Estimation of Potential Evapotranspiration for a Coastal Savannah Environment by Comparison of Different Methods

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Abstract: Six potential evapotranspiration models namely, Penman-Monteith, Hargreaves-Samani, Priestley-Taylor, IRMAK1, IRMAK2 and TURC were used to estimate daily PET (Complete name) values at Atomic-Kwabenya in the coastal savannah environment of Ghana for the year 2005. The objectives of the study were to compare PET values generated by the six models and comparison ofof different methods for for PET estimatiion. Cross comparison analysis showed that the daily estimates of PET of Hargreaves-Samani model correlated reasonably (r = 0.82) with estimates by the Penman-Monteith model. Additionally, PET values by the Priestley-Taylor and TURC models were highly correlated (r = 0.99) as well as those generated by IRMAK2 and TURC models (r = 0.96). Statistical analysis, based on pair comparison of means, showed that daily PET estimates of the Penman-Monteith model were not different from those of Priestley-Taylor model for the Kwabenya-Atomic area located in the coastal savannah environment of Ghana. Therefore, the Priestley-Taylor model could be used, in place of the Penman-Monteith model, to estimate daily PET for the Atomic-Kwabenya area of the coastal savannah environment of Ghana. The Hargreaves-Samani model could also be used to estimate PET for the study area because its PET estimates correlated reasonably with those of the Penman-Monteith model (r = 0.82) and it requires only air temperature measurements as inputs.

Key words: Potential evapotranspiration · Models · Comparison

INTRODUCTION

Potential evapotranspiration (PET) is the maximum amount of water lost to the atmosphere via evaporation and transpiration from vegetation [1]. Potential evapotranspiration data are required for effective scheduling and management of irrigation and estimation of water budget and recharge of aquifer [2]. Additionally, PET estimates are required by crop models such as DSSAT [3], WOFOST [4], SWAP [5] and EPIC [6] to simulate crop development and productivity, water and solute dynamics in response to weather and management conditions.

Although PET can be measured directly by lysimeters, the process is tedious, time consuming and expensive [7]. Several models have, therefore been developed for estimating PET based mainly on weather data. Available PET models are Blaney-Criddle model [8], Hargreaves and Samani model [9], Makkink model [10], Penman-Monteith model [11] and Priestley and Taylor model [12]. These models vary in complexity and data requirement with the Penman-Monteith model [11] being the most complex and it requires the full range of weather variables. Consequently, the Penman-Monteith model [11] can only be used to estimate daily PET values at few locations where detailed daily weather variables are collected.

Despite its use for only areas that have detailed weather variables, the Penman-Monteith model [11] is universally accepted [13, 14]. This is because the model is based on detailed physical principles, it is an energy conservation equation [15] and it takes into account all climatic factors. As a result, the Penman-Monteith model [11] is considered the standard method for estimating PET [16] to which other PET models are compared.

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It is, therefore, imperative to estimate PET values using different models and assess their performance against each other. Additionally, assessing the performance of other PET models against the Pen-Monteith PET model is helpful to identify which model to use in place of the Penman-Monteith model when detailed weather variables are lacking. The objectives of this study, therefore, are to (i) perform cross comparison of daily PET values generated by the six different models and (ii) identify the PET model (s) which could be used in place of the standard Penman-Monteith model for the Atomic-Kwabenya area located in the coastal savannah environment of Ghana. Write the objective of this study here.

MATERIALS AND METHODS

Description of Models: The PET models used in the study vary in complexity and data requirements are described as follows:

Penman-Monteith (PM) Model: The PM model [11] is a combination method and estimates the flux of energy and moisture between the atmosphere, land and water surfaces [15]. The model is complex and requires daily weather variables such air temperature, humidity, wind speed and solar radiation. The model is described as.

$$PET = \frac{0.408\Delta(\text{Rn - G}) + \gamma\dfrac{900}{Ta + 273}u(e_s - e_a)}{\Delta + \gamma(1 + 0.34u)}$$

Where PET is the potential evapotranspiration (mm day^{-1}), Δ is the slope of the saturation vapour pressure temperature curve (kPa°C^{-1}), Rn is the net radiation (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2}day^{-1}) and assumed zero in this study because of the daily time step used for PET computation [11], γ is the psychrometric constant (KPa°C^{-1}), Ta is the daily mean air temperature (°C), u is the wind speed (m s^{-1}), e$_s$ is the saturation vapour pressure (kPa) and e$_a$ is the actual vapour pressure (kPa).

Hargreaves-Samani (HS) Model: The HS model [9] requires daily maximum and minimum air temperatures and the extra terrestrial solar radiation computed using latitude and day of the year [17, 18]. Therefore, air temperature is the only measured weather input required. The HS model [9] for estimating daily PET is, therefore, expressed as:

$$PET = \frac{(0.0023 \times \text{Ra})(\text{Tmax - Tmin})^{0.5}(Ta + 17.8)}{\lambda}$$

Where λ is the latent heat of evaporisation (MJ kg^{-1}), Tmax and Tmin are the maximum and minimum daily air temperature (°C), respectively, Ta is the mean daily air temperature (°C) and Ra is the extra terrestrial solar radiation (MJ m^{-2} day^{-1}) and was computed based on the procedure outlined by Campbel [19]. The latent heat of vapourisation (λ) is estimated as:

$$\lambda = 2.501 - 0.002361Ta$$

Where Ta is the daily mean temperature (°C).

Priestley-Taylor (PT) Model: Priestley-Taylor [12] developed this model for estimating daily PET using the daily mean air temperature and net solar radiation as inputs. This model is a simplified combination equation with an empirical coefficient to account for mass transfer effects [15]. According to the model,

$$PET = 1.26\frac{\Delta}{\lambda(\Delta + \gamma)}(Rn - G)$$

Where PET is the potential evapotranspiration (mm d^{-1}), Rn is the net radiation (MJ m^{-2} d^{-1}), G is the soil heat flux density (MJ m^{-2} d^{-1}) which was assumed to be zero in this study because of the daily time step for the computation [11], λ is the latent heat of vapourisation (MJ kg^{-1}), Δ is the slope of the saturation vapour pressure temperature curve (kPa) and γ is the psychrometric constant (kPa°C^{-1}). The psychrometric constant was estimated as:

$$\gamma = \frac{CpP}{0.622\lambda}$$

Where Cp is the specific heat of moist air at constant pressure (0.001013 MJ kg^{-1} °C^{-1}), P is the atmospheric pressure (kPa) computed as:

$$P = 101.3 - 0.01055H$$

Where H is the elevation (m) of the site.

IRMAK1 Model: This PET model is basically multi-linear regression models developed by Irmak *et al.* [20] for the humid environments using as in puts the daily solar shortwave radiation and daily mean air temperature data.

The daily potential evapotranspiration (PET) is estimated as:

$$PET = -0.611 + 0.146\,Rs + 0.079\,Tmean$$

Where *PET* is the evapotranspiration (mm d^{-1}), Rs is the solar shortwave radiation (MJ m^{-2} d^{-1}) and Tmean is the daily mean air temperature (°C).

IRMAK2 Model: Irmak *et al.* [20] developed this PET model for the humid environments using as inputs the daily net solar radiation and mean daily air temperature data. The daily potential evapotranspiration (PET) is estimated as:

$$PET = 0.489 + 0.289\,Rn + 0.079\,Tmean$$

Where PET is the potential evapotranspiration (mm d^{-1}), Rn is the net radiation (MJ m^{-2} d^{-1}) and Tmean is the daily mean air temperature (°C).

TURC Model: The TURC model [21] for estimating daily PET uses daily values of the mean relative humidity (RH in percent), mean air temperature (°C) and solar radiation (cal cm^{-2} d^{-1}). The daily potential evapotranspiration (PET) is estimated as:

When *RH* < 50 percent,

$$PET = 0.013\frac{Tmean}{(Tmean+15)}(Rs+50)(1+\frac{50-RH}{70})$$

and when *RH* > 50 percent, $\frac{50-RH}{70} << 1$ and Eq. (9) reduces to the expression

$$PET = 0.013\frac{Tmean}{(Tmean+15)}(Rs+50)$$

Where *PET* is the potential evapotranspiration (mm d^{-1}), *Tmean* is the daily mean air temperature (°C), R*s* is the daily solar radiation (ly d^{-1} or cal cm^{-2} d^{-1}) and *RH* is the daily mean relative humidity (in percent).

Study Area and Data Used: The study area is the Atomic-Kwabenya which is situated on latitude 05° 40'N and longitude 0° 13'W in the coastal savannah environment of Ghana. The site is about 76.0 m above sea level and 20 km north of Accra (Ghana), which is located close to the sea. The daily weather variables for one calendar year

(2005) were used for the study. Weather variables collected daily at the site were maximum and minimum air temperatures, relative humidity, solar radiation and wind speed. The data were used to generate daily PET values using the six models described above.

Evaluation of Performance of the PET Models: Simple linear correlation coefficient values were employed to assess how the estimated PET values generated by any two models are correlated. Additionally, pair comparison of mean daily PET values, based on student t-analysis, assisted in the selection of the best PET models whose performance closely matched that of the Penman-Monteith model.

RESULTS

The daily PET predicted by the six models varied during the year, reflecting the changing weather conditions and atmospheric evapotranspirative demand (Fig. 1). The models predicted similar trend in PET values over the year. Additionally, the times at which the maximum and minimum PET occurred during the year were also similar (Fig. 1).

Generally, daily PET values for the year predicted by IRMAK2 and PET were higher than those of the other four models, with IRMAK2 predicting the highest PET values and PET the lowest PET values. The comparatively low PET values generated by PT model could be explained by the fact that the model does not use daily temperature values as input. Additionally, IRMAK1 predicted fairly uniform PET values throughout the year as the range between the maximum and minimum PET values is small and the lowest (Fig. 1). This suggests that IRMAK1 predictions are not very sensitive to changing weather variables.

Based on cross comparison (Table 1) using the simple linear correlation coefficient (r), PET values for PT correlated highly with those of TURC (r = 0.99) and IRMAK2 (r = 0.96). Similarly, PET estimates by TURC and IRMAK2 models correlated highly (r = 0.96). On the other hand, PET values generated by PT and HS were weakly correlated (r = 0.39) and those for the PM and IRMAK1 models were also weakly correlated (r = 0.40). The lowest correlation was found between PT and HS. However, PET values generated by PM model positively correlated well (r = 0.82) with only those of the HS model (Table 1), indicating that PM and HS PET predictions were in similar trend.
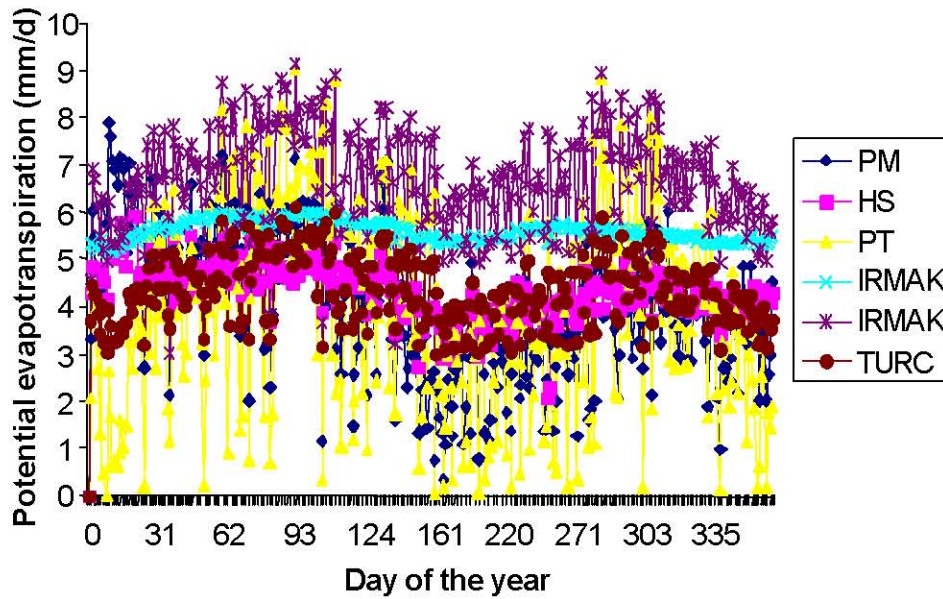
Fig. 1: Time course of daily PET for the year 2005 as predicted by six models at Kwabenya-Atomic area located in the coastal savannah environment of Ghana.
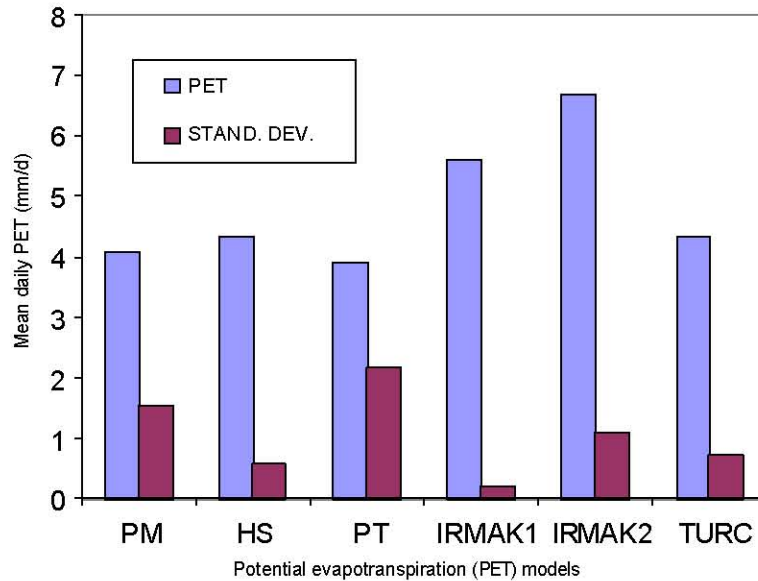

Fig. 2: Mean daily PET and its standard deviation for the different PET models.

Table 1: Simple correlation coefficients (r) for cross comparison of PET values generated by different models. The r-values are significantly different from zero at $p = 0.01$

PET Model	PET Model					
	PM	HS	PT	IRMAK1	IRMAK2	TURC
PM		0.82	0.58	0.40	0.62	0.63
HS	0.82		0.39	0.45	0.41	0.45
PT	0.58	0.39		0.49	0.96	0.99
IRMAK1	0.40	0.45	0.49		0.51	0.58
IRMAK2	0.62	0.41	0.96	0.51		0.96
TURC	0.63	0.45	0.99	0.58	0.96	

Table 2: Computed t-values for pair comparison of mean daily PET generated by six models. The tabulated student t-value is 2.576 at p = 0.01

PET Model	PET Model					
	PM	HS	PT	IRMAK1	IRMAK2	TURC
PM		2.847	1.129	17.303	24.467	2.818
HS	2.847		3.454	36.290	33.936	0.105
PT	1.129	3.454		13.881	20.406	3.438
IRMAK1	17.303	36.290	13.881		17.464	29.925
IRMAK2	24.467	33.936	20.406	17.464		32.042
TURC	2.818	0.105	3.438	29.925	32.042	

The mean daily PET for the year ranged from 3.9 mm d^{-1} for PT to 6.7 mm d^{-1} for IRMAK2, with PET values for the other four PET models ranging between 4.1 mm d^{-1} and 5.6 mm d^{-1} (Fig. 2). Though TURC and HS had about the same mean daily PET value of 4.3 mm d^{-1} (Fig. 2), the correlation between their daily PET values was 0.45 (Table 1). This poor correlation between HS and TURC PET values, despite similar daily mean PET values for the year, is due to the fact that PET values for HS varied more widely during the year compared to those of TURC (Fig. 1). Additionally, the comparatively high mean daily PET values by IRMAK2 compared to values by the other models, are due to the fact that the model was developed using data from the humid environment of the United States (Irmak *et al.*, 2003), an environment different from the non-humid environment of the coastal savannah region of Ghana. Cross comparison of mean daily PET values, based on student t-test analysis at 1% level, showed that the mean daily PET estimates by PM are not different from those of PT; also HS and TURC estimated similar mean daily PET values (Table 2).

DISCUSSION

Time course of daily PET estimates by the Modified Penman-Monteith [11], Hargreaves-Samani [9], Priestley-Taylor [12], Irmak *et al.* [20] and Turc [21] models followed a similar trend. The Penman-Monteith model [11] produced daily PET values that correlated reasonably (r = 0.82) with only PET values of the Hargreaves-Samani model [9]. Daily PET values for Priestley-Taylor [12] and TURC [21] models and for TURC [21] and IRMAK2 [20] models were highly correlated (r = 0.96). The mean daily PET values generated by the Penman-Monteith [11] and Priestley-Taylor [12] models were similar. Additionally, the Hargreaves-Samani [9] and TURC [21] models generated similar value for the mean daily PET. We, therefore, conclude that the Priestley-Taylor model [12] could be used in place of the Penman-Monteith model [11] to estimate daily PET for the Atomic-Kwabenya area located in the coastal savannah environment of Ghana. However, in view of the fact that PET estimates by the Hargreaves-Samani (1985) model requires only air temperature as input and its PET estimates reasonably correlated with those by the Penman-Monteith model [11], the Hargreaves-Samani model [9] could be used in place of the Penman-Monteith model [11] to estimate daily PET data for the Atomic-Kwabenya area, especially when detailed weather variables are not available.

REFERENCES

1. Jensen, M.E., R.D. Burman and R.G. Allen, 1990. Evapotranspiration and irrigation water requirements, American Society of Civil Engineers, New York.

2. Sharma, M.L., 1985. Estimating evapotranspiration, Advances in Irrigation. Hillel, D (ed.), Academic Press, London, pp: 213-281.

3. Tsuji, G.T., G. Uehara. and S. Salas, 1994. DSSAT version 3.0, Honolulu, Hawaii, University of Hawaii.

4. Van Diepen, V.A., J. Wolf, H. van Keulen and C. Rappolt, 1989. WOFOST: a simulation model of crop production. Soil Use Management, pp: 5: 16-24.

5. Kroes, J.G., J.C. Van Dan, J. Huygen and R.W. Vervoort, 1999. User's guide of SWAP version 2.0. Simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant environment. Technical Document 48, Alterra Green World Research, Wageningen, Report 81, Department of Water Resources, Wageningen University, pp: 127.

6. Williams, J.R., C.A. Jones and P.T. Dyke, 1984. A modeling approach to determining the relationship between erosion and soil productivity. TRANSACTION of the ASAE, 27: 129-144.

7. Alkaeed, O., C. Flores, K. Jinno and A. Tsutsumi, 2006. Comparison of several reference evapotranspiration methods for Itoshima Peninsula area, Fukuoka, Japan. Memoirs of the Faculty of Engineering, Kyushu University, 66(1): 1-14.

8. Blaney, H.F. and W.D. Criddle, 1950. Determining Water Requirements in Irrigated Area from Climatological Irrigation Data, US Department of Agriculture, Soil Conservation Service, Techical, 96: 48.

9. Hargreaves, G.H. and Z.A. Samani, 1985. Reference crop evapotranspiration from temperature. Appl. Engineering in Agri., 1(2): 96-99.

10. Makkink, G.F., 1957. Testing the Penman formula by means of lysimeters. J. Inst. of Water Eng., 11: 277-288.

11. Allen, R.G., L.S. Pereira, D. Raes and M. Smith, 1998. Crop Evapotranspiration – Guidelines for computing Crop Water Requirements, FAO Irrigation and Drainage, 56, FAO, ISBN 92-5-104219-5.

12. Priestley, C.H.B. and R.J. Taylor, 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Mon. Weath. Rev., 100: 81-92.

13. McKenney, M.S. and N.J. Rosenberg, 1993. Sensitivity of some potential evapotranspiration estimation methods to climate change. Agricultural and Forest Meteorol., 64: 81-110.

14. Smith, M., R. Allen, J.L. Monteith, A. Perrier, L. Santos Pereira and A. Segeren, 1992. Report on the Expert Consultation on Revision of FAO Methodologies fror Crop Water Requirements, Land and Water Development Division, Food and Agriculture Organisation of the United Nations, Rome.

15. Lee, T.S., M.M.M. Najim and M.H. Aminul, 2004. Estimating evapotranspiration of irrigated rice at the West Coast of the Peninsular of Malaysia. J. Appl. Irrigation Sci., 39: 103-117.

16. Walter, I.A., R.G. Allen, R. Elliott, B. Mecham, M.E. Jensen, D. Itenfisu, T.A. Howell, R. Snyder, P. Brown, S. Eching, T. Spofford, M.K. Hattendorf, R.H. Cuenca, J.L. Wright and D. Martin, 2000. ASCE Standardized reference evapotranspiration equation. In: Evans, R.G., B.L. Benham and T.P. Trooien (eds.) Proc. National Irrigation Symposium, ASAE, Nov. 14-16, 2000, Phoenix, AZ. pp: 209-215.

17. Duffie, J.R. and W.A. Beckman, 1980. Solar engineering of thermal processes. John Wiley and Sons, New York, New York.

18. London, J. and C. Frohlich, 1982. Extended abstracts presented at the symposium on the solar constant and the spectral distribution of solar radiance. International Association of Meteorology and Atmospheric Physics, 3rd Scientific Assembly, Hamburg, Germany, pp: 17-128.

19. Campbell, G.S., 1985. Soil Physics with Basic: Transport Models for Soil-Plant Systems. Elsevier, New York, NY.

20. Irmak, S., A. Irmak, R.G. Allen and J.W. Jones, 2003. Solar and net radiation-based equations to estimate reference evaporation in humid climates. J. Irrigation and Drainage Engineering, ASCE, 129(5): 336-347.

21. Turc, Y.L., 1961. Evaluation de besoins en eau d'irrigation, ET potentielle. Ann. Agron., 12: 13-49.