Plant height based evapotranspiration model for eucalyptus

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Abstract: Eucalyptus (Eucalyptus camaldulensis) is commonly recommended for biodrainage due to its high evapotranspiration (ET) demand, tolerance to waterlogging, salinity and sodicity. ET demand is an essential plant input data required for planning and designing a biodrainage system. A height-based ET model is needed for long-term ground water budgeting. An analytical solution of ET as a function of plant height was developed from the governing differential equations. Constants for the model were obtained using lysimetric data from three years. Plant height model predicted maximum plant height of 17.12 m in seven years matching with reported plant height data. Eucalyptus tree height at eight years was 99.43% of its total height at ten years' optimum economic life span. The ET model predicted the highest ET values in May, with corresponding values of 1.57, 3.74, 9.98, 20.20, 31.22, 39.66, 44.50, 46.66, 47.42 and 47.64 mm/day over a period of ten years. The plant height-based ET model performed well over the life span of ten years. The model will be useful in designing the extent of biodrainage belt and planning water use of eucalyptus plantations with progressively changing ET.

Keywords: Canal seepage, biodrainage, evapotranspiration, plant height model, waterlogging

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1 Introduction

Salinization is a global problem and it affects about 20-30 M ha of the world's 260 M ha of irrigated land (FAO, 2000). Canal irrigated areas over the globe are mostly affected by waterlogging and salinization in absence of proper drainage systems (Randhawa and Sharma, 1996). Irrigated agriculture is developing over the globe with continuous increase in waterlogging and salinization of agricultural field (Valipour, 2014a). Less than 20% of the global area is drained, emphasizing the need of drainage for controlling waterlogging and salinity (FAO, 2013; IDD, 2013). In India alone, nearly 3.95 M ha of productive agricultural is suffering due to severe waterlogging (Singh and Bandyopadhyay, 1996) and 6.75 M ha due to salt buildup (Sharma and Gupta, 2010). The main reason for waterlogging in canal irrigation is the excessive seepage from unlined wetted periphery. Drainage development is indispensable to maintain favorable moisture conditions for optimal crop growth and to control soil salinity. Current drainage improvement rate is less than 0.5 million ha per year which is insufficient to balance the current growth of affected drainage areas. Only 10%-20% of the irrigated land is equipped with drainage while 40%-60% is in need of drainage (Smedema et al., 2000). Agenda 21 of Earth Summit stresses the need for drainage as a necessary complement to irrigation development in arid and semi-arid areas (UNCED, 1992).

Subsurface drainage is a well-recognized engineering measure for reclamation of waterlogged salt affected soils for increasing agricultural productivity. In developing countries, government initiatives are required for planning and executing of subsurface drainage projects besides providing financial support and safe passage to the drainage effluent. Specialized knowledge,

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gravity outlet and high cost are the limitations of the subsurface drainage system. Reclamation of waterlogged sodic soils and undulating terrain with poor fertility status through subsurface drainage may prove quite uneconomical due to extremely poor saturated hydraulic conductivity. Biodrainage may become a feasible solution in such areas due to low cost of plantation besides being environmental friendly (Chauhan, 2000).

Biodrainage is the pumping of excess soil water by deep rooted plants using bio-energy (Ram et al., 2011). Due to high evapotranspiration demand, suitability to different ecological conditions and tolerance to salinity, sodicity and waterlogging, eucalyptus are recommended to biodrain waterlogged salt affected areas (Kapoor, 2001; Zahid and Nawaz, 2007). Water uptake by the growing trees is dependent on climatic factors, type and species, age, soil salinity/sodicity and water table conditions and is an index for overall physiological responses (Whitehead and Beadle, 2004; Gazal, 2006). Water extraction by biodrainage belt is dependent on ET of the plant. Evaporation from soil surface, plant surface and transpiration from plant stomata together is referred as ET of the plant. Long-term evapotranspiration data is essentially required for the design of biodrainage system. Several studies have been carried out on measurement of ET demand of short duration crops. Models are also available for estimation of ET in short-cycle crops under varying climatic conditions. Lysimetric study provides precise measurement of actual evapotranspiration (Xu and Chen, 2005; Valipour, 2012). FAO Penman-Monteith model has been widely used for estimating reference crop evapotranspiration (Valipour and Eslamian, 2014), but it requires several parameters for calculation. Hence, empirical methods such as mass transfer, radiation, temperature and pan evaporation based method were developed for estimating reference crop evapotranspiration with limited data (Valipour, 2015a). Some new approaches have been also tried for testing and comparing the results with earlier model (Valipour, 2015).

Limited experimental ET data are available for trees with long life under growing canopy and varying situations of soil moisture status, salinity and sodicity. Unlike seasonal crops, ET of biodrainage plants keeps on increasing with time and need to be measured or assessed for design purpose. Direct measurement of ET under actual field conditions at different locations is time consuming and expensive. Since the ET cannot be studied and measured at every location, ET needs to be modelled and correlated with growth for its wide applicability. Empirical methods have been developed to estimate the ET using different climatic data in the past. Modern instruments such as sap flow using thermal probes and infrared gas analyzers are being used to measure water uptake (Deans and Munro, 2004). These methods require complex and very costly instrumentation and are generally recommended only for specific research purposes. Regression model had been tried for describing plant height of eucalyptus which may be useful deciding economic maturity and ET demand (Singh et al., 2014). Mathematical modeling may avoid many associated limitations for estimating ET at a given time. Regression models have limited application and explain less about the interrelated processes. Artificial Neural Network (ANN) had been also used for modeling of ET **(**Khoshhal and Mokarram, 2012). Use of ANN model for predicting time series data of ET for growing eucalyptus is still awaited. Available models are not suitable for estimating ET of growing eucalyptus or other trees. There is need to develop a model to estimate ET in response to easily measurable plant parameter instead of weather parameters.

A plant height based ET model for growing eucalyptus was developed in the present study. Lysimeteric data were used to determine characteristic constants of the developed model and predict the ET of eucalyptus trees up to ten years to test the model suitability.

2 Materials and methods

2.1 Experimental location

The study area is located in Sharada Sahayak Canal Command at Kashrawan in district Raibareli, U.P., India (26°30'18.90" N and 81°6'40.18" E, at an elevation of 110 m above the sea level). The weather data were collected from the nearest observatory located at Indian Institute of Sugarcane Research, Lucknow. The area represents a humid sub-tropical climate, characterized by hot summers and a cool winter with mean annual rainfall of 984 mm, most of which occur during June to September. Average maximum and minimum temperature in ten years varies between 21.36°C to 38.53°C and 7.72°C to 26.81°C, respectively.

The land presents flat topography with general slope of 1.5% in the direction of East. Sharda Sahayak Canal system is a large canal taking off water from the right bank of the lower Sharada Barrage supplying irrigation water to 2.0 M ha. The total length of the branch, secondary and tertiary canal is 8,704 km. The capacity of canal is 650 m^3/s. A vast area on either side of the canal is waterlogged coupled with sodicity. Water table depth fluctuates from zero to 1.5 m below ground surface throughout the year. The bottom width of canal at the site is 46 m and canal depth is 2.2 m with side slope of 1:2. Canal discharge at full supply level at this reach of canal is 170 m^3/s.

The soil textural classes were observed as loam up to 30 cm, clay from 30 to 60 cm and sandy clay loam from 60 to 120 cm soil depth. Soil pH were observed to be 10.5, 10.3, 9.78, 9.43, 8.83 and 8.72; and electrical conductivity (EC) were 2.60, 2.10, 1.02, 0.80, 0.54 and 0.55 dS/m for soil depths of 0 to 15, 15 to 30, 30 to 45, 45 to 60, 60 to 90 and 90 to 120 cm, respectively. The soil pH and EC are high toward soil surfaces and decreases with increase in soil depths.

2.2 Establishing bio drainage belt

Auger hole plantation technique was used for establishing eucalyptus saplings. Tractor mounted auger was used for making a circular hole of 300 mm diameter in the soil to a depth of 600 mm from soil surface. An input mixture of 5 kg gypsum, 5 kg farm yard manure and 10 kg canal sand was filled in holes. After filling mixture holes, eucalyptus seedlings were planted and manually irrigated. Spacing between row and plants was 1.5 m x 1.5 m. The biodrainage belt was established over an area of 1.2 ha in a strip of 400 m length along the canal and 30 m width across the canal. There were 267 rows in biodrainage belt with 20 plants in each row.

2.3 Installation of lysimeters

Four locally manufactured non-weighing type metallic lysimeters of 1 m diameter and 2 m depth were installed inside the biodrainage belt for measuring plant heights and ET data at regular interval. For lysimeter installation, a circular pit of 1.25 m diameter and 2 m depth was dug out manually and lysimeter was lowered down inside the pit and soil was backfilled immediately into the lysimeters to avoid overthrow of lysimeter due to excessive back seepage pressure. Installation of lysimeters inside the biodrainage belt was done with the sole objectives to avoid boundary effect and damage or uprooting by animals and passerby.

2.4 Measurement of plant height and evapotranspiration

Eucalyptus plant heights were measured on a monthly basis using a staff rod and measuring tape. Evapotranspiration of eucalyptus plant was measured by lysimeters water balance on a daily basis. Constant water table depths inside the lysimeters by replenishing every morning. The amount of water required to maintain the desired water level inside the lysimeters was considered as the total ET demands of the eucalyptus plant. Monthly average ET was calculated by measured daily ET values.

2.5 Modeling of plant height and evapotranspiration

2.5.1 Plant height model

For developing plant height-based ET model, a sub model for plant height was developed using the following assumptions:

1) The rate of increase in eucalyptus height is directly proportional to the difference between maximum tree heights and tree/plant height at a reference time. Mathematically it can be expressed as Equation (1).

$$\frac{dH}{dT} \propto (H_m - H) \qquad (1)$$

Where, H is tree height at a reference time T and H_m is the plant/tree height.

2) The rate of increase in tree height is directly proportional to time, which can be mathematically written as Equation (2).

$$\frac{dH}{dT} \propto T \qquad (2)$$

The above hypothesis holds good during the peak growing period of the trees but in the later part the growth rate ceases with time. After reaching the maximum height, the tree does not grow with time any more. The physiological activities of fully-grown tree reach the peak and do not change thereafter for practical purposes. Economic maturity of the tree or intended use maturity will be different from the maturity height. When the intended use of tree is to reach its full biological growth for maximum physiological response, the growth of tree height can be comparatively described easily. Eucalyptus or other tree species when intended to be used as bio-pump for extracting maximum water from the soil the rate of increase in tree height is not directly proportional to time but a power form time function. This modification takes care of ceasing behavior of tree growth rate (Equation (3)).

$$\frac{dH}{dT} \propto T^{\mu} \qquad (3)$$

Where, μ is the characteristic power constant.

Combining Equation (1) and Equation (3) one will get Equation (4).

$$\frac{dH}{dT} \propto (H_m - H)T^{\mu} \qquad (4)$$

Governing equation

Equation (4) can be rewritten as Equation (5).

$$\frac{dH}{dT} = \lambda (H_m - H)T^{\mu} \qquad (5)$$

Where, λ is proportionality constant.

The above equation after rearrangement takes the following form of Equation (6).

$$\frac{dH}{(H_m - H)} = \lambda T^{\mu}\, dT \qquad (6)$$

The solution

Equation (6) can be now integrated as Equation (7) and Equation (8).

$$\int \frac{dH}{(H_m - H)} = \lambda \int T^{\mu}\, dT \qquad (7)$$

$$-\ln(H_m - H_T) = \lambda \frac{T^{\mu+1}}{\mu+1} + C \qquad (8)$$

Where, C is integration constant.

Equation (8) can further solved as Equation (9) and Equation (10).

$$(H_m - H_T) = e^{-\lambda \frac{T^{\mu+1}}{\mu+1} + C} \qquad (9)$$

$$(H_m - H_T) = e^{C}\, e^{-\lambda \frac{T^{\mu+1}}{\mu+1}} \qquad (10)$$

Integration constant can now be determined by using the initial conditions (T = 0, H_T = H_s) as shown in Equation (11) and Equation (12).

$$(H_m - H_s) = e^{C}\, e^{0} \qquad (11)$$

$$(H_m - H_s) = e^{C} \qquad (12)$$

Substituting the value of e^C in Equation (10) one will get solution as Equation (13).

$$H_m - H_T = (H_m - H_s)\, e^{-\lambda \frac{T^{\mu+1}}{\mu+1}} \qquad (13)$$

If $\alpha = \frac{\lambda}{\beta}$ and $\beta = \mu+1$, above equation takes the following form of Equation (14).

$$H_T = H_m - (H_m - H_s)\, e^{-\alpha T^{\beta}} \qquad (14)$$

Equation (14) is similar to the regression model of Singh et al. (2014). The derived model explains the rational of the tree growth and better understanding of natural biological process for plant or tree growth. Hypothesis based models are superior over empirical or regression models. The constants of Equation (14) could be worked out using field data of plant heights and its age.

2.5.2 Evapotranspiration model

Rate of ET change with respect to plant height is directly proportional to tree height (H) and canopy area (A) as shown Equation (15).

$$\frac{d\,ET}{dH} \propto H\,A \qquad (15)$$

Canopy area is a function of tree height (Arzai and Aliyu, 2010). A common relation between canopy area and tree height is expressed as Equation (16).

$$A = \eta\,H^{\theta} \qquad (16)$$

Where, η and θ are constants.

Substituting Equation (16) in Equation (15) will arrive at Equation (17).

$$\frac{d\,ET}{dH} \propto \eta\,H^{\theta+1} \qquad (17)$$

The Governing equation

Equation (17) can be rewritten in following equation form of Equation (18).

$$\frac{d\,ET}{dH} = \zeta\,\eta\,H^{\theta+1} \qquad (18)$$

Where, ζ is proportionality constant.

Above governing equation can be solved for ET in response to plant height.

The model

Equation (18) can be now solved by integrating as Equation (19) and Equation (20).

$$\int d\,ET = \zeta\,\eta \int H^{\theta+1}\,dH \qquad (19)$$

$$ET = \zeta\,\eta\,\frac{H^{\theta+2}}{\theta+2} + \omega \qquad (20)$$

Where, ω is integration constant and can be worked out using initial condition (H=0, ET=0).

The value of ω = 0 and Equation (20) becomes as Equation (21).

$$ET = \zeta\,\eta\,\frac{H^{\theta+2}}{\theta+2} \qquad (21)$$

If $\xi = \frac{\zeta\eta}{\psi}$ and $\psi = \theta + 2$ the Equation (21) can be written as Equation (22).

$$ET = \xi\,H^{\psi} \qquad (22)$$

Where, ξ and ψ are characteristic constants.

The model needs to be tested with field data and characteristic constants need to be worked out. For obtaining an expression for ET as a function of time, Equation (14) must be substituted in Equation (22) to obtain Equation (23).

$$ET = \xi\left[H_m - (H_m - H_s)\,e^{-\alpha\,T^{\beta}}\right]^{\psi} \qquad (23)$$

2.6 Model constants and estimation of evapotranspiration

Lysimetric eucalyptus plant height and ET data for a period of three years were used to estimate optimized values of the characteristic constants of Equation (23). Regression analysis was performed between ET and corresponding values of plant heights for working out model constants for different months. Optimized values of ξ and ψ are presented in Table 1. Optimized characteristic constants of Equation (14) were worked out as α = 3.0×10^{-04} and β = 2.1289. The maximum eucalyptus height under waterlogged sodic conditions was worked out to be 17.47 m at an age of ten years. The uprooted eucalyptus height at the time of plantation in lysimeter was taken as 2.476 m. ET of eucalyptus for different months was estimated by substituting values of model constants in Equation (23) for a period of ten years.

Table 1 Monthly evapotranspiration model constants and correlation parameters

Month	Parameter		r	S
	ξ	*Ψ*		
Jan	0.219812	2.116743	0.9979	0.4225
Feb	0.297069	2.164935	0.9989	0.5070
Mar	0.690200	1.886300	0.9994	0.5445
Apr	0.976481	1.801711	0.9996	0.5297
May	1.111126	1.799062	0.9980	1.5359
Jun	0.880176	1.816281	0.9965	1.8201
July	0.780679	1.693496	0.9975	1.0876
Aug	0.435737	1.830358	0.9999	0.0986
Sep	0.697042	1.611874	0.9973	0.9256
Oct	0.801228	1.640237	0.9993	0.5855
Nov	0.216200	2.084700	0.9990	0.5830
Dec	0.149345	2.190541	0.9999	0.0602

Note: ξ= constant, ψ = exponent, r = correlation coefficient and S= Standard error

3 Results and discussion

3.1 Measured plant heights and evapotranspiration

The range of average monthly eucalyptus plant heights were observed to be 2.45 to 3.40 m, 3.51 to 5.80 m and 6.19 to 9.40 m for first, second and third year, respectively (Figure 1). Plant heights kept on increasing linearly with time initially. Ayyoub et al. (2002) and Myers et al. (1995) reported eucalyptus plant heights of 9.82 m and 9.40 m in Faislabad, Pakistan and Wagga Wagga, New South Wales, Australia; respectively at an age of 3 years. The measured values of eucalyptus plant height of 9.40 m are quite close to the reported values.

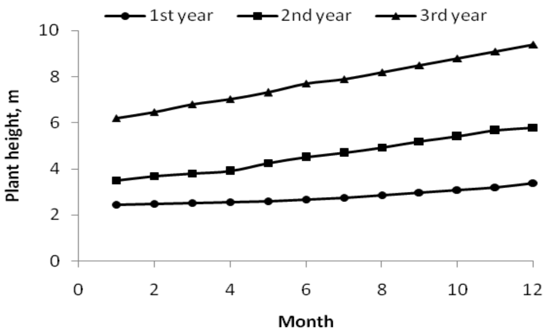

Figure 1 Measured eucalyptus heights with age

Measured ET of eucalyptus plants in lysimeters for a period of three years are presented in Figure 2. The range of measured ET of eucalyptus plant were 0.45 to 1.86 mm/day, 0.72 to 3.52 mm/day and 2.61 to 9.99 mm/day for first, second and third year, respectively. As expected, the ET was the maximum during summer season and the lowest during winter. Evapotranspiration of eucalyptus presented two peaks in a year: the major peak is observed during the driest period of May and minor peak during October (Figure 2). The average ET of eucalyptus was 1.05, 2.22 and 6.26 mm/day for first, second and third year, respectively. Chhabra and Thakur (1998) measured the ET of eucalyptus plants grown in lysimeter and observed average ET as 7.89, 15.06 and 15.11 mm/day for first, second and third year, respectively. The average values of ET reported by Chhabra and Thakur are much higher than the present measured values due to extreme boundary effect and dry experimental conditions. Albaugh (2013) reported ET value of three-year-old eucalyptus was 7.00 mm/day, which is quite close to the present measured value.

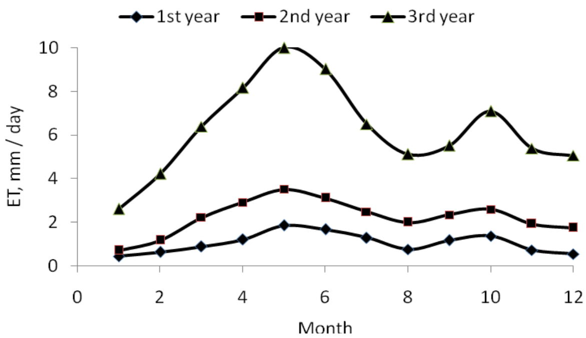

Figure 2 Measured ET of eucalyptus with age

3.2 Model validation

Plant height is a good indicator of evapotranspirative demand for the trees with minimum lateral canopy expansion such as Eucalyptus and Polyathia longifolia. Eucalyptus plants grow straight with minimum lateral canopy spread. Polyathia longifolia is tree with a straight stems wrapped with leaves having minimum branches. These characteristics further strengthened due to minimum basal area of plantation. Due to close spacing between plants, eucalyptus grew straight with mostly a single trunk. Predicted eucalyptus heights with the help of Equation (14) were found to be 3.35, 5.92, 9.39, 12.68, 15.07, 16.47, 17.12, 17.37, 17.45 and 17.47 m for every month of December over a period of ten years (data not shown). Plant heights increased steadily up to 5th year and reaches a plateau thereafter. A very slow growth rate was observed after a period of five years of plantation. The maximum plant height of 17.47 m was obtained at the end of 10th year. The attained plant height at the end of 6th year was 16.47 m. There was a marginal increase of 1 m in the last four years. The estimated values of ET for a period of ten years are shown in Figure 3. The ranges of estimated ET variations were 0.38 to 1.57, 0.78 to 3.74, 2.61 to 9.98, 6.72 to 20.20, 12.36 to 31.22, 17.26 to 39.66, 18.79 to 44.50, 19.39 to 46.66, 19.58 to 47.42 and 19.63 to 47.64 mm/day (Figure 3). Evapotranspiration is having two peaks in a year: the major peak falls during the extreme summer month of May while minor peak falls during the month of October immediately after the rainy season and before the onset of the winter (Figure 3).

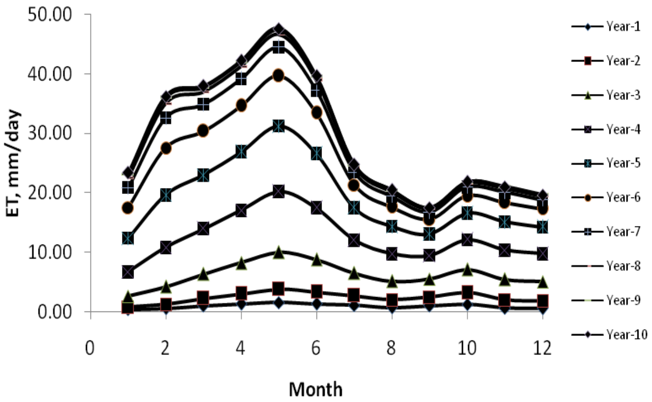

Figure 3 Estimated monthly ET values variation with time

For better understanding of ET, the average monthly minimum-maximum temperature, relative humidity and pan evaporation are shown in Figure 4a, Figure 4b and Figure 4c. The highest values of ET were observed during the peak summer (May) with high temperature and low relative humidity. Evaporation and ET are directly related to temperature. The minimum and maximum temperature curves also have two peaks: during midsummer (April and May) and after monsoon (September). Relative humidity is inversely related to evaporation and ET. Relative humidity curves at 7:00 h and 14:00 h have two inverse peaks during March-April and October-November. Pan evaporation is a combined effect of all-weather parameters and an indicator of ET variation during different months. The shape of variation of mean daily pan evaporation during different months is identical to shapes of variation of estimated ET of corresponding months with two peaks during midsummer and after rainy season. With the use of lysimetric data, the proposed ET model acquired inbuilt capability to combine effects of weather parameters in estimating ET values.

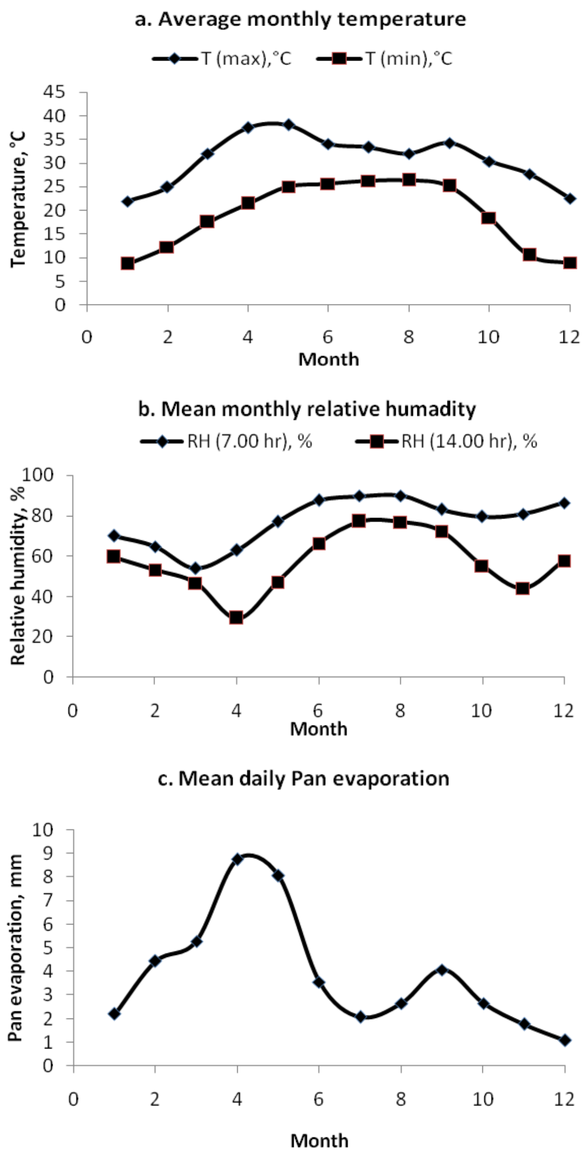

Figure 4 Mean monthly temperature, relative humidity and pan evaporation variation at experimental site

The annual ET values from first to tenth years were estimated as 347, 867, 2276, 4550, 7002, 8890, 9978, 10465, 10640 and 10690 mm, respectively. Albaugh (2013) reported ET of 7 mm/day during mid-summer for three-year-old *Eucalyptus grandis* under South African conditions. The maximum ET estimated with present model for the month of May, the driest month of midsummer, is 9.99 mm/day for third year of plantation in Indo-Gangetic plain of India. The reported value of ET is lower than the estimated value by the model demonstrating estimation capability fairly well. Genetic, climatic, soil and water variability are the main reasons for variations in ET values.

Chhabra and Thakur (1998) reported from a lysimetric study that eucalyptus can biodrain 2880, 5499, 5518 and 5148 mm of water in first, second, third and fourth year of plantation. Estimated ET during first, second, third and fourth years were 347, 867, 2276, 4550 mm. Estimated ETs during initial years are lower however, the value of ET at the end of fourth years is reaching the same level. The difference seems to be due to boundary effect in case of lysimetric studies of Chhabra and Thakur (1998). Lysimetric data of present study seems to be more reliable due to its installation in large-scale established biodrainage plantation. Local environment such as relative humidity and temperature will be lower in case of large-scale plantation.

Kapoor (1999) reported 3446 mm of transpiration of eucalyptus at an age of six years while the estimated value of ET during sixth years of plantation comes out to be 8890 mm, indicating the significant surface evaporation component due to high temperature, low humidity, low rainfall and high wind speed of the region. The present analytical ET model is simple and less time consuming over the weather parameter based ET models and has ability to predict ET of growing eucalyptus tree with single input parameter of plant height. ET model has been found accurate enough in predicting ET of growing eucalyptus hence can be successfully used for designing biodrainage belt for controlling waterlogging and salinity. The model has made it possible to design the biodrainage belt based on long term ET estimates.

4 Conclusions

The developed ET model was satisfactorily used for estimating ET of eucalyptus plant/tree at a given age for the designing of the extent of biodrainage belt and hydrologic planning of the region. The highest values of ET were estimated during the driest midsummer month of May and minimum during the extreme winter month of January. ET model combines the effect of weather parameters in ET estimation. The period when biodrainage belt starts bio-pumping exceeding the rate of canal seepage could be worked out with the use of present ET model. Waiting period and effective period of biodrainage belt can be also calculated besides expected economic return at different age of plantation.

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