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Analysing Pan Evaporation to Understand Wastewater Treatment Plant Performance, A Case Study in A Manufacturing Industry

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Abstract

Water loss has become a problem with the balance of a water system, including one in the industry. General opinion has considered evaporation as one of the main justifications for explaining the water loss, especially in the area with a higher daily temperature. A study was conducted on a wastewater treatment system owned by a manufacturing industry, which consists of semi-open-air sedimentation and aeration ponds, which suddenly experienced a significant deficit in its water balance. To analyse the WWTP performance, the 8-Step Problem Solving method was used. The problem was defined by causal branching analysis. The suggested root cause i.e., water evaporation rate (E) was assessed using the pan evaporation (E_{pan}) approach, involving the partial pressure of the water vapour and the pan evaporation coefficient (K_{pan}). The estimated evaporation rate was then compared to the states in which the WWTP experiences both normal and abnormal water losses. The study revealed that evaporation (1.67±0.59 mm.d^{-1} and 1.72±0.62 mm.d^{-1}, for sedimentation pond and aeration pond, respectively) was not the main cause of sudden significant water loss ($R^2 = .000$, p-value = .954) and confirmed another root cause. In parallel, a water balance model was constructed and fitted the actual condition ($R(11) = .988$, $p\text{-value} < .001$). A countermeasure was performed against the confirmed root cause followed by a monthly evaluation of water loss using the constructed model with a 3σ threshold value (UCL = 9.55%) which showed the elimination of the problem.

Keywords: evaporation, problem-solving, water balance, wastewater, WWTP modelling

1. Introduction

From water distribution and wastewater treatment systems to indoor swimming pools, the undesirable disparity between input and output values of water remains commonly identified (Al-Washali et al., 2018; Turza and Füri, 2017). Commonly, the unevenness that leads to an output deficit in the water balance is known as water loss. In a wastewater treatment plant (WWTP), water loss mainly occurs as a consequence of water removal via evaporation, non-water discharge (e.g., sludge removal), and even leakage (Judd, 2019). According to Khater et al. (2016), WWTP has average water losses of 10.63±4.59%.

The evaporation rate may be relatively high as a WWTP is located in a semiarid and tropical area (Delclaux et al., 2007; Martínez-Granados et al., 2011). This is mainly due to the evaporation does correspond to its contributory parameters i.e., water temperature, air temperature, relative humidity, and air velocity (Asdrubali, 2009). This condition overall affects the sum of water loss. To understand the evaporation rate, evaporation pans have become a popular method. This method estimates the actual evaporation rate of a system (E) by converting pan evaporation (E_{pan}) using a specific coefficient K_{pan} (Izady et al., 2016; Wang et al., 2019). There are numerous methods to determine K_{pan} value. Most calculations aim the evapotranspiration (ET_o) as the result of water loss from the agricultural system, for instance the Penman-Monteith model (Djaman et al., 2017; Poddar et al., 2021). K_{pan} was determined as a function of relative humidity, wind speed, upwind fetch distance, wind run, and even temperature and psychrometric constant (Kaya et al., 2012; Talaee et al., 2014). In addition, it must be noted that the evaporation from the pan is also sunny hours in its capacity to estimate the evaporation rate from the water surface (Roderick et al., 2007). Standardised floating and class-A are two among several types of evaporation pans which are commonly used to estimate the evaporation rate from the open water system (Jensen, 2010). Some studies used this method for determining the evaporation rate of lakes (Mesquita et al., 2020), dams (Martínez-Granados et al., 2011), and pools (Smith et al., 1994). In addition, Izady et al., (2016) did conduct a study on the evaporation of WWTP in arid subtropical climates. It has been rarely identified for this study to be performed in WWTP ponds located in a tropical area. Therefore, a study involving a WWTP system in a humid tropical climate has the potential to uncover novel data.

For the time being, water loss has also been identified in industrial settings. As a case study, a WWTP owned by PT Organon Pharma Indonesia, Tbk was reported to experiencing a sudden significant water loss in April 2021 (*the information was obtained from the company*). For the six consecutive months, the disparity of water balance increased with an average of 21.17±2.73% compared to 2.59±1.43% in the previous twelve months. An unpublished internal study was conducted and concluded if the leakage became the root cause. Follow-up was done to check the condition but no leakage was identified. Since the company had no water balance for WWTP, evaporation had become the only proposed reason for this water loss as a general consideration. A study was needed to confirm if evaporation does become the root cause of water loss in the respective system as well as to propose appropriate problem-solving in line with the company's standard.

Hence, this study was performed by applying techniques related to water evaporation to the practical implementation of problem-solving with three objectives i.e., 1) to understand the evaporation rate of the WWTP, 2) to construct the water balance and model using evaporation and other supportive data, and 3) to confirm the root cause, propose appropriate countermeasure, and evaluate the result, ensuring the control takes the place. In addition, this study also fulfilled the opportunity to understand the evaporation rate of tropical WWTP ponds as mentioned above.

2. Methodology

2.1. Area Description

The study was conducted in the wastewater treatment plant (WWTP) owned by PT Organon Pharma Indonesia Tbk, in Pasuruan, East Java. Geographically, it is located at 7°39'44.97" S and 112°41'58.72" E. The study was conducted between September and October 2021. The closest meteorological station (Geophysics Station Class II Pasuruan) provided the average air temperature, relative humidity, and rainfall as 22.29°C, 84.84%, and 7.77 $mm.d^{-1}$, respectively. These parameters confirmed the humid tropical climate.

The WWTP has a capacity design of 200 $m.d^{-1}$ and consists of a sedimentation pond, a pre-aeration pond, three parallel aeration ponds, four intermediate basins, and an advanced oxidation system, sequentially from the influent to the effluent point. There are three flow meters installed in the WWTP i.e., at the total wastewater inlet, at the domestic wastewater inlet, and at the outlet. The semi-open-air system can only be found at sedimentation (S) and aeration (A) ponds.

2.2. 8-Step Problem Solving

The framework for performing problem-solving in this study followed the standard procedure developed by the company called 8-Step Problem Solving (Merck & Co., 2019). This standard procedure covers eight systematic steps of problem-solving comprising Plan, Do, Check, and Action section and consists of the below steps.

1. Clarify the problem,
2. Breakdown the problem,
3. Set a target,
4. Analyse the root cause,
5. Develop countermeasures,
6. See countermeasure through,
7. Evaluate both result and process, and
8. Standardise success.

Each step conducted in this study was performed in accordance with this framework. The prioritised problem (*PP*) at the point of occurrence (*POO*) was identified using problem break-down analysis and root causes were identified using the causal branching method.

2.3. Pan Evaporation

Measurement of pan evaporation followed the methodology of Izady et al. (2016) instead of Penman-Monteith method since the transpiration was not experienced in WWTP ponds (Djaman et al., 2017; Poddar et al., 2021). As evaporation is expected from ponds that enable direct contact between air and water surface, measurement was done in S

and *A*. Two customised class-A pans (aluminium layered, Ø = 120 cm) were used in the study. Pans were filled with water to the specific depth of 20 cm and placed in the area of the sedimentation pond (*PS*) and aeration pond (*PA*). Set up can be seen in Figure 1.

Twice daily, measurement was done for the temperature over the water of the sedimentation pond (T_S), aeration pond (T_A), pan at sedimentation pond (T_{PS}), and pan at aeration pond (T_{PA}) using a calibrated thermometer. The change in the depth of the water surface was also measured twice daily as well for pan at sedimentation and aeration ponds using a standard ruler. Pan evaporation was measured from the change of the depth on daily basis for both pans at sedimentation (E_{PS}) and aeration (E_{PA}) ponds. Measurement was conducted and documented for 28 days between September and October 2021.

Figure 1. From upper left clockwise. Sedimentation ponds (S), aeration ponds (A), evaporation pan at aeration (*PA*), and evaporation pan at sedimentation (*PS*).

2.4. Pond Evaporation

This step aimed to obtain both evaporations from sedimentation (E_S) and aeration (E_A) ponds. Partial pressures for sedimentation pond (e_S), aeration pond (e_A), pan at sedimentation pond (e_{PS}), and pan at aeration pond (e_{PA}) were calculated using temperature data generated from measurement T_S, T_A, T_{PS}, and T_{PA}, respectively. The calculation was carried out following Equation (1) (Murray, 1967; Izady et al., 2016), respective for each place.

$$e=6.1078e^{\left[\frac{a(T-273.16)}{T-b}\right]} \tag{1}$$

Remark:
e = partial pressure (mbar)
T = temperature (K)
a = constant (17.2693882)
b = constant (35.86)

Note that the usage of parameter *T* follows the identification according to the type of pan and pond (places). On the other hand, the partial pressure of ambient air (e_a) value was modified following Webb (1966) which equals to 102.5 percent of (e-e_a). The e_a used in the following calculations are the average of e_a generated from each respective place.

After obtaining partial pressures, the pan coefficient to approach actual pond evaporation (K_{pan}) was determined following Equations (2) and (3), for sedimentation and aeration ponds, respectively (Izady et al., 2016), where *k* is a constant with the value of 0.7 (Webb, 1966).

$$K_{pan}=k\frac{e_S-e_a}{e_{PS}-e_a} \tag{2}$$

$$K_{pan}=k\frac{e_A-e_a}{e_{PA}-e_a} \tag{3}$$

Remark:
Kpan = pan coefficient
eS = partial pressure of sedimentation pond (mbar)
ePS = partial pressure of sedimentation pond’s pan (mbar)
eA = partial pressure of aeration pond (mbar)
ePA = partial pressure of aeration pond’s pan (mbar)
ea = partial pressure of ambient air (mbar)

To obtain pond evaporation, the value of pan evaporation was multiplied by respective K_{pan} or can be written following Izady et al. (2016) in Equations (4) and (5) for E_S and E_A, respectively.

$$E_S=K_{pan}E_{PS} \tag{4}$$
$$E_A=K_{pan}E_{PA} \tag{5}$$

Remark:
ES = evaporation rate at sedimentation pond (mm)
EPS = evaporation rate at sedimentation pond’s pan (mm)
EA = evaporation rate at aeration pond (mm)
EPA = evaporation rate at aeration pond’s pan (mm)

The evaporation rate for WWTP (*E*) was then obtained from summarising E_S and E_A. *E* was tested for its correlation significance to water loss using Pearson’s correlation method with α = .05. The result was then used to challenge the proposed root cause related to water evaporation. An insignificant test result shall initiate the development of a countermeasure from another identified root cause.

2.5. Water Balance Construction

To understand the flow of water entering and exiting the WWTP, a water balance was constructed. The input was identified from the industrial influent (Q_{iI}) and domestic influent (Q_{iD}). Meanwhile, output was identified from the effluent (Q_f), E, and estimated disposed water via sludge (V_W). No extraneous water was taken into account since climatic data obtained from the meteorology station showed this is negligible in affecting the balance.

V_W was estimated from the monthly solar-dried sludge disposal weight. Thirty-three data were extracted from log records between January 2019 to September 2021 and analysed for the mean value. This value was then converted to the volume of water from sludge following Equation (6) as follows. All data were then combined into a diagram.

$$V_W = \frac{MC_i \times SC_f \times W}{SC_i \times \rho} \qquad (6)$$

Remark:

V_W = volume of disposed water via sludge (m^3)
MC_i = moisture content of sludge (0-1)
SC_f = solid content of solar-dried sludge (0-1)
SC_i = solid content of sludge (0-1)
W = weight of solar-dried sludge (kg)
ρ = water density (997 $kg.m^{-3}$)

2.5. Water Balance Modelling

The model was constructed according to Judd (2019) to obtain estimated water discharge at the outlet using data from water balance i.e., Q_{iD}, Q_{iI}, E, and V_W. Data between March 2020 and March 2021 were considered to be incorporated into the model reflecting the water losses in those thirteen months were under the acceptable value of 10.63±4.59% (Khater et al., 2016). The model was then challenged with actual water discharge to observe the fitness at $\alpha = .01$. An upper control limit was then set by considering 3σ of the range to set the acceptable water loss in the system.

2.6 Evaluation

The confirmed identified root cause was used as a base for countermeasure implementation. An evaluation was done by analysing actual water loss for the consecutive six months after the implementation of the countermeasure using the control limit.

3. Results and Discussion

3.1. Identifying The Root Causes

By employing Steps 1 to 3 of the 8-Step Problem Solving, the problem statement and root causes were identified accordingly. A brainstorming involving a team from the utility and EHS departments of the company was performed to clarify and break down the problem. The gap was defined as 6 of 9 monthly WWTP water loss was out of specification according to trend. This gap led to *PP* which was a significantly higher water loss. The problem break-down analysis based on current practice generated the *POO* of calculating water loss based on flow meter data as is shown in Figure 2.

Given that logbook data accurately depicted the actual recorded value of the flow meters and the task after this step follows the number presented, the *PP* at *POO* was the calculated water loss significantly exceeded the trend between normal conditions (M = 2.59, SD = 2.37) and abnormal conditions (M = 21.17, SD = 2.60); $t(9) = -14.86$, p-value < .01. Root causes were obtained using the causal branching method and provided potential root causes as described in Figure 3.

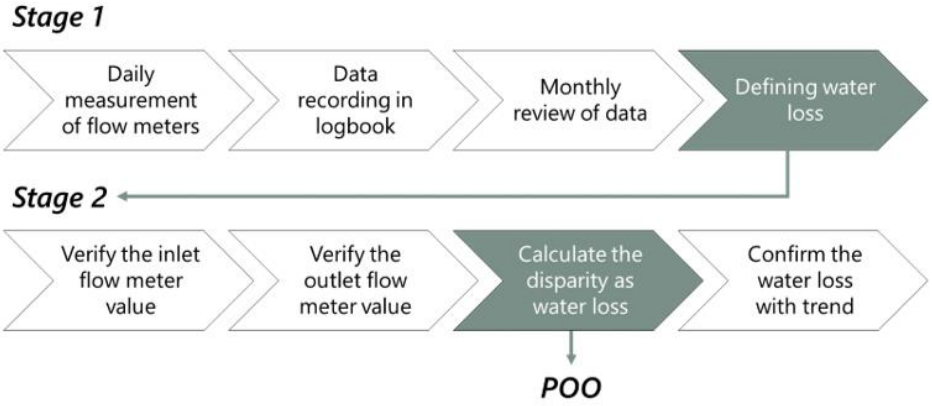

Figure 2. Two stages of sequential timeline gap assessment where darker box denotes the prioritised point to be analysed further

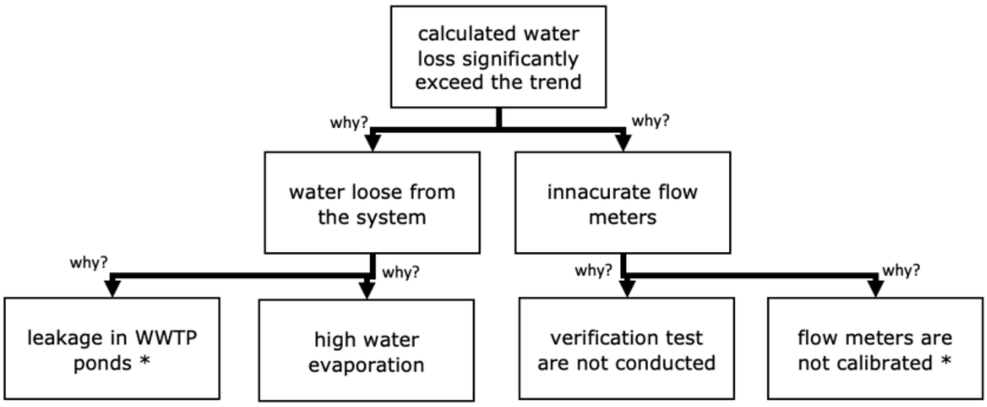

Figure 3. Causal branching to identify root causes. Asterisk mark denotes residual proposals which were not proceeded

The analysis provided two main root causes i.e., evaporation rate from WWTP ponds and flow meters inaccuracy. The evaporation rate was firstly prioritised for analysis as it was considered the main root cause according to the general perspective of the public and need scientific support to unveil.

3.2. Analysing The Evaporation

The following two stages implied to Step 4 of 8-Step Problem Solving. There was a significant difference between T_S (M = 30.55, SD = 1.39) and T_{PS} (M = 29.63, SD = 1.26); $t(77) = 1.99$, p-value $< .05$. On the other hand, there was no significant difference between T_A (M = 29.86, SD = 1.12) and T_{PA} (M = 30.05, SD = 1.09); $t(78) = 1.99$, p-value $= .444$. This is in place since *S* is the foremost step in WWTP that receives wastewater from manufacturing processes. Temperature of water is a parameter which determines air temperature and evaporation (Asdrubali, 2009).

Equations (1), (2), and (3) were used to calculate pan coefficient K_{pan} from temperature and generated values as much as 0.74 and 0.69 for *S* and *A*, respectively. Compared to present works, the above values remained within the range of pan coefficient for several water reservoirs as can be seen in Table 1. The observation led to a new idea that the K_{pan} in arid subtropical and humid tropical climates do not vary that significantly. The comparison indicated that the man-made structure e.g., industrial-scale ponds, generally has a higher pan coefficient than natural structures e.g., larger facultative ponds and tropical lakes which may result from broader meteorological variables affecting the water surface (Mesquita et al., 2020). It was presumed that the meteorological variables played a role since Izady et al. (2016) conducted the study in readily open-air ponds meanwhile this study worked on industrial-scale ponds of a much smaller size.

Table 1. K_{pan} for several ponds

Source	K_{pan}	Remark
S	0.74	Sedimentation pond, tropic, semi open-air
A	0.69	Aeration pond, tropic, semi open-air
Izady et al. (2016)	0.75 – 0.79	Anaerobic pond, subtropic, open-air
Izady et al. (2016)	0.59 – 0.73	Primary facultative pond, subtropic, open-air
Izady et al. (2016)	0.54 – 0.66	Secondary facultative pond, subtropic, open-air
Mesquita et al. (2020)	0.66 – 0.69	Tropical lake

Using the K_{pan}, E_S and E_A can be determined as 1.67±0.59 $mm.d^{-1}$ and 1.72±0.62 $mm.d^{-1}$, respectively, following Equations (4) and (5). By considering the surface area of *S* and *P* (25.25 m^2 and 112.16 m^2, respectively), the amount of evaporated water can be estimated as 0.04±0.01 $m^3.d^{-1}$ and 0.19±0.07 $m^3.d^{-1}$, respectively. Statistical analyses were conducted between estimated evaporation rate and actual water loss for a duration from April 2021 to September 2021 where the abnormality was observed. The overall regression was not statistically significant ($R^2 = .000$, $F(1,4) = .004$, p-value $= .954$). It confirmed that evaporation did not significantly predict the water loss ($\beta = 14.84$, p-value $= .954$). This explained that there are other variables explaining water loss and the assumption of evaporation as the main cause of water loss can be neglected.

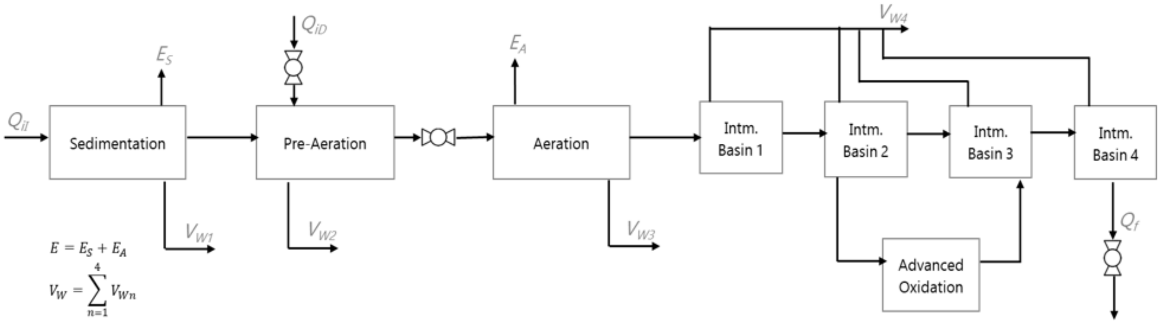

Figure 4. Water balance diagram of WWTP

3.3. Modelling The Water Balance

Water balance followed the diagram of WWTP as illustrated in Figure 4. Average *W* was estimated from monthly *W* with n = 33 and yielded a result of 131.91±113.52 kg. The variance of the data was especially high because the disposal of sludge was conducted not on a regular basis. Extreme data cannot be treated as outliers as data showed the accumulation of sludge prior to disposal. Therefore, a bulk analysis of the sample was performed.

Dry sludge was obtained after a 10 – 15d sun drying process. The approachable equation for drying is dependent on the time for the sludge to drain and the time for the moisture to evaporate from the drained sludge. Partial drying (up to 30 – 40% of dry solid) and total drying (80 – 97% of dry solid) were suggested as the most reasonable approaches for the drying process (Obianyo and Agunwamba, 2015). Mathioudakis et al. (2009) suggested that the dried WWTP sludge contains moisture of around 6% after 7 to 12 days of the solar drying process in the regions which receive annual solar radiation. Meanwhile, the original state of wastewater sludge moisture content ranged from 99.14% to 99.72% with a mean value of 99.45% (Deng et al., 2015). Hence, by employing the above reference, MC_i, SC_i, and SC_f are defined as 0.9945, 0.0055, and 0.94, respectively. It must be noted that since the bulk analysis was performed to estimate the V_W, *W* shall be re-calculated each month following the addition of new *W* data and thus is referred as $\overline{W}$. Therefore, Equation (6) can be rewritten as in Equation (7) below.

$$V_W=0.1705\overline{W} \tag{7}$$

Remark:
$\overline{W}$ = average weight of solar dried sludge (kg)

By using data from the sample, V_W was estimated as 0.74±0.63 $m^3.d^{-1}$ for 33 months of sample origin. Compared to water loss from *E* (0.24±0.08 $m^3.d^{-1}$), V_W was identified to have a higher value. This is in line with the understanding that water loss from sludge disposal is relatively higher compared to evaporation from a WWTP system, as fresh sludge withdrawn from the system consists of 99.14% - 99.72% water (Deng et al., 2015). According to Ahmad et al. (2017), sludge disposal signifies around 0.3 – 0.9% of water losses from a water treatment plant.

By combining the flow at the inlet (Q_{iD} and Q_{iI}), *E*, and V_W data, an ideal model of water balance in the WWTP which estimates flow at the outlet (Q_f) can be constructed following Judd (2019) and written in Equations (8) and (9) as follow.

$$Q_{iD}+Q_{iI}=Q_f+E+V_W \tag{8}$$

$$Q_{iD}+Q_{iI}=Q_f+0.23n+0.1705W \tag{9}$$

Remark:

Q_{iD} = domestic wastewater inlet flow (m^3)
Q_{iI} = industrial wastewater inlet flow (m^3)
Q_f = wastewater outlet flow (m^3)
E = evaporation ($m^3.d^{-1}$)
n = day count of respective month (d)

Considering the acceptable water loss range (Khater et al., 2016), the model included data from March 2020 to March 2021 (*n* = 13) and can be seen in Table 2.

The model showed that there was no significant difference between actual Q_f (M = 1316, SD = 317) and estimated Q_f (M = 1326, SD = 319); *t*(24) = -0.08, *p*-value = .936 and strongly correlated with *R*(11) = .988, *p-value* < .001. In addition, it was observed that no significant difference in actual water loss percentage (M = 2.98, SD = 3.50) and estimated water loss percentage (M = 2.30, SD = 0.54); *t*(13) = 0.69, *p*-value = .499). The estimated water loss percentage was observed below 10.63±4.59%, which may result from a much smaller and controllable system in this study.

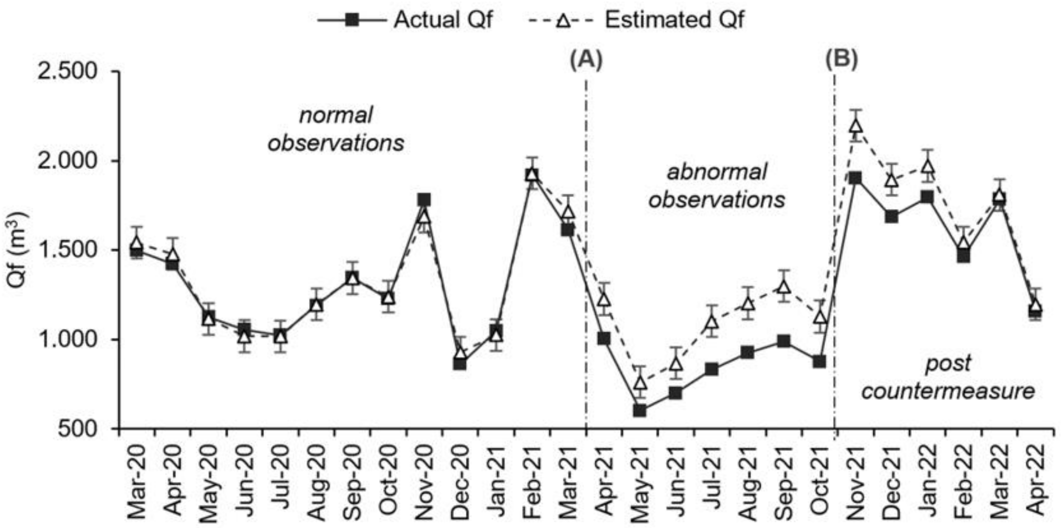

Figure 5. The comparison between estimated (model) and actual water loss during three conditions. (A) denotes the initiation of study and (B) denotes the implementation of countermeasure

Table 2. Actual and Estimated Q_f

Month	Actual Q_f (m^3)	Estimated Q_f (m^3)	Range (m^3)
03/2020	1,497	1,542	45
04/2020	1,423	1,479	56
05/2020	1,125	1,116	9
06/2020	1,055	1,019	36
07/2020	1,024	1,018	6
08/2020	1,190	1,196	6
09/2020	1,344	1,344	0
10/2020	1,228	1,239	11
11/2020	1,779	1,687	92
12/2020	863	928	65
01/2021	1,047	1,025	22
02/2021	1,919	1,929	10
03/2021	1,613	1,718	105

An upper control limit (UCL) was proposed by using 3σ of the range between actual and estimated water loss and defined as 9.55%. This number fell under the WWTP water loss reported by Khater et al. (2016), showing the estimated water loss was in line with the previous studies.

This result described that the model fitted with the actual condition where WWTP had experienced normal observations in water balance as illustrated in Figure 5. This also confirmed that the root cause as previously proposed as evaporation is not accepted and another root cause i.e., verified flow meters for the inaccuracy must be followed up.

3.4. Developing Countermeasure

Since the root cause was verified not to originate from evaporation, the inaccuracy of the flow meters became the identified potential root cause. In line with Step 5 of the 8-Step Problem Solving, countermeasure was defined as verifying the accuracy of flow meters which measure Q_{iD}, Q_{iI}, and Q_f. This finding was proposed to the company and was followed up immediately by October 2021. The company performed the verification test on flow meters and set the flow meters to meet the calibration threshold limit (*the data is considered confidential and hence is beyond the scope of this article*).

3.5. Evaluating Countermeasure

Water loss was further monitored until April 2022 using the model, reflecting Steps 6 and 7 of 8-Step Problem Solving. Monitoring data showed an improvement after implementing the countermeasure, as seen in Figure 6. Water loss was gradually decreasing in post countermeasure and was able to achieve the internal target of below UCL in the fourth month after implementation.

In line with step 8 of 8-Step Problem Solving, all the above parameters were documented in an internal company's procedure to assure the process quality and used to monitor the water loss after implementation of the countermeasure. The monthly check of flow meters accuracy was incorporated into company's SOP of water management. By obtaining the expected result, the 8-Step Problem Solving was considered complete and the model was standardised to be used in the company.

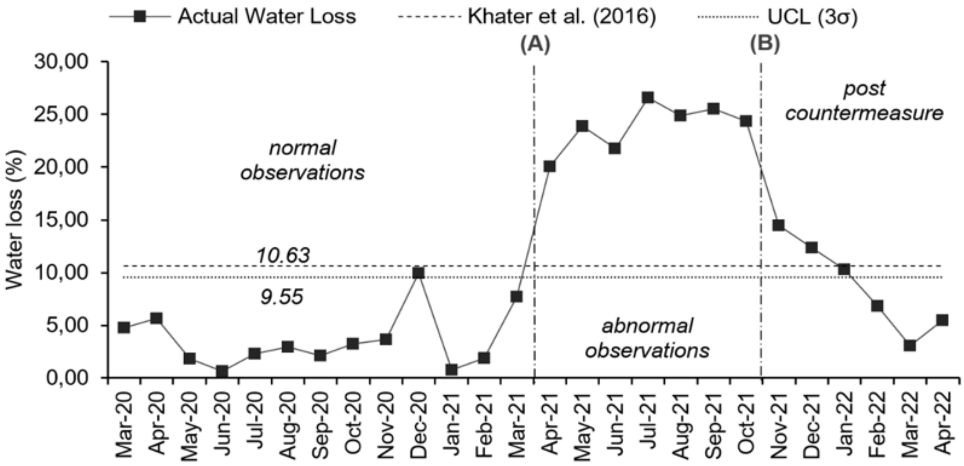

Figure 6. Evaluation of water loss using UCL to show improvement. (A) denotes the initiation of study and (B) denotes the implementation of countermeasure

4. Conclusion

The 8-Step Problem Solving approach was successfully applied to identify the root cause and the countermeasure against sudden significantly higher water loss at the WWTP of the company. In parallel, the effort of analysing the presumable root cause i.e., evaporation, has uncovered a novel understanding of the evaporation coefficient (K_{pan}) and evaporation rate at such industrial-size WWTP ponds in the tropical region. In this case study, the evaporation rate of such WWTP was identified as ranging between 0.04 to 0.19 $m^3.d^{-1}$ with K_{pan} relatively lying on a range determined by previous studies. This value lies even lower than water loss from sludge evaporation. A water balance model was constructed from estimated evaporation and sludge weight. The model showed an acceptable water loss of 9.55% with good fitness to estimate the effluent flow value. The model was accepted to ensure that the WWTP plan works appropriately. Contrary to public opinion, evaporation was confirmed as neither a single nor main cause of water loss. The root cause of water loss was identified as coming from flow meters which had a hindrance in accuracy. The proposed countermeasure i.e., to work on the calibration has shown a positive result in solving th problem, proven by the constructed method. Therefore, this model was standardised and has been used by the company to evaluate the countermeasure addressing the confirmed root cause of sudden significant water loss with a satisfactory outcome. Forthrightly, it is essential to analyse the moisture content of the sludge using a more appropriate method if equipment usage is feasible for further research.

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