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Brine Evaporation Modeling in WAIV System Using Penman, Priestley-Taylor, and Harbeck Models

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Highlights:

- Parameter values calculated with regression gave better results than parameter values from the literature without regression.
- The Penman model performed better than the Priestley-Taylor and Harbeck models.
- The Penman model could predict the evaporation rate closer to the actual water evaporation rate in the Kupang area.

Abstract. Indonesia is a maritime country with a vast ocean area. Indonesia has high potential to produce salt because it has a lot of saltwater resources. When sea salt is harvested, seawater evaporates from a concentration of 3.5°Be to 29°Be. Evaporation can be affected by several factors, such as air temperature, wind speed, water vapor pressure, humidity, radiation, geographical location, time interval, and season. Many modifications have been made to increase the evaporation rate in salt production. One of them is the WAIV (Wind-Aided Intensified eVaporation) method. WAIV evaporation systems utilize sunlight and wind to accelerate the evaporation rate. The modeling in this study was adjusted to the environmental conditions in the case study for which it was necessary to determine new parameter values for the existing models. The Penman, Priestley-Taylor, and Harbeck models were used. The Harbeck model has been studied in previous studies, which were used as a reference in the present study. This study first determined and then validated the parameter values obtained. A simulation of the evaporation rate was conducted in a different place, namely Kupang, East Nusa Tenggara, Indonesia using Meteorology, Climatology, and Geophysical Agency (Indonesian: *Badan Meteorologi, Klimatologi, dan Geofisika* / BMKG) data.

Keywords: *evaporation; Harbeck; parameters; Penman; Priestley-Taylor; salt; seawater; WAIV.*

1 Introduction

Salt is a primary need in human life. Salt is widely used not only in households but also in industry. The largest constituent of salt is sodium chloride. Apart from sodium chloride, there are also impurities such as $CaSO_4$, $MgSO_4$, $MgCl_2$, and

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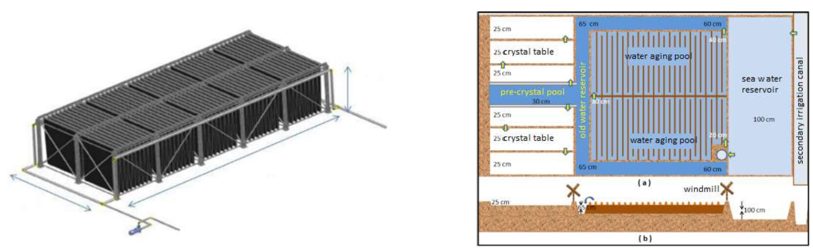
others. Salt can be obtained in three ways, namely by evaporation of seawater with the help of sunlight, by mining rock salt, or by harvesting from underground water (brine) [1]. Salt obtained from the evaporation of seawater is widely used in Indonesia because of its abundant saltwater resources. In general, Indonesia uses ponds to harvest salt. The yield of these ponds varies depending on the location and also the content of the seawater used. Evaporation from salt ponds is influenced by many factors, such as weather and location. Evaporation is the main step in the manufacture of salt in order to concentrate seawater from 3.5°Be to 29°Be (when bittern water is removed). Several internal and external factors influence evaporation. Direct factors are air temperature, wind speed, water vapor pressure, air humidity, and radiation from the sun. In addition, there are also indirect factors, namely, geographic location, time interval, and season. According to Santoso, *et al.* [2], heat and mass transfer in evaporation are affected by capacity, air velocity, and temperature. In the manufacture of salt, the rate of evaporation plays a key role in the aging of existing seawater. A greater evaporation rate allows the aging of seawater to be faster.

One of the technologies being developed to accelerate the rate of evaporation is Wind Aided Intensified eVaporation (WAIV). From the name it can be seen that this system utilizes wind in its evaporation process. The main component in WAIV is a sheet of cloth, usually made from black cotton and installed vertically. The way it works is that first water containing salt will be pumped into the system. The water goes through a perforated pipe that hangs over the cloth. The water is dispensed from the pipe to wet the entire surface of the cloth. The dripping water is then accommodated and recirculated. By using the WAIV method, the evaporation area can be increased tremendously.



(a) (b)

Figure 1 (a) WAIV setup, (b) salt pond.

Various models can be used with different approaches. According to Xu & Singh [3], models can be divided into six groups based on the approach, namely: (1) empirical, (2) formulation of the amount of water, (3) formulation of the amount of energy, (4) mass transfer, (5) combination, and (6) radiation. Although many models can be used to determine the evaporation rate, most evaporation models were made to calculate the evaporation rate in fresh water, whereas few models can determine the evaporation rate of seawater. In addition, each model can only be used in the same system for which the model was created or in places with similar conditions. Thus, it was necessary to adjust certain parameters used in the models to match the environmental conditions in the case study.

In this study, using data from Murray, *et al.* [4], we developed and evaluated the performance of several evaporation models of a WAIV system, based on Penman, Priestley-Taylor, and Harbeck. The models developed were tested to estimate the evaporation rate of the WAIV system when it was used in Kupang, one of the salt producing areas in Indonesia.

2 Methodology

WAIV is a technique used to accelerate the evaporation rate. By using this method, the evaporation rate can be as much as 24 times greater than a typical evaporation pond method. In this study, data were taken from application of the WAIV method in Queensland, Australia in 2013 by Murray. The data were taken on February 21st, 2013, and November 20th, 2013. The WAIV system used had a length, width, and height of 20, 7.6, and 4 m, respectively. The data obtained were cumulative volume of evaporated water, air temperature, brine concentration, relative humidity, and wind speed [4]. Harbeck [5-9], Penman, and Priestley-Taylor [10] models were used in this study. The Penman model used was a Penman model modified by the Food and Agriculture Organization in order to use heat capacity, where originally only net radiation was used [10]. The Penman approach combines the effects of radiation and aerodynamic forces that control evaporation and has proven to be quite good in predicting evaporation in various environments [11]. The Penman equation is stated as follows:

$$\lambda E = \frac{\Delta}{\Delta+\gamma} R_n + \frac{\gamma}{\Delta+\gamma} f(u)(e_s - e_a) \tag{1}$$

where e_s is the saturated vapor pressure of water (kPa); for brine, the value of e_s is affected by the value of water activity a_w; e_a is the saturated vapor pressure of air (kPa), which can be calculated from the saturated vapor pressure of water at T_a (air temperature) multiplied by RH (relative humidity); $f(u)$ is a function of wind speed (m/s^2); R_n is the net radiation (MJ/m^2); γ is the psychometric constant (kPa/°C); λ is the latent heat flux (MJ/m^2); Δ is the slope of the saturated vapor pressure against temperature (kPa). The Priestley-Taylor model, as stated in Eq. (2), has been validated by many researchers.

$$\lambda E = -\alpha \left[\frac{s}{s+\gamma}\right] R_n \tag{2}$$

where α is the Priestley-Taylor constant, s is the change of water storage (MJ/m^2).

Another equation that was used in the evaporation modeling was Harbeck's equation, as stated in Eq. (3):

$$E = N.u.(e_s - e_a) \tag{3}$$

The simulation was conducted with the assumption that evaporation depends on the equipment used. The initial guesses for the parameters used in the Penman and Priestley-Taylor models were a_s = 0.25 and b_s = 0.50 respectively, which were needed to calculate parameter R_n (net radiation), while k_h = 3.367 x 10^{-9} and a_h = -0.05 was stated in the coefficient of *N* in the Harbeck model. Parameter checking was conducted with the curve fitting method using the research data obtained. By comparing the results of the evaporation rate from the data to the evaporation rate from modeling, the *SSE* (the sum of squares for error) was calculated. The *SSE* equation used in this study is stated in Eq. (4):

$$SSE = \sum_{i=1}^{n}(X_i - \bar{X})^2 \tag{4}$$

where X_i is the observation value and $\bar{X}$ is the value from the Harbeck, the Penman, or the Priestley-Taylor equation.

To determine the existing parameter values, the data set from Murray (2013) was used, which was taken on February 21st, 2013, in Queensland, Australia. Validation was done by comparing the results of the evaporation rate calculated using the parameter values previously obtained with the other data set from Murray, which was taken on November 20th, 2013.

The simulation was conducted by calculating the evaporation rate using data from Meteorology, Climatology, and Geophysical Agency (Indonesian: *Badan Meteorologi, Klimatologi, dan Geofisika* / BMKG). The area used for the data capture was Kupang Regency in East Nusa Tenggara. Using the above-mentioned model parameter values, the rate of evaporation in the Kupang area with the WAIV method was then determined. This area was chosen because Kupang is a potential location for the salt industry. This simulation used predetermined parameter values because most model parameter values in the literature are for evaporation of freshwater in lakes/ponds. Other than that, the parameter values could change according to the existing environmental conditions.

3 Result and Discussion

3.1 Parameter Determination

In the models, several different parameters are used. The parameters used in the Penman and Priestley-Taylor models are a_s and b_s, which are regression parameters to determine the net radiation, while in the Harbeck model, the parameters used are k_h and a_h, which are area parameters. The initial parameter values used were k_h = 3.367 x 10^{-9}, a_h = -0.05, a_s = 0.25, and b_s = 0.5. The parameter values needed to be adjusted to get an evaporation rate that is close to the actual evaporation rate.

From the parameter determination stage, the cumulative evaporation graphs from the Penman, Priestley-Taylor, and Harbeck models before and after the regression was performed can be seen in Figures 2 to 4. The black line is the cumulative evaporation when the parameter values have been regressed, while the red line is the cumulative evaporation without regression of the parameter values.

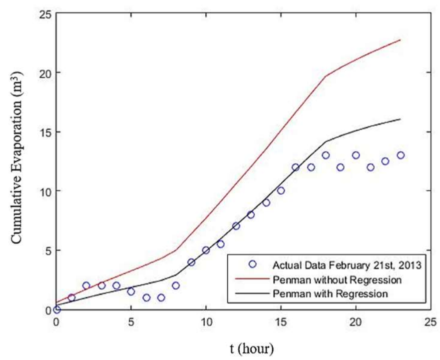


Figure 2 Comparison between the actual cumulative evaporation measured on February 21st, 2013 (blue dot) and that from the Penman model calculated using the parameter values given by Eq. (1) without regression (red line) and the parameter values given by Eq. (1) with regression (black line).

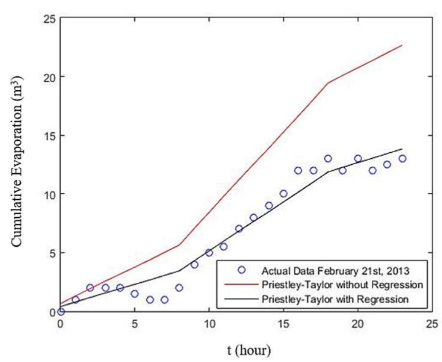


Figure 3 Comparison between the actual cumulative evaporation measured on February 21st, 2013 (blue dot) and that of the Priestley-Taylor model calculated using the parameter values given by Eq. (2) without regression (red line) and the parameter values given by Eq. (2) with regression (black line).

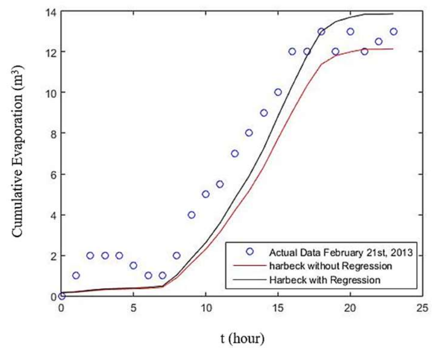


Figure 4 Comparison between the actual cumulative evaporation measured on February 21st, 2013 (blue dot) and that from the Harbeck model calculated using the parameter values given by Eq. (3) without regression (red line) and the parameter values given by Eq. (3) with regression (black line).

From Figures 2 to 4 it can be seen that with regression of the existing parameters (a_s, b_s, k_h and a_h) the cumulative evaporation results were closer to the actual data. In the Penman and Priestley-Taylor models, the parameters used were a_s and b_s, where these two parameters were regression constants that determine the sunlight absorption factor [12]. The parameter values for a_s and b_s used as initial guesses were values that were obtained from experiments in an open space, while the data used were the data resulted from WAIV, thus allowing for a more limited absorption of solar heat compared to open areas such as ponds.

Table 1 Parameter determination for Penman, Priestley-Taylor, and Harbeck models.

Model	Parameter	Parameter Value		R^2		*SSE*	
		Before	After	Before	After	Before	After
Penman	a_s	0.25	0.0953	0.1892	0.9045	656.94	52.73
	b_s	0.5	0.4007				
Priestley-Taylor	a_s	0.25	0.0953	0.2211	0.9688	674.44	17.24
	b_s	0.5	0.4007				
Harbeck	k_h	3.367e-09	3.7124e-09	0.8634	0.9074	552.41	51.16
	a_h	-0.05	-0.046				

From Table 1 it can be seen that the Priestley-Taylor equation could describe the evaporation rate more closely than Penman and Harbeck. This is because the Penman and Harbeck models use air velocity to determine the evaporation rate. The creation of these three models was conducted for open environments such as ponds and lakes, while the data used were WAIV evaporation data, which allow the reduction of wind speed.

3.2 Parameter Validation

After determining the parameter values, validation was conducted using the parameter values that were obtained. Validation was done to see if the parameters matched the new data. At this stage, the Murray research data from November 20th, 2013, in Queensland, Australia, were used. In Figures 5 to 7, the black line is the cumulative evaporation calculated using the Penman, Priestley-Taylor, and Harbeck models. In these graphs it can be seen that by using the new parameter values, the models could predict the cumulative evaporation quite accurately. The *SSE* of the validation results can be seen in Table 2.

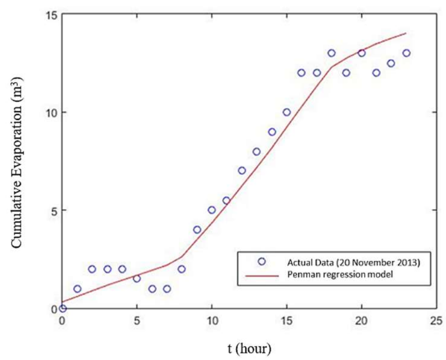


Figure 5 Comparison between the actual cumulative evaporation in Murray's research data from November 20th, 2013, in Queensland, Australia (blue dot) and that from the Penman model calculated using the parameter values given by Eq. (1) with regression (red line).

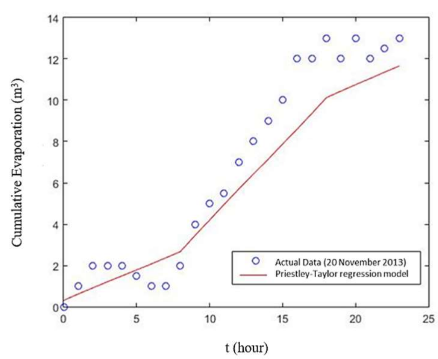


Figure 6 Comparison between the actual cumulative evaporation in Murray's research data from November 20th, 2013, in Queensland, Australia (blue dot) and that from the Priestley-Taylor model calculated using the parameter values given by Eq. (2) with regression (red line).

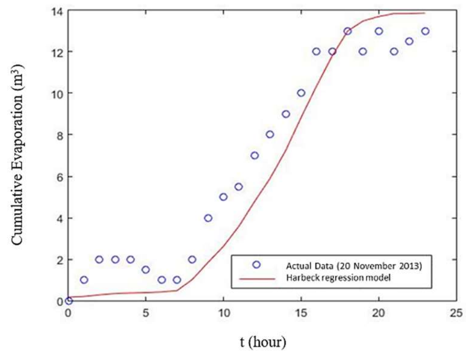


Figure 7 Comparison between the actual cumulative evaporation in Murray's research data from November 20th, 2013, in Queensland, Australia (blue dot) and that from the Harbeck model calculated using the parameter values given by Eq. (3) with regression (red line).

Table 2 Validation of result comparison between Penman, Priestley-Taylor, and Harbeck models.

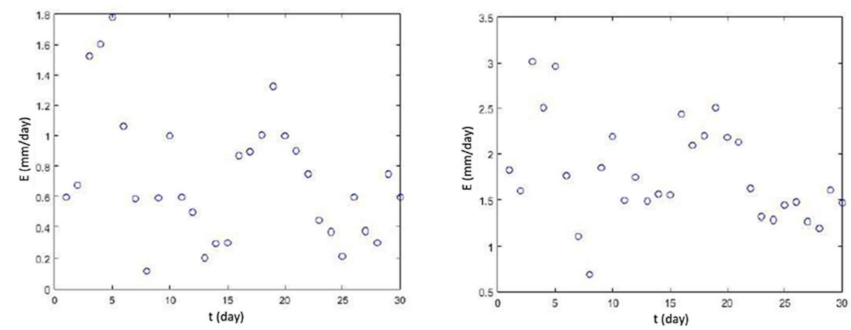
Model	Parameter	Parameter Value	R^2	*SSE*
Penman	a_s	0.0953	0.9676	17.8995
	bs	0.4007		
Priestley-Taylor	a_s	0.0953	0.8960	57.4474
	bs	0.4007		
Harbeck	k_h	3.7124e-09	0.9640	39.4123
	a_h	-0.046		

From Table 2, the Penman model with regression performed better than the Priestley-Taylor and Harbeck models, which can be seen from the *SSE* and R^2 values in each model. Thus, it can be concluded that it is more suitable to use the Penman model compared to the Priestley-Taylor and Harbeck models.

3.3 Case Study

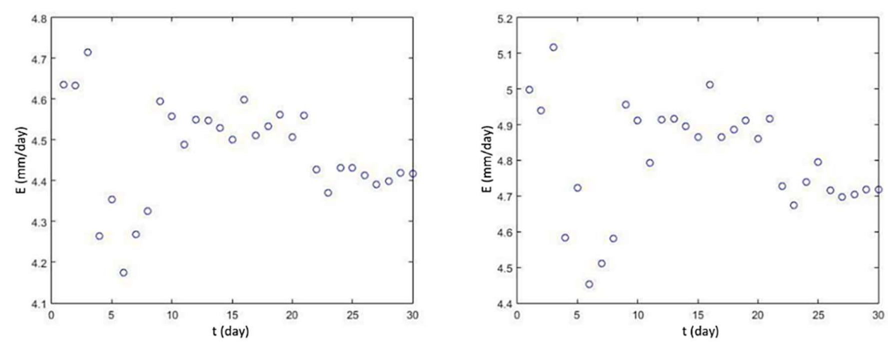
Calculation of the evaporation rate in Kupang, East Nusa Tenggara was conducted using data obtained from BMKG, such as temperature, wind speed, relative humidity, in June 2020. In this case study, the assumption made was that the WAIV system had the same evaporation area as Murray's. Also, the cloth used was the same as Murray's. The calculation of the evaporation rate was conducted using the Harbeck, Penman, and Priestley-Taylor models with previously regressed parameter values. In addition, the brine concentration was also varied, namely, water activity (a_w), where a_w = 0.954 according to Murray's data, while $a_w = 1$ is a_w for freshwater. Using the above values and the existing assumptions, the following results were obtained.

Figure 8 is the evaporation rate using the Harbeck model. By using this model, the average evaporation rate at $a_w = 0.954$ was 0.7269 mm/day while at $a_w = 1$ it was 1.7866 mm/day. Figure 9 is the evaporation rate of the Kupang area using the Penman model. By using this model, the average evaporation rate at $a_w = 0.954$ was 4.4706 mm/day while at $a_w = 1$ it was 4.8034 mm/day. Figure 10 shows the evaporation rate of the Kupang area using Priestley-Taylor modeling. By using this model, the average evaporation rate at $a_w = 0.954$ was 5.3708 mm/day while at $a_w = 1$ it was 5.4408 mm/day.



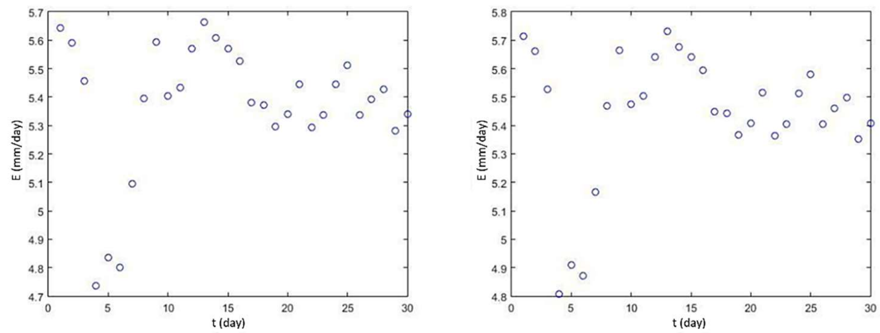
(a) (b)

Figure 8 Evaporation rate (blue dot) in Kupang using the Harbeck method (a) with $a_w = 0.954$ (b) with $a_w = 1$.



(a) (b)

Figure 9 Evaporation rate (blue dot) in Kupang using the Penman method (a) with $a_w = 0.954$ (b) with $a_w = 1$.



(a) (b)

Figure 10 Evaporation rate (blue dot) in Kupang using the Priestley-Taylor method (a) with $a_w = 0.954$ (b) with $a_w = 1$.

We can see the difference in the evaporation rate results from the same models, namely Harbeck, Penman, and Priestley-Taylor, where the value of the evaporation rate at $a_w = 1$ had a higher rate than $a_w = 0.954$. This shows that a value of water activity close to 1 (freshwater) will be more volatile so that the evaporation rate is greater than the value of water activity that is less than 1 (brine solution).

Table 3 Average evaporation rate calculated using Harbeck, Penman, and Priestley-Taylor models ($a_w = 0.954$)

Model	E average (mm/day)
Harbeck	0.7269
Penman	4.4706
Priestley-Taylor	5.3708

Table 4 Average evaporation rate calculated using Harbeck, Penman, and Priestley-Taylor models ($a_w = 1$).

Model	E average (mm/day)
Harbeck	1.7866
Penman	4.8034
Priestley-Taylor	5.4408

From the above tables it can be seen that the evaporation rate calculated using the Priestley-Taylor model was the largest, while the Harbeck model gave the smallest evaporation rate. It should be noted that since actual evaporation data for the WAIV system in Kupang area are not available yet, the average evaporation rate of freshwater for open water, such as lakes, ponds, or irrigation systems, in the Kupang area, was used as an indicative value to be expected for the evaporation rate of the WAIV system. When compared to the average evaporation rate for freshwater in the Kupang area in June at about 4.7 to 5.0 mm/day, the average evaporation rate of the Penman model came closest. The Harbeck model gave the largest deviation from the average evaporation rate because the Harbeck model must be used in a similar environment as the one that was used for the modeling [13].

4 Conclusion

Using parameter values calculated from regression, the *SSE* of the Penman, Priestley-Taylor, and Harbeck models became significantly smaller compared to the *SSE* of the respective models using parameter values found in the literature without regression. The Penman model could predict the evaporation rate better at the validation stage, thus it can be considered to be more suitable than the other models. In the case study, the Penman model could also predict the evaporation rate closer to the actual water evaporation rate in the Kupang area compared to the other models.

Acknowledgement

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References

[1] Sedivy, V.M., *The Environmental Balance of Salt Production Speaks in Favor of Solar Saltworks*, Global Nest Journal, **11(**1), pp. 41-48, 2009.

[2] Santoso, D.I, Antoko, B., Prabowo, P. & Ichsani, D., *Study of the Evaporation Process in the Spray Zone of a Mechanical Draft Wet Cooling Tower*, Journal of Engineering and Technological Sciences, **53**, pp. 247-257, 2021.

[3] Xu, C.Y. & Singh, V.P., *Evaluation and Generalization of Radiation-Based Methods for Calculating Evaporation*, Hydrological Processes, **14**(2), pp. 339-349, 2000.

[4] Murray, B., McMinn, D. & Gilron, J., *WAIV Technology: An Alternative Solution for Brine Management: Results of a Full-Scale Demonstration Trial Conducted at a Location near Roma in Queensland*, Journal of the Australian Water Association, **42**(5), pp. 77-83, 2015.

[5] Henrietta, Santoso, H. & Witono, J.R., *Modelling of Saltwater Evaporation using WAIV*, IOP Conf. Ser.: Mater. Sci. Eng., 742 012013, 2020.

[6] Pallavi, K. & Rajeev, S., *Evaluation of Evaporation Models Based on Climate Factors*, International Journal of Civil Engineering and Technology, **7**(4), pp. 111-120, 2016.
[7] Harbeck, G.E. Jr., *A Practical Field Technique for Measuring Reservoir Evaporation Utilizing Mass-Transfer Theory*, United States Government Printing Office: Washington DC, 1962.
[8] Gilron, J., Folkman, Y., Savliev, R., Waisman, M. & Kedem O., *WAIV – Wind Aided Intensified Evaporation for Reduction of Desalination Brine Volume. Desalination*, **158**(1-3), pp. 205-214, 2003.
[9] Katzir, L., Volkmann, Y., Daltrophe, N., Korngold, E., Mesalem, R., Oren, Y. & Gilron, J., *WAIV – Wind Aided Intensified Evaporation for Brine Volume Reduction and Generating Mineral Byproducts*, Desalination and Water Treatment, **13**(1-3), pp. 63-73, 2010.
[10] Hussein, M.M.A., *Evaluation of Alexandria Eastern Harbor Evaporation Estimate Methods*, Arabian Journal of Geosciences, **11**(24), 768, 2018.
[11] Finch, J.W., *A Comparison Between Measured and Modelled Open Water Evaporation from a Reservoir in South-East England*, Hydrological Processes, **15**(14), pp. 2771-2778, 2001.
[12] Akridge, D.G., *Methods for Calculating Brine Evaporation Rates during Salt Production*, Journal of Archaeological Science, **35**(6), pp. 1453-1462, 2008.
[13] Singh, V.P. & Xu, C.Y. *Evaluation and Generalization of 13 Mass-Transfer Equations for Determining Free Water Evaporation*, Hydrological Processes, **11**(3), pp. 311-323, 1997.