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SENSITIVITY ANALYSIS OF A FAO PENMAN MONTEITH FOR POTENTIAL EVAPOTRANSPIRATION TO CLIMATE CHANGE

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Abstract

Sensitivity of the FAO Penman-Monteith (FPM) potential evapotranspiration (PET) model under tropical climates has been studied in the present study. A total of 17 meteorological stations covering Peninsular Malaysia starting from 1987-2003 were used as model inputs. A sensitivity analysis (SA) was carried out using the graphical method for temperature, wind speed and solar radiation within the possible range of ±20% with increments of 5%. From the comparison done on the sensitivity of PET to climatic change, the Kuala Krai station gave the highest percentage change in terms of temperature (±6%). The highest percentage change for wind speed (±2%) and solar radiation (±17%) were shown at the Alor Setar and Kuala Krai stations, respectively. The Alor Setar station had the lowest percentage change for temperature (±0.3%) and solar radiation (±9.9). The lowest percentage change of wind speed (± 0.2%) was observed at the Kuala Krai station. PET percentage changes have a positive correlation to the percentage change of all climatic variables except for the Cameron Highlands station. Results revealed that solar radiation has the most significant effect on PET (±14%), followed by temperature (±4%) and wind speed (±1%). Taken together, these results suggest that solar radiation plays an important role in estimating PET in Peninsular Malaysia.

Keywords: Potential evapotranspiration, sensitivity analysis, FAO Penman-Monteith, meteorological parameters, climate change

Abstrak

Kajian ini dijalan untuk mengkaji kepekaan FAO Penman-Monteith (FPM) terhadap potensi evapotransporasi (PET) di kawasan tropika. Data daripada tahun 1987 hingga 2003 dari 17 stesen meteorologi sekitar Semenanjung Malaysia telah diguna pakai. Analisis kepekaan ini telah dijalankan menggunakan kaedah grafik dengan menaik turunkan parameter suhu, halaju angin dan radiasi solar sebanyak ±20% dengan 5% peningkatan setiap satunya. Hasil analisis kepekaan PET terhadap perubahan iklim, stesen Kuala Krai menunjukkan peratus tertinggi terhadap suhu iaitu sebanyak ±6%. Peratusan tertinggi untuk halaju angin (±2%) dan radiasi solar (±17%) masing-masing ditunjukkan pada stesen Alor Setar dan Kuala Krai. Stesen Alor Setar memberikan peratus terendah untuk suhu (±0.3%) danradiasi solar (±9.9). Peratusan yang terendah untuk halaju angin dapat dilihat di stesen Kuala Krai. Peratusan terendah untuk halaju angin dicatatkan oleh stesen Kuala Krai. Keseluruhan stesen memberikan hubungan yang positif kecuali stesen Cameron Highlands. Hasil kajian mendapati radiasi solar memberikan kesan ketara terhadap PET sebanyak ±14% diikuti oleh suhu ±4% dan halaju angin ±1%. Oleh itu, dapat disimpulkan bahawa radiasi solar memainkan peranan penting dalam menganggarkan PET di Semenanjung Malaysia.

Kata kunci: Potensi evapotranspirasi, kajian kepekaan, FAO Penman-Monteith, meteorologi parameter, perubahan iklim

1.0 INTRODUCTION

The hydrological cycle is an important process as it maintains surface water availability for human beings as well as to habitats. As part of the elements in the hydrological cycle, evapotranspiration (ET) plays a major role in irrigation and domestic water supply planning systems. Potential evapotranspiration (PET) is the amount of water loss under a given climate with vegetation covering the ground continuously [1] and without considering the crop's characteristics and soil factor [2]. The challenge faced in water resources management in this century is to adapt to the increasing water demand due to climate change [3, 4]. Climate change has influenced the pattern of ET which in turn has affected precipitation [3]. An increase of 0.85°C in land and ocean surface temperatures per decade over the period of 1880 to 2012 [5] had caused significant impact on the environment and human lifestyle. Hence, studies on the impact of climate change towards irrigation [6, 7], water resources management [8], public health [9], and food supplies [10] have been conducted ever since.

The SA method is used to determine the most appealing input suitable to the output of a certain model [11, 12]. There are three types of SA; mathematical, statistical and graphical methods. In this study, the graphical method is used. Through SA, a better understanding on the relationship between climatic conditions and PET variability can be known [13, 14]. The significance of SA is to obtain a better view on which climatic parameters control changes in PET. However, PET's theoretical sensitivity results do not consider the actual changes in climatic parameters[15]. PET studies in Malaysia have been conducted mainly to determine the most suitable models to be used on corresponding study areas, such as on the Muda Irrigation Scheme [16, 17] and Seberang Perak [18]. The most recent ET sensitivity analysis was conducted on [15]15 stations located in an arid climatic zone in the Heihe River Basin, China. The study concluded that temperature and solar radiation affect the most in the upper region, while solar radiation and wind speed play major roles in the lower region. [19] conducted a study in four different climates and found that the humid climate is sensitive to sunshine hours. Both cold and warm semi-arid climates are influenced by wind speed. As for the arid climate, wind speed and temperature play a significant effect on ET. According to [20],wind speed and relative humidity are not important climatic parameters for the Mediterranean climate. A study by [21]on the semi-arid climate located in North China found that temperature and sunshine hours have a significant effect on ET. Similar results were obtained by [22]who also concluded that temperature is a key factor for changes in ET. [23] found that under the arid climate at Rajasthan, India, temperature affects ET more. The wind speed variable has more influence on semi-arid regions than any other climatic variables [19, 24]. [25] stated that solar radiation plays a significant effect towards ET in humid climates as it supplies most of the energy required to change water to vapor. The results may vary depending on the study area although it has been classified under the same climate category. All of the studies mentioned use FPM as their observed model in conducting SA analysis. In this study, a sensitivity analysis was done using the graphical method by taking the FPM model as an observation model following literature from [19, 23].

There is no standard model to be used to compute a sensitivity analysis. The selection of ET model depends on a region's data availability. However, most studies use the FPM model because it does consider all climatic variables that influence ET [26]. Although there are other simpler PET models, the results may not be as reliable than the ones which take other climatic parameters into consideration [25]. Hence, researchers are more comfortable to use the FPM model for SA purposes [13, 27, 28, 29].

The aims of this study are to obtain the most influential PET climatic variable in Peninsular Malaysia using the FPM model and evaluate the climatic variables that have significant impact towards PET corresponding to the climate change that can provide a better water management supply. The finding from this paper can help in formulating a simpler ET model that can be used for Malaysia's climate.

2.0 METHODOLOGY

2.1 Study Area and Climate Data

Peninsular Malaysia is located at longitude 1°and 7°N and between latitude 100° to 120°E,with a total area of 132000km^2 [30]. Malaysia is dominated by the hot and humid climate and receives an annual rainfall of approximately 1400mm [30]. Two main monsoons happen in Malaysia every year, which are the Southwest Monsoon from late May to September and the Northeast Monsoon from November to March.

The Malaysia Meteorological Department (MMD) has provided datasets from 17 major meteorological stations (Figure 1) consisting of daily data observations of maximum, minimum and mean air temperature, wind speed measured at 10m height, relative humidity and daily sunshine energy for the period starting from 1 January 1985 till 31 December 2003. Figure 1 shows the map of Peninsular Malaysia with the 17 meteorological stations used in this study. The stations were selected based on the availability of data needed for the analysis.

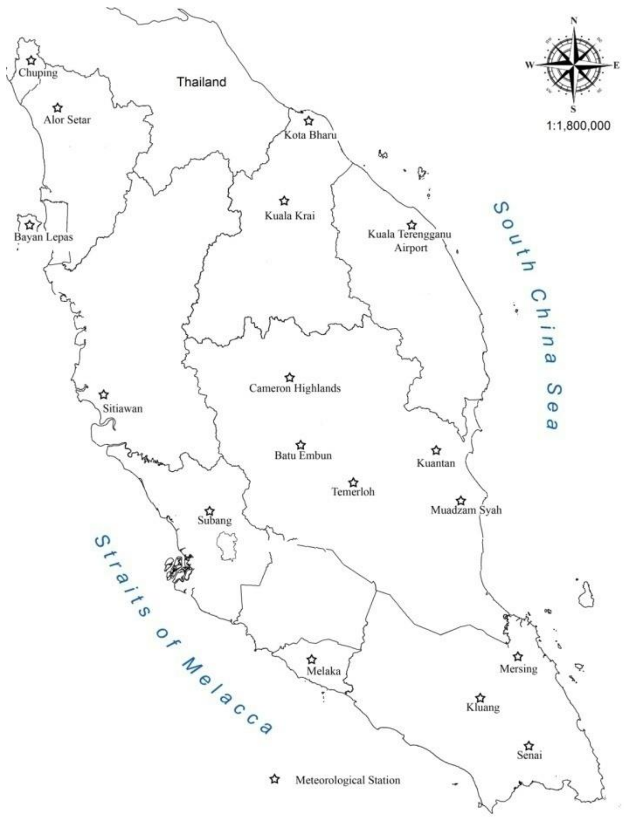

Figure 1 Location of Study Area in Peninsular Malaysia

2.2 Pre-Processing Data

Outlier detection and data imputation are the processes involved in this stage. According to [31] in [32], approximately 40% of data is 'dirty' in one way or another. Hence, the outlier detection is used to eliminate any outrageous values that might disturb the final result, and to enhance data reliability. Help from useful and powerful tools that automatically assist in eliminating outliers are necessary as it reduces the time consumed and tendency for error if done manually. The SPSS software was used as an aid in eliminating outliers and in the data imputation process. For the purpose of this study, the Tukey's boxplot outlier detection method and expectation-maximization (EM) method were used to remove outliers and impute data respectively. The Tukey's boxplot method is well-known due to its simplicity in displaying information on continuous univariate data. The concept of this method is to eliminate the values that lie outside the inner fence that has been detected as outliers. This new set of data is assumed to be a missing-at-random (MAR) dataset. As suggested by [33], regression and multiple imputation methods are applicable for the MAR dataset and as guided in Table 1, the EM method is used to predict the missing value dataset. This method provides excellent parameter estimates [34]. The EM method comprises of the E step and M step. The Estep finds the conditional expectation of the missing data for both observed values and current estimates of the variables. These expectations then substitute with the missing data. In the M-step, maximum likelihood estimates of the parameters are computed as though the missing data had been filled in.

FPM is a physically-based model that takes all climatic variables into the calculation. The FPM for calculating PET is [35]:

$$PET = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T_A+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (1)$$

where PET is the potential evapotranpiration (mm/day), R_n is the net radiation (MJ/m^2/day), G is the soil heat flux (MJ/m^2/day), γ is the psychrometric constant (kPa/°C), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure-temperature curve (kPa/°C), T_A is the average daily air temperature (°C) and u_2 is the average daily wind speed at 2m height (m/s). Therefore, grass height and bulk canopy resistance were assumed to be 0.12m and 70m/s respectively. The measured daily wind speed at the meteorological station obtained for this study was recorded at 10m height and the corrections were applied to determine its values at 2m height as according to the equation;

$$u_2 = u_z\frac{4.87}{\ln(67.8z - 5.42)} \qquad (2)$$

where u_z is the measured wind speed at z m above the ground surface (m/s) and z is the height of measurement above the ground surface (m).

$$\Delta = \frac{4098\left[0.6108exp\left(\frac{17.27T_A}{T_A+273.3}\right)\right]}{(T_A + 237.3)^2} \qquad (3)$$

$$\gamma = 0.665 \times 10^{-3}P \qquad (4)$$

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \qquad (5)$$

where P is the atmospheric pressure (kPa). The computation of all required data for the calculation followed the method and procedure in Chapter 3 of the FAO paper 56 [35].

The sensitivity of daily ET at each station was quantified with respect to air temperature, wind speed and solar radiation by making a ±20% (-20%, -15%, -10%, -5%, +5%, +10%, +15%, +20%) change in each variable while assuming other variables were fixed. The increment percentage is based on other literature review used by other workers [19, 23]. The base PET values were calculated without any changes in climatic variables. Then, each of the climatic variables was increased and decreased individually forming a new dataset of PET for each meteorological station.

Table 1 Mean, maximum, minimum and standard deviation value for climatic variables

	T_{max} (°C)	T_{min} (°C)	u (m/s)	RH (%)	R_S (MJ/m2/d)
Mean	31.6	22.9	3.1	84.4	17.0
Max	35.8	25.3	6.0	97.4	28.1
Min	27.1	20.0	0.5	71.2	4.3
Std Deviation	1.6	0.9	1.1	4.7	4.3

3.0 RESULTS AND DISCUSSION

Daily PET was calculated using the FPM model and analysed for its sensitivity by varying the climatic variables. Table 1 represents the minimum, maximum, mean and standard deviation for the climatic variables used in this study. Table 2 presents the annual average weather data of meteorological stations including PET and the corresponding site elevations and coordinates. The average temperature was 27.3°C while the highest and lowest temperatures recorded were 33°C and 15.4°C respectively, while the ranges of other variables were 14.1-18.4 MJ/m^2/day for solar radiation, 80.1-91.1 for relative humidity and 0.6-8.7m/s for wind speed. The calculated PET ranged between 2.6-4.6mm/d. The lowest temperature recorded at 15.4°C had resulted in 2.4 mm/d, the lowest measured PET. However, the highest temperature recorded did not result in the highest PET. The mean monthly PET for each station is illustrated in Figure 2. The highest mean PET value recorded was 5.17mm/month in March at the Alor Setar station, while the lowest mean PET value was 2.26mm/month in December at the Cameron Highlands station.

The amount of percent change in PET with respect to change in climatic variables is given in Table 3 and illustrated in Figure 3 for all 17 stations around Peninsular Malaysia. Solar radiation shows the most significant effect on the percent change of PET at all stations. Temperature is the second best influential climatic variable at all stations except at the Alor Setar and Temerloh stations where temperature is the least influential climatic variable on PET change since these two stations have similar climatic data. Wind speed shows the least effects towards PET. Results obtained indicate that with 5%, 10%, 15%, and 20% solar radiation increases, the PET increased by 4%, 7.2%, 10.8% and 14.4% respectively. The decrease in solar radiation shows similar negative percentage as the increasing percentage. The percentage change of wind speed shows a significant change towards PET. Decreases in wind speed by 5%, 10%, 15%, 20% decreased PET by 0.23, 0.46, 0.69 and 0.93 respectively. The change in PET increases with the percentage of climatic variable for wind speed at all stations except for the Cameroon Highlands station which showed otherwise. This may be due to the analysis which used a default value of a=0.25 and b=0.5 as recommended. However,[36] stressed that these values should not be used for high elevation regions. A further calibration study of these two values can be done. The percentage of relative humidity at Cameron Highlands is the highest and this may also affect the percentage of PET. High relative humidity causes the air to be in a saturated state. Hence, the air can no longer contain the evaporated air molecules [23].

4.0 CONCLUSION

The PET sensitivity analysis in Peninsular Malaysia was conducted using data from 17 meteorological stations around Peninsular Malaysia from the year 1987 till 2003. The climatic variables tested by using FPM are temperature, wind speed and solar radiation. The result indicates that solar radiation has caused more effect on PET, followed by temperature and wind speed. With the change of ±20% in solar radiation, the PET values had varied ±14%. With respect to the ±20% of air temperature, the change in PET was more than ±4%, while the change of ±20% in wind speed had caused a mere±1% change in PET. While the climatic variables at all stations revealed a positive correlation to the increase in all climatic variables, the wind speed at the Cameron Highlands station showed a negative correlation.

The PET sensitivity analysis conducted in this study can be useful in formulating a simpler ET equation derived from FPM. For a developing country like Malaysia, sensitivity analysis can still be considered as lacking. Information gathered in this study can help in managing both domestic and agricultural water supply.

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Table 2 Summary of weather stations site characteristics used in this study

ID	Station	Latitude (N)	Longitude (E)	MSL (m)	Temperature Max (°C)	Temperature Min (°C)	Rs (MJ/m2/d)	u (m/s)	RH (%)	PET mm/day
48603	Alor Setar (AS)	6° 12'	100° 44'	4.0	32.6	23.7	18.3	8.7	82.2	4.6
48642	Batu Embun (BE)	3° 58'	102° 21'	59.5	32.6	22.8	17.5	6.6	86.5	3.9
48601	Bayan Lepas (BL)	5° 18'	100° 16'	2.8	31.6	24.4	17.9	1.7	80.9	3.9
48632	Cameron Higlands (CH)	4° 28'	101° 22'	1545.0	22.5	15.4	14.1	1.9	91.1	2.6
48604	Chuping (Chu)	6° 29'	100° 16'	21.7	32.8	23.7	18.4	1.5	82.6	4.0
48672	Kluang (Klu)	2° 01'	103° 19'	88.1	31.9	23.1	16.0	1.1	86.5	3.4
48615	Kota Bharu (KB)	6° 10'	102° 17'	4.6	31.5	23.9	18.4	2.1	81.5	4.0
47616	Kuala Krai (KKrai)	5° 32'	102° 12'	68.3	32.8	22.6	17.4	0.6	86.4	3.7
48618	Kuala Terengganu Airport (KT)	5° 23'	103° 06'	5.2	31.6	23.8	17.8	2.0	83.0	3.9
48657	Kuantan (Ktn)	3° 47'	103° 13'	15.3	32.0	23.3	16.4	2.0	84.4	3.6
48665	Melaka (Mlk)	2° 16'	102° 15'	8.5	32.2	23.6	17.2	1.5	82.7	3.8
48674	Mersing (Ms)	2° 27'	103° 50'	43.6	30.9	23.3	17.0	2.7	86.7	3.6
48649	Muadzam Syah (Mdz)	3° 03'	103° 05'	33.3	32.4	22.8	16.4	8.2	85.7	3.9
48679	Senai (Sn)	1° 38'	103° 40'	37.8	32.1	22.8	15.3	1.3	86.1	3.3
48620	Sitiawan (Stwn)	4° 13'	100° 42'	7.0	32.3	23.3	17.4	1.2	84.6	3.7
48647	Subang (Sbg)	3° 07'	101° 33'	16.5	32.8	23.9	15.8	1.5	80.1	3.6
48653	Temerloh (Tm)	3° 28'	102° 23'	39.1	33.0	23.0	17.0	7.6	84.3	4.1
MEAN					**31.6**	**22.9**	**17.0**	**3.1**	**84.4**	**3.7**

R_s:Solar radiation; RH:Relative humidity; u: Wind speed

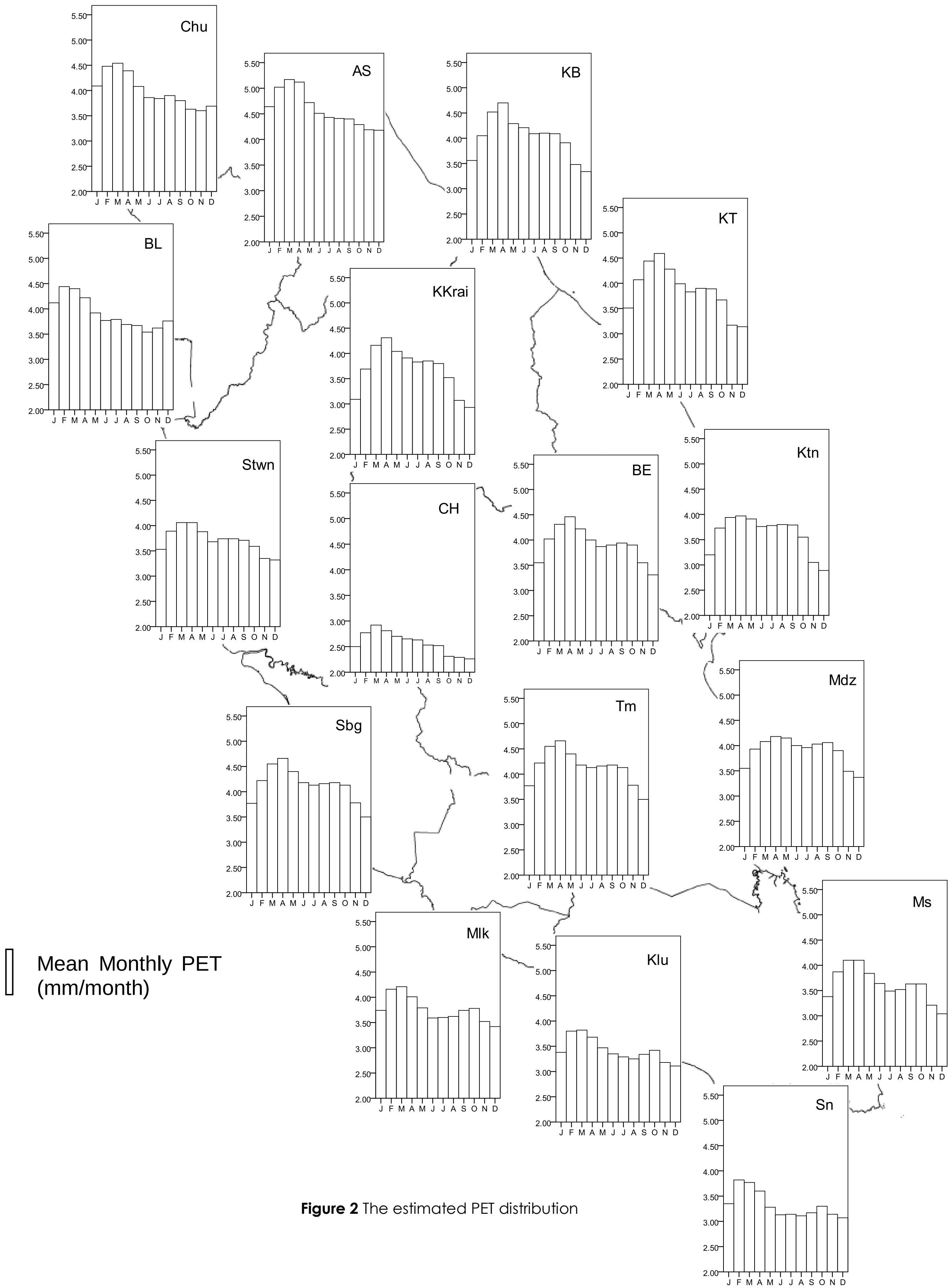

Figure 2 The estimated PET distribution

Table 3 Percent change of PET correspond to climatic variables

Station	Climatic Variables	Change in ET with respect in climatic variables							
		-20%	**-15%**	**-10%**	**-5%**	**+5%**	**+10%**	**+15%**	**+20%**
Alor Setar	T	-0.26	-0.22	-0.16	-0.08	0.10	0.20	0.32	0.44
	U	-2.42	-1.78	-1.17	-0.57	0.55	1.09	1.61	2.11
	Rs	-9.91	-7.43	-4.96	-2.48	2.48	4.96	7.43	9.91
Baru Embun	T	-2.89	-2.17	-1.44	-0.72	0.72	1.43	2.13	2.82
	U	-0.98	-0.73	-0.48	-0.23	0.23	0.45	0.67	0.88
	Rs	-12.11	-9.08	-6.06	-3.03	3.03	6.06	9.08	12.11
Bayan Lepas	T	-4.37	-3.23	-2.12	-1.04	1.01	1.98	2.91	3.81
	U	-1.19	-0.89	-0.59	-0.29	0.29	0.58	0.86	1.14
	Rs	-15.07	-11.30	-7.54	-3.77	3.77	7.54	11.30	15.07
Cameron Highlands	T	-6.18	-4.59	-3.03	-1.50	1.47	2.91	4.32	5.70
	U	0.75	0.56	0.37	0.18	-0.18	-0.36	-0.53	-0.70
	Rs	-14.89	-11.17	-7.44	-3.72	3.72	7.44	11.17	14.89
Chuping	T	-5.11	-3.77	-2.47	-1.21	1.16	2.28	3.35	4.38
	U	-0.80	-0.59	-0.39	-0.20	0.19	0.39	0.58	0.77
	Rs	-15.86	-11.90	-7.93	-3.97	3.97	7.93	11.90	15.86
Kluang	T	-6.06	-4.46	-2.92	-1.43	1.37	2.69	3.95	5.16
	U	-0.34	-0.26	-0.17	-0.09	0.08	0.17	0.25	0.34
	Rs	-16.37	-12.28	-8.19	-4.09	4.09	8.19	12.28	16.37
Kota Bharu	T	-4.16	-3.08	-2.02	-1.00	0.97	1.90	2.80	3.67
	U	-1.21	-0.90	-0.60	-0.30	0.29	0.58	0.87	1.16
	Rs	-14.75	-11.06	-7.37	-3.69	11.06	7.37	11.06	14.75
Kuala Krai	T	-6.60	-4.85	-3.16	-1.55	1.48	2.90	4.25	5.53
	U	-0.17	-0.13	-0.08	-0.04	0.04	0.08	0.13	0.17
	Rs	-17.19	-12.89	-8.60	-4.30	4.30	8.60	12.89	17.19
Kuala Terengganu Airport	T	-4.60	-3.40	-2.23	-1.10	1.06	2.09	3.08	4.03
	U	-0.98	-0.73	-0.48	-0.24	0.24	0.47	0.70	0.93
	Rs	-15.06	-11.30	-7.53	-3.77	3.77	7.53	11.30	15.06

Station	Climatic Variables	Change in ET with respect in climatic variables							
		-20%	-15%	-10%	-5%	+5%	+10%	+15%	+20%
Kuantan	T	-4.68	-3.46	-2.27	-1.12	1.08	2.12	3.12	4.09
	u	-0.94	-0.70	-0.46	-0.23	0.23	0.45	0.67	0.89
	Rs	-15.04	-11.28	-7.52	-3.76	3.76	7.52	11.28	15.04
Melaka	T	-4.89	-3.61	-2.36	-1.16	1.12	2.20	3.23	4.22
	u	-0.92	-0.69	-0.46	-0.23	0.22	0.45	0.67	0.89
	Rs	-15.42	-11.55	-7.68	-3.80	3.94	7.82	11.69	15.56
Mersing	T	-4.97	-3.68	-2.43	-1.20	1.16	2.30	3.39	4.45
	u	-0.53	-0.39	-0.26	-0.13	0.13	0.25	0.38	0.50
	Rs	-14.77	-11.08	-7.38	-3.69	3.69	7.38	11.08	14.77
Muadzam Syah	T	-1.50	-1.14	-0.77	-0.39	0.39	0.79	1.19	1.59
	u	-1.67	-1.23	-0.80	-0.40	0.38	0.75	1.11	1.46
	Rs	-10.62	-7.96	-5.31	-2.65	2.65	5.31	7.96	10.62
Senai	T	-5.63	-4.15	-2.72	-1.33	1.28	2.52	3.70	4.84
	u	-0.54	-0.40	-0.27	-0.13	0.13	0.26	0.39	0.52
	Rs	-15.85	-11.89	-7.92	-3.96	3.96	7.92	11.89	15.85
Sitiawan	T	-5.74	-4.23	-2.77	-1.36	1.31	2.56	3.76	4.91
	u	-0.51	-0.38	-0.25	-0.13	0.13	0.25	0.37	0.50
	Rs	-16.22	-12.16	-8.11	-4.05	4.05	8.11	12.16	16.22
Subang	T	-3.98	-2.94	-1.93	-0.95	0.91	1.79	2.64	3.45
	u	-1.46	-1.09	-0.72	-0.36	0.36	0.71	1.06	1.41
	Rs	-14.89	-11.17	-7.44	-3.72	3.72	7.44	11.17	14.89
Temerloh	T	-1.14	-0.87	-0.59	-0.30	0.31	0.62	0.93	1.25
	u	-1.97	-1.46	-0.96	-0.47	0.46	0.90	1.33	1.74
	Rs	-10.74	-8.05	-5.37	-2.68	2.68	5.37	8.05	10.74
MEAN	**T**	**-4.28**	**-3.17**	**-2.08**	**-1.03**	**0.99**	**1.96**	**2.89**	**3.78**
	u	**-0.93**	**-0.69**	**-0.46**	**-0.23**	**0.22**	**0.44**	**0.65**	**0.86**
	Rs	**-14.40**	**-10.80**	**-7.20**	**-3.60**	**4.04**	**7.21**	**10.81**	**14.41**

T;temperature , u;wind speed, Rs;solar radiation

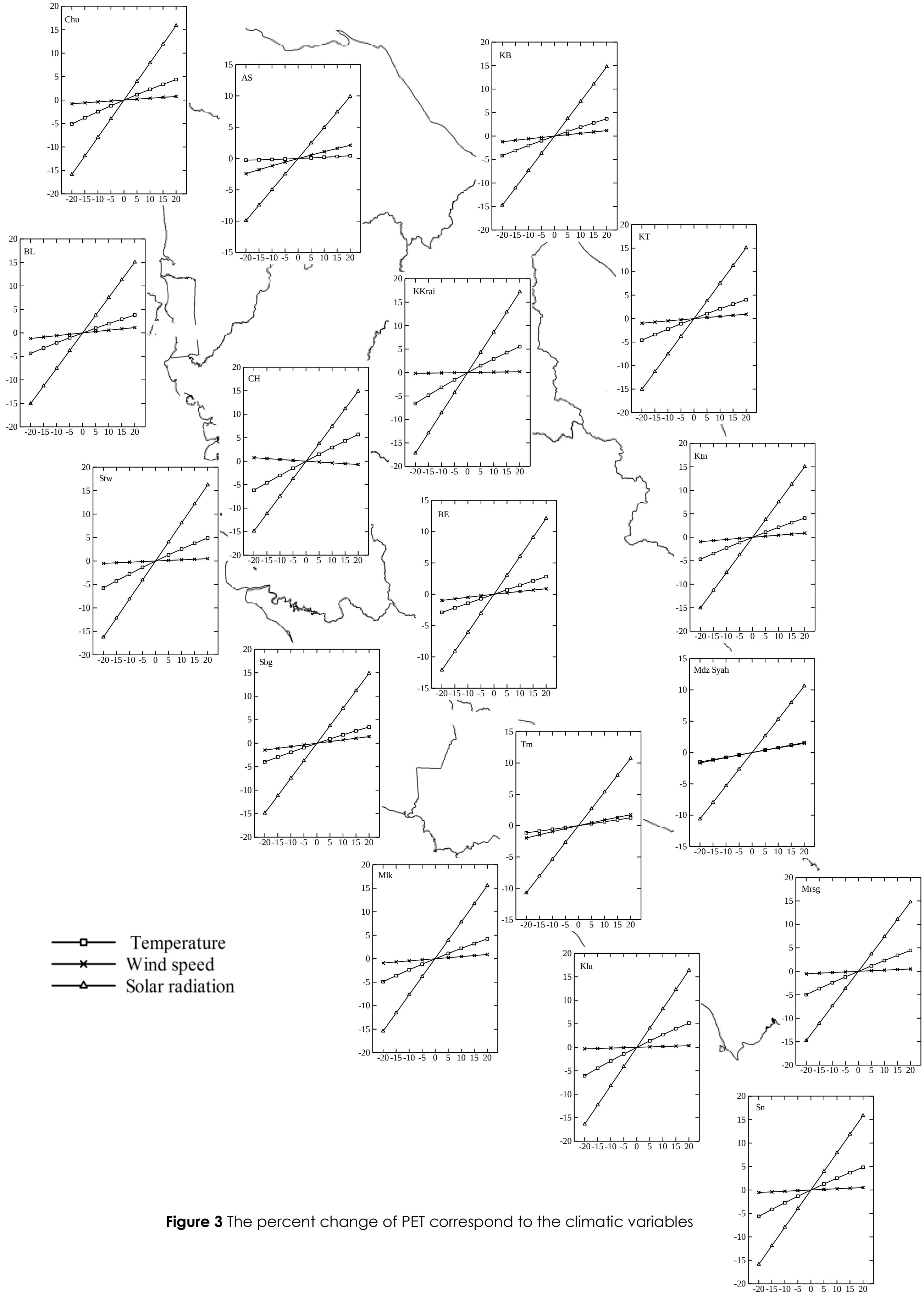

Figure 3 The percent change of PET correspond to the climatic variables

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