Determination of domestic water meter accuracy degradation rates in Uganda

Deanroy Mbabazi, Noble Banadda, Nicholas Kiggundu, Harrison Mutikanga and Mohammed Babu

ABSTRACT

This research was aimed at determining the meter accuracy degradation profiles and rates and testing them with the optimal consumption patterns using the comparative billing analysis methodology for 2 meter models (Model 1 and Model 2) of volumetric type and one model (Model 3) of velocity type of size 15 mm which are the most dominant in the Kampala water distribution system (KWDS), Uganda, by applying statistics. The meter accuracy degradation rates were determined as 6.67% per year for Model 1, 4.68% per year for Model 2, and 1.45% per year for Model 3 meters. Annual water losses due to meter inaccuracies were 24.1 m^3 for Model 1, 16.9 m^3 for Model 2, and 5.3 m^3 for Model 3, totaling to US$1.5 million every year. This study recommends that degradation rates are used to determine the optimal meter replacement period, and Model 3 meters are the most suitable meters for the KWDS.

Key words | degradation profiles, Kampala water distribution system, meter accuracy, water, water meters

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INTRODUCTION

Water covers 71% of the Earth's surface and is vital for all forms of life. On Earth, water in the oceans accounts for 96.5%, with equal amounts of 1.7% in ground aquifers and in Antarctica and Greenland as glaciers and ice caps, and the remaining water is found in other large surface water bodies and the atmosphere. Only 2.5% of the Earth's water is fresh water, of which 98.8% is in a form where it cannot be easily extracted like ice and groundwater (Han 2010). Less than 3% of all freshwater is in rivers, lakes, and the atmosphere, and an even smaller amount of the Earth's fresh water is contained within biological bodies and manufactured products.

Access to water is a fundamental need and a human right vital for the dignity and health of all people (WHO 2000). Water utilities supply water for commercial and domestic consumption. This comprises a huge cost in the management and service delivery to customers. Approximately 783 million people in the world do not have access to improved water supply resources (UNICEF (United Nations Children's Fund) & WHO 2012). A major challenge affecting water utilities in the developing countries is the considerable difference between the amount of water input into the distribution system and the amount of water billed to customers, also called non-revenue water. Kingdom *et al.* (2006) showed that, in developing countries, nearly $45 \times 10^6\,m^3$ of water per day (enough to supply 200 million people) is lost through leakage in water distribution systems and 30×10^6 water per day is delivered to customers but not invoiced due to metering inaccuracies, billing errors, theft and corruption by utility managers, resulting in costs of about US$6 billion per year.

In Uganda, the National Water and Sewerage Corporation (NWSC) is responsible for water and sewerage service provision. The NWSC uses water meters to measure water distributed to the water distribution system and that delivered to consumers. The water meters consist of four

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basic components: a sensor to detect flow, a transducer to transmit the flow signal, a counter to keep track of the total volume passing through the meter, and an indicator to display the meter reading (Van Zyl 2011). There are two types of water meters used in Uganda, namely, volumetric meters and velocity meters. Water meters are important to both the utility and customers to measure and monitor water usage. Water metering has four fundamental drivers which include equity, water efficiency and losses, economic benefits, and system management (Mutikanga 2012). Water meters are the cash register of water utilities. A well-managed and accurate water meter system improves water sales and utilities income. When mechanical meters are installed, they lose their accuracy as usage increases due to wear and tear of the meter component parts, thus revenue losses increase due to the increase of unregistered water volume (non-revenue water) (Arregui *et al.* 2006). It is known that about 94% of all customer meters in Kampala, Uganda, are of small size with 15 mm nominal diameter (DN) and generate about 70% of total revenues (Mutikanga *et al.* 2010). In addition, Mutikanga *et al.* (2010) found that the NWSC is operating at a global metering accuracy of 79% in Kampala city. About 21% loss in accuracy for a meter, with an average monthly bill of US$10, results in annual loss of US$25.2 per meter. With over 137,300 such meters, the utility loses US$3.5 million per year due to metering inaccuracies. Since high revenues are lost due to inaccurate meters, optimal meter replacement is essential for the NWSC. Under optimum meter replacement, meters that are still providing accurate recordings may be replaced, which leads to wastage of resources and an additional economic burden for utilities (Allender 1996). Addressing the problem meant there was the need for a study about optimal scheduling of meter replacement and rehabilitation. Several methodologies allowing determination of optimum meter type and replacement frequency have been proposed (Male *et al.* 1985; Allender 1996; Arregui *et al.* 2010). However, these methodologies require intense laboratory testing of used meters and field measurements of real consumption patterns. Therefore, a huge input of labor and economic resources are required which cannot be afforded by small utilities in various districts in Uganda. Mutikanga (2012) developed an optimal water meter replacement tool to help small water utilities improve water meter management; however, the tool needs data from rigorous meter testing to develop meter accuracy degradation profiles as well as determining the meter accuracy degradation rates, which is very expensive and time-consuming. It is against this background that our study aims at two objectives: (1) to develop the meter accuracy degradation profiles for volumetric and velocity meters using the KWDS customer billing database; and (2) to determine the domestic meter accuracy degradation rates and to determine annual water losses for each meter model using the meter degradation rates and the optimal water consumption patterns.

MATERIALS AND METHODS

The comparative billing analysis methodology proposed by Arregui *et al.* (2003) which relies on existing data and not on costly field work and statistical studies was the basis of the research. Statistical sampling tools (stratified random sampling) and regression analysis techniques were applied to group meters in order to determine sample sizes and to develop the meter accuracy degradation profiles.

Analysis of the customer water use data in the billing database

Only meters of DN of 15 mm were considered. This is because they constitute about 94% of the meters installed in Kampala water (Mutikanga 2012). Three different meter models were examined: (1) two types of volumetric meter models (Model 1 and Model 2) from two different manufacturers; and (2) a multi-jet meter type (Model 3). Models 1 and 2 are the most dominant in the network and make up 76% of all the small meters of size 15 mm; 24% are of the velocity type.

Sampling and stratification of meters

In sampling of the meters, meter data (model, DN, and installation date), monthly consumption and meter cumulative volume data were taken from the utility's billing database, and meters were grouped based on model and total accumulated volume. Strata of meters were based on meter models. Within each stratum, the meters were grouped based on cumulative volume to build more homogenous groups and reduce variability associated with sampling. Sample size was selected according to The Research Advisors (2006) sample size table recommendations at 95% confidence level considering a 2.5% margin of error for each sub-stratum in order to have a more reliable statistical judgment derived from sample collection. Analysis of customer water use data was based on these sampled meters to determine the user's consumption patterns.

Analysis of the billing database

Data for 128,201 meters of size 15 mm were obtained from the Kampala water billing database for 8 months to analyze the consumption patterns of the consumers. This was because it was not possible to obtain the historical data which would have provided a better analysis of the consumption patterns for these meters. However, it should be noted that many of the meters included in the 8 month study had been in use for several years before. This data limitation was due to the KWDS customer billing database policy and legal restrictions which do not allow these data to be available to external personnel. However, the data obtained included the meter installation dates, current reading rates, and meter cumulative volume readings for each meter. The data obtained consisted of 16 meter model types. However, the most dominant meter models, constituting 71.8%, were Models 1, 2, and 3. Of these, 29,354 (22.9%) were Model 1 meters, 34,336 (26.8%) were Model 2, and 27,808 (22.1%) were Model 3. Meters were grouped into five sub-strata (0–2,000, 2,000–4,000, 4,000–6,000, 6,000–8,000, and more than 8,000 m^3) based on cumulative volume through the meter. The last group was set to more than 8,000 m^3 because the expected meter life for a half inch meter is when the odometer reading clocks 8,000 m^3 (Mutikanga 2012). Upon stratification of the database, the sample sizes selected were 4,276 for Model 1 meters, 5,000 for Model 2, and 3,500 for Model 3 meters compared to 1,460 for Model 1, 1,471 for Model 2, and 1,456 for Model 3 meters recommended by the required sample size table developed by The Research Advisors (2006). These samples were further reviewed and screened to eliminate data that were inaccurate. Upon screening of the data, 7,769 meters were selected for the research (Table 1) and data used to develop the profiles are shown in Table 2. Screening of the data involved eliminating inaccurate readings such as negative billing indices and infinite readings, which are not expected for meters. Reasonable results presented in Table 1 were obtained in each of the meter groups after screening.

Table 1 | The number of meters for each model sampled from the population for each billing index

Billing index (m^3)	Model 1	Model 2	Model 3
0–2,000	1,770	1,558	1,202
2,000–4,000	1,100	988	78
4,000–6,000	94	600	10
6,000–8,000	41	172	4
>8,000	23	98	1
Total	3,028	3,446	1,295

Development of the evolution of the average yearly metered volume versus age profiles

Out of each group of similar meters, the average metered volume for a year for each meter was calculated. This was done because the time elapsed between the last two readings of the meters is not necessarily the same for all meters. The age of the meter was also determined, and evolutions of the average yearly metered volume (annual billed volume) versus total age curves for each model were developed in Microsoft Excel.

Determination of domestic meter accuracy degradation rates

Graphs of the annual billed volume against total age of the meter were analyzed to determine the meter accuracy degradation rates. Water meter accuracy degradation is a function

Table 2 | Samples considered after screening data to develop degradation rates

Meter model	Meters considered after screening
Model 1	122
Model 2	349
Model 3	32

of many variables (pressure, water quality, leaks, and users' storage tanks and age (or volume)). In these studies, different researchers (Allender 1996; Arregui *et al.* 2006; Mutikanga 2012) assumed a linear relationship between accuracy and age (or cumulative volume through) of the meter for domestic meters. In this research, a regression analysis with a linear relationship to predict meter accuracy degradation rate was assumed due to its simplicity and also because it is cheaper, involves less time and technical requirements and thus can be afforded by the small utilities in Uganda. The regression model was performed for specific meter models (same manufacturer, meter size, and metering technology) and including other variables apart from the totalized registered volume which is explicitly included. The resultant model took the form of Equation (1):

$$y = \beta_0 + \beta_1 x \quad (1)$$

where x was the totalized age of the meter, y was the annual billed volume, and β_j $(j = 0, 1)$ were the regression coefficients.

Equation (2) was used to determine the meter accuracy degradation rate:

$$D = \frac{\beta_1}{\beta_0} \quad (2)$$

where D is the meter accuracy degradation rate (% per meter per year).

Testing of the meter accuracy degradation rates using the optimal consumption patterns to determine annual water losses

Testing was done to determine the amount of water that is not measured by a water meter for every model in a year. This was determined using Equation (3):

$$W = DP \quad (3)$$

where D was the meter accuracy degradation rate, W was the annual unmeasured water, and P is the average annual water consumption which was obtained from the billing database.

RESULTS AND DISCUSSION

Development of the evolution of the average yearly metered volume versus total age profiles

The profiles developed show the degradation profiles for each meter. Figure 1 shows the meter accuracy degradation profile for Model 1 meters, Figure 2 shows the meter accuracy degradation profile for Model 2 meters, and Figure 3 shows the degradation profiles for Model 3 meters.

Using linear regression analysis, the following mathematical models were obtained for the degradation of Model 1, 2, and 3 meters according to Equation (1). The meter degradation models for Model 1, 2, and 3 meters and the coefficients of determination R^2 are shown in Equations (4)–(6), respectively.

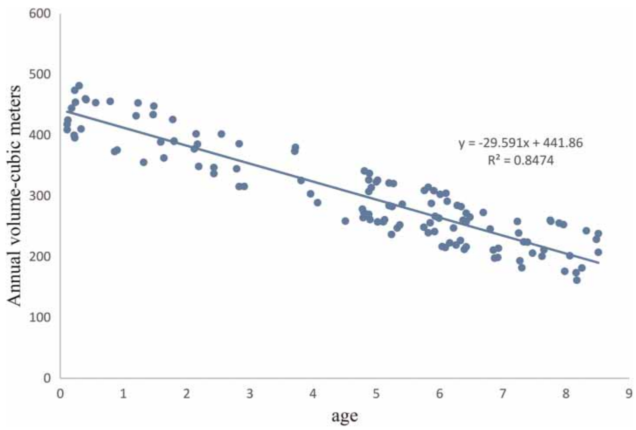

Figure 1 | Meter degradation profile for Model 1 meters. Annual volume is the annual billed volume per meter per year.

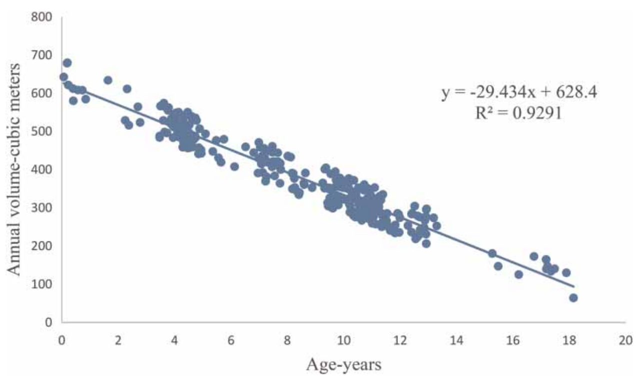

Figure 2 | Meter degradation profile for Model 2 meters. Annual volume is the annual billed volume per meter per year.

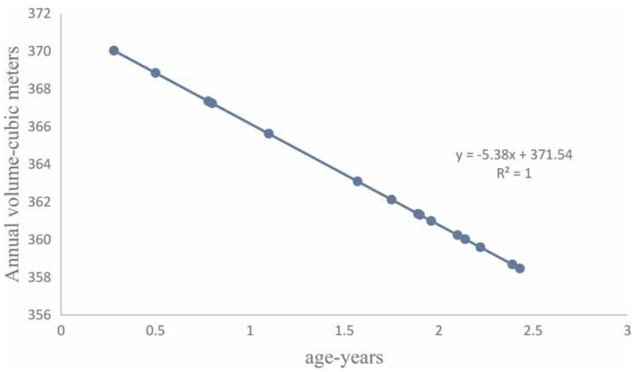

Figure 3 | Meter degradation profile for Model 3 meters. Annual volume is the annual billed volume per meter per year.

Model 1 meters:

$$y = -29.59x + 443.86,\ R^2 = 0.85 \tag{4}$$

where $y =$ is the annual billed volume (m^3) and x is the totalized age of the meter.

Model 2 meters:

$$y = -29.43x + 628.4,\ R^2 = 0.93 \tag{5}$$

where y is the annual billed volume (m^3) and x is the totalized age of the meter.

Model 3 meters:

$$y = -5.38x + 371.54,\ R^2 = 1 \tag{6}$$

where y is the annual billed volume (m^3) and x is the totalized age of the meter.

The meter accuracy degradation rates were determined as 6.67% per year for Model 1, 4.68% per year for Model 2, and 1.45% per year for Model 3 meters. The degradation rates obtained were higher than observed for water meters because the methodology only considered meter age as the sole factor influencing meter degradation and did not include pressure, water quality, leaks, and users' storage tanks, and thus consideration of meter age does not explain meter degradation entirely. This was, however, the main goal of the study because considering all the factors involves rigorous meter and field tests which are expensive and cannot be afforded by small water utilities in Uganda. The high meter degradation rates also suggest that the degradation of the water meters is not linear and the relationship between meter degradation and age should be studied further to provide insight for further meter accuracy degradation models based on meter volume and age. This was not possible to investigate in this study due to data limitations for each meter, but it would be interesting to investigate for systems with well-managed databases for each water meter. The degradation rates obtained, however, were comparable to the degradation rate of 2.1% per year obtained by Arregui *et al.* (2006).

Model 1 meters had the highest meter accuracy degradation rates and, thus, were the worst meters for the KWDS system characteristics, and Model 3 meters had the lowest meter accuracy degradation rates and, thus, were the best meters for the KWDS characteristics. The meter accuracy degradation rates obtained were higher than those normally observed for water meters, but this was due to factors which the comparative billing analysis methodology does not account for. Such factors include: water quality, meter mounting position, leaks, and users' storage tanks and partial blockage of inlet strainer (Arregui *et al.* 2005). Buck *et al.* (2012) examined the effects of particulates on different meter types over their estimated life in a controlled environment and observed that oscillating piston meters were most affected by a slug of sand while nutating disk, single jet, multi-jet, and fluidic oscillator meters were less affected, with multi-jet meters affected least which is consistent with the results obtained in this study. Criminisi *et al.* (2009) analyzed the effect of water meter age and private storage tanks on meter performance in Palermo, Italy through laboratory studies to characterize measuring error, field monitoring of real users and a mathematical model and showed that apparent losses increase with age and that private water tanks fed by float valves produce apparent losses between 15 and 40%. Fontanazza *et al.* (2012) suggested that the use of single parameters like age or volume through the meter do not provide accurate insight for meter replacement due to the complexity involved in meter errors. They presented a replacement strategy based on a composite replacement indicator (RI) which signals when a meter should be replaced, and tested this using Monte Carlo uncertainity analysis and found that the RI performed better than using single variables (age or meter error curves); however, in this study the authors were more interested in finding a simplified approach to estimate meter degradation rate that would be used by water management districts in every part of Uganda with minimal technical knowledge requirements and expenses incurred.

The degradation rates were also high because the meters are not homogenously installed in the utility system. This is because characteristics of pipes and pressure in the system are not similar for every water meter. The water consumption patterns of the users are also not necessarily the same and, thus, the results were biased by the differences in the users' consumption behavior. The consumption of water by customers in Kampala seasonally varies especially during rainy seasons when people harvest rainwater and later use it for domestic chores, watering lawns, when necessary, and providing water for domestic animals. Also, during the festive seasons most people in Kampala travel out of the city and thus less water is used during these periods; and yet the comparative billing analysis methodology does not take this into consideration which caused biased meter accuracy degradation rates.

Testing of the water meter degradation rates using the optimal consumption patterns

With an average annual consumption of 361.3 m^3, the amount of unmeasured water was determined by Equation (3) as 24.1, 16.91, and 5.3 m^3 per meter per year for Model 1, 2, and 3 meters, respectively. These values are relatively similar to the average annual loss due to meter inaccuracies of 22.8 m^3 per meter per year reported in the Kampala Water balance report for the financial year 2011/2012. The values were less than the amount of unmeasured water of 58 m^3 per meter per year shown in this study (Mutikanga 2012), because in their study losses were estimated due to metering errors and failures. The difference also shows an improvement in the management of non-revenue water at KWDS.

The figures for the average annual unmeasured water were also less than the estimated figures for Westchester Joint Water Works in New York and Taunton Water Works (TWW) in Massachusetts, which were determined as 43 $m^3\,m^{-1}\,yr^{-1}$ for both utilities in 1982 according to Mutikanga (2012), because losses were also estimated due to metering errors and failures. These annual losses obtained indicate that 1.5 million m^3 of water are lost every year due to meter inaccuracies of Model 1, Model 2, and Model 3 meters resulting in losses of US$1.5 million every year for a water tariff of US$1 per m^3.

CONCLUSIONS AND RECOMMENDATIONS

In this study, meter accuracy degradation profiles and rates for Model 1, Model 2, and Model 3 meters were determined based on assumptions of uniform system characteristics, consumption patterns, and that only meter age drives meter degradation for the KWDS domestic customers. The study was augmented by data collected over several years. Therefore, the meter degradation curves were not solely developed for an 8 month period. Results showed that Model 3 meters are the most suitable meters for the KWDS system characteristics, since they have the lowest meter degradation rate of 1.45% per year. Model 1 meters are the worst meters for the KWDS system since they have the highest meter accuracy degradation rate of 6.67% per year, and the utility loses US$1.5 million every year due to meter inaccuracies of Model 1, Model 2, and Model 3 meters.

Since the current replacement strategy for most small utilities in Uganda involves no replacement criteria or replacements in case of vandalism or theft of meters, the authors recommend use of the determined meter accuracy degradation rates in the optimal meter replacement tool developed by Mutikanga (2012) to determine optimum replacement periods for the KWDS water meters as the developed meter accuracy degradation rates will provide a more robust estimate of when to replace meters compared to the current strategy.

Further research should be carried out to determine how water quality, meter mounting position, sub-metering, leaks, and users' storage tanks affect the meter accuracy degradation rates; also, the relationship between volume and meter age should be investigated further for linear or non-linearity. The utility must develop systems and protocols necessary to guarantee the reliability and accuracy of the data, especially with regard to the registered volumes, installation dates, serial numbers, and models since these are the variables used to query the database.

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