

Chapter 17

Modelling of Reference Crop Evapotranspiration in Humid-Wet Tropical Region of India



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Abstract Reference crop evapotranspiration is an essential parameter for crop water management and the hydrological cycle. Therefore, selecting methods to predict the reference crop evapotranspiration plays an essential role in agriculture water management and the hydrological cycle. This study attempts to compare different methods for the estimation of reference crop evapotranspiration in the subtropical region of Assam. The Indian Meteorological Department (IMD) gridded temperature, and rainfall data at $1^\circ \times 1^\circ$ spatial resolution was used for the period 1971–2011. Three methods of estimation and comparison of reference crop evapotranspiration were used, which include Thornthwaite’s plan (1948), Hargreaves and Samani’s method (1985), and Turc’s method (1961). Thornthwaite’s method was likely to give better results for humid regions for the estimation of reference crop evapotranspiration. The reference crop evapotranspiration, as well as rainfall in eastern Assam, was found to be high in comparison to other districts of Assam.

Keywords Reference crop evapotranspiration · Thornthwaite’s method · Hargreaves and Samani’s method · Turc’s method · Brahmaputra valley · Assam

1 Introduction

Crops exhibit distinctly different responses to rain with high humidity than irrigation with low humidity (Breazeale et al., 1950). Winter crops grown under favourable atmospheric conditions with humidity and temperature show less stress than summer-grown crops. Some crops grow where fog exists, even without irrigation and with less rainfall (Breazeale et al., 1950). Food grains in Assam, India,

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accounted for approximately 66% of the total cultivated area during 2006–2008 and for 2.8–5.1% of the total irrigated area. Any delay in the monsoon or shortfall experienced in the amount of precipitation received aggravates the risk of crop failure or steep reductions in crop yield (Isik & Devadoss, 2006; Lamaoui et al., 2018). The paucity of irrigation adversely affects farmers as well as the contribution to the gross domestic product of the state (Touch et al., 2016). The region is experiencing an increase in temperature at a rate of 0.15 °C per decade and erratic patterns of rainfall (Baruah, 2018; Kothawale et al., 2005).

For developing irrigation systems and estimating crop moisture availability, evapotranspiration is crucial for a sustainable agriculture (Djaman et al., 2015). Evapotranspiration (ET) is an important component in water-balance models and irrigation scheduling and was often estimated in a two-step process (Fisher & Pringle, 2013).

Reference crop evapotranspiration (ET_o) has been defined as the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m⁻¹, and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground, and not short of water (Allen et al., 1998a). Evapotranspiration rates vary between plant species over different times of the year and during different stages of plant growth. The Food and Agricultural Organisation (FAO) recommended the Penn-Monteith method for computation of reference crop evapotranspiration which requires many variables (Allen et al., 1998b). On the other hand, Thornthwaite and Hargreaves-Samani's method requires only air temperature (Sepaskhah & Razzaghi, 2009). The paucity of weather stations across North-East India (Saikia, 2009) necessitates the use of equations with a minimal number of climate variables. Reference crop evapotranspiration has been calculated by three methods to check the variation in their estimation using Thornthwaite (1948), Turc (1961), and Hargreaves et al. (1985a) methods (Table 17.1).

Although the potential evapotranspiration and reference crop evapotranspiration are two different concepts, the potential evapotranspiration (PET) values approximates the values derived from reference crop evapotranspiration (ET_o), provided the data used in the equations are from same station (Michalopoulou & Papaioannou, 1991). Thus, in the present study, we used Thornthwaite's (1948) potential evapotranspiration equation along with the other two models to estimate reference crop evapotranspiration.

2 Database and Methodology

2.1 Study Area

Assam is situated in the north-eastern part of India. According to Human Development Report, India 2011, the Human Development Index (HDI) score for Assam during 2007–2008 was 0.444 (India 0.467), and it ranked 16th out of 23 states in

India. It is categorized as a humid and wet region under the broad classification of humidity province after Thornthwaite (1931) (Baruah, 2018). However, area wise there may be local variation. In the higher Barails due to altitude, the climate tends to be temperate. The climate of Assam can be summed up as ‘tropical monsoon type’. Generally, the state enjoys a hot and humid climate during summer, while the winter months are cool and dry. The climate of Assam is slightly different from Cwg (humid mesothermal gangetic type) of Koppen climate classification, because of the development of an orographic low, a spectacular, but complex thermodynamic phenomenon. Perhaps it is more appropriate to designate the climate of Assam as Cwa (monsoon-influenced humid subtropical climate) instead of Cwg.

The layout of the hills and mountains and their height influence the climate of the state. The Himalayas in the north, the Patkai and other Hills in the east, and the Meghalaya Plateau-Barail Range in the central part play a major role in shaping the climate of Assam with its distinctive local characters. These hills and plateaus exert both mechanical and thermodynamic influences on the general and seasonal circulation of winds, distribution of pressure, temperature, and precipitation. The mountain wall of Bhutan and Arunachal Himalayas prevent the invasion of severe cold air masses of Central Asia in winter. On the other hand, it acts as a barrier to the moisture-bearing south-west monsoon winds with the result that the whole area receives a very heavy amount of rainfall in summer.

Of the total geographical region of Assam, only 2.38% (186,806 ha) was irrigated during 2013–2014. Agriculture remains the mainstay of Assam’s economy. Of the total work force, 33–39% were farmers, while 13–15% were agricultural labourers during 2001–2011. More than 80% of the rainfall occurs monsoon season (June–September). However, in recent years, even during monsoons and winter season, the state reported drought-like situation as well as floods (Bhattacharjya et al., 2021; Mudi & Das, 2022). The unpredictability of prevailing vivid climatic conditions creates an uncertainty in the mindsets of farmers. However, with proper artificial irrigation system, farmers would be encouraged to perform agricultural activities during adverse climatic condition. For proper management and monitoring of irrigation system, the assessment of reference crop evapotranspiration becomes a prerequisite condition (Fig. 17.1).

2.2 Data Sources

We used daily gridded rainfall and temperature dataset available at $1^\circ \times 1^\circ$ latitude-longitude resolution for the period 1971–2011 developed by the India Meteorological Department (IMD). These datasets were developed using modified Shepard’s angular distance weighting algorithm to interpolate the station data into $1^\circ \times 1^\circ$ grids (Rajeevan et al., 2005, 2006; Revadekar et al., 2009; Srivastava et al., 2009). The daily rainfall data were averaged over months and years for each district of Assam.

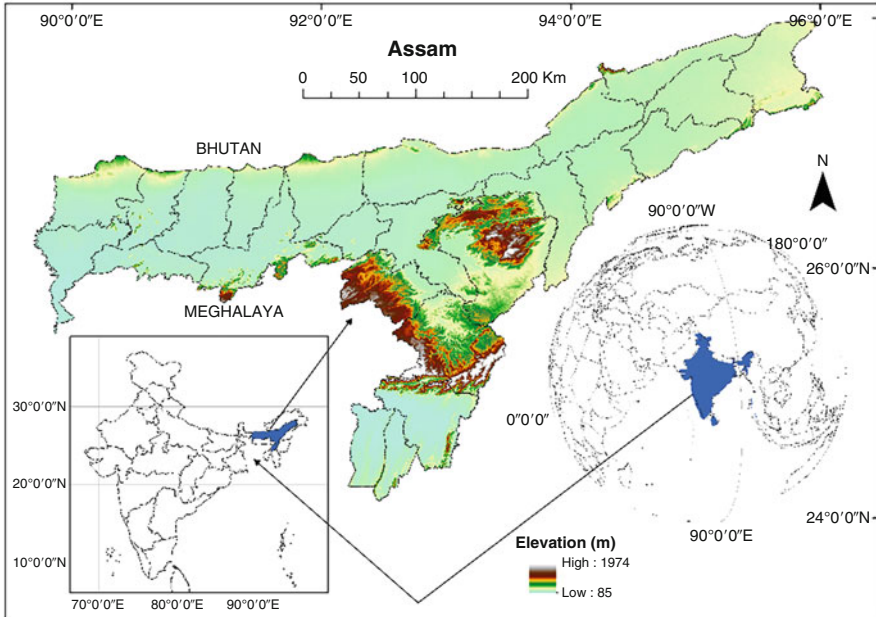


Fig. 17.1 Location of the study area

2.3 Methodology

2.3.1 Thornthwaite’s Method (1948)

The potential evapotranspiration (Thornthwaite, 1948) in each area and the relationship with the range of temperature involved were expressed by an equation of the form

$$e = ct^a$$

in which ‘*e*’ was monthly evapotranspiration (cm) and ‘*t*’ was mean monthly temperature in °C. The coefficients ‘*c*’ and ‘*a*’ vary from one place to another. The exponent *a* in the above equation varies from 0 to 4.25. Thus, an equation having coefficients derived from observations made in a warm climate does not yield correct values of potential evapotranspiration for an area having a cold climate, and vice versa (Thornthwaite, 1948). Reference Evapotranspiration Was Calculated by the Following Steps

1. The Thornthwaite’s heat index was calculated by $i = (\frac{t}{5})^{1.514}$, where ‘*t*’ was mean monthly average temperature (°C). The coefficient ‘*c*’ in the equation above varies inversely with ‘*T*’.

2. Summation of the Thornthwaite's heat index gives the annual heat index (I). This heat index varies from 0 to 160 and is given by

$$I = \sum_{i=1}^{12} i$$

3. The unadjusted PET (UPET) was calculated as

$$\text{UPET} = 1.6 \times \left(\frac{10I}{I}\right)^a$$

4. Where a was calculated by the equation

$$a = 0.000000675 \times I^3 - 0.0000771 \times I^2 + 0.01792 \times I + 0.49239$$

Adjusted PET was given by $\text{PET} = \text{UPET} \times \frac{N}{12} \times \frac{d}{30}$.

2.3.2 Hargreaves and Samani's Method (1985)

This method is radiation based and uses maximum and minimum temperature for estimating reference crop evapotranspiration (ET_o) (Droogers & Allen, 2002; Hargreaves et al., 1985a, b; Sepaskhah & Razzaghi, 2009).

$$ET_o = 0.0023(0.408)(T_{\text{mean}} + 17.8)(T_{\text{max}} - T_{\text{min}})^{0.5} R_a$$

where T_{mean} , T_{max} , and T_{min} are mean, maximum, and minimum temperature ($^{\circ}\text{C}$) respectively. R_a was extraterrestrial radiation ($\text{M}\cdot\text{J}\cdot\text{m}^{-2}$), 0.408 was a factor to convert $\text{M}\cdot\text{J}\cdot\text{m}^{-2} \text{d}^{-1}$ to mmd^{-1} , and 0.0023 was an empirical coefficient proposed by Hargreaves and Samani (1985). R_a depends on the Julian day number and latitude and can be computed as described by Allen et al. (1998a) and was calculated by

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

where G_{sc} was solar constant ($0.0820 \text{ MJ}\cdot\text{m}^{-2}\cdot\text{min}^{-1}$); φ was latitude in radians; the term $24(60)$ was a factor to convert min to day; and $[\omega \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)]$.

Based on the calendar day of the year,

$$d_r = 1 + 0.33 \cos\left(\frac{2\pi}{365} J\right)$$

where d_r is the inverse relative distance from earth to sun and J is the calendar day of the year

$$\delta = 0.409 \sin\left(\frac{2\pi}{365}J - 1.39\right)$$

where δ = solar declination (radians), and

$$\omega_s = \arccos(-\tan(\varphi)\tan(\delta))$$

where ω_s = sunset hour angle (radians).

or R_a in daily joules per square meter per day

$$R_a = \frac{24 \times 3600 G_{sc}}{\pi} \left(1 + 0.033 \cos \frac{360n}{365}\right) \\ \times \left(\cos \varphi \cos \delta \sin \omega_s + \frac{\pi \omega_s}{180} \sin \varphi \sin \delta\right)$$

where G_{sc} is in (wattm^{-2}).

2.3.3 Turc Method (1961)

Reference crop evapotranspiration (mm/month) was given by $ET_o = 0.40 \left(\frac{T_{\text{mean}}}{T_{\text{mean}} + 15}\right) (R_s + 50)$, where R_s = solar radiation ($\text{MJ}\cdot\text{m}^{-2}$) and T_{mean} = average air temperature ($^{\circ}\text{C}$) calculated as $(T_{\text{max}} + T_{\text{min}})/2$. To estimate ET_o on a daily basis, the factor 0.40 was divided by 30 (average days per month), and the final equation for daily ET_o (mm/day) was given by

$$ET_o = 0.0133 \left(\frac{T_{\text{mean}}}{T_{\text{mean}} + 15}\right) (R_s + 50)$$

where R_s can be estimated by, $R_s = 0.16 (T_{\text{max}} - T_{\text{min}})^{0.5} R_a$.

Thornthwaite's reference crop evapotranspiration, rainfall, and water balance for each year in 23 districts (2001 census) of Assam was calculated and averaged during the period 1971–2011.

3 Results and Discussion

Thornthwaite's method yielded the highest reference crop evapotranspiration (ET_o) in comparison to Hargreaves-Samani's method contrary to the previous findings of Lu et al. (2005) and Djaman et al. (2015). Turc's (1961) method underestimated the

Table 17.1 Reference crop evapotranspiration (mmd^{-1}) and rainfall estimated using different methods

	Reference crop evapotranspiration (mmd^{-1})			Rainfall (mmd^{-1})
	Hargreaves's method	Turc's method	Thornthwaite's method	
Jan	1.21	0.38	0.99	0.55
Feb	1.45	0.41	1.36	1.17
Mar	1.81	0.45	2.63	2.27
Apr	1.92	0.46	3.59	6.08
May	2	0.48	4.7	9.65
Jun	1.99	0.49	5.56	14.34
Jul	1.9	0.48	5.75	16.77
Aug	1.93	0.49	5.69	12.76
Sep	1.72	0.48	4.76	10.28
Oct	1.58	0.46	3.78	4.88
Nov	1.4	0.43	2.19	1.25
Dec	1.21	0.39	1.24	0.8

ET_o in case of Assam, similar to the findings of Djaman et al. (2015). Suitability of these methods differs, depending on the situation and location of a region.

The areas which were studied by Djaman et al. (2015) and Lu et al. (2005) are climatologically not similar to Assam; the former are closer to oceans (Southeastern US and West Africa, respectively) and at higher latitudes.

Assam is a monsoon-dominated region; it was inevitable to show large variations in ET_o . Hence, the Thornthwaite's method was likely to give better results, since variation in the ET_o in Hargreaves-Samani method was very less (Table 17.1). Hargreaves-Samani method was best suited for arid and semiarid regions (Tabari, 2010; Tabari & Aghajanloo, 2013) but overestimates in humid areas (Rojas & Sheffield, 2013). Turc's method is the best-suited model in cold humid and arid climates (Tabari, 2010). Turc's method underestimated the reference evapotranspiration in this hot-humid tropical part of the world. Therefore, for the purpose of the actual evapotranspiration estimation and irrigation water need, Thornthwaite's ET_o estimates may be used.

3.1 Estimation of ET_o Based on Thornthwaite's Method

Based on the Thornthwaite's method, potential evapotranspiration was estimated during 1970–2011. It was observed that the highest ET_o occurred during the monsoon season and lowest during the winter season (Fig. 17.2). The effect was plausibly due to heat during the summer/monsoon season, when the temperature levels was generally at a peak. The ET_o during July was 170 mm, while the lowest occurred in January (30 mm), during 1970–2007 in Assam (Fig. 17.2).

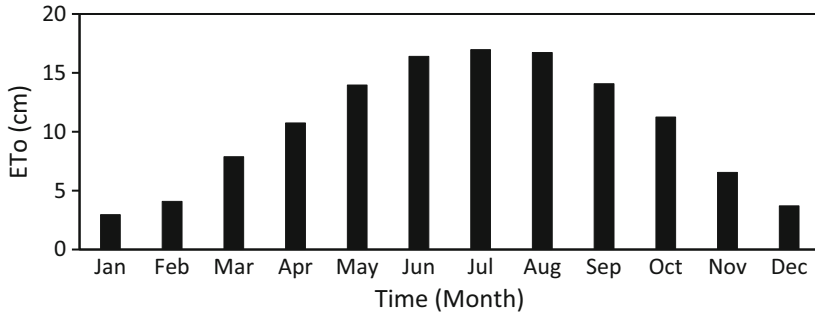


Fig. 17.2 Potential evapotranspiration based on Thornthwaite’s method, Assam, 1971–2011

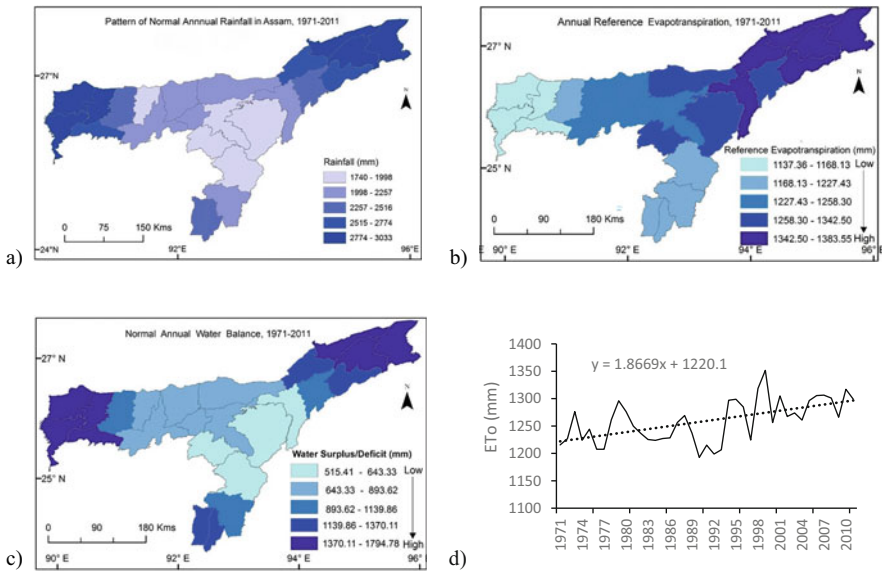


Fig. 17.3 (a) Normal annual rainfall, (b) annual reference crop evapotranspiration, (c) normal annual water balance, and (d) trend of reference evapotranspiration in Assam using Thornthwaite’s method (1948) during 1971–2011

There was at least 200 mm difference in the annual normal ET_o between districts of Assam during 1971–2011 (Fig. 17.3b). High ET_o concentrations were observed in the eastern parts of Assam and the least concentrations accrued in the western parts of Assam. Although high rainfall in the eastern Assam compensates the loss of water through evapotranspiration in eastern Assam, the amount of water availability in these regions varied according to the ET_o . Assam’s crop water availability was found to be naturally compensated by rainfall. Although the water balance amount is not uniform throughout the region, the crop water availability in upper Brahmaputra region (eastern Assam), western (lower Brahmaputra valley (western Assam), and

southern (Barak valley) Assam was high in comparison to central Brahmaputra valley (central Assam) and Hill zones (Karbi Anglong and Dima Hasao) (Fig. 17.3c). The ET_o increased at the rate of 1.82 mm/year during 1971–2011, statistically significant at 0.01 level of significance (p value 0.0013) (Fig. 17.3d). The rise in ET_o indicates that sooner or later the moisture requirements for crops would be inadequate for sustainable agriculture primarily in central Assam. The irrigation system needs to be developed in areas of low crop water availability.

4 Conclusion

Three methods were compared for estimating the reference crop evapotranspiration (ET_o). Turc and Hargreaves-Samani methods were found to be less suitable for tropical regions with wet-humid type of climate in contrast to previous study (Tabari, 2010). The estimated values from Thornthwaite's method were best fitted for the study area of Assam, India. However, the accuracy of Thornthwaite's method depends on the type of data used for estimating reference crop evapotranspiration. The data from high density of weather stations would give better results rather than gridded datasets. Shortfall in real-time data availability and reliability along with possible technical errors due to sophisticated techniques may lead to several problems in estimating evapotranspiration (Hargreaves et al., 1985a). Thornthwaite's simple method was tested and found to be suitable for tropical areas, where data is an acute problem.

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