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Analysis of the factors influencing the fluctuation of non-revenue water in Luangprabang City, Laos

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ABSTRACT

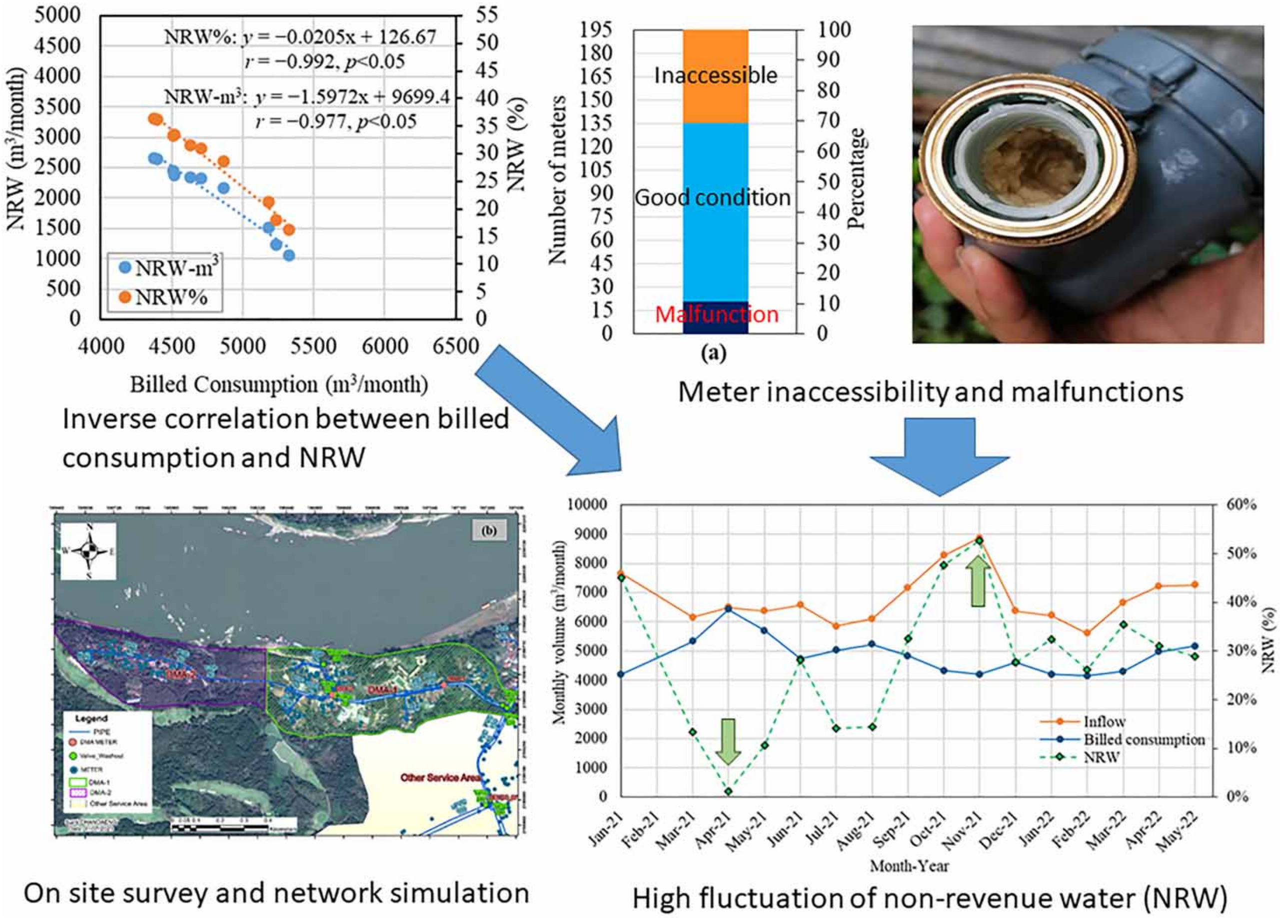
Non-revenue water (NRW) in Luangprabang City, Laos, has been high and fluctuating. Therefore, we aimed to analyze the factors influencing the fluctuation of NRW in two district-metered areas (DMAs). The average NRWs for 16–17 months in DMA-1 and DMA-2 were 28.92 and 43.92%, respectively, whereas the coefficients of variation of the monthly NRWs were high at 49.7 and 11.7%, respectively. Among the factors causing the fluctuation of NRW, meter inaccuracies were less than 2%, although inaccessibility to customer meters was high at 46.4 and 38.7% in DMA-1 and DMA-2, respectively. However, the meter reading intervals had little influence on billed water consumption. Using the IWA Water Balance table, the apparent loss was estimated as 2.6%, whereas the real loss (24.9%) was the main component of NRW (27.5%) in DMA-2. The monthly and 3–7-month moving averages of NRW were inversely correlated with billed water consumption, indicating that both volumetric and percentage NRWs were strongly influenced by fluctuations in billed water consumption. Network simulation verified that high inaccessibility to customer meters, particularly during the COVID-19 lockdown, caused large fluctuations in billed water consumption and NRWs. Therefore, access to customer water meters should be improved to alleviate the fluctuation of NRW.

Key words: billed water consumption, district metered area, metering inaccuracy, meter reading interval, non-revenue water, real loss

HIGHLIGHTS

- High rates of meter malfunction and inaccessibility caused NRW fluctuation.
- Apparent loss was only 9.4%, whereas real loss was 90.6% for non-revenue water.
- Volumetric and percentage NRWs are inversely correlated with billed consumption.
- Taking moving averages helps find relations between water consumption and NRW.
- Meter reading errors can be estimated using DMA inflow data and EPANET simulation.

GRAPHICAL ABSTRACT



INTRODUCTION

The 2030 Agenda for Sustainable Development Goal 6 calls for access to safe water and sanitation for all (Ortigara *et al.* 2018). Although urban water demand is expected to increase by 80% by 2050 (Flörke *et al.* 2018), developing new water resources remains difficult. Water loss, which is often reported as non-revenue water (NRW), is high in many cities. NRW comprises unbilled authorized consumption and water losses, which are further divided into apparent (or commercial) losses and real (or physical) losses (Lambert & Hirner 2000; Al-Omari 2013). Real water losses arise from leaks in distribution networks (Jang 2018) and represent the largest fraction of NRW (Selek *et al.* 2018); however, reliable data on water losses are limited in many water utilities (Liemberger & Wyatt 2019). Although high NRW rates impede sustainability, comprehensive strategies to address this issue are lacking (Farouk *et al.* 2023).

Kizilöz (2021) found that high pressure and pipe aging in distribution networks increase leakage in water distribution systems. Other factors, including increases and decreases in customer connections, malfunctioning and reading errors of water meters, and variations in water consumption, influence fluctuations in NRW (Güngör-Demirci *et al.* 2018; Ncube & Taigbenu 2019). Farley & Trow (2003) found that high consumption decreases the NRW% and *vice versa*, leading the American Water Works Association to discontinue support for NRW percentage indicators, as percentages are not actionable and fluctuate because of their nature as ratio indicators (AWWA 2003, 2019); instead, they promoted two new key performance indicators: the loss cost rate (value per service connection per year) and normalized water losses (water loss volume per service connection per day) (AWWA 2020). Recently, we have proved that fluctuations in billed water consumption have a considerable influence on NRW fluctuations using the data obtained for the DMAs in Colombo City, Sri Lanka, because fluctuation in water consumption influences water flow rates in the networks, causing variations of pressure in the supply networks

(Pathirane *et al.* 2024). In theory, NRW decreases with increasing water consumption because of reductions in supply pressure, and *vice versa*, which was proved by the network simulation.

Understanding and evaluating the factors influencing water loss are fundamental to implement NRW reduction programs (van den Berg 2015; Jang & Choi 2017). However, in the previous studies in the literature, although each of the influencing factors on NRW fluctuations was investigated, none compared multiple factors influencing the fluctuation of NRW (Şisman & Kızılöz 2020; Chawira *et al.* 2022). Therefore, this study aimed to analyze and compare the multiple factors influencing the fluctuation of NRW, including meter reading inaccuracy, meter reading intervals, inaccessibility to customer meters, fluctuation of water consumption, and pressure in the supply networks.

Luangprabang City (LPBC) is the ancient capital of Laos and the provincial city of Luangprabang Province located in the central-northern part of Laos. NRW in the Luangprabang Water Supply State-owned Enterprise (LWSSE), Laos, is high and fluctuating (LWSSE 2020). However, the causes of high fluctuations in NRW remain unclear. Therefore, this study was conducted to analyze and compare the factors influencing fluctuations in NRW in the LWSSE. The data on pressure at the inlet to and water flow into the district metered areas (DMAs) of the water supply networks, monthly billed water consumption, and meter reading intervals within the DMAs were obtained from LWSSE. The accuracy of customer water meters in the DMAs was tested. The accuracy of reported billed water consumption, namely over- or under-estimation of the actual water consumption, was verified by the network simulation using the data on water supply networks.

METHODS

Study area

The population of LPBC was 128,513 in 2020. The water supply coverage in LPBC was 83.89%, and the daily water supply volume was 56,800 m^3/d. The LWSSE supplies piped water to the central zone, whereas two private companies, namely, Asia Co., Ltd, and DEMCO De Laos Co., Ltd, supply piped water to the northern and southern zones of LPBC since 2015. The study area is in the southern water service zone of the LPBC, where the LWSSE supplies water in collaboration with a private company, DEMCO De Laos Co., Ltd. Figure 1(a) and 1(b) shows the LWSSE supply and study areas, respectively. The two DMAs, namely DMA-1 and DMA-2, in the study area, have total distribution pipe lengths of 1,593 and 1,083 m and 195 and 77 service connections, respectively.

Estimation of NRW in the DMAs

Inflow meters were installed at the inlets of the DMAs (di Nardo & di Natale 2011). NRW (m^3) was calculated by subtracting billed water consumption from the DMA inflow volume (Equation (1)), and NRW (%) was calculated using 17-month data from January 2021 to May 2022 volume (Equation (2)). Inflow meter data for the DMAs were collected from official reports of the LWSSE. Billed water consumption data were obtained from 195 and 77 customers in DMA-1 and DMA-2, respectively.

$$\text{NRW} \ \ (\text{m}^3) = \text{DMA inflow} - \text{billed water consumption} \tag{1}$$

$$\text{NRW}(\%) = \frac{\text{NRW} \ \ (\text{m}^3)}{\text{DMA inflow}} \times 100 \tag{2}$$

Moving averages and statistical analysis

Moving averages of billed water consumption and NRWs were calculated for 3, 5, and 7 months; NRW was plotted against the billed water consumption for linear correlation analysis using R v. 4.3.0 (R Core 2021). The correlation between the two parameters was considered statistically significant when $p < 0.05$.

Customer meter testing

From August to September 2022, the accuracies of 135 and 65 customer meters among 195 and 77 meters, respectively, were tested in DMA-1 and DMA-2, respectively, using a flow rate testing instrument (TR-IV, Aichi Tokei Denki Co., Nagoya, Japan) because of limitations in access to the meters. The LWSSE sets the acceptable range of meter accuracy to $\pm 5.0\%$ following the standard ISO4064-1 for the accuracy of customer meters at low flow rates (International Organization for Standardization (ISO) 2017; Ferrante *et al.* 2022).

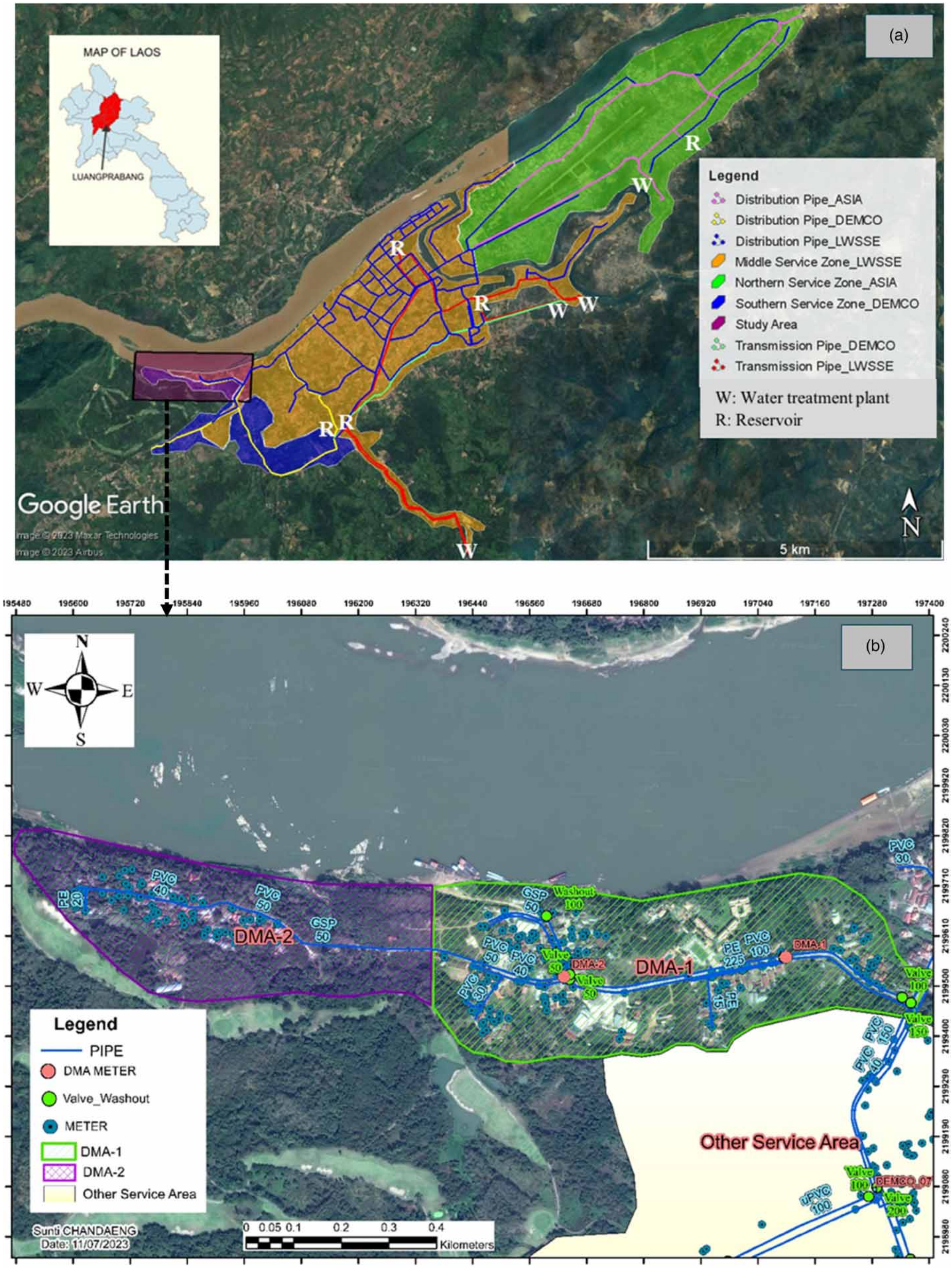


Figure 1 | (a) Water supply area of LWSSE, and (b) DMA-1 and DMA-2.

Effects of meter reading intervals on billed water consumption

The LWSSE designates the customer meter reading date as between the 10th and 28th of each month. Thus, variations in the meter reading intervals may have caused fluctuations in the monthly billed water consumption. Therefore, the effect of meter reading intervals on billed water consumption was evaluated using monthly data from January 2021 to May 2022 for 16 months (excluding February 2021 because of meter malfunctions) in DMA-1 and 17 months in DMA-2.

Estimation of real and apparent losses

Using the IWA Water Balance table, the main cause(s) of NRW were analyzed in DMA-2. We measured the minimum night flow, which represents real water losses (Farley *et al.* 2001; Liemberger & Farley 2004; Puust *et al.* 2010), using a portable ultrasonic flow meter (UFP-20, FUJI TECOM Co., Tokyo, Japan) in DMA-2, where water consumption at night was negligible because the area is residential.

Factors influencing NRW fluctuation evaluated using network simulation

The influence of water demand and inlet pressure variation on water losses in DMA-1 was estimated through network simulation using EPANET 2.2. The inlet pressure of DMA-1 was measured using a portable pressure recorder (FJN-501, FUJI TECOM Co.); however, the pressure was uncontrolled and unmeasured during the data acquisition period from January 2021 to May 2022. Since August 2022, the inlet pressure has been maintained at 0.335–0.355 MPa using a pressure-regulating valve.

A network simulation model for DMA-1 was constructed using the pipe network data obtained from the LWSSE (Figure 1(b)). The monthly billed water consumption data were used to calculate the 16-month average, minimum, and maximum consumption from January 2021 to May 2022 (excluding February 2021, because of the inflow meter malfunction).

Water demand at each node was calculated as the sum of the billed water consumption of the houses allocated to the nodes. We set 12 nodes in the simulation model, and the total pipe length was 1,593 m (Table A1).

The simulation was run using an average inlet pressure of 0.345 MPa and an average water demand of 6.719 m^3/h. The simulation was then run under the following two conditions to evaluate the influence of water demand and inlet pressure on water loss:

(1) Fixed inlet pressure at 0.345 MPa, and varied monthly water demand from a minimum of 5.758 m^3/h (February 2022) to a maximum of 8.925 m^3/h (April 2021).
(2) Fixed water demand at 6.719 m^3/h, and varied inlet pressure at five levels: 0.145, 0.245, 0.345, 0.445, and 0.545 MPa.

RESULTS AND DISCUSSION

NRWs in the DMAs

The average NRWs for 16 and 17 months in DMA-1 and DMA-2 were 28.92 and 43.92%, respectively, higher than the previously reported NRW of 28% for the entire LWSSE service area.

Figure 2 shows the fluctuations in the monthly inflow, billed water consumption, and NRW in DMA-1. Data from February 2021 were excluded because of an inflow meter malfunction. Among these three parameters, NRW showed the most significant fluctuations of between 1.14% in April and 52.65% in November 2021, with a coefficient of variation (CV) of 49.7%. The CVs for billed water consumption and inflow were 12.8 and 12.6%, respectively. Similar results were obtained for DMA-2, as shown in Figure A1.

Figure 3 shows the correlation between billed water consumption and NRW using monthly and 3-, 5-, and 7-month moving average data. As evidenced by the negative values of correlation coefficients (r), NRW% and NRW-m^3 were inversely correlated with billed water consumption in all of the four figures (Figure 3(a)–3(d)). Furthermore, the monthly NRW varied considerably with the correlation coefficients at −0.840 and −0.735 for NRW% and NRW-m^3, respectively (Figure 3(a)). The use of moving averages reduced NRW variations in the monthly data, as shown by the increasing absolute values of the correlation coefficients (r) to −0.992 and −0.977 for NRW% and NRW-m^3, respectively, with the 7-month moving average (Figure 3(d)). These results indicate that taking 3–7-month moving averages mitigates fluctuations of monthly data and helps identify the true relationship between billed water consumption and NRW.

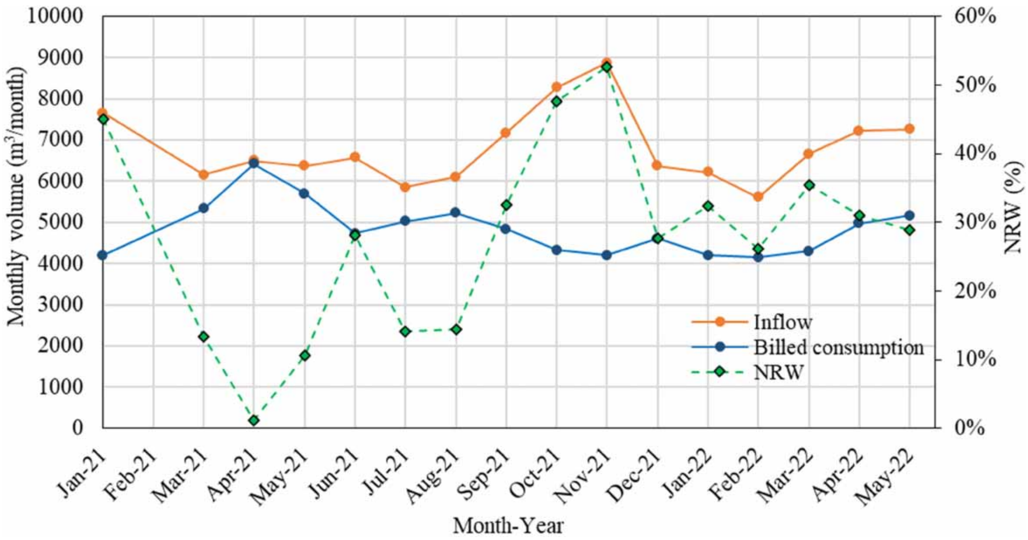


Figure 2 | Monthly variation of inflow, billed water consumption, and NRW in DMA-1 from January 2021 to May 2022 (excluding February 2021).

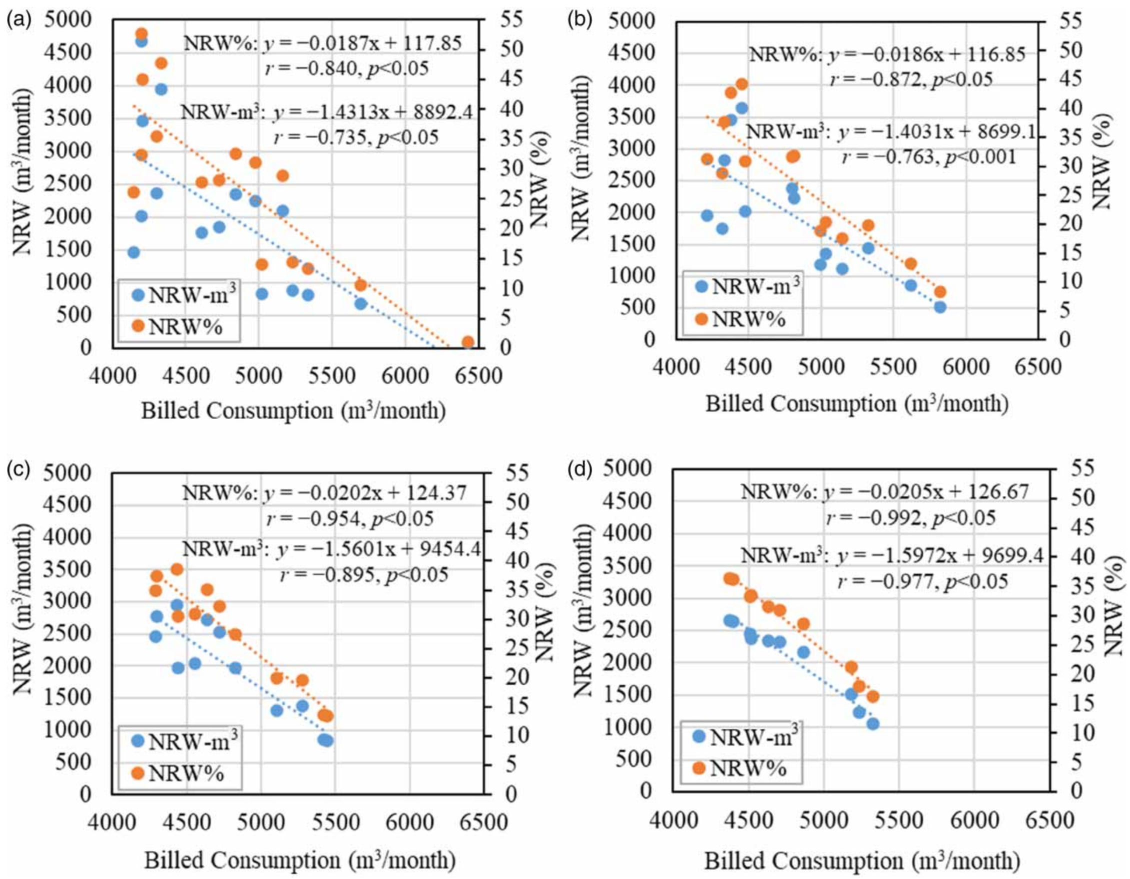


Figure 3 | Correlation between billed water consumption and NRW-m^3 or NRW% in DMA-1. (a) Monthly; (b) 3-month moving averages (MA); (c) 5-month MA; and (d) 7-month MA. Data period: 16 months from January 2021 to May 2022 (excluding February 2021).

Customer meter testing

In DMA-1, metering inaccuracies ranged from −72.92 to +25.20%, with an average of −1.66% (Figure A2a). Of the 135 tested meters, 7 meters had inaccuracies exceeding 5%, 14 meters fell below −5%, and the remaining 114 meters were within 5%. Similarly, in DMA-2 (Figure A2b), the metering inaccuracies ranged from −37.41 to +40.35%, with an average of −1.97%. Of the 65 tested meters, 4 meters had inaccuracies that exceeded 5%, 11 meters fell below −5%, and the remaining 50 meters were within 5%. The accuracy of mechanical water meters is reported to be in the range of 1.0–2.0% (Farley *et al.* 2008). Although Infantri Yekti *et al.* (2019) measured the accuracy of 23 customer meters and found that the average inaccuracy was 0.214%, Chen *et al.* (2023) estimated the error to be 3.7%. While the average inaccuracies of the two DMAs were within 2.0% in this study, some water meters were registering high inaccuracies. Thus, the regular testing of customer meters and the replacement of meters registering high inaccuracies are strongly recommended.

Customer metering inaccuracies

Although the average meter inaccuracies were within 2%, as mentioned above, meter reading inaccuracies arose from factors such as inaccessibility to water meters, errors in meter reading and data entry, meter malfunctioning, and customer tampering with meters.

In DMA-1, of 195 customer meters, 60 meters were inaccessible (30.8%); of the 135 meters tested, 21 (15.6%) were malfunctioning (Figure A3a), totaling 46.4% inaccessible or malfunctioning meters. In DMA-2, of the 77 meters, 12 were inaccessible (15.6%), and of the 65 meters tested, 15 meters (23.1%) were malfunctioning (Figure A3b), totaling 38.7% of meters. This high rate of inaccessible or malfunctioning customer meters is among the major causes of inaccuracies and possible fluctuations in billed water consumption and NRW.

Such high ratios of meter malfunctioning arise from customers frequently opening and closing taps to store water in tanks (Figure A4a) and sediment deposition inside meters because of poor water quality and infiltration of dirt during pipe repairs (Figure A4b). Meter tampering or small pieces of objects inside the meters can disrupt moving parts and lead to inaccuracies in meter readings (Figure A4c).

Effects of meter reading intervals on billed water consumption

Figure 4(a) and 4(b) shows that we found no significant correlation between the meter reading intervals and billed water consumption in DMA-1 ($r = 0.051$, $p > 0.05$) and DMA-2 ($r = -0.180$, $p > 0.05$). Instead, billed water consumption increased during festival months: April (Lao New Year), August (Boat Racing), and December (National Day – Year End) in 2021–2022, indicating that people consume more water during festival periods (Figure A5).

Estimation of apparent and real losses

In DMA-2, the inlet pressure decreased during periods of high flow rates and *vice versa* (Figure A6). The pressure was 0.34–0.37 MPa, and the minimum night flow was 0.60 m^3/h at 1:14 AM on September 20, 2022, which was considered a real loss.

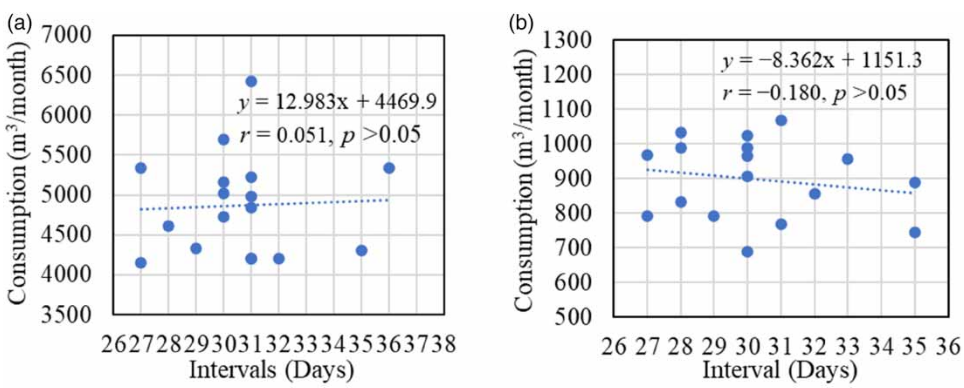


Figure 4 | Effects of meter reading intervals on billed water consumption: (a) DMA-1; (b) DMA-2. Data period: DMA-1, 16 months from January 2021 to May 2022 (excluding February 2021); DMA-2, 17 months from January 2021 to May 2022.

Figure A7 shows the correlation between the water pressure and inflow at the DMA-2 inlet. The flow rates varied extensively at low pressure (0.34 MPa during the day), whereas these values were low and did not vary at high pressure (0.37 MPa during the night).

In DMA-2, the apparent (commercial) loss was 2.6% (Table A2), which is slightly higher than the average metering inaccuracy of 1.97% (Figure A2b). The real (physical) loss was 24.9% of the overall 27.5% NRW. Thus, the apparent loss was only 9.4% of the overall NRW, indicating that decreasing real loss is important for reducing NRW. The average apparent loss in Asian countries was estimated to be 25.4% of the total NRW; thus, the ratio of apparent loss in our study was less than the average (Frauendorfer & Liemberger 2010). Al-Washali *et al.* (2020) compared various methods of estimating apparent and real water losses, and found that different methods estimate the water loss components differently. Thus, they suggested using at least two different methods to estimate water loss components. Therefore, although we used the minimum night flow method in this study to estimate the real loss, we should note that the estimated amounts of real loss are dependent on the method we employed.

Evaluating factors influencing NRW fluctuation by network simulation

Table 1 shows the results of network simulation in DMA-1. First, the inlet pressure and water demand were set to 16-month averages of 0.345 and 6.719 m^3/h, respectively. Simulated inflow and water loss were 9.450 m^3/h and 28.90%, respectively, which are close to the actual values of 9.453 m^3/h and 28.92%, respectively.

To analyze the influence of inlet pressure variation on water loss, the inlet pressure was varied from 0.145 to 0.545 MPa, while the average water demand was kept fixed. Because the inlet pressure influenced the pressure at all nodes, DMA inflow (8.530–10.120 m^3/h) and water loss (1.811–3.401 m^3/h, 21.23–33.61%) were also influenced by the inlet pressure. Thus, controlling the inlet pressure is very important for reducing NRW because water loss and consumption can be reduced by controlling the inlet pressure (Vicente et al. 2016; Karakatsanis & Theodossiou 2022). Flow control using a pressure-reducing valve and active pressure control can reduce leakage in water distribution systems (Kowalski & Suchorab 2023).

Then, to analyze the influence of water consumption fluctuations on water loss, the monthly water demand was varied from the minimum (5.758 m^3/h) to maximum (8.925 m^3/h) values of meter reading during the study period, while the inlet pressure was fixed at an average value of 0.345 MPa (Table 2). The results show that the simulated inflow (8.490 and 11.650 m^3/h) and water loss (2.732 and 2.725 m^3/h, 32.18 and 23.39%), which are underlined in Table 2, were greater than the reported values based on meter reading, indicating that the water demand was overestimated by the meter readers because of inaccessibility to water meters during the COVID-19 lockdown periods. Thus, assuming that the DMA inflow measured by the water flow meter was correct, the actual water demand was estimated using the simulation (bold figures in Table 2). In the minimum and maximum water demand cases, water demand was overestimated by 13.7 and 41.8%, respectively, and water losses (%) were underestimated by 8.87 and 29.08% by the meter readers. Thus, meter reading errors because of meter malfunctioning and inaccessibility to customer meters, particularly during the COVID-19 lockdown period, were the main causes of erroneous estimations and fluctuations in billed water consumption and water losses.

Table 1 | Influence of inlet pressure on inflow and water loss by network simulation (DMA-1)

Inlet pressure (MPa)	Simulated pressure (MPa)			Inflow (m^3/h)		Water loss (m^3/h)		Water loss (%)	
	Minimum	Maximum	Water demand (m^3/h)	Actual	Simulated	Actual	Simulated	Actual	Simulated
0.145	0.136	0.198	6.719		8.530		1.811		21.23
0.245	0.234	0.297	6.719		9.020		2.301		25.51
0.345[a]	0.334	0.396	6.719[b]	9.453[b]	9.450	2.734[b]	2.731	28.92[b]	28.90
0.445	0.433	0.496	6.719		9.820		3.101		31.58
0.545	0.532	0.595	6.719		10.120		3.401		33.61

[a]Average inlet pressure between 0.335 and 0.355 MPa.

[b]Average data for 16 months from January 2021 to May 2022 (excluding February 2021) in DMA-1.

Table 2 | Effect of water demand on inflow and water loss by network simulation (DMA-1)

Inlet pressure (MPa)	Simulated pressure (MPa)		Water demand (m^3/h)	Inflow (m^3/h)		Water loss (m^3/h)		Water loss (%)	
	Minimum	Maximum		Actual	Simulated	Actual	Simulated	Actual	Simulated
0.345	0.336	0.398	5.758[a]	7.800	8.490	2.042	2.732	26.18	32.18
	0.337	0.399	**5.066**[b]		7.800		2.734		35.05
0.345	0.334	0.396	6.719[c]	9.453	9.450	2.734	2.731	28.92	28.90
0.345	0.328	0.393	8.925[d]	9.028	11.650	0.103	2.725	1.14	23.39
	0.335	0.397	**6.294**[e]		9.020		2.726		30.22

Figures are described in the text and are both bold and underlined.
[a]Minimum water demand in February 2022.
[b]Simulated water demand.
[c]Average water demand in 16 months from January 2021 to May 2022 (excluding February 2021).
[d]Maximum water demand in April 2021.
[e]Simulated water demand.

CONCLUSION

Although previous studies evaluated one of the factors influencing NRW, this study contributed to the literature by presenting the methods to evaluate and compare multiple factors influencing the fluctuation of NRW. Variations in meter reading intervals did not influence billed water consumption. Rather, major events for citizens influenced water consumption. Meter testing revealed that the average metering inaccuracies were within 2%. However, the ratios of meter malfunction and inaccessibility were high at 46.4% and 38.8 in DMA-1 and DMA-2, respectively. Meter malfunctioning is caused by customers tampering with meters, accumulation of sediment inside meters, and clogging of small objects inside meters. The analysis of NRW using the IWA Water Balance table revealed that the apparent (commercial) loss was only 9.4% of the total NRW, whereas the real (physical) loss was 90.6% of the total NRW, demonstrating that real (physical) loss is the main cause of the high NRW.

Monthly NRW was inversely correlated with monthly billed water consumption, as shown by plotting the correlation between billed water consumption and NRW using 3–7-month moving averages. The results of the network simulation verified that fluctuations in the billed water consumption and inlet pressure strongly influenced fluctuations in the NRW. Controlling the DMA inlet pressure to counter the fluctuation in water consumption can stabilize the network pressure and thereby reduce NRW. In addition, this study presented the network simulation method to estimate the errors in reporting billed water consumption, which was found to be the main cause of inaccuracies and fluctuations in billed water consumption and NRW. Therefore, it is important to improve meter reading accuracy by replacing malfunctioning water meters and providing easy access to customer meters. The limitation of this study was that the data period was rather short: thus, it is recommended to take data for longer periods. The method to estimate inaccuracies of billed water consumption presented in this paper can be applied to DMAs of any other cities with fluctuating NRWs.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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