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Comparing various methods to Estimate Evapotranspiration and its Correlation with Air Temperature

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Abstract

Evapotranspiration (ET) is one of the significant processes in the hydrological cycle. Its measurement is difficult as it is a function of complex weather variables (temperature, radiation, humidity, etc.,). Air temperature can be used to infer the characteristics of weather data like evapotranspiration. The main objective was to develop a correlation between air temperature and evapotranspiration (ET) in a relatively cold climate basin. To achieve this purpose, spatial evapotranspiration (both actual and potential evapotranspiration) was calculated using Penman-Monteith (PM) method by SWAT model and also calculated manually using the FAO-56 method which is the updated version of the well-known Penman equation (Penman,1948). As both of these methods are radiation-based, the Thornthwaite method to estimate PET which is based on temperature was also compared and correlated. The evapotranspiration results from all methods were compared and the relationship between air temperature and evapotranspiration was determined. The rise and fall patterns of evapotranspiration with respect to time were similar for PM and FAO-56 methods. However, the PET values from PM were found to be more dispersed than the reference ET obtained using the FAO-56 method. The general relationship between ET and temperature was found to be positive for all sub-basins and the polynomial regression relationship can be applied to estimate the evapotranspiration both daily and monthly for the desired temperature. Even so, the low value of goodness of fit (R^2) indicated that ET is challenging to predict for any region especially the colder regions.

Keywords

Evapotranspiration, Penman-Monteith, FAO-56, Thornthwaite, SWAT, Air temperature

1. Introduction

The hydrological cycle involves many processes such as evaporation, transpiration, precipitation, run-off, infiltration, interception, etc. When the liquid form of water from sources such as land, waterbodies, etc. is converted to water vapor into the atmosphere, it is called evaporation [1]. But if the vaporization of liquid water occurs within vegetations via leaf stomata, the process is known as transpiration. Both evaporation and transpiration are closely related and happens simultaneously. Hence, they are collectively described as evapotranspiration (ET). ET depends on air temperature, solar radiation, wind speed and, relative humidity (RH). However, the transpiration process is also influenced by plant attributes and cultivation practices. Thus, its measurement becomes challenging as it is a function of complex weather variables (temperature, radiation, humidity, etc.)[2]

The rate of ET from an extensive surface actively growing, completely covering the ground, and when the moisture supply/water is not limiting is called Potential evapotranspiration (PET). Real evapotranspiration occurring in a specified situation is called Actual evapotranspiration (AET). Moreover, reference evapotranspiration is similar to PET and considered as the rate at which effortlessly accessible soil water is vaporized from definite vegetated land with the uniform, dense, actively growing plants having specified height and surface resistance[3]. Reference ET also include the surface resistance factor in addition to the PET.

SWAT (Soil and Water Assessment Tool) is a comprehensive tool widely used in the hydrologic analysis [4]. In this study, it is used to obtain AET and PET by the Penman-Monteith method [5] [6] using DEM, land use, soil, and other meteorological data (precipitation, temperature, wind speed, relative humidity, solar radiation) together with the GIS platform. The SWAT model calculates ET using detailed parameters such as canopy resistance, aerodynamic resistance, etc. The results obtained from SWAT are compared to the values computed using a manual method Penman-Monteith (FAO-56) method which was recommended by FAO [6]. It is an updated form of Penman-Monteith's equation [7][5] which simplifies the Penman-Monteith equation by using some assumed constant parameters.Both Penman-Monteith equation (from SWAT model) and FAO-56 (from Manual Calculation) methods are the radiation-based calculation of ET. The temperature-based ET calculation method, the Thornthwaite method [8] was applied to further compare the results for the basin in cold climatic conditions.All evapotranspiration results are correlated with the temperature data using a polynomial equation for the watershed. The equation can be applied to estimate the evapotranspiration when the temperature is known for any sub-basins in the watershed.

2. Study Area

The study area for the research is the watershed area generated with the outlet point being the hydrological station no. 600 (Latitude=27.6°N, Longitude=87.33°E, and Elevation=1294m), Arun River at Uwa Gaon in Sankhuwasabha district which lies in the Koshi river basin of Nepal. As the Arun River originates from Tibet, the catchment extends to China with a watershed area of 26,197.48 sq. km which is divided into 26 sub-basins.

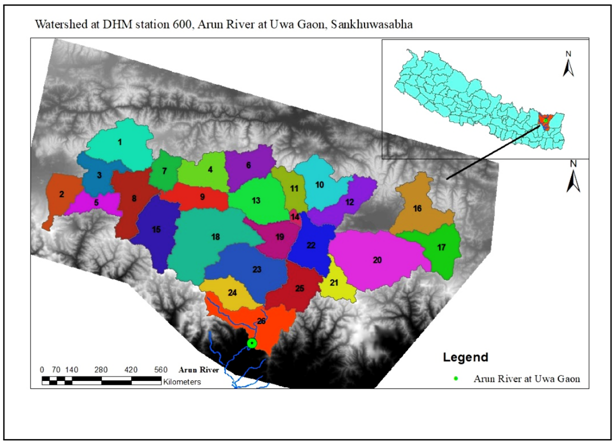

Figure 1: Watershed at DHM station 600, Arun River at Uwa Gaon, Sankhuwasabha, Nepal

3. Methodology

3.1 Penman-Monteith Method (Using SWAT model):

Digital Elevation Model (DEM) data (source: United States Geological Survey (USGS)) was used to delineate the watershed at the hydrological station no. 600, and it was divided into multiple hydrologically connected sub-basins. The land use land cover and the soil type data were loaded into the SWAT to determine different hydrologic parameters within each sub-basin. The look-up table method was used to demarcate the classes of land cover. Similarly, by loading the soil look-up table, the soil layer in the map was linked to the user soil database information and then reclassification was applied.The land slope classes were also integrated into defining the hydrologic response units (HRUs). The DEM data was used for the watershed delineation as well as slope reclassification. As the sub-basin has a wide range of slopes in terrain, the multiple slope discretization operation was adopted over the single slope discretization. Based on minimum, maximum, mean and median slope statistics of watershed, five slope classes ((0-10) %, (10-20)%, (20-30) %, (30-50) %, >50%) were classified. The climate variables: daily precipitation(mm), maximum and minimum temperature(°C), solar radiation (MJ/m^2), wind speed (m/s), and relative humidity, required by SWAT were prepared and daily values of climate data were also imported together with their weather locations. The calibration and validation for the parameters of the basin are done using the SWAT-CUP tool [9]. Two years of data ranging from 1st Jan 1991 to 31st Dec 1992 were utilized as the warm-up period for the initialization of the model variables. The calibration of the simulated flow data for daily observed values was done for the period of 1st Jan 1993 to 31st December 1996 using SWAT-Cup with 28 parameters responsible for the runoff generation. The validation was done for the period of 1st Jan 1998 to 31st December 2001 using calibrated parameters as input for the simulation.

3.2 FAO-56 method:

The Food and Agriculture Organization (FAO) recommended modified Penman-Monteith equation [5] by utilizing some assumed constant parameters for a clipped grass reference crop [6]. It was assumed that a hypothetical reference crop with crop height of 0.12 m, a fixed surface resistance of 70 s/m, and an albedo value (i.e., the portion of light reflected by the leaf surface) of 0.23 [10] The FAO-56 Penman-Monteith equation:

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

Where,
ET_o= reference evapotranspiration, mm/day;
R_n= net radiation at the crop surface ($MJm^{-2}d^{-1}$)
G= soil heat flux density ($MJm^{-2}d^{-1}$)
T=T_{mean}= average daily air temperature at two meter height (°C)
u_2= wind speed at 2 m height (m/s)
e_s= saturation vapor pressure (kPa)
e_a= actual vapor pressure (kPa)
$e_s - e_a$= saturation vapor pressure deficit (kPa)
Δ= slope of the vapor pressure curve (kPa/°C)
γ=the psychrometric constant, (kPa/°C)
The supporting equations for this method are as follows [1]:

$$u_2 = u_h \frac{4.87}{ln(67.8h - 5.42)} \quad (2)$$

Where,
u_2 =the wind speed 2 m above the ground surface, (m/s)
h = height of the measurement above the ground surface, (m)

$$\Delta = \frac{4098[0.6108exp(\frac{17.27*T_{mean}}{T_{mean}+237.3})]}{(T_{mean} + 237.3)^2} \quad (3)$$

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \quad (4)$$

$$\gamma = \frac{C_pP}{\varepsilon\lambda} = 0.000665P \quad (5)$$

Where,
z = elevation above sea level, (m)
P = atmospheric pressure, (kPa)
λ= latent heat of vaporization, 2.45, (MJ/kg)
C_p = specific heat at constant pressure, $1.013 * 10^{-3}$, ($MJkg^{-1}{}^{\circ}C^{-1}$)
ε = ratio molecular weight of water vapor/dry air = 0.622.

$$e_{(T)} = 0.6108exp\left(\frac{17.27 * T}{T + 237.3}\right) \quad (6)$$

$$e_{(s)} = \left(\frac{e_{(T_{(max)}} + e_{(T_{(min)}}}{2}\right) \quad (7)$$

$$e_{(a)} = \frac{RH_{mean}}{100}\left(\frac{e_{(T_{(max)}} + e_{(T_{(min)}}}{2}\right) \quad (8)$$

Where,
e_a = actual vapor pressure, (kPa)
$e_{(T_{min})}$ = saturation vapor pressure at daily minimum temperature, (kPa)
$e_{(T_{max})}$ = saturation vapor pressure at daily maximum temperature, (kPa)
The inverse relative distance Earth-Sun, d_r, and the solar declination, δ, are calculated by:

$$d_r = 1 + 0.033cos[\frac{2\pi}{365}J] \quad (9)$$

$$\delta = 0.409[\frac{2\pi}{365}J - 1.39] \quad (10)$$

Where,
J = number of the day in the year between 1st January and 31st December (365 or 366)

$$R_a = \frac{24(60)}{\pi}G_{sc}d_r[(\omega_s sin\phi sin\delta) + (cos\phi cos\delta sin\omega_s)] \quad (11)$$

Where,
R_a = extraterrestrial radiation, ($MJm^{-2}day^{-1}$)
G_{sc} = solar constant = 0.0820 ($MJm^{-2}min^{-1}$)
d_r = inverse relative distance Earth-Sun
ω_s = sunset hour angle, rad

$$\omega_s = cos^{-1}[-tan(\phi)tan(\delta)] \quad (12)$$

ϕ= latitude, (rad)
δ= solar declination, (rad)
Also, clear sky radiation is given by

$$R_{so} = \left(0.75 + \frac{2 * z}{1,00,000} * R_a\right) \quad (13)$$

Where,
z = elevation above sea level, m
R_a = extraterrestrial radiation, $MJm^{-2}day^{-1}$

$$R_{ns} = (1 - a)R_s \quad (14)$$

R_{ns} = net solar or shortwave radiation, $(MJm^{-2}day^{-1})$
a = albedo or canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop, dimensionless
R_s = the incoming solar radiation,$(MJm^{-2}day^{-1})$

$$R_{nl} = \sigma \left(\frac{(T_{max} + 273.16)^4 + (T_{min} + 273.16)^4}{2} \right) A$$

Where,
$A = (0.34 - 0.14\sqrt{e_a}) \left(1.35\frac{R_s}{R_{so}} - 0.35\right)$
Where,
R_{nl} = net outgoing longwave radiation, $(MJm^{-2}day^{-1})$
σ = Stefan-Boltzmann constant $[4.903 * 10^{-9} MJm^{-2}day^{-1}]$
T_{max} = K maximum absolute temperature during the 24-hour period [K = °C + 273.16]
T_{min} = K minimum absolute temperature during the 24- hour period [K = °C + 273.16]
e_a = actual vapor pressure, (kPa)
R_s = the incoming solar radiation,$(MJm^{-2}day^{-1})$
R_{so} = clear sky solar radiation,$(MJm^{-2}day^{-1})$

$$R_n = R_{ns} - R_{nl} \tag{15}$$

Where,
R_n = net radiation, $(MJm^{-2}day^{-1})$
R_{ns} = net solar or shortwave radiation,$(MJm^{-2}day^{-1})$
R_{nl} = net outgoing longwave radiation, $(MJm^{-2}day^{-1})$

3.3 Thornthwaite Method:

This method is the temperature-based method to estimate ET using an empirical relationship between potential evapotranspiration and average air temperature [8]. It can be used for any location if the temperature is recorded. Despite the simplicity and limitations of the method, it does surprisingly well which has led to widespread use of this method [11]. The basic formula for computing monthly PET is:

$$PET = 16 * \left(\frac{10 * T_{mean}}{I} \right)^{\alpha} \tag{16}$$

where,
PET= monthly potential ET in mm
T_{mean} = monthly mean temperature (°C)
I = heat index for the location $= \sum_{i=1}^{12} i$
i = monthly Thornthwaite heat index $= (\frac{T_{mean}}{5})^{1.514}$
$\alpha = 6.75 * 10^{-7} I^3 - 7.71 * 10^{-5} I^2 + 1.79 * 10^{-2} I + 0.49$

4. Result and Analysis

4.1 SWAT model:

The calibration of the simulated flow data for daily observed values was done for the period of 1st Jan 1993 to 31st December 1996. The Nash-Sutcliffe efficiency was observed to be 73% for 4 years using 28 parameters relating to surface and subsurface flow, physical soil properties, infiltration, evapotranspiration, permeability/conductivity, etc. within the defined parameter ranges of SWAT.The validation of the simulated flow data for daily observed values was done for the period of 1st Jan 1998 to 31st December 2001 using the same 28 parameters. The Nash-Sutcliffe efficiency was observed to be 59%.The global sensitivity analysis showed that the most sensitive parameters were maximum melt rate for snow during year, moist bulk density, water capacity of soil, SCS curve number, Manning's n value for overland flow, groundwater delay, etc.

The hydrological processes including actual evapotranspiration (AET), potential evapotranspiration (PET) calculated from different methods along with the temperature are summarized in Table 1

Figure 4 showed that both AET and PET (from Penman-Monteith) increased with the temperature rise and attained peak values in June and July. However, the Thornthwaite method showed lower PET values in comparison to the Penman-Monteith method and PET was nil for months with the temperature lower than 0°C because it assumes that evapotranspiration ceases for temperatures at or below 0 °C, and, consequently, evapotranspiration does not occur.

4.2 Penman-Monteith (FAO-56) method and its Comparison:

Using Penman-Monteith (FAO-56) equation, manual calculations for the daily reference ET for each sub-basin and the data obtained were compared with the evapotranspiration data from the SWAT model as shown in Table 2.

The comparison showed that the pattern of change in evapotranspiration with time was similar for Penman-Monteith (PM) (from SWAT) and FAO-56 methods.The maximum and minimum evapotranspiration were computed during similar months. However, the standard deviation values for

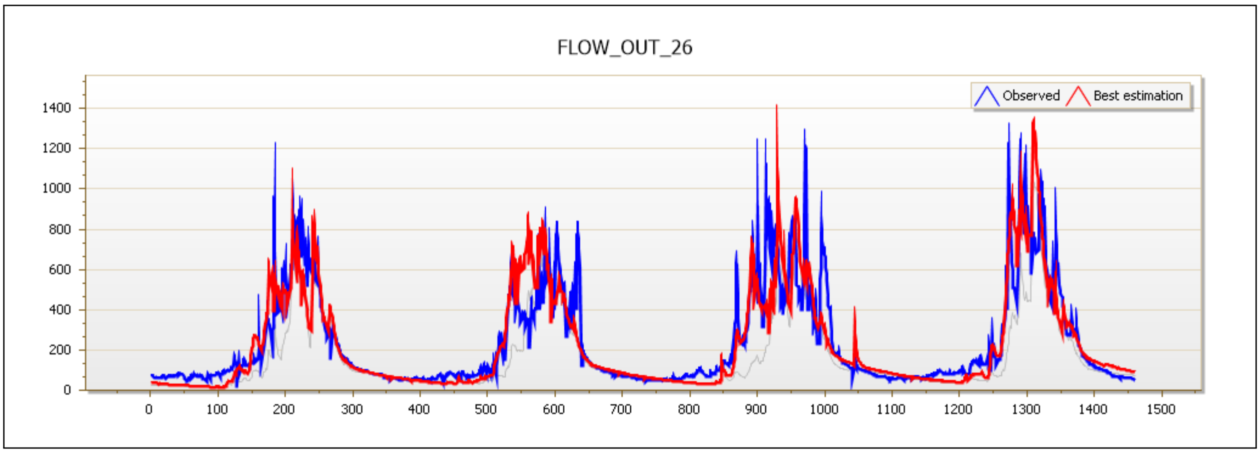

Figure 2: Calibration (1st Jan 1993 to 31st Dec 1996)

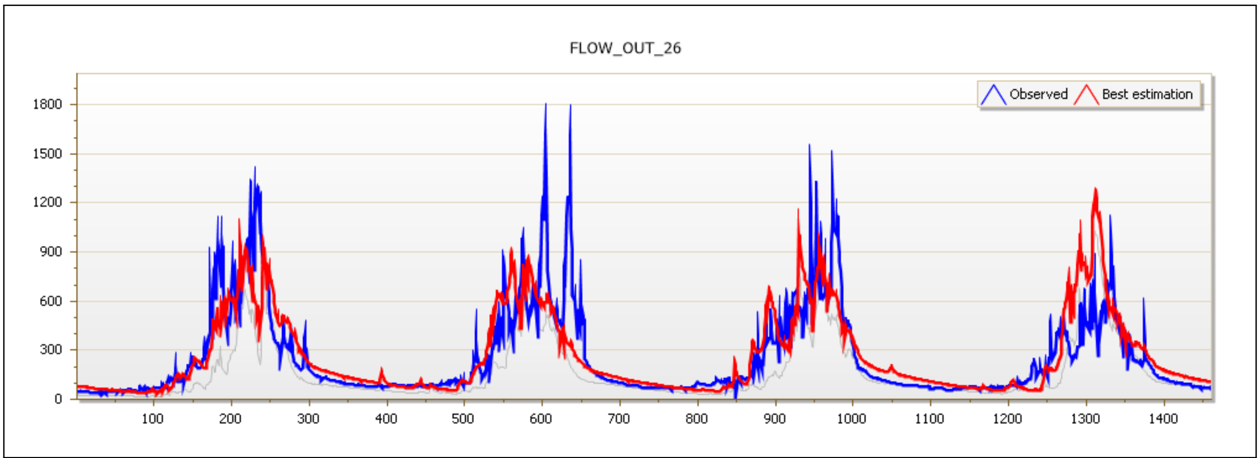

Figure 3: Validation (1st Jan 1998 to 31st Dec 2001)

Table 1: Average Monthly Basin Values for different hydrological processes

Month	Rain	Snowfall	Surface runoff	LAT soil	PM-AET	PM-PET	Thornthwaite PET	Avg TEMP
	mm	mm	mm	mm	mm	mm	mm	Deg C
1	27.41	27.4	1.49	0.66	1.64	14.61	0	-12.55
2	32.64	32.42	2.07	0.45	1.99	14.83	0	-11.35
3	43.55	41.72	8.67	0.38	3.72	16.78	0	-7.89
4	43.05	37.78	23.59	0.29	10.05	29.55	0	-4.05
5	39.8	17.27	85.29	0.33	27.71	75.05	30.29	1.72
6	66.86	2.8	39.11	0.59	38.49	98.22	62.36	6.03
7	119.9	0.07	29.77	1.14	49.08	88.46	77.65	8.21
8	126.8	1.07	29.76	1.62	49.81	79.54	71.63	7.18
9	93.82	9.29	21.87	1.85	39.89	63.9	54.18	4.77
10	30.8	18.42	4.78	1.67	18.57	58.94	0	-0.99
11	15.06	13.93	0.66	1.22	4.49	30.87	0	-6.94
12	11.23	11.21	0.29	0.93	2.41	27.33	0	-11.11
Total	650.9	213.38	247.35	11.13	247.9	598.08	296.1	

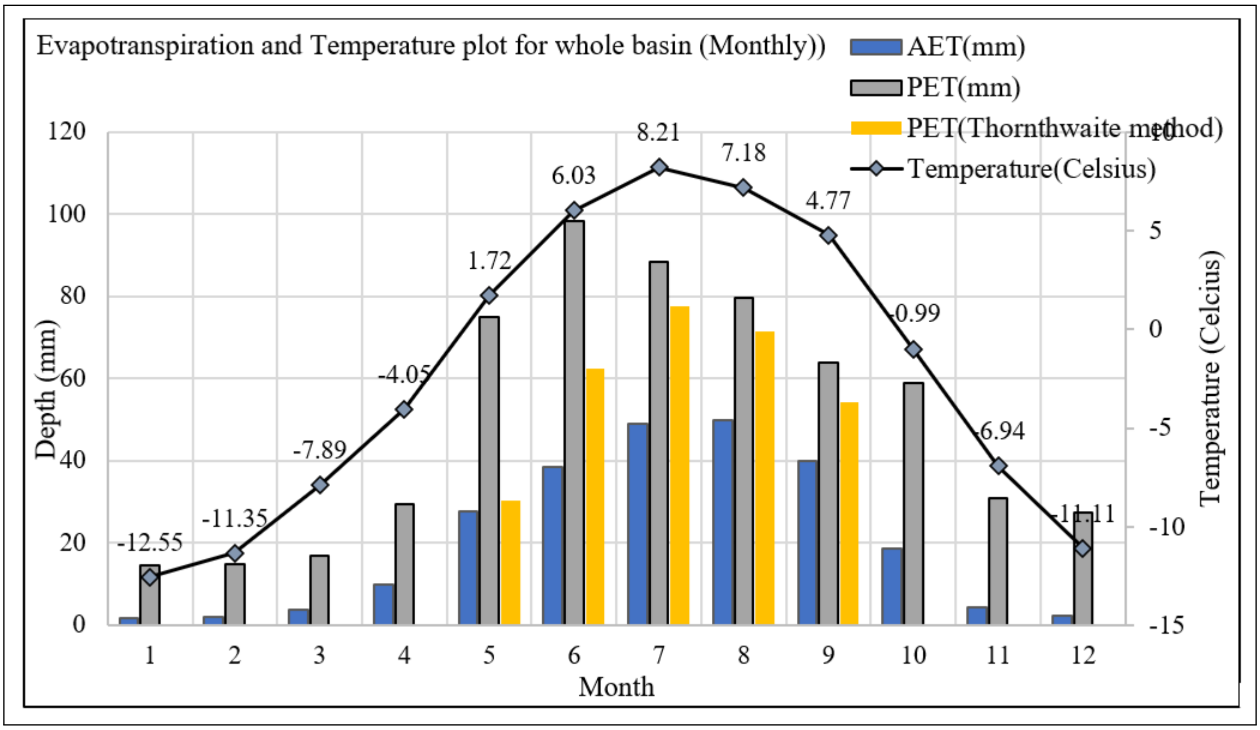

Figure 4: Different ET and Temperature plot for the whole basin (Monthly)

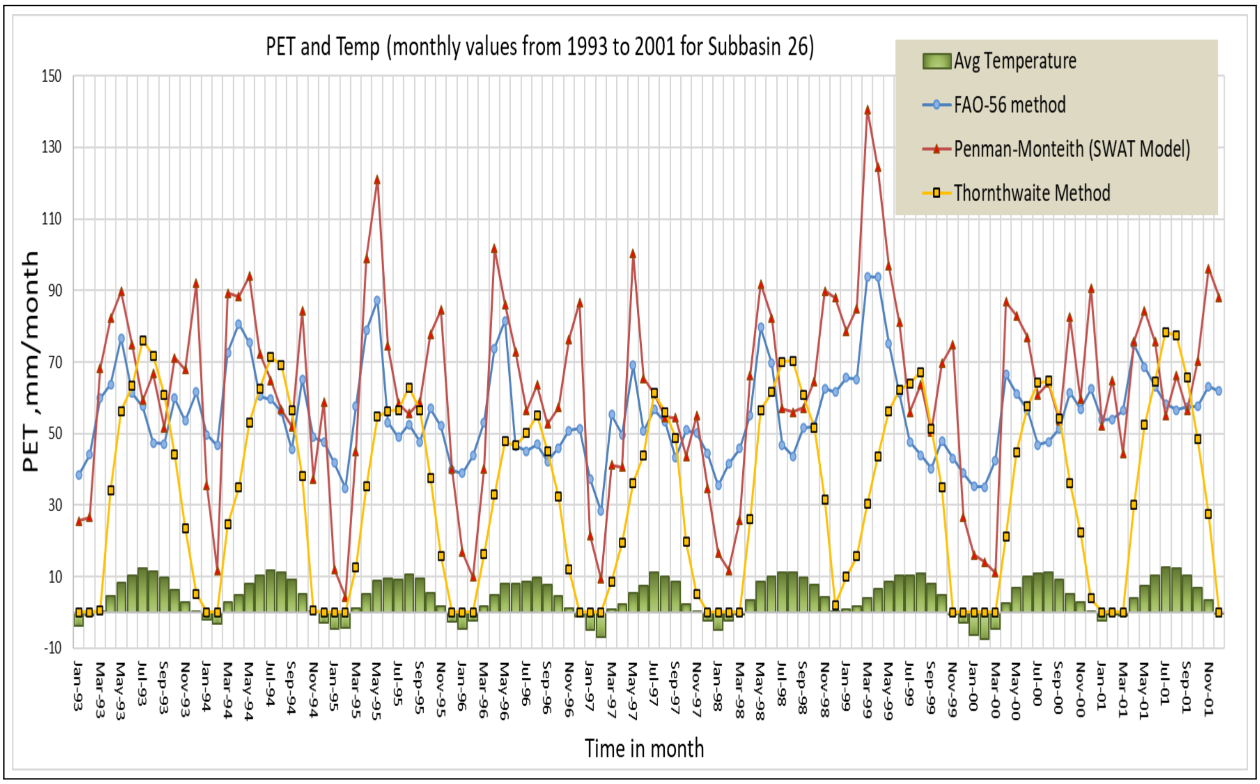

Figure 5: Correlation between Temp and PET (Calculated from different methods)

Table 2: Sample Monthly PET from different methods for Sub-basin 26

Date	Month	Avg Monthly Temp	Penman-Monteith (SWAT)	FAO-56 (Manual)	Thornthwaite Method
		Deg C	mm	mm	mm
1/1/1993	Jan-93	-3.78	38.36	25.66	0
2/1/1993	Feb-93	-0.99	44.04	26.66	0
3/1/1993	Mar-93	0.02	59.84	68.17	0.46
4/1/1993	Apr-93	4.7	63.8	82.23	34.26
5/1/1993	May-93	8.42	76.72	89.67	56.24
6/1/1993	Jun-93	10.18	61.28	74.82	63.33
7/1/1993	Jul-93	12.32	57.62	59.39	76.16
8/1/1993	Aug-93	11.45	47.41	66.71	71.83
9/1/1993	Sep-93	9.7	47.18	51.68	60.93
10/1/1993	Oct-93	6.2	59.9	71.19	44.09
11/1/1993	Nov-93	2.95	53.61	67.91	23.65
12/1/1993	Dec-93	0.42	61.61	92.03	5.17

the PM method and the FAO-56 method were found to be 12.79 and 26.79 respectively. It showed that the ET calculated from the SWAT model using the PM method was more dispersed than the ET computed in the FAO-56 method. The assumptions made in the FAO-56 method brought ET values less deviated than the PM method. However, the basic nature concerning temperature was more or less similar both being the radiation-based method derived from the Penman equation. On the other hand, the Thornthwaite method was simplest among all of them, yet it gave satisfactory results. But the nil PET values for months with a temperature lower than 0°C indicates its limitation to use in cold climatic regions.

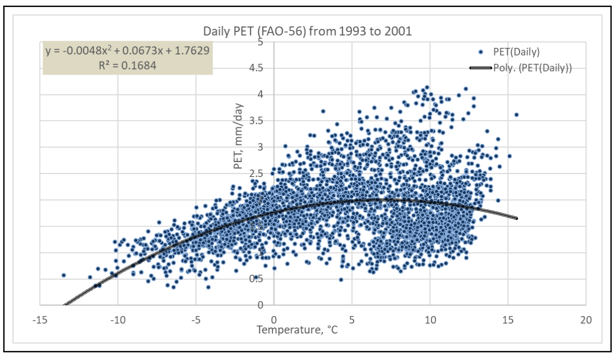

Figure 6: Daily PET (mm) vs Temperature (Celsius)

The daily PET data were plotted with daily temperature and regression analysis was done to obtain the relationship between them. A polynomial equation of degree two was fitted which can be used to determine daily PET (y in mm) if the temperature is known (x, in degree Celsius). However, the low value of goodness of fit (R^2) indicated that ET is simply harder to predict for any region.

Moreover, to correlate the ET and temperature monthly, the daily data were summed up for each month for the simulation periods, and the graph was plotted again along with a regression line with the polynomial equation of second degree as shown in Figure 7.

5. Conclusion

The study area taken for research is situated in a relatively cold climate. The average annual precipitation (rainfall and snowfall) of that area was found to be 864.29 mm and AET was found to be 247.8mm annually which is approximately 28.68% of total precipitation. Moreover, analyzing the average monthly data, the maximum rainfall occurs in August which was 126.79 mm and the maximum actual evapotranspiration occurred in the same month which was 49.81 mm i.e., 39.28% of rainfall. Also, it was observed that the maximum temperature (around 7 to 8°C in the case of the whole basin) lies around the same months i.e., July and August for the basin. However, for the coldest months of January with the temperature dropping to -12.55°C, the contribution of the snowfall in the precipitation was significantly higher which led to negligible actual evapotranspiration (about 3%) with a low PET contribution of 26.66%. Also, the Thornthwaite

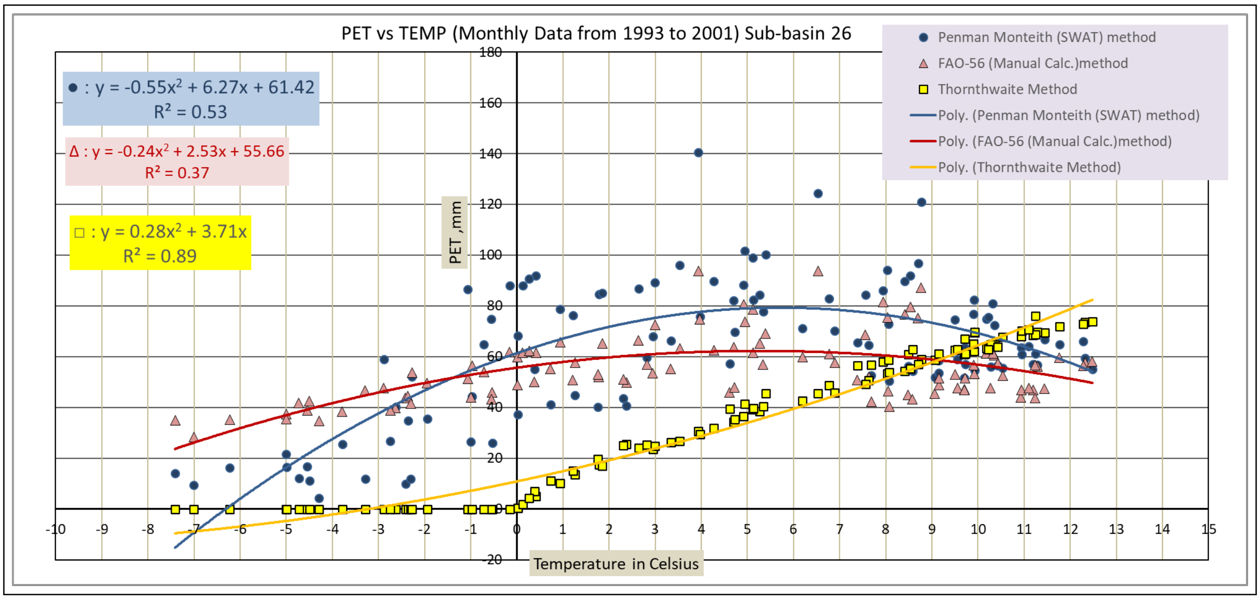

Figure 7: Monthly PET from different methods vs Temperature for Sub-basin 26

method doesn't report any ET for months with temperatures below 0 °C.

The rise and fall patterns of evapotranspiration with respect to time were similar for both radiation-based PET calculating methods namely Penman-Monteith (SWAT model) and FAO-56 method. The maximum and minimum evapotranspiration resulted during similar months. However, the ET calculated from the SWAT model was more dispersed than the ET computed in the FAO-56 method for the basin due to the assumptions and inclusion of bulk surface resistance which is taken as 70 s/m that reduces ET value and the average daily temperature data used in this method results in under-estimation of ET as the saturation vapor pressure which plays vital role in ET process has non-linear correlation with the temperature. The FAO-56 method should be chosen over Penman-Monteith using SWAT simulation for calculation of ET for the area where more accurate evapotranspiration is required such as agricultural planning, irrigation planning, etc. However, for relatively large and complex basins for hydrological models, SWAT analysis also provides a satisfactory result. Also, it is not recommended to use the Thornthwaite method in colder climates although it gives satisfactory ET estimations during warmer seasons despite using the temperature data only.

Since the study area covers huge landscapes with varying topography, the relationship between evapotranspiration and temperature was developed individually for each sub-basin. Analyzing all results, the general relationship was found to be positive for all sub-basins. For all sub-basins, a polynomial regression relationship between ET and temperature can be developed to estimate the evapotranspiration both daily and monthly for the desired temperatures. Nonetheless, the low value of goodness of fit (R^2) indicated that ET is simply challenging to predict for any region especially the colder regions.

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References

[1] Lincoln Zotarelli, Michael D Dukes, Consuelo C Romero, Kati W Migliaccio, and Kelly T Morgan. Step by step calculation of the penman-monteith evapotranspiration (fao-56 method). *Institute of Food and Agricultural Sciences. University of Florida*, 2010.

[2] Preeyaphorn Kosa. Air temperature and actual evapotranspiration correlation using landsat 5 tm satellite imagery. *Agriculture and Natural Resources*, 43(3):605–611, 2009.

[3] Marvin Eli Jensen, Robert D Burman, and Rick G Allen. Evapotranspiration and irrigation water requirements. ASCE, 1990.

[4] Arnold Srinivasan. Arcswat interface for swat2012 user's guide. In *University of cambridge*. Cambridge university press, 2013.

[5] John L Monteith. Evaporation and environment. the stage and movement of water in living organisms. In *19th Symp. Soc. Exp. Biol.* Cambridge university press, 1965.

[6] Richard G Allen, Luis S Pereira, Dirk Raes, Martin Smith, et al. Crop evapotranspiration-guidelines for computing crop water requirements-fao irrigation and drainage paper 56. *Fao, Rome*, 300(9):D05109, 1998.

[7] Howard Latimer Penman. Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, 193(1032):120–145, 1948.

[8] Charles Warren Thornthwaite. An approach toward a rational classification of climate. *Geographical review*, 38(1):55–94, 1948.

[9] Villamizar. Procedure for swat-cup calibration. *Institute of Food and Agricultural Sciences. University of Florida*, 2013.

[10] Monteith Smith. Report on the expert consultation on procedures for revision of fao guidelines for prediction of crop water requirements. *Land and Water Development Division, UN FAO*, 1992.

[11] Wayne C Palmer and A Vaughn Havens. A graphical technique for determining evapotranspiration by the thornthwaite method. *Monthly Weather Review*, 86(4):123–128, 1958.