



Water Meter Inaccuracy Assessment and Operation Control Considering Customer Information

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Abstract: Water Meter Inaccuracy (WMI) is one of the apparent loss components contributing to an increase in non-revenue water. The estimation of the volume of water lost due to WMI and control within a utility is still a challenge; thus, the current study investigated its field operation using customer consumption records. A few studies estimated WMI using data obtained in a controlled experimental environment; however, WMI assessment requires a significant computation that includes unforeseen field fault operating environment. This study is of the view that experimental results are necessary for meter type selection, based on the designed flow characteristics and proposes a WMI assessment and control approach in which the field under- or over-registering meters are identified in a billing system. The analysis of this study reveals that a utility operation environment, economic factor and social trust can be efficiently improved using customers water consumption records.

Keywords: Water loss reduction; Apparent loss reduction and control; Meter inaccuracy assessment; Meter operation management.

1. Introduction

Apparent Loss (AL), also known as a non-physical Water Loss (WL) or commercial WL refers to water that is successfully delivered to consumers and consumed, yet the consumption results in no payment to the water utility. It includes water not measured due to water meter inaccuracy (WMI), improper data recording and handling, illegal water consumption, and water meter reading errors (Mutikanga et al., 2011a). Published studies

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that examined AL in developing and developed countries have found the level of AL in developing countries to average 40 percent non-revenue water (NRW), which is high when compared to the 20 percent NRW in developed countries (González-Gómez et al., 2011). However, the European Commission (2015) reported some developed countries like Malta to have an AL of 53 percent NRW. The study of Seago et al. (2004) indicates that water supply utilities in developing countries estimate AL as 20 percent of billed authorised consumption or 5 percent of production and some 20 percent of WL. This is due to a lack of understanding of reliable data for AL assessment; the estimate results in a low and wrong AL estimation (Ncube & Taigbenu, 2018; Thornton et al., 2008).

The majority of WL publications available focus on leakage management with less insight into assessment, reduction, and control of AL components (AL-Washali et al., 2016; Kumpel et al., 2017). For example, AL-Washali et al. (2016) examined the methods of assessment of WL in water supply systems, and suggested AL estimation after leakage analysis. The study by AL-Washali et al. (2016) presented a collection of findings introducing active leakage estimation and control measure based on minimum night flow (MNF) and the bursts and background estimates (BABE) concept that was proposed to estimate the total AL after deducting the volume due to leakages from WL. Contrastingly, a few studies and utilities use benchmarked standard information for estimating the level of AL in components (Arregui et al., 2016). The use of suggested values for analysing WMI in another utility is questionable, because other utility might supply water with different quality parameters that effect an operation and lifespan of a water meter (Arregui et al., 2016; Smith, 1999). In utilities supplying raw water, a water meter is affected by the quality of water (requiring regular cleaning to operate) and even, in a repeated cleaning environment, water meter accuracy deteriorates and increases the loss of revenue collection (Smith, 1999). In low- and medium-income countries, water meters installed in the field are exposed to environment which on the other hand endanger their operations (Fontanazza et al., 2015). These factors are among the long-term causes of water meter under-registration and cannot easily be detected within a short-term experiment environment. The situation urges the development of an approach that measures WMI using water consumption information.

AL has been estimated following a top-down approach and a bottom-up approach (AL-Washali et al., 2016; AL-Washali et al., 2018; Mutikanga et al., 2011a). A review conducted by AL-Washali et al. (2016) presents a WL assessment following the bottom-up approach whereby AL is calculated by deducting estimated leakage from a total WL. In contrast, the study of

Mutikanga et al. (2011a) presents a WL assessment following the top-down approach whereby leakage is estimated by deducting AL from the total WL. The use of the bottom-up approach limits a utility to understand the extent of various AL components, though its result is more reliable compared to AL assessment based on 20 percent of billed authorised consumption or 5 percent of production or other published standards. Although Mutikanga et al. (2011a) estimated AL using a recommended approach (top-down), their assessment approach requires reliable information relating to a long-term field water meters operating under the mentioned environment as their study was short based on only two factors, namely (1) water flow rates and (2) water meter age. The current study uses a top-down approach and introduces the approach to estimate AL due to WMI using customer consumption records that in addition account for control of illegal water consumption which one of the main AL components contributing to WMI. In other words, this method takes into consideration the short- and long-term field water meter-operating environment and control its performance in billing system.

This study mainly investigates WMI occurrence and proposes an assessment methodology to reduce and control WMI using customers' information compiled by the water utility. The Mwanza Urban Water Supply Authority (Mwanza WSSA) in Tanzania was selected. Tanzania is among the developing countries suffering from high NRW (> 20%) in the water distribution systems (Shushu et al., 2021), and many of its utilities supply raw water where water meters are not properly protected and thus, affected within a short time by a fault-inducing operational environment. The Tanzanian Government, through the Ministry of Water (MoW), assigned the Energy and Water Regulatory Authority (EWURA) the duty of monitoring utility performance under Act No. 12 of 2009 amended in 2019. The EWURA monitors the performance of 94 utilities (EWURA, 2020a), the regulated utilities lack a knowledge of estimating and controlling WMI. The complexity makes it difficult for a utility manager to select and apply appropriate AL reduction measures. In 2018 the EWURA reported the level of NRW in Tanzania to be constantly increasing by 1 percent each year from 2008 (EWURA, 2018) however, a few utilities decreased the level of NRW from 40 percent in 2013 to 38 percent in 2014.

The current study proposes an analysis that should be integrated in a billing system to get a consistent analysis between water consumption in the first months of the first year of the operation of a water meter and the current month of the current year of assessment. Thus, a billing system should be developed in a way that water meters of the same diameter have a single access room where the administrator will have access to monitoring

individual water meter operation; lastly a room showing a % error. Consequently, the variation of percentages between the months will alarm the manager to investigate a highly affected water meter and replace or follow up for the control of illegal water consumption activities. The developed methodology monitors water consumption trends of an individual customer for a long-term; thus, it is easier to identify a water meter with fault operation within a short period. A study of Arregui et al. (2016) testified that customer information is not sufficient to confirm the actual 'consumption flow rate distribution pattern for different types of users and countries'. Recently, many water meter inaccuracy experiments have been conducted to determine the accuracy of different types of water meters under different flow patterns. Thus, this study recommends a utility for selecting and installing a water meter type with characteristics related to a system's designed flow, and simply control the WMI using long-term customers' information as per the proposed methodology.

2. Material and Methods

2.1 Overview of WMI Assessment and AL Control Approaches

The majority of the literature studies that presented WMIs have generated erroneous results by doing experiments in utilities supplying treated water under controlled environment referenced to a field water meter operation environment (Arregui et al., 2018; Arregui et al., 2016; Yee, 1999). Experiment results can be useful to estimate WMIs only in systems with the same experiment environment settings. The ability to measure low/maximum flow rates is useful to guide any utility in its selection of a water meter type that measures the volume accurately according to the water system characteristics (Michalec et al., 2019). In most cases, utilities and some empirical studies use published standards to estimate the level of WMI (Arregui et al., 2016; Couvelis & Van Zyl, 2015). However, water meter can be affected by long-term field operations factors like regular cleaning necessitated by water quality problems, heavy traffic passing nearby, faulty installations, customer influences like tampering and reversing and any other unforeseen environment faults (Smith, 1999; Takahashi et al., 2010).

These factors are not easily captured within a short-term experiment and the use of default proposed standards 'probably underestimate' the level of WMI (González-Gómez et al., 2011; Smith, 1999). In a controlled water supply environment, only customer consumption records can provide

reliable WMI information thus, making experiments' benchmark information and standards useful only in a limited situation for WMI assessment. The term '*faulty installation*' refers to a water meter which was properly installed having a few months of operation where it was perfectly registering the volume of water flow but then, due to an unforeseen faulty environment, ceased its accurate operation and started under-registering. This type of fault occurs mostly in low- and medium-income countries where water meters in the field are not properly protected.

This study expands the calibration method proposed in the ISO-4064-3 (1993) that has also been used by many other WMI assessment experiment studies and the Marshallian demand function extended by Moffitt (1986) and Hewitt & Hanemann (1995) to assess the effect of water tariffs change in the water industry. The Eqns are useful to WMI in utilities supplying raw and treated water using customers' records information. Studies of Arregui et al. (2016), Mutikanga et al. (2011b) and Criminisi et al. (2009) used the experiment assessment approach to identify AL due to WMI caused by different system flow rate and aging. The experiments identified the best water meter operating under different flow rates and associated aging inaccuracies. The under-registration of old water meters in each study was determined using the differences between the volume recorded by old and newly installed water meters using the ISO-4064-3 (1993) calibration approach.

Additionally, a study by Arregui et al. (2018) examined the performance of a Single-Jet water meter using the experiment environment of the above named studies and applied the linear regression analysis approach proposed by Smith (1999) to determine the WMI. However, Peduzzi et al. (1995) and Armstrong (2011) revealed that the regression analysis does underestimate the accuracy. Alongside, Mutikanga et al. (2011a) used the methodology approach presented by Yee (1999) and Arregui et al. (2006). Mutikanga et al. (2011a) followed the Arregui et al. (2006) experimental environment and employed Yee (1999) empirical approach to determining the percentage of water under-registration. The study of Arregui et al. (2006) examined AL caused by water meter inaccuracies and proposed an approach that uses customer information and a water meter error curve (characteristics curve). The approach used by Arregui et al. (2006) in their study needs to establish a new water meter flow pattern based on the water system flow rates. To estimate the volume of water lost due to water meter aging, a new operating curve is reconstructed in the existing curve (established using a new water meter based on system water flow) and identifies performance variation between the existing curve and the newly constructed curve. However, 'obtaining

the error curves is not an easy task' and error determination requires a specific meter type performance curve (Arregui et al., 2006) that we view as a challenge to non-expert readers/managers.

This study demonstrates the potential of developed assessment to resolve some of the extant research puzzles. The study presents an alternative approach to that of Arregui et al. (2006) and Mutikanga et al. (2011a), one that does not rely on curves or onsite experiment and yet can be integrated in the billing system for WMI control through the proposed WMI assessment approach. The experiment studies reviewed by this study reported a very small WMI detected in the first year of water meter operation and an increase in WMI in the subsequent years of operations. Thus, the analysis approach followed by this study (1) relies on the average volume of water registered during the first year of water meter operation and (2) the average volume of water registered in a year of inaccuracy assessment under a controlled operating environment. For notational convenience, the term '*controlled situation*' has been used to mean the number of users per connection and the water meter performance characteristics are well known by the utility, and there is timely pressurising of the water supply system throughout the assessment period. This study assumes that an old installed water meter had been selected according to a system's flow characteristics and tested to meet the performance curve characteristics in the year it was installed. Thus, the first and current years recorded information in a billing system can be used for self-inaccuracy estimate as demonstrated in previous sections.

Taking another step, the WMI assessment approach proposed by Arregui et al. (2006) and this study both depends on a controlled operating environment to provide an accurate estimation. In a controlled water supply situation, the proposed approaches have broad application to both WMI assessment and replacement programs. The distinction between the proposed methodology and Arregui et al. (2006) study is that in the proposed users need to monitor the number of family occupancy, water supply frequencies for intermittently pressurised systems and average hours of water supply which is a formal strategy for a utility management (Howard et al., 2004; Mugabi & Njiru, 2006). For notation convenience, we define *family occupancy* to be the number of people sharing the same residential water connection metered at the edge of the street or in a family compound. Thus, the under-registered volume of water should be deduced based on the differences between the water volume registered in the current month and the same month in the first year of installation (taking into consideration the mentioned factors between the first year's month and the current year's month). Water consumption drop per connection during

tariffs change should be taken into account to detect unusual consumption (consumption drop controlled under the boundaries of uncertainties due tariff change) as proposed in Eqn. [8].

2.2 Proposed WMI Assessment Based on Customer Database

Assume family occupancy, hours when the system is pressurised and the frequency of pressurising the system in the same month of two different years of assessment is known to be different. The use of relative factors to determine the equivalent volume of water registered in the first/current year of operation using the ISO-4064-3 (1993) approach to analyse the WMI is recommended. Means that the current year's month family occupancy or hours should be divided by the family occupancy or hours observed in the same month of the first year of water meter operation then multiplied by the volume of water recorded in the first-year month to get the relative volume, v'_0 . Assume the volume of water registered in the month of the first year of water meter operation represented by v_0 and the volume of water registered by the same meter in the same month of the assessment year represented by $v_n, n = 1, \dots, s$. Let the number of family occupancy of the first year's month represented by a and the number of family occupancy of the assessment year's month represented by b , if $a \neq b$ then $v'_0 = b/a \times v_0$. Again, let d stands for the average hours of water supply in the month of the first year and f stands for the average hours of water supply in the month of the current year, if $a = b, f \neq d$ then $v'_0 = f/d \times v_0$. It is well known that a water meter measurement has an error of $\pm 2\%$ to $\pm 5\%$ (calibrated by the manufacturer); thus, by default a letter e stands for a water meter operating error. Let n stand for a requested assessment duration; then, a general Eqn. extended from ISO-4064-3 (1993) can be written as

$$Mi_n = \frac{v_n - v'_0}{v'_0} \times 100\% - e$$

where

(1)

$$v'_0 = \left(\frac{b}{a}, \frac{f}{d}, \frac{b}{a} \times \frac{f}{d} \right) v_0; b, f \neq a, d$$

$$\pm 2\% \leq e \leq \pm 5\%$$

$$v'_0, v_n > 0, \forall n = 1, \dots, s$$

Assume a WMI assessment conducted during the tariff change period. The study of Nieswiadomy & Molina (1989) and Nauges & Blundell (2002) examined the consumption drop under increased or decreased domestic block tariffs using Marshallian demand function. The studies show that tariffs change affect customer's water consumption behaviour even if the family occupancy and other parameters are the same (Herschey, 2002; Nauges & Blundell, 2002; Nieswiadomy & Molina, 1989; Olivier, 2010). This type of uncertainty requires analysing and monitoring WMI, considering the effect of tariff change to avoid wrong WMI estimates due to customer behaviour change (Hernández-Sancho et al., 2012; Molinos-Senante, 2014; Olivier, 2010). Water consumption is divided into domestic, institutional, commercial, industrial, irrigation etc.; and over 80 percent of water consumers in developing countries are domestic customers (Mutikanga et al., 2011a) and their water consumption behaviour changes during a new tariff setting. To demonstrate the analysis, this study employs the Marshallian demand function and relative factors to present WMI assessment for domestic customers. A water meter installed in an institution or commercial or domestic areas behaves in the same way if they are of the same age and flow characteristics do not vary. The operation fault-inducing environment differentiates their measuring accuracies; thus, we opt to use the domestic consumption customers to demonstrate the analysis that represents other categories.

Studies by Nauges & Blundell (2002) and Olivier (2010) extended the application of residential water demand analysis under block rate pricing from Burtless & Hausman (1978) and Hewitt & Hanemann (1995) detailed in the Moffitt (1986) study. These studies present analysis theories and propose the maximum-likelihood approach to estimate water consumption uncertainty after tariff change. Tariff change affects WMI assessment because a drop in water consumption may result into a low water consumption detected as caused by the WMI. Thus, to support a WMI assessment during tariff change and avoid a large number of low water consumption grouped as caused by WMI, this study includes the analysis of uncertainties due to nonlinear tariff structure proposed by Moffitt (1986) applied by Nauges & Blundell (2002) and Olivier (2010) to estimate water consumption elasticities. The analysis approach has been chosen due its simplicity in application and availability of customer information in the utility database (Olivier, 2010). When integrated in a billing system, an abnormal water meter operation during tariff change (consumption beyond the elasticities) can be detected and helps a utility management to perform a regular water meter operation check-up and come up with an immediate solution.

Thus, consider a utility with two blocks domestic tariffs. A customer with an income I has water consumption derived from a function $U(q, z)$ where $q = q^*(p, y)$ stand for water consumed, $q^*(p, y)$ is the demand function and z stands for composite good (fixed charges) normalised to one. Let p stand for relative price of q in the j^{th} block and l stands for the limit of water consumption in the j^{th} block. Thus, j^{th} block income I can be interpreted as

$$I = \begin{cases} p_1 q + z & \text{if } q \leq l_1 \\ p_1 l_1 + p_2 (q - l_1) + z & \text{if } q > l_1 \end{cases} \quad (2)$$

deduced as:

$$y_1 = p_1 q + z \quad \text{if } q \leq l_1 \quad (3)$$

$$y_2 = p_2 q + z \quad \text{if } q > l_1 \quad (4)$$

where $y_2 = I + (p_2 - p_1)l_1$ termed as the ‘virtual income (full income)’ and $(p_2 - p_1)l_1$ is termed as the ‘difference variable’ denoted as D , the difference variable is positive when tariffs increase and negative when tariffs decrease (Moffitt, 1986; Nauges & Blundell, 2002). Income extension to multiple block tariffs with water consumption limitation, $l_j, j = 1, \dots, n$ in the j^{th} block is straightforward, for analysis demonstration we use two blocks tariff structure demonstrated in Eqns. (2), (3) and (4) (the majority of the studied utilities use two blocks tariff structure). However, the analysis in Eqn. (2) to (4) does not represent a full consumer behaviour because it cannot handle the estimate of desirable large-samples requiring consistency, asymptotic normality and efficiency. The analysis of these types of properties during tariffs change are covered by the maximum likelihood approach. The approach analyses a customer behaviour either in a ‘conditional’ or ‘unconditional’ water consumption plan. By ‘conditional plan’ means the demand function states the quantity of water q used conditionally to the choice made by the user inside one particular block and ‘unconditional plan’, corresponding to the combination of choice of consumption block and continuous supply (Moffitt, 1986; Nauges & Blundell, 2002; Olivier, 2010).

The maximum likelihood approach generates mean consumption ($\bar{q}$), standard deviation, minimum q_{min} and maximum q_{max} consumption and elasticities (see Moffitt (1986), Nieswiadomy & Molina (1989), Hewitt & Hanemann (1995) and Nauges & Blundell (2002)). In this study, q_{min} and q_{max} plus elasticities (ϵ, η) are essential to monitor a customer consumption behaviour, meaning that customer consumption record after tariff change should be close to mean value depending on the standard deviation value estimate but not out of the minimum and maximum boundaries plus

elasticities. When noticed that a customer consumption is beyond a boundary, a water meter operation should be investigated. To assess a WMI, relative factors should be included in the analysis as used in Eqn 1; thus, conditionally q demand function in the j^{th} block can be expressed as

$$q = \begin{cases} q^*(p_1, y_1) & \text{if } q < l_1 \\ l_1 & \text{if } q = l_1 \\ q^*(p_2, y_2) & \text{if } q > l_1 \end{cases} \quad (5)$$

In developing and some developed countries this type of water consumption rarely happen within the domestic consumption division but it occurs in other water consumption divisions; the majority of the domestic water consumers are in the unconditional water consumption behaviour. Unconditionally, the current water consumption q function in the j^{th} block can be analysed as

$$q = \begin{cases} q^*(p_1, y_1) & \text{if } q^*(p_1, y_1) < l_1 \\ l_1 & \text{if } q^*(p_2, y_2) \leq l_1 \leq q^*(p_1, y_1) \\ q^*(p_2, y_2) & \text{if } q^*(p_2, y_2) > l_1 \end{cases} \quad (6)$$

Studies of Burtless & Hausman (1978), Moffitt (1986), Nieswiadomy & Molina (1989) and Hewitt & Hanemann (1995) examined the maximum likelihood assessment approach under unconditional consumption environment and identified two types of errors (elasticities) to include in the analysis. Studies identified errors due to the ‘heterogeneity in preference, ε ’ which accounts for conditional choice (both continuous and discrete) and an optimization or perception error, η which accounts for the discrepancy between desired and observed levels of consumption’ behaviour for the continuous choice (Hewitt & Hanemann, 1995; Nauges & Blundell, 2002). The addition of errors take care of the unforeseen faults like different levels of unconditional water consumption (Hewitt, 2000; Olivier, 2010). Following these explanations, the Marshallian model under tariffs change environment becomes

$$q = \begin{cases} q^*(p_1, y_1) + \varepsilon + \eta & \text{if } \varepsilon < l_1 - q^*(p_1, y_1) \\ l_1 + \eta & \text{if } l_1 - q^*(p_1, y_1) \leq \varepsilon \leq l_1 - q^*(p_2, y_2) \\ q^*(p_2, y_2) + \varepsilon + \eta & \text{if } \varepsilon > l_1 - q^*(p_2, y_2) \end{cases} \quad (7)$$

We are presenting water consumption drop/increase using the maximum likelihood Marshallian approach considering unconditional consumption environment for domestic division. Let q_{min}^- stand for $q_{min} + (\varepsilon, \eta)$ and q_{max}^+ stand for $q_{max} + (\varepsilon, \eta)$; thus, incorporating the effect of tariff change and flow measurement uncertainties in Eqn. (1), the proposed WMI assessment approach is modified as

$$Mi_n = \frac{v_n - v'_0}{v'_0} \times 100\% - e$$

where

(8)

$$\begin{aligned} v'_0; v_n &= \left\{ \left(\frac{b}{a}, \frac{f}{d}, \frac{b}{a} \times \frac{f}{d} \right) v_0; q|q \rightarrow \bar{q} \right\} b, f \neq a, d \\ \pm 2\% \leq e \leq \pm 5\%; q_{min}^- \leq q \leq q_{max}^+ \\ v'_0, v_n &> 0; \forall n = 1, \dots, s \end{aligned}$$

The estimation of water consumption drop/increase during tariff change is necessary to identify unusual water consumption behaviour that question the water meter operation or customer water consumption. During tariff change some customers employ illegal activities that distort the water meter measurement and reduce the volume of water registered to pay less (Deyà-Tortella et al., 2016; Mutikanga et al., 2009). It is well known that after tariff change, domestic customer water consumption behaviour changes and probably maintain such behaviour for a long-term. However, institutional, commercial, industrial and irrigation customers' consumption might remain the same (Deyà-Tortella et al., 2016; Deyà-Tortella et al., 2017); thus, the methodology to estimate water consumption in these divisions remain as in Eqn. (1) and monitored using approaches proposed in Eqn. (1).

On the other hand, the use of Eqn. (8) only does not allow us to locate a percentage error in the first year (Mi_0) of a water meter operation as in experiments. Using Eqn. (8) results in a default percentage error, e which differs from the error values due to water meter aging in operation. Thus, we applied the correlation analysis of the volume of water registered in Mwanza WSSA for a period of 5 years based on 556 water meters installed in 2015 (considering $v'_0 = v_0$) that operated up to 2019. The correlation coefficients were used to discern the 'degree or strength of this type of relationship' that are basically the association between the two identified variables (Taylor, 1990). Focusing on volume of water variation from v_0 , the correlation analysis indicated that the volume of water recorded in 2015 (v_0) was highly correlated with volumes recorded in 2016 (v_1). The correlations were positive and significant at the 0.01 level. Thus, from this conclusion, this study assumes that $Mi_0 * v_0$ is equivalent to $Mi_1 * v_1$ and Mi_0 can be derived from $\frac{v_1}{v'_0} * Mi_1$. Taking into consideration the relative factors assumed that $v_0 \neq v'_0$ then

$$Mi_0 = \frac{v_1}{v_0} Mi_1 \mid Mi_1 < 0 \text{ estimated using Eqn. (8)} \quad (9)$$

It is necessary to monitor the operation of newly installed water meters under known operating environment to avoid illegal water consumption activities like tampering and reading reverse. The study of Kumpel et al. (2017) examined water meter operating under intermittently pressurized systems, it was observed that estimating WMI in an intermittent water supply system is difficult. Because the number of users per connection, frequency of water supply, and water supply hours are predicted to change throughout the operation period. Thus, using the proposed assessment approach, this study recommends that if a water supply system is intermittently pressurised, a utility should use the monthly variation average hours. However, in low- and middle-income countries which pressurise the system intermittently, the probability of getting a higher reading between years might be high due to an increase in the unknown number of external water users sharing a single connection (De Marchis et al., 2013). Such sharing makes a difficult environment for this study proposed WMI assessment approach. If a utility is unable to control the identified factors, with proper water meter type installed, the study recommends estimating WMI using recommended standard values.

3. Results and Discussion

3.1 Dataset Description

The datasets considered in this study were retrieved from the EWURA (2020b) annual report and ten years information collected in 2020 from the Mwanza WSSA billing database (993 one zone connections out of 90,603 utility domestic connections). The study used only 556 customers' information who were observed to have a water meter installed in 2011 and paying their bill accurately from 2011 to 2020; zone identification code, customer's account and category, monthly consumption and revenue, meter number, size and status information of customers with meters working from 2011 to 2020 were collected in monthly basis. However, information like family characteristics (size, occupation etc.) were missing in a utility database for the studied periods; thus, a standard figure (six people per household recognised by the Tanzania Government) is considered in assessment as a family occupancy. The Mwanza WSSA supplied water for an average of 22 hours/day annually covering 84 percent of the licenced area with 788.8 km main lengths. The studied zone received water for 24/7 with

an average flow of 800 L/hour and their customers had sewer connections which made it different from other zones.

During data screening, 53 percent of customers were observed to consume more than 15 m³ continuously in two consecutive months, and less than 6 m³/month in the next months; meaning that monthly consumptions were irregular. For the analysis purpose, the study-ignored consumptions below 6 m³/Month because it is below the minimum consumption in cities (200 L/ca/d; see Shaban & Sharma (2007)). The approximate figure of 90 L/ca/d in cities with block tariff and flushing systems like zone A in the Mwanza WSSA is proposed in the MoW (2020); a minimum of six people's as family occupancy indicated in the NBS (2021) is used in this study. Thus, 6 people consumption should be 16.2 m³/month and for a single person an approximation of 6 m³ is acceptable. According to EWURA (2020b), a new water tariff of TZS 1,040 from TZS 700 for consumption up to 10 m³/month and TZS 1,290 from 865 for consumption above 10 m³/month was effective in November, 2019. A utility produced 29,888,025 m³ and, 20,622,737.25 m³ was billed in 2020 leaving 31 percent of production as NRW. Mwanza WSSA uses a three block tariffs setting. However, for analysis demonstration this study applied a two-block structure employed by the majority of the WSSA in Tanzania. Table 1 reports about analysed descriptive statistics used for consumption estimation as a guide to help monitoring a water meter operation after tariff change.

Table 3.1: Statistical summary of the difference on tariff effect

Variable	Average Consumption before tariff change	Average consumption after tariff change	Difference
Minimum, q_{min}	7.00	6.667	-2.49
Maximum, q_{max}	305.33	352.33	-
Median	25.67	26.333	-0.3333
Mean	35.04	34.610	-0.4275

3.2 The Model Analysis and WMI Assessment

3.2.1 Development of Present Water Consumption (v_n) Through Tariff Change

To assess a long-term, real field situation considering water meter inaccuracies, this study investigated customers billing database (water meters installed nine years back) in the Mwanza WSSA and operation results compared with Yee (1999) and Arregui et al. (2006) experiment results. A utility supplied treated water for an average of 22 hours a day; a studied area received water for 24 hours/day and had sewerage system. During the analysis, this study observed that some customers had consumptions of less than 6 m³ per month for more than five months; consumptions below 6 m³/month were omitted in the analysis. However, there were a few domestic customers with extremely higher consumptions sported during analysis (higher consumption before and after tariff change, Figure 1 and Table 3.1). This is an alert for change of purpose of water use to some customers from domestic to commercial use.

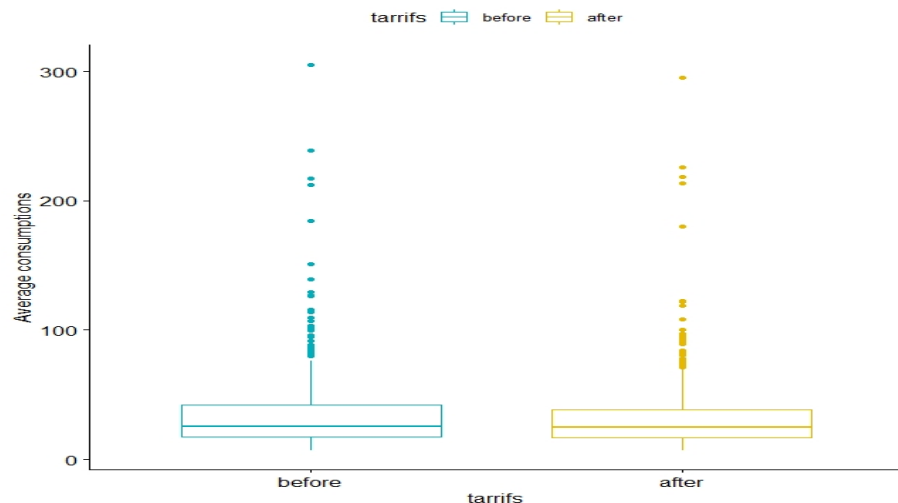


Figure 3.1: Water consumption variation before and after imposed

Thoroughly investigation, this study further found that 49.6 percent of 556 customers increased water consumption and 50.4 percent of 556 decreased their consumption after tariff change (Figure 2, average of three months before and after tariffs change). Customers within a positive deviation means had increased their consumption and customers within a negative deviation means had decreased consumption after increase of

tariffs. The drastic positive increase of water consumption for consecutive three and more months signifies that the customer is wrongly counted in domestic consumption category; a customer should be investigated and allocated to a specific water consumption category. Customers with negative deviation had no problem since during tariff change that is what usually expected (Deyà-Tortella et al., 2016); however, outliers (drastic decrease/increase for months) still should be crosschecked to avoid illegal water consumption or tampering with water meters that permanently distort the accuracy of a water meter operation. It is well known that during water supply system design, 200 L/c/d (6 m³/c/month) is usually used for domestic consumption estimation. Considering a household of 6 people, the volume is equivalent to 37 m³/household/month; adding a volume during peak hours it is envisaged that at peak hours the consumption cannot exceed 52 m³/household/month.

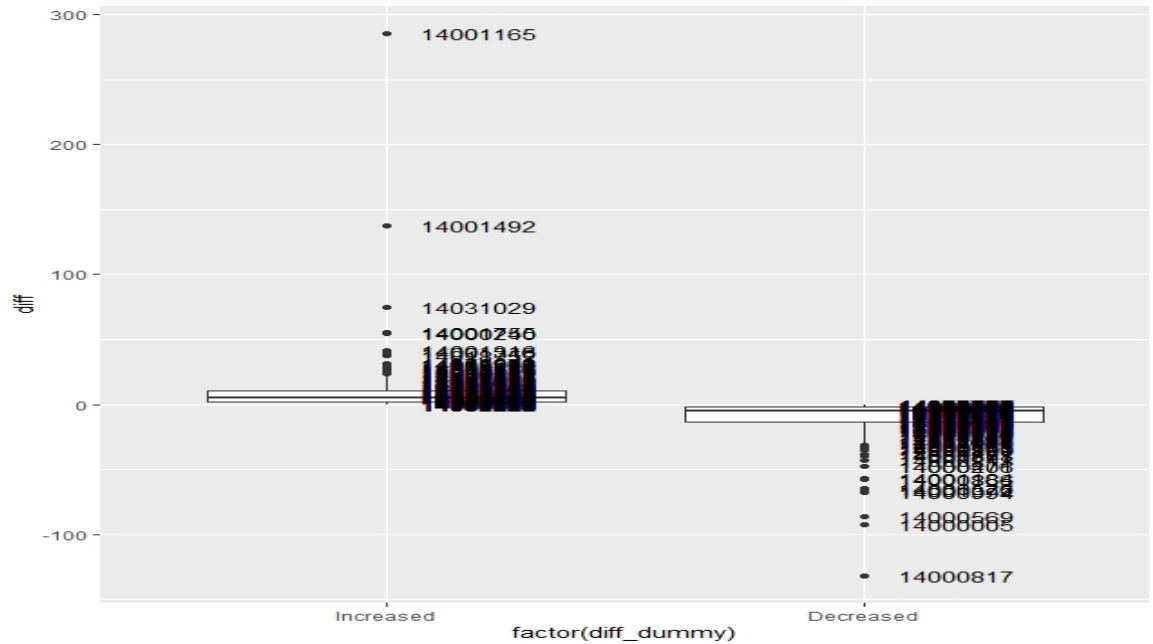


Figure 3.2: Deviation of the mean difference as an effect after imposed new tariff

Figures 3.1 - 3 presents the movement of customers water consumption before and after tariff change, which is the basis for the analysis using Eq. 8 described in previous paragraphs, here, v_n is estimated equivalent to q such that q approaches to $\bar{q}$ (mean). For this case, $\bar{q}$ was observed to be 34.61 m³/month after tariff change with $q_{\min} = 6.7$ m³/month and $q_{\max} = 352.33$ m³/month; an

elasticity of -2.49 m^3 after tariff change was observed during analysis. Thus, in a billing system a customer with $4.21 \text{ m}^3/\text{month}$ ($q_{\min}^-$) after tariff change should be considered as a minimum practical water consumption. However, a few $q_{\max}$ in this analysis is far beyond the *mean* consumption obtained and not practical to be considered under the domestic category. According to direction of the model analysis, consumptions less than $70 \text{ m}^3/\text{month}$ (approaching to *mean*) is far better practical. It was observed that 118 customers out of 556 involved in this study had their water consumption information to deviating far away from the *mean* and their consumption ranged above $70 \text{ m}^3/\text{month}$. Incorporating this analysis in a billing system will signify the identification of outliers (customers with

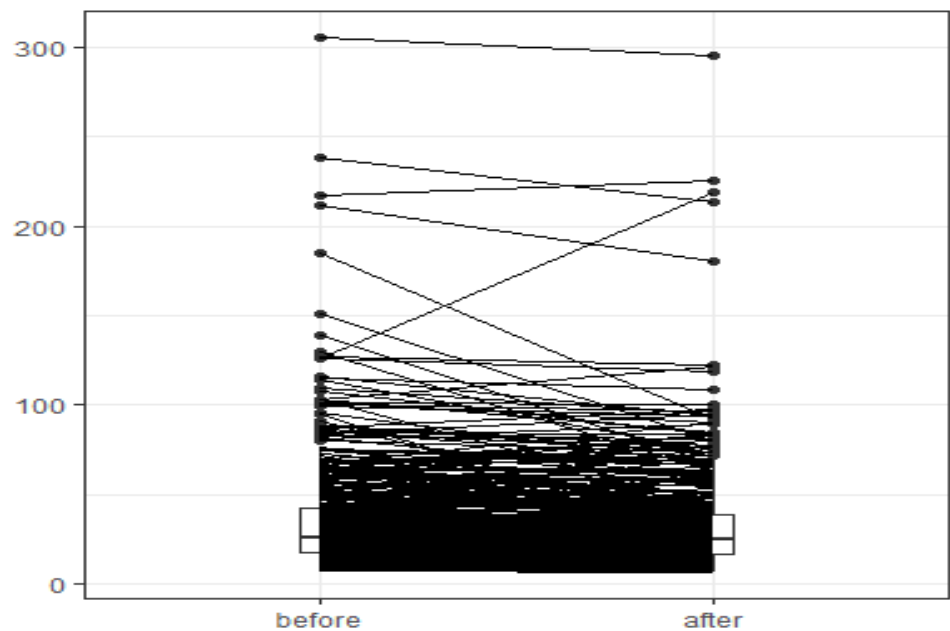


Figure 3.3: Movement of water consumption change before and after tariffs

lower/higher water consumption beyond the monthly *mean*) as an alert for a customer water consumption investigation and the most important, change of water consumption category to increase a utility revenue collection efficiency as well as an economic aspect of a utility.

3.2.1 Development of Previous Water Consumption (v_0) And WMI Assessment

The estimation of previous water consumption is straightforward with the availability of relative information. However, it is not a common practice in Tanzania to record some of this information though, Water Act No. 5 of 2019 of Tanzania requires a meter reader to take a water meter reading in the presence of a utility customer. For example, the number of customers family members were missing in a database; the parameter is extremely important to estimate equivalent volume of water used by a customer for years back to conclude whether a customer water meter operate properly. Apart from being a very important information in estimating previous water consumption, it also helps a utility to manage complains about overbilling received from a customer and under billing observed in a utility database which apparently improves a utility revenue collection efficiency as well as operation practice and social trust. Due to the requirement of the Water Act for meter reader to take reading registered by a water meter in the witness of a customer; it is apparent that the regulator can use the gap to make the availability of the mentioned information on a monthly basis through regulation made by the responsible Minister.

The absence of some of the relative information make us use actual information observed in 2011 and deduced information in 2020 as demonstrated in Table 3.2. After tariff change, a consumption drop is expected when estimating error volume; a water meter can register a drastic decrease in water consumption which gives a high percentage error compared to a year before tariff change. There were a slight decrease of an average of 1.52 m³ in 2020 compared with the same month of 2019 for selected pilot customers. Besides, the studied utility system pressure was adequate in all outlet points; the study tested a flow rate by investigating duration of filling a container of 20 litres volume where the average flow was observed to be 800 L/h. According to Arregui et al. (2006), Mutikanga et al. (2011b) and Arregui et al. (2016) the flow rate is adequate for a water meter operating under $\pm 2\%$ thus, used in this analysis.

Table 3.2: Analysis and comparison of water meters operation for ten years

No. of water meters analysed in 2011 and 2020	Meter size	Average volume of water registered in January, (m ³ /year)		% Error volume (Mi_{10})	Remark
		2011 (v'_0)*	2020 (v_n)†	$= \frac{v_n - v'_0}{v'_0} \times 100\% - 2\%$	
20	$\frac{1}{2}$ "	28.02	21.02	-7.0	Information were collected from houses in a commercial area with an average flow of 800 L/hr
20	$\frac{3}{4}$ "	26.21	18.01	-8.2	
	Average error due to different meters diameter			-7.6	
	Yee (1999) experiment study – An error for a water meter operating in the 10 th year			-5.7	

*Relative factors due to water consumption uncertainties were not considered

Act No. 5 of 2019 gives power to the Minister for Water to make regulations, a responsible Minister can add a phrase requiring a water stakeholder to disclose family occupancy information during customer registration for the first time and regular water meter reading periods. Note that analysis of water meters of the same sizes together will not reveal a highly affected water meter for a replacement/follow up programme; using Eqn. [8] on individual customer records, it is easier to identify a badly under- or over-registering water meter because each type of water meter is monitored individually in the billing system. Based on Yee (1999) and this study, the errors for water meters analysis are -7.6 percent and -5.7 percent respectively. However, due to unavailability of relative information and

climate change effect from 2011 to 2020, our analysis could have reported a high percentage error compared to Yee (1999) results. Contrastingly, Yee (1999) study recommended a water meter replacement after 15 years since a water meter operating for 15 years was estimated to have an average error value of -4.6 percent, which is equivalent to that of a 10-year-old water meter in our study without default error ($\pm 2\%$).

Based on these statistical data, this study further conclude that our analysis gives a way for users to decide an economically optimal duration before replacing a water meter based on individual water meter operating environment, and the water meter is not subject to a fixed replacement duration identified by the faulty operation of other water meter. The approach is helpful to water meters operating in low- or medium-income countries where the control of illegal water use is very difficult. The replacement programme proposed by Yee (1999) study is for water meters installed all at the same time, but in low- and medium-income countries, it is difficult to find a system of that natures after 15 years, especially when a utility supplies raw water or a system with pressure variation. This study recommends an immediate individual water meter replacement when the assessment based on a faulty water meter operation environment indicates in a billing system. The replacement intervention should be self-paying, and over time the utility will replace all old meters and enjoy the benefits of AL reduction intervention.

3.3 Economic Significance of the Methodology

The discussion earlier in this paper leads to the conclusion that diligent work by the data handling and billing department is the main way for a utility to discover errors due to water meter faults, illegal activities, meter reading, and similar problems. The doubt about a customer's water consumption starts in this department and should be channelled to the responsible senior managers. Senior managers track utility operations and address customers' requirements based on the information provided by this department. However, changes in water tariffs directly affect water affordability. The most affected group is the poor population whose relative cost of purchasing satisfying quantities of water is inversely related to their monthly income. The poor strive to meet their household water demand as the demand is inelastic due to its importance in supporting daily life. García-Valiñas et al. (2010) conducted a study on the affordability of residential water tariffs in different municipalities of Spain and developed a household annual-minimum water threshold and affordability index useful for controlling minimum water consumption. The negative relationship between tariffs and water consumption in this study indicates the adverse effect of the increased

tariffs on household water consumption. The effect is higher during the first three months of tariff change than in the subsequent six months.

Due to its importance, the majority reduces household water consumption emanating from increased tariffs at the start of a new policy and later resumes to normal consumption pattern. This was also noted in Deyà-Tortella et al. (2017) study when they analysed water prices reforms and household water consumption in Calvia. The results showed that only in the first year there was a decrease in aggregate consumption. However, the consumption was restored and increased in subsequent years. The response to price changes was not the same across the household income. The majority of high-income households retained and later increased their consumption while the poor households drastically reduced water consumption. Water consumption control improves a utility economy that conversely hand allows for water services extension in non-benefiting areas using utility budgets obtained through increased revenue collections. For example, this study observed 118 customers in a studied zone having consumptions beyond the mean limit proposed in the model (2 times observed *mean*). The same customers might be present in other zones too that increase loss of utility revenues, controlling customers consumption might save the quantity and cost of water illegally consumed by these customers.

4. Conclusions

This paper presents a WMI assessment methodology and operation control using customer information that accounts for the field fault water meter operation environment. Using the default actions of previous methods, AL is estimated using standard values (such as 20 percent of billed authorised consumption or 5 percent of production), which is an assessment technique observed to overestimate the volume of water lost due to leakages. Likewise, some experiment studies have presented AL assessment considering water meter age observed through different water flow patterns. These experiments have been conducted over only a short-time frame and in a controlled operating environment that does not account for the field fault environment that reduces a water meter's accuracy in measuring the volume of water flow. In real life, water meter operations can be affected by short- and long-term field operations factors like regular cleaning necessitated by water quality problems, faulty installations, customer influences like tampering and reversing, and other unforeseen factors in the operating fault environment. These factors are not easily captured within a short-term experiment and the use of default proposed standards probably underestimates the level of AL. In contrast, estimating WMI using customer

information produces an AL value that take into consideration all the fault environment constraints. However, managing WMI using customer information requires the utility management to understand the customer's family occupancy and control water supply trends, especially in utilities pressuring a water system intermittently or supplying water continuously for only a short part of each day.

One last point is that, our literature review has shown that water meter tampering and illegal use was observed to be the main illegal water use activity, which causes high WMI; Using the WMI assessment approach proposed by this study, inaccuracy errors can be identified using the billing and data handling department. It is expected that there will be timely, continuous, and constant WMI control which will keep AL at a minimum level, enabling the utility to increase revenue collection efficiency. This can be done mainly by following the variation of percentage errors within the billing system. It is envisaged that the level of AL occurrence will be under control, the utility will manage to estimate the volume of water lost due to leakages easily, the utility will generate more revenue and concentrate on leakage reduction, and in the future, the utility will be able to expand water services to non-benefiting areas without depending upon development funds allocated by the government each year.

We recommend future researchers to expand the scope of the WMI analysis approach proposed in the current study by investigating customers water consumption behaviour based on the effect of climate change and incorporate factors in the analysis to balance previous years and current consumptions, investigating customers connection sharing behaviour, propose rational factors to integrate in a billing system so as to overcome uncertainty due to unknown number of external water users sharing a single connection.

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