EFFECTS OF DAILY NET RADIATION MODEL EXTRACTED FROM MODIS ON DAILY REFERENCE EVAPOTRANSPIRATION

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ABSTRACT

The phenomenon of evapotranspiration (ET) has long been recognized as a key process and plays an essential role in the exchange of energy and mass between the hydrosphere, atmosphere and biosphere. This is one of the important parameters in the model study of global climate change. Our study aimed to clarify the following issues using net radiation R_n model derived from satellite data (Modis) to calculate the daily reference evapotranspiration ETo over Vietnam terrain. To achieve that goal, 3 daily average net radiation models R_{nd} have been used: (1) net radiation model derived from satellite data (Modis), R_{ndRS}. (2) Net radiation model of the FAO-56 Penman-Manteith, R_{ndFAO} and (3) net radiation model of ASCE-EWRI according Irmak, R_{ndIR}. Three methods for calculating daily reference evapotranspiration ETo are the FAO-56 Penman-Manteith (FAO-56 PM), Priestley-Taylor (PT), and the method of multiple regression proposed by Irmak (IR) at the Institute of the Environment and Water Resources of the of American Seciety of Civil Engineers (ASCE-EWRI). The study results showed that using the model R_{ndRS} can be replaced alternative model R_{ndFAO} in FAO-56 PM method with Root Mean Square Error, RMSE = 5.04%, Mean Absolute Error, MAE = 3.85%, and the correlation coefficient between ETo_FAO (R_{ndFAO}) and ETo_FAO (R_{ndRS}), R^2 = 0.8206.

1. INTRODUCTION

The phenomenon of evapotranspiration (ET) has long been recognized as a key process and plays an essential role in the exchange of energy and mass between the hydrosphere, atmosphere and biosphere. Land surface evapotranspiration, ET is the process of converting volumes of water from ground surface (evaporation) and vegetation (transpiration) into the atmosphere. Actual ET estimates are important in modeling the water balance in the basin, serving management and agricultural irrigation in the weather forecast. However, it is difficult to directly measure ET; and in most applications, ET is estimated using theoretical-experimental models. Reliable quantitative ET is not only a critical task for water resource management, but also a challenge for scientists.

Net radiation (R_n) is the amount of solar energy that vegetation, water and ground absorb, and is a strong driving force in the process of evaporation of water as an unlimited resource. Therefore, the accuracy of R_n affect reliability ET determined from the different models, for example combined model FAO-56 Penman-Monteith (FAO-56 PM) [1, 2, 7]; and the other surface energy balance models [2, 5, 7]. R_n normally is not be measured directly at the weather station due to restrictions on economic and technical condition. R_n primarily estimated from the theoretical-experimental equations [1, 2, 5, 7]. The equations have substantially different requirements for their inputs as calibration parameters, methods used to calculate the parameters of atmospheric turbidity, emission coefficient, and net long waves radiation. The climate variables commonly used in the R_n model including short-wave solar radiation, R_s; air temperature, actual vapor pressure and cloud cover fraction.

To evaluate and compare the effect of daily net radiation extracted from the Modis satellite data (R_{ndRS}) [1, 2, 3, 13, 15] to the results of reference evapotranspiration (ETo), the paper also refers to daily net radiation of the FAO-56 PM (R_{ndFAO}) [1, 2, 11] and daily net radiation as a function of Irmak's multiple regression (R_{ndIR}) [1, 5, 15] . At the same time, the three ETo methods are used: 1 / FAO-56 PM method (ETo_FAO) [1, 2.7], 2 / Priestley- Taylor method (ETo_PT) [6, 8, 11] and 3 / Irmak's multiple regression method (ETo_IR) [1, 5, 14].

2. MATERIALS AND METHODS

2.1 Input Data

Input materials include:

- Modis image acquisition date was on November 10, 2008 at 03:40:05, GTM (10:40:05, Hanoi local time (Table 1). Modis image geometry has been corrected in the Vietnam Datum System VN-2000. Some Modis products were taken to use: the surface temperature Ts; aerosol; land-surface emissivity coefficient of channels 31, 32.

- Digital Elevation Model, DEM of 90m resolution.

- The field data from 14 meteorological stations on the North Vietnam such as solar radiation incoming to land surface R_s, air temperature Ta, wind speed, pressure (by DEM) were collected in Table 2. Incoming solar radiation R_s of 14 meteorological stations were calculated by experimental formula under the number of effective daylight hours *n* for the North Vietnam in the period of three months. In our experiment, according Modis image acquisition date, incoming solar radiation R_s has been taken for the period of 3 months of September, October and November as follows: $R_s = 0.025 * n + 6.0$

Table 1. Some parameters of Modis image and DEM for North Vietnam

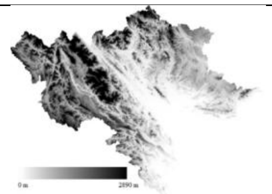
	Parameters		
Image ID	A2008313.h27v06		
Acquisition time	03:40:05 10-11-2008		
Sensor	Aqua		
Image level	1A		
RGB image	+		
Spatial resolution	1000 m	Modis image	DEM

Table 2. Meteorological data acquired at 14 stations on November 10, 2008

No	Station	Height Z (m)	Air temperature (°C)			Wind velocity (m/s)	Presure (kPa)	Daily incoming solar radiation Rs (from Meteorol. Data) [$W/m^2/d$]
			T_a	T_{min}	T_{max}			
	1	3	4			5	6	7
1	Ha Giang	123	27.5	13.4	25.4	0.5	100.027	**3020.324**
2	Lao Cai	93	24	13.8	24.0	0.75	100.343	**3008.209**
3	Lai Chau	52	23.2	14.0	23.2	0.25	100.776	**3000.940**
4	Tuyen Quang	219	24.3	15.2	24.3	0.75	99.014	**3008.209**
5	Lang Son	260	20.9	13.6	20.9	1.5	98.582	**3025.170**
6	Viet Tri	8	24	16.9	24.0	0.75	101.240	**3017.901**
7	Son La	627	24	10.5	22.1	1	94.710	**3032.440**
8	Lang	21	22.1	18.6	23.6	1.25	101.103	**3013.055**
9	Bai Chay	13	23.6	16.9	23.8	2.25	101.188	**3016.690**
10	Phu Lien	24	24	16.8	24.0	2.5	101.072	**3023.959**
11	Hoa Binh	4	24.1	15.2	24.1	1	101.283	**3027.594**
12	Nam Dinh	1	22.8	17.5	22.8	1.5	101.314	**3022.748**
13	Hoi Xuan	234	24.4	14.8	24.4	1.5	98.856	**2991.248**
14	Thanh Hoa	5	23.4	17.0	23.4	2.25	101.272	**3015.478**

2.2. Methods

2.2.1.Methods for calculating daily reference evapotranspiration

Method 1: *FAO-56 Penman-Monteith daily reference evapotranspiration, ETo_ FAO*

The FAO-56 Penman-Monteith equation (FAO-56 PM) is a grass reference equation that was derived from the ASCE equations by fixing h = 0.12 m for clipped grass and by assuming measurement heights of wind and air temperature at z_w = 2 m, z_T = 2 m, respectively; bulk surface resistance of 70 s m^{-1}, and albedo of 0.23. For 24-hour time steps, FAO-56 Penman-Monteith daily reference evapotranspiration, ETo_ FAO [2] is:

$$ETo\_FAO = \frac{0.048\Delta(R_{nd} - G) + \gamma \frac{900}{T + 273} U_2 (e_S - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

where: ETo_FAO = grass reference evapotranspiration [mm day^{-1}], Rn = net radiation at the crop surface [MJ m^{-2} day^{-1}], G = soil heat flux density [MJ m^{-2} day^{-1}], T = mean daily air temperature at 2 m height [°C], u_2 = wind speed at 2 m height [m s^{-1}], e_s = saturation vapor pressure [kPa], e_a = actual vapor pressure [kPa], e_s-e_a = vapor pressure deficit [kPa], Δ = slope of saturation vapor pressure temperature relationship [kPa $°C^{-1}$], γ = psychrometric constant [kPa $°C^{-1}$].

Method 2: *Priestley-Taylor daily reference evapotranspiration, ETo_PT*

Priestley-Taylor reference evapotranspiration, ETo_PT, is in the following form:

$$ETo\_PT = a \frac{\Delta}{\Delta + \gamma} \frac{Rnd}{\lambda} + b \quad (2)$$

Coefficients *a, b* in (2) have been calibrated in Priestley-Taylor equation (1972) of 1,26 and 0, respectively; calibrated in Europe (Switzerland), 1984, *a* = 0.90 ad *b* = 0; in Asia (Taiwan) *a* = 1.00 and *b* = 0 (*Chen, Yen, Lee, Lo,* 2005) [3].

Method 3: *Irmak (ASCE-EWRI) daily reference evapotranspiration, ETo_IR*

Irmak (ASCE-EWRI) used data for many years in the USA and has launched multiple regression to calculate the amount of evaporation, ETo_IR that is a function of average daily net radiation Rn and average daily temperature Ta (*Irmak, et al., 2003*):

$$ETo\_IR = 0.289R_{nd} + 0.023T_a + 0.489 \quad (3)$$

2.2.2. Daily net radiation models, R_{nd}

Model 1: *Daily net radiation model in FAO-56 PM method, (RndFAO)*

Daily net daily radiation model in FAO-56 PM method, RndFAO [1, 2] is in the following presentation:

$$R_{nd} = (1 - \alpha)R_s - f\varepsilon\sigma T_a^4;\ f = a_1 \frac{R_s}{R_{so}} + b_1;\ \varepsilon = a_2 e_a + b_2;\ T_a = \frac{1}{2}(T_{max} + T_{min});$$

$$R_a = \frac{24(60)}{\pi} G_{SC}.d_r.[\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s];R_{so} = (0.75 + 2.10^{-5}.Z)R_a\ ;R_s = \left(a + b\frac{n}{N}\right)R_a \quad (4)$$

where R_{nd} = daily net radiation (MJ m^{-2} day^{-1}); $R_{ns} = (1 - \alpha)R_s$ - Incoming net short-wave radiation (MJ $m^{-2}day^{-1}$); R_s = total incoming shortwave radiation that reaches the earth's surface on a given day (MJ $m^{-2}day^{-1}$); $R_{nl} = f\varepsilon\sigma T_a^4$ - outgoing net longwave radiation (MJ $m^{-2}day^{-1}$); α = fraction of solar radiation reflected by the surface. The other parameters can be exactly look for at [1, 2, 8].

Model 2: *Daily net radiation model extracted from remote sensing image, (RndRS)*

According *Bastiaanssen, et al. 1996* [2, 12] instantaneous net radiation at the satellite overpass moment *i* can be extracted from image data basing on the surface energy balance R_{niRS} as follows:

$$R_{niRS} = R_{ns} + R_{nl} \equiv [(1 - \alpha)R_s] + [R_L^{\downarrow} - R_L^{\uparrow} - (1 - \varepsilon_o)R_L^{\downarrow}] \quad (5a)$$

For calculating daily net radiation, the following integral could be performed (*Jackson, et al., 1983*) [4] using sine function:

$$R_{ndRS} = \int_0^{DL} R_{max}\ \sin(\pi.t/DL) = A.R_{iRS} \quad (5b)$$

where R_{max} – Solar radiation at noon (12h); *DL* – Length of Daytime (from the moment of sunrise to moment of sunset); *t* – the argument of the moment of sunrise to the moment *i*. A is the coefficient.

Model 3: *Daily net radiation based on Irmak (ASCE-EWRI) multi-regression, (RndIR)*

A multiple regression model of study (*Irmak, et al., 2003*) at EWRI of ASCE to calculate the average daily net radiation Rnd based on maximum and minimum air temperature, Tmax, Tmin,; incoming solar radiation Rs measured *in- situ*, and relative distance between the Sun – Earth, dr on the day of the year, is in the following form [5, 15]:

$$R_{ndIR} = -0.054T_{max} + 0.111T_{min} + 0.462R_s - 49.243d_r + 50.831 \quad (6)$$

For analyzing derived results, following statistical parameters are used: Correlation coefficients, R^2; Root mean square error, RMSE; Mean absolute error, MAE; Mean bias error, MBE; Mean ratio, MR.

3. RESULTS AND DISCUSSION

For calculating daily reference evapotranspiration ETo by three methods as presented in 2^{-d} section, the results of three net daily radiation models such as R_{ndFAO}, R_{ndRS}, and RndIR described in 2^{-d} section have been taken from [15]. Basing on the equations (1), (2), (3), the reference evapotranspiration of three methods (denote ETo_FAO ***in solid lines***, ETo_PT ***in dashed lines***, ETo_IR ***in dotted lines***) have been calculated and shown in **figure 1**. The graphic presentations of RMSE and MAE of three methods using daily net radiation of remote sensing model (extracted from MODIS) and of IRMAK model in comparison with FAO daily net radiation model are described **in figure 2**. It is clear from figure 1 that:

- For three methods the direct use of R_{ndIR} model proposed by Irmak [5] gives the lowest accuracy in calculation of ETo (red color in figure 1). For specific region or countries the coefficients of equation (6) need to be calibrated.

- In ETo_FAO method, when using R_{ndFAO} or R_{ndRS} models the results of ETo are closer each other.

- When using R_{ndFAO} or R_{ndRS} models the resuts of ETo_PT and ETo_RG are similar each other.

In order to evaluate the effect of remote sensing based daily net radiation on daily reference evapotranspiration, *the internal precision of each method for ETo using different models Rnd* was conducted, basing on analyzing statistical parameters. For this goal the results of ETo_FAO(R_{ndFAO}), ETo_PT(R_{ndFAO}) and ETo_RG(R_{ndFAO}) are considered as the "*standard*" values; remain other results are considered as the "*estimated*". Statistical parameters are presented in table 3.

Table 3. Internal precision of each method for ETo using different R_{nd} models

Statistical Parameters	ETo_FAO			ETo_PT			ETo_RG		
	R_{ndFAO}	R_{ndRS}	R_{ndIR}	$R_{nd\ FAO}$	R_{ndRS}	R_{ndIR}	R_{ndFAO}	R_{ndRS}	R_{ndIR}
MAE(%)	-	**3.85**	12.98	-	**4.52**	16.89	-	**3.79**	12.56
RMSE(mm/d)	-	0.164	0.430	-	0.238	0.610	-	0.183	0.465
RMSE(%)	-	**5.04**	13.20	-	**6.71**	17.18	-	**5.02**	12.79
MBE(mm/d)	-	-0.112	0.423	-	-0.161	0.600	-	-0.123	0.456
Mean Ratio	1	**0.966**	1.170	1	**0.955**	1.169	1	**0.966**	1.126
R^2	1	**0.8206** **1**	**0.9112** **0.9044**	1	**0.2588** **1**	**0.4402** **0.6281**	1	0.0323 1	0.1544 0.0926

Some conclusions can be output from table 3:

- In ETo_FAO method, the correlation coefficients R^2 between the ETo using R_{ndFAO}, R_{ndRS}, R_{ndIR} models are very strong. Specifically, R^2 between ETo_FAO(R_{ndFAO})and ETo_FAO(R_{ndRS}), FAO(R_{ndFAO}) and ETo_FAO (R_{ndIR}), between ETo_FAO(R_{ndRS}) and ETo_FAO(R_{ndIR}) respectively are 0.8206, 0.9112 and 0.9044. In ETo_PT method the correlation coefficients are lighter and respectively equal to 0.2588, 0.4402, 0.6281. Contrast, in method ETo_RG, these correlation are very weak.

- In all three methods, when R_{ndRS} model used to calculate Eto, the MAE and RMSE errors are approximately 3 times smaller than the case of using model R_{ndIR}.

- ***Important identifying***: R_{ndRS} can be used to replace R_{ndFAO} model for all three methods of determining ETo_FAO, ETo_PT and ETo_RG. Then its influence to MAE (%), RMSE (%) and MBE (%) are less than or approximately equal to 5% (see fig. 2). In particular, ETO-FAO method gives stronger correlation than the other (R^2 = 0.8206).

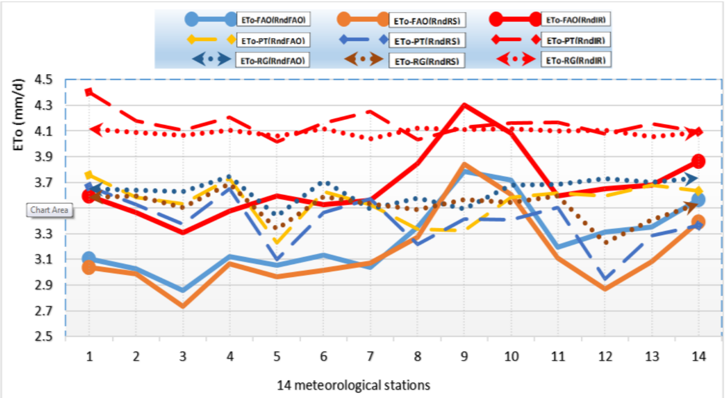


Figure 1. Results of three reference evapotranspiration methods using three models of daily net radiation

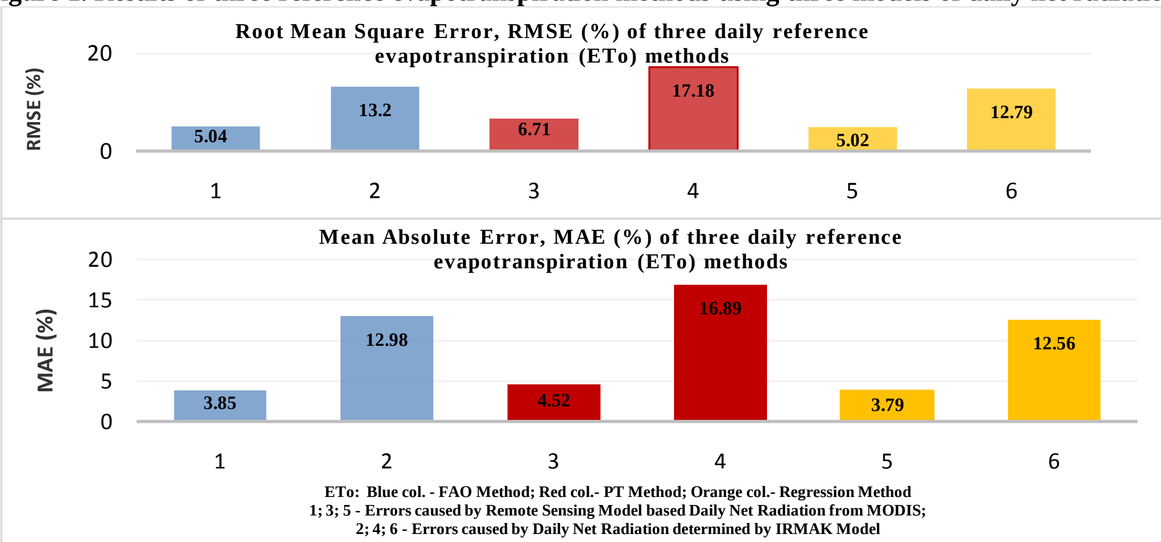


Figure 2. RMSE (on top) and MAE (on bottom) of three daily reference evapotranspiration methods using daily net radiation of remote sensing and IRMAK models in comparison with FAO daily net radiation model (taken from table 3)

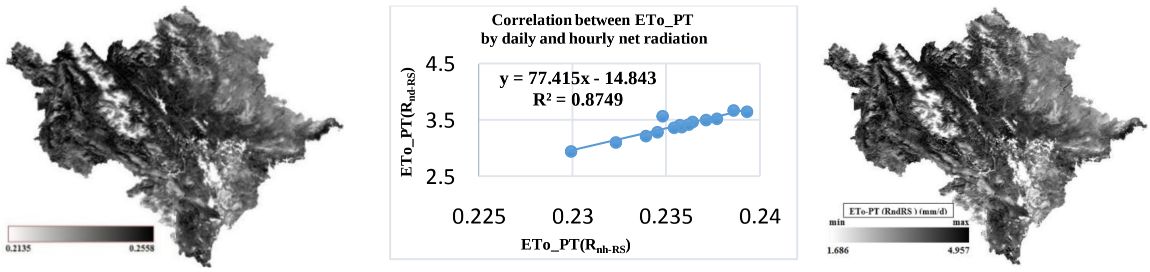


Figure 3. Relationship between daily and hourly reference evapotranspiration ETo based on Priestley-Taylor method (PT) calculated by hourly ($R_{nh\text{-}RS}$) and daily ($R_{nd\text{-}RS}$) net radiation extracted from MODIS image: Hourly reference evapotranspiration ETo_PT($R_{nh\text{-}RS}$) in left hand; Daily reference evapotranspiration ETo_PT($R_{nd\text{-}RS}$) in right hand; and correlation between ETo_PT($R_{nd\text{-}RS}$) and ETo_PT($R_{nh\text{-}RS}$) in the middle.

The relationship between hourly and daily reference evapotranspiration ETo calculated by Priestley-Taylor method (ETo_PT) using MODIS satellite image for hourly ($R_{nh\text{-}RS}$) and daily ($R_{nd\text{-}RS}$) net radiation is represented in **figure 3**. Hourly reference evapotranspiration ETo_PT($R_{nh\text{-}RS}$) can be look for in [12, 14]. This relationship is very strength (R = 0.94; R^2 = 0.8749).

4. CONCLUSION

Based on experimental results presented, some conclusions would be outlined as follows:

- For three methods the direct use of R_{ndIR} model proposed by Irmak [5] gives the lowest accuracy in calculation of ETo. For specific region or countries the coefficients of equation (6) need to be calibrated.

- For the same method as ETo_FAO, ETo_PT, ETo_RG, daily net radiation R_{ndRS} extracted from MODIS or R_{ndIR} can be used to replace R_{ndFAO}, when the request errors of MAE (%), RMSE (%) and MBE (%) does not exceed 10% and 20% respectively. Especially in ETo_FAO method, using R_{ndRS} and R_{ndIR} alternative to R_{ndFAO} model, the quantities of reference evapotranspiration ETo are in strong correlation (table 3).

- When using the corresponding R_{ndFAO}, R_{ndRS}, R_{ndIR} models for comparing two ETo_PT, ETo_IR methods with ETo_FAO, the MAE (%), RMSE (%) and MBE (%) errors does not exceed 15%. In other words: we can use ETo_PT and ETo_RG methods alternative to ETo_FAO method, the accuracy of the ETo will decrease less than 15%.

- R_{ndRS} model can be used for ETo_PT and ETo_RG methods to replace R_{ndFAO} model of ETo_FAO method, the accuracy of the ETo would decrease approximately 12%. The MAE (%), RMSE (%) and MBE (%) errors does not exceed 12%. Similarly, for using R_{ndIR} model replaced by R_{ndFAO} in ETo_PT and ETo_RG methods, the accuracy of the ETo would decrease approximately 30%. Other word, the MAE (%), RMSE (%) and MBE (%) errors does not exceed 30%.

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