Evapotranspiration for cotton in plain and hilly areas in Chuadanga and Rangamati districts in Bangladesh using Penman method

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Abstract: Water management and its appropriate application for cultivating cotton have been a promising issue to ensure the best quality and quantity of production. Rainfall intensity and pattern, differences in temperature and cloudiness and non-cloudiness during the growing season, will affect crop water requirement. Different studies showed that excess or less water uses result into a lower yield. Evapotranspiration of any crop is predominantly dependent on environmental factors and crop factors. The environmental factors are further critical for energy requirement for crop development where sunshine hours, intensity of sunshine, duration of sunshine, temperature and relative humidity play the vital role. Due to the change in geographical location, the energy availability for contributing in the evapotranspiration is also different. Hence, the water requirement for the same cotton crop may vary for two different locations. A dependable and reliable scheduling system for irrigating is desirable for timeliness and quantity of water to irrigate for potential yield of cotton. In this article, a reliable approach to determine crop water requirement for cotton cultivation is proposed using the Penman method for Chuadanga, representing the flat land and Rangamati, representing hilly areas of Bangladesh.

Keywords: Penman method; reference crop coefficient; K_c; cotton irrigation; evapotranspiration; ET_c; net radiation; R_n; energy balance; Bangladesh.

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1 Introduction

Bangladesh, the then East Pakistan was a famous cotton exporting country before and during British colonial rule. Bengal textile was very famous worldwide. Bangladesh is a flood prone country and the flood almost every year causes devastating situation in the low lying areas. It mainly happens due over flooding normally occurs due to the added volume of huge relief rainfall and melt water from Himalayas, flowing of water in the river Ganges and many other smaller tributaries that finally delivers water into the Bay of Bengal (Ninno et al., 2003) which is situated at the south of Bangladesh. It happens during monsoon season almost every year. Two-third of Bangladesh is lower floodplain and creates a severe catastrophe for the nation with an unexplainable risk of thousands of sufferers entailing severe damage to the major crops. Considering the plenty rainfall amount and abundant flood water, most of the farmers having lack of appropriate knowledge of water conservation, storage and utilisation of water resource. They have no clear idea about "when and how much of water" needs to be applied for the maximum yield of their crops. It may be because of lack of advanced knowledge or lack of problem appropriate extension activities to motivate and train the farmers.

Bangladesh ranks as the sixth most vulnerable country in the world for floods and the first for tropical cyclones, but has also severe regional water deficits during the dry season (Gain et al., 2017). On the other hand, rainwater available in Chuadanga, from hereafter represented as low lying flat land, are 1,834 mm and 1,620 mm in the year 2008 and 2011, respectively (Chuadanga – Bangladesh Bureau of Statistics, 2013). Southern portion of Bangladesh consists of hilly areas and Rangamati is selected as the best representative area for cotton cultivation. Rangamati has been reported to have rainwater of 1,824 mm and 2,158 mm in the year 2008 and 2011, respectively (Rangamati – Bangladesh Bureau of Statistics, 2013). Climatically, these two areas are in good locations of the country to have enough rainwater. These areas also get huge flood water almost every year. Even though due to the lack of appropriate and modern approaches of water management practices, traditional irrigation method and water management does not yield the potential level of production.

Cotton is the second ranked fibre crop in Bangladesh. As textile and garment industries are flourishing now, about 728 million kilogram of cotton is needed every year for this industry sector. 2% to 3% of the national requirement of cotton is supported by local production and the remaining 96% to 97% is imported from foreign countries using hard earned currency (Uddin and Mortuza, 2014). Water requirement and its appropriate management need to be well established for cotton production to economise the textile and garment sectors. Cotton cultivation has been getting priority and interest as it is giving better economic return. Maximum area coverage by cotton cultivation has become the target of the government. The possible areas of cultivation are either flat land or hilly areas or both. There are mainly two varieties of cultivars used in Bangladesh. The one used in the hilly areas is locally known as Comilla cotton which is believed to have originated in the British period. The hilly variety is cultivated in limited scale by the tribal people in the southern districts of Bangladesh like in Rangamati, Khagrachori and Bandarban in the Chittagong Hill Tracts.

Even Bangladesh has huge water resources, water management practices for different crops are yet to be improved. In case of critical water requirement stage for cotton is the time when cotton ball opens and this happens when weather is dry (Hasan et al., 2018). This ball opening period of cotton is an active growth period. As hilly and low lying plane areas are differing by various environmental factors, like altitude, day light time length, humidity, temperature, wind speed, etc., value of evapotranspiration should be also different. This study was undertaken with an aim to determine the specific volume of water requirements for maximum cotton production in a low lying and hilly areas.

Maximum production of cotton is possible only if there is an optimum amount of irrigation water and their efficient uses can be confirmed. Irrigation scheduling answers two questions:

1 when to apply water

2 how much water to apply to the crop (Hasan et al., 2018).

Combination of the two points stated above will lead to determine the correct amount of water for cotton cultivation on a specific growth stage of crop for a specific location. In Bangladesh, the farmers rarely know how much water is drawn from the source, how much of water is conveyed and distributed and how much of water is going to be utilised. An easy method for determining the water requirement or readily available information on how much water is needed for cotton production is very much needed for the farmers. The objectives of this study were to propose the methodology to the farmers, stakeholders and the decision makers for improving the quality and quantity of cotton in Bangladesh. As indicated above, two different locations of hilly and non-hilly areas were considered in this study to determine the water requirement for these two areas by using the Penman equation.

Zotarelli et al. (2013) explained a reliable step by step process for deriving the reference crop evapotranspiration by using Penman-Monteith (FAO-56) method and claimed it to be most accurate for Florida conditions. Penman-Monteith method needs several parameters which are not available in the areas of consideration in Bangladesh. The findings of this research will serve as a primary footstep for estimating evapotranspiration in flat and hilly geographic locations similar to the study area.

2 Study areas

This study was conducted on two areas in Bangladesh:

1 Chuadanga, representing the flat land

2 Rangamati, representing hilly areas (Figure 1).

Determination of water requirement which is termed as evapotranspiration is very important not only for the quantity of water, it may be an indicator to dictate if there is a need to provide supplemental irrigation for potential cotton crop yields. Improving irrigation water management methods and issues in the dry areas is becoming increasingly essential to stay competitive. In the USA, supplemental irrigation has been shown to nearly double the non-irrigated cotton yield from about 750 to near 1,200 to 1,500 lbs. of lint per acre during water limited years in the sandy coastal plain soils (Hamid and Munk, 2012).

Figure 1 Map of Bangladesh showing the locations of two study areas and surrounded with red coloured rectangles (see online version for colours)

Source: Bangladesh Map (https://www.mapsofworld.com/bangladesh/)

In Bangladesh, most of the farmers apply water for their crops based on their experiences, with minimum understanding of the actual crop water requirement. Evaporation of water from open water and bare soil surface is the process that takes place the transference of water from the reservoir or open soil surface into the atmosphere in the form of vapour. Evaporation needs:

a source of heat to vaporise the water

b a gradient between the evaporating surface and the surrounding air (Michael, 1997).

Transpiration is another important parameter of hydrologic cycle that leads water vapour moving away from the living plant body and mixes with environment. Evapotranspiration depends on the type of soil, soil texture, soil structure, land-cover, existing soil moisture content, hydraulic conductivity, porosity, existing soil swelling colloids and organic matter, intensity and duration of rainfall or irrigation and viscosity of water (Charbeneau, 2000). For irrigating the crops, it is important to know the quantity of water to be applied to reach the crop-water requirement.

Table 1 Distinguishing features of Chuadanga and Rangamati*

Study areas	*Latitude, °N*	*Longitude, °E*	*Elevations (m)*
Chuadanga	23.60	88.70	17
Rangamati	22.60	92.20	33

Note: According to 2011 census.

Source: Chuadanga, Bangladesh Geographic Information (http://www.latlong.net/place/paik-para-chuadanga-bangladesh-11266.html) and Elevation Map of Rangamati (http://elevationmap.net/rangamati-bd#menu2)

3 Measurements of evapotranspiration by Penman method

The Penman method for determining evapotranspiration is mainly based on local atmospheric data. This method consists of the following.

Using energy balance equation for estimating evaporation which is represented by:

$$R_n = E + A + S + C \tag{1}$$

where

R_n net radiation energy available at the earth's surface

E energy required for evaporating water

A energy required for heating air

S energy required for heating the water

C energy required for heating the surroundings of the water.

Michael (1997) explained the energy balance concept and how it can be used to make the solution for evapotranspiration. The energy balance equation in combination with Dalton's law of evaporation yields the equation for saturated or well-watered grass or reference ET_0 as suggested by Penman (1963). Jensen et al. (1990) derived and presented equation using SI units, as follows:

$$\lambda ET_0 = \frac{\Delta}{\Delta+\gamma}\left(R_n - G\right) + \frac{\gamma}{\Delta+\gamma} 6.43\left(1.0 + 0.53 v_2\right)\left(e_s - e_d\right) \tag{2}$$

where δET_0 = reference ET for a saturated or well-watered grass expressed as latent heat flux density, MJ m^{-2}day^{-1} and Δ is the slope of the saturation vapour pressure curve in kPa/°C is given by equation (3):

$$= 0.20 \times (0.00738T + 0.8072)^7 - 0.000116 \quad (3)$$

where T is the mean daily temperature in °C.

Value of γ which is used as the psychometric constant in kPa/°C is considered as:

$$= 0.00163 \times p/\lambda \quad (4)$$

Here, the values for p and λ are the functions of atmospheric pressure and temperatures. They are expressed as:

$$p = 101.3 - 0.01055(EL) \quad (5)$$

$$\lambda = 2.501 - 0.002361T \quad (6)$$

In equation (5), EL is the elevation in m and λ represents the latent heat of vaporisation of water in MJ/kg.

$$R_n = \text{net radiation in MJ m}^{-2}\text{day}^{-1}$$
$$= (1-\alpha)R_s - \sigma T_a^4 \left[0.34 - 0.139(e_d)^{0.5}\right]\left(0.1 + 0.9\, n/N\right) \quad (7)$$

In equation (7), R_s is the solar radiation received at the earth's surface in MJ/m^2/day, α is the albedo, radiation reflection coefficient and considered to be 0.25 for green crops, σ is called the Stefan-Boltzmann constant, which is equal to 4.903×10^{-9} MJ/m^2/day/°K^4, T_a is the absolute air temperature in °K (°C + 273) and n/N is the ratio of actual to the possible sunshine hours. In some meteorological station, R_s may not be available. In that case, the value of R_s is calculated by equation (8):

$$R_s = \left(0.35 + 0.61\, n/N\right) R_{so} \quad (8)$$

Here, the value of R_{so} is the mean solar radiation for cloudless skies in MJ/m^2/day. Values of R_{so} are shown in Table 2.

G heat flux density to the soil in MJ/m^2/day

v_2 average wind speed at a height of 2 m in m/s

e_s saturated vapour pressure at mean air temperature in kPa

e_d saturated vapour pressure at mean dew-point temperature in kPa (or e_s × mean relative humidity)

The value of soil heat flux is very small and often considered to be zero. Saturation vapour pressure is calculated using equation suggested by Bosen (1960):

$$e_s = 3.38639\left[(0.00738T + 0.8072)^8 - 0.00019\,|1.8T + 48| + 0.001316\right] \quad (9)$$

where T is the mean air temperature in °C. e_d can be calculated using same equation (9) by substituting the mean dew-point temperature for T.

Table 2 shows the interpolated values mean solar radiation for cloudless skies, R_{so} for the latitudes of 22.6°N and 23.6°N for Rangamati and Chuadanga, respectively. The mean and the maximum dew point temperatures (t_d) are calculated using a simplified equation (Lawrence, 2005) relating the daily temperature (t, in degree Celsius) and the relative humidity (RH, in percent):

$$t_d = t - \left[\frac{100 - RH}{5}\right] \qquad (10)$$

Actual ET for any specific crop can be calculated with crop coefficient from equation (11):

$$ET_c = K_c \times \lambda ET_o / \lambda \qquad (11)$$

where

ET_c estimated crop evapotranspiration in mm/day

K_c crop coefficient from a specific crop and location.

Table 2 Mean solar radiation for cloudless skies, R_{so}

Month	*North latitude*						
	0	*10*	*20*	*22.6*	*23.6*	*30*	*40*
	MJ/m²/day						
Jan.	28.18	25.25	21.65	20.56	20.14	17.46	12.27
Feb.	29.18	26.63	25	24.13	23.79	21.65	17.04
Mar.	30.02	29.43	28.18	27.60	27.38	25.96	22.9
Apr.	28.47	29.6	30.14	30.06	30.04	29.85	28.34
May	26.92	29.6	31.4	31.58	31.66	32.11	32.11
Jun.	26.25	29.31	31.82	32.18	32.32	33.2	33.49
Jul.	26.67	29.43	31.53	31.82	31.94	32.66	32.66
Aug.	27.76	28.76	30.14	30.22	30.25	30.44	29.18
Sep.	29.6	29.6	28.47	28.00	27.82	26.67	23.73
Oct.	29.6	28.05	25.83	24.96	24.62	22.48	18.42
Nov.	28.47	25.83	22.48	21.39	20.98	18.3	13.52
Dec.	26.8	24.41	20.5	19.34	18.89	16.04	10.76

3.1 Systematic steps for calculating evapotranspiration

1 Calculate the mean temperature, $T = (T_{\max} + T_{\min}) / 2$, then calculate the value of Δ using equation (3).

2 Calculate P using equation (5).

3 Calculate the latent heat of vaporisation λ using equation (6).

4 Calculate psychometric constant γ using equation (4).

5 Calculate the values of e_s and e_d using equation (9) for mean and dew-point temperatures, respectively.

6 Calculate the climatic constant value of $\frac{\Delta}{\Delta + \gamma}$.

7 From Table 2, find the interpolated values of the mean cloudless solar radiation for:

   1 Chuadanga, representing the flat land

   2 Rangamati, representing hilly areas of Bangladesh which are located at 23.6°N and 22.6°N, respectively.

   Then, calculate the value of R_s by using equation (8).

8 Calculate the net radiation R_n by equation (7).

9 Calculate λET_0 by equation (2).

10 Calculate the crop evapotranspiration by using equation (11).

If the total number of days in the cultivation period is known, the total volume of water in mm can be calculated by multiplying the number of days by the value of crop evapotranspiration as obtained by equation (11).

3.2 Assumptions for calculating ET

Based on literatures, the following assumptions were taken into account throughout calculation procedures:

a Value of heat flux density to the soil, G, as shown in equation (2) was considered to be zero as described by Schwab et al. (1993).

b Radiation reflection coefficient which is also called albedo indicated in equation (7) as α has been considered to be 0.25 for any green crop (Schwab et al., 1993).

c Solar radiation availability is a function of the ratio of total available sunshine hour to total day time hours which is shown as n / N in equation (8), has been considered to be 0.95 (Michael, 1997).

d Crop coefficient values K_c were taken as the values for different months as described by Michael (1997). K_c should be based on the local atmospheric conditions which are very relevant with the values shown for cotton in Michael (1997) as used for Delhi. Based on Michael (1997), values for crop coefficient for short grasses can be taken as 0.6 for November to February, 0.7 for March, April, September and October and from May to August, it can be considered to be 0.8.

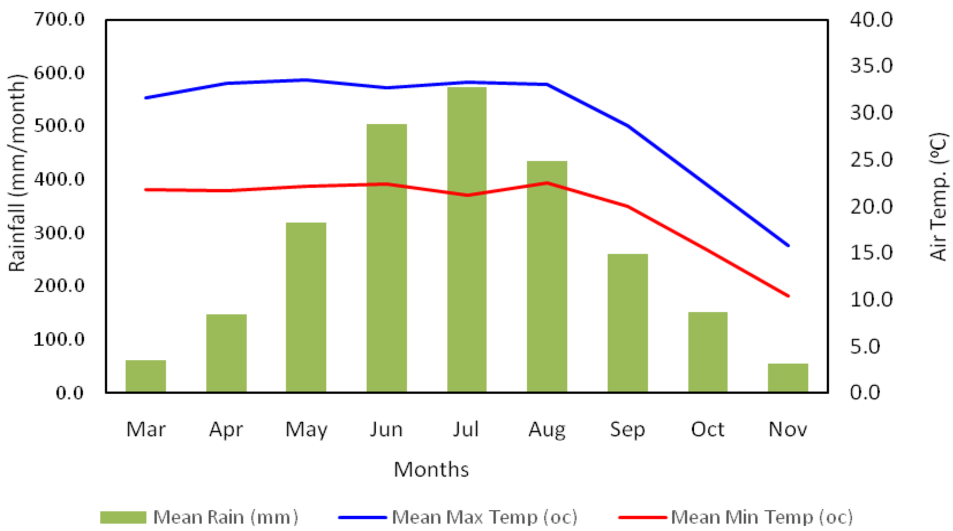
4 Results and discussion

In Bangladesh, the districts Chuadanga and Rangamati, considered as the low lying flat and hilly area, respectively were selected to determine the evapotranspiration for cotton.

The related information and data for establishing the fact for best water management practices are not available. Research on this specific topic is still in embryonic stage. With that critical limitation, approach for determining evapotranspiration for cotton was initiated using Penman method as an alternate method other than determining evapotranspiration using Penman-Monteith (FAO-56) method. Results of this research show a positive direction of initiating different modern research and boost up the economic development of the country. Among other crops, cotton has been considered because it is the second largest crop and involves huge foreign currency to meet up the yearly requirement.

The planting to harvesting period of cotton, like most other crops, depends on various tillage operations and their times. It mainly depends on land preparation, weather condition and other related issues (Hasan et al., 2018). Table 3 shows a detailed data of min. and max. temperature in °C and mean monthly rainfall in mm.

Figure 2 Mean of minimum, maximum and mean monthly rainfall and average air temperature of Rangamati for 2015 (see online version for colours)



The monthly-based rainfall received during the crop growing season in the study area of Rangamati is shown in Figure 2. The rainfall pattern is inconsistent and ranged from 55.7 mm in November and the highest mean rainfall was 572.60 mm in July. When cotton is sown typically in July and the harvesting is done by late February, the maximum mean rainfall occurs at the sowing period. Highest rainfall in July ensures good seed germination and crop stand. Even though the rainfall pattern is inconsistent, the crop growth periodic water requirement and availability from rainfall is a good match for successive crop growth activities. Availability of rainwater before July ensures a good land preparation with enough moisture obtainability for extra need of water for good germination and good standing of the crop. Figure 2 further shows the required water availability in the following months guarantees the best possible flowering and all-encompassing uniform boll split.

Table 3 Mean max. and min. monthly temperature in °C and mean monthly rainfall in mm in 2015 of Chuadanga and Rangamati

	Mar.	*Apr.*	*May*	*Jun.*	*Jul.*	*Aug.*	*Sep.*	*Oct.*	*Nov*
Chuadanga									
Mean max. temp. (°C)	31.26	31.89	33.65	33.22	32.89	32.56	29.57	22.75	16.94
Mean min. temp. (°C)	19.72	23.15	25.15	23.86	26.02	24.35	21.10	15.55	10.70
Mean rain (mm)	20.20	39.80	142.80	235.40	351.70	232.80	297.10	101.30	21.00
Mean monthly ET_c	4.52	4.68	5.74	5.43	5.39	4.93	4.13	3.74	2.29
Rangamati									
Mean max. temp. (°C)	31.59	33.14	33.49	32.70	33.35	33.05	28.59	22.28	15.76
Mean min. temp. (°C)	21.74	21.71	22.11	22.37	21.13	22.48	20.00	15.34	10.42
Mean rain (mm)	62.10	147.90	319.70	504.80	572.60	435.20	259.60	152.20	55.70
Mean monthly ET_c	4.47	5.21	5.74	5.76	5.84	5.98	4.24	3.46	2.40

Monthly basis reference crop evapotranspiration (ET_o) was calculated and the statistical parameters are presented in Table 4. The mean values of reference crop evapotranspiration (ET_o) are 3.93 and 3.82, and their standard deviation values are 0.58 and 0.38, respectively and it is higher in Rangamati compared to Chuadanga both in November. The crop coefficient (K_c) values were considered as it is suggested in Michael (1997) and explained in the previous section. In Table 4, it is further observed that the mean values of reference crop evapotranspiration (K_o) in Rangamati are higher in every corresponding month compared to Chuadanga which support our finding that hilly area has a higher value of crop evapotranspiration (K_c) because the value of (ET_c) is the product of reference crop evapotranspiration, ET_o and crop coefficient, K_c.

Figures 3 and 5 illustrate the ET_c based on various crop growth stages for both areas. Here, it is understood that the maximum *ET* occurs between first open boll and first bloom stages, which falls between 55 to 140 days past planting that conforms with the typical water requirement stated by Boman and Warren (2014). This can be good tool to determine the irrigation scheduling and decision making for any supplemental irrigation. A clear idea available through the results of this research can be a handy information for the farmers about the length of time for their lands to be irrigated once the water intake rate and other related data are available to meet the exact quantity of water needed by the crop for the highest possible production (Hasan et al., 2018). This information needs to be determined in the specific location and available with the extension workers to ensure best management practices (BMP). Values of the maximum water requirements for Chuadanga and Rangamati were found to be within reasonable quantities in both the areas. ET_c values in July shows reasonable values due to maximum temperature and humidity at that time of the year. This finding agrees with the theory on evapotranspiration as described in Penman equation that radiation levels play an essential role in water requirement determination.

Both Figures 3 and 5 show an amount of water is being lost, shown here as *ET*. This occurs from the surface even before the crop is planted, which is taking place not due to the plant other than from the soil surface as evaporation. However, the water requirements increase from first bloom to first open ball periods. This is a peak consumption stage when the crop is at full canopy between early blooms to first open boll phase of the crop in mid-August for both the places. The peak water requirements as predicted by our method and that reported by Fisher and Udeigwe (2012) and Bednarz et al. (2016) were similar and indicated the stage when the cotton crop is most sensitive to water stress. The data indicate the period from first flower to first flower plus three weeks is very sensitive to water stress. In addition, these data indicate withholding water from emergence to first flower can reduce yields. As in the case of other field crops, in cotton, the water use increases remarkably from 5 mm to nearly 9 mm from first flower to peak bloom stage. Water stress during this phase of the cotton crop can reduce crop growth, fruiting sites and continued water stress can result in poor lint yield due to boll drop. Severe water stress can reduce fibre quality as well (Bauer et al., 2012). Withholding irrigation from first flower through three weeks following resulted in significant reduction in cotton yields in a study reported by Bednarz et al. (2016).

Figure 3 Crop water requirement ET_c for Rangamati (see online version for colours)

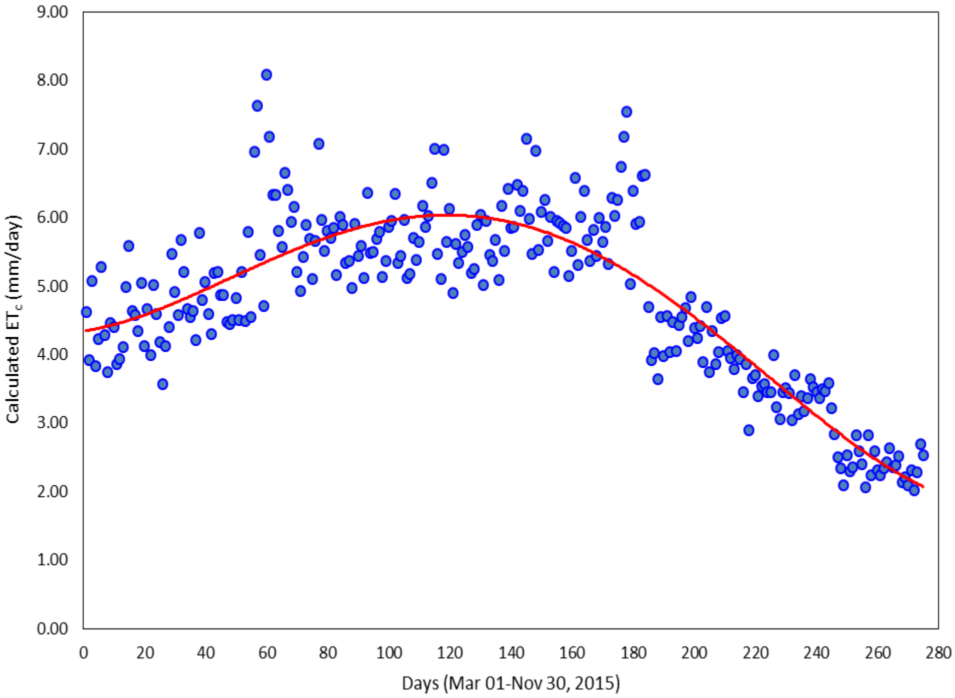


Figure 4 Mean of minimum, maximum and mean monthly rainfall and average air temperature of Chuadanga for 2015 (see online version for colours)

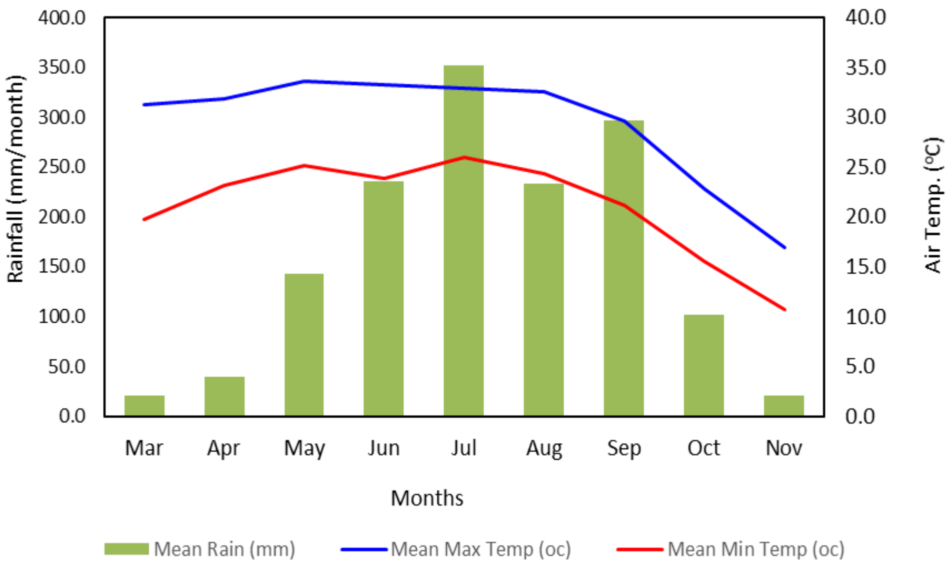


Figure 5 Crop water requirement ET_c for Chuadanga (see online version for colours)

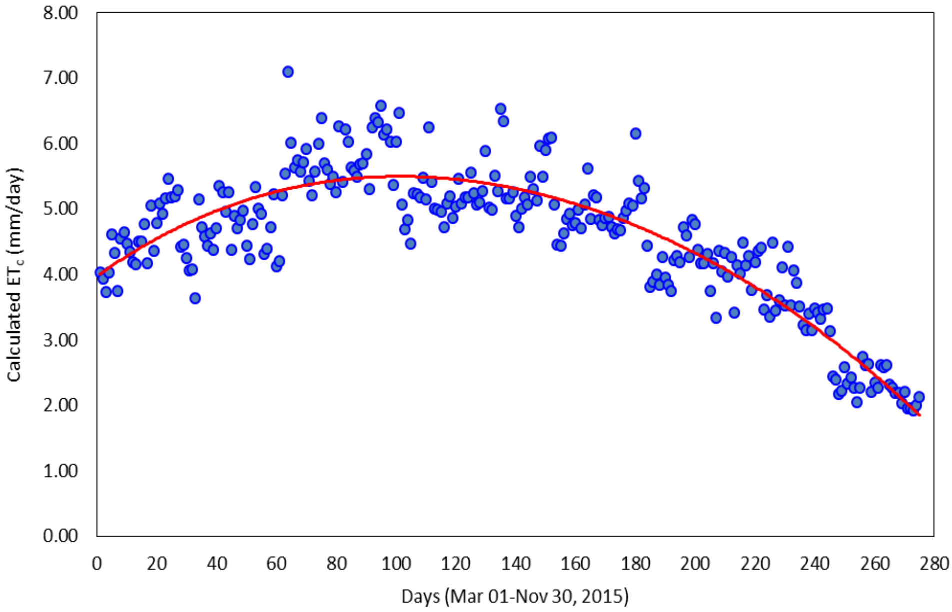
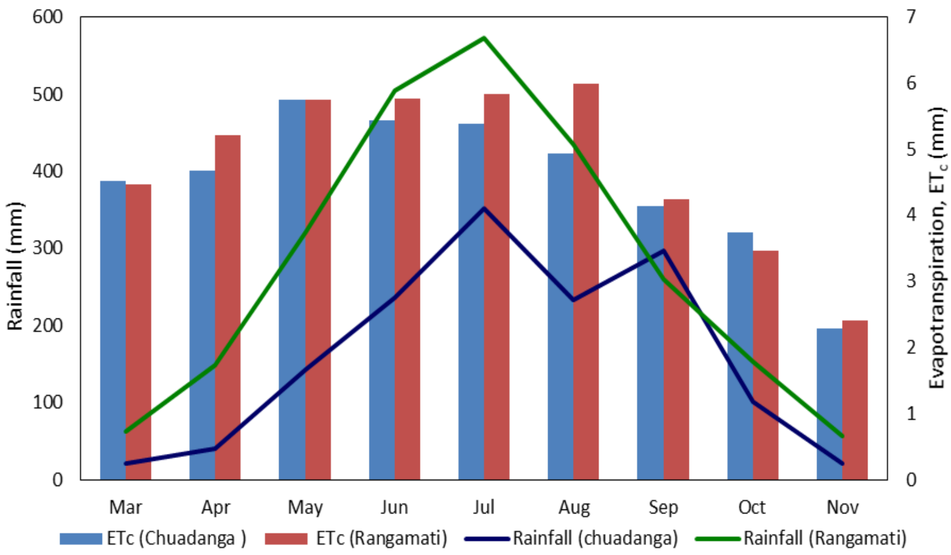


Table 4 Monthly basis statistical parameters of reference crop evapotranspiration (ET_o) during April to September, 2015

Month	*Chuadanga*				*Rangamati*			
	Mean	*St. dev.*	*Min.*	*Max.*	*Mean*	*St. dev.*	*Min.*	*Max.*
April	6.69	0.61	5.18	7.65	8.46	2.22	6.37	14.88
August	6.17	0.45	5.54	7.69	8.55	1.17	6.69	11.66
July	6.74	0.56	5.90	8.16	8.25	0.95	6.79	10.78
June	6.79	0.76	5.58	8.23	8.07	0.97	6.72	10.56
March	6.46	0.66	5.33	7.79	6.84	1.10	5.02	9.22
May	7.17	0.51	6.52	8.87	7.97	0.90	6.55	10.39
November	3.82	0.38	3.20	4.55	3.93	0.58	3.03	5.05
October	5.34	0.63	4.48	6.41	4.88	0.47	3.91	5.97
September	5.90	0.50	4.76	6.90	6.19	0.64	5.02	7.33

The results of this study can be used to determine the water requirements of cotton and for scheduling irrigation to avoid water stress and its effects on lint yield and fibre quality. This method also allows for the determination of when and how much water to apply as stated by Hasan et al. (2018). Figure 6 shows the trend of ET_c and rainfall during March to November of 2015 for both Rangamati and Chuadanga in Bangladesh. This figure indicates that the trend of ET_c and rainfall for both places are similar. One important phenomena observed here is that the evapotranspiration ET_c in Rangamati is higher than ET_c in Chuadanga during pin head through first open ball growing stages.

Figure 6 Rainfall and evapotranspiration ET_c for Chuadanga and Rangamati of Bangladesh, 2015 (see online version for colours)



5 Conclusions

The water requirements of cotton crop calculated by using the Penman method using data from the meteorological stations in Chuadanga, representing the flat land and Rangamati, representing hilly areas. The amount and pattern of water use in relation to crop growth stages were similar to those reported for cotton in Hasan et al. (2018). Thus, prediction of cotton crop water use, using the Penman method is an accurate and useful method for scheduling irrigation, determining irrigation amount for cotton crop in the flat land and hilly areas. It can further be concluded that the hilly area yields a higher value of ET_o than a flat land and it follows the results of statistics as shown in Table 4.

Calculation of evapotranspiration of cotton was a successful attempt even with the limitations of data availability, lack of information and related references. Applying the concept stated in equations (5) and (6) regarding pressure and temperature due to change in elevation to represent the difference of hilly and low lying flat land was reasonable. Assumptions made on heat flux density to the soil (G) to be zero as suggested by Schwab et al. (1993), radiation reflection coefficient (α) to be 0.25 (Schwab et al., 1993), ratio of available day light hour to the total hour of the day (n / N) to be 0.95 (Michael, 1997) and values of crop coefficient (K_c) during different months as described by Michael (1997) were very reasonable to yield the realistic results of crop evapotranspiration (K_c). Further, comparative studies should be done to get the reliability and judge acceptability of application of Penman method for determining the evapotranspiration of cotton.

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