Estimation of Solar Radiation for Evaporation Evaluation in Mae Suai Reservoir

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ARTICLE INFO

Article history:
Received: 09 November 2021
Revised: 02 September 2022
Accepted: 09 October 2022

Keywords:
Solar radiation
Angstrom coefficient
Evaporation
Penman
Mae Suai
Chiang Rai

ABSTRACT

Evaporation due to solar radiation is an important factor leading to water loss from the reservoir. In this study the solar radiation was estimated using the Angstrom–Prescott model using three methods: FAO ($S_{t(FAO)}$), latitude ($S_{t(Lat)}$), and spatial data from Mae Suai, Chiangrai ($S_{t(CR)}$). The Angstrom coefficients (a_s and b_s) for each model were determined to estimate the total radiation with correlation coefficient (r) values greater than 0.75. The most effective method was $S_{t(CR)}$. Angstrom coefficient a_s was 0.3169 and b_s was 0.3465 while Nash-Sutcliffe efficiency (NSE) was 0.30. Subsequently, successive evaporations were calculated using the Penman model and it was found that the evaporation based on the total solar radiation by spatial data ($S_{t(CR)}$) with NSE was 0.285 and statistically indifferent from pan evaporation. In addition, the evaporations from all methods were in good agreement with the pan evaporation in the dry period, while during the wet period were slightly higher than the pan evaporation.

1. INTRODUCTION

Evaporation is a major water loss process that must be carefully handled in the design and management of water supply reservoirs, especially for small-size reservoirs. The evaporation may cause a water loss of up to 40% [1]. Accurate evaporation is difficult to measure directly. Pan evaporation is typically used to estimate evaporation within the reservoir [2]. During the past few decades, various mathematical models for evaporation estimation have been developed based on mass transfer, energy balance, or a combination of both, e.g., Penman, Priestly, and Taylor equations [3]. These models rely solely on meteorological data. The Mae Suai reservoir, the largest medium-sized reservoir in the Mae Suai basin, is the main reservoir in the area providing the community, both water supply and disaster prevention, such as floods, droughts, etc. The reservoir has complete and accurate meteorological and hydrological data from all available monitoring stations except for pan evaporation. However, solar radiation data remains a problem in terms of data quantity and quality. The lack of this data would probably mislead the water management scheme. Therefore, in this study, Angstrom's estimation of total solar radiation was used to calculate surface evaporation using the Penman method and compared with the actual measurement.

2. MATERIALS AND METHODS

2.1. Study site

Mae Suai reservoir located at the coordinates 19.67–19.98 °N and 99.38–99.58 °E in the north of Thailand, is a medium–sized multipurpose reservoir. It is the largest reservoir in the Kok river basin (Figure 1). The basin area is 434 km^2. The reservoir has a normal capacity of 73 Mm^3, the water surface area at a normal water capacity is 3.5 km^2 [4], and the average meteorological data [5, 6] is shown in Table 1.

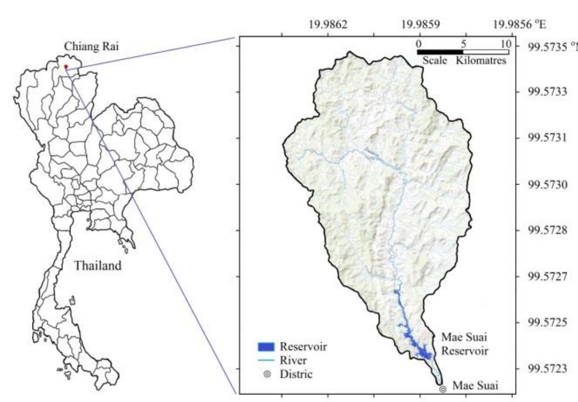

Fig. 1. Location of Mae Suai reservoir.

In Table 1, the general climate characteristics present the

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mean temperature is 24.16 °C, the relative humidity is 76.33%, and annual rainfall is 1702.20 mm of which roughly 85% took place during the wet period (May to October).

Table 1. Average metrological statistics (1981–2010)

Metrological Data	Period		Whole Year
	Dry[1]	Wet[2]	
Precipitation (mm)	214.00	1488.20	1702.20
Average Temp. (°C)	22.08	26.23	24.16
Maximum Temp. (°C)	30.43	31.23	30.83
Minimum Temp. (°C)	15.25	22.40	18.83
Relative Humidity (%)	71.50	81.17	76.33
Evaporation (mm)	695.30	613.80	1309.10

Note: 1 Dry period is November to April
2 Wet period is May to October

2.2. Evaporation model

Evaporation is the process in which water as a liquid changes into water vapor. In hydrological studies, one of the most widely used methods in estimating evaporation is the combination calculation method. The combination method was modified by Penman which is based on two concepts, namely mass transfer and energy balance. The concept of Penman is that evaporation of water is due to solar radiation heating. Then, the water vapor will cover the water surface. If these vapors are not removed from the water surface, the atmosphere is said to be saturated with water vapor. Therefore, for evaporation to proceed, the water vapor must be removed from the surface. The important factor in removing the water vapor is wind, so the Penman equation has both terms as shown in Equation (1).

$$E = \frac{\Delta R_n}{\Delta + \gamma} + \frac{\gamma\, f(u)(e_s - e_a)}{\Delta + \gamma} E_a \quad (1)$$

where, E is the evaporation rate (mm d^{-1}); Δ is a gradient of the saturated vapor pressure (kPa $°C^{-1}$); R_n is net radiation on the earth surface; γ is the psychometric constant 0.067 kPa $°C^{-1}$; f(u) is the wind function; e_s is the saturated vapor pressure (kPa $°C^{-1}$); e_a is the vapor pressure (kPa $°C^{-1}$) and E_a is drying power or aerodynamic evaporation (mm d^{-1}).

The first term in Equation (1) is related to the main energy that causes water to evaporate by solar radiation. The second term is related to the wind which is an important factor removing the water vapor from the water surface [7, 8].

2.3. Solar radiation model

Solar radiation originates from the sun in the form of short wave radiation. Upon impacting the atmosphere, some radiations are reflected and absorbed. When solar radiation incidents the Earth's surface, it is called total solar radiation. Some portions are reflected back to the atmosphere from the Earth's surface in the form of longwave radiation. Therefore, the net radiation on the Earth's surface can be expressed as Equation (2).

$$R_n = L_n + S_n \quad (2)$$

where, R_n is net radiation (MJ m^{-2} d^{-1}); L_n is net longwave radiation (MJ m^{-2} d^{-1}) and S_n is net short wave solar radiation (MJ m^{-2} d^{-1}).

The net short and longwave radiation represents the difference between their incoming and outgoing components. Generally, the equation for estimating net longwave radiation (L_n) by the Food and Agriculture Organization of the United Nations, irrigation and drainage paper 56 (FAO–56) manual originates from the Stefan–Boltzmann law and can be described as Equation (3).

$$L_n = -f\varepsilon'\sigma T^4 \quad (\mathrm{MJ\ m^{-2}\ d^{-1}}) \quad (3)$$

where, f is cloudiness factor; ε' is net emissivity; σ is Stefan-Boltzmann Constant 5.6806×10^{-14} MJ m^{-2} K^{-4} s^{-1}; T is the temperature (K) and S_n can be estimated by

$$S_n = S_t - \alpha S_t \quad (4)$$

where, α is the albedo which depends on the type of surface and S_t is the total of shortwave radiation on the earth's surface (MJ m^{-2} d^{-1}).

The total shortwave radiation on the Earth's surface is a function of solar radiation at the top of the atmosphere and the duration of the daylight [9, 10] as shown in Equation (5).

$$S_t = \left(a_s + b_s \frac{n}{N}\right) S_0 \quad (5)$$

where, S_0 is solar radiation at the top of atmosphere (MJ m^{-2} d^{-1}); a_s and b_s are the empirical coefficient of the model; n is the actual duration of the daylight (hrs.); N is the maximum possible number of daylight hours that can be calculated from the sunset hour angle (ω_s) [7] as:

$$N = 24\,\omega_s/\pi \quad (\mathrm{hrs}). \quad (6)$$

The ω_s is depends on the latitude and the solar declination angle of the sun [11]. Equation (5) is called Angstrom–Prescott model where a_s and b_s are typically called Angstrom coefficients. The original value of a_s is 0.25 and b_s is between 0.50 [12]. However, if n is zero the linear equation is not suitable for estimating relative S_t. For the values of the Angstrom coefficient in Thailand, several researchers conducted a study by relating the latitude to determine the coefficients [13]–[15] as shown in Equations (7) and (8).

$$a_s = 0.2296 + 0.00494\ \mathrm{Latitude} \quad (7)$$

$$b_s = 0.5709 - 0.01254\ \mathrm{Latitude} \quad (8)$$

From their study, it was found that the coefficients a_s and

b_s of Mae Suai Dam were 0.3169 and 0.3465, respectively, while the FAO used the values of 0.25 and 0.50, respectively. The equation for approximation solar radiation can be expressed as:

Solar radiation by latitude

$$S_{t(Lat)} = \left(0.3169 + 0.3465\frac{n}{N}\right)S_0 \quad (9)$$

and solar radiation by FAO

$$S_{t(FAO)} = \left(0.25 + 0.5\frac{n}{N}\right)S_0 \quad (10)$$

2.4. Data and research methodology

In this study, estimation of solar radiation and evaporation was based on meteorological data as follows:

1. Daily meteorology data from the Agricultural Meteorological Station, Chiang Rai Province between 1993–2020, which includes air temperature, relative humidity, day length, wind speed, air pressure, and evaporation from Class A pan.

2. Average daily total solar radiation data per month from the ground measurement station by the Department of Energy Development and Promotion, Ministry of Higher Education, Science, Research and Innovation between 1996–2020.

3. Average monthly solar radiation data at the top atmospheric on a horizontal plane from solar radiation and meteorological data services [16] between 1993–2020.

This study was divided into two stages. The first stage was the estimation of total solar radiation data by the Angstrom method using solar radiation data from measurements at terrestrial stations and satellites combined with day length from the measurement and the calculation with Equation (5). The second stage was the calculation of water surface evaporation by using the Penman method which relied on meteorological data collected and the first stage estimation of total solar radiation. In both of these stages, the correlation coefficient (*r*), coefficient of determination (R^2) root mean square error (RMSE), and Nash-Sutcliffe efficiency (NSE) were used to measure performance:

Correlation coefficient (*r*):

$$r = \frac{n\sum Obs_i Sim_i - \sum Obs_i \sum Sim_i}{\sqrt{n\sum Obs_i^2 - (\sum Obs_i)^2}\sqrt{n\sum Sim_i^2 - (\sum Sim_i)^2}} \quad (11)$$

Coefficient of determination (R^2):

$$R^2 = r^2 \quad (12)$$

Root mean square error (RMSE):

$$RMSE = \sqrt{\frac{1}{n}\Sigma(Obs_i - Sim_i)^2} \quad (13)$$

Nash-Sutcliffe efficiency (NSE).

$$NSE = 1 - \frac{\Sigma(Obs_i - Sim_i)^2}{\Sigma(Obs_i - \overline{Obs})^2} \quad (14)$$

where, n is the sample size; Obs_i is the observation value at indexed i; Sim_i is the forecast value at indexed i and $\overline{Obs}$ is the average of observation values. In addition, the variance and average of the evaporation in each model were analyzed with *F*-test and *t*-test statistics.

3. RESULTS AND DISCUSSION

3.1. Total Solar Radiation

The total solar radiation on the Earth's surface was estimated by the Angstrom-Prescott model using solar radiation on the Earth surface (S_t), the solar radiation at the top of the atmosphere (S_0), the average day length per month by measurement (n) and by calculation (N) during 1996–2015 as input data. The relationship between S_t/S_0 and n/N is illustrated as shown in Figure 2.

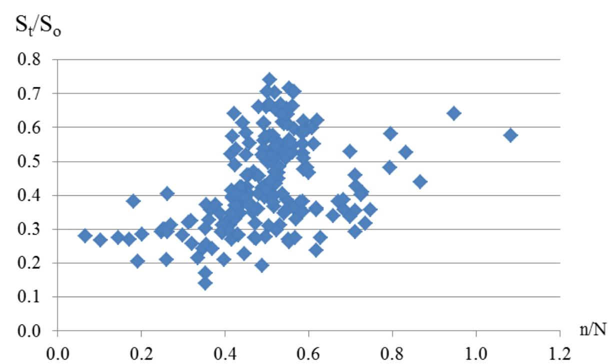

Fig. 2. The scattered plot of S_t/S_0 against n/N between 1996-2015.

Although Figure 2 shows that the plot was relatively scattered, the trend of the relationship can still be observed. This could be due to the fact that total solar radiation on the Earth was not dependent solely on the day length. There are other factors such as ambient airborne particles, water vapor in the atmosphere and cloud cover in the sky, or ozone concentration in the atmosphere [17]. To reduce the data variation, therefore, the solar radiation was calculated with the long-term monthly average. The results of the calculation can be shown in Figure 3.

Figure 3 shows the relationship between S_t/S_0 and n/N and the trend line with coefficients a_s was 0.2778 and b_s was 0.3775. This equation was called solar radiation at Chiang Rai ($S_{t(CR)}$) according to the study site in Chiang Rai and can be shown as Equation (16).

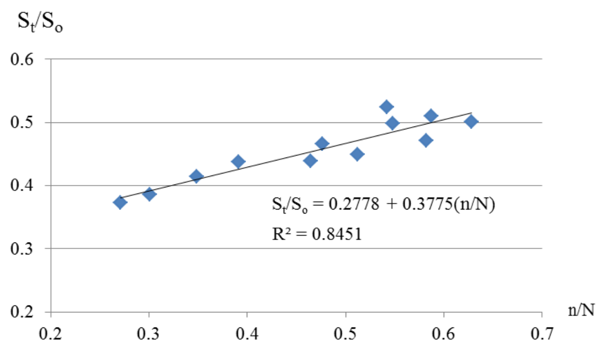

Fig. 3. The scattered plot of monthly average daily S_t/S_0 against n/N.

$$S_{t(CR)} = \left(0.2778 + 0.3775\,\frac{n}{N}\right)S_0 \qquad (16)$$

The $S_{t(CR)}$ was subsequently validated using data observed in 2016–2020 by calculating the average daily total radiation per month and compared with $S_{t(Lat)}$ and $S_{t(FAO)}$ based on measurement data. The result of the study was shown in Figure 4. It was found that the $S_{t(FAO)}$ had the weakest relationship between observation and estimation. However, the relationship from the $S_{t(CR)}$ was the strongest and closest to the observed data than other methods. When analyzing the performance of the model, it was found that $S_{t(CR)}$ was the most highly efficient, while $S_{t(FAO)}$ was the least efficient, as shown in Table 2.

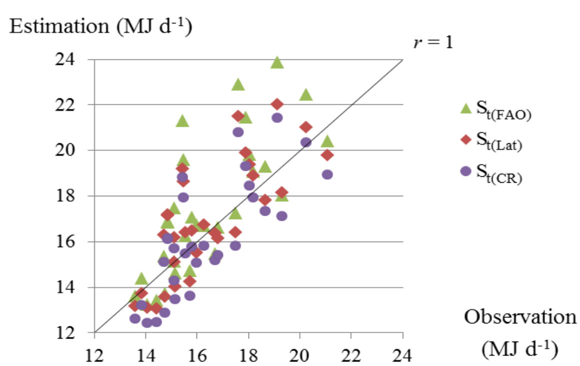

Fig. 4. Relationship of daily solar radiation by observation and estimation.

Table 2. The efficiency of solar radiation models.

Model	*r*	R^2	RMSE	NSE
$S_{t(FAO)}$	0.750	0.563	2.224	-0.334
$S_{t(Lat)}$	0.775	0.600	1.670	0.248
$S_{t(CR)}$	0.770	0.593	1.609	0.301

3.2. Evaporation

On the basis of previously determined total solar radiation and average daily meteorological data, the evaporation was calculated using the Penman equation. Three evaporation models were identified based on the computed total solar radiation models: $E_{(FAO)}$, $E_{(Lat)}$, and $E_{(CR)}$. The findings of evaporation models and actual evaporation from pan evaporation (E_p) are displayed in Table 3 and Figure 5 respectively.

Table 3. Daily evaporation by models and pan evaporation (mm d^{-1})

Month	$E_{(FAO)}$	$E_{(Lat)}$	$E_{(CR)}$	E_p
January	2.50	2.37	2.26	2.63
February	3.32	3.12	3.05	3.47
March	4.08	3.87	3.74	3.67
April	4.91	4.65	4.52	4.38
May	5.05	4.90	4.72	4.78
Jun	4.76	4.74	4.47	4.06
July	4.17	4.34	4.01	3.58
August	4.05	4.21	3.90	3.21
September	4.01	4.00	3.78	3.41
October	3.55	3.45	3.28	3.25
November	2.99	2.86	2.72	2.93
December	2.45	2.36	2.22	2.56
Average	3.82	3.74	3.56	3.49
SD	0.88	0.90	0.85	0.67

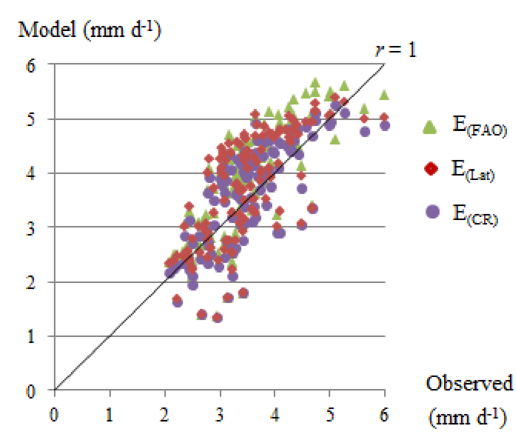

Fig. 5. The scattered plot of daily evaporation by penman models and observation (E_p).

In the overview from Table 3, the average daily evaporation from the $E_{(CR)}$ was closer to the pan evaporation (3.49), followed by the evaporation from the $E_{(Lat)}$ and $E_{(FAO)}$ in which the average of daily evaporation was 3.56, 3.74 and 3.82 mm d^{-1} respectively. While in the scatter plots of the daily evaporation by the Penman models versus observations by pan evaporation, the evaporation was similar in their pattern. When visualizing the average daily evaporation compared to pan evaporation, it was found that the calculated evaporation during the dry period was close to the pan evaporation whereas evaporation during the wet period overestimated the pan evaporation, as shown in Figure 6.

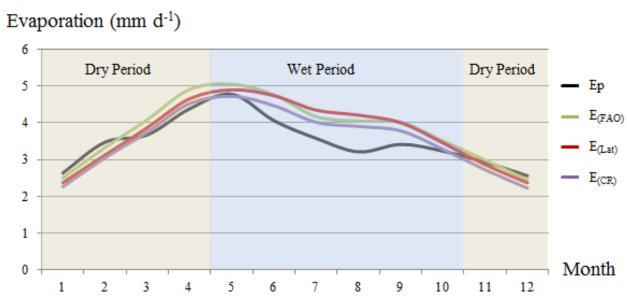

Fig. 6. Average daily evaporation by models and pan evaporation.

The estimated evaporation from this study was consistent with the previous studies in that the calculated evaporation was higher than pan evaporation. The reason possibly came from Penman's model relying on solar radiation and wind speed data, as well as a large amount of meteorological data which caused discrepancies in estimated evaporation [18, 19].

According to RMSE and NSE, it was found that $E_{(CR)}$ based on the total radiation data from $S_{t(CR)}$ was the most efficient, followed by evaporation $E_{(Lat)}$. However, when considering the correlation coefficient (*r*) and the coefficient of determination (R^2), it was found the evaporation model based on $S_{t(FAO)}$ gave a slightly higher efficiency. The performance of the model is shown in Table 4.

Table 4. The efficiency of irradiance solar radiation equation in evaporation

Method	*r*	R^2	RMSE	NSE
$E_{(FAO)}$	0.738	0.545	0.751	0.004
$E_{(Lat)}$	0.704	0.496	0.743	0.026
$E_{(CR)}$	0.737	0.543	0.636	0.285

Analyzes of variance and the average of daily evaporation using *F* and *t*-tests, it was found that the evaporation variances from the $E_{(lat)}$ and the $E_{(FAO)}$ were statistically different. Meanwhile, the averages of daily evaporation from the three models were significantly different at a confidence level of 0.05, as shown in Table 5.

Further statistical analyses showed that the variance of evaporation from the different models did not differ significantly from the variance of pan evaporation. However, the averages of evaporation $E_{(FAO)}$ and $E_{(Lat)}$ were significantly different to the pan evaporation. Whereas the average of evaporation $E_{(CR)}$ was found indifferent from the average of the pan evaporation. The results of the analysis of variance and the average of evaporation are shown in Table 6.

Table 5. Statistical analyses of variances and averages of calculated evaporation

Model	Average	SD	N	Df	*F*	*t*
$E_{(FAO)}$	3.820	1.014	120	119	0.961*	03.879*
$E_{(Lat)}$	3.740	0.975	120			
$E_{(FAO)}$	3.820	1.014	120	119	1.159	14.322*
$E_{(CR)}$	3.556	0.875	120			
$E_{(Lat)}$	3.740	0.975	120	119	1.114	19.676*
$E_{(CR)}$	3.556	0.875	120			

* Significance level of 0.05

Table 6. Statistical analysis of variance and average of calculating evaporation against pan evaporation

Model	Average	SD	N	Df	*F*	*t*
E_P	3.493	0.571	120	119	-	-
$E_{(FAO)}$	3.820	1.014	120	119	0.563*	5.267*
$E_{(Lat)}$	3.740	0.975	120	119	0.586*	3.836*
$E_{(CR)}$	3.556	0.875	120	119	0.653*	1.078

* Significance level of 0.05

4. CONCLUSIONS

This study aimed to evaluate and determine the most suitable method for estimating solar radiation on parameters for Mae Suai reservoir based on day length and calculating daily evaporation using the Penman model. In this study, it was found that the Angstrom–Prescott method using spatial data was most suitable for total solar radiation estimation. The second alternative was the total solar radiation that was estimated from the relationship between the Angstrom coefficients and the latitude. Both methods were more efficient than using the Angstrom coefficients from the FAO. Considering the ability to predict the total solar radiation of the three methods, the coefficients of determination were between 0.563–0.600 indicating that the total solar radiation did not only depend on the day length. However, the estimation also depended on other factors such as cloud cover in the sky and water vapor in the atmosphere.

The evaporations calculated by the Penman method using prior solar radiation calculation and daily meteorological data were close to pan evaporation, especially in the dry period of the year. In contrast, during the wet period, the estimations were slightly higher. However, according to RMSE and NSE, the evaporation model $E_{(CR)}$ based on the total solar radiation at Chiang Rai was the most efficient, followed by the $E_{(Lat)}$. The use of the angstrom coefficients suggested by the FAO to estimate the solar radiation was still appropriate for the area where data on day length and solar radiation on the top of the atmosphere were not available.

ACKNOWLEDGEMENTS

This research is supported by Mae Fah Luang University. The courtesy of the staff of the Agricultural Meteorological Station, Chiang Rai Province, Thailand is gratefully acknowledged for providing meteorological data.

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