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Water Practice & Technology Vol 14 No 3
doi: 10.2166/wpt.2019.056

Real benefits of leak repair and increasing the number of inlets to energy

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Abstract

Two real cases of energy audit were investigated in a district metered area (DMA) of the Metropolitan Waterworks Authority in Bangkok, Thailand. The first case was energy audits before and after leaks were repaired. The repairs resulted in a 9% reduction of inflow to the DMA. We estimated that the input energy to the DMA reduced 8% while the energy in water delivered to customers increased 8%. Thus, two benefits of reducing leakage to energy were found. In the second case, we temporarily opened a boundary valve connecting to the trunk main to function as another inlet to the DMA, so the number of inlets increased to two. The new inlet was nearer to main distribution pipes that delivered water to more customers than the first one. Thus, the inflow from the old inlet decreased to only 10% of the total inflow. The estimated input energy increased slightly by 4% because the inflow and leakage did not reduce, but the energy delivered to customers increased greatly (16%) due to a significant decrease in friction loss. Thus, reducing leakage and selecting the right hydraulic locations of inlets can benefit energy efficiency in DMAs substantially.

Key words: DMA, energy, inlet, leak repair, water distribution

INTRODUCTION

Water supply is one of the most energy-intensive sectors (Pelli & Hitz 2000; Napoli & Garcia-Tellez 2016). According to California Energy Commission (2005), its urban water supply and treatment consumed 3% of the total electricity energy used by the city and as much as 15.7% of the total water-related energy use. Vilanova & Balestieri (2015) estimated that 2–3% of the world electricity energy use is consumed by pumping in water supply systems. Pumping energy is required to compensate for friction and minor losses in the water supply network and the remaining energy reaches users in the form of pressure. However, if the network system has leaks, the energy is wasted through leaks. Leaks are not only a loss of water but are also shown to increase the energy cost substantially depending on spatial distribution of leaks and complexity of the networks (Colombo & Karney 2002).

Leakage is generally a large volume of water loss. It can be reduced and controlled using a four-pillar approach (pressure management, speed and quality of repairs, active leakage control, and pipeline and asset management). The conventional active leakage control methods can be categorized into two techniques as follows (AWWA 2016a). The acoustic techniques use listening devices that can detect the sound of water leaking from the pressurized system. The flow measurement techniques use flow measuring devices to identify flow quantities exceeding the normal water demand in a specific area of the distribution system, and a district metering area (DMA) system is one of the most popular flow measurement techniques that has been applied worldwide (e.g. Charalambous 2008; Galdiero *et al.* 2016; Jitong & Jothityangkoon 2017).

In the DMA system, a water distribution network will be divided into many smaller areas (DMAs) using permanent boundaries, and accurate inflow and outflow are measured. Thus, water balance and water loss for each DMA can be estimated and monitored. One of the monitoring parameters is the minimum night flow (MNF) for each day. Generally, at night between 2 a.m. and 4 a.m. when authorized water consumption is at a minimum, leakage is at its highest percentage of the total flow. Thus, monitoring and analyzing MNF can quantify the volume of leakage (Thornton *et al.* 2008).

There are few real-world case studies in which energy assessment in water distribution networks has been investigated (Lenzi *et al.* 2013; Dziedzic & Karney 2015; Mamade *et al.* 2017; Wong *et al.* 2017; Lapprasert *et al.* 2018). To the best of the authors' knowledge, however, none of these has studied the real cases of energy change due to leak repair or an increase in inlets to DMAs. In this study, we performed an energy audit to investigate the benefits of leak repair and increasing the number of inlets in a real DMA.

STUDY AREA

The Metropolitan Waterworks Authority (MWA), Thailand is the sole agency that produces and distributes potable water for three provinces (Bangkok, Nonthaburi, and Samutprakarn). MWA covers the total area of 3,195 km^2 and produces around 5.3 million m^3 per day. At present, MWA has divided its service area into 18 branches. Our study area was DMA 54-09-03 in the Bang Bua Thong Branch.

The pipe network system and the hydraulic information of DMA 54-09-03 are shown in Figure 1 and Table 1, respectively. Before the DMA establishment, the network was fed by two inlets at the district meter (DM) and the boundary valve (BDV). However, due to difficulty installing a meter at BDV, the BDV had been closed, and the inflow to the network was from DM alone. We installed three pressure loggers (P1-P3) on fire hydrants in the DMA during the period of our investigation. Our study area was a residential area with very low pressure (less than 10 m) but a high percentage of water loss of more than 30% (Table 1).

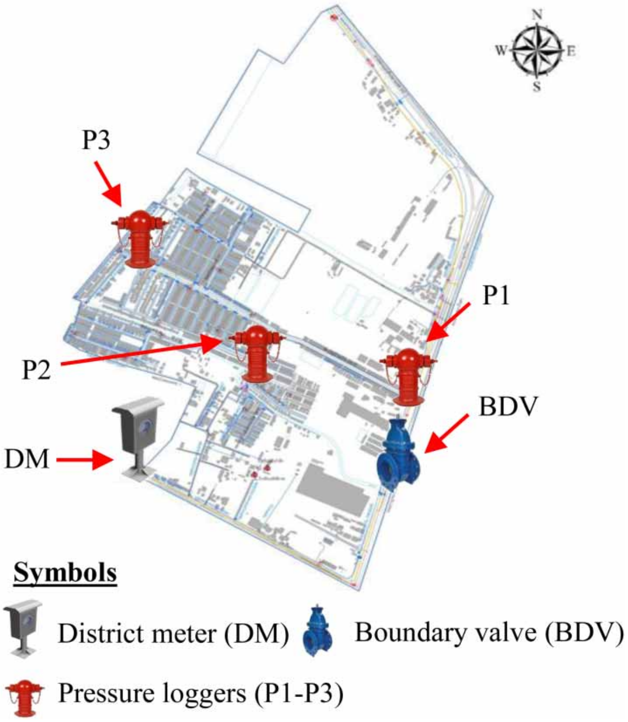

Figure 1 | DMA 54-09-03 and the locations of an inlet (DM), a boundary valve (BDV) and pressure loggers (P1-P3).

Table 1 | Network information of DMA 54-09-03, November 2016

Information	Value
Service area	2.10 km^2
Number of customers	2,457 connections
Inflow	118,894 m^3/month
Consumption	77,267 m^3/month
Percentage of water loss	34.61 %
Average pressure at the DM	6.8 m
Total length of distribution pipes	26.13 km
Types of distribution pipe	PVC (80%), AC (20%)

METHODOLOGY

Two cases (pipe repair and BDV opening), consisting of four simulations with a timeline, are shown in Table 2. Our study was undertaken in December 2016. Simulation no. 1 represents the hydraulic situation before pipe repair by an active leakage control activity during December 3–5. During December 6–9, MWA repaired 38 leaking service connections. This information of pipe repair can be converted to an unreported break rate of 15.5 breaks per 1,000 connections per year, which is much higher than the international standard value of 0.75 breaks per 1,000 connections per year for the calculation of unavoidable annual real losses (Lambert *et al.* 1999; Thornton *et al.* 2008). MWA uses polybutylene pipes (PB) for its service connections. However, there are many reported incidents where a PB pipe fails prematurely when it is exposed to chlorinated water (Vibien *et al.* 2001; AWWA 2016b). Thus, using PB material might be one of the factors causing the very high unreported break rate. Simulation no. 2 used the data from December 10–12, which represented the network after the repair. Both periods of simulations (no. 1 and 2) were over 3-day holidays (Saturday to Monday). Thus, our first case study to investigate the benefits to energy of pipe repair were done by comparing the energy from simulations no. 1 and 2.

Table 2 | Two cases, pipe repair and BDV opening, consisting of four simulations with a timeline

Simulation No.	Description	Pressure Measurement Date	Remark
1	Before pipe repair	3–5 Dec. 2016	Repaired 38 leaking service connections
2	After pipe repair	10–12 Dec. 2016	
3	Before BDV opening	13–14 Dec. 2016	Inflow from BDV was much higher than DM
4	After BDV opening	20–21 Dec. 2016	

In the opening the BDV case, our staff were available to open the BDV on December 19 and to close it on December 22. Thus, we used the data during December 13–14 (Tuesday to Wednesday) for simulation no. 3 before opening the BDV and the data during December 20–21 (Tuesday to Wednesday) for simulation no. 4 after opening the BDV. Comparing the results of simulations no. 3 and 4, we could analyze the effect on energy of increasing the number of inlets. The steps of our work can be described as follows.

Model built-up

We built up the DMA 54-09-03 pipe network model (Figure 2) using the EPANET software (Rossman 2000). The GIS data were collected from water sale data and the measured flow and pressure data from the district meter (DM). In Figure 2, the nominal diameters of distribution pipes in the DMA

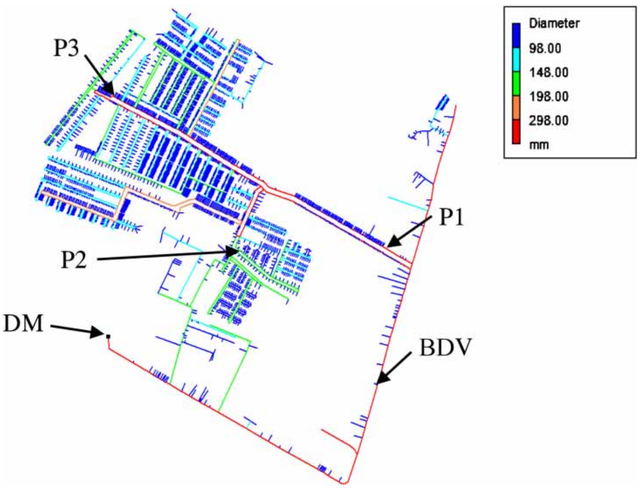

Figure 2 | DMA 54-09-03 and the locations of an inlet (DM), a boundary valve (BDV) and pressure loggers (P1-P3) in the EPANET software. The color legend shows pipe diameters.

were 300, 200, 150, and 100 mm, which are shown in red, orange, green, and cyan, respectively. The service connections had a diameter smaller than 100 mm, shown in blue. It was found that water had to flow from the DM through 150 mm diameter pipes (green) before it could be delivered to most customers. Thus, a high energy loss can be expected along the 150 mm pipes. If the BDV opens, however, water can flow to users to the west more efficiently through two parallel 300-mm diameter pipes at the east of the area. From a personal communication with MWA, there were two reasons why the DM was not installed at the BDV. Firstly, it was difficult to install a DM there because of the limitation of space. Secondly, the two parallel 300-mm diameter pipes were constructed after the DMA establishment in 2005 and the DMA hadn't been redesigned.

For calibration, we considered hourly pressure at the pressure loggers (P1-P3) and hourly flow at the DM. We adjusted the Hazen-William coefficient C_{HW} of each pipe to change pipe roughness for the pressure calibration. For the flow, we used the emitter function as pressure-dependent leakage, expressed as:

$$Q_L = C_L P^{N1} \tag{1}$$

where Q_L is the leakage flow, C_L is the emitter coefficient, and $N1$ is the emitter exponent. In our study, we used $N1 = 1.07$ from the average value by the field pressure step test data in MWA (Lapprasert *et al.* 2018).

In all simulations, C_{HW} remained the same value while the value of $C_L$in the simulation 1 was reduced in the simulations 2–4 due to the leak repairs. In the simulation 4, we adjusted the pressure pattern at the BDV that produced the accurate inflow at the DM. The pressures at the loggers (P1-P3) were used for calibration and verification.

Energy audit methodology

In the past, energy saving of water distribution systems was focused on pump operation and efficiency. Pelli & Hitz (2000) proposed two indicators to evaluate the energy consumption and efficiency of the entire water distribution system. Colombo & Karney (2002, 2005) presented the impact of leaks on energy consumption. Later, Cabrera *et al.* (2010) proposed the first well-defined method to audit the energy of pressurized distribution systems. In their concept, the energy lost due to leakage can be assessed. Dziedzic & Karney (2015) presented an alternative partition of the energy balance by network components (e.g. pipes, pumps, valves). Since our network had no pumps and throttled valves, Cabrera *et al.* (2010)'s approach was more suitable for our study, and our results were compared with Lenzi *et al.* (2013)'s study that used the same approach.

Conceptual energy balance and components proposed by Cabrera *et al.* (2010) are shown in Table 3. Input energy (E_{Input}) to the network was divided into three components: energy delivered to users (E_U), outgoing energy through leaks (E_L), and friction energy (E_F). Since leak flow causes a higher flow in a network, E_F can be split into friction energy without leaks (E'_F) and friction energy due to leaks (E''_F). Thus, the impact of leaks on energy losses is the combination of E_L and E''_F. Each component can be computed using the following equations:

$$E_{Input} = \gamma \cdot \sum_{i=1}^{n_{in}} \left[\sum_{t_k=t_1}^{t_p} q_{in_i}(t_k) \cdot h_{in_i}(t_k) \right] \cdot \Delta t \tag{2}$$

$$E_U = \gamma \cdot \sum_{i=1}^{n_u} \left[\sum_{t_k=t_1}^{t_p} q_{u_i}(t_k) \cdot h_{u_i}(t_k) \right] \cdot \Delta t \tag{3}$$

$$E_L = \gamma \cdot \sum_{i=1}^{n_l} \left[\sum_{t_k=t_1}^{t_p} q_{l_i}(t_k) \cdot h_{l_i}(t_k) \right] \cdot \Delta t \tag{4}$$

$$E_F = \gamma \cdot \sum_{i=1}^{n_F} \left[\sum_{t_k=t_1}^{t_p} \{q_{u_i}(t_k) + q_{l_i}(t_k)\} \cdot \Delta h_i(t_k) \right] \cdot \Delta t \tag{5}$$

where t_p is the total time of simulation equal to 24 hrs in our study, i and t_k are the element and time indices respectively, n_{in}, n_u, n_l and n_F are the numbers of inlets, users, leaks, and pipes, respectively, γ is the specific gravity of water, q_{in} and h_{in} are hourly inflow and head at each inlet respectively, q_u and h_u are hourly consumption and head at each user respectively, q_l and h_l are hourly leak flow and head at each leak respectively, Δh is head loss, and Δt is the time interval of simulation equal to 1 hr in our study.

Table 3 | Conceptual energy balance and components

E_{Input} (Input energy)	E_U (Energy delivered to users)		E_{Output} (Output energy)
	E_L (Outgoing energy through leaks)		
	E_F (Friction energy)	E'_F (Friction energy without leaks)	$E_{Dissipated}$ (Dissipated energy)
		E''_F (Friction energy due to leaks)	

To calculate E'_F and E''_F, a sub-simulation, in which all leaks in the network are removed, needs to be computed. Thus:

$$E'_F = \gamma \cdot \sum_{i=1}^{n_F} \left[\sum_{t_k=t_1}^{t_p} q_{u_i}(t_k) \cdot \Delta h_{0,i}(t_k) \right] \cdot \Delta t \tag{6}$$

$$E''_F = E_F - E'_F \tag{7}$$

where Δh_0 is head loss in the leak-free simulation.

To perform the energy audit, we introduced five indicators proposed by Cabrera *et al.* (2010), expressed in the forms:

Excess of supplied energy (I_1)

$$I_1 = E_{Input}/E_{U,min} \tag{8}$$

Network energy efficiency (I_2)

$$I_2 = E_U / E_{Input} \tag{9}$$

Energy dissipated through friction (I_3)

$$I_3 = E_F / E_{Input} \tag{10}$$

Leakage energy (I_4)

$$I_4 = (E_L + E_F - E'_F) / E_{Input} \tag{11}$$

Standards compliance (I_5)

$$I_5 = E_U / E_{\mathrm{min},U} \tag{12}$$

where $E_{U,min}$ is the minimum energy requirement at users to satisfy both consumption and pressure in the form:

$$E_{\mathrm{min},U} = \gamma \cdot \sum_{i=1}^{n_u} \left[\sum_{t_k=t_1}^{t_p} q_{u_i}(t_k) \cdot h_{\mathrm{min},u_i}(t_k) \right] \cdot \Delta t \tag{13}$$

where $h_{\mathrm{min},u}$ is the minimum pressure requirement at users. According to the American standard (GLUMRB 2012), the value of $h_{\mathrm{min},u}$ is 20 psig (~14 m). Since our network has pressure less than 10 m, it was not possible to use this standard. Thus, we used the Manila standard of 7 psig (~4.9 m) in this study (Rivera Jr 2014).

RESULTS AND DISCUSSION

Repair case

From Figure 3, the minimum night flow (MNF) before the repair was 80.3 m^3/hr at 3:00 a.m. while the MNF after the repair was 73.1 m^3/hr at 3:00 a.m. as well. The repair reduced the MNF by 8.9%. Furthermore, the average inflow reduced from 154.3 to 140.6 m^3/hr (−8.9%). It was found that the flows from our model captured the pattern and the average values of the measured flows before and after the repair. In addition, it could follow the peaks and troughs of the curves very well. The correlation coefficients (r) are 1.00 and 0.99, and the root mean square errors (RMSE) are 1.12 m^3/hr and 4.79 m^3/hr before and after the repairs, respectively.

Figure 4 shows the measured and simulated pressures at P1-P3 for the repair case. Since MWA reduced the pressure at night, the pressures at P1-P3 before and after the repair were low and had

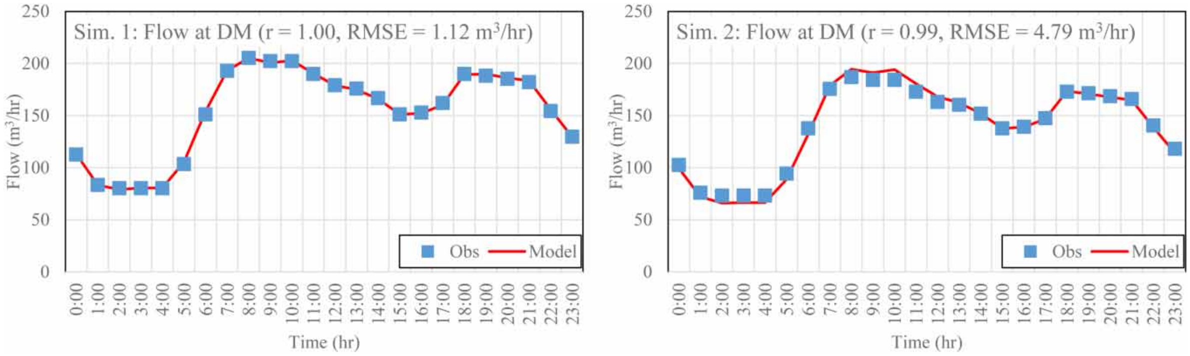

Figure 3 | Measured and simulated flows at the DM. Simulation no. 1 (left, before repair) and simulation no. 2 (right, after repair).

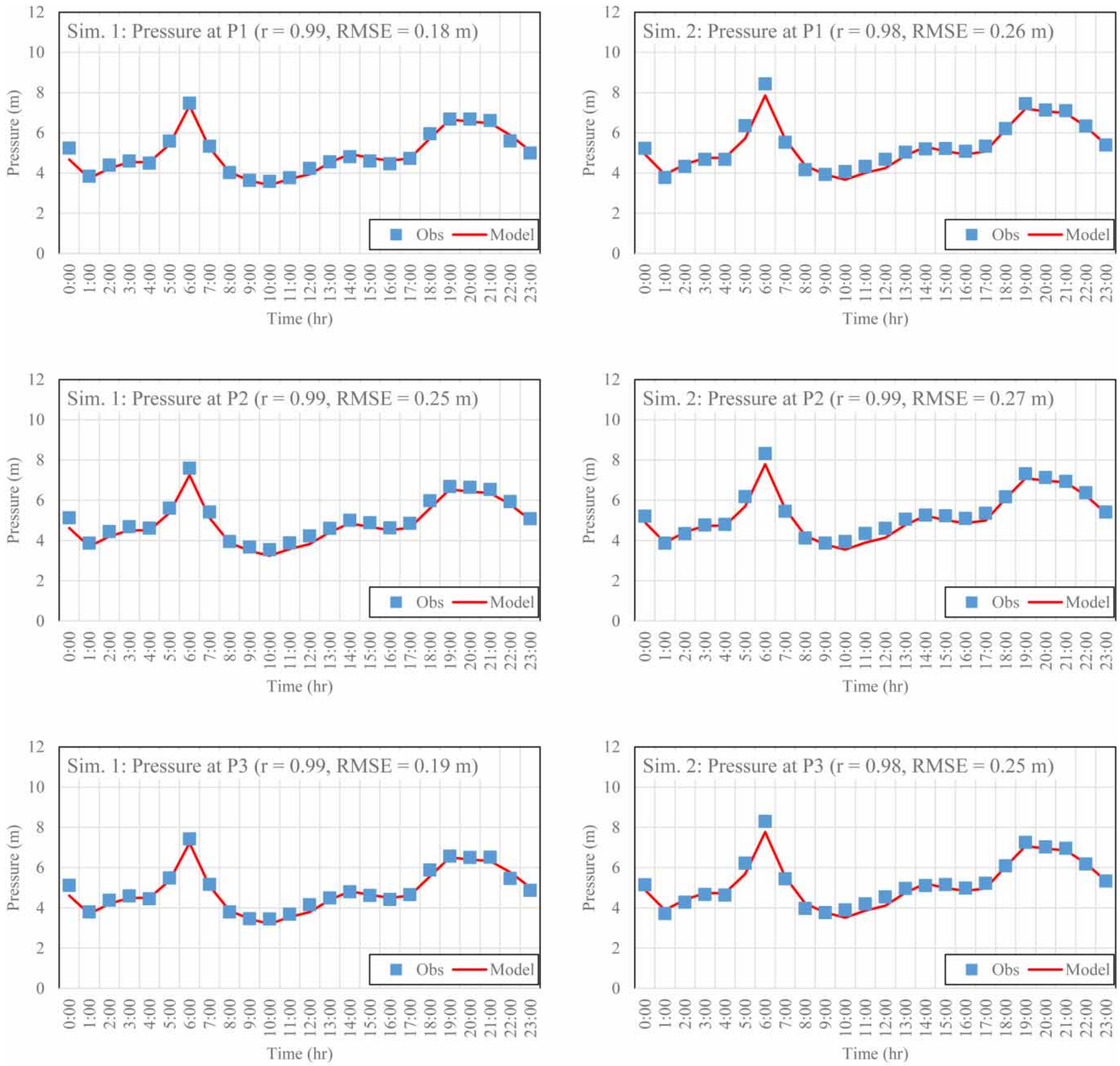

Figure 4 | Measured and simulated pressures at P1-P3. Simulation no. 1 (left, before repair) and simulation no. 2 (right, after repair).

similar values (4–5 m). When MWA increased the pressure in the morning, the highest pressure at 6:00 a.m. increased from 7.5 to 8.4 m after the repair and the average pressure from the three loggers increased from 5.0 to 5.4 m, implying that the inflow reduced by the repair decreased energy loss and increased pressure in the network. The comparison between the measured and simulated pressures in Figure 4 shows a very good agreement with r between 0.98 and 0.99 and RMSE between 0.18 m and 0.27 m.

BDV opening case

In Figure 5, the average inflow at the DM decreased greatly from 143.2 to 13.2 m^3/hr after opening the BDV. As shown in Figure 2, the new inlet at the BDV could feed water in two directions, and it was nearer to the two main 300 mm distribution pipes that delivered water to most customers. Thus, a large portion of the inflow (141.1 m^3/hr) was fed by the new inlet at the BDV. In addition, the total inflow slightly increased from 143.2 to 154.3 m^3/hr. The values of r are 0.99 and 1.00, and the values of RMSE are 3.09 m^3/hr and 0.05 m^3/hr before and after opening the BDV, respectively.

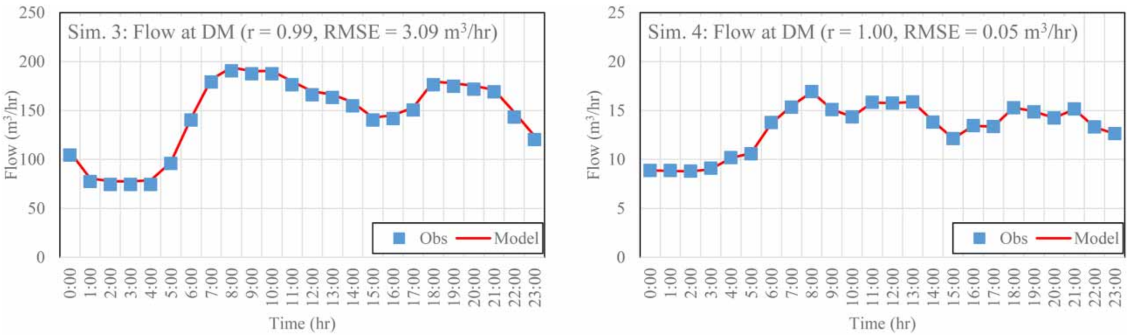

Figure 5 | Measured and simulated flows at the DM. Simulation no. 3 (left, before opening the BDV) and simulation no. 4 (right, after opening the BDV).

Unlike the repair case, the whole pressure shifted up substantially (Figure 6). The average pressure increased from 6.2 to 7.0 m (+13%). At the peak time (6:00 a.m.), the pressure increased from 8.7 to 9.4 m. Again, we found a good agreement between the measured and simulated pressures with r between 0.93 and 0.97 and RMSE between 0.32 m and 0.51 m.

Figure 6 | Measured and simulated pressures at P1-P3. Simulation no. 3 (left, before opening the BDV) and simulation no. 4 (right, after opening the BDV).

Water balance

Table 4 shows the water balance for both the leak repair and BDV opening cases. It was found that leak repair reduced water losses (WL) from 1,306 to 965 m^3/day (−26%). Thus, the percentage of water losses (%WL) after the repair was less than 30%. However, the average pressure (Avg. P) continuously increased and caused an increase in leakage because leakage relates to pressure as shown in (1). In particular, water losses after opening the BDV were almost the same volume as that before the leak repair. The average pressure increased from 5.0 to 7.0 m after opening the BDV.

Table 4 | Water balance

	Leak repair case			BDV opening case		
Indicator	**Before (m^3/day)**	**After (m^3/day)**	**Change (%)**	**Before (m^3/day)**	**After (m^3/day)**	**Change (%)**
Inflow	3,706	3,366	−9%	3,509	3,703	+6%
Flow to user	2,401	2,401	–	2,401	2,401	–
WL	1,306	965	−26%	1,109	1,302	+17%
%WL	35.2%	28.7%	−6.5%	31.6%	35.2%	+3.6%
Avg. P (m)	5.0	5.4	7.4%	6.2	7.0	+13.4%

Energy balance

Using our simulations no. 1–4, we estimated the network energy balance as shown in Table 5. In the case of the leak repair, E_{Input} reduced from 67.00 to 61.88 kW-h/day (−8%) while E_U increased from 31.30 to 33.67 kW-h/day (8%). As shown in Table 4, the inflow reduced from 3,706 to 3,366 m^3/day (−9%) because of the repair. Thus, E_{Input} decreased mainly due to less inflow, while E_U increased due to the increasing pressure because less flow means less friction loss. Reducing leakage provides two benefits to energy.

Table 5 | Energy balance for leak repair case (a) and BDV opening case (b)

	(a) Leak repair case			
Indicator	**Before (kW-h/day)**	**After (kW-h/day)**	**Change (%)**	**Summary explanation**
E_{Input}	67.00	61.88	−8%	The repairs caused less leakage and inflow. Thus, E_L and E_{Input} reduced. Less flow in pipes led to a decrease in friction loss (E_F), and the users obtained higher pressure and energy (E_U). Minimum energy requirement for the users ($E_{\min,U}$) was set, and E'_F was friction loss of an ideal case without leakage. Thus, $E_{\min,U}$ and E'_F were unchanged.
E_U	31.30	33.67	8%	
$E_{\min,U}$	31.96	31.96	0%	
E_L	18.07	14.36	−21%	
E_F	17.63	13.85	−21%	
E'_F	6.30	6.30	0%	

	(b) BDV opening case			
Indicator	**Before (kW-h/day)**	**After (kW-h/day)**	**Change (%)**	**Summary explanation**
E_{Input}	71.79	74.75	4%	Most inflow went through the opening BDV. Flow directions changed, and more water flew through larger pipes causing less E_F and higher E_U. As system pressure increased, leakage and E_L increased. Thus, inflow and E_{Input} increased. $E_{\min,U}$ remained constant. But E'_F reduced due to the change in flow directions.
E_U	38.58	44.86	16%	
$E_{\min,U}$	31.96	31.96	0%	
E_L	18.22	24.69	36%	
E_F	14.99	5.20	−65%	
E'_F	6.30	1.83	−71%	

In the opening the BDV case, E_{Input} increased slightly from 71.79 to 74.75 kW-h/day (+4%) because the inflow increased after opening the BDV as described earlier. E_U increased greatly from 38.58 to 44.86 kW-h/day (+16%), while E_F decreased dramatically. However, E_L increased due to increasing pressure and leakage implying that opening the BDV helped to increase the energy to users while energy loss due to friction reduced considerably, but the outgoing energy through leaks also increased unlike the leak repair case.

Energy efficiency

Five efficiency indicators for each case are shown in Table 6. Our results were compared with the study of Lenzi *et al.* (2013). They investigated energy balance and efficiency of two DMAs, Ganaceto and Marzaglia, in Italy. The percentages of water loss in these two DMAs were 42.1% and 9%, respectively, while the percentages of water loss in our DMA were 34.61% and 16.78% in a month before and after our field experiment, respectively. Lenzi *et al.* (2013) provided the value of $E_{U,min}$ for Marzaglia DMA, but not Ganaceto DMA. Thus, I_1 and I_5 cannot be calculated for Ganaceto DMA.

Table 6 | Energy efficiency

	Leak repair case			**BDV opening case**			**Lenzi *et al.* (2013)**	
Indicator	**Before**	**After**	**Change (%)**	**Before**	**After**	**Change (%)**	**Ganaceto DMA**	**Marzaglia DMA**
$I_1 = E_{Input}/E_{U,min}$	2.10	1.94	−8%	2.25	2.34	4%	–	1.92[a]
$I_2 = E_U/E_{Input}$	0.47	0.54	16%	0.54	0.60	12%	0.50	0.90
$I_3 = E_F/E_{Input}$	0.26	0.22	−15%	0.21	0.07	−67%	0.14	0.02
$I_4 = (E_L + E_F - E'_F)/E_{Input}$	0.44	0.35	−19%	0.37	0.38	0.1%	0.46	0.09
$I_5 = E_U/E_{\min,U}$	0.98	1.05	8%	1.21	1.40	16%	–	1.72[a]

[a] The minimum required pressures used in $E_{U,min}$ were 4.9 m for our DMA but 20 m for Marzaglia DMA.

The first indicator ($I_1 = E_{Input}/E_{U,min}$), indicating the excess in supplied energy in (8), shows how the input energy exceeds the minimum energy requirement at point of use. Since $E_{U,min}$ is a constant value, E_{Input} and I_1 were reduced in the leak repair case due to a decrease in inflow, but they increased in the opening the BDV case because of higher inflow. It is found that the I_1 values of our DMA and the Marzaglia DMA were comparable and around 2. Thus, E_{Input} was approximately twice $E_{U,min}$. Anyway, Lenzi *et al.* (2013) used the minimum required pressures of 20 m while we used 4.9 m.

The network energy efficiency is the second indicator ($I_2 = E_U/E_{Input}$) in (9). Before the repair, $I_2 = 0.47$ indicating that 47% of the input energy was delivered to the customers while the remaining was dissipated as friction and through leaks (Cabrera *et al.* 2010). After the repair, I_2 increased to 0.54. Reducing leakage benefits energy efficiency. Therefore, Marzaglia DMA had the highest I_2 (0.90) because it had the lowest percentages of water loss (9%). Before opening the BDV, I_2 was 0.54 as well because both E_U and E_{Input} increased. After opening the BDV, I_2 increased from 0.54 to 0.60 (+12%) due to less friction loss. Thus, selecting the right hydraulic locations of DMs also improves energy efficiency.

I_3 is the energy dissipated through friction (E_F/E_{Input}). It was found that opening the BDV can reduce the friction loss significantly. Thus, the redesign from the looped system to the DMA system can raise the energy loss greatly in water distribution networks. As user consumption grows or leakage increases, the impact becomes greater (Lapprasert *et al.* 2018).

Leakage energy (I_4) is the ratio between all energy losses due to leakage and the input energy ($(E_L + E_F - E'_F)/E_{Input}$). For the leak repair case, I_4 reduced clearly due to smaller leakage. However, I_4 slightly changed in the opening the BDV case because E_L increased but E_F and E'_F decreased. This was clearly because opening the BDV did not help to reduce leakage energy. Thus, I_4 can reflect the leakage levels in pipe networks in the perspective of energy.

The last indicator (I_5), standards compliance, represents the normalized real energy delivered to users by the minimum energy requirement of the users ($E_U/E_{\min,U}$). If I_5 is less than unity, it implies that on average, the users do not receive the energy to meet the minimum pressure requirment. This shows that before the leak repair, $I_5 < 1$ while $I_5 > 1$ after the leak repair and after opening the BDV. I_5 of Marzaglia DMA was the highest, and thus it implied the largest excess energy at users.

Monetary benefit

Colombo & Karney (2005) showed that leaks increase operating costs in terms of lost water and extra energy consumption. To evaluate the real cost of the extra energy consumption in their theory, the pressure and energy delivered to users must be fixed during a leakage event by the pressure compensation at sources such as pumping stations. However, they mentioned that practically water utilities often do not exercise the pressure compensation for marginal or even moderate leakage. In our cases, we investigated only one of 935 DMAs of MWA. We cannot evaluate the pressure compensation at sources, and it seemed that there was no pressure compensation according to our measured data. So, we cannot use their approach to evaluate the monetary benefit in our study. On the other hand, we implemented the IWA/AWWA water audit methodology (AWWA 2016a) to calculate costs for leakage (real losses) using the variable production cost. Although we cannot evaluate the monetary benefit for the BDV opening case in this study, its benefit can be found in terms of energy efficiency as shown in Table 6.

The cost and benefit for the leak repair case were estimated here. The cost of the survey and repairs was 90,555 baht (~2,800 USD). According to MWA survey data, the leak surveys on DMA 54-09-03 were conducted on July, 2016 and May, 2017 before and after our study time period, respectively. Thus, the inspection interval was approximately 150 days. The leak repairs caused water saving of 341 m^3/day. Thus, we estimated the total volume of water saving of $150 \times 341 = 51{,}150\ m^3$. In the fiscal year 2016, the total annual cost of operating MWA system was 12,831 million baht, and the system input volume of water was 1,966 million m^3 (MWA 2016). So, the unit production cost was evaluated to be $12{,}831/1{,}966 = 6.527$ baht/m^3 (~0.2 USD/m^3), and the benefit of the leak repair case was $51{,}150 \times 6.527 = 333{,}850$ baht (~10,500 USD). The benefit-cost ratio was $333{,}850/90{,}555 = 3.69$. As a result, MWA should perform more aggressive active leakage control and pipe repairs.

CONCLUSIONS

We investigated the energy benefits of leak repair and increasing the number of inlets in a real DMA. The leak repair reduced inflow, so both the energy loss due to friction and the outgoing energy through leaks decreased. Thus, the benefits were less input energy and more energy to customers. Although the DMA system helps to monitor and quantify leakage, sometimes some inlets must be closed. Having a sufficient number of DMA inlets and choosing the right hydraulic locations are very important factors, as correct placement should not cause any additional large friction loss. In our study area, opening another inlet at the right hydraulic location had an impact resembling reducing leakage, which benefited the energy efficiency of our DMA because of more energy being supplied to customers, but it did not reduce the input energy as the inflow and leakage did not reduce. Thus, the leakage energy indicator (the ratio between all energy losses due to leakage and the input energy) did not decrease in the case of increasing the number of inlets.

ACKNOWLEDGEMENTS

The authors thank the editor and two anonymous reviewers for their constructive reviews that helped to improve the manuscript greatly. The data and assistance provided by Metropolitan Waterworks Authority were greatly appreciated. Kaewsang was supported by the PhD scholarship by the Faculty of Engineering, Kasetsart University (61/01/WE/D.ENG).

REFERENCES

AWWA 2016a *Water Audits and Loss Control Programs*, 4th edn. Manual of Water Supply Practices M36, Denver.

AWWA 2016b *Water Distribution Grades 1 & 2 WSO: AWWA Water System Operations WSO*. American Water Works Association, Denver.

Cabrera, E., Pardo, M. A., Cobacho, R. & Cabrera Jr., E. 2010 Energy audit of water networks. *Journal of Water Resources Planning and Management* **136**, 669–677. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000077.

California Energy Commission California's water energy relationship 2005 *Final Staff Report Prepared in Support of the 2005 IEPR Proc. (Sacramento, CA)*. CEC-700-2005-011-SF.

Charalambous, B. 2008 Use of district metered areas coupled with pressure optimisation to reduce leakage. *Water Science and Technology: Water Supply* **8**(1), 57–62. https://doi.org/10.2166/ws.2008.030.

Colombo, A. F. & Karney, B. W. 2002 Energy and costs of leaky pipes: toward comprehensive picture. *Journal of Water Resources Planning and Management* **128**(6), 441–450. https://doi.org/10.1061/(ASCE)0733-9496(2002)128:6(441).

Colombo, A. F. & Karney, B. W. 2005 Impacts of leaks on energy consumption in pumped systems with storage. *Journal of Water Resources Planning and Management* **131**(2), 146–155. https://doi.org/10.1061/(ASCE)0733-9496(2005)131:2(146).

Dziedzic, R. & Karney, B. W. 2015 Energy metrics for water distribution system assessment: case study of the Toronto network. *Journal of Water Resources Planning and Management* **141**(11), 04015032. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000555.

Jitong, T. & Jothityangkoon, C. 2017 Reducing water loss in a water supply system using a district metering area (DMA): a case study of the provincial waterworks authority (PWA) Lop Buri Branch. *Engineering and Applied Science Research* **44**(3), 154–160. https://doi: 10.14456/easr.2017.23.

Galdiero, E., De Paola, F., Fontana, N., Giugni, M. & Savic, D. 2016 Decision support system for the optimal design of district metered areas. *Journal of Hydroinformatics* **18**(1), 49–61. https://doi.org/10.2166/hydro.2015.023.

GLUMRB (Great Lakes Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers) 2012 *Recommended Standards for Water Works*. Health Research, Health Education Services Division, Albany, NY.

Lambert, A. O., Brown, T. G., Takizawa, M. & Weimer, D. 1999 A review of performance indicators for real losses from water supply systems. *Journal of Water Supply: Research and Technology-AQUA* **48**(6), 227–237. https://doi.org/10.2166/aqua.1999.0025.

Lapprasert, S., Pornprommin, A., Lipiwattanakarn, S. & Chittaladakorn, S. 2018 Energy balance of trunk main network in Bangkok, Thailand. *AWWA Journal* **110**(7), E18–E27. https://doi.org/10.1002/awwa.1053.

Lenzi, C., Bragalli, C., Bolognesi, A. & Artina, S. 2013 From energy balance to energy efficiency indicators including water losses. *Water Science and Technology: Water Supply* **13**(4), 889–895. https://doi.org/10.2166/ws.2013.103.

Mamade, A., Loureiro, D., Alegre, H. & Covas, D. 2017 A comprehensive and well tested energy balance for water supply systems. *Urban Water Journal* **14**(8), 853–861. https://doi.org/10.1080/1573062X.2017.1279189.

MWA (Metropolitan Waterworks Authority) 2016 *Annual Report 2016, Thailand*. Available from: https://www.mwa.co.th/download/pln0201/annual2016/Annual_Report_2016_Eng.pdf (accessed 13 May 2019).

Napoli, C. & Garcia-Tellez, B. 2016 A framework for understanding energy for water. *International Journal of Water Resources Development* **32**, 339–361. https://doi.org/10.1080/07900627.2015.1122579.

Pelli, T. & Hitz, H. U. 2000 Energy indicators and savings in water supply. *AWWA Journal* **92**, 55–62.

Rivera Jr., V. 2014 *Tap Secrets: The Manila Water Story*. Asian Development Bank, Philippines.

Rossman, L. A. 2000 *Epanet 2 Users Manual*. US Environmental Protection Agency, Cincinnati.

Thornton, J., Sturm, R. & Kunkel, G. 2008 *Water Loss Control*, 2nd edn. McGraw-Hill, New York.

Vibien, P., Couch, J., Oliphant, K., Zhou, W., Zhang, B. & Chudnovsky, A. 2001 Chlorine resistance testing of cross-linked polyethylene piping materials. *Annual Technical Conference – Society of Plastics Engineers* **3**, 2833–2837.

Vilanova, M. R. N. & Balestieri, J. A. P. 2015 Exploring the water-energy nexus in Brazil: the electricity use for water supply. *Energy* **85**, 415–432. https://doi.org/10.1016/j.energy.2015.03.083.

Wong, H. G., Speight, V. L. & Filion, Y. R. 2017 Impact of urban development on energy use in a distribution system. *AWWA Journal* **109**(1), E10–E18. https://doi.org/10.5942/jawwa.2017.109.0001.