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A Novel Approach to Modeling Wastewater Evaporation Based on Dimensional Analysis

A. Izady[1] · O. Abdalla[1] · M. Sadeghi[2] · M. Majidi[3] · A. Karimi[4] · M. Chen[1]

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Abstract Wastewater from municipal and industrial sources is becoming increasingly important in being reused, for example, for irrigation purposes. Wastewater is commonly stored in treatment lagoons in which evaporation is the main cause of water loss. Nonetheless, modeling wastewater evaporation (*WWE*) has received little attention. Driven by this knowledge gap, this study was performed to explore extent to which impurities affect water evaporation. A dimensional analysis was used to formulate *WWE* as a function of clear water evaporation (*CWE*), wastewater properties and climatic variables. We based our modeling approach on experimental data collected from the Neishaboor municipal wastewater treatment plant, Iran. As a result of this analysis, a multiplicative model to formulate *WWE* as a function of the influencing variables is proposed which indicated a reasonably well accuracy ($RMSE = 1.09$ mm) for the *WWE* estimation. Clear water evaporation indicated to be the most correlated variable in the model such that a constant coefficient can also be used to estimate *WWE* from *CWE* at the cost of losing accuracy only by 4.6 %.

Keywords Wastewater · Evaporation · Clear water · Class A pan · Dimensional analysis

1 Introduction

Due to ever-increasing demand for water resources, many regions of the world (e.g. Middle East, North Africa, India, China, Japan and Spain) face critical water resource sustainability

✉ A. Izady
az.izady@gmail.com

[1] Water Research Center, Sultan Qaboos University, Muscat, Oman

[2] Department of Plants, Soils and Climate, Utah State University, Logan, UT, USA

[3] Water Engineering Department, College of Agriculture, Ferdowsi University of Mashhad, Mashhad, Iran

[4] Built and Natural Environment Department, Caledonian College of Engineering, Muscat, Oman

issues (Llamas and Custodio 2002). Therefore, water resources supply has become a major concern for development especially in arid and semi-arid areas. Wastewater as an alternative resource is considered for non-potable applications such as irrigating agricultural lands (MacDonald 2003). Wastewater is commonly stored in treatment lagoons in which evaporation is the most important term in estimating water balance components and is the only cause of water loss in most cases (i.e. most lagoons are designed to be impermeable) (Cumba and Hamilton 1998; Parker et al. 1999; Ham 2002). Hence, wastewater evaporation rate which differs from that of clear water, as discussed in the following, needs to be investigated.

There are several factors causing a discrepancy between evaporation rate of wastewater and clear water. Wastewater stored in lagoons is typically dark brown to reddish brown due to the presence of significant amount of purple sulfur bacteria and suspended sediments (Wenke and Vogt 1981; Freedman et al. 1983; Parker et al. 1999). Dark colored wastewater absorbs more solar radiation, enhancing its evaporation compared to clear water. Additionally, increasing vapor pressure of the solution due to the high ammonia concentrations in wastewater, wastewater evaporation may be enhanced. Conversely, the high salinity of the wastewater resists against evaporation by decreasing vapor pressure of the solution (Parker et al. 1999).

Parker et al. (1999) discussed how physical and chemical properties of feedyard effluent may affect evaporation rate. They conducted four experiments to compare evaporation rates at different concentrations of feedyard effluent comprising of 100 % pure effluent, 50 % effluent mixed with 50 % groundwater, 25 % effluent mixed with 75 % groundwater and 100 % groundwater. A fifth experiment was conducted to compare clear water evaporation at different salt concentrations to test for potential vapor pressure effects. They found that evaporation rate for fresh effluent was 8.3 to 10.7 % higher than clear water evaporation rate. As the effluent stayed for about 4 days in the evaporation pans leading to settling and algal growth, differences in evaporation rates between the effluent and clear water diminished.

In spite of its crucial importance, modeling wastewater evaporation has received little attention. To the best of our knowledge, there is no model to specifically relate wastewater evaporation to clear water evaporation occurring in the same environment. This relationship is particularly important for estimating lagoons wastewater evaporation rate using the surrounding environmental variables (e.g. clear water pan evaporation, weather data). Driven by this knowledge gap, this study was performed to explore extent to which impurities affect water evaporation. Dimensional analysis method based on the Buckingham Π theorem (Buckingham 1914) was used to derive a novel model for estimating wastewater evaporation as a function of clear water evaporation and several influencing variables including total suspended solids (TSS), electric conductivity (EC), wastewater temperature (T_w), air temperature (T_a), wind speed (W), and solar radiation (R). We based our modeling approach on experimental data collected from the Neishaboor municipal wastewater treatment plant, Iran.

2 Material and Methods

2.1 Study Area

Neishaboor wastewater treatment plant is located at the Neishaboor city between 36° 05 N to 36° 06 N latitude and 58° 40 E to 58° 41 E longitude in the northeast of Iran (Fig. 1). The city is characterized by a semi-arid to arid climate, with an average annual precipitation of 265 mm. The mean annual temperature and potential evapotranspiration are 13.8 °C and

2335 mm, respectively (Izady et al. 2012, 2015). The Neishaboor wastewater treatment plant started operation in 2008. It has three anaerobic, primary and secondary facultative lagoons with 1.2, 7.8, and 8.3 hectare (ha) area, respectively (Fig. 1). Wastewater is treated using stabilization lagoons in which the municipal wastewater is collected and after settling, the organic materials are decomposed and stabilized under natural ample sunlight, microorganisms and algal growth. The facultative lagoons are commonly designed to remove most of the remaining biochemical oxygen demand (BOD) through the coordinated activity of algae and heterotrophic bacteria (Tilley et al. 2014). The treated wastewater is used for irrigation of surrounding agricultural lands having an area of 300 ha commonly cultivated with corn silage and winter wheat (Izady 2014).

2.2 Experimental Setup and Methodology

This study was undertaken in three steps namely *i*) installing class A pans and measuring daily evaporation and temperature of the wastewater and clear water from the pans as well daily wastewater lagoons parameters including T_w, *EC* and *TSS*, *ii*) calculating pan coefficients and estimating the evaporation rate from the wastewater lagoons, *iii*) adopting dimensional analysis to formulate and obtain a mathematical model that relates wastewater evaporation (*WWE*) to clear water evaporation (*CWE*) and wastewater and climatic variables.

2.2.1 Class A Pan and Data Measurement

Class A pan (U.S. Department of Commerce 1970), a widely used evaporation pan, was employed for this study. It is made of stainless steel with cylindrical shape of dimensions 12.1 cm diameter and 25.4 cm height. It is installed on a wooden frame so that air circulates easily around and under the pan (Allen et al. 1998). Owing to the fact that the anaerobic, primary and secondary facultative lagoons have different solutions, three class A pans were installed for our experiment which were filled with wastewater from different lagoons (Fig. 2). Evaporation rate as well as daily temperature of the wastewater of each pan were continuously recorded along the study. In addition, another Class A pan filled with clear water was installed for measuring *CWE* (Fig. 2).

Wastewater T_w, *TSS* and *EC* were measured daily for the three lagoons. To measure *TSS*, the wastewater sample was filtered through a pre-weighed filter. The residue retained on the filter was determined by weighing after oven drying at 105 °C. The T_w and *EC* were measured with alcohol thermometer and portable WTW handheld meters (WTW GmbH), respectively. Temperature was measured 10 cm below the wastewater surface within the pans and lagoons. Daily wastewater data (T_w, *EC* and *TSS*) were recorded over 4 months from April to July 2014. Wind speed and solar radiation data were acquired from the Neishaboor synoptic meteorological station.

2.2.2 Estimation of Wastewater Evaporation

Measurements of pan evaporation can rarely be used directly as estimates of evaporation from a wastewater lagoon because of the scale discrepancy affecting the ambient sensible heat fluxes. A water body contained in the lagoons could have comparatively large thermal inertia leading to slow temperature variations, whereas the pan temperature

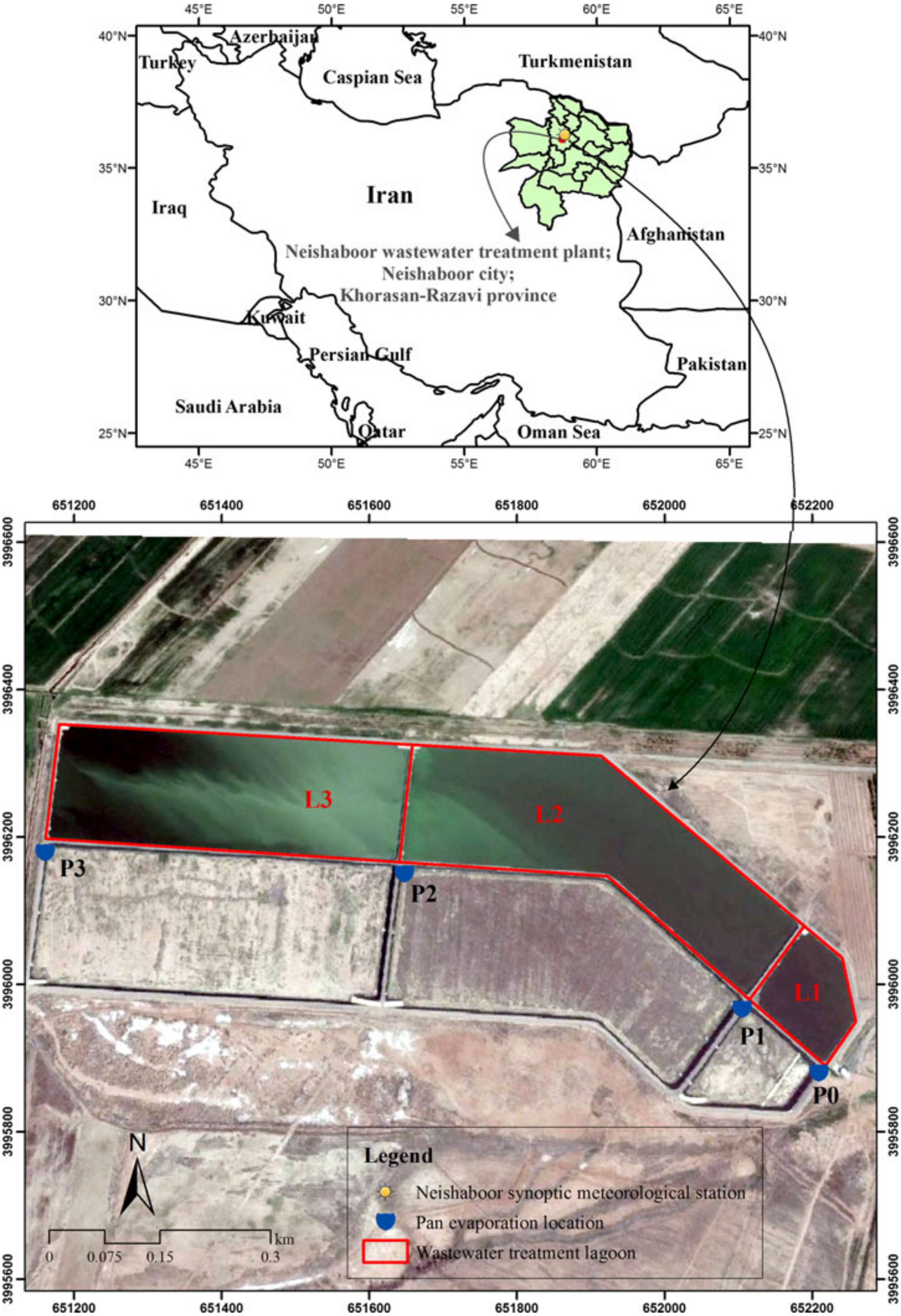

Fig. 1 Location of the study area in north east of Iran along with aerial photo of the Neishaboor wastewater treatment plant. L1, L2, and L3 are acronym for three different anaerobic, primary and secondary facultative lagoons. P0, P1, P2, and P3 show the location of the installed class A pans filled with clear water, wastewater from anaerobic, primary and secondary facultative lagoons, respectively

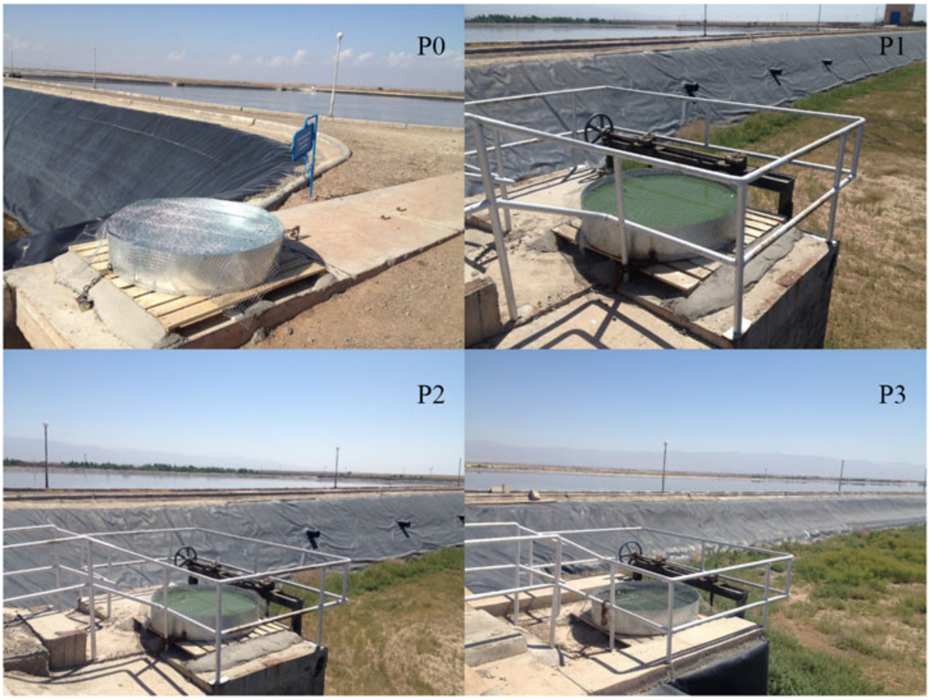

Fig. 2 Installed class A pan near to each lagoon: P0 filled with clear water, P1 filled with wastewater from anaerobic lagoon, P2 filled with wastewater from primary facultative lagoon, and P3 filled with wastewater from secondary facultative lagoon

could vary greatly from day to day with changing environmental conditions. Therefore, the following common correction was applied:

$$E_L = K_{pan} E_P \tag{1}$$

where K_{pan} is pan coefficient and E_L and E_P are evaporation from wastewater lagoon and pan, respectively. The generally accepted "conversion pan" method (Webb 1966) was used to calculate daily K_{pan}. This method is based on the assumption that evaporation rates from lagoon and pan are a function of vapor pressure difference between the particular water surface and a convenient observation height in the air:

$$K_{pan} = k\frac{e_l - e_a}{e_p - e_a} \tag{2}$$

where k is a constant, equal to 0.7 as suggested by Webb (1966), and e_l, e_p, and e_a denote the saturation vapor pressure of lagoon, pan, and air at a reference height above the ground surface (KPa), respectively. The saturation vapor pressure (KPa) was calculated as a function of T (°C) using the equation of Murray (1967):

$$e = 0.61078\exp\left(\frac{17.269T}{237.3 + T}\right) \tag{3}$$

Wastewater evaporation rate was estimated separately for the three wastewater lagoons based on the pan coefficients calculated using Eqs. (2) and (3). Evaporation rate for the clear water was estimated using the average pan coefficient of 0.7 (Kohler 1954; Kohler et al. 1955; Lapworth 1965; Hounam 1973; Winter 1981).

2.2.3 Dimensional Analysis

Dimensional analysis is commonly used to relate different variables tied to a specific phenomenon especially when the mathematical model of the system is unavailable or complex (Buckingham 1914). Due to the complexity of the relationship between the studied variables here, we applied a dimensional analysis based on the Buckingham Π theorem (Buckingham 1914) to find the effect of wastewater properties and climatic conditions on the wastewater evaporation. The measured daily cumulative wastewater evaporation (*WWE*), daily cumulative clear water evaporation (*CWE*), wastewater variables including *TSS*, *EC*, and T_w and climatic variables including wind speed (*W*), air temperature (T_a) and daily cumulative solar radiation (*R*) were considered for this analysis. Dimension of the *WWE*, *CWE*, *TSS*, *EC*, T_w, *W*, T_a, and *R* respectively is L, L, ML^{-3}, T^{-1}, θ, LT^{-1}, θ, and MT^{-2} (L: Length, M: Mass, T: Time, θ: Degree). Therefore, the number of variables are 8 and the number of basic dimensions are 4, meaning that all the variables can be combined into 4 (=8 – 4) dimensionless variables (Π terms) to construct the final model.

Because of the key role of the water body temperature in relation with air temperature in evaporation from water bodies (Majidi et al. 2015), we considered T_w/T_a to be one of the dimensionless variables. Then, after an extensive search for the best model, *WWE*, *CWE* and *EC* were chosen as the best non-repeating variables and hence *TSS*, *W*, and *R* were considered as repeating variables, leading to the following dimensionless variables:

$$\begin{cases} \Pi_1 = W^{a1}\, R^{b1}\, TSS^{c1}\, WWE \\ \Pi_2 = W^{a2}\, R^{b2}\, TSS^{c2}\, CWE \\ \Pi_3 = W^{a3}\, R^{b3}\, TSS^{c3}\, EC \end{cases} \quad (4)$$

where $a1$, $a2$, $a3$, $b1$, $b2$, $b3$, $c1$, $c2$, and $c3$ are the powers of each variable making the Π terms dimensionless and can be solved by equating the units as follows:

$$\begin{cases} (LMT\theta)^0 = \left(LT^{-1}\right)^{a1}\left(MT^{-2}\right)^{b1}\left(ML^{-3}\right)^{c1} L \\ (LMT\theta)^0 = \left(LT^{-1}\right)^{a2}\left(MT^{-2}\right)^{b2}\left(ML^{-3}\right)^{c2} L \\ (LMT\theta)^0 = \left(LT^{-1}\right)^{a3}\left(MT^{-2}\right)^{b3}\left(ML^{-3}\right)^{c3} T^{-1} \end{cases} \quad (5)$$

By solving Eq. (5) for the powers, the Π terms are resulted as follows:

$$\begin{cases} \Pi_1 = W^2\, R^{-1}\, TSS\, WWE \\ \Pi_2 = W^2\, R^{-1}\, TSS\, CWE \\ \Pi_3 = W^{-3}\, R\, TSS^{-1}\, EC \end{cases} \quad (6)$$

Considering the general form of Π terms function, $\Pi_1 = f\,(\Pi_2, \Pi_3, \Pi_4 = T_w/T_a)$, Eq. (6) results in the general formulation for the wastewater evaporation as follows:

$$WWE = \frac{R}{W^2\, TSS} f\left(\frac{W^2\, TSS\, CWE}{R}, \frac{R\, EC}{W^3\, TSS}, \frac{T_w}{T_a}\right) \quad (7)$$

A multiplicative form of the function *f* may be applied, leading Eq. (7) to our final mathematical model for the wastewater evaporation:

$$WWE = \frac{CR}{W^2\ TSS}\left(\frac{W^2\ TSS\ CWE}{R}\right)^{\alpha}\left(\frac{R\ EC}{W^3\ TSS}\right)^{\beta}\left(\frac{T_w}{T_a}\right)^{\gamma} \tag{8}$$

where C, α, β and γ (all dimensionless) are constants to fit Eq. (8) to the true physical relationship holding in reality and can be determined using a regression analysis on the experimental data.

Data of all three lagoons were considered together for the dimensional analysis and then randomized to calculate the coefficients C, α, β and γ. Daily measurements from three lagoons were taken into account as sample and therefore total samples were 366 based on 4 months (April to July) and three lagoons data in which 70 and 30 % of the data were respectively considered for the parameter estimation and validation phases. Three different performance criteria consisting of coefficient of determination (R^2), root mean square error (*RMSE*) and mean absolute relative error (*MARE*) were used to evaluate the effectiveness and also the accuracy of the proposed method.

$$MARE = \frac{1}{N}\sum_{i=1}^{N}\frac{Abs(WWE_m - WWE_e)}{Max(WWE_m,\ WWE_e)} \times 100 \tag{9}$$

where WWE_m *and* WWE_e are measured and estimated wastewater evaporation, and N is number of the samples.

3 Results and Discussion

3.1 Wastewater Data Analysis

As stated earlier, wastewater variables consisting of T_w (°C), *EC* (μS/cm) and *TSS* (mg/l) were measured daily over 4 months from April to July 2014. Figure 3 shows the variation of wastewater average daily temperature for different lagoons along with average daily air

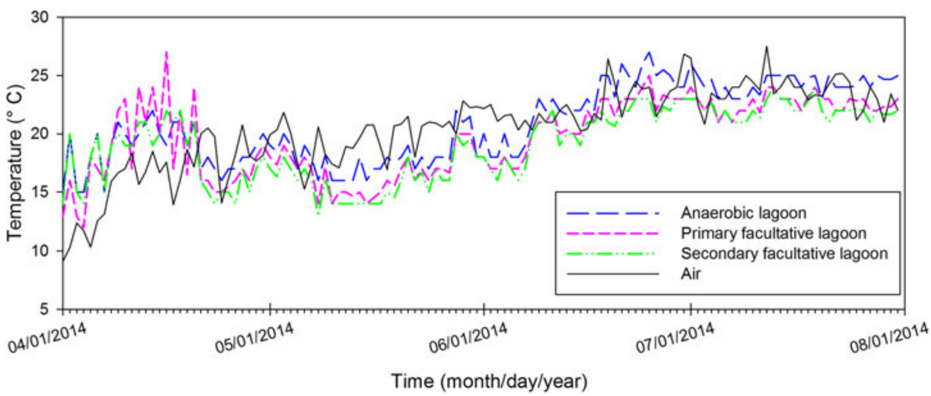

Fig. 3 Variation of wastewater average daily temperature for different lagoons along with average daily air temperature

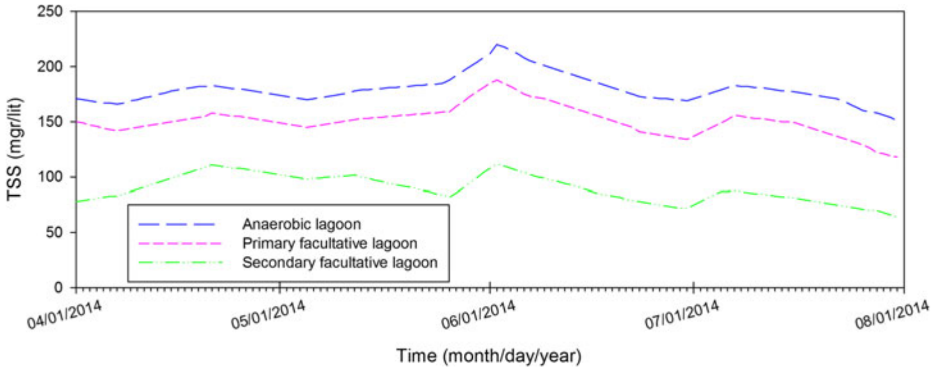

Fig. 4 Variation of *TSS* for different lagoons

temperature. The anaerobic lagoon has the highest temperature in comparison with the other two. Moreover, the difference between air and wastewater temperature generally increases from anaerobic lagoon to secondary facultative lagoon. In other words, wastewater gets cooler when becomes clearer from settling and aerobic activities in the secondary facultative lagoon. This observation is fully understandable, because the anaerobic lagoon has a significantly higher *TSS* than that of the secondary facultative lagoon (see Fig. 4) leading to higher absorption of the solar radiation and hence the temperature rise in this lagoon. Figure 5 shows the variation of wastewater daily *EC* for different lagoons. The anaerobic lagoon has the highest *EC* in comparison with two other lagoons indicating that treatment operation significantly reduces the *EC* which is an indirect measure of the total dissolved solids.

3.2 Pan Coefficient and Wastewater Evaporation

As mentioned above, the "conversion pan" method, Eqs. (2) and (3), was used for the estimation of pan coefficients based on *T* of the pan's wastewater, lagoon's wastewater and air. Figure 6 exhibits the variation of wastewater temperature of lagoons and their corresponding pans and also air temperature. It is observed that there is no significant discrepancy between the temperatures of different pan wastewater. However, the difference between temperature of lagoon and its corresponding pan is significant and the temperature of all pans are higher than that of the lagoons. As mentioned earlier, this observation reflects the fact that the wastewater in lagoons

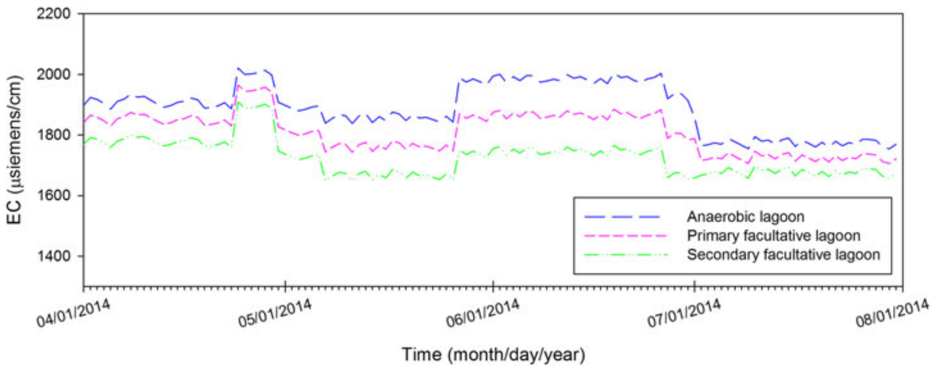

Fig. 5 Variation of *EC* for different lagoons

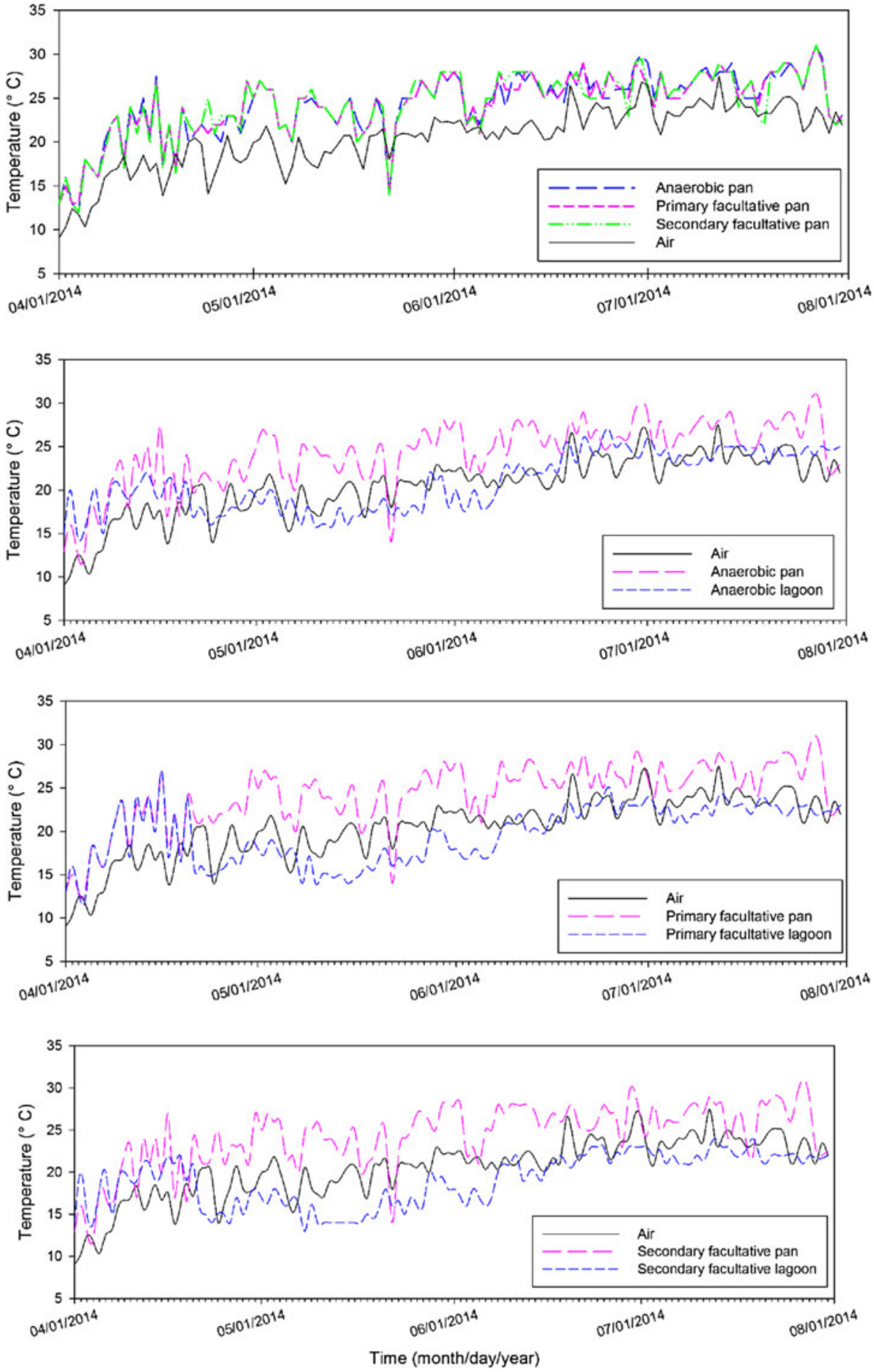

Fig. 6 Variation of wastewater temperature of lagoons and their corresponding pans along with air temperature

Table 1 Calculated pan coefficients for the three pans along with monthly average temperature (°C)

Month	Anaerobic pan	Primary facultative pan	Secondary facultative pan
April	0.75 (20.5[a])	0.59 (20.3)	0.62 (20.2)
May	0.78 (23.9)	0.73 (23.8)	0.58 (23.7)
June	0.73 (26.3)	0.67 (26.1)	0.54 (26.1)
July	0.79 (26.8)	0.68 (26.7)	0.66 (26.5)
Average	0.76	0.67	0.60

[a] Numbers in parentheses are monthly average temperature in ° C

have large thermal inertia and its temperature varies slowly, whereas the pan wastewater temperature various instantaneously with variation of the environmental conditions.

Table 1 shows monthly calculated pan coefficients for the three evaporation pans with different wastewater. It is observed form Table 1 that the pan coefficient increases as monthly average temperature of the pan's wastewater increases. The pan coefficient ranges from 0.60 for the pan filled with secondary facultative lagoon's wastewater up to 0.76 for the pan filled with anaerobic lagoon's wastewater. Also, these coefficients vary monthly such that they generally increase from April to July as a result of changing weather conditions. In fact, pan coefficient variations are attributed to the effects of wastewater type that controls the gain and loss of solar radiation to different evaporation pans.

The calculated pan coefficients were used along with Eq. (1) to estimate the evaporation rate for each wastewater lagoon (Fig. 7). Daily evaporation rates generally increase from April to July for all three lagoons. In addition, dark brown colored anaerobic wastewater lagoon exhibits the highest evaporation rate. This result arises from the fact that wastewater often includes a substantial portion of solid materials that are not biodegradable. A part of such materials are very light tending to rise and float on the surface of the suspension and form a so-called "scum layer" (Schofield and Rees 1988). This phenomenon is evident in the anaerobic lagoon with the highest *TSS* in which a reddish brown scum layer is formed (see Fig. 8) and leads to more radiation absorption in this lagoon.

The evaporation rate of clear water was estimated considering average pan coefficient of 0.7 (Kohler 1954; Kohler et al. 1955; Lapworth 1965; Hounam 1973; Winter 1981) and

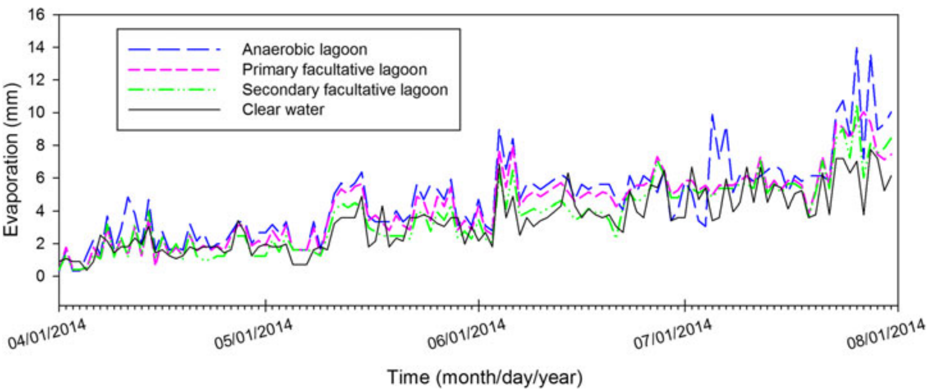

Fig. 7 Estimated evaporation from anaerobic, primary facultative and secondary facultative wastewater lagoons along with evaporation form clear water

Fig. 8 Reddish brown scum layer in the anaerobic lagoon

compared with the wastewater evaporation rate. The results show that the clear water evaporation rate is lesser than evaporation rate of all three wastewater lagoons (Table 2). Average evaporation rates for the wastewater of the three lagoons are 40.5, 24, and 8.5 % higher than clear water evaporation rates for the study period.

3.3 Dimensional Analysis Results

Based on the regression analysis, the constants of Eq. (8) were obtained as $C=2.608$, $\alpha=0.895$, $\beta=-0.076$, and $\gamma=0.256$ and the final mathematical model as follows:

$$WWE = \frac{2.608}{K} (K.CWE)^{0.895} \left(K.\frac{R^2 . EC}{W^5 .TSS^2} \right)^{-0.076} \left(\frac{T_w}{T_a} \right)^{0.256} \qquad (10)$$

where K is defined as $K= W^2.TSS/R$, WWE and CWE are respectively cumulative daily wastewater and clear water evaporation (mm), W is wind speed (m/s), TSS is total suspended solids (mg/l), R is cumulative daily solar radiation (MJ/m2) and T_w and T_a are respectively wastewater and air temperature (° C).

Table 3 shows performance statistics of Eq. (10) for the calibration phase in which R^2, $RMSE$ and $MARE$ are 73.2 %, 1.23 mm, and 20.6 %, respectively. The derived equation was afterward validated using independent dataset. The comparison between measured and estimated wastewater evaporation is shown in Fig. 9 which indicates that the

Table 2 Monthly evaporation rates of three wastewater lagoons and clear water

Month	Anaerobic pan	Primary facultative pan	Secondary facultative pan	Clear water
April	67.93 (42 %)	52.98 (11 %)	49.84 (4 %)	47.56
May	119.58 (47 %)	108.02 (32 %)	86.58 (6 %)	81.31
June	162.64 (36 %)	155.95 (31 %)	129.30 (8 %)	118.93
July	226.20 (37 %)	202.00 (22 %)	192.27 (16 %)	164.64

[a] Numbers in parentheses are percentage of wastewater to clear water evaporation rate

Table 3 Performance statistics of the proposed method

Phase	R^2 (%)	*RMSE* (mm)	*MARE* (%)
Calibration	73.2	1.23	20.6
Validation	72.1	1.09	22.0

dynamic fluctuations of the measured and estimated wastewater evaporation match very well verifying the efficiency and accuracy of the proposed model. According to the performance indicators (R^2, *RMSE* and *MARE*) the derived equation fairly predicts the wastewater evaporation, as demonstrated by Table 3. The *RMSE* statistic, which is a measure of the global goodness of fit between the estimated and measured wastewater evaporation is 1.09 mm that is considered quite satisfactory. The *MARE* statistic, which is used to quantify the prediction accuracy of the proposed method, is 22.0 %.

The power α in Eq. (10) is substantially higher than β and γ, apparently indicating that the dimensionless variable *K.CWE* has the most significant influence on the wastewater evaporation. Therefore, we also evaluated Eq. (10) by assigning $\alpha = 1$ and $\beta = \gamma = 0$, and recalculating the constant *C*. As a result, Eq. (10) was reduced to a simple linear relationship:

$$WWE = 1.292 \times CWE \quad (11)$$

This simple relationship comes as a substantial finding of this study after evaluating the effect of all the influencing variables through the dimensional analysis, verifying that a constant coefficient can be used to estimate wastewater evaporation from clear water evaporation at the cost of losing accuracy only by 4.6 % (validation $RMSE = 1.14$ mm for Eq. (11) compared to 1.09 mm for Eq. (10)).

4 Conclusions

The problem of estimating wastewater evaporation either in municipal wastewater treatment plants or in animal waste ponds and lagoons is that there is no specific model to relate wastewater evaporation to clear water evaporation and some wastewater

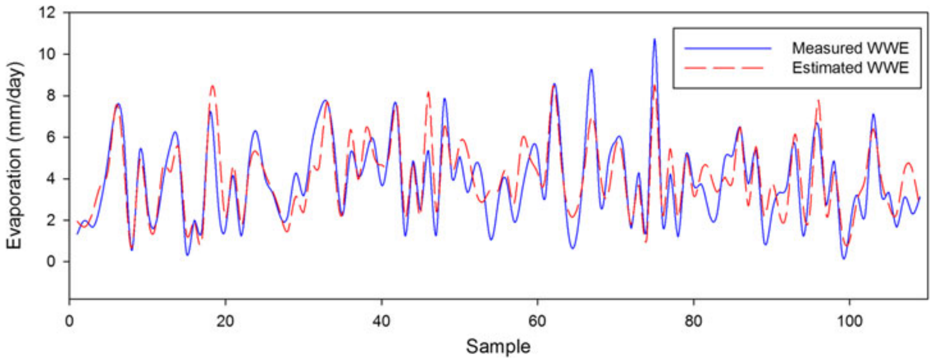

Fig. 9 Measured and estimated wastewater evaporation using derived equation for the validation phase

properties and climatic variables. Several studies applied a percentage of clear water-filled class A pan evaporation to estimate evaporation form wastewater ponds or lagoons. Robinson (1973) used 70 % of the clear water-filled class A pan evaporation rate to estimate evaporation from a beef cattle holding pond in California. Davis et al. (1973) utilized 100 % of the clear water to estimate evaporation from a newly constructed dairy waste pond in California. Cumba and Hamilton (1998) used 70 % of the evaporation rate estimated using the Modified Penman Combination Method and they stated that evaporation was the most sensitive parameter in their model. On the contrary, Parker et al. (1999) found that evaporation rate for fresh effluent was 8.3 to 10.7 % higher than clear water evaporation rate. Hence, a question arises as to the accuracy of estimating wastewater evaporation using clear water evaporation. To cope with this issue, Eq. (10) based on dimensional analysis was developed here for estimating wastewater evaporation and was validated using experiments conducted in the Neishaboor municipal wastewater treatment plant, Iran. The derived equation advances the estimation by involving several other variables besides clear water evaporation. This approach also verifies that wastewater evaporation relative to clear water evaporation fairly remains a constant over time. The relationship can be approximately expressed by Eq. (11) which can significantly reduce time and cost needed for the field measurements using class A pan evaporation measurements.

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