Research article

Influence of Meteorological Variable Combinations on Reference Evapotranspiration Estimated by the FAO56 Penman-Monteith Method

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Received 29 Decemberber 2015 Accepted 31 October 2016 (*Corresponding Author)

Abstract An estimate of potential evapotranspiration (PET) is typically required for rainfall runoff modeling, and such as estimate of PET is often determined from use of the Penman-Monteith (PM) method using air temperature, humidity, wind speed, solar radiation and sunshine hours data. This method is recommended by the FAO and used widely across the world. The estimated PET is known to vary depending on the combination of meteorological data used in the PM equation. For example, PET can be estimated by using wind speed and air temperature data only, or by using all five meteorological data. There have been no cases that were examined regarding how combinations of the five data influence estimated PET for the Asian Monsoon region. Air temperature, wind speed, solar radiation, sunshine hours and humidity were measured and recorded at ten-minute intervals for three years at a weather station in the Minami-Soma City, Fukushima Prefecture, Japan. The daily PET was estimated for the 13 combinations of the five data. It was found that PET is overestimated when the solar radiation is not included in the combination. The above results show that data on the solar radiation are indispensable for PET estimation that uses the PM equation in the Asian Monsoon region.

Keywords hydrological model, potential evapotranspiration, FAO, Penman-Monteith method

INTRODUCTION

In recent years, there have been hydrological hazards such as floods and landslides due to heavy precipitation and metrological hazards such as storms and extreme temperature that have occurred in many areas of the world. Particularly in the Asia-pacific region including the Asian monsoon region, hydrological and metrological hazards were the most frequent disasters in 2014. Furthermore, economic losses due to those disasters were estimated in more than 50 billion USD (ESCAP, 2014). Therefore, river development and watershed management for mitigating flood damage have been called for. In planning projects for river development and watershed management for natural disaster mitigation, it is necessary to simulate the effectiveness of the project by using a rainfall runoff model, with which it is possible to predict the changes in the river discharge in relation to the rainfall in the watershed scale.

For such a rainfall runoff model to be used, data on potential evapotranspiration (PET) is required. Measured PET data is not generally used for the model. The PET data is determined from the five meteorological data of air temperature, intensity of solar radiation, humidity, wind velocity and sunshine hours and by using a FAO-56 Penman-Montieth (PM) method, which was described in the FAO Irrigation and Drainage Paper No 56 “Crop Evapo-transpiration” in 1998 by the Food and

Agriculture Organization (FAO) of the United Nations, to revise guidelines for computing crop water requirements (Allen et al., 1998). The most common equation for estimating PET, which is recommended by the FAO and is used widely in the world, is the Penman-Monteith (PM) equation.

OBJECTIVE

The estimated PET is known to vary depending on the combination of meteorological data used in the PM equation (Todorovic et al, 2013; Pereiraa et al. 2015). For example, PET can be estimated by using wind velocity and air temperature data only, or by using all five meteorological data. There have been no cases that were examined regarding how combinations of the five data influence estimated PET for the Asian Monsoon region. In this study, comparisons between measured and estimated values were performed for atmospheric pressure, vapor pressure, and solar radiation by using the root mean squared error (*RMSE*), and the accuracy of the estimation method recommended for use in the PM method was examined. The influence of the estimation accuracy of these three items on the estimated PET was clarified.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} PET_i - \widehat{PET_i}} \tag{1}$$

Where N is number of calculation data, PET_i is computing value by using all five meteorological data, $\widehat{PET_i}$ is computing value by using 2 to 4 meteorological variables.

METHODOLOGY

Meteorological observation was done for the 22 months from November 2011 to September 2013. A weather station was installed at a location 2km inland from the sea coast of Minami-Soma City, Fukushima Prefecture (Fig.1 and Photo.1), during those 22 months. The observation items were precipitation (P), wind direction (WD), wind speed (WS), temperature (T), relative humidity (RH), solar radiation (R_S), and actual hours of sunshine (AH). These were measured at 10-minute intervals. The daily average, daily lowest, and daily highest values for these seven items were determined. Atmospheric pressure (P) could not be measured at the observation site. Instead, the atmospheric pressure observed by the Japan Meteorological Agency at Sendai City, 60 km from the observation station, was used.

In calculating the daily potential evapotranspiration (PET), the Penman-Monteith (PM) method, which is recommended by the FAO, was used. The equation used for the PM method is shown below.

$$ET_0 = \frac{0.408\Delta(R_n - \mathrm{G}) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

Where ET_0 is the reference evapotranspiration (= PET) (mm/d), R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}), T is the air temperature at 2 m height (^{O}C), u_2 is the wind speed at 2 m height (m s^{-1}) e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), Δ is the slope vapour pressure curve (kPa ^{O}C^{-1}), γ is the psychrometric constant (kPa ^{O}C^{-1}) G is the soil heat flux density (MJ m^{-2} d^{-1}). For day and ten-day periods, as the magnitude of the day or ten-day soil heat flux beneath the grass reference surface is relatively small, it was ignored.

In using the PM method to determine the PET, it is necessary to obtain several variables: R_n, T, u_2, e_s, e_a, Δ, γ, and G. The meteorological data, including T, RH, R_s or AH, and P are used to determine the variables. The PET can be determined even without data such as R_s (or AH), RH, or P. The flows of calculation for the items relevant to the PM method are shown in Fig. 2. The P can be estimated from the elevation. To determine the vapor pressure e_a, *RH* and *T* are used; however, when the *RH* data are unavailable, it is possible to estimate e_a by using the *T* data. When the R_s data are not available, R_s can be estimated from the *AH*.

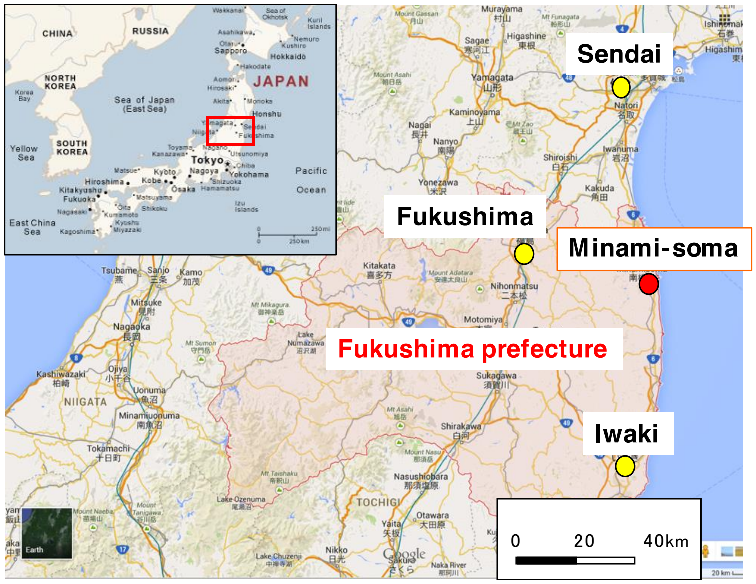

Fig. 1 Investigation site (Red point)

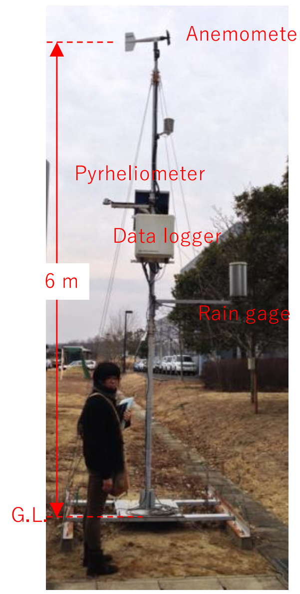

Photo. 1 Weather station

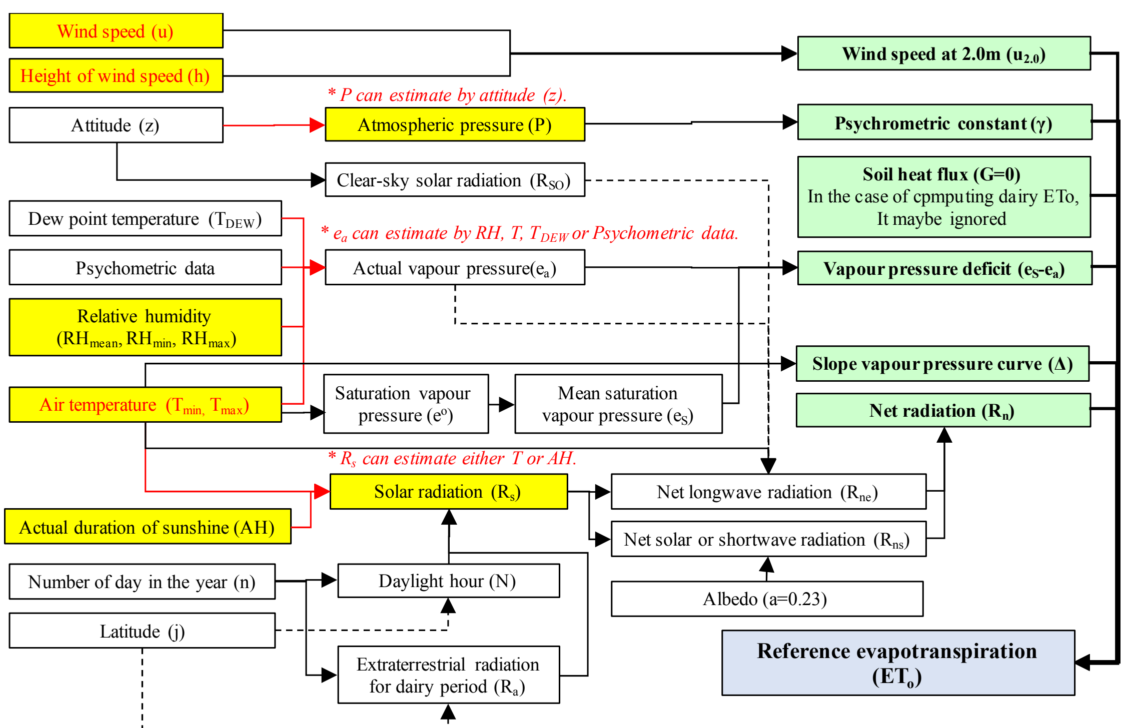

Fig. 2 Flow diagram of potential evapotranspiration calculation by the PM method

As shown in Table 1, when determining the PET by using the meteorological data such as *T*, *RH*, R_s (or *AH*), and P as variables, there are 13 combinations of data items, here designated A to M (Table 1). The estimated PET differs according to what combinations of meteorological data items are used. However, no previous reports have investigated how combinations of the meteorological data influence estimation of the PET for the Asian monsoon region.

Table 1 Thirteen patterns of meteorological data set for calculating PET by the PM method

	Air temperature	Wind speed	Atmospheric pressure	Relative humidity	Actual hours of sunshine	Solar radiation	Reference
	T	WS	P	RH	AH	R_S	
A	●	●	●	●	●		
B	●	●	●	●			
C	●	●	●		●		
D	●	●		●	●		
E	●	●		●			
F	●	●			●		
G	●	●	●				
H	●	●					
I	●	-	-	-	-	-	Hargraves equation
J	●	●	●	●		●	Basic data set
K	●	●	●			●	
L	●	●		●		●	
M	●	●				●	

●: Observation data

RESULTS AND DISCUSSION

Weather Characteristics of Minami-Soma City

The meteorological data obtained during the 22 months is shown in Fig. 3. The daily data for the 22 months are shown in the graphs for the monthly data. The daily average temperature was the highest in August and the lowest in February. The annual temperature difference was 25°C. The humidity was high in summer (July), at 70% or greater, and low in winter (Jan., Feb., March), at 60%. The wind speed ranged between 1.0 and 1.5m/s. The wind speed in this area was extremely low throughout the year. The variation in atmospheric pressure was small; it ranged between 1000 and 1010 hPa. The solar radiation and sunshine hours were the greatest in June and the smallest in December. These changed with an annual cycle. The precipitation was great in spring (April, May) and fall (September, October). This area has little snowfall. There is no snow cover during winter.

When *P* data were unavailable, *P* was estimated by using the elevation in the PM method. Here, the measured and estimated *P* are compared and the estimation accuracy is examined. Fig. 4 shows the relationship between the measured and estimated daily data for P during the 22 months. As there was only one elevation reference location, the *P* estimated from that elevation was 100kPa. The estimated values varied between 97kPa and 103 kPa. The RMSE was an extremely small value of 0.71kPa. The above result clarified that the *P* could be accurately estimated from the elevation, even when the P data were unavailable.

The actual vapor pressure (e_a) is determined as a function of the daily average *RH* and daily highest and lowest *T*. The value of e_a can be determined from the daily lowest *T* even when the *RH* data are unavailable. Here, e_a determined by using the *RH* and *T* data was compared to that determined by using only the *T* data. The estimated values determined in the two methods were compared (Fig. 6). The comparison revealed a high correlation between the two values. The RMSE was an extremely small value of 0.16kPa. Based on the above, it was thought that e_a can be accurately estimated irrespective of the use of the *RH* data.

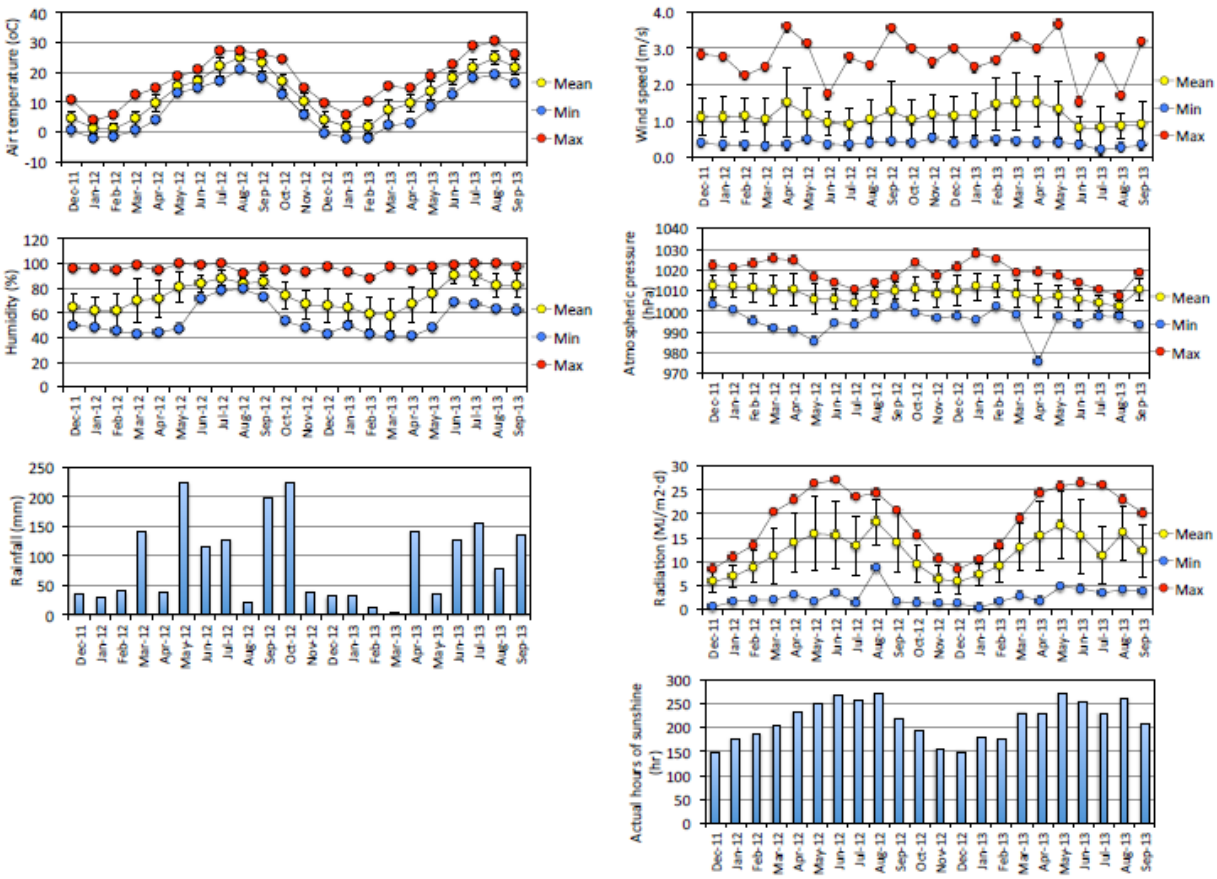

Fig. 3 Meteorological data obtained during the 22 months

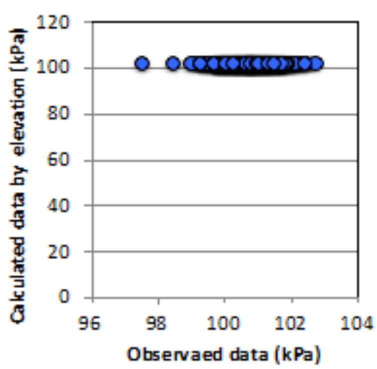

Fig. 4 Relationship between the observed and the calculated daily data for *P*

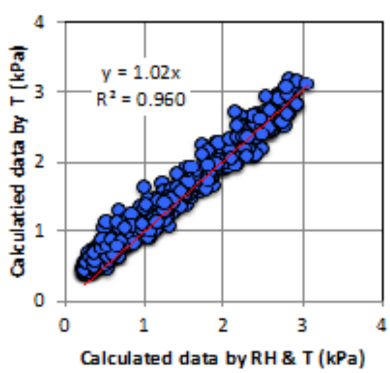

Fig. 5 Relationship between the calculated data by *RH* & *T* and the calculated data by *T*

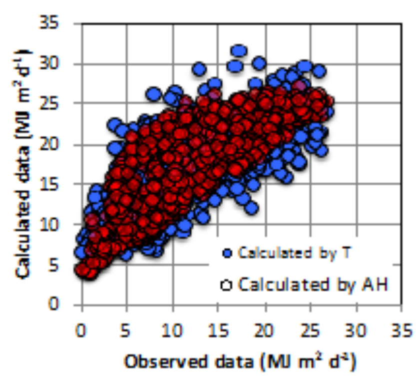

Fig. 6 Relationship between the observed and the calculated daily data for R_s

Estimation Accuracy of Atmospheric Pressure, Vapor Pressure and Solar Radiation

When the R_s (net radiation) data were unavailable, the R_s was estimated from the *AH* or *T*. Here, the observed solar radiation is compared with the values estimated from the *AH* and the values estimated from the *T* (Fig. 7). The values estimated from the *AH* and the values estimated from the *T* show a positive correlation with the observed values. However, the RMSE is the great value of 6 MJ m^2 d^{-1} for both types of estimated values. The Fig. 7 shows that the difference between the observed and estimated values is small in the areas near the highest and lowest observed values. The estimated values were 20, 25 and 25 MJ m^2 d^{-1}, while the observed values were 5, 10, 15 and 20 MJ m^2 d^{-1}. The estimated values overestimated the observed values by a factor of 4, 2.5 and 1.25, respectively. This comparison found that R_s is unable to be accurately estimated from the *AH* or *T*.

The Influence of Combinations of Meteorological Data Items on the Estimation of the PET

Figure 7 shows the daily average of the PET determined from the data obtained during the 22 months. The error bar indicates the standard deviation. The graph shows the 13 patterns of combinations of meteorological data items. J shows the PET (2.07mm/d) that was determined by the estimation calculation using *T*, *WS*, *RH*, R_s, and *P*, which is recommended in the PM method. The discussion will be done using the J value as the standard. For the combinations of meteorological data items A to I, in which R_s was not used, the PET values (2.51 - 2.27) are overestimated and are higher than those of J (1.21 - 1.10). For the combinations of meteorological data items K to M, in which the R_s was used but one or more data were not used, the PET was between 1.98 and 2.07, which are small values equal to or 0.96 times that of J. From the above, it was clarified that the PET can be accurately estimated by using the PM method when R_s data are available, even when the *RH* or *P* data are unavailable. It was also clarified that when the PM method is used in the Asian monsoon region, R_s is an important variable in addition to *WS* and *T*.

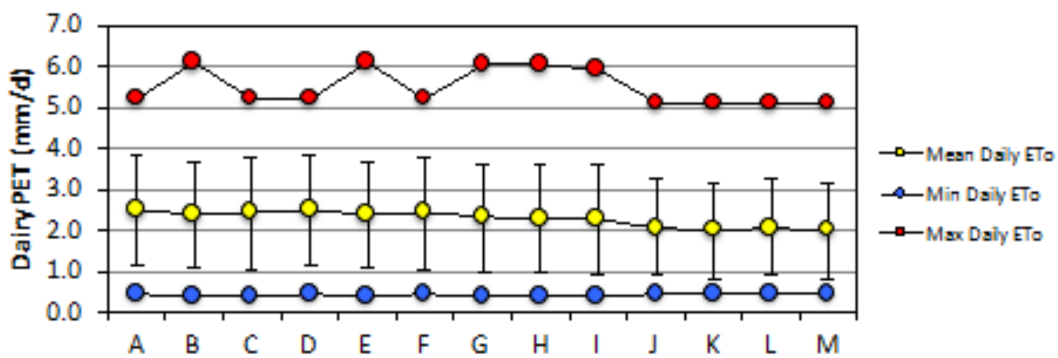

Fig. 7 Daily average of the PET determined from the data obtained during the 22 months

CONCLUSION

In this study, examination was done on the use of the PM method for estimating the PET of the relatively warm regions with small precipitation. As the results, the potential evapotranspiration can be accurately estimated by using the Penman-Monteith method when solar radiation data are available, even when the relative humidity or atmospheric pressure data are unavailable. It was also clarified that when the Penman-Monteith method is used in the Asian monsoon region, solar radiation is an important variable in addition to wind speed and air temperature.

However, the climatic divisions are varied even in the Asian monsoon region. It is necessary to conduct an examination that is similar to the one done in this study in areas with heavy rain and in cold areas. It is also necessary to conduct an examination in which the year is divided into quarters so that the accuracy of PET estimation in seasons with small or great solar radiation can be examined.

ACKNOWLEDGEMENTS

This research was supported by the Grant-Aid from Tokyo University of Agriculture (TUA), Japan.

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