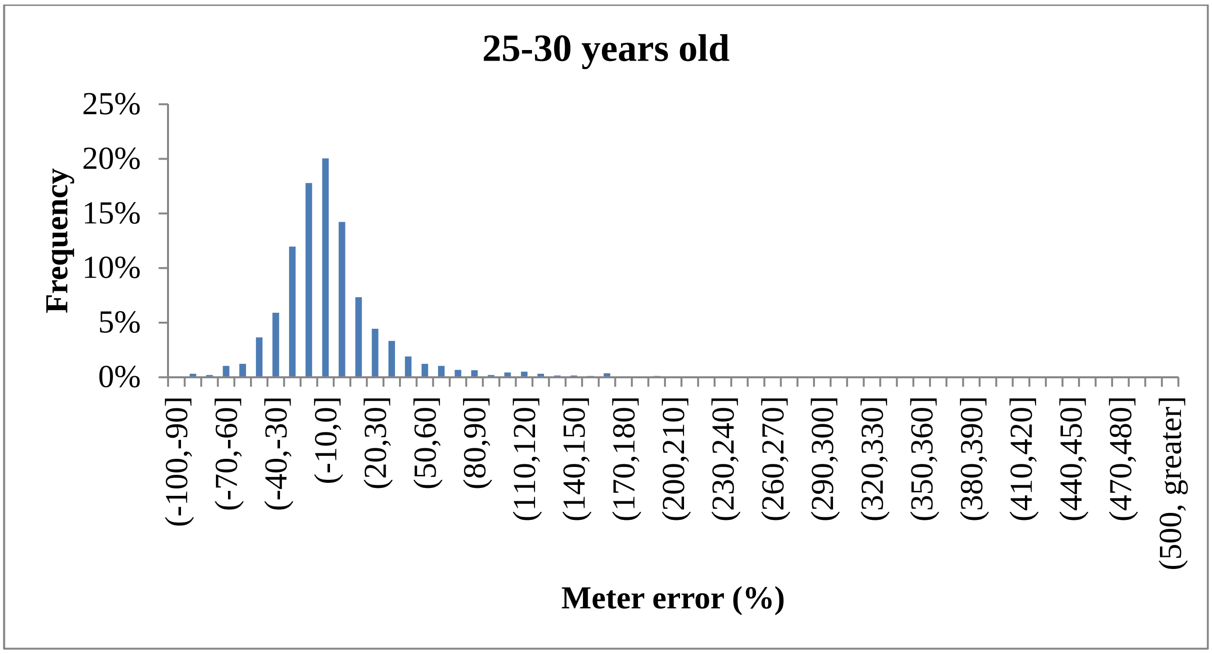


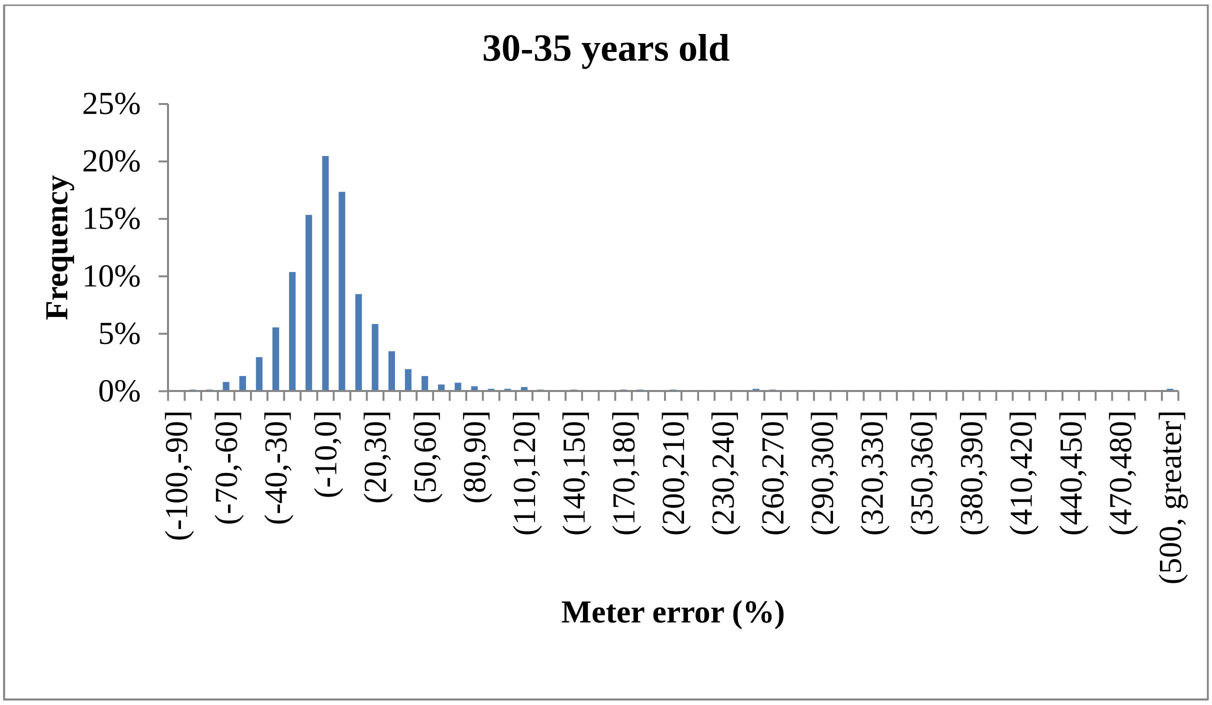


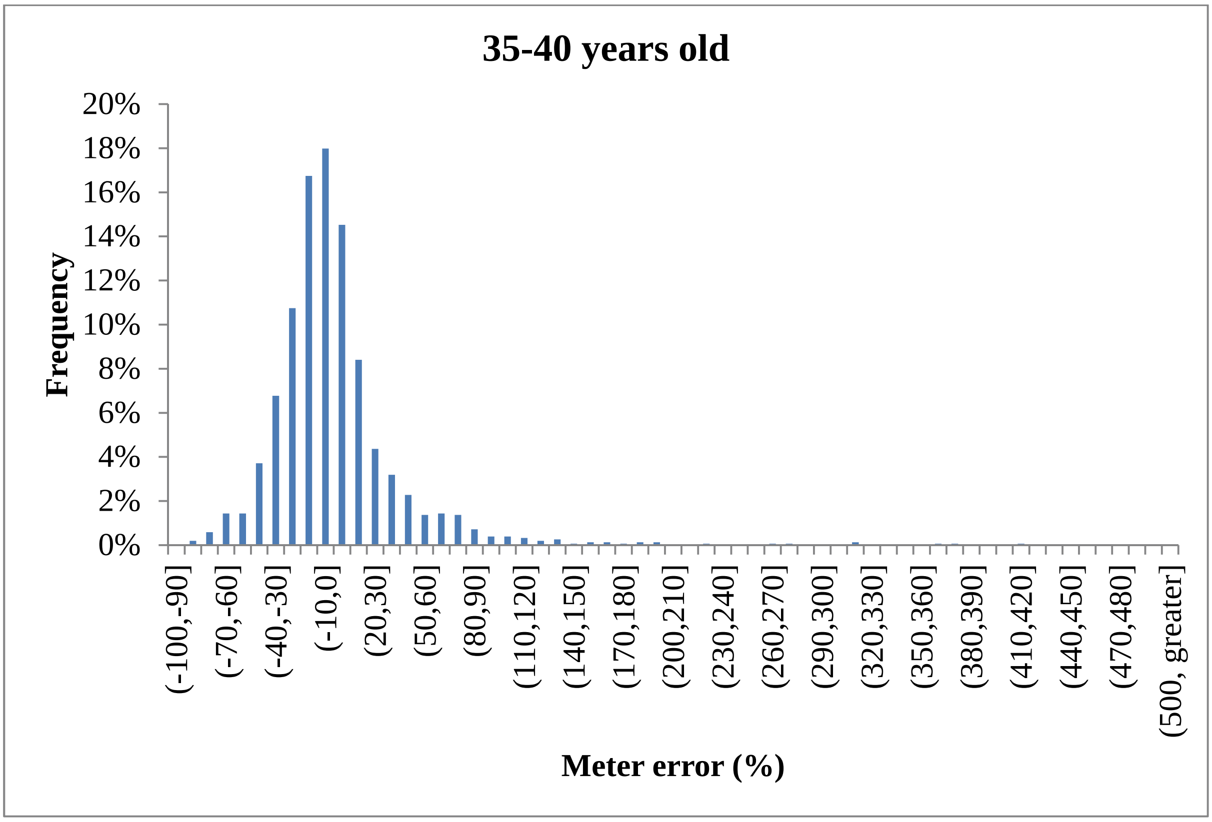

10-15 years old
Frequency
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
(-100,-90]
(-70,-60]
(-40,-30]
(-10,0]
(20,30]
(50,60]
(80,90]
(110,120]
(140,150]
(170,180]
(200,210]
(230,240]
(260,270]
(290,300]
(320,330]
(350,360]
(380,390]
(410,420]
(440,450]
(470,480]
(500, greater]
Meter error (%)

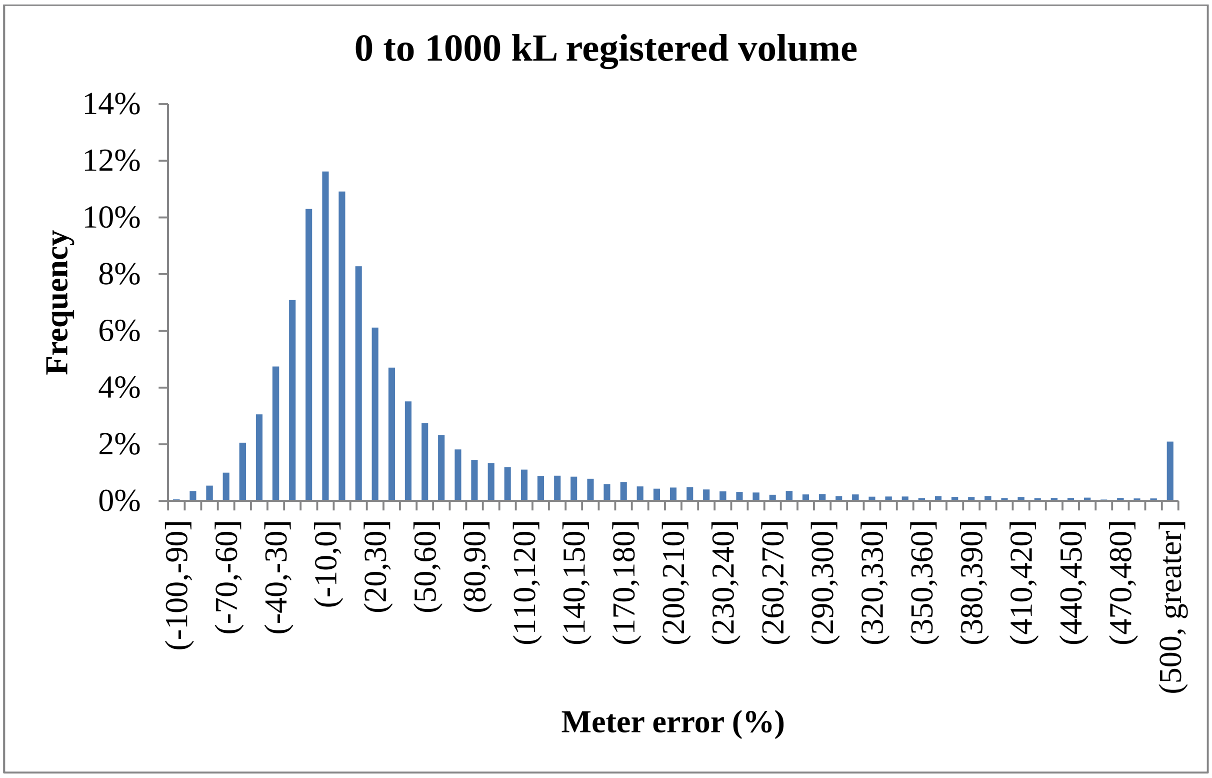

15-20 years old
Frequency
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
(-100,-90]
(-80,-70]
(-60,-50]
(-40,-30]
(-20,-10]
(0,10]
(20,30]
(40,50]
(60,70]
(80,90]
(100,110]
(120,130]
(140,150]
(160,170]
(180,190]
(200,210]
(220,230]
(240,250]
(260,270]
(280,290]
(300,310]
(320,330]
(340,350]
(360,370]
(380,390]
(400,410]
(420,430]
(440,450]
(460,470]
(480,490]
(500, greater]
Meter error (%)

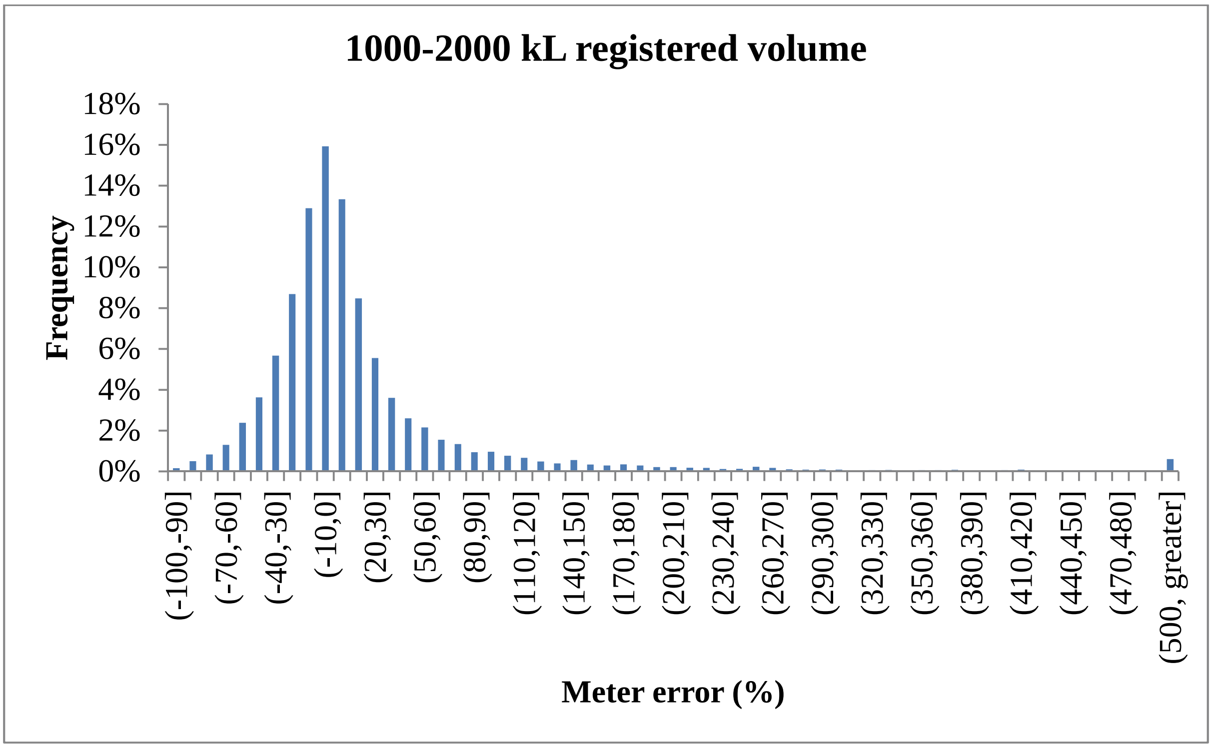

20-25 years old
Frequency
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
(-100,-90]
(-70,-60]
(-40,-30]
(-10,0]
(20,30]
(50,60]
(80,90]
(110,120]
(140,150]
(170,180]
(200,210]
(230,240]
(260,270]
(290,300]
(320,330]
(350,360]
(380,390]
(410,420]
(440,450]
(470,480]
(500, greater]
Meter error (%)

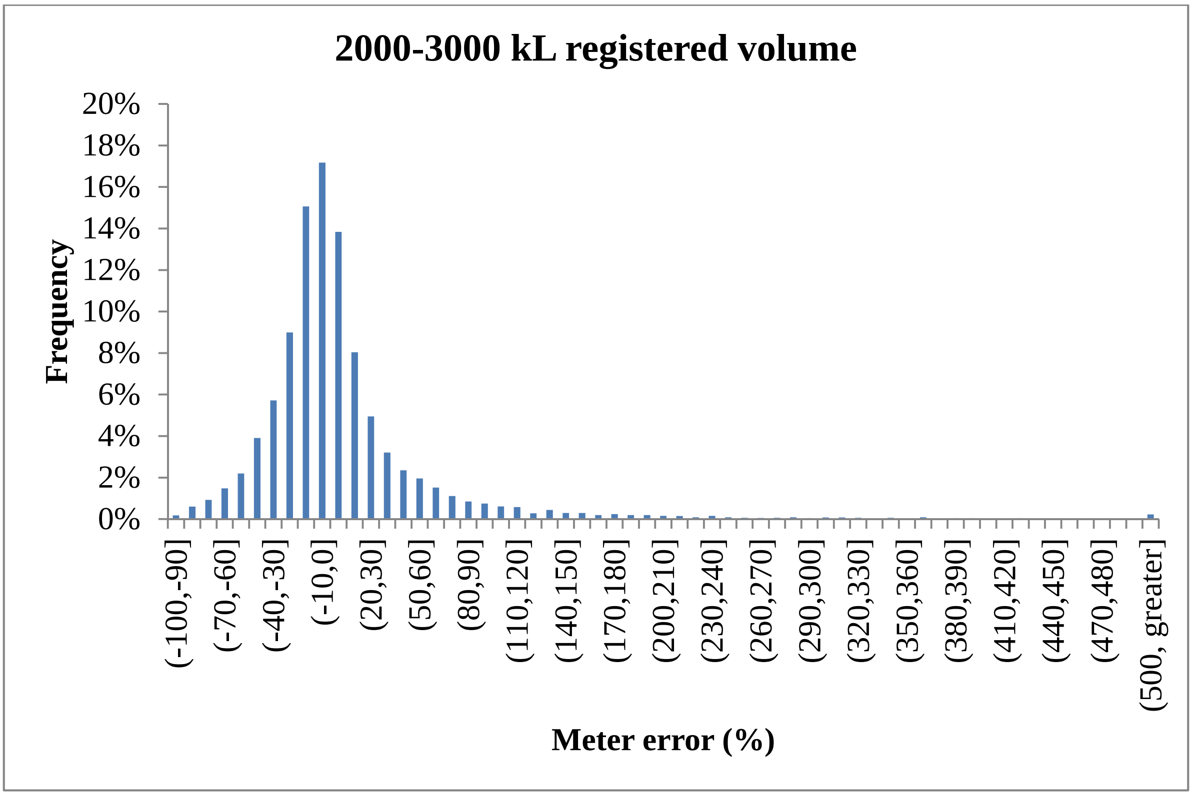

25-30 years old
Frequency
25%
20%
15%
10%
5%
0%
(-100,-90]
(-70,-60]
(-40,-30]
(-10,0]
(20,30]
(50,60]
(80,90]
(110,120]
(140,150]
(170,180]
(200,210]
(230,240]
(260,270]
(290,300]
(320,330]
(350,360]
(380,390]
(410,420]
(440,450]
(470,480]
(500, greater]
Meter error (%)

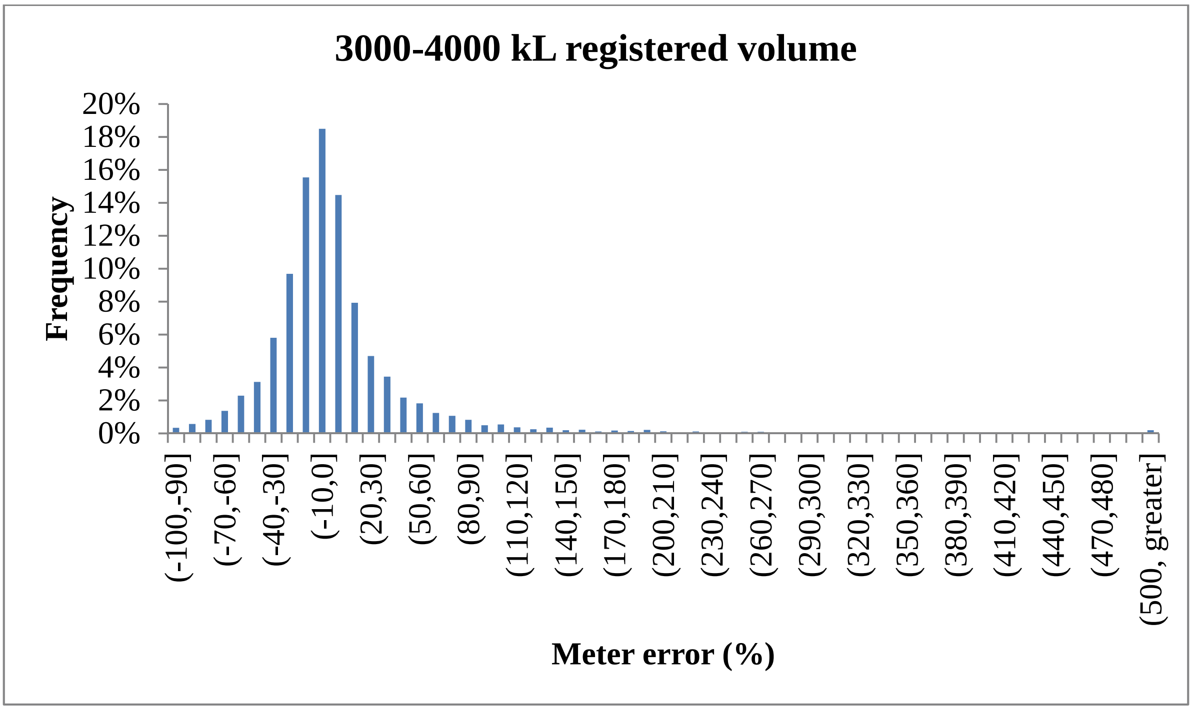

30-35 years old
Frequency
25%
20%
15%
10%
5%
0%
(-100,-90]
(-70,-60]
(-40,-30]
(-10,0]
(20,30]
(50,60]
(80,90]
(110,120]
(140,150]
(170,180]
(200,210]
(230,240]
(260,270]
(290,300]
(320,330]
(350,360]
(380,390]
(410,420]
(440,450]
(470,480]
(500, greater]
Meter error (%)

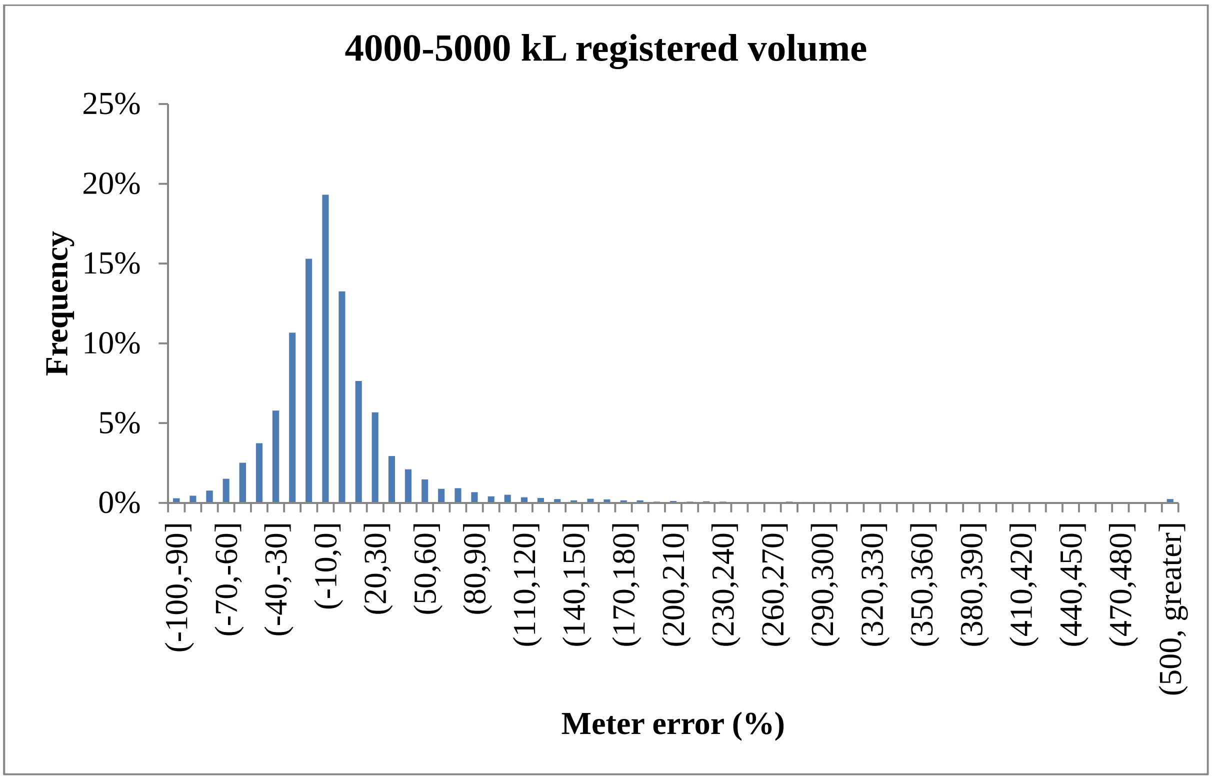

35-40 years old
Frequency
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
(-100,-90]
(-70,-60]
(-40,-30]
(-10,0]
(20,30]
(50,60]
(80,90]
(110,120]
(140,150]
(170,180]
(200,210]
(230,240]
(260,270]
(290,300]
(320,330]
(350,360]
(380,390]
(410,420]
(440,450]
(470,480]
(500, greater]
Meter error (%)


0 to 1000 kL registered volume
Frequency
14%
12%
10%
8%
6%
4%
2%
0%
(-100,-90]
(-70,-60]
(-40,-30]
(-10,0]
(20,30]
(50,60]
(80,90]
(110,120]
(140,150]
(170,180]
(200,210]
(230,240]
(260,270]
(290,300]
(320,330]
(350,360]
(380,390]
(410,420]
(440,450]
(470,480]
(500, greater]
Meter error (%)

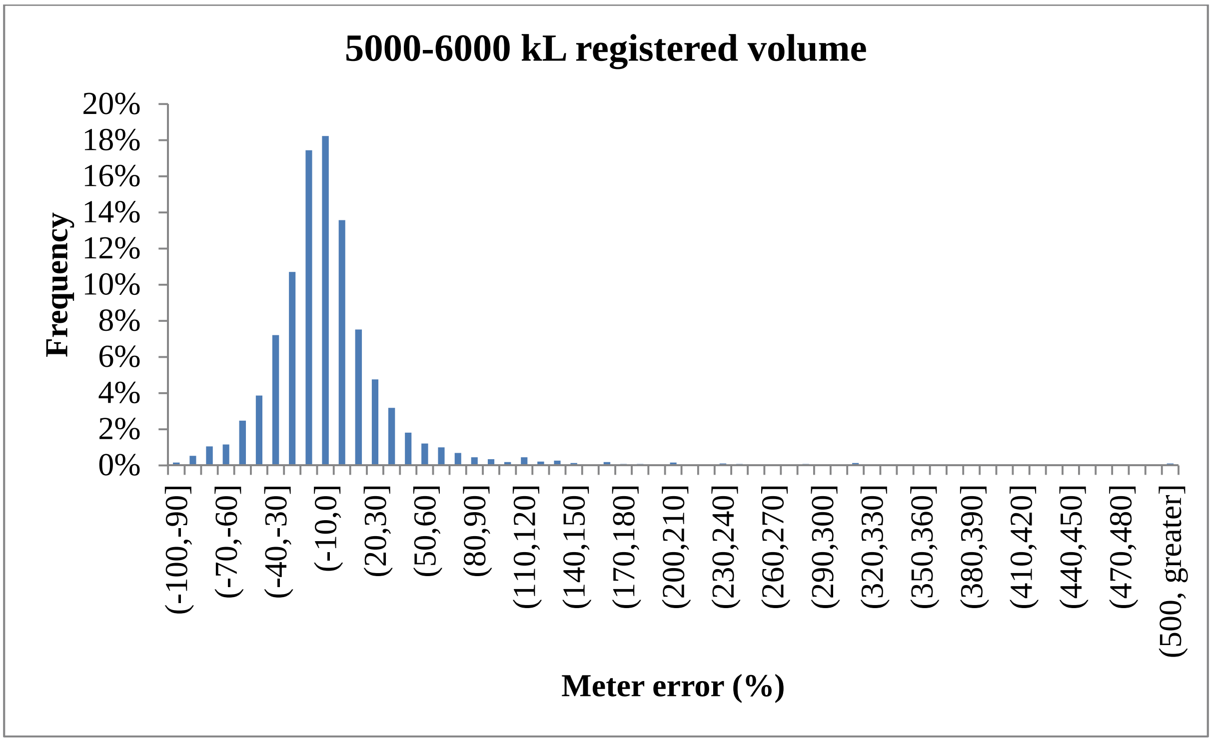

1000-2000 kL registered volume
Frequency
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
(-100,-90]
(-70,-60]
(-40,-30]
(-10,0]
(20,30]
(50,60]
(80,90]
(110,120]
(140,150]
(170,180]
(200,210]
(230,240]
(260,270]
(290,300]
(320,330]
(350,360]
(380,390]
(410,420]
(440,450]
(470,480]
(500, greater]
Meter error (%)


2000-3000 kL registered volume
Frequency
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
(-100,-90]
(-70,-60]
(-40,-30]
(-10,0]
(20,30]
(50,60]
(80,90]
(110,120]
(140,150]
(170,180]
(200,210]
(230,240]
(260,270]
(290,300]
(320,330]
(350,360]
(380,390]
(410,420]
(440,450]
(470,480]
(500, greater]
Meter error (%)

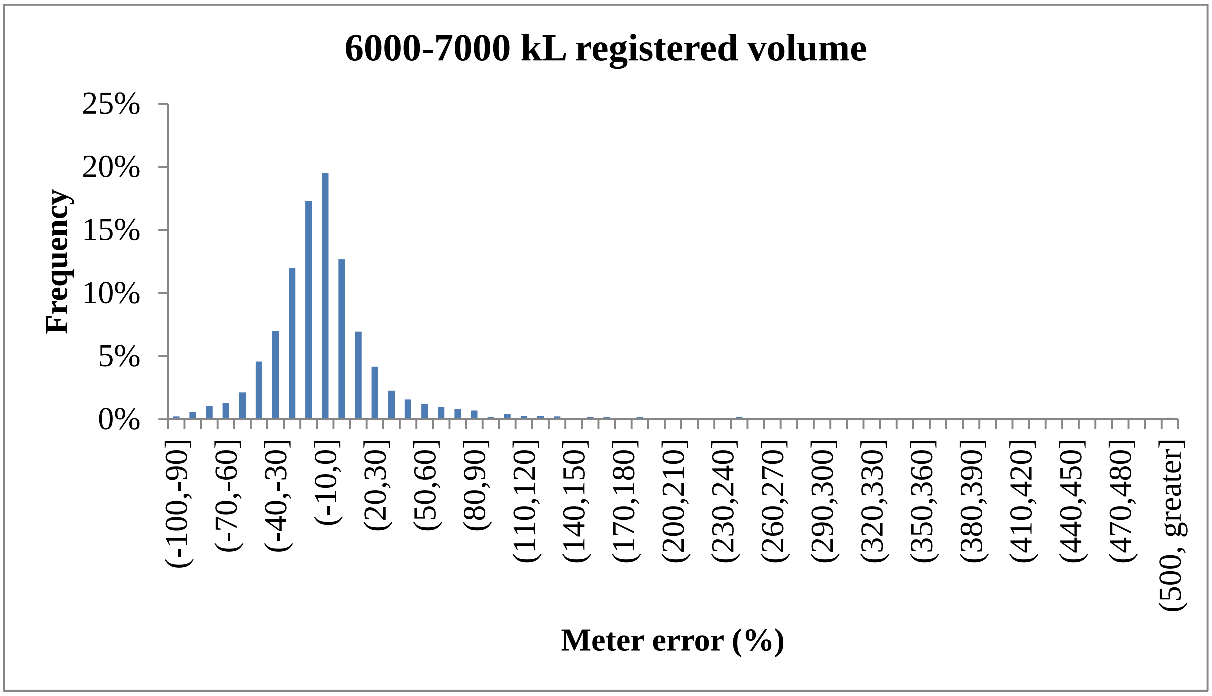

3000-4000 kL registered volume
Frequency
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
(-100,-90]
(-70,-60]
(-40,-30]
(-10,0]
(20,30]
(50,60]
(80,90]
(110,120]
(140,150]
(170,180]
(200,210]
(230,240]
(260,270]
(290,300]
(320,330]
(350,360]
(380,390]
(410,420]
(440,450]
(470,480]
(500, greater]
Meter error (%)

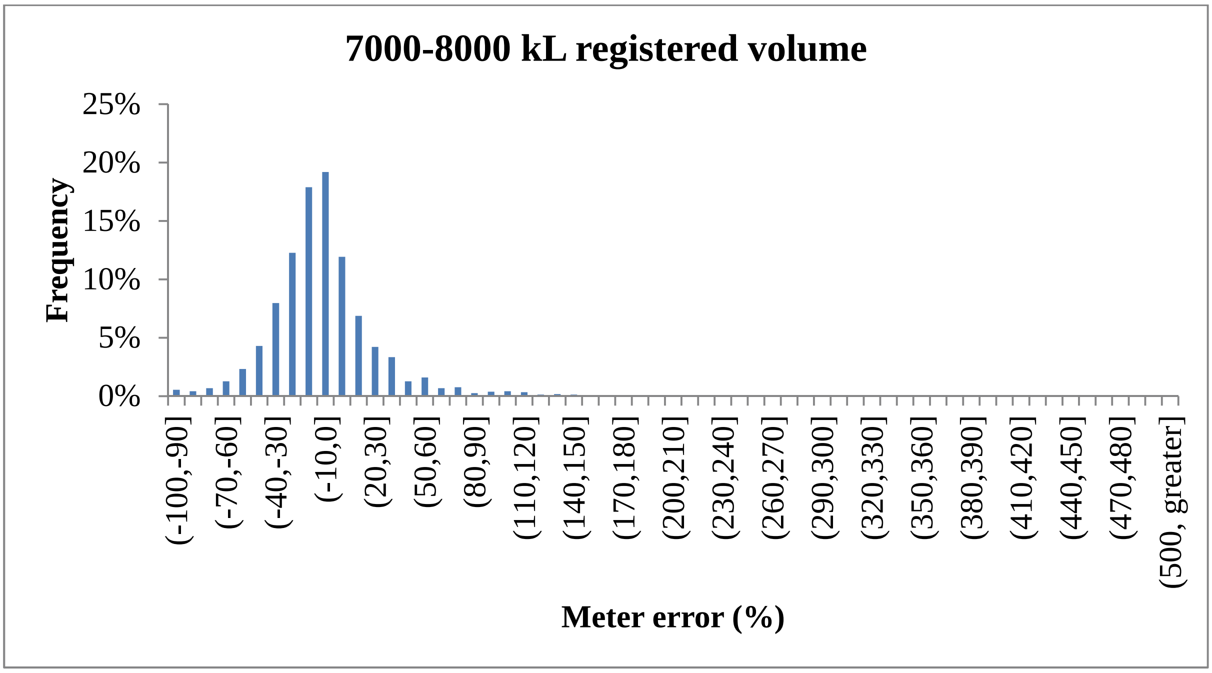


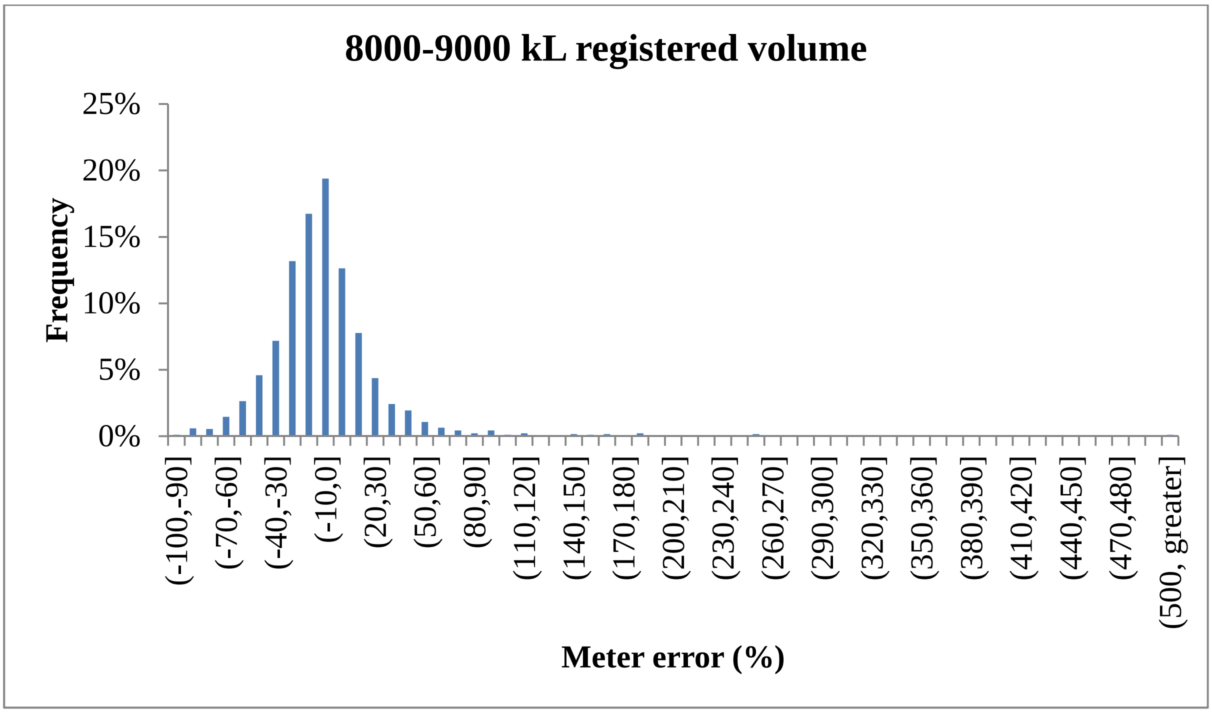
4000-5000 kL registered volume
Frequency
25%
20%
15%
10%
5%
0%
(-100,-90]
(-70,-60]
(-40,-30]
(-10,0]
(20,30]
(50,60]
(80,90]
(110,120]
(140,150]
(170,180]
(200,210]
(230,240]
(260,270]
(290,300]
(320,330]
(350,360]
(380,390]
(410,420]
(440,450]
(470,480]
(500, greater]
Meter error (%)

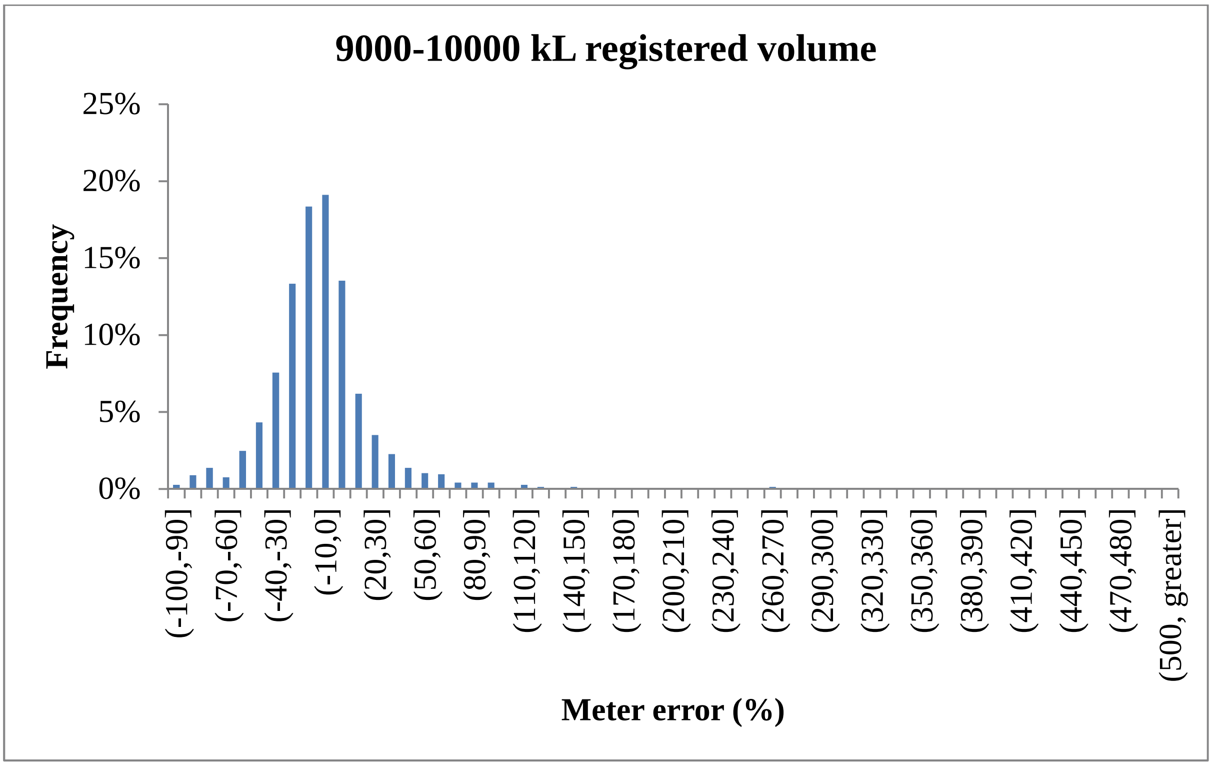


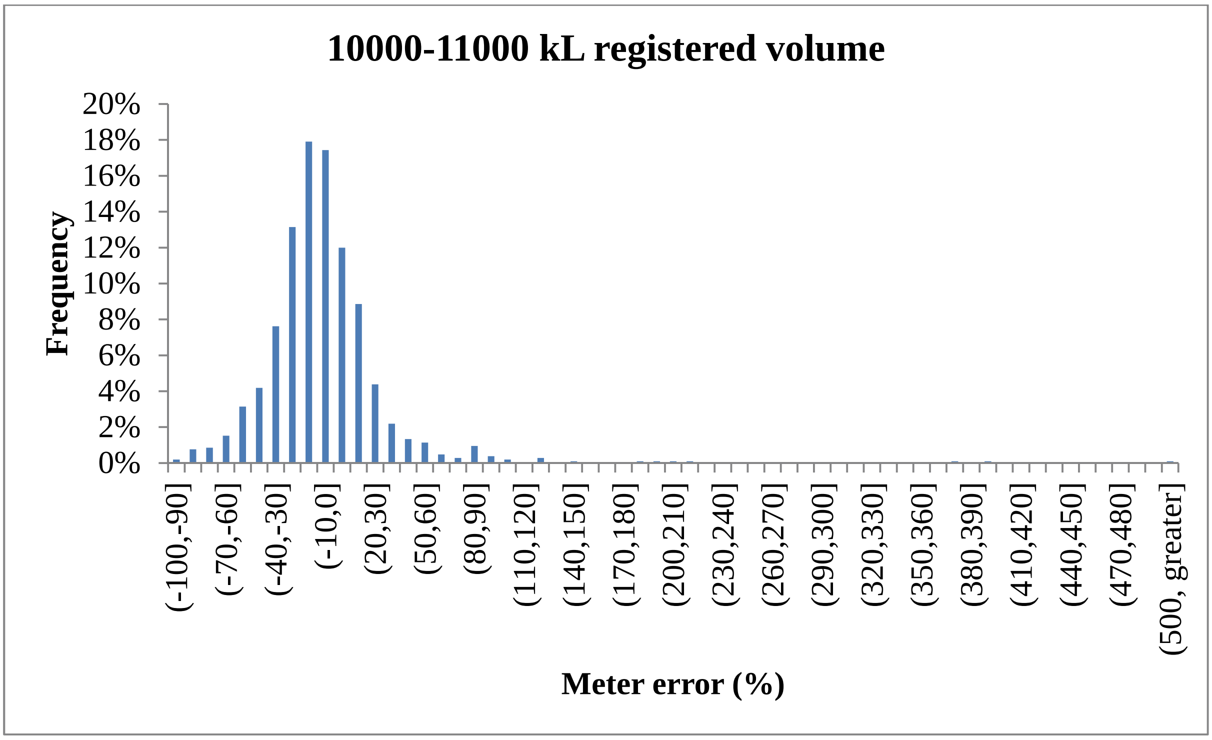
5000-6000 kL registered volume
Frequency
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
(-100,-90]
(-70,-60]
(-40,-30]
(-10,0]
(20,30]
(50,60]
(80,90]
(110,120]
(140,150]
(170,180]
(200,210]
(230,240]
(260,270]
(290,300]
(320,330]
(350,360]
(380,390]
(410,420]
(440,450]
(470,480]
(500, greater]
Meter error (%)


6000-7000 kL registered volume
25%
20%
15%
10%
5%
0%
Frequency
(-100,-90]
(-70,-60]
(-40,-30]
(-10,0]
(20,30]
(50,60]
(80,90]
(110,120]
(140,150]
(170,180]
(200,210]
(230,240]
(260,270]
(290,300]
(320,330]
(350,360]
(380,390]
(410,420]
(440,450]
(470,480]
(500, greater]
Meter error (%)

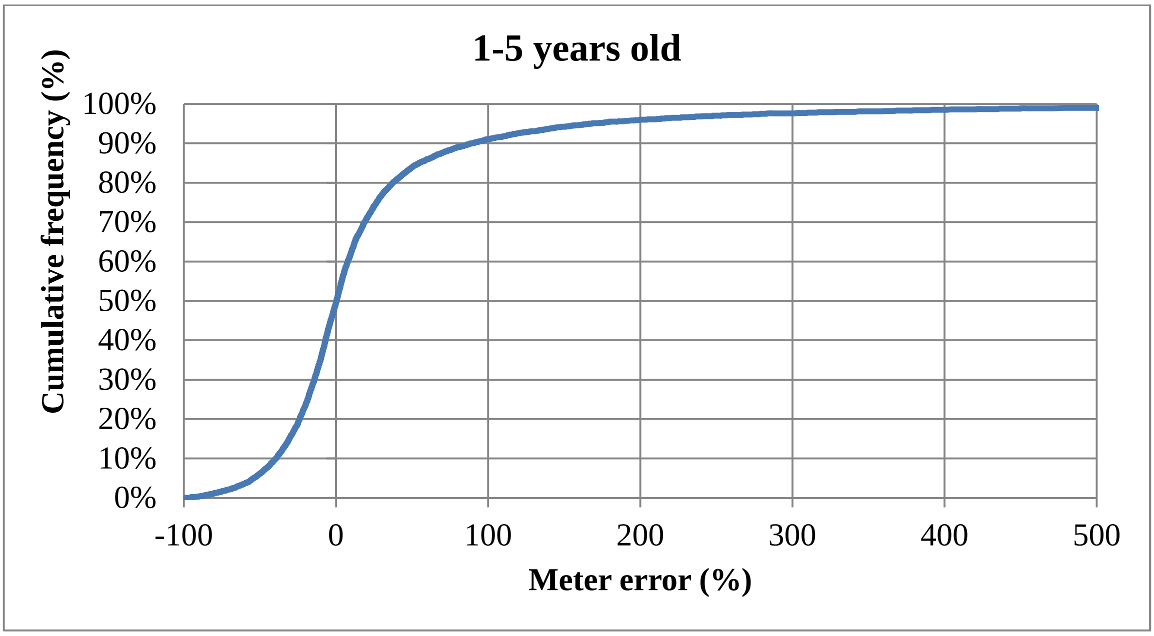

7000-8000 kL registered volume
25%
20%
15%
10%
5%
0%
Frequency
(-100,-90]
(-70,-60]
(-40,-30]
(-10,0]
(20,30]
(50,60]
(80,90]
(110,120]
(140,150]
(170,180]
(200,210]
(230,240]
(260,270]
(290,300]
(320,330]
(350,360]
(380,390]
(410,420]
(440,450]
(470,480]
(500, greater]
Meter error (%)

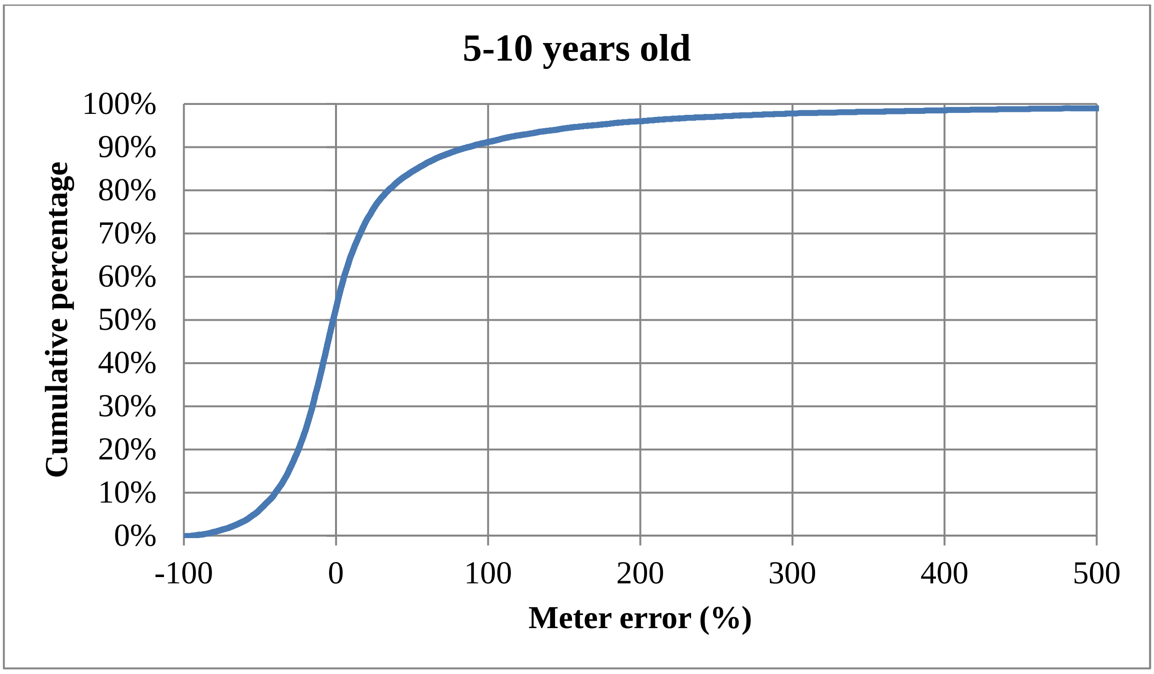

8000-9000 kL registered volume
Frequency
25%
20%
15%
10%
5%
0%
(-100,-90]
(-70,-60]
(-40,-30]
(-10,0]
(20,30]
(50,60]
(80,90]
(110,120]
(140,150]
(170,180]
(200,210]
(230,240]
(260,270]
(290,300]
(320,330]
(350,360]
(380,390]
(410,420]
(440,450]
(470,480]
(500, greater]
Meter error (%)

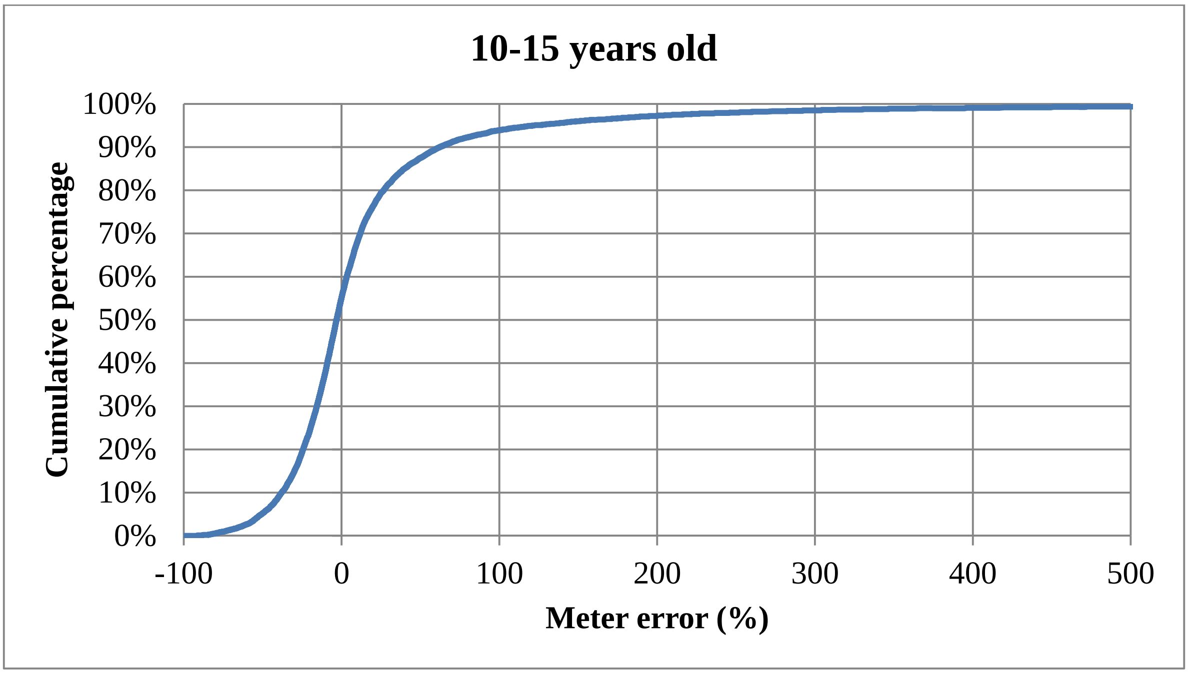

9000-10000 kL registered volume
Frequency
25%
20%
15%
10%
5%
0%
(-100,-90]
(-70,-60]
(-40,-30]
(-10,0]
(20,30]
(50,60]
(80,90]
(110,120]
(140,150]
(170,180]
(200,210]
(230,240]
(260,270]
(290,300]
(320,330]
(350,360]
(380,390]
(410,420]
(440,450]
(470,480]
(500, greater]
Meter error (%)

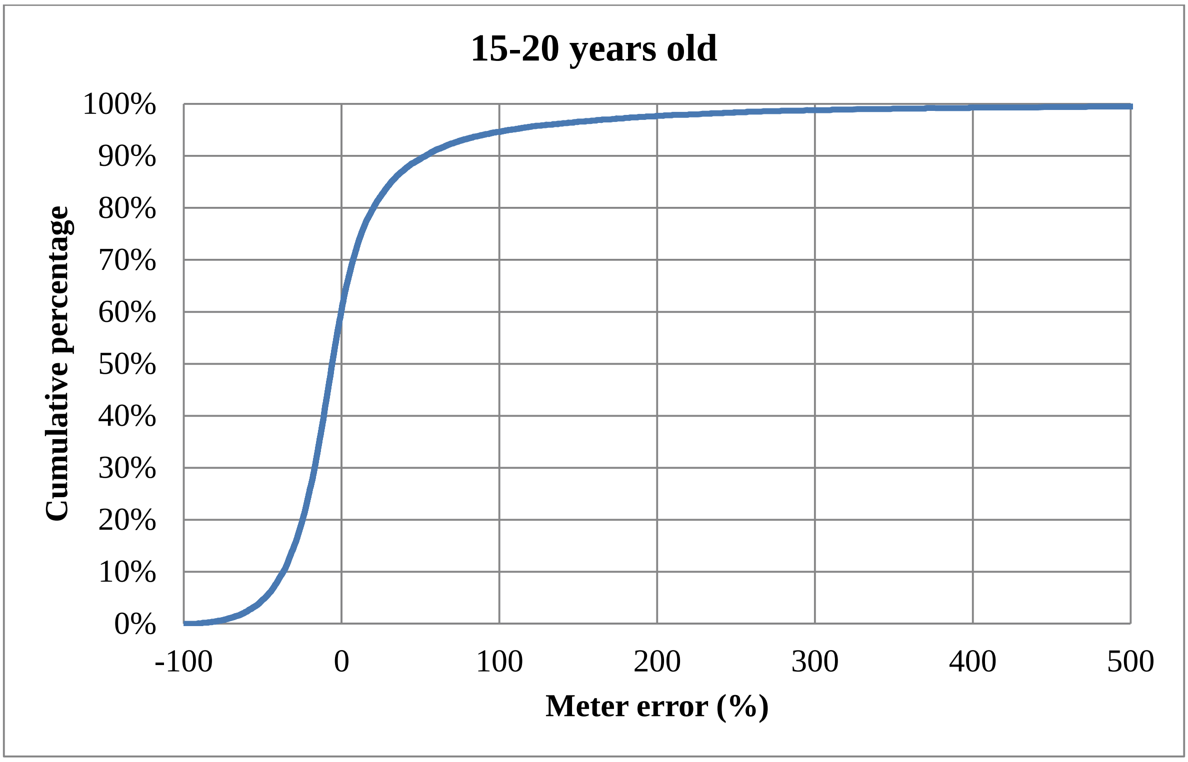

10000-11000 kL registered volume
Frequency
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
(-100,-90]
(-70,-60]
(-40,-30]
(-10,0]
(20,30]
(50,60]
(80,90]
(110,120]
(140,150]
(170,180]
(200,210]
(230,240]
(260,270]
(290,300]
(320,330]
(350,360]
(380,390]
(410,420]
(440,450]
(470,480]
(500, greater]
Meter error (%)

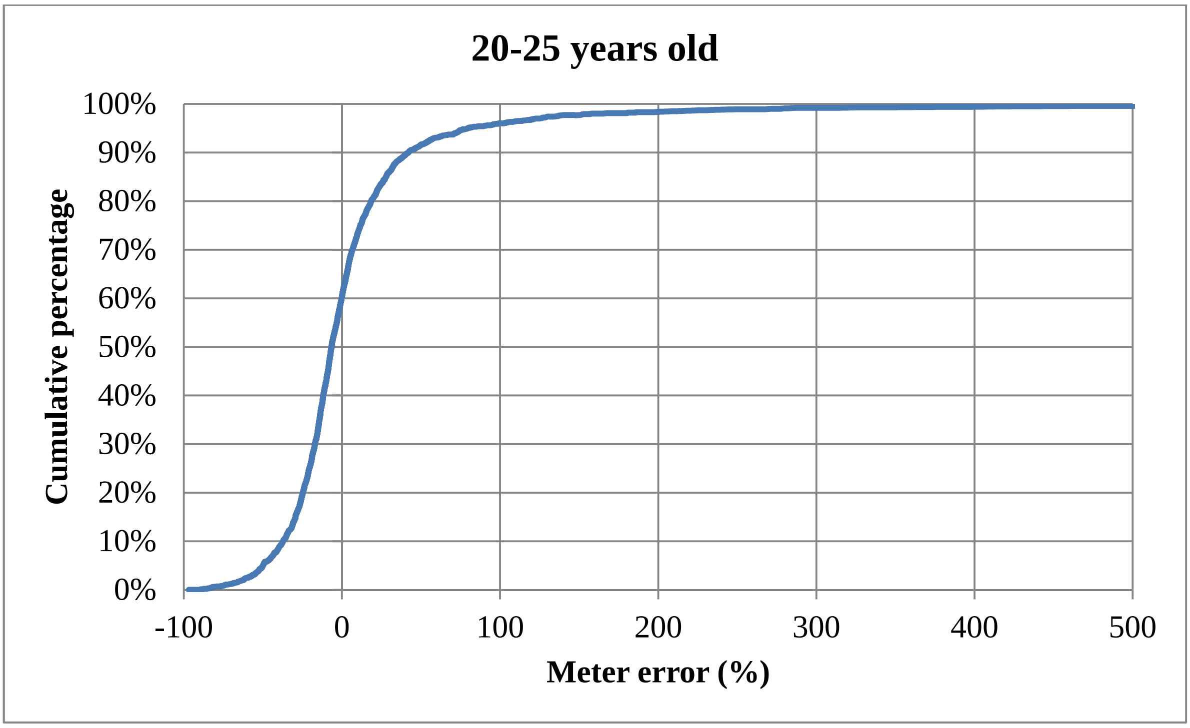
APPENDIX D: DATABASE ANALYSIS CUMULATIVE PERCENTAGE GRAPHS

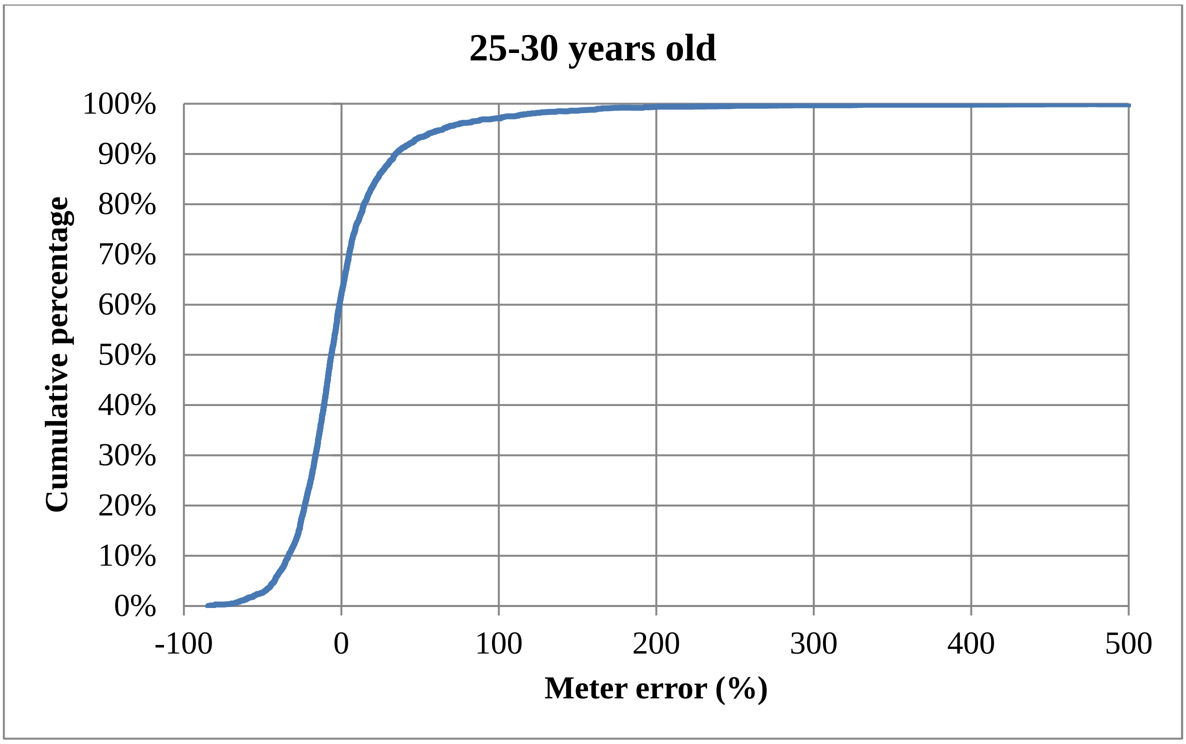


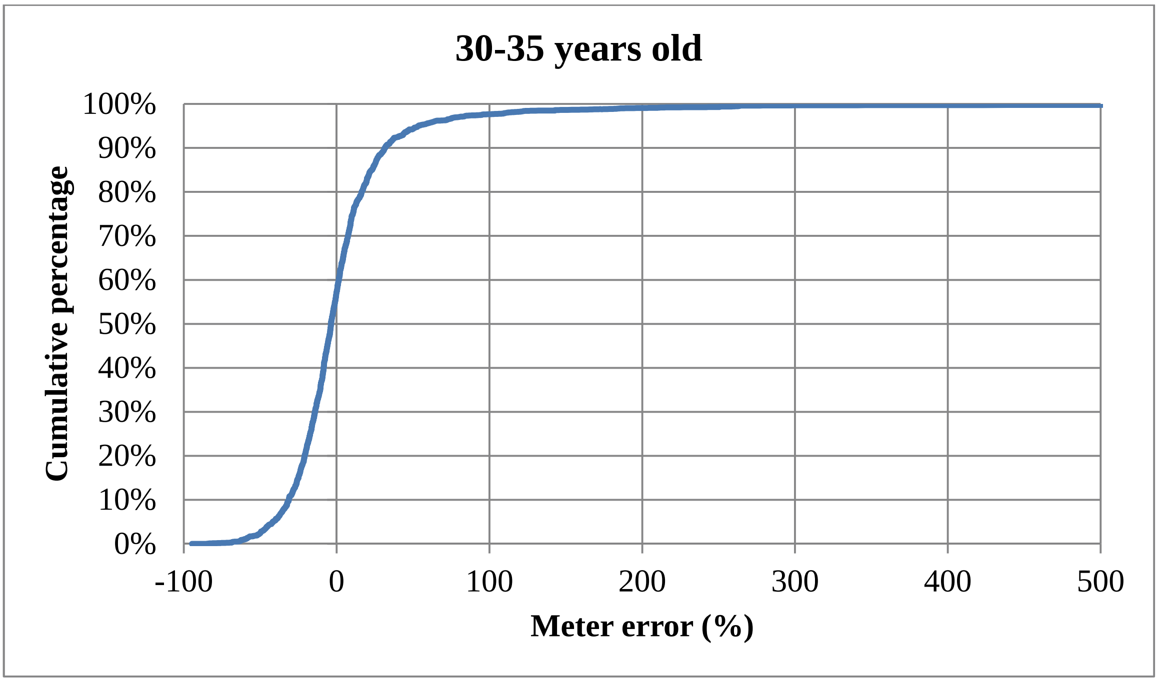



10-15 years old
Cumulative percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-100
0
100
200
300
400
500
Meter error (%)

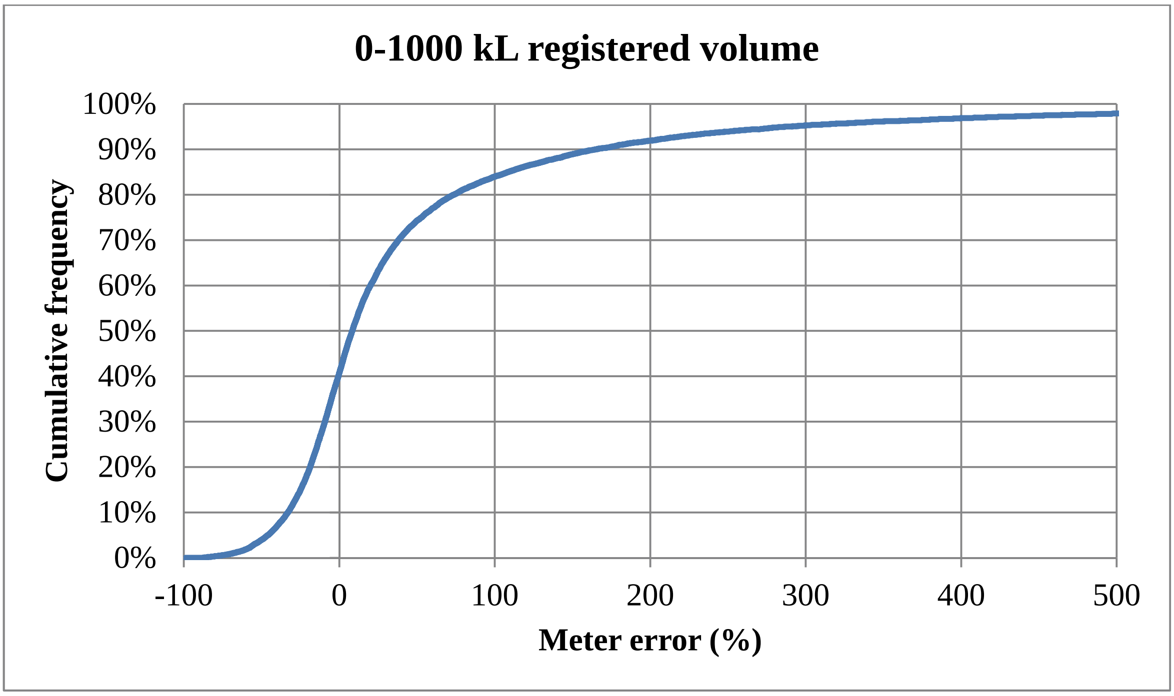

15-20 years old
Cumulative percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-100
0
100
200
300
400
500
Meter error (%)

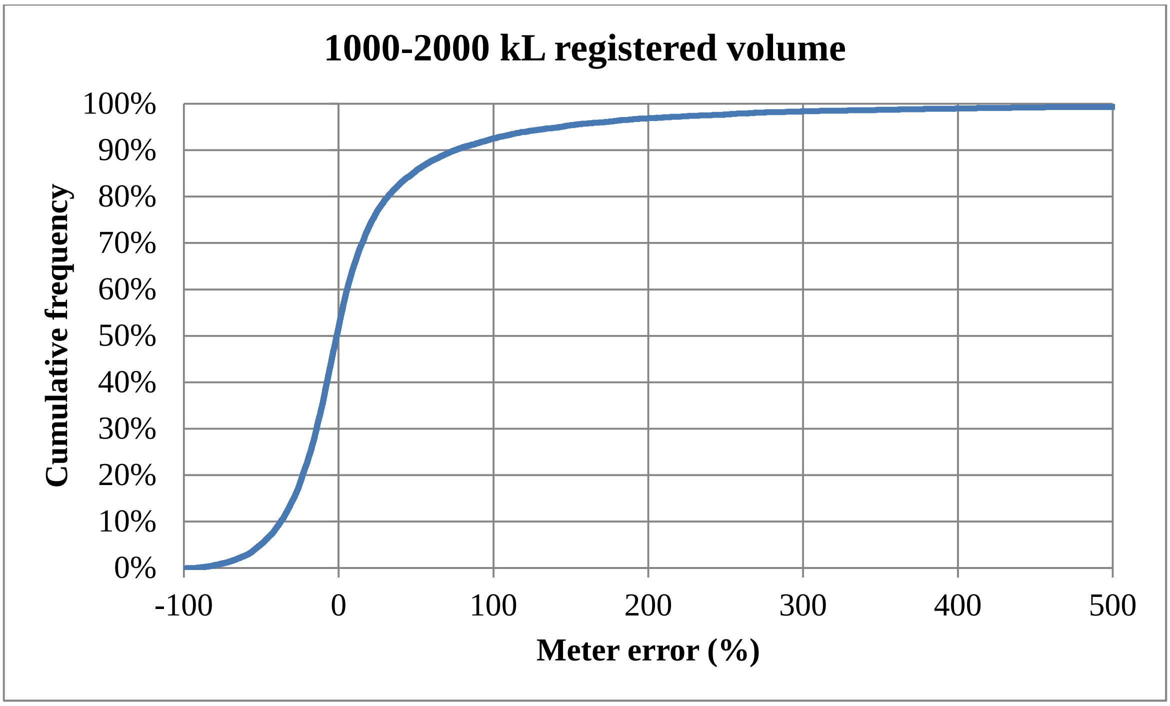

20-25 years old
Cumulative percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-100
0
100
200
300
400
500
Meter error (%)

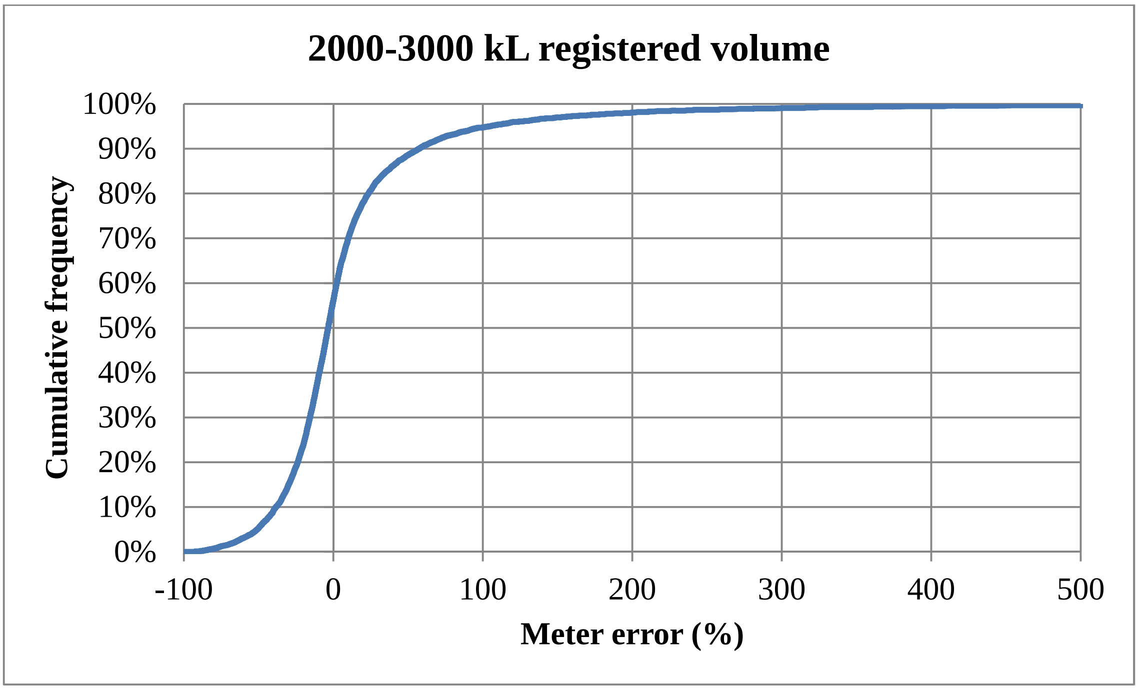

25-30 years old
Cumulative percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-100
0
100
200
300
400
500
Meter error (%)

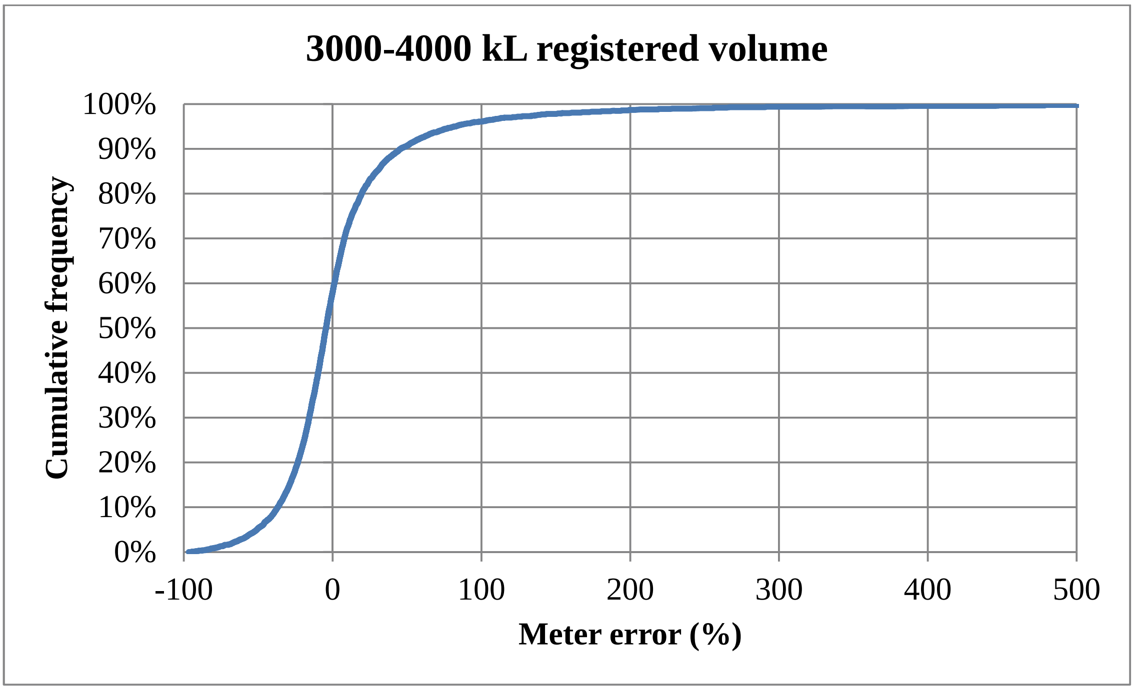

30-35 years old
Cumulative percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-100
0
100
200
300
400
500
Meter error (%)

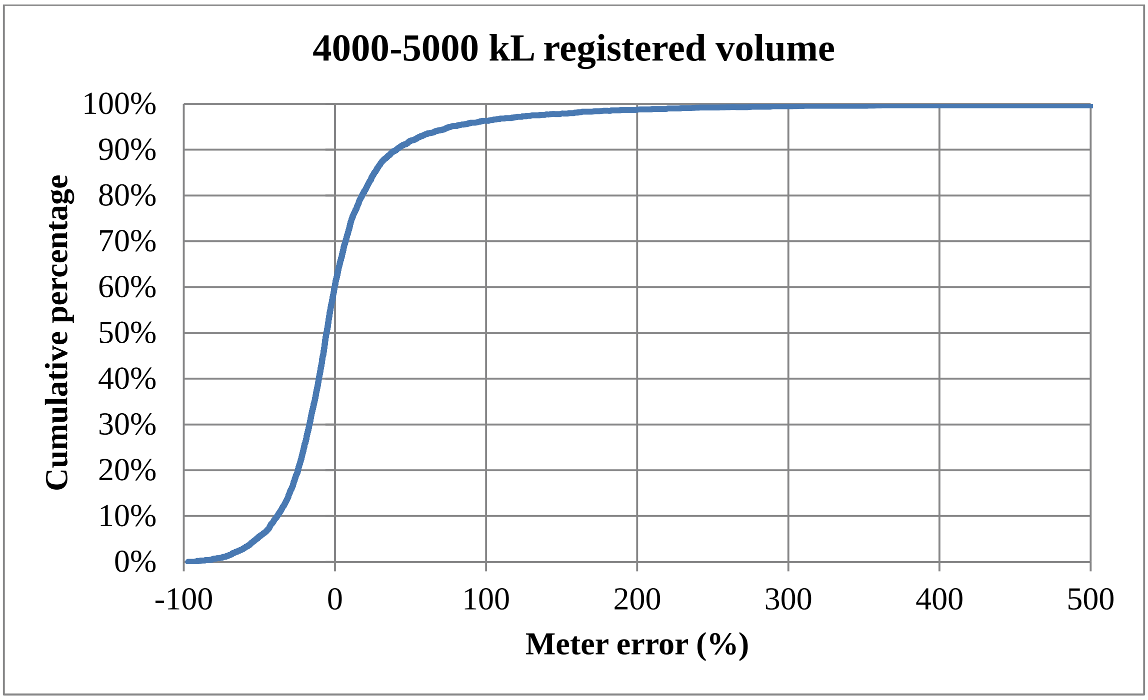

35-40 years old
Cumulative percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-200
-100
0
100
200
300
400
500
Meter error (%)

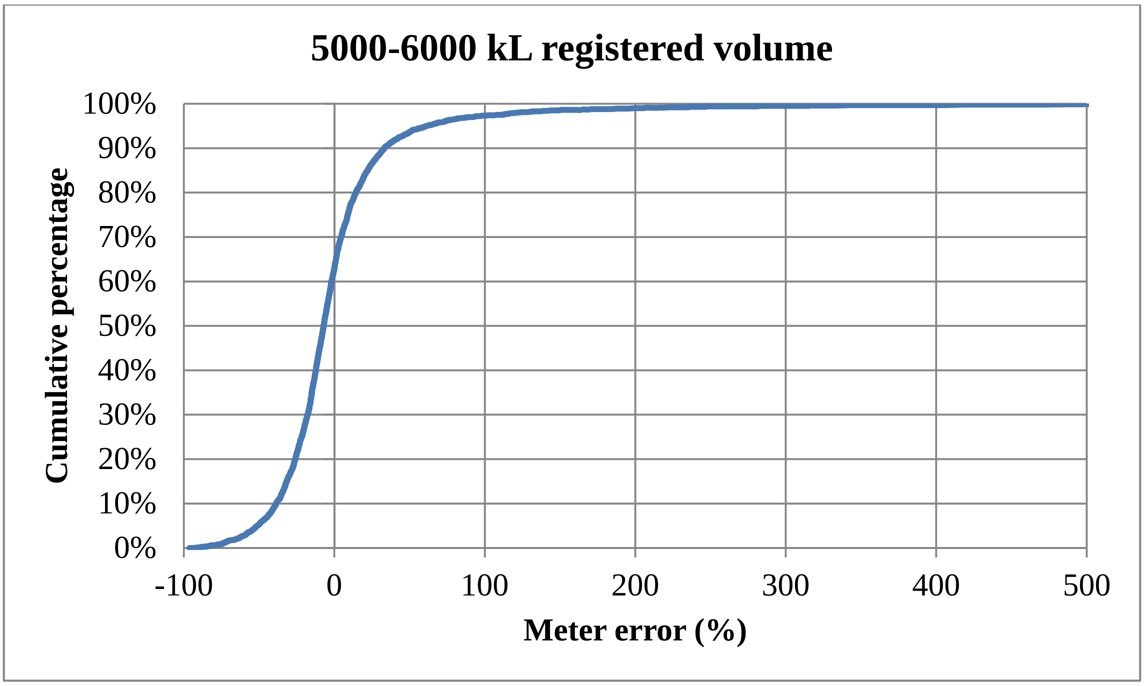

0-1000 kL registered volume
Cumulative frequency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-100
0
100
200
300
400
500
Meter error (%)

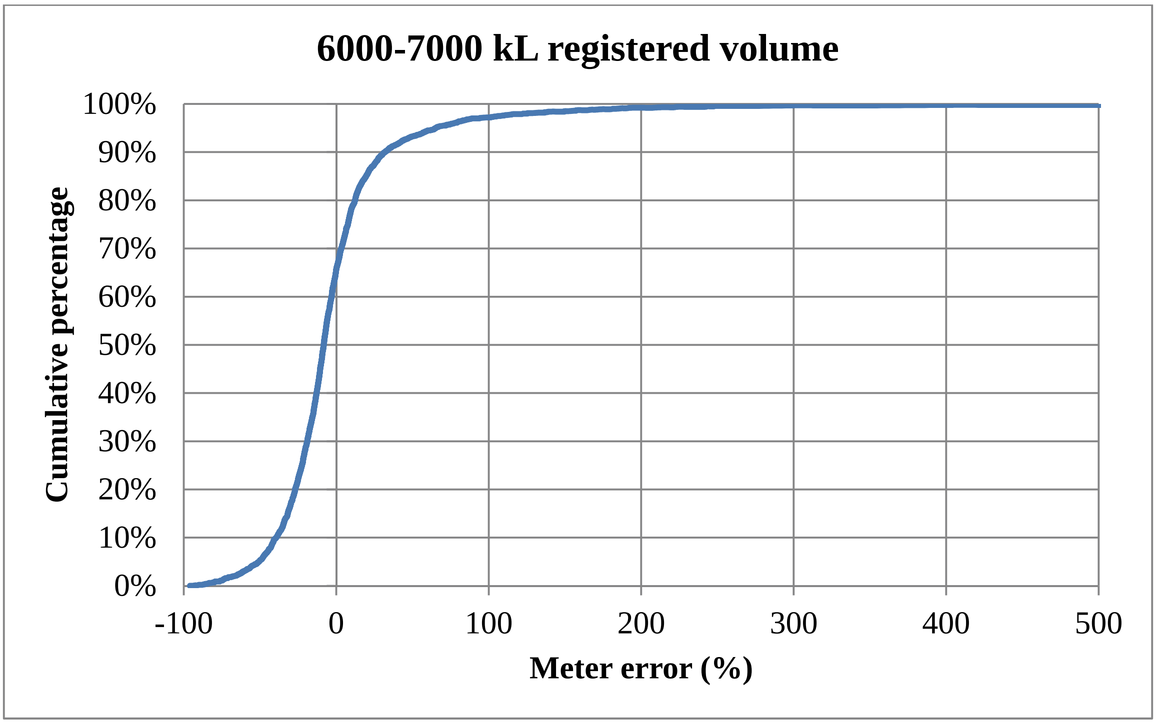

1000-2000 kL registered volume
Cumulative frequency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-100
0
100
200
300
400
500
Meter error (%)

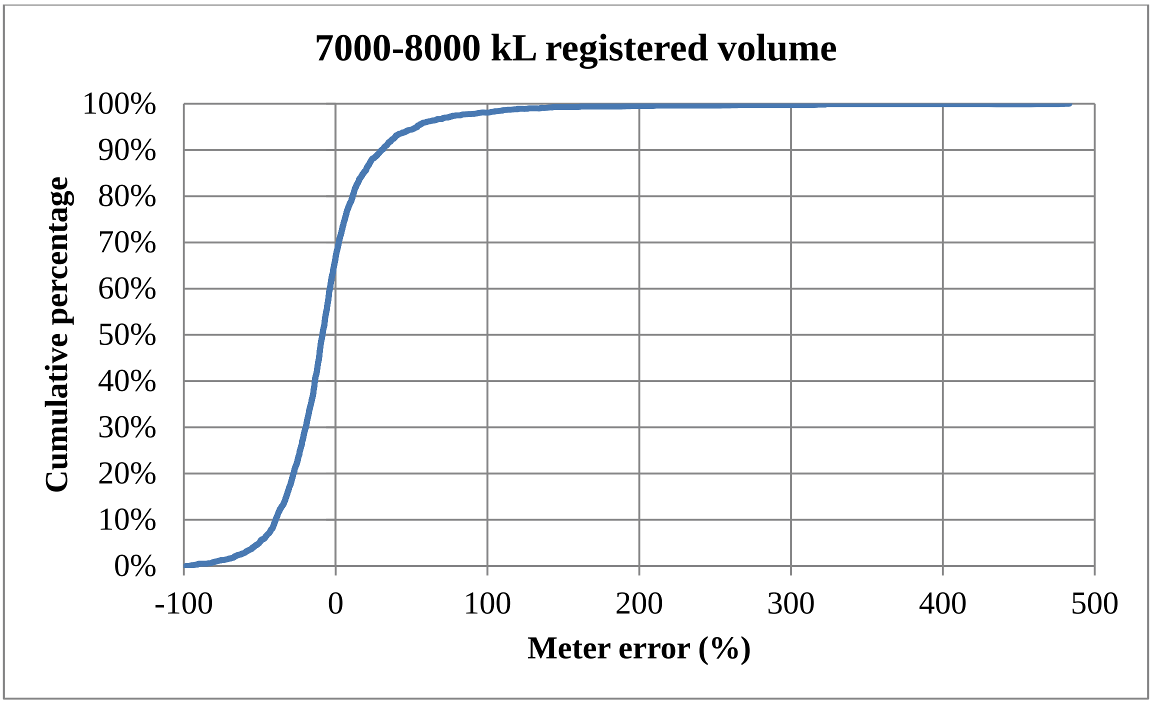

2000-3000 kL registered volume
Cumulative frequency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-100
0
100
200
300
400
500
Meter error (%)

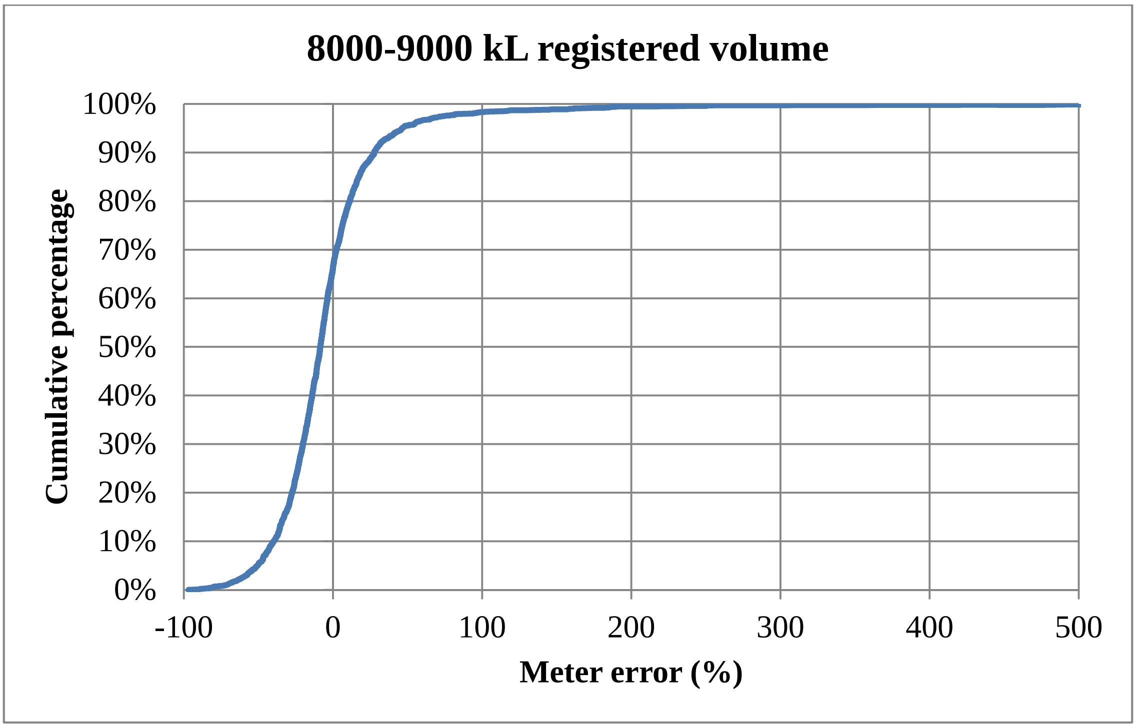

3000-4000 kL registered volume
Cumulative frequency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-100
0
100
200
300
400
500
Meter error (%)

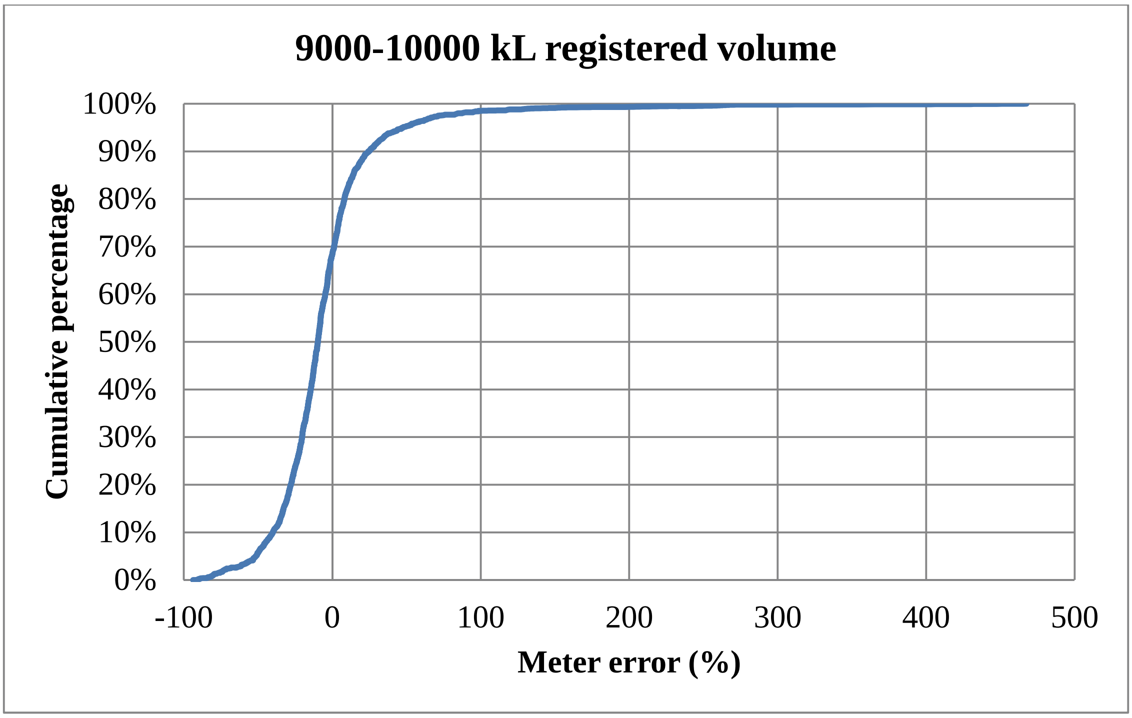

4000-5000 kL registered volume
Cumulative percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-100
0
100
200
300
400
500
Meter error (%)

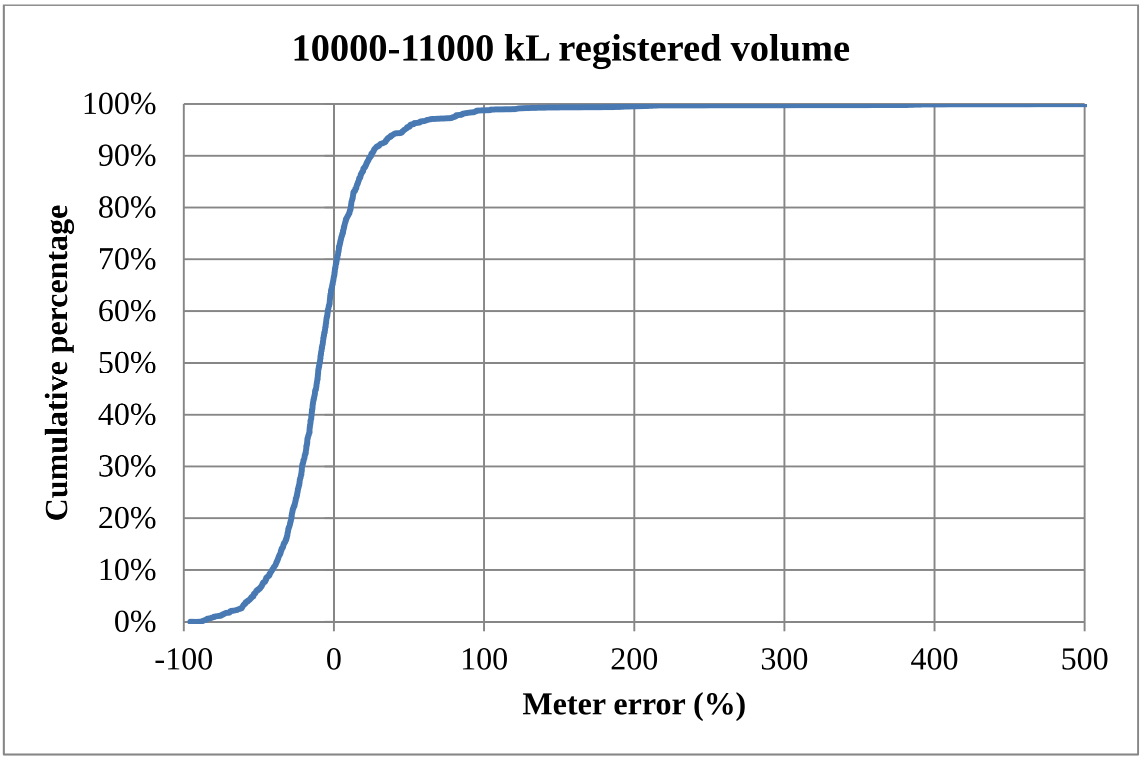

5000-6000 kL registered volume
Cumulative percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-100
0
100
200
300
400
500
Meter error (%)


6000-7000 kL registered volume
Cumulative percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-100
0
100
200
300
400
500
Meter error (%)


7000-8000 kL registered volume
Cumulative percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-100
0
100
200
300
400
500
Meter error (%)


8000-9000 kL registered volume
Cumulative percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-100
0
100
200
300
400
500
Meter error (%)


9000-10000 kL registered volume
Cumulative percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-100
0
100
200
300
400
500
Meter error (%)


10000-11000 kL registered volume
Cumulative percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-100
0
100
200
300
400
500
Meter error (%)

APPENDIX E: MASTER METER ERROR CURVES TESTED IN THE LABORATORY

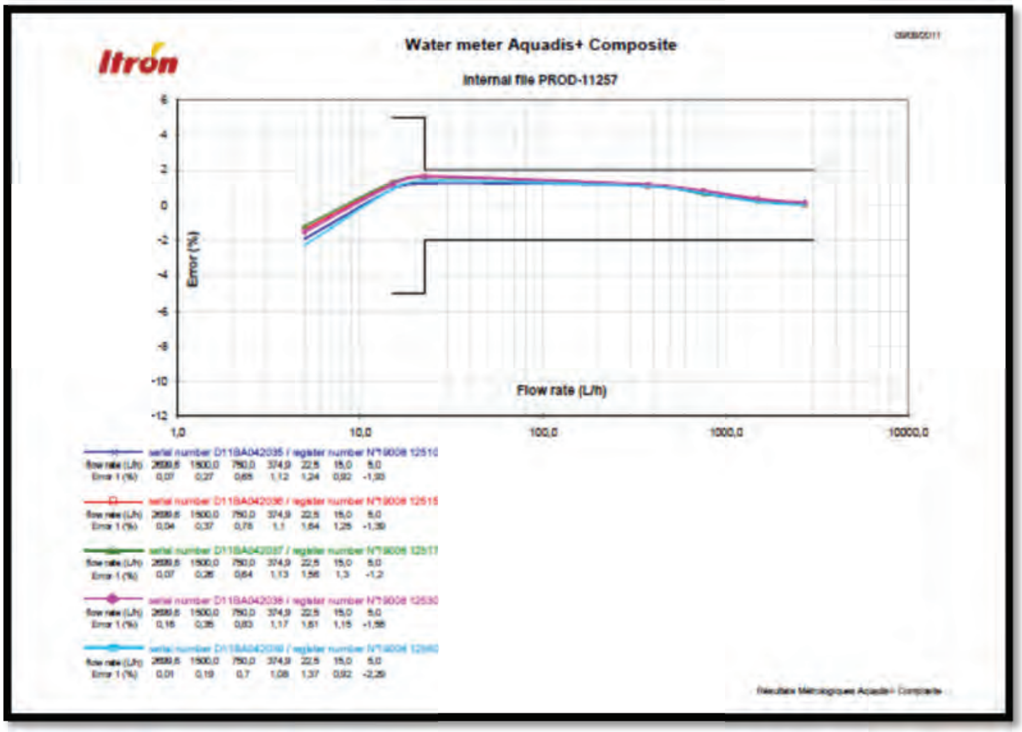


Figure 1: Meter error curves of master meters tested in the manufacturer's lab

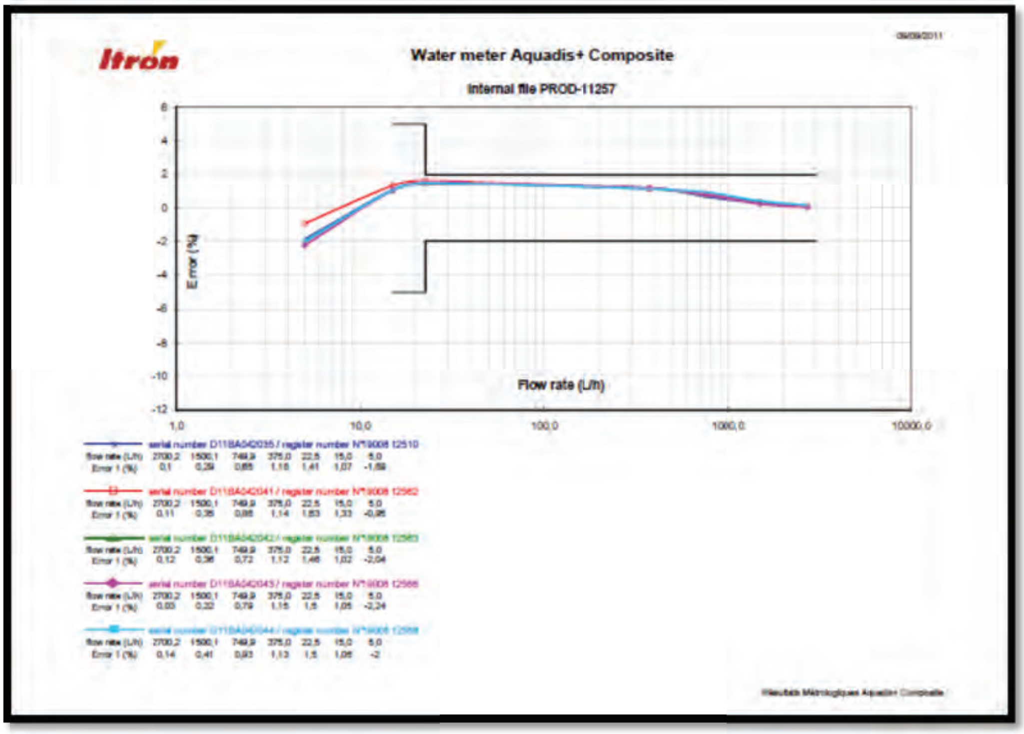


Figure 2: Meter error curves of master meters tested in the manufacturer's lab

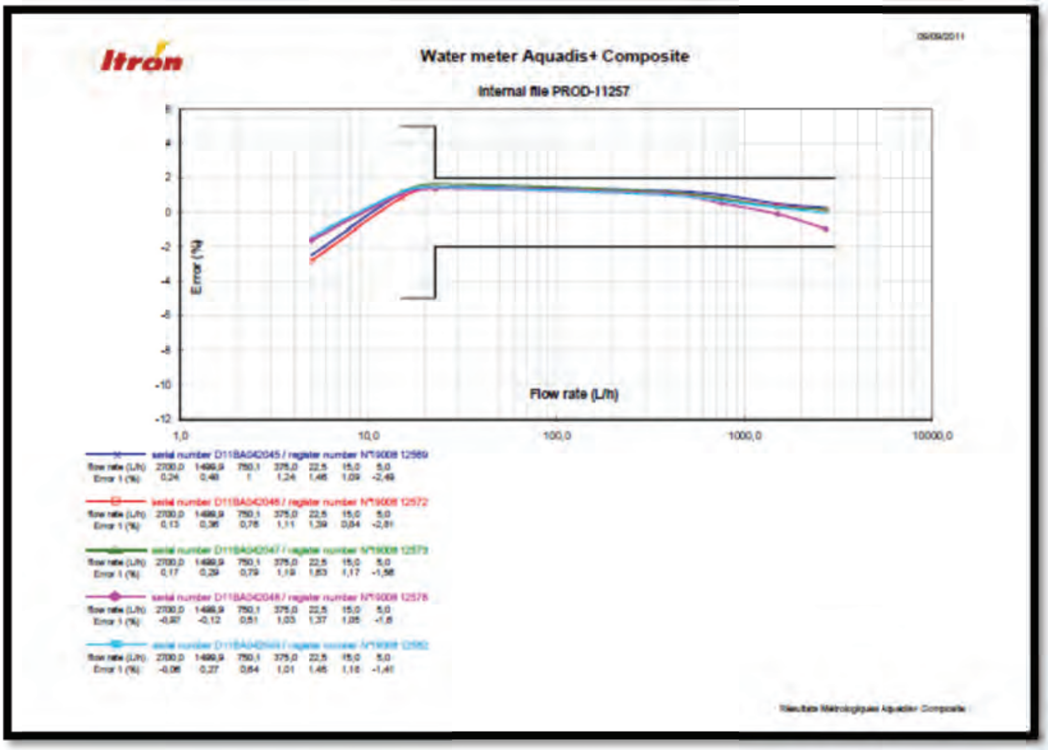
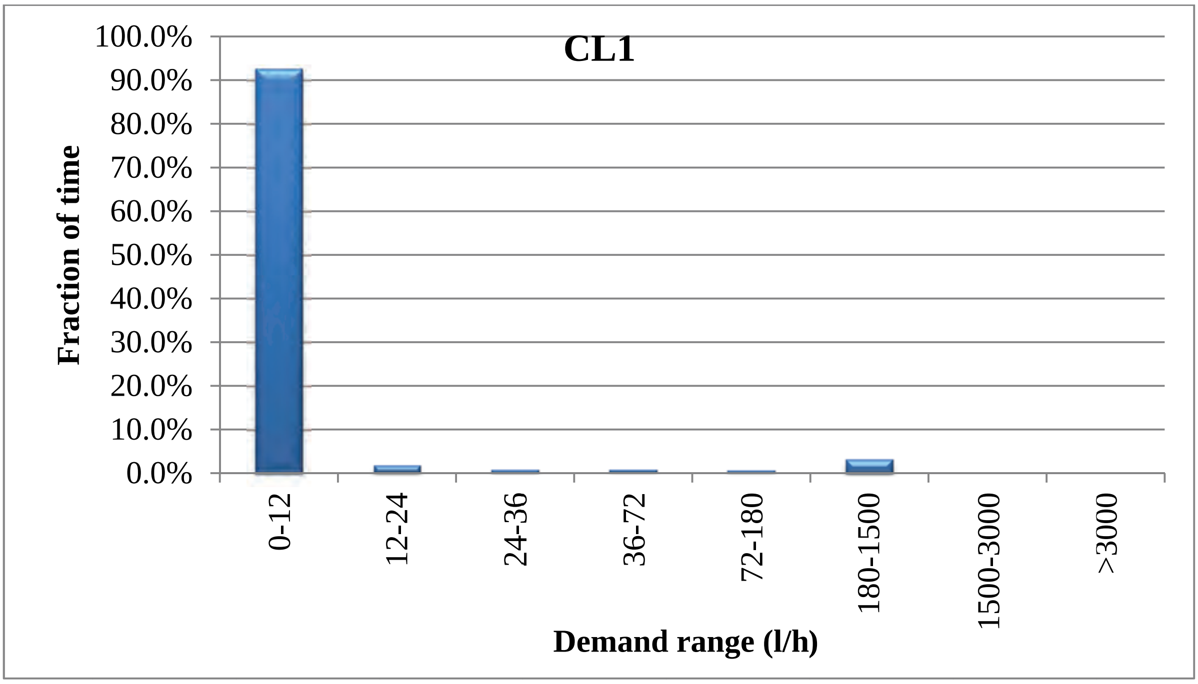
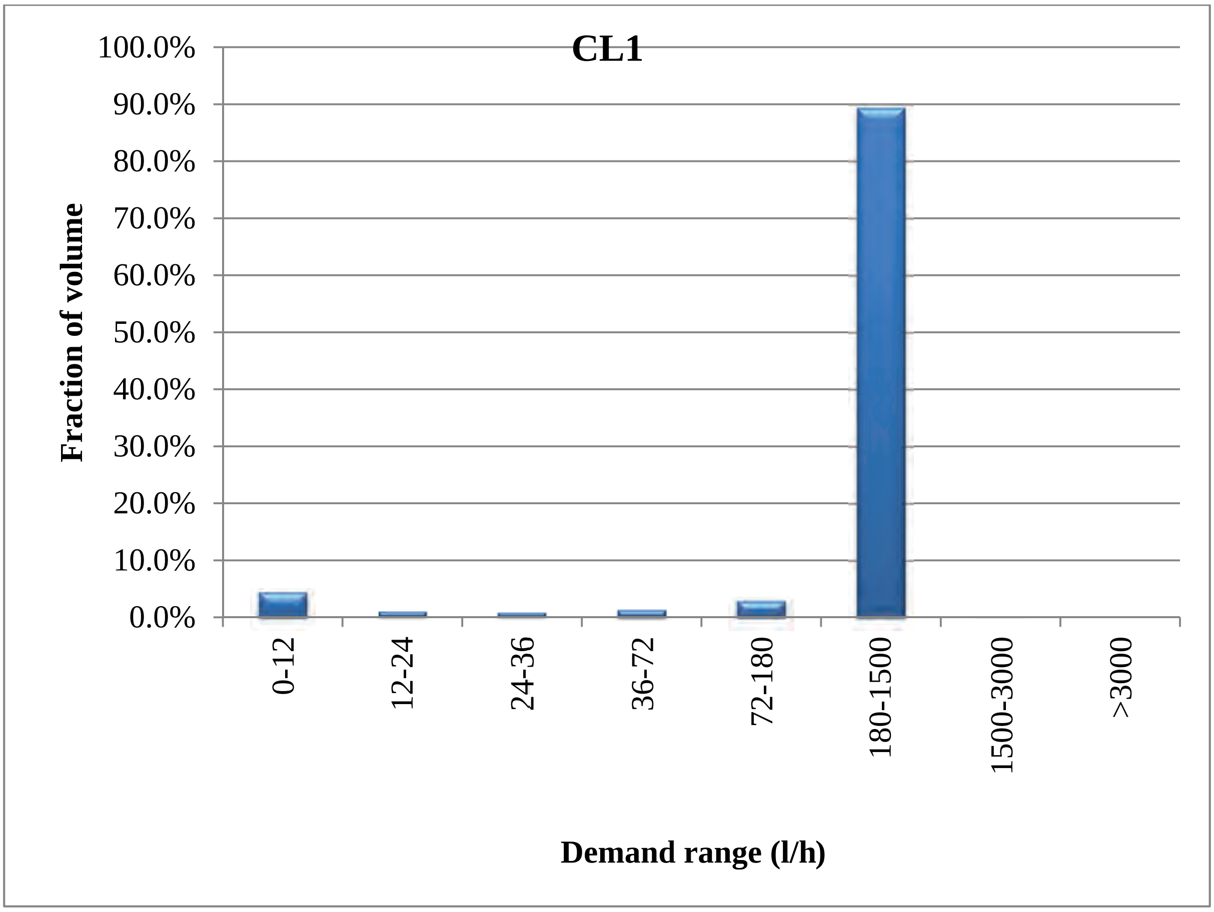
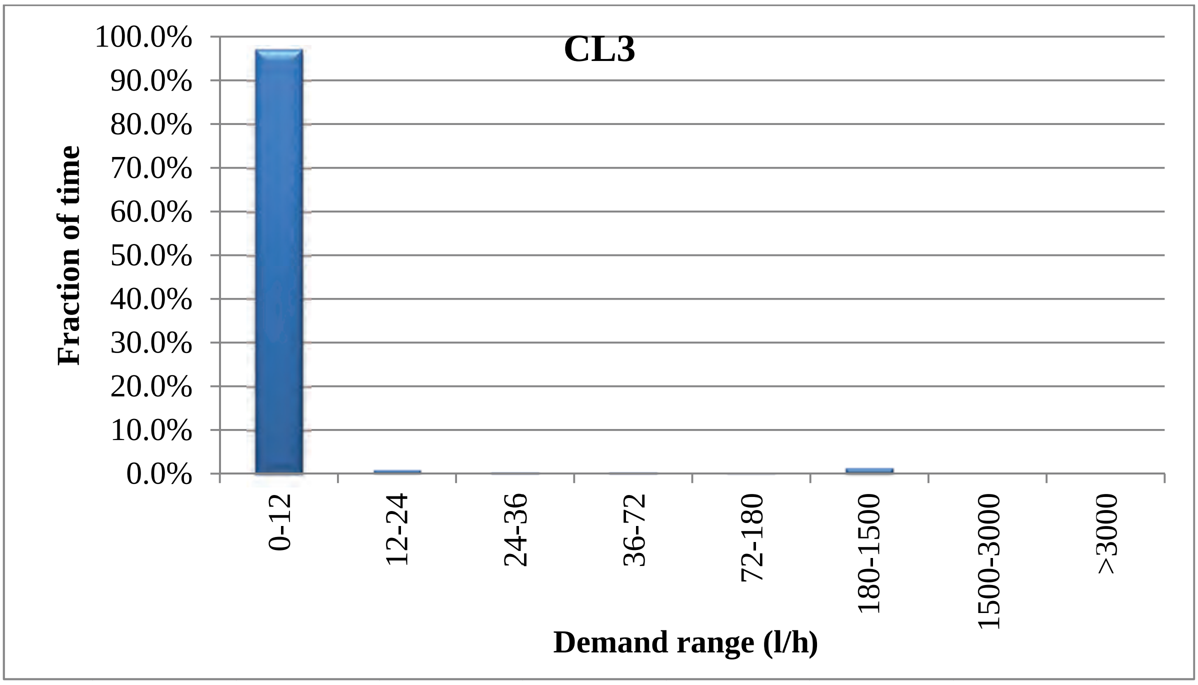


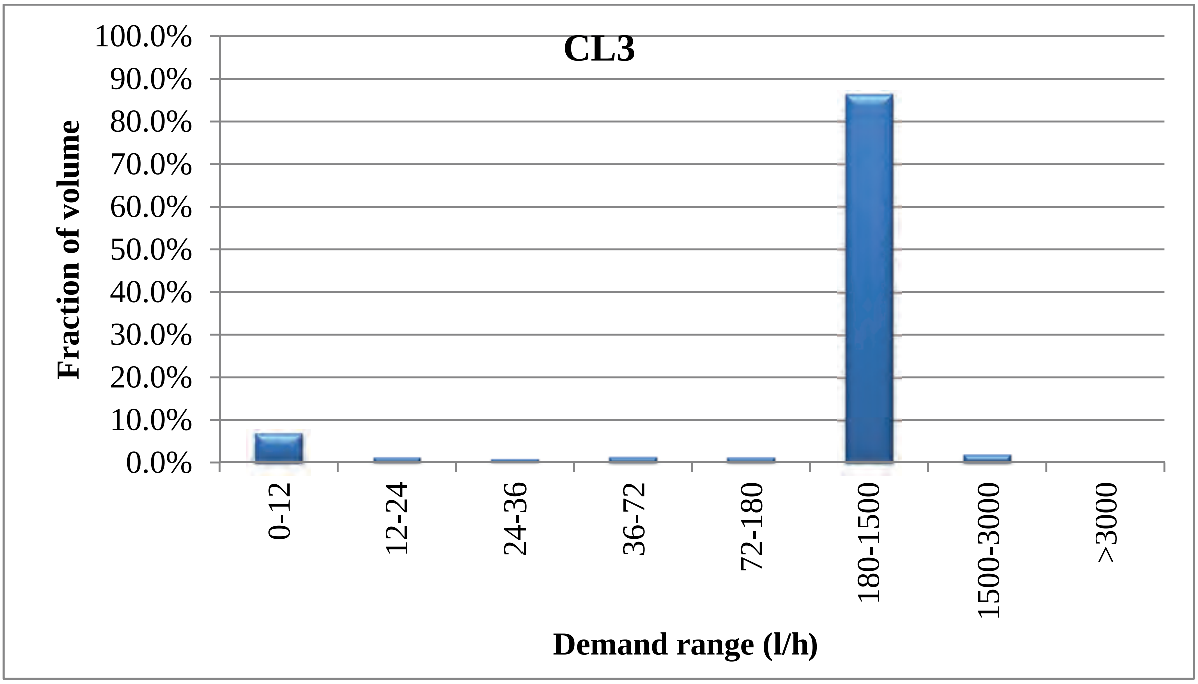
Figure 3: Meter error curves of master meters tested in the manufacturer's lab

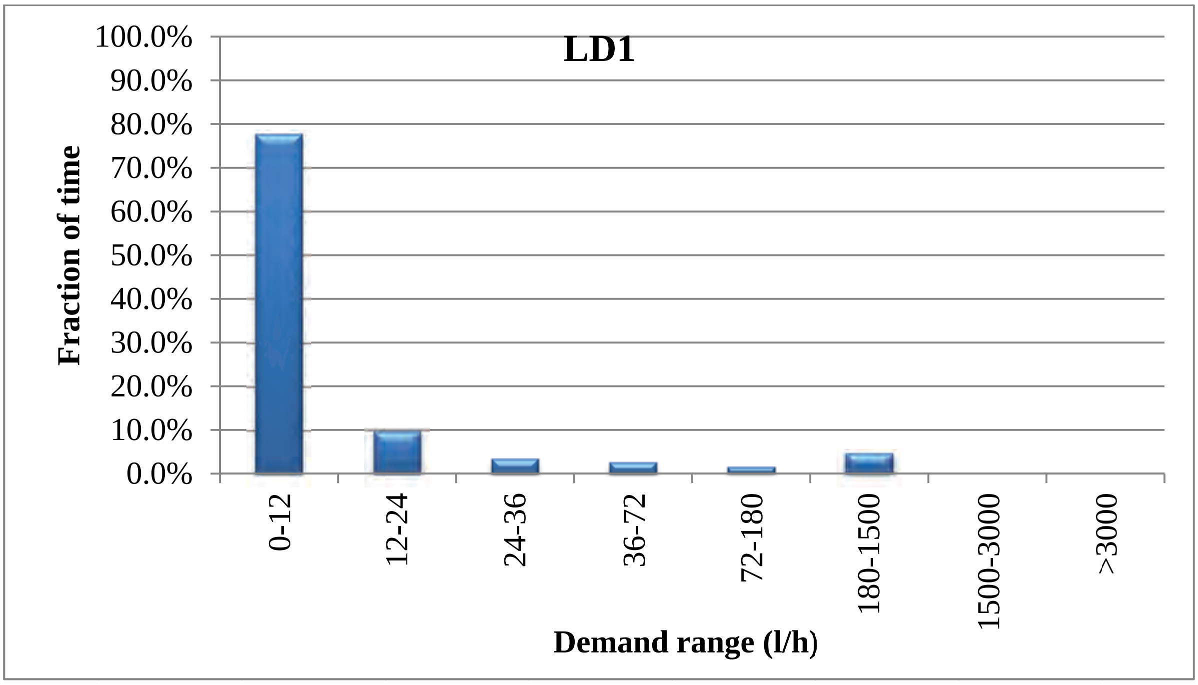
APPENDIX F: HISTOGRAMS OF LOGGED DOMESTIC CONSUMER METERS

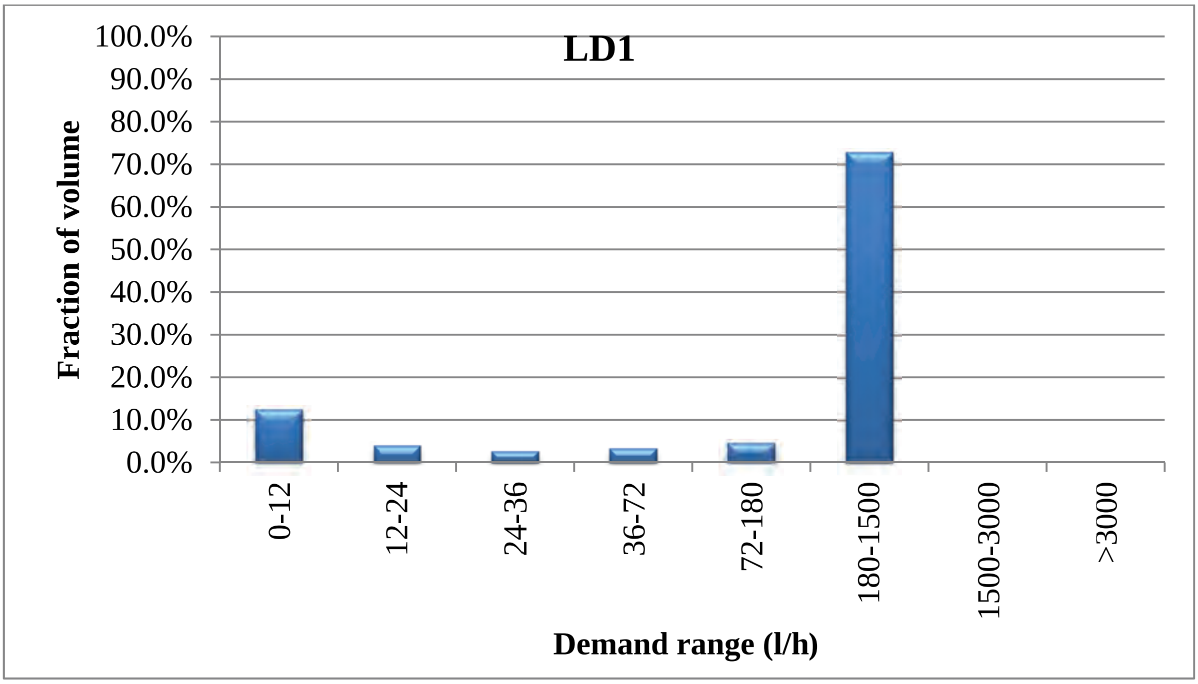



CL1
Fraction of volume
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
0-12
12-24
24-36
36-72
72-180
180-1500
1500-3000
>3000
Demand range (l/h)

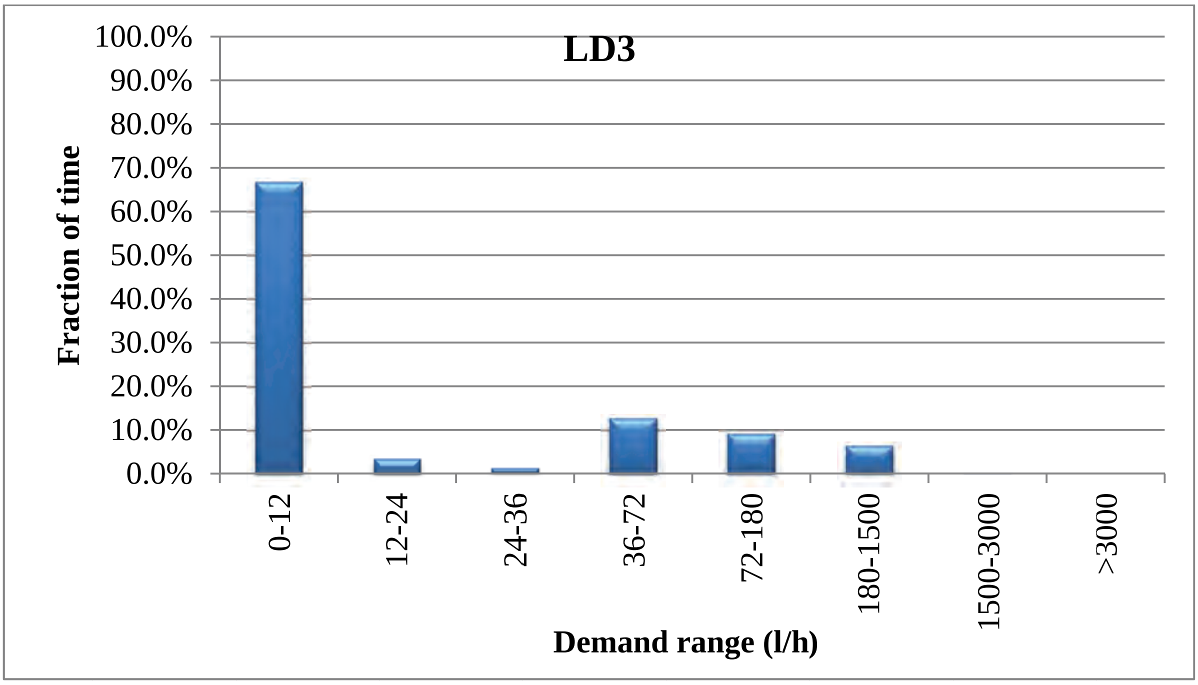

CL3
Fraction of time
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
0-12
12-24
24-36
36-72
72-180
180-1500
1500-3000
>3000
Demand range (l/h)


CL3
Fraction of volume
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
0-12
12-24
24-36
36-72
72-180
180-1500
1500-3000
>3000
Demand range (l/h)

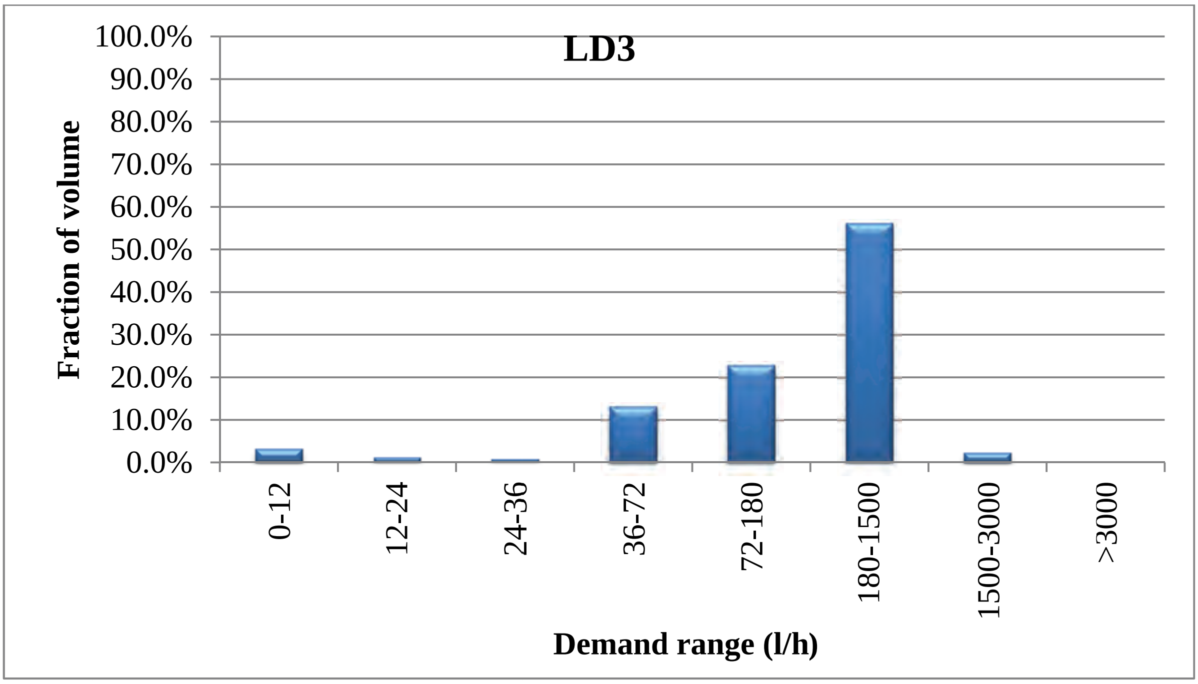

LD1
Fraction of time
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
0-12
12-24
24-36
36-72
72-180
180-1500
1500-3000
>3000
Demand range (l/h)

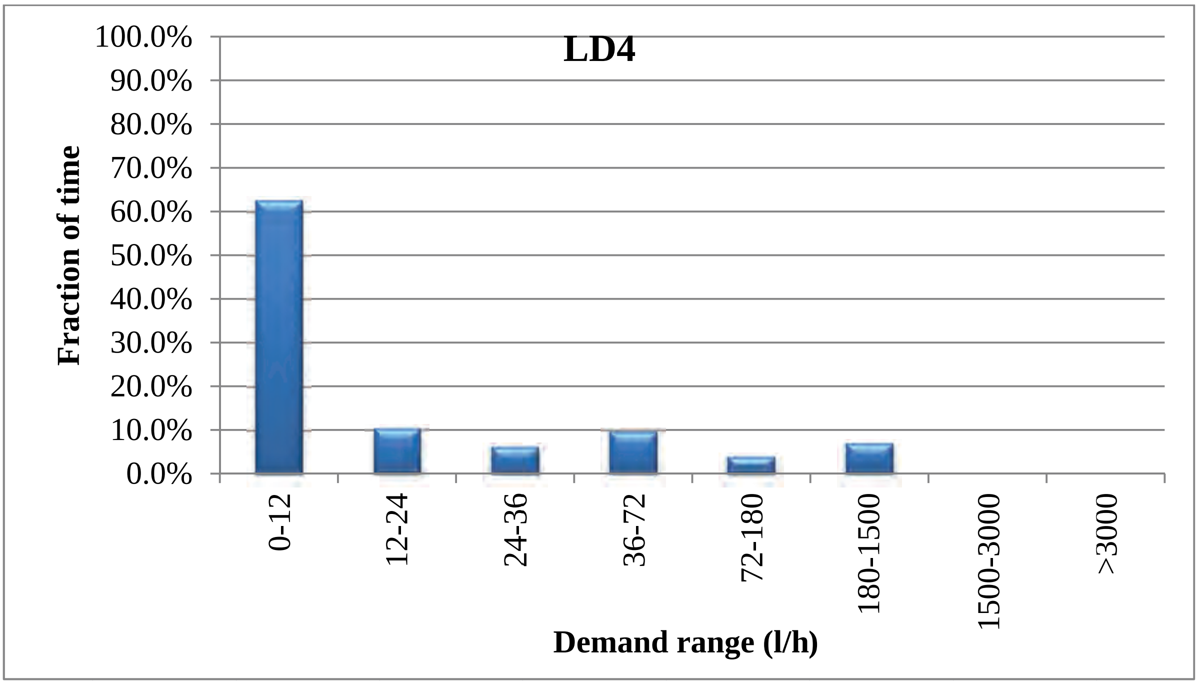


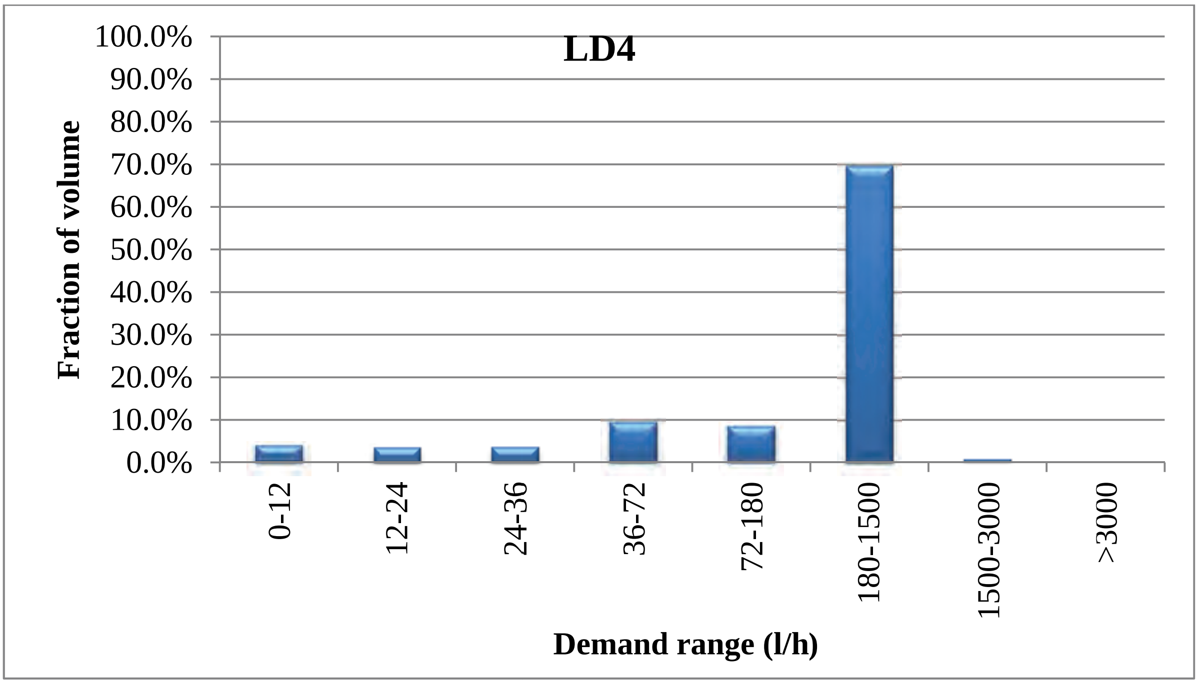
LD1
Fraction of volume
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
0-12
12-24
24-36
36-72
72-180
180-1500
1500-3000
>3000
Demand range (l/h)



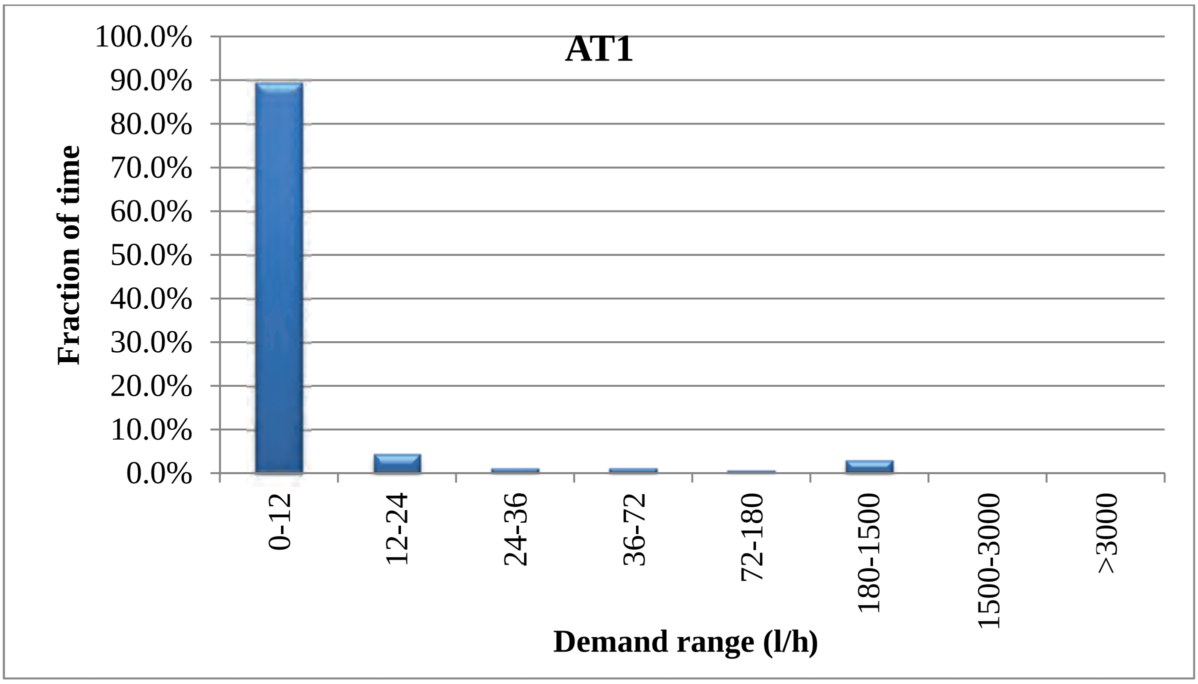
LD3
Fraction of time
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
0-12
12-24
24-36
36-72
72-180
180-1500
1500-3000
>3000
Demand range (l/h)

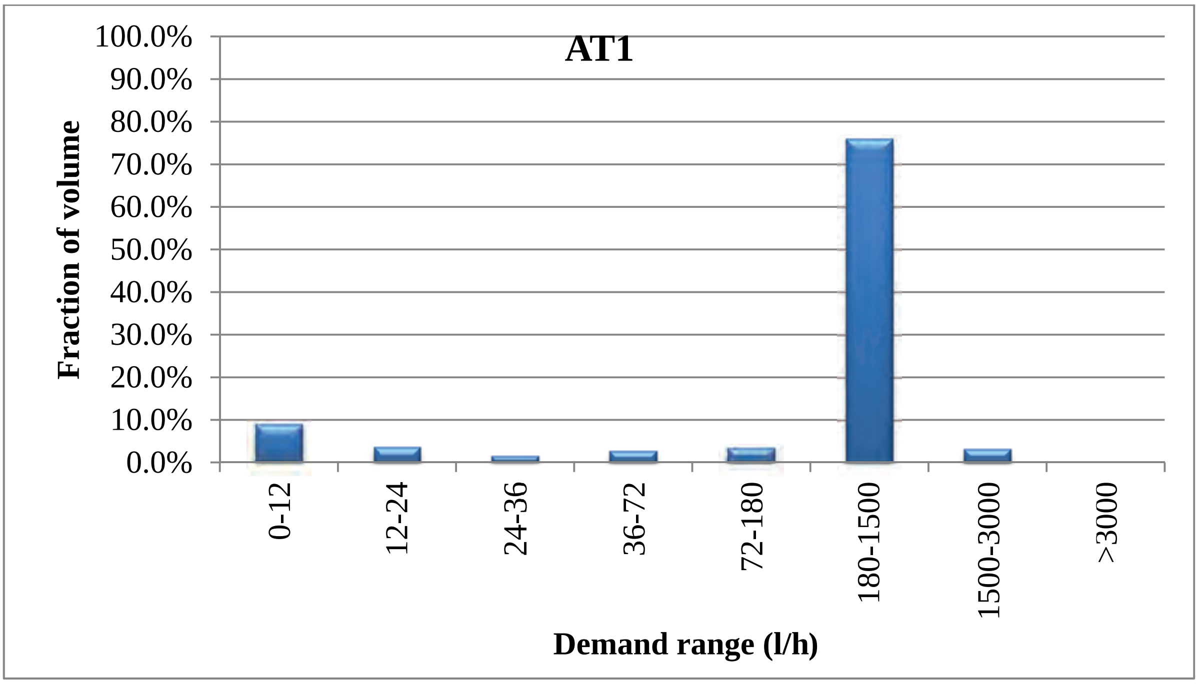

LD3
Fraction of volume
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
0-12
12-24
24-36
36-72
72-180
180-1500
1500-3000
>3000
Demand range (l/h)

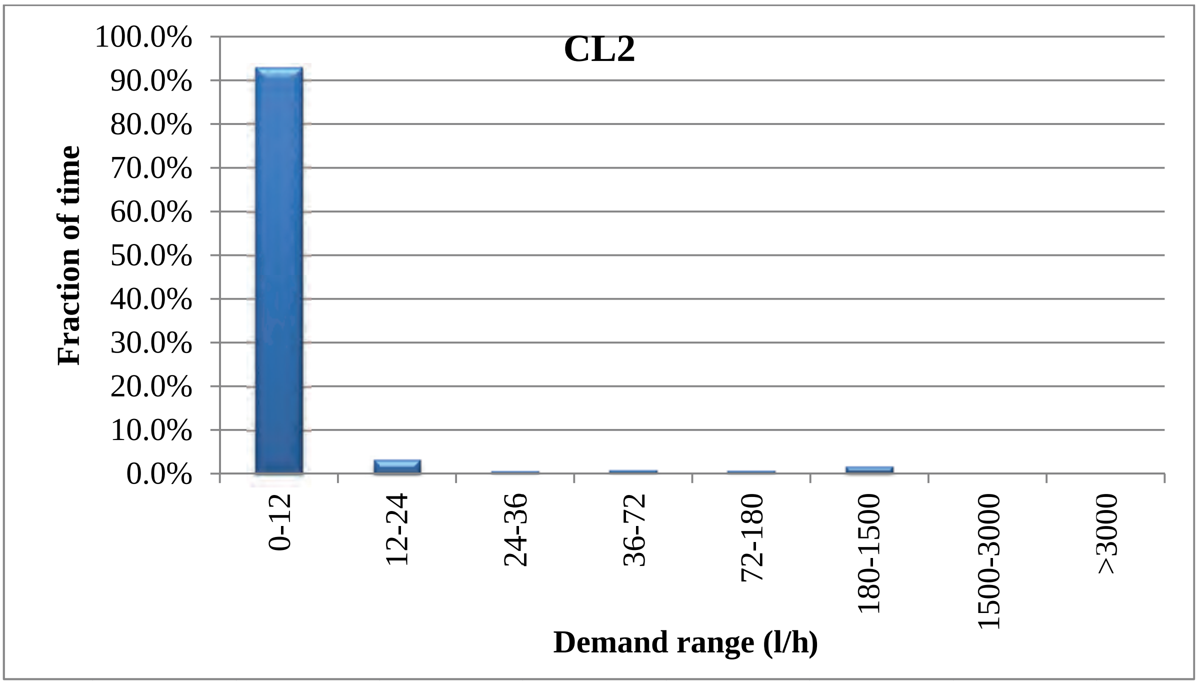

LD4
Fraction of time
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
0-12
12-24
24-36
36-72
72-180
180-1500
1500-3000
>3000
Demand range (l/h)

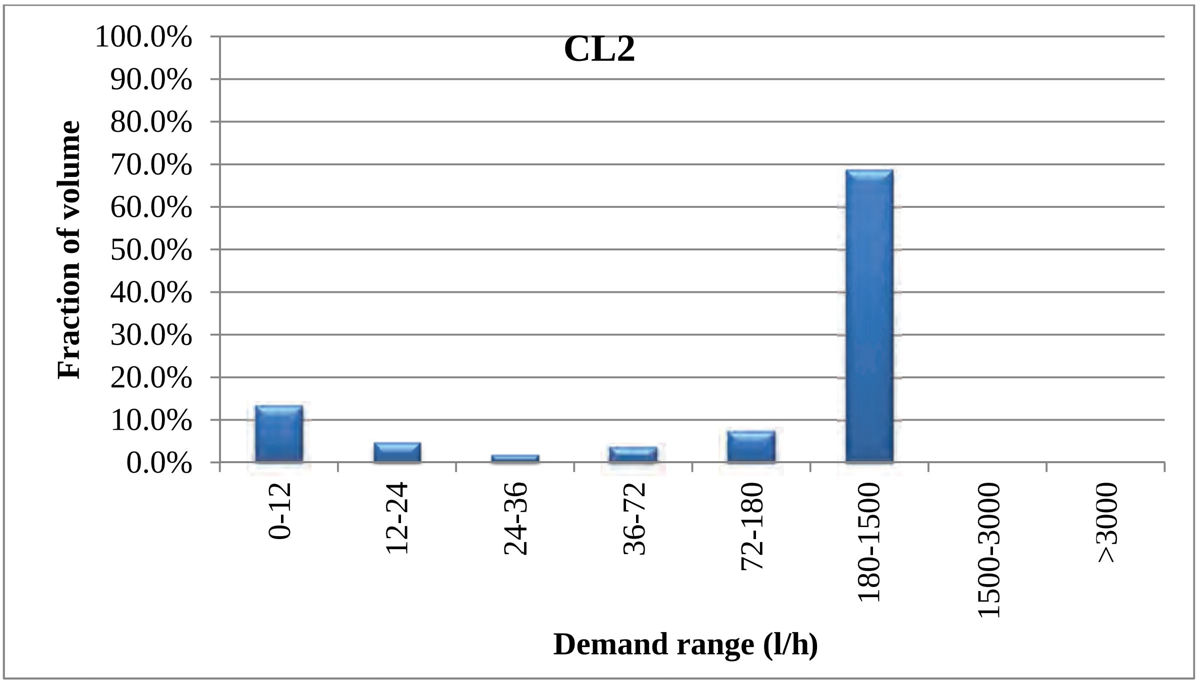

LD4
Fraction of volume
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
0-12
12-24
24-36
36-72
72-180
180-1500
1500-3000
>3000
Demand range (l/h)

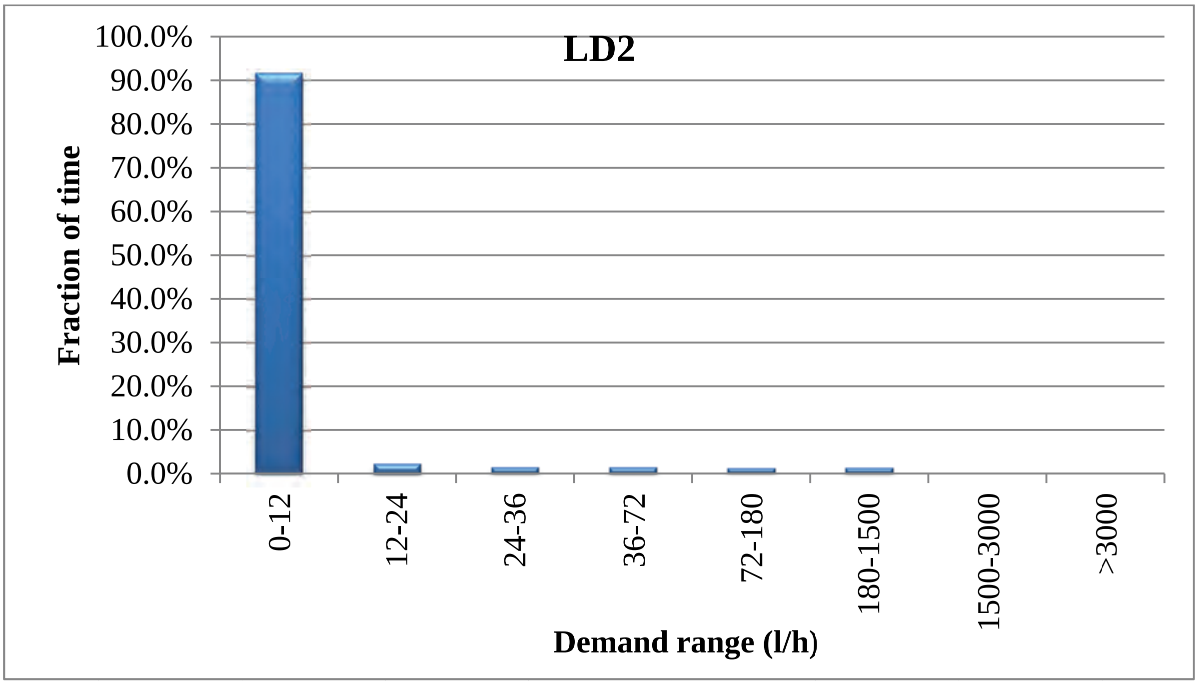
APPENDIX G: HISTOGRAMS OF LOGGED DOMESTIC CONSUMERS WITH UFRS

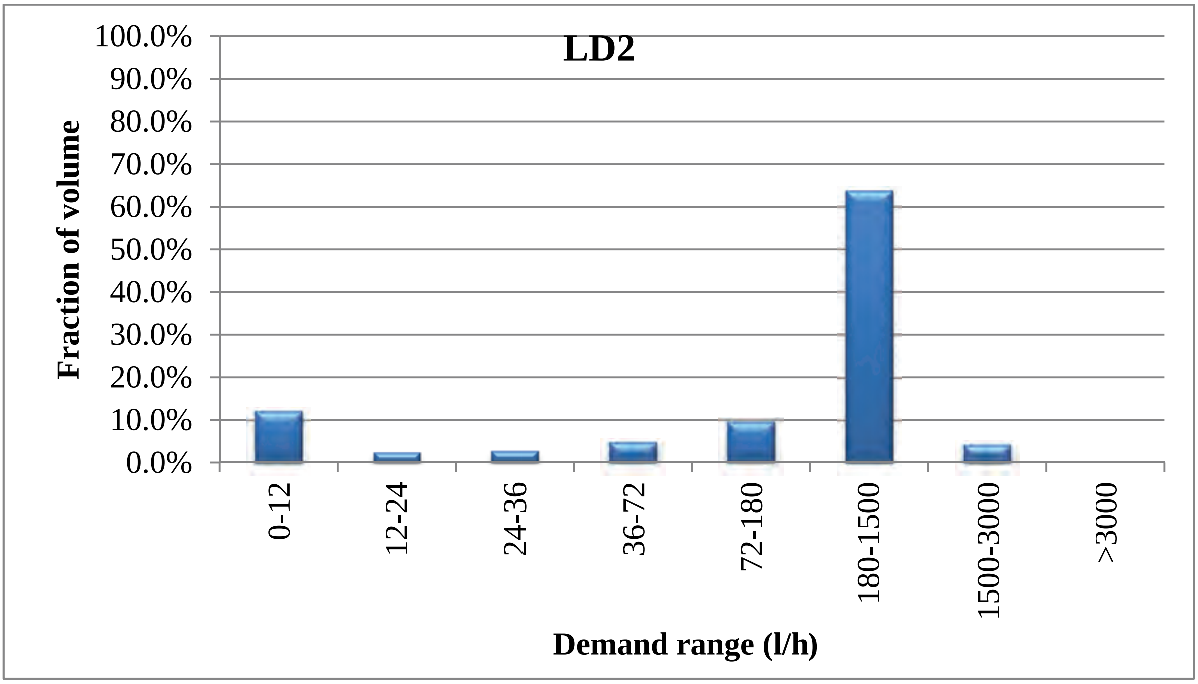



AT1
Fraction of volume
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
0-12
12-24
24-36
36-72
72-180
180-1500
1500-3000
>3000
Demand range (l/h)


CL2
Fraction of time
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
0-12
12-24
24-36
36-72
72-180
180-1500
1500-3000
>3000
Demand range (l/h)


CL2
Fraction of volume
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
0-12
12-24
24-36
36-72
72-180
180-1500
1500-3000
>3000
Demand range (l/h)


LD2
Fraction of time
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
0-12
12-24
24-36
36-72
72-180
180-1500
1500-3000
>3000
Demand range (l/h)


LD2
Fraction of volume
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
0-12
12-24
24-36
36-72
72-180
180-1500
1500-3000
>3000
Demand range (l/h)