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Estimate measurement errors of household water meters using a large amount of on-site data feedback

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Abstract

Water meter measurement error is considered as one important component of non-revenue water by International Water Association. Its magnitude depends combinedly on users' consumption behaviors (intake spectrum) and metrological characteristics of water meters (meter error curve). Most published researches have only analyzed the meter error curves without taking the users' consumption behaviors into consideration. This study developed a practical approach by using the relative difference chart of master-meters and sub-meters groupings (i.e., R_M-μ_z chart) to identify average metering errors for a major water utility company in Taiwan. About 120,000 sets of "master-meter and sub-meter grouping" data of Taipei Water Department were analyzed. The approach successfully estimated average metering errors of its 99.6% domestic meters (around 1.6 million water meters), the results are 9.9, 6.1, and 10.0% less than the actual water consumption recorded by the sub-meters, master-meters, and direct-meters, respectively.

Keywords Metering error, Meter error curve, Meter readings, Relative difference between readings, Random variable

1 Introduction

A water meter is an instrument and an important component of system management for water conservation. Yet, water meters do not often provide accurate measurements. It is understood that any water meter has metering errors in nature, and the magnitude of errors depends on its type, size, age, and conditions of use [1, 2]. In addition, once a meter is put into service, its performance starts to deteriorate. The accurate degradation of water meters can pose severe challenges for utilities, and it is usually presented in the form of a non-revenue increase [3].

Due to cost consideration, most of the water meters are mechanical meters (e.g., single-jet, multi-jet, and piston) [1]. The main challenge for using mechanical meters is to accurately measure individual water withdrawals. The accuracy is affected by many factors, including meter wear and tear, blockage of the meter inlet or strainer, depositions on the meter components, incorrect sizing, incorrect mounting position, the filling process of an empty pipe [4], generation of cavitation [5], and incorrect flow profile [6–8].

In addition to mechanical water meters, there are also some non-mechanical water meters such as ultrasonic meters, electromagnetic flowmeter. Baker [9] provided an introductory guide to the measurements of some conventional types of water flow meters including differential pressure meters, momentum meters, ultrasonic meters, vortex-shedding meters, and laser flow meters. Some of them, especially differential pressure meters, might have difficulties in installation and maintenance; while those with higher accuracies, such as ultrasonic meters, could

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be more expensive [10]. Development of cheaper, more convenient, and more accurate methods for measuring water flow rates is of necessity.

In addition to using the above mentioned physical flow meters, flow rates can also be determined mathematically through pertinent measurable variables coupled with calibrated characteristics correlations [11]. Some researchers used computational fluid dynamics numerical modeling to study the measurement accuracy of ultrasonic water meters [12]. Wang [13] developed water flowrate models based on inherent relationships among flow rate, pressure difference, and pipe resistance coefficients. Those models improved the accuracy of flow measurements, especially in the low flow range. Guo and Jin [14] demonstrated that every meter's relative error can be calculated. By using autonomous algorithm, providing the accuracy class of any meter, the relative errors of remaining meters in the cluster can be worked out.

In general, the water meter measurement error is a function of two parameters: the water consumption patterns of the users (Intake Spectrum) [15–17] and the characteristic error curves of the meters (Meter Error Curve). The main factor affecting the intake spectrum is the water consumption habits of the customers and it is the main unknown of all [18]. The flow rate that passes through a meter is the governing factor of the meter accuracy [7]. For a specific meter, its metering error would be different with different intake behaviors (Fig. 1). In other words, the inaccuracy levels of the user meters depend on the metrological performance of the meter at a specific flow rate. Consequently, the water consumption behaviors of the customers needs to be taken into account to fully understand the measurement errors.

In most countries, water meters are required to be tested under specified constant flow rate conditions [19]. However, these testing conditions may not represent the actual consumption behaviors of the consumers. Actual water consumption profiles would have dynamic load changes, including rapidly changing flow rates. Buker et al. [1] proposed a unique test equipment for calibrating domestic flow meters under dynamic flow conditions. Arregui et al. [15] considered the consumption characteristics of domestic users, and tested several types of residential meters to obtain the error curves coupled with measured consumption patterns of domestic users. Additionally, the information about the orders of magnitude of the initial measuring error as a function of the residential meter model and user characteristics was obtained.

Water utilities and academics have not reached an agreement on universal methods of evaluating average metering errors. Some of them adopted testing methods to estimate metering errors. However, the cost of testing is high so that it is almost impossible to launch a full-scale testing project to obtain representative results for the overall behavior. In addition, the fatal drawback of using a testing method is that it cannot simulate the water consuming behaviors of all the customers. It means that a testing approach can only establish a Meter Error Curve, not the actual meter measurement errors.

This study analyzed the historical meter reading records of a major water utility company, which contain both water consumption behaviors and meter characteristics. The approach is better than using a testing method alone and the estimated metering errors are less biased.

2 Materials and methods

2.1 Relative difference between readings of master-sub meter groupings

There are three types of water meters in Taipei Water Department (TWD) in Taiwan; they are direct-meters,

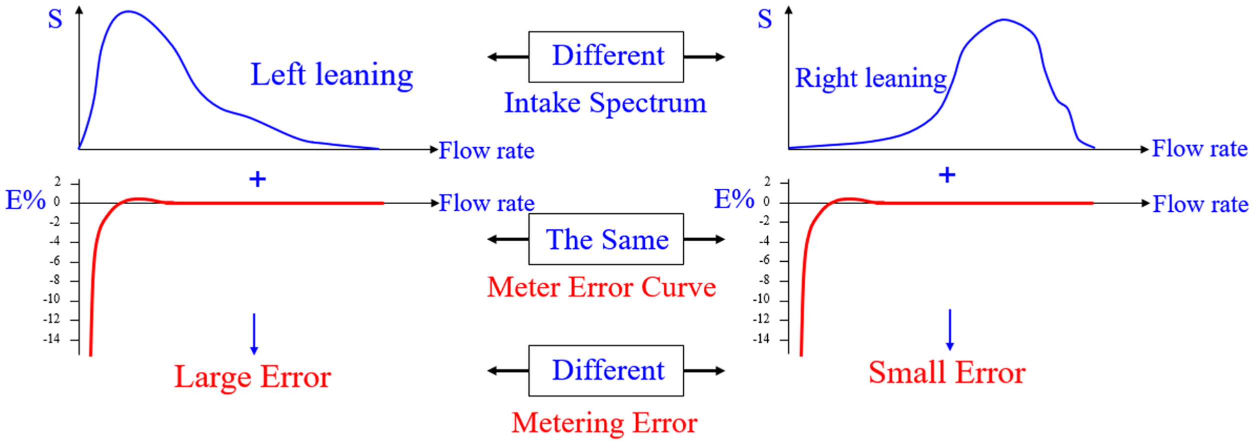

Fig. 1 Two major factors for water metering errors (S: frequency of water consumption; E%: metering errors)

master-meters and sub-meters, as shown in Fig. 2. Direct-meters are installed for customers who use water directly without passing thought building reservoir; while master-meters and sub-meters are provided for customers who use water passing through building reservoir.

Theoretically, the water consumption recorded by the master-meters should be the same as the sum of those recorded by the total sub-meters. However, due to the fact that the characteristics of each water meter and the water consumption patterns of the users are different, the readings of master-meters and the sum of sub-meter readings are not the same. In this study, we use the relationship between the master-meter reading and the sum of sub-meter readings to derive the water meter measurement error. Since this method uses actual water consumption data from the TWD's meter reading records, the analysis results are a composite of the actual conditions on site. In other words, all factors that affect the accuracy of the water meter (including meter wear and tear, blockage of the meter inlet or strainer, depositions on the meter components, incorrect sizing, incorrect mounting position, etc.) are taken into account.

Data used in this study were obtained from the TWD's meter reading records of "master-meter and sub-meter grouping". TWD has about 120,000 of such groups, and each group produces 6 reading records annually. Thus, there are about 720,000 pieces of data in a year. Out of these data, the master-meters with diameters of 20 to 40 mm accounted for about 96.4% of the total, while those with a diameter of 25 mm accounted for the highest proportion, 52.5%. The average numbers of sub-meters per master-meter for each diameters size are shown in Table 1. The relative difference between the readings of the master-meters and the sum of the sub-meter readings is mostly within ± 10%, for 82.7% of all data.

Comparing the reading records of master-meters divided by number of sub-meters with the corresponding sub-meter readings, we found that there are similar water

Table 1 The master-meter and sub-meter groupings in TWD

Meter Diameter (mm)	Number of Master-meters	Percentage (%)	Average Number of Sub-meters per Master-meters
13	1,824	1.5	3.0
20	28,114	23.2	4.3
25	63,480	52.5	7.7
40	25,017	20.7	18.4
50	1,089	0.9	58.2
≧75	1,409	1.2	110.5
Total	120,933	100.0	

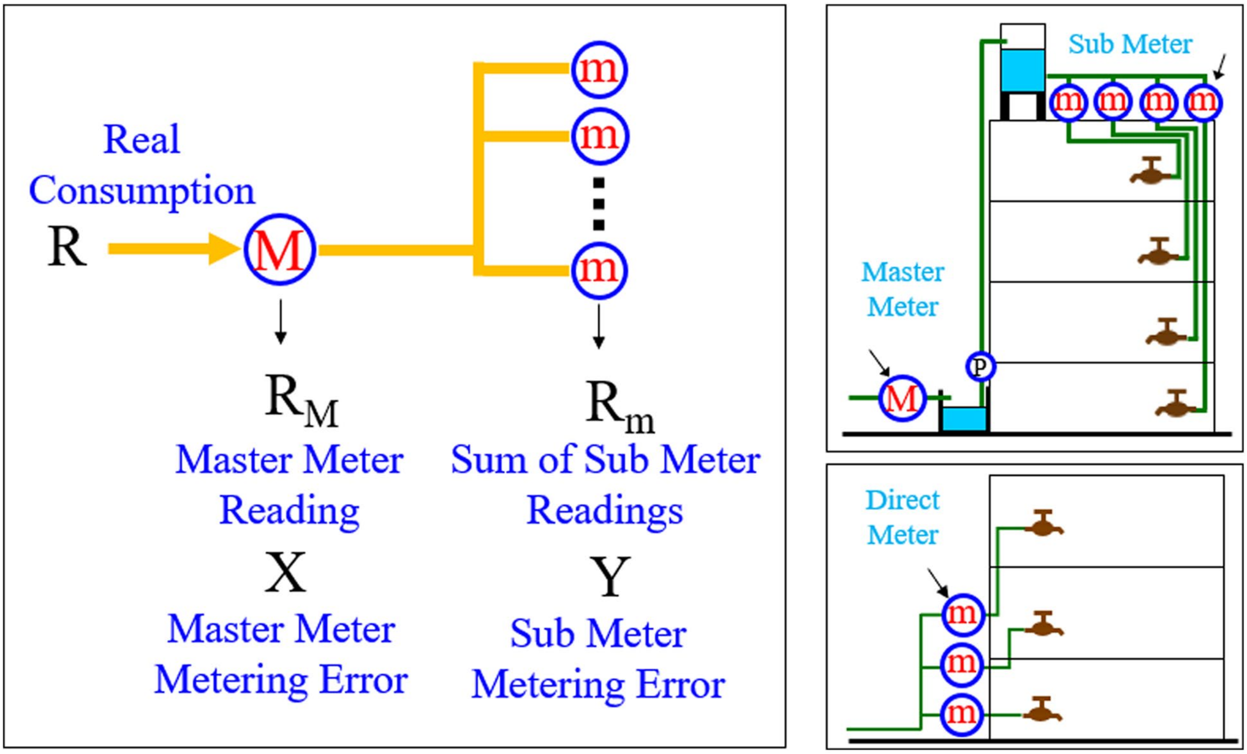

Fig. 2 Master-meter and sub-meter grouping and direct-meters

meter reading differences for each diameter, with an average value of about 1.9 m^3, as shown in Fig. 3. These differences may come from the building's public water usage, water leaks, etc.

The readings of the master-meters are noted as R_M and the sum of the sub-meter readings are noted as R_m, as shown in Fig. 2.

The metering errors of the master-meters (X) and the sub-meters (Y) are:

$$X = \frac{R_M - R}{R} \tag{1}$$

$$Y = \frac{R_m - R}{R} \tag{2}$$

where R is the real water consumption. Since R is unknown, both X and Y could not be determined directly. In this study, we introduced a relative difference between readings which could be determined, because the R_M and R_m are known meter readings. The relative difference between readings (Z) is defined as:

$$Z = \frac{R_m - R_M}{R_M} \tag{3}$$

From Eqs. (1) to (3) the relationship among X, Y and Z can be obtained as

$$Z = \frac{Y - X}{X + 1} \tag{4}$$

Since X, Y and Z are all random variables (i.e., the values change randomly), the individual data of X, Y or Z cannot reflect the overall behavior. On the other hand, only their statistical data, μ_x and μ_y, can describe the behaviors of average metering errors (μ_x is the average metering error of the master-meters and μ_y is the average metering error of the sub-meters). Once these statistical values are obtained, the overall behavior can be determined. Consequently, acquiring these statistical values became the main task of this study.

For obtaining those statistical values, a common approach is to take the expected values (E) on both sides of the equation of random variable, (i.e., Eq. (4),) as

$$E[Z] = E\left[\frac{Y - X}{X + 1}\right] \tag{5}$$

However, (Y-X)/(X+1) is a non-linear function and it is difficult to derive the closed-form expected value from exp((Y-X)/(X+1)). To solve the non-linear problem, we used the Taylor Series by expanding (Y-X)/(X+1) at $X = \mu_x$, $Y = \mu_y$, and each term would then turn into linear. Neglecting the high order terms and taking the expected value for a proximate derivative, then we could come up a relationship among μ_x, μ_y and μ_z; that is

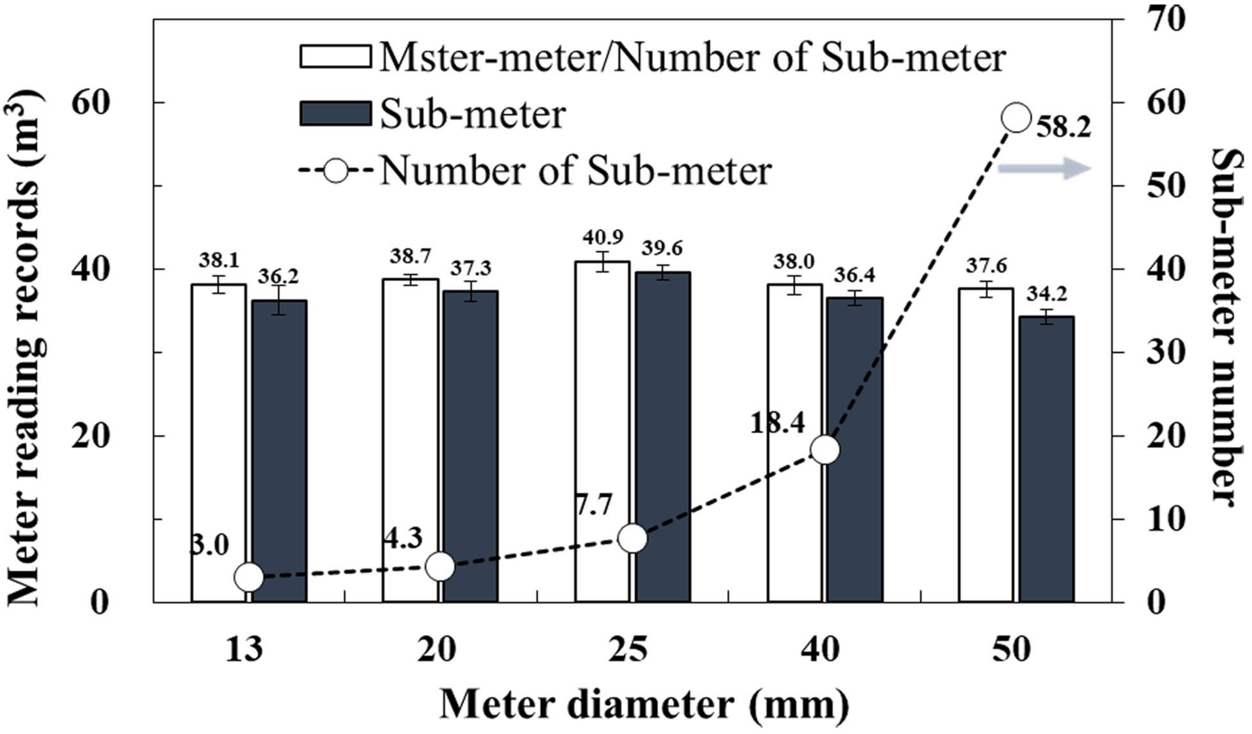

Fig. 3 Comparison of water meter reading differences

$$\mu_z = \frac{\mu_y - \mu_x}{\mu_x + 1} + \frac{\mu_x + 1}{(\mu_x + 1)^3}\sigma_x^2 \quad (6)$$

Similarly, with the same processing method, we can take the variance value on both sides of the equation of random variable to get:

$$\sigma_z^2 = \frac{(\mu_y + 1)^2}{(\mu_x + 1)^4}\sigma_x^2 + \frac{1}{(\mu_x + 1)^2}\sigma_y^2 \quad (7)$$

where $\mu_x = E[X]$, $\mu_y = E[Y]$, $\mu_z = E[Z]$, $\sigma_x{}^2 = E[(X—\mu_x)^2]$, $\sigma_y{}^2 = E[(Y—\mu_y)^2]$, $\sigma_z{}^2 = E[(Y - \mu_z).^2]$.

Since each Z value can be determined from using Eq. (3), its mean value (μ_z) and standard deviation (σ_z) could then be readily calculated. However, since μ_x, σ_x and μ_y, σ_y are unknown (because there are only two equations (i.e., Eqs. (5) and (6)) for four unknowns), it is necessary to introduce other constraint conditions to reduce the number of unknowns to be solvable.

2.2 Assumptions made by this study

All TWD water meters with diameters of 20 to 40 mm are Class B "Multi-Jet" wet-type mechanical meters and their metrologies are featured with large metering errors in low flow rates. On the other hand, the characteristic error curves of this type of meters have an apparent linear section at high flow rates and the metering accuracy in this region is relatively high. According to the specification of the Class B meters, the metering error is within ± 2% in the linear section. It means that the average metering error (μ_x) is equal to zero and the standard deviation (σ_x) approaches zero within the linear section. This is the constraint condition. When the master-meters are under high flow conditions, the statistical value of X will converge to $\mu_x = 0$ and $\sigma_x \approx 0$. Since the metering errors of the sub-meters (Y) and the metering error of the master-meters (X) are independent from each other, (i.e., Y is not affected by X), so that the sub-meter statistical values (μ_y, σ_y) will not be changed with the adoption of the constraint conditions of the master-meters.

We define the average metering error and standard deviation for variable X at high flow conditions as, $\widehat{\mu}_y$ and $\widehat{\sigma}_y$, respectively. Place the constraint conditions ($\mu_x = 0$ and $\sigma_x \approx 0$) and the known μ_z and σ_z values into Eqs. (6) and (7), they could be simplified into the following equations:

$$\widehat{\mu}_y \approx \mu_z \quad (8)$$

$$\widehat{\sigma}_y \approx \sigma_z \quad (9)$$

Now the estimated value of the average metering errors of the sub-meters could be determined. We will illustrate below how to use a simple and powerful tool, the relative difference chart of "master-meter and sub-meter groupings" (i.e., R_M-μ_z chart) to select master-meters of high flow from meter reading data.

2.3 Making of the RM-μz chart

Several equidistant intervals of R_M from the master-meter and sub-meter groupings were first set, and then all the Z values within each interval were averaged to obtain a value of μ_z. These (R_M, μ_z) pairs were then plotted to derive an R_M-μ_z chart. As shown in Fig. 4 as an example, a setting of 100 m^3 as an interval width, the average relative difference (μ_z) was calculated to be -0.07 for the interval between 500 and 600 m^3. All the center points of each interval were then connected to make the chart simple and easier to read.

3 Results and discussion

3.1 Metering error of sub-meters

For example, taking master-meters with 40-mm diameter and less than 5 years in service (i.e., excluding the

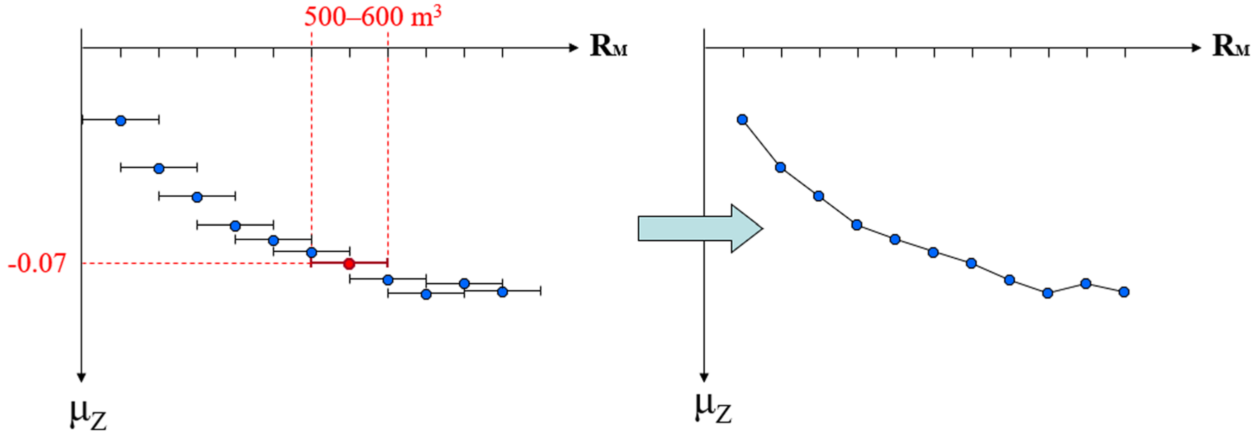

Fig. 4 The R_M-μ_z curve (R_M: readings of master-meters; μ_z: average relative difference)

aged meters) and plotting the R_M-μ_z chart in the way as described earlier, there is an obvious flat zone of R_M in the range between 2,100 and 3,100 m^3 with μ_z of around -0.1, as shown in Fig. 5. Within the flat zone, the intake flows of the master-meters fall within the linear section of the Meter Error Curve and subjected to the constraint conditions (i.e., $\mu_x = 0$ and $\sigma_x \approx 0$).

With aged meters older than 5 years excluded and plotting all the master-meters of different sizes into the R_M-μ_z charts (as shown in Fig. 6), their flat zones are apparently close to $\mu_z = -0.1$ and the curve profiles are pretty similar to each other. This is because the master-meters of TWD with diameters of diameter 20 to 40 mm are all of Class B wet-type multi-jet meters. However, the master-meters

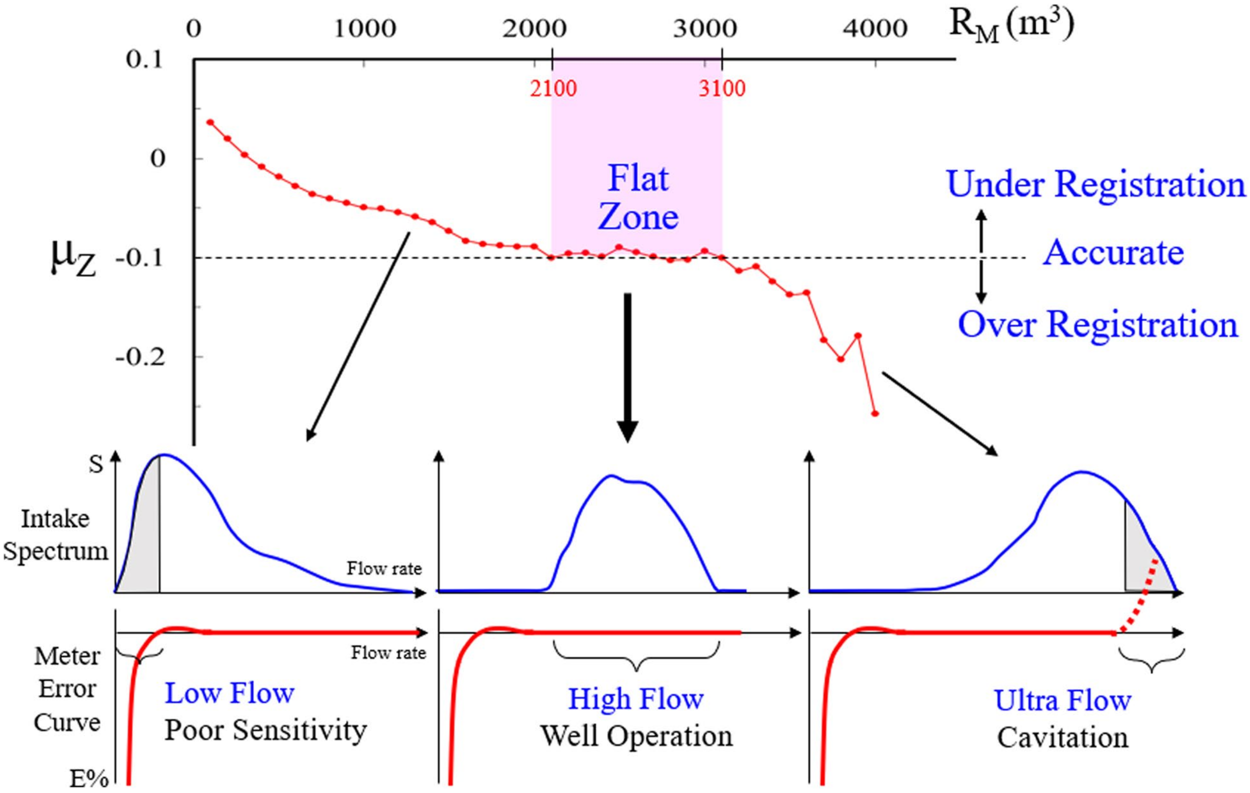

Fig. 5 Flat zone in the R_M-μ_z curve subject to the constraint conditions

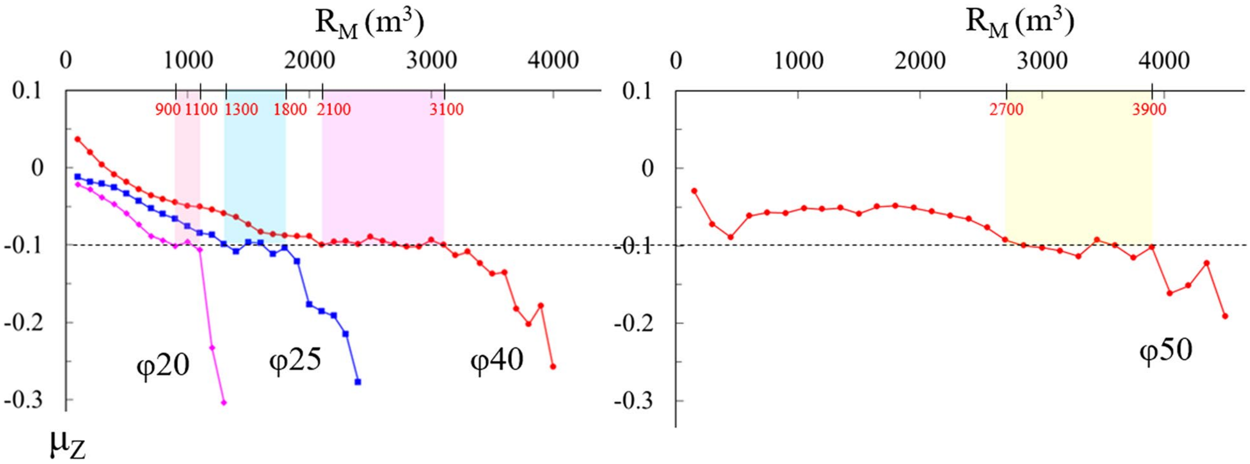

Fig. 6 The R_M-μ_z charts of master-meters with diameter 20 to 50 mm

with diameter of 50 mm of TWD comprise many different types of electronic and mechanical meters (multi-jet meters, horizontal and vertical Woltmann meters, wet-type and dry-type meters, etc.). Their Meter Error Curves are slightly different from another. That is the reason why the profile of the R_M-μ_z chart for diameter of 50 mm is slightly different from those with diameters of 20 to 40 mm. However, the R_M-μ_z chart for diameter of 50 mm still has a flat zone with μ_z of around -0.1 in the profile, as shown in Fig. 6.

The master-meter reading (R_M) in the flat zone is about 900–1100, 1300–1800 and 2100–3100 m^3 (as shown in Fig. 6) recorded every 2 months for the diameters of diameter 20, 25 and 40 mm, respectively. The master-meter reading in the flat zone with corresponding sub-meter average readings are shown in Table 2. Since the water meter readings are recorded every 2 months, the average daily flow rate for the master-meters and the corresponding sub-meters are calculated as shown in Table 2.

The master-meters and sub-meters of TWD with diameters of diameter 20, 25 and 40 mm are all of Class B wet-type multi-jet meters. According to Arregui et al. [15], there is a critical flow rate for Class B single-jet meters with a value about 100 L h^{-1} (2.4 m^3 d^{-1}). Moreover, we also can find the sub-meter average readings in the flat zone are quite close to the critical flow rate, but at the same time the flow rate of the master-meters lies in the linear section, as shown in Table 2. This is why we assume that the average metering error of the master-meter (μ_x) is equal to zero, and the standard deviation of the master-meter (σ_x) approaches zero within the linear section in this study.

Using the R_M-μ_z chart of Fig. 6, it is relatively easy to choose the master-meters of high flow within the flat zone for calculating the μ_z and σ_z values. Fitting them with Eqs. (8) and (9), $\widehat{\mu}_y \approx \mu_z = -0.0985$ and $\widehat{\sigma}_y \approx \sigma_z = 0.1572$ were found. It means that the average metering error of the sub-meters is -0.0985, 9.9% less than the actual water consumption. The results were similar to those of Arregui et al. [15] (the measuring errors for single-jet and multi-jet AWWA meters were as high as -10.8 and -12.2%, respectively in that study).

3.2 Metering error of master-meters

Using the estimated values of μ_y and σ_y of -0.0985 and 0.1572, and all the data of the master-meter and sub-meter groupings, μ_z and σ_z were calculated to be -0.0245 and 0.1235, respectively. With Eqs. (6) and (7), the solutions for μ_x and σ_x (2 equations with 2 unknowns) were obtained. Since the exponents of μ_x and σ_x in Eqs. (6) and (7) would be as high as 4, it would be difficult to solve μ_x and σ_x. In order to deal with this problem, (i) the term of $Z=(Y-X)/(X+1)$ was shifted to arrive $X=(Y-Z)/(Z+1)$, (ii) the Taylor series expansion of $(Y-Z)/(Z+1)$ was taken around $Y=\mu_y$ and $Z=\mu_z$ with the omission of the high-order terms, and (iii) taking the expected value on both sides, the equations for calculating μ_x and σ_x were derived as,

$$\mu_x = \frac{\mu_y - \mu_z}{\mu_z + 1} + \frac{\mu_y + 1}{(\mu_z + 1)^3}\sigma_z^2 \tag{10}$$

$$\sigma_x^2 = \frac{(\mu_y + 1)^2}{(\mu_z + 1)^4}\sigma_z^2 + \frac{1}{(\mu_z + 1)^2}\sigma_y^2 \tag{11}$$

Placing $\mu_z=-0.0245$, $\sigma_z=0.1235$, $\widehat{\mu}_y = -0.0985$, $\widehat{\sigma}_y = 0.1572$ into Eqs. (10) and (11), the estimated value of master-meter average metering error ($\widehat{\mu}_x$) was obtained as -0.0611. Thus, the overall average metering error of the master-meters is -0.0611, 6.1% less than the actual water consumption.

In summary, we have obtained the average metering error of the master-meters and the sub-meters. Furthermore, we can find the average metering error of the sub-meters is larger than the metering error of master-meters, about 3.7% as shown in Table 3. This result is similar to the water meter reading differences found in Fig. 3. The reading records of master-meters divided by number of sub-meters is large than the corresponding sub-meter readings. In other words, the master-meters record more water usage than the sub-meters. Since the reading records for both master-meters and sub-meters are less than the actual water consumption, the larger the reading records means the larger the metering errors.

Table 2 The master-meter and the corresponding sub-meter reading in the flat zone

Meter Diameter (mm)	The Master-meter Reading in the Flat Zone		The Sub-meter Average Reading in the Flat Zone		Average Number of Sub-meters per Master-meters
	(m^3)	(m^3 d^{-1})	(m^3)	(m^3 d^{-1})	
20	900–1100	15.0–18.3	209.3–255.8	3.5–4.2	4.3
25	1300–1800	21.7–30.0	168.8–233.8	2.8–3.9	7.7
40	2100–3100	35.0–51.7	114.1–168.5	1.9–2.8	18.4

Table 3 Average measurement errors of domestic water meters in TWD

Category of meters	Meter Diameter (mm)	Number of Meters	Percentage of Meters (%)	Average Metering Error (%)
Master-meters	13–50	119,524	7.5	-6.1
	≧75	1,409	0.1	unable to estimate
Sub-meters	13–40	1,273,108	80.0	-9.9
	≧50	2,722	0.2	unable to estimate
Direct-meters	13–40	191,572	12.0	-10.0
	≧50	2,200	0.1	unable to estimate
	Total	1,590,535	100.0	

3.3 Metering error of direct-meters

As mentioned earlier, the direct-meters are installed for customers who use water directly without passing through water tanks, as shown in Fig. 2. In spite of this difference, the intake behaviors between the sub-meters and the direct-meters are similar. In other words, as long as the customers turn on faucets, the intake behaviors (Intake Spectrum) for water passing through the sub-meters and the direct-meters should be similar. Moreover, the types of water meters used for the sub-meters and the direct-meters are the same. All of them are multi-jet wet-type mechanical meters. It implies that the water meter characteristics of the sub-meters and the direct-meters are the same.

As mentioned in the earlier section, the metering error of a water meter depends on the users' consumption behaviors (Intake Spectrum) and the metrological characteristics of the water meter (Meter Error Curve). Since those of the sub-meters and the direct-meters were similar, it implies that both the sub-meters and the direct-metes used in TWD should have similar metering errors. In other words, the average metering error of the direct-meters is around 10% less than the real water consumption.

4 Conclusions

From the R_M-μ_z charts (as shown in Fig. 6), we can find the curve profiles are pretty similar to each other for the master-meters with diameters of diameter 20 to 40 mm. This is because the master-meters of TWD with diameters of diameter 20 to 40 mm are all of Class B wet-type multi-jet meters. However, the master-meters with diameter of 50 mm of TWD comprise many different types of electronic and mechanical meters (multi-jet meters, horizontal and vertical Woltmann meters, wet-type and dry-type meters, etc.). Their Meter Error Curves are slightly different from another. That is the reason why the profile of the R_M-μ_z chart for diameter of 50 mm is slightly different from those with diameters of 20 to 40 mm. However, the R_M-μ_z chart for diameter of 50 mm still has a flat zone with μ_z of around -0.1 in the profile, as shown in Fig. 6.

Similar results can be found in Fig. 3, comparing the reading records of master-meters divided by number of sub-meters with the corresponding sub-meter readings, we found that there are similar water meter reading differences for those with diameters of 20 to 40 mm, with an average value of about 1.5 m^3. However, the water meter reading differences for diameters of 50 mm is quite different, about 3.4 m^3. Furthermore, we also can find the relative difference distribution for "master-meter and sub-meter grouping" with diameters of 20 to 40 mm are similar to each other, while those for diameters of 50 mm are slightly different from another.

From the previous results, we can find the average metering error of the sub-meters is larger than the metering error of master-meters, about 3.7% as shown in Table 3. This result is similar to the water meter reading differences found in Fig. 3. The reading records of master-meters divided by number of sub-meters is large than the corresponding sub-meter readings. In other word, the master-meters record more water usage than the sub-meters. Since the reading records for both master-meters and sub-meters are less than the actual water consumption, the larger the reading records means the larger the metering errors.

In most countries, water meters are required to be tested under specified constant flow rate conditions. However, these testing conditions may not represent the actual consumption behaviors of the consumers. Furthermore, the cost of testing is high so that it is almost impossible to launch a full-scale testing project to obtain representative results for the overall behavior. In addition, the fatal drawback of using a testing method is that it cannot simulate the water consuming behaviors of all the customers.

This study developed a practical approach to identify average metering error for a water utility company by using the R_M-μ_z chart. The historical meter reading records, containing both water consumption behaviors and meter characteristics of a major water utility company were analyzed. The approach is better than using a testing method alone and the estimated metering errors are less biased. In addition, this approach is relatively less expensive.

From the analysis of 120,000 sets of "master-meter and sub-meter grouping" data of TWD in Taiwan, the average metering errors for 99.6% of its domestic meters (around 1.6 million water meters) were successfully estimated. The estimated average metering errors are 9.9, 6.1, and 10.0% less than the actual water consumption recoded by the sub-meters, master-meters, and direct-meters, respectively.

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Authors' contributions
All authors contributed to the study conception and design. Material preparation and analysis were performed by Hsin-Liang Chen. Data collection was performed by Chin-Ling Huang. The first draft of the manuscript was written by Hsin-Liang Chen and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
Not applicable.

Declarations

Competing interests
The authors declare no competing interests.

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