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Comparison of different methods in estimating potential evapotranspiration at Muda Irrigation Scheme of Malaysia

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Abstract

Evapotranspiration (ET) is a complex process in the hydrological cycle that influences the quantity of runoff and thus the irrigation water requirements. Numerous methods have been developed to estimate potential evapotranspiration (PET). Unfortunately, most of the reliable PET methods are parameter rich models and therefore, not feasible for application in data scarce regions. On the other hand, accuracy and reliability of simple PET models vary widely according to regional climate conditions. The objective of the present study was to evaluate the performance of three temperature-based and three radiation-based simple ET methods in estimating historical ET and projecting future ET at Muda Irrigation Scheme at Kedah, Malaysia. The performance was measured by comparing those methods with the parameter intensive Penman-Monteith Method. It was found that radiation based methods gave better performance compared to temperature-based methods in estimation of ET in the study area. Future ET simulated from projected climate data obtained through statistical downscaling technique also showed that radiation-based methods can project closer ET values to that projected by Penman-Monteith Method. It is expected that the study will guide in selecting suitable methods for estimating and projecting ET in accordance to availability of meteorological data.

Keywords: Potential evapotranspiration, Statistical downscaling (SDSM), temperature trend, climate change

1 Introduction

Evapotranspiration (ET) is a term used to describe the sum of evaporation and plant transpiration from the Earth's land surface to atmosphere. It is the second most important variable in the hydrological cycle after rainfall and has an important role as controlling factor of runoff volume or river discharge, irrigation water requirement and soil moisture contents (Mohan & Arumugam, 1996). Accurate estimation of ET is therefore essential for water budgeting and planning. It has been anticipated that direct impact of climate change on water resources will be mainly trough evapotranspiration. Hydrological changes constitute one of the most significant potential impacts on global climate change in the tropical regions (IPCC, 2007). It is now clear that climate change will cause a steady rise of temperature and changes in rainfall pattern. Higher temperature will induce higher evapotranspiration which in turn will affect the hydrological system and water resources (Shahid, 2011). Thus, quantifying the changes in ET due to climate change is very important for the management of long-term water resources. Especially in the crop lands, it is essential to measure the possible changes in ET and probability of water losses due to climate change.

Considering the importance of ET, hydrologists have developed numerous methods for its estimation. Each method has its own perspective and concept, and has been developed for specific climatic setup. Some of these methods are basically the modified version of other methods. However, the major concern in estimating ET is the reliability and accuracy of the methods (Burnash, 1995).

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As many of these methods have been developed from a certain perspective and for a specific climate region, they often fail to estimate the potential evapotranspiration (PET) in other climatic regions. Nevertheless, there are few methods such as the Penman-Monteith method which are reliable over a broad climatic region. Reliability of these methods has been tested in different parts of the world including Malaysia and they are found to estimate ET very close to field observation. Unfortunately, these methods are parameter rich model and require extensive data and information for reliable estimation of ET. This poses a problem in making accurate future ET projection for data scarce region. Most meteorological stations only measure temperature and rainfall while other meteorological parameters that are required for parameter rich models for ET estimation are rarely measured.

Another challenge often encountered in application of these methods in projecting ET due to climate change. For example, the general circulation models (GCM) predict future changes only in mean temperature and rainfall. But, since parameter rich ET methods need many other data beside mean temperature to estimate ET, we often need to use computation intensive downscaling models to predict those parameters. All of these problems can be overcome by using simple ET methods which can estimate ET from few readily available meteorological data. However, the major concern related to these simple ET methods is their accuracy and reliability. It has been found that the accuracy and reliability of these simple ET methods are unequal and depend heavily on the climatic conditions of a region. Therefore, performance study of simple ET methods is essential for selecting suitable ET method in accordance to regional climate and availability of meteorological data.

Muda Irrigation Scheme is the largest paddy field in Malaysia. Accurate estimation of ET and its possible variations due to climate change are very crucial for water resources planning and management in the scheme. The objective of this paper is to compare the performance of six widely used simple ET methods, namely Hargreaves Samani Method, Thornthwaite Method, Blaney-Criddle Method, Priestley-Taylor Method, Makkink Method and Turc Method in estimating ET at Muda irrigation scheme area. In the present research, the performance of these simple ET methods is evaluated by comparing them with Penman-Monteith method. Penman-Monteith method provides the most reasonable estimation of ET and it is one of the most reliable methods which consider the atmospheric changes comprehensively (Allen *et al.*, 1998, 2006; Sentelhas *et al.*, 2010; Ravazzani *et al.*, 2011; Lee & Cho, 2012).

2 Materials and Methods

2.1 *Study area*

Muda Irrigation Scheme is located at Kedah, north of peninsular Malaysia (Figure 1). Covering 97,000 hectares, it is the largest double paddy cultivation area in Malaysia. Geographically, the area lies between 5°45’ – 6°30’N latitude and 100°10’ – 100°30’E longitude (MADA, 1977).

The topography of the area is almost flat with a slope ranging from 1 in 5,000 to 1 in 10,000. The meteorological data are collected from the Alor Setar station located at the center of the Muda Irrigation Scheme. Therefore, it can be considered that the climate of this station represents the climate of the entire area under study. Climate data at this station consists of daily mean, maximum and minimum temperatures over the time period 1972–2001 and daily mean precipitation over the period 1961–1990.

The climate of the area like other parts of Malaysia can be classified into four seasons viz. south-west monsoon (May–Sept), north-east monsoon (Nov–Mar) and two inter-monsoon seasons. Dec–Feb and June–July are considered as warm seasons in the area, while Apr–May and Sept–Nov are considered as humid seasons. The type of soil in the study area is heavy clayey in nature. The mean temperature varies between 27 °C and 32 °C. The relative humidity fluctuates between 54 % and 94 %. Monthly distribution of climate parameters in the study area is given in Table 1. Water resources for the paddy field are derived from direct rainfall (33 %), runoff (32 %) and Pedu-Muda reservoir storage (35 %) through Pedu River and Padang Terap River.

2.2 *Statistical downscaling tools*

The projection of future temperature at regional scale is required to determine possible changes in ET due to climate change. Statistical Downscaling Model version 4.2 (SDSM) was used to downscale the GCM output at regional scale and to project the temperature in the study area over the years 2010–2099. SDSM is a hybrid tool which can predicts climate change at local scale by linking local climate variables with large scale atmospheric variables using multiple regression technique. The downscaling requires two types of data viz. predictand and predictor. In the present study, historical temperature (1972–2001) at Alor Setar station was used as predictand and the atmospheric variables produced by the Hadley Center General Circulation Model (HadCM3) under A2 scenario were used as predictors.

2.3 *PET methods*

Six simple methods were selected to estimate historical ET of the study area to compare their per-

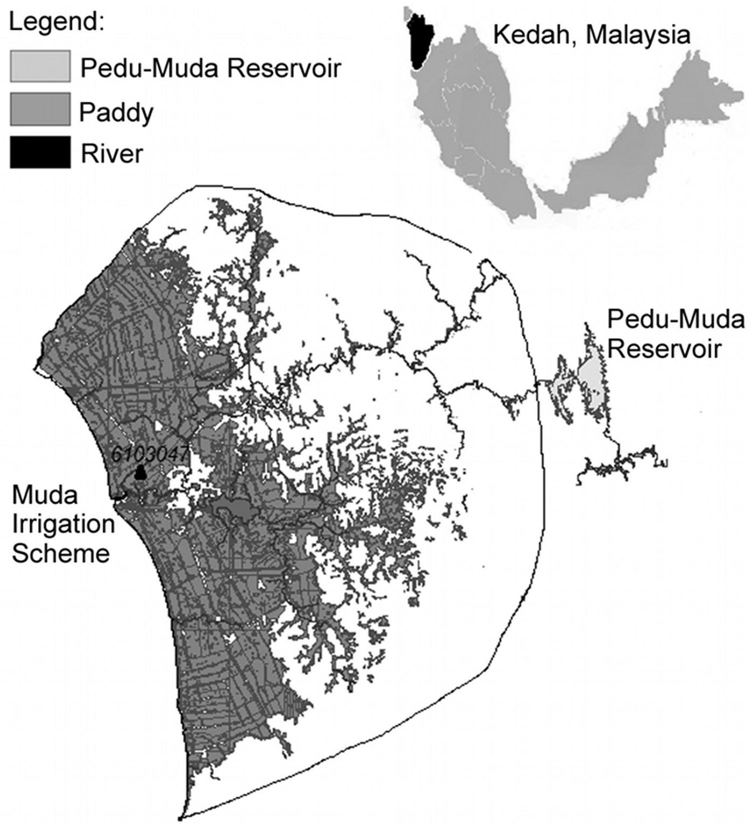

Fig. 1: *Geographic location of the Muda Irrigation Scheme in Malaysia.*

Table 1: *Average monthly parameters used in different methods for estimating ET at the study area. Meteorological data are collected from the Alor Setar station.*

Parameter	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Max Temp (°C)	33.2	34.2	34.5	33.6	32.9	32.2	31.9	31.8	31.8	31.6	31.7	31.4
Min Temp (°C)	22.7	23.1	23.6	24.4	24.8	24.3	23.9	23.7	23.8	23.9	23.7	23.1
Rainfall (mm)	20.1	43.8	95.6	148.4	206.9	162.0	206.2	256.5	271.0	251.0	200.0	71.9
Avg. RH (%)	72.9	73.0	76.6	81.5	85.2	85.6	86.3	86.3	86.4	87.0	85.0	79.7
Avg. U at 2 m altitude ($m\,s^{-1}$)	1.4	1.3	1.0	0.9	0.8	0.7	0.8	0.8	0.8	0.8	0.8	1.2
Sunshine, n ($h\,day^{-1}$)	8.70	9.00	8.50	8.70	7.70	7.10	6.60	6.70	5.70	5.70	6.10	7.00
Net Radiation ($MJ\,m^{-2}\,day^{-1}$)	19.1	20.8	20.8	21.2	19.2	17.8	17.3	17.8	16.3	15.9	15.7	16.4
Extraterrestrial Radiation ($MJ\,m^{-2}\,day^{-1}$)	33.8	36.0	37.5	37.5	36.8	35.9	36.4	37.1	37.3	36.5	34.5	33.3
Solar radiation ($MJ\,m^{-2}\,day^{-1}$)	21.5	23.0	22.7	22.5	20.2	19.1	18.9	19.6	18.0	17.2	17.0	18.2

formance, namely Priestley-Taylor Method, Makkink Method, Turc Method, Hargreaves-Samani Method, Thornthwaite Method, and the Blaney-Criddle Method. These methods can be divided into two broad groups viz., radiation-based methods (Priestley-Taylor Method, Makkink Method, Turc Method) and temperature-based methods (Hargreaves-Samani Method, Thornthwaite Method, Blaney-Criddle Method). The ET techniques were selected by considering the availability of meteorological data required by those models. Performance of the ET techniques was measured by comparing them with the Penman-Monteith reference ET.

2.4 Penman-Monteith equation

The Penman-Monteith method (Monteith, 1965) combines the fixed bulk surface resistance and vapor aerodynamic. It has a strong theoretical basis and can be expressed as below:

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \quad (1)$$

where, ET_o is the reference evapotranspiration (mm day^{-1}); Δ is the slope vapor curve (kPa °C^{-1}); R_n is the net radiation of the crop surface (MJ m^{-2} day^{-1}); G is the soil heat flux density (MJ m^{-2} day^{-1}); T is the air temperature at 2 m height (°C); u_2 is the wind speed at 2 m height (m s^{-1}); e_s is the saturation vapor (kPa); e_a is the actual vapor pressure (kPa); and γ is the psychrometric constant (kPa °C^{-1}).

2.5 Priestley-Taylor method

Priestley & Taylor (1972) found that the actual evaporation is 1.26 times greater than the potential evaporation and hence they replaced the aerodynamic terms with a constant value of 1.26. Consequently, Priestley-Taylor method needs only long-wave radiation and temperature to estimate ET. Priestley-Taylor equation for computing ET is given below:

$$ET_o = 1.26 \frac{\Delta}{\Delta + \gamma} (R_n - G) \frac{1}{\lambda} \quad (2)$$

where, Δ is the slope vapor curve (kPa °C^{-1}); γ is the psychrometric constant (kPa °C^{-1}); R_n is the net radiation of the crop surface (MJ m^{-2} day^{-1}); G is the soil heat flux density (MJ m^{-2} day^{-1}); and λ is the latent heat of vapor (MJ kg^{-1}).

2.6 Makkink Method

Makkink (1957) proposed a simple method for ET estimation by using only temperature and radiation parameters:

$$ET_o = 0.61 \frac{\Delta}{\Delta + \gamma} \frac{R_s}{\lambda} - 0.12 \quad (3)$$

where, Δ is the slope vapor curve (kPa °C^{-1}); γ is the psychrometric constant (kPa °C^{-1}); R_s is the solar radiation of the crop surface (MJ m^{-2} day^{-1}); and λ is the latent heat of vapor (MJ kg^{-1}).

2.7 Turc Method

Turc (1961) proposed a simple equation for computing ET by using only mean temperature, solar radiation and relative humidity. Jensen *et al.* (1990) reported that the Turc method is reliable under humid conditions similar to present study area. The Turc equation is as follows:

when $RH < 50\%$

$$ET_o = 0.0133 \frac{T_m}{T_m + 15} (R_s + 50) \quad (4)$$

when $RH > 50\%$

$$ET_o = 0.0133 \frac{T_m}{T_m + 15} (R_s + 50) \left(1 + \frac{50 - RH}{70}\right) \quad (5)$$

where, T_m is mean of temperature (°C); R_s is the solar radiation of the crop surface (MJ m^{-2} day^{-1}); and RH is the relative humidity (%).

2.8 Hargreaves-Samani method

The Hargreaves-Samani equation (Hargreaves & Samani, 1982) is derived through regression of temperature reduction coefficient and relative humidity factor. The equation is expressed below:

$$ET_o = 0.0023 (T_{max} - T_{min})^{0.5} (T_m + 17.8) R_a \quad (6)$$

where, T_m, T_{max} and T_{min} refer to mean, maximum and minimum temperatures (°C); and R_a is the extraterrestrial radiation of the crop surface (MJ m^{-2} day^{-1}).

2.9 Thornthwaite Method

The Thornthwaite equation (Thornthwaite, 1948) is based on an empirical relationship between ET and mean air temperature changes. Thornthwaite equation can be written as:

$$ET_o = ET_{osc} \left(\frac{N}{12}\right) \left(\frac{d_m}{30}\right) \quad (7)$$

$$ET_{osc} = 16 \left(\frac{10\, T_{med}}{I}\right)^{\alpha} \quad (8)$$

$$I = \sum_{i=1}^{12} \left(\frac{T_{med\,i}}{5}\right)^{1.514} \quad (9)$$

where, ET_{osc} is the gross evapotranspiration; N is the maximum number of sunny hours in function of the month latitude; d_m is the number of day per month; T_{med} is the mean temperature (°C); I is the monthly heat index; and

$$\alpha = 0.49239 + 1792 \times 10^{-5} I - 771 \times 10^{-7} I^2 + 675 \times 10^{-9} I^3 \quad (10)$$

2.10 Blaney-Criddle method

The Blaney-Criddle method is one of the simplest techniques used to calculate ET. It was widely used before the introduction of Penman-Monteith equation. This method only considers temperature changes at a particular region for measuring reference ET. The Blaney-Criddle formula for estimating ET is as follows:

$$ET_o = p(0.46\,T_{mean} + 8) \quad (11)$$

where, p is the mean daily percentage of annual daytime hours due to the latitude of region; and T_{mean} is mean temperature (°C).

3 Results

3.1 Temperature projections in the study area

The simulated temperature using SDSM tool at Alor Setar station over the time period 2010–2099 is shown in Figure 2. The projection shows that maximum temperature will rise by 1.8 % and the minimum temperature by 0.4 % in the study area by the year 2039. The results show that the maximum temperature will be constant in the range of 30 °C to 32 °C during the south-west monsoon (May to September) season, but it will increase continuously during north-east monsoon (February to March) season.

A similar trend is projected over the years 2040–2099. The downscaling results show that maximum temperature will rise by 7 % and may reach up to 37.6 °C by the end of this century. The study reveals that average temperature of the study area will continue to rise by 0.2 °C per decade.

3.2 Comparison of PET methods

To measure the accuracy and reliability of ET methods, ET estimates by each method were compared with the estimation of the Penman-Monteith method. Performances of ET methods were measured by computing three parameters: (1) absolute error, which gave the amount of physical error in the measurement; (2) relative error, which gave an indication of how good the measurement was relative to the size of the thing being measured; and (3) Pearson correlation coefficients which gave a measure of association between ET estimates.

The ETs estimated by radiation-based methods (Priestley-Taylor Method, Makkink Method, and Turc Method) correlated significantly with Penman-Monteith estimations (Table 2). The correlation coefficients of radiation-based methods were much higher (more than 0.9) compared to temperature based methods (less than 0.4). However, the absolute and relative errors were least for the Hargreaves-Samani method and highest for Blaney-Criddle method. As the correlations between radiation-based methods and Penman-Monteith method are high, it can be remarked that radiation-based method can efficiently reconstruct the actual ET pattern.

The mean daily ET values estimated by different methods are shown in Figure 3. In general, the ET values at Kedah, Malaysia are in the range of 4.0 mm/day to 5.0 mm/day. The peak values are found in February-April as the temperature is high during this period. On the other hand, the least ET values are observed in the months of October and November. The monthly pattern produced by different methods is not similar. The Blaney-criddle method and Turc method showed almost equal ET for all months. The Makkink method, Priestley-Taylor method and Thornthwaite method showed similar pattern like the Penman-Monteith method. The ET estimated by Blaney-criddle Method was slightly higher (5.9 mm/day) than that computed by other methods.

The relations of Penman-Monteith method with six others methods are shown in Figure 4. The relationships can be well expressed in the polynomial form $aX^2 + bX + c$. The square root of correlation coefficient (r^2) was used to measure the strength of correlation. The results showed higher correlation coefficients for the radiation-based methods and lower correlation coefficients for the temperature-based methods.

The Makkink Method yielded the highest correlation coefficient (0.92) among the radiation-based methods. The Priestley-Taylor method and Turc method also showed higher correlation coefficients compared to temperature-based methods. Though the capability of these two methods are almost similar, Turc method needs less number of parameters to estimate ET compared to Priestley-Taylor method and therefore, much easier to use.

Temperature-based methods yielded correlation coefficients in the range of 0.32 to 0.35. This means that the ET methods based on temperature have a poor relationship with the Penman-Monteith method. The Hargreaves-Samani method produced least correlation coefficient compared to other temperature-based methods.

3.3 Future Projection of ET in the study area

Figure 5 shows the changing pattern of ET predicted by Penman-Monteith, Turc, Blaney-Criddle, Thornthwaite and Hargreaves-Samani methods for the time period 2010–2099. The Priestley-Taylor and Makkink methods were not used as they are not sensitive to temperature changes. The ET values were estimated by inputting the future temperatures projected by SDSM tools into the ET models. It was considered that all other parameters would not be affected by climate change and therefore, all parameters would remain constant.

In general, all the methods showed an increase of the ET in the area over the time period 2010–2099. This was acceptable as the SDSM also projected a sharp

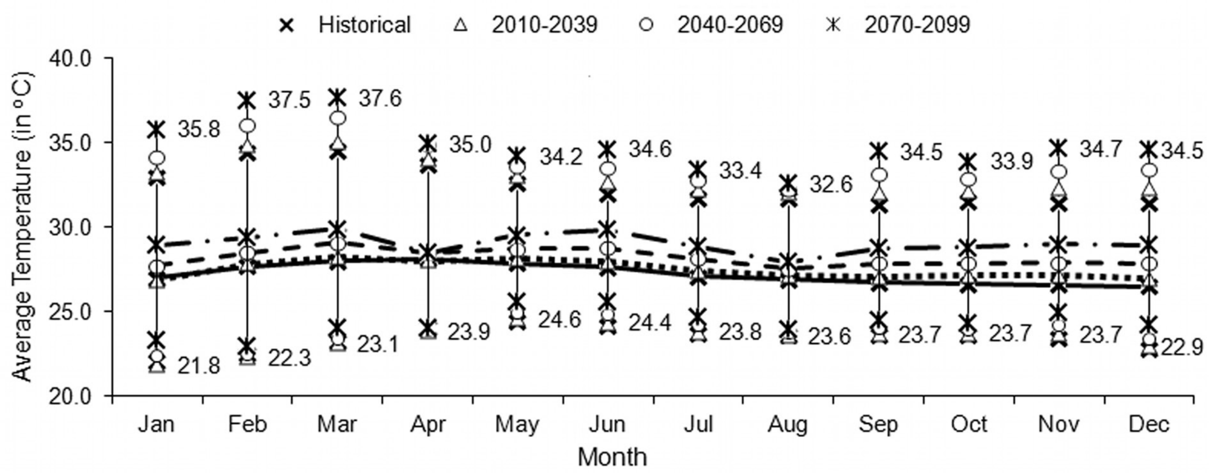

Fig. 2: *Projected mean monthly temperatures at different time intervals.*

Table 2: *Errors and correlation between Penman-Monteith method and ET models under study.*

PET	*Method Type*		*Error*		*Pearson Correlation*
	Temperature	Radiation	Absolute Error	Relative Error	
Penman-Monteith	×	×	–	–	–
Priestley-Taylor		×	0.74	0.17	0.90
Makkink Method		×	0.56	0.13	0.95
Turc Method		×	0.63	0.15	0.95
Hargreaves Samani	×		0.48	0.11	0.39
Thornthwaite Method	×		0.55	0.12	0.24
Blaney-Criddle Method	×		1.32	0.31	0.30

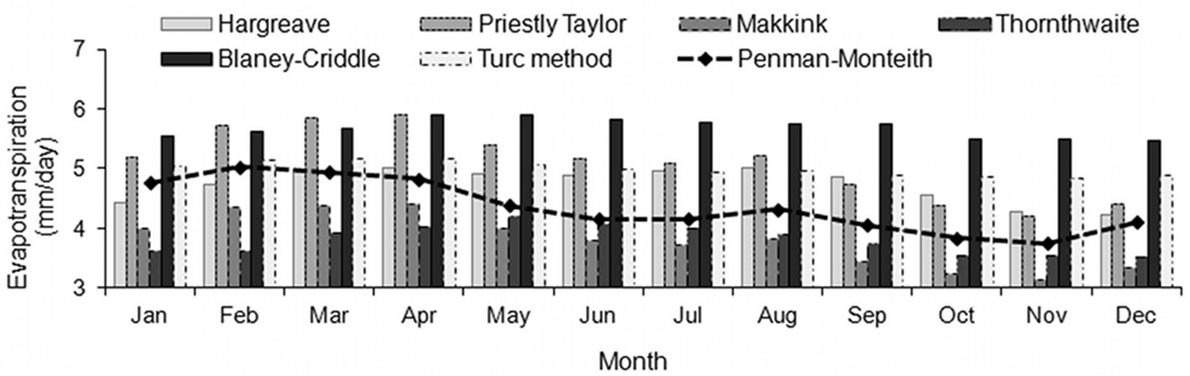

Fig. 3: *Mean daily ET simulated by Penman-Monteith and six simple ET methods.*

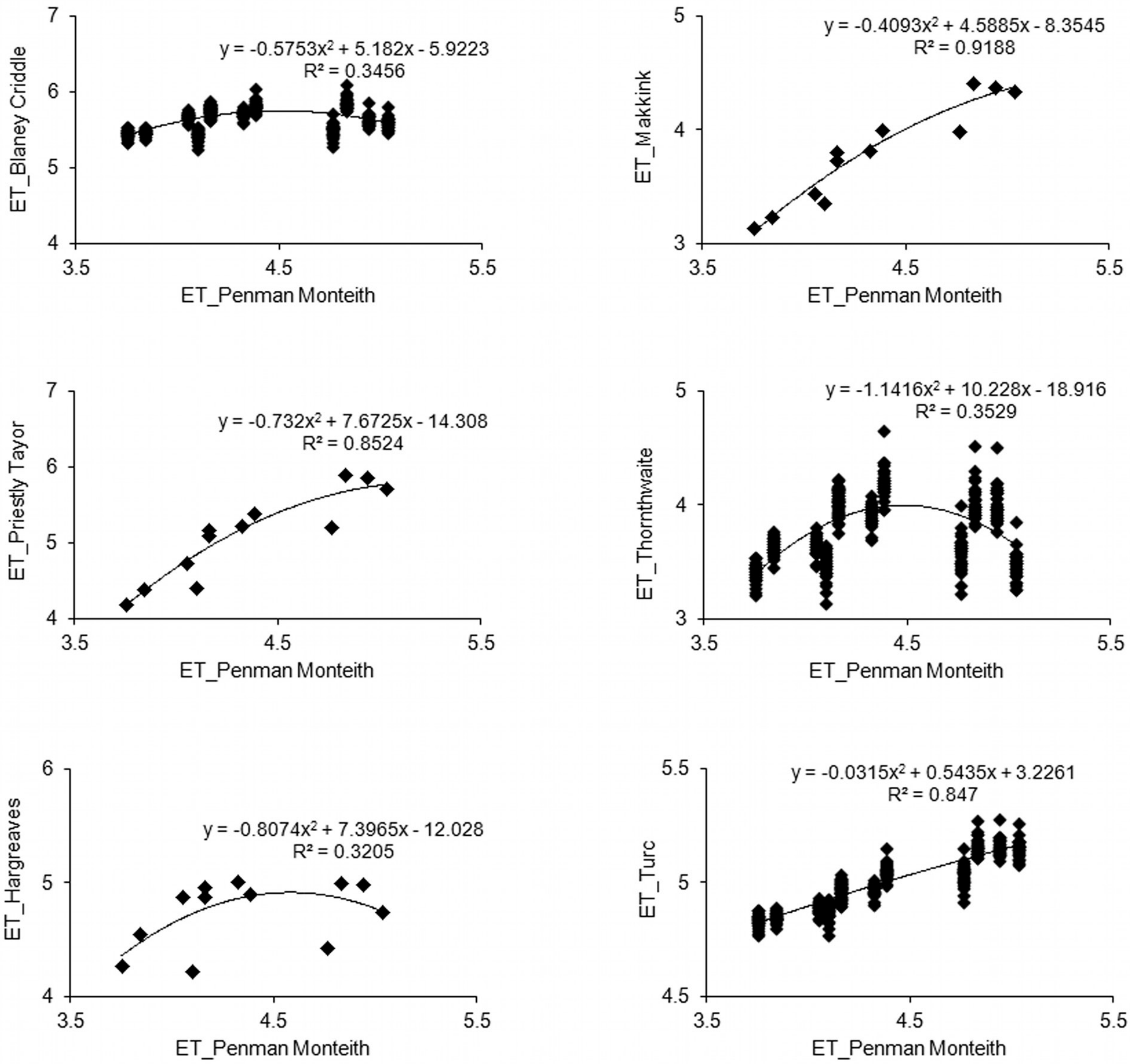

Fig. 4: *The relationship between Penman-Monteith and the ET methods under study.*

rise of temperature which would certainly accelerate the evaporation and transpiration processes. The Blaney-Criddle method predicted the highest changes in PET (2000 mm year^{-1} to 2150 mm year^{-1}). This method predicted an increase of ET by about 0.49 % per year on average compare to present ET.

4 Discussion and Conclusion

Evapotranspiration is a major controlling factor of hydrological processes. Climate change will affect the hydrological processes mainly through Evapotranspiration. Assessment of ET especially in the context of climate change is therefore very important. Performance of six simple ET methods had been tested in this study with an aim to guide the researchers and water practitioners in selecting appropriate method for estimating and projecting ET at the Muda irrigation scheme in Kedah, Malaysia. The study showed that ET in the region ranges from 1360 mm year^{-1} to 1490 mm year^{-1}. Among the six ET methods, radiation-based methods were found to perform better in term of producing similar pattern as produced by the Penman-Monteith method. The Turc, Makkink, Priestley-Taylor methods showed high correlation with reasonable errors. However, two temperature based methods viz., Hargreaves-Samani and Thornthwaite methods showed their capability to estimate ET with minimum errors. This proves that both the temperature and radiation-based methods have their own pros and cons in estimating ET in the study area. However, as the radiation-based methods were found to produce similar ET pattern with reasonable errors, it can be concluded that the radiation based methods are suitable for estimating ET in the study area.

Among the radiation-based method, Makkink method was found to perform best followed by the Turc method and the Priestley-Taylor method. Makkink method showed the highest correlation among all the methods and less errors among the radiation based methods used in the present study. During fitting polynomial regression line with the Penman-Monteith estimates, Makkink method also showed the highest correlation followed by Priestley-Taylor and Turc methods. Capability of Priestley-Taylor and Turc methods in estimating ET is more or less similar. However, Turc method needs only three parameters to estimate ET compared to Priestley-Taylor method which needs five parameters. Therefore, Turc method can be used more easily compared to Priestley-Taylor method in estimating ET in the study area.

Previous study by Toriman *et al.* (2009) suggested Thornthwaite method as the most suitable method for ET estimation in north Kedah, Malaysia. The finding of present research contradicted with that as the correlation and error analysis revealed that the Thornthwaite method was able to produce reasonable errors, but it had poor correlation with the reference ET. As correlation tells how a method follows actual pattern, poor correlation coefficient by Thornthwaite method means that it is inadequate to predict ET reliably. Other temperature-based methods were also found to perform unsatisfactory in estimating ET in the study area. Among all the methods, the Blaney-Criddle method performed the worst.

To predict the changing pattern of ET due to climate change, future temperatures projected by SDSM tools were imputed into the ET models. However, as most of the radiation based methods are not sensitive to temperature, they can not be used to project ET in the context of rising temperature. In the present paper, three temperature based methods and the radiation based Turc method were compared with Penman-Monteith method to show their capability to predict future changes of ET due to climate change. Among the radiation based method, only Turc method was used as it is sensitive to temperature. The study revealed that all the methods except Thornthwaite method overestimate ET under climate change scenario.

From the above analysis, it can be concluded that the radiation based methods are most suitable for estimating ET in the study area. Among the radiation-based method, Makkink method is the most suitable method followed by Turc method and Priestley-Taylor method. Temperature based methods are suitable for projecting changing pattern of ET under climate change scenarios. Among the temperature based method Thornthwaite method is the most suitable method for projecting future changes of ET due to temperature rise.

It is expected that the study will be beneficial to a number of stakeholders, particularly water managers, and also the hydrology researchers, agricultural organisations, water resources development/planning authorities, and environmental agencies to improve their understanding on preferred methods for estimating ET in irrigated areas of Malaysia. It is hoped that the study in general will assist to select better methods in accordance to the availability of meteorological data.

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