ASSESSMENT OF EVAPOTRANSPIRATION MODELS FOR THE HUMID TROPICAL REGION OF TAVANUR

by

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2017

DECLARATION

I hereby declare that this thesis entitled **"Assessment of Evapotranspiration Models for the Humid Tropical Region of Tavanur"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award of any degree, diploma, associateship, fellowship or other similar title of any other University or Society.

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CERTIFICATE

Certified that this thesis entitled **"Assessment of Evapotranspiration Models for the Humid Tropical Region of Tavanur"** is a record of research work done independently by **Ms. Pravalika Y.R. (2015-18-004)** under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

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Pravalika Y. R.

Dedicated to
My beloved parents
Smt.Umadevi .
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SYMBOLS AND ABBREVIATIONS

AET : Actual evapotranspiration
% : Percentage
> : Greater than
& : And
” : Second
‟ : Minute
= : equal to
° : Degree
°C : Degree Celsius
atm : Atmosphere
BCM : FAO-24 Blaney-Criddle (1977) model
CHM : Christiansen (1968) pan evaporation model
CO_2 : Carbon dioxide
cm : Centi meter
cm^3 : Centi meter cube
D : Index of agreement
Dept. : Department
ET : Evapotranspiration
et al. : and others
ETc : Crop evapotranspiration
ETo : Reference evapotranspiration
ETo_{BCM} : Estimated evapotranspiration by Blaney-Criddle model
ETo_{CHM} : Estimated evapotranspiration by Christiansen pan evaporation model
ETo_{HAM} : Estimated evapotranspiration by Hargreaves model
ETo_{LYM} : Measured evapotranspiration from lysimeter
ETo_{MKM} : Estimated evapotranspiration by Makkinik model

ETo_{MPM}	Estimated evapotranspiration by Modified Penman model
ETo_{OPM}	Estimated evapotranspiration by Open Pan method
ETo_{PMM}	Estimated evapotranspiration by Penman-Monteith model
ETo_{PTM}	Estimated evapotranspiration by Priestly-Taylor model
ETo_{THM}	Estimated evapotranspiration by Thornthwaite model
ETo_{TUM}	Estimated evapotranspiration by Turc model
exp	Exponential
FAO	Food and Agricultural Oganisation
Fig.	Figure
G	Gram
g/cc	gram per cubic centimeter
gm^{-3}	gram per cubic meter
Hz	Hertz
H	Hour
ha	Hectare
Hort.	Horticulture
IS	Indian Standard
J.	Journal
K	Potassium
KAU	Kerala Agricultural University
Kc	Crop Coefficient
KCAET	Kelappaji College of agricultural Engineering and Technology
km^3	kilo meter cube
km/h	kilometer per hour
kPa	kilo pascal
l	Litre
LAI	Leaf Area Index

lph	:	litre per hour
LYM	:	Lysimetric method
m	:	Meter
m^2	:	square meter
m^3	:	cubic meter
ms^{-1}	:	meter per second
MAE	:	Mean absolute error
min	:	Minute
Mha	:	Million hectare
$MJ^{-1}m^{-2}day^{-1}$	:	Mega joules per square meter per day
MKM	:	Makkinik model
mm	:	Millimeter
MPM	:	FAO-24 Modified Penman (1977) model
OPM	:	FAO-24 Open pan (1977) method
PET	:	Potential Evapotranspiration
PMM	:	FAO-56 Penman-Monteith (1991) model
PTM	:	Priestly-Taylor model
PVC	:	Poly vinyl chloride
R^2	:	Coefficient of determination
RARS	:	Regional Agricultural Research Station
RH	:	Relative humidity
RMSE	:	Root mean square error
RelRMSE	:	Relative root mean square error
Sci.	:	Science
t	:	Time
THM	:	Thornthwaite (1948) model
TUM	:	Turc (1961) model
W/m^2	:	Watt per square meter

Introduction

CHAPTER I
INTRODUCTION

The increase of world population, food demand, land degradation and droughts causes the world to face an acute water crisis. This increases the concerns regarding the reliability of precious water resources and its ability to provide a stable, secure, and prosperous life. The debate on water scarcity has revolved around the water, that we need and use. Day by day the water resources of per capita availability are reducing. As per the international norms, if per-capita water availability is less than 1700 m^3 per year then the country is categorized as water stressed and if it is less than 1000 m^3 per capita per year then the country is classified as water scarce. In India per capita surface water availability in the years 1991 and 2001 were 2309 and 1902 m^3 and these are projected to reduce to 1401 and 1191 m^3 by the years 2025 and 2050 respectively (Gangwar, 2013). The above estimate represents that India has only limited resources for future use. The country faces the problem of drought syndrome and frequent floods due to spatial and temporal variability in precipitation.

Out of global water use, agriculture accounts for 70 per cent of the water. Irrigation plays a crucial role in increasing agricultural production. The irrigated area in the country was only 22.6 million hectare (Mha) during 1950–51. Since the food production was much below the requirement of the country, due attention was paid for expansion of irrigation. The ultimate irrigation potential of India has been estimated as 140 Mha. Out of this, 76 Mha would come from surface water and 64 Mha from groundwater sources. The quantum of water used for irrigation by the last century was of the order of 300 km^3 of surface water and 128 km^3 of groundwater accounting to a total 428 km^3. This estimates indicated that by the year 2025, the water requirement for irrigation would be 561 km^3 for low-demand scenario and 611 km^3 for high-demand scenario. These requirements are likely to further increase to 628 km^3 for low-demand scenario and 807 km^3 for high-demand scenario by 2050 (Suhag, 2016). Hence, there is a need for proper planning, development and management of this greatest asset of the country.

One of the most important factors for water resources planning and irrigation scheduling is crop evapotranspiration or crop water use. Crop water requirement varies with climate, season crop, space and time. Therefore it is necessary to know the actual crop water requirement to minimise the water loss and optimise the water use. For the design and management of an irrigation system the optimal crop water requirement estimation is necessary. When water is applied optimally the output of a crop is maximum and the output of crop reduces if any deficient or excess amount of water applied to the crop. The accurate estimation of evapotranspiration is very important to determine the optimal crop water requirement.

Evapotranspiration is evaporation of water from soil surface and transpiration from plant tissues to the atmosphere (Allen *et al.*, 1998). Evapotranspiration is classified into two types: actual evapotranspiration and potential evapotranspiration. "When unlimited water is available, the maximum water lost from a short green crop under climatic conditions is termed as potential evapotranspiration (PET)" (Jensen *et al.*, 1990). The rate of evapotranspiration from a well-defined reference environment is referred as reference evapotranspiration (ETo) and is commonly used as the standard. Reference evapotranspiration (ETo) is 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 sec/m and albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered and completely shading the ground" (Allen *et al.*, 1998).

Limited water is available for evapotranspiration in most of the cases and therefore the actual amount of water loss is of interest. So, the actual evapotranspiration rate is considered as the gold standard for irrigation management and it is defined as the rate at which actual amount of water removed by evapotranspiration from the crop to the atmosphere (Jensen *et al.*, 1990). The grass reference evapotranspiration (ETo) multiplied with crop coefficient give the actual evapotranspiration of a crop. For hydrological, agricultural and environmental studies, especially under climate mitigation conditions and increasing water scarcity the accurate determination of grass-reference evapotranspiration (ETo) is very important (Djaman *et al*., 2016).

Reference evapotranspiration can be measured directly (using lysimeters) or indirectly (using models). Lysimeter is a device which is hydrologically separated from the adjacent soils by using a container in which water loss and gain can be found easily and crop evapotranspiration can be calculated by using water balance equation. But, this direct measurement of ET using lysimeter is very cumbersome, expensive and time consuming. However, it is used to validate and calibrate ET models (Farahani *et al*., 2007). Owing to the difficulty of obtaining accurate field measurement, ETo is commonly computed from estimation models.

Through field experiments, some of ETo estimation models were derived while others were derived theoretically (Jensen *et al*., 1990). A few of these models use metrological data to estimate ET. Thus estimation of evapotranspiration can be done by a large number of indirect methods using metrological data like Thornthwaite (1948), Open Pan method (1977), Turc (1961), Christiansen pan evaporation (1968), Blaney-Criddle (1977), Modified Penman (1977), Hargreaves (1985), FAO-56 Penman-Monteith (1991) etc. However under all climatic regimes no single existing method using meteorological data is universally adoptable. Due to the condition in which they developed the use of specific method is limited. Though The FAO-56 Penman-Monteith model is renowned for being the most accurate model, it requires a full set of climate data that is not always available at all weather stations, especially in most of the developing countries like India. Under such conditions use of a specific method become very difficult and application of an alternative method may not yield results with desired accuracy. Moreover evapotranspiration models performance is influenced by spatial and temporal variation. Hence the measurement and estimation of ETo are recommended to be studied continuously for a specific region for accuracy. Determination of inter-relationship between the estimation methods and the lysimetric data enable the user to easily convert the values obtained from different methods to actual values. Thus, calibrating ETo models that require a reduced set of climate data with lysimetric data continues to be an important alternative in such cases (Djaman *et al*., 2016).

Only a few studies have been conducted in India to measure and estimate evapotranspiration. In all these studies many of the existing ET models were tested and calibrated for arid and semi-arid environments. However, no major models have been specifically developed for use in humid tropical environments. In view of all the above facts the present investigation is planned with the following specific objectives:

1. To compute reference crop evapotranspiration for the humid tropical region using empirical models.
2. To evaluate the performance of these empirical models by actual field measurements using lysimeter.
3. To determine the relationship between the model outputs and the observed values.

Review of Literature

CHAPTER II

REVIEW OF LITERATURE

Water resources for agricultural use are decreasing day by day in the context of climate change and environmental pollution. Therefore crop water use is to be accurately determined to improve water management strategies and then to increase the water use efficiency. This chapter provides a brief introduction about evapotranspiration mechanism and processes behind evapotranspiration. It also includes the description of different theoretical models and water balance study for estimating the evapotranspiration. According to the objectives of this study the previous studies relevant to the topic are briefly reviewed in the forgoing section under the following subtitles.

2.1 OUTLINE OF EVAPOTRANSPIRATION

Evapotranspiration (ET) is the water returned to the atmosphere through the processes of evaporation and transpiration. In the irrigation planning, hydrological cycle and water management processes the most important component is the evapotranspiration process (Allen *et al*., 1998). ET and precipitation components are essential for proper planning and operating water resource projects.

Loss of water from soil surface to the atmosphere is known as evaporation whereas loss of water from vegetation through its stomata and leaves is known as transpiration (Jensen *et al*., 1990). Transpiration process supports to absorb and transport mineral nutrients in plants. During radiant periods it also cools the leaves by removing the latent heat of vaporization. However, too much transpiration can lead to plant stress. Through reduction of the leaf area most of the crops eliminate high transpiration stress (Pereira *et al*., 1999).

Weather parameters such as temperature, humidity, wind speed and solar radiation; crop factors such as crop variety, type, management and plant density and environmental factors such as poor land fertility and soil salinity are influenced on ET process (Allen *et al*., 1998; Jensen *et al*., 1990). Considering both components of evapotranspiration separately, weather parameters influenced on evaporation whereas crop characteristics and soil moisture are influenced on transpiration process. ET is often expressed as energy per unit area over a specified time (MJ m^{-2} day $^{-1}$) or units of depth per time (mm/day) (Allen *et al*., 1998). The evapotranspiration can be expressed as either potential evapotranspiration (PET) or actual evapotranspiration (AET).

2.2 CONCEPT OF EVAPOTRANSPIRATION

When soil water is limited, the AET can be occurred in the case of arid environment. Therefore, the soil water content is very much influenced on evapotranspiration. Penman (1956) defined PET as “if unlimited water is available, the amount of water transpired from a short green crop in unit time, and the grass is completely shading the ground of uniform height”. De Jong and Tugwood (1987) and Van Bavel (1966) stated that the surface vapour found from surface pressure is fundamental condition for potential evapotranspiration. Under a given climatic conditions the maximum possible level of water loss is equivalent to the term “potential”. Evapotranspiration decreases due to soil moisture depletion and it reduces from potential to actual evapotranspiration (Katerji and Rana, 2011). The available water is very limited and then the potential evapotranspiration is extremely high in arid regions.

As per the definition proposed by Penman the selection of specific crop is difficult and many scientists get confused in the selection of crop which can be used as a short green crop. During an international meeting held in the Netherlands, a clear definition of PET was given (Anon, 1956) and it was defined as the amount of water lost from short green canopy under the following conditions: unlimited water availability, homogeneous height of crop maintained throughout the growing stage of the crop and fully covering the ground surface (Katerji and Rana, 2011). However, in a humid region the meaning of potential makes a conflict and it also gives a crucial criticism of PET which is the possible maximum evaporation rate from the soil surface, PET was observed to be less than AET (Katerji and Rana, 2011). As a result, engineering scientists accepted that the potential evapotranspiration (PET) has gained least significant over the reference evapotranspiration (ETo). Furthermore, critical to the processes of water supplies (surface and ground water), water management and the economics of the multi-purpose water projects (irrigation, power, water transportation, flood control, municipal, industrial water uses and wastewater reuse systems), an accurate evapotranspiration estimation is extremely important (Jensen *et al*, 1990) and hence the need for reference evapotranspiration (ETo).

Allen *et al*. (1998) defined reference evapotranspiration (ETo) 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 sec/m and albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered and completely shading the ground”.

The evaporating power of the atmosphere at a specific location with respect to specific time of year is well known as ETo (Allen *et al*., 1998). According to Irmak *et al*. (2003) the grass that is assumed to be free of water stress and diseases is known as reference crop. Grass and alfalfa are the two main crops have been used historically to estimate reference crop evapotranspiration (ETo) (Penman, 1948; Blaney and Criddle, 1950; Jensen and Haise, 1963; Hargreaves, 1974; Doorenbes and Pruitt, 1977; Linacre, 1977; Jensen *et al*., 1990; Allen *et al*., 1998; Pereira *et al*., 1999). For determining ETo, alfalfa is a better crop used because it has a deep root system and stomatal resistance and exchange values that are very similar to many agricultural crops. Grass was selected as the primary reference surface by the FAO for international use due to short clipped grass had more experimental data (Pereira *et al*., 1999).

2.3 EVAPOTRANSPIRATION MEASUREMENT AND ESTIMATION

It is very complicated to measure evapotranspiration process. Therefore, for this purpose several methods have been developed. There are three different approaches to measure ET and these approaches were helped to fulfil the variable objectives. For measurement of ET, hydrological, micrometeorological and plant physiological are the three different approaches (Rana and Katerji, 2000). On the other hand, for detailed understanding of a system or interpreting experimental results to obtain a management tool, modelling of ET is very much necessary. Hence estimation of ET is required and there are two approaches for ET estimation: analytical and empirical.

2.3.1 Measurement of Evapotranspiration

Three different approaches were used to measure the evapotranspiration. Quantification of evaporation over a period of time is intended by the hydrological approach. To understand the energy and mass transfer process between the surface and the atmosphere, micrometeorological approach is designed. Set of individual plants or plant parts water relations are studied by using plant physiology approach (Rana and Katerji, 2000).

2.3.1.1 The hydrological approach

a) Lysimeters

To develop, calibrate and validate ET methods lysimeters have been extensively used (Doorenbos and Pruitt, 1977; Jensen *et al.*, 1990; Allen *et al.*, 1998). Environmental factors are influenced on lysimeter. Unfortunately, lysimeters don't have sufficient documentation and description in literature as reported by Allen *et al.* (2011). Therefore the problem of uncertainty of the data was found in many research studies (Allen *et al.*, 2011). However, it is most reliable method to measure ET. There are three groups of classifications in the lysimeter: (1) Non-weighting lysimeters, which have water tables constant. In the areas of water table level is the same inside and outside lysimeter and high water table exists, the lysimeter provide reliable weekly data or for longer periods; (2) Non-weighing lysimeters of percolation types where changes in water stored in the soil are determined by sampling methods of inputs and the rainfall and percolate are measured. (3) Weighing lysimeters: by weighing the entire unit using the mechanical balance the soil water changes are detected. (Jensen *et al.*, 1990).

For the accurate determination of evapotranspiration, instead of using lysimeters certain other shortcomings of this method exist. Lysimeters represent a small sample as similar to field area and therefore it is not suitable for water management plans and for large vegetated areas and also, after construction of lysimeter systems it is very difficult to maintain original soil profile characteristics including density (Allen *et al.*, 2011). Moreover, especially in an arid environment the heating of the metallic rim caused by radiation produces micro advection of heat into the lysimeter canopy; therefore, the measurement will be influenced (Rana and Katerji, 2000; Allen, 2011).

b) Water balance

For measuring ET the soil water changes has been used from nearly a century. Up to 1960, for determining soil moisture content the gravimetric analysis was the primary method used. After the 1980s, to measure soil moisture content with the best results in coarser textured soils a number of electromagnetic devices based on dielectric and capacitance measurements were introduced. Neutron scattering methods as well as time domain reflectometry-based methods have also been used and intensively studied by a number of scientists (Evett *et al.*, 2006; Sumner, 2000) as cited by Allen *et al.* (2011). The average ET in the water balance method is determined by calculating the change in soil moisture between sampling dates plus rainfall minus any known drainage that may have occurred, (Allen *et al.*, 2011; Farahani *et al.*, 2007). Therefore, the AET can be determined by calculating the soil water balance, the amount of water entering, remaining and leaving the soil profile within a given time (Rana and Katerji, 2000).

2.3.1.2 Micro-metrological approaches

The energy involved in transfer of water to the atmosphere as a vapour from inner leaves and plant organs is called as evapotranspiration. From an energy point of view, this is referred to as "latent heat" (λE, where λ is the latent heat of vaporization). Energy flux density is used as measurement of latent heat in Wm^{-2} (Rana and Katerji, 2000). The main methods of latent heat flux measurement are discussed as follows. These techniques are: energy balance, aerodynamic method and the eddy covariance.

a) Bowen Ratio and Energy balance

According to Jensen *et al*. (1990) for estimating evapotranspiration the Bowen ratio approach is a commonly used method. The energy is required for the evaporation of the water; therefore energy input into the system limits the ET process. The energy received at the surface must be equal to the energy leaving the surface at a particular moment (Allen *et al*., 1998). This is showed in the following energy balance equation:

$$R_n - G - \lambda ET - H = 0$$

Where, R_n is net radiation, G is soil heat flux, λET is the latent heat flux and H is the sensible heat flux. In the above equation, the other variables such as the energy used by metabolic activities or heat stored in the plant are not considered because the other four variables having greater values compare to these variables (Allen *et al*., 1998). By using climatic parameters the R_n and G can be measured or estimated. It is very difficult to measure H because it requires accurate temperature gradients above the surface. On the other hand, loss of energy from the surface will occur because the other three variables having positive values (G, T and H). It should be noted that in areas of homogenous land cover when the horizontal gradient is absent only the vertical flux gradient is considered (Allen *et al*., 1998). Due to the dependency of the energy balance method on technical procedures it is extensively used only in research. It is applicable only to the short period of time which is the main limitation to this method (Jensen *et al*., 1990) and when the water is limited the relative errors will increase (Allen *et al*., 2011).

b) Aerodynamic Method

Assuming that a flux density is related to the gradient of the concentration in the atmospheric surface layer (ASL), then the latent heat flux is determined by

$$\lambda E = -\lambda p u^* q^*$$

Where, q* is the specific air humidity, u * is the friction velocity as determined by

$$u^* = Ku/ (\ln (z-d/z_0)) - \psi_m$$

d (m) is the zero displacement height, K = 0.41 is the von karman constant, ψ_m is the stability correction function or moment transport, z_0 (m) is the roughness length of surface and q* is determined from the humidity profile measurements (Rana and Katerji, 2000). A series of iterative functions are used for the calculation of stability functions.

At different heights above the crop, in the correct measurement of the vapour pressure the above method proposes a major difficulty. As a result, the latent heat flux λE is usually derived indirectly by the energy balance when the sensible heat flux is determined by the flux gradient relation:

$$H = -\rho C_p u^* T^*$$

Where, T* is calculated using the air temperature profile:

$$T^* = k (T-T_0)/(\ln (z-d/z_0))-\psi_h)$$

T_0 is the temperature extrapolated at $z = d+z_0$ and ψ_h is the correction function for heat transport. Other variables are defined in above paragraph.

c) Eddy covariance

To measure the evapotranspiration eddy covariance method also can be used. To measure vertical wind fluctuations it is used. By using sonic anemometer vertical wind fluctuations can be measured and by using a fast response hygrometer vapour density is measured; both of which have to be acquired at a frequency of 10-20 Hz (Allen *et al.*, 2011).

Based on the transport of vectorial amounts that is momentum and scalar variables such as CO_2, heat and vapour in low atmosphere in contact with the canopies the eddy covariance method will work and air turbulence was used to govern this method (Stull, 1988). Vapour density (ms^{-1} and gm^{-3}) and vertical wind speed was used to determine the latent heat and it is given by

$\lambda E = \lambda w' q'$

Where, q' = humidity and w' = vertical wind speed.

λE can be obtained directly from the energy budget by avoiding any issues arising from the fluctuations of humidity measurements. It is used only for research purposes because it very costly and labour intensive method (Allen *et al.*, 2011).

2.3.1.3 Plant physiological approach

By using plant physiology methods, water loss from a whole plant or a group of plants can be measured. Of these methods, the sap flow method and the chambers system are mentioned in the following such as,

a) Sap flow method

Plant transpiration is influenced by Sap flow. Two different methods are used to measure sap flow. They are heat balance and heat pulse. Cohen *et al.* (2002) introduced heat pulse in herbaceous plants and it is applied as a basic method (Rana and Katerji, 2000). By measuring heat velocity, stem area and xylem conductive area, heat pulse can be estimated. For every crop type it requires constant calibration and hence at a low transpiration rate this method proved to be inaccurate (Rana and Katerji, 2000).

b) Chambers system

Reicosky and Peters, 1977 were first introduced the Chambers system and it is a rapid measure for ET as cited by Rana and Katerji, 2000. The first version of the system was portable. It is made up of aluminium conduits covered with polyethylene, mylar or glass films or other plastic and the fans which is located strategically helps to mix the air within the chambers. This system is used to measure the daily ET and it is not suitable for long term measurements. ET measurements being influenced by surrounding conditions and this weakness is shown in many Researches. Due to the high cost of the key components the most recent improved chamber systems are very expensive (Rana and Katerji, 2000).

2.3.2 Estimation of Evapotranspiration

The need for other indirect methods has arisen because it is very difficult to measure evapotranspiration directly and by multiplying the reference evapotranspiration (ETo) with crop coefficient (Kc) the actual evapotranspiration can be obtained. The crop data, meteorological data and the ability of models to represent the physical laws governing the process influenced on the accuracy of actual evapotranspiration (Jensen *et al.*, 1990). The actual evapotranspiration is given as ETc = Kc X ETo.

2.3.2.1 Reference crop evapotranspiration models

Based on meteorological data many empirical models have been developed to estimate reference crop evapotranspiration (ETo) for different regions of world. To evaluate their performance many studies have been conducted. Some of these models are physically-based and others are semi-empirical and empirical based (Jensen *et al.*, 1990). Based on climatic parameters these models can be categorized into three groups. They are combination models, radiation based models and temperature based models (Igbadun, 2012). The availability of climatic parameters plays a dominant role in the selection of these models.

a) Combination models

Penman model (1948) is a combination model. Penman proposed the first estimation model in 1948. It works to combine water vapour with the surface energy balance equation and the aerodynamic formulae for the vertical transfer of sensible heat (Jensen *et al*., 1990). Air saturation at the surface and horizontal uniformity of the surface were the assumptions of Penman's model (1948). The complexity occurs when the surface was partly wetted or dry because the model was only applicable for open water and completely wet land surfaces. Negligence of the advection effects led to serious errors when considering open water such as rivers or lakes (Hooghart, 1987). During the 1940s there is no direct measurements of net radiation existed. In the evaporation process the net radiation as a significant factor, this was first considered by Penman's model. By using percentage of sunshine, extra-terrestrial radiation (Ra) and humidity Penman estimated the net radiation (Jensen *et al*., 1990). Hence it became necessary to revise this Penman's model over time as depended on semi-empirical expressions.

Using the same physical principles as the Penman model, monteith revised a formula that describe the transpiration from a dry, extensive-horizontal uniform surface in 1965; it was used to a dry crop which is completely shading the ground (Hooghart, 1987). He discussed the relationship of aerodynamic and canopy resistance. His model was later referred to as the Penman-Monteith equation (Katul *et al*., 1992).

b) Radiation models

When wind speed and humidity are not measured the radiation methods were adopted by Makkink (1957); Turc (1961); Priestley and Taylor (1972) (Doorenbos and Pruitt, 1977). The performances of these models vary from under or over prediction depending on the region where they were applied. Therefore these models did not perform well always. In a semiarid environment radiation models are not recommended (Berengena and Gavilan, 2005; Trajkovic and Gocic, 2010). However, Priestley-Taylor performed well in a semiarid environment (Stannard, 1993). In arid regions, Jensen and Haise (1963) are recommended only radiation models (Mustafa *et al.*, 1989; Ismail, 1993; Alazba *et al.*, 2003). In estimating reference evapotranspiration (ETo) models FAO-56 Penman-Monteith (FAO-56 PM) model performance is superior. Hence evaluation of radiation models based on FAO-56 PM has been focused in recent researches (Alexandris *et a*l., 2006; Trajkovic and Kolakovic, 2009; Tabari, 2010). Before radiation models inferred to another environment calibration is needed for these models.

c) Temperature models

Hargreaves-Samani (1985) and Thornhwaite (1948) are temperature based models. Due to the simplicity of temperature models, these have been tested worldwide. The temperature-based methods performance variation depends on the version of the model. Before extrapolating temperature models to another environment calibration is needed for these models.

For estimating reference evapotranspiration, the Food Agriculture Organization has been selected the FAO-56 Penman-Monteith as a standard equation all over the world (Tabari, 2010). The meteorological data such as relative humidity, temperature, solar radiation and wind speed were required for the FAO-56 Penman-Monteith equation but in developing countries like India these data are not always available. Models that use readily available weather data are therefore preferable (Tabari, 2010).

2.4 PERFORMANCE OF EVAPOTRANSPIRATION MODELS

To test the models applicability in different climates the ETo estimated by different empirical models are compared with measured ETo data from lysimeters (Jensen *et al.*, 1990; Alazba *et al.*, 2003; Denmirtas *et al.*, 2007; Saghravani *et al.*, 2009; Trajkovic and Gocic, 2010).

Georgieve and kazandjiev (1994) evaluated water regime for cereals using climatic data in the region of semiarid climate. Six different methods for estimating PET were evaluated and the methods were Penman, Christiansen, Thornthwaite, Gorcio, Hargreaves and Turc. He concluded that all six methods worked quite well, but Thornthwaite method was the most rapid one.

Masteorilli *et al*. (1994) conducted experiment on operational estimate of reference ET at regional scale in arid region. Reference ET was calculated using eight different models. The results showed that ETo estimates varied between methods and their accuracy was dependent on the selection of empirical coefficients. Direct measurements of ETo from a weighing type evaporimeter were utilized to provide local coefficients for converting estimates of ETo to measurements. The Blaney-Criddle formula was found to be highly correlated with measured ETo. However after calibration the penman method appeared to represent best evapotranspiration demand of the site.

Meshram *et al*. (2010) conducted a study on reference crop evapotranspiration of western part of Maharashtra, India. In this study, six reference crop evapotranspiration methods were studied. Comparison was made between the Modified Penman, Hargreaves-Samani, Pan Evaporation, Blaney-Criddle, FAO Radiation methods and the Penman-Monteith equation (which was standardized by Food and Agricultural Organization as FAO56-Penman-Monteith). To evaluate the performance of these models the least root mean square error and regression analysis were used. The results of this study showed that modified Penman gave best performance when compared to the other methods like Blaney-Criddle, Pan Evaporation, Hargreaves-Samani and the radiation method.

George and Raghuwanshi (2012) conducted a study on Inter-comparison of reference evapotranspiration estimation using six methods namely, Hargreaves (Temperature based), FAO-24 Radiation, Priestley-Taylor and Turc (Radiation Based) and FAO-24 Penman and Kimberly-Penman (Combination). They evaluated the models using meteorological data from four climatological stations to determine the best and worst method for each location. The reference crop evapotranspiration (ETo) values estimated by all methods were compared with the FAO-56 Penman-Monteith ETo estimates. Based on the Standard Error Estimates, the FAO-24 radiation method ranked first for the Jagdalpur and Bombay stations. The 1982 Kimberly-Penman ranked first for Kharagpur and Bellary.

Csaba *et al*. (2013) conducted study on comparison of several methods for calculation of reference crop evapotranspiration. The objective of the study was to explore the output range and sensitivity of models of different physical approaches under local conditions. They performed descriptive statistical and sensitivity analysis of ten commonly used estimation models one of them with two variants. Correlations between modelled and measured evapotranspiration data series were assessed. The magnitude of the model outputs, their variability and responses to the changes of selected atmospheric parameters were also evaluated. Priestley-Taylor, FAO-56 Penman-Monteith, Shuttleworth-Wallace, Szasz and Makkink proved to be the most sensitive methods. The Makkink and Shuttleworth-Wallace methods showed the best agreement with pan evaporation, while Shuttleworth-Wallace, Blaney-Criddle and Makkink models were found to be the closest to the FAO-56 Penman-Monteith method.

Nikam *et al*. (2014) made a comparative evaluation of different potential evapotranspiration estimation models. This study used two most popular temperature based approaches (Hargreaves and Thornthwaite) and two radiation based approaches (Priestley-Taylor and Turc) to estimate monthly potential evapotranspiration (ETo) at Pantnagar (Uttarakhand), India. The performance of all these methods were evaluated based on the regression and error analysis between standard ETo derived using FAO-56 Penman-Monteith method. The Turc method performed well on the monthly basis with lowest RMSE and high coefficient of determination. Based on the season values, the Priestley-Taylor method was found to be the best for Rabi season with lowest error values. In Rabi season Turc method holds second rank. However Turc method performed better than any other method in Kharif season with lowest error terms. In summer season all the methods performed poorly compared to other two seasons, but Hargreaves method performed better than any other methods.

Naorem and Devi (2014) conducted a study on estimation of potential evapotranspiration for Imphal. In this study, ten empirical methods were used to estimate the Potential evapotranspiration (PET) viz. Blaney-Criddle, Thornthwaite, Hargreaves, Penman, Penman-Monteith, Jensen-Haise, Turc, Priestley-Taylor, Makkink and Open pan method. The empirically estimated PET values from all these models were validated with the actual measured mesh covered pan evaporation values, by using calibration coefficients. The results of this study showed that, Hargreaves method with least biasness and minimum errors was found to be the most suitable method for the region.

Edebeatu and Callistus (2015) compared four empirical evapotranspiration models against the Penman–Montieth in a mangrove zone. In this study, comparison was made between the four empirical evapotranspiration equation models such as Jensen–Haise, Lincare, Romanenko's and Hargreaves with the FAO-56 Penman–Monteith as a standard method. He reported that Jensen–Hasie model proved a better value of evapotranspiration among the ET models. This was strictly followed by the Lincare method.

Moroozeh and Bansouleh (2015) used Hargreaves equation for estimating monthly reference crop evapotranspiration in the south of Iran. The daily mean, maximum and minimum air temperature and extra-terrestrial radiations were used in the Hargreaves equation. The comparison was made between results of Hargreaves and Penman-Monteith method. Calibration process had significant effect on efficiency of Hargreaves method as showed by the statistical analysis. The analysis indicated that both monthly and yearly means by the Hargreaves method were significantly correlated with that of the Penman-Monteith method. Hence, it is possible to compute monthly and yearly ETo values precisely in other areas where the required data for the Penman-Monteith estimations were unavailable.

Basanagouda and Suresh (2016) conducted a study to identify the suitable method for assessment of crop water requirements in the agriculture lands at Malaprabha river bed, Bagalkot, India. In this study, the comparison was made for the Christiansen pan evaporation, Blaney-Criddle, Turc, Hargreaves and Thornthwaite methods with standard Penman-Monteith. Blaney- Criddle, Hargreaves and Christiansen pan evaporation methods results gave much closer to each other and the standard method. Turc and Thornthwaite methods resulted in more deviation from reference method. However, Blaney-Criddle method yielded optimum results. Hence, Blaney-Criddle method was selected as most suitable method.

Valipour *et al*. (2016) made a study for finding the best model to estimate potential evapotranspiration with respect to climate change and magnitudes of extreme events. The types of climate were arid, semiarid, mediterranean and very humid. The objective of this study was to find spatial and temporal variation of ETo according to the peak and low events (extreme events) and climate change alarms. For estimating the ETo, five radiation based, five temperature based and five mass transfer based models were used. The results showed that the Blaney−Criddle and Abtew are the best models for predicting ETo in the arid and semiarid regions, respectively. While, modified Hargreaves−Samani 2 showed the best performance in the mediterranean and very humid regions. In addition, radiation and mass transfer based models were proper tools to predict ETo in warm and cold seasons.

Yanga *et al*. (2016) evaluated the Penman-Monteith model for short-term forecasting of daily reference evapotranspiration using weather forecasts. They forecasted daily 7-day-ahead ETo. The results indicated that the forecasting performance for the minimum temperature was the best, followed by maximum temperature, sunshine duration and wind speed. Also, it was found that use of public weather forecasts and the Penman-Monteith model improved the forecasting performance of daily ETo compared to those attained when using the Hargreaves−Samani model. Hence it is clear that weather type and wind scale forecasts also have positive influence on ETo forecasting. Further, the hugest impact on ETo forecasting error was found to be caused by the errors in sunshine duration and wind speed, followed by maximum and minimum temperature forecasts.

2.5 WATER BALANCE STUDIES USING LYSIMETER

Green *et al*. (1984) conducted study to compare evapotranspiration (ET) data computed using two independent measurement techniques with lysimetric data. One set of ET measurements was made using a lysimeter with surface area $2m^2$ and a soil depth of 1 m. Other set of ET data was obtained using the Bowen ratio-energy balance technique. Daily ET estimates were made with the Priestley-Taylor formula. The daily ET for a well-watered full-covered pasture measured by the lysimeter on rain-free days was in good agreement with the ET measured using the Bowen ratio-energy balance technique. Daily measured ET values by the lysimeter were highly correlated with Priestley-Taylor estimates, even over longer periods.

Hakkim *et al*. (1989) conducted an experiment to estimate the evapotranspiration of a short duration variety paddy red triveni in the wetland of Tavanur region during the mundakan season. The evapotranspiration obtained by lysimeter measurement was compared with that estimated using various formulae viz. Blaney–Criddle, Modified Penman and radiation methods. The average evapotranspiration and crop coefficient of red triveni paddy was obtained as 555.37 mm and 1.45 respectively for the season. ET estimated using Modified Penman method was more close to the ET obtained by direct measurement.

Allen and fisher (1990) studied about low cost electronic weighing lysimeters for measuring evapotranspiration. By using commercially available cantilever load cells the research lysimeters with 1 m^2 area 1.2 m depth were designed and constructed. From the fescue/forage grass mix the daily measurements of evapotranspiration was made. Lysimeter measurements agreed well with evapotranspiration estimated using the Penman-Monteith model.

Tyagi *et al*. (2000) carried a study on determination of evapotranspiration and crop coefficients of rice and sunflower with lysimeter at Karnal. Lysimeter experiments were conducted on rice during rainy season (July-October) and sunflower during summer seasons (March-June) in a set of two electronic weighing type lysimeters of size 2 m X 2 m X 2 m. The weekly average ET of rice varied from <3 mm/day at the early growing period to >6.6 mm/day at milking stage. When LAI was 3.4 the peak ETc was 6.61 mm/day and it proceeded for 11 weeks after transplanting at the reproductive stage. In case of sunflower, at the initial stage ETc was <1.0 mm/day, acquired a peak value of 14.1 mm/day between 8 and 9 weeks after sowing and during maturity phase it declined to 3 mm/day. The estimated values of Kc values for sunflower were 0.52, 1.1, 1.32 and 0.41 and corresponding crop coefficient for rice at the four crop growth stages (initial, crop development, reproductive and maturity) were 1.15, 1.23, 1.14 and 1.02 respectively. The values suggested by FAO were less than 11.6-74.2 per cent of the estimated Kc values of sunflower.

Kashyap and Panda (2001) conducted a study on evaluation of evapotranspiration estimation methods with lysimetric data. The models FAO-Penman, FAO-Corrected Penman, 1982-Kimberley Penman, Penman-Monteith, Turc, Priestley-Taylor, FAO-radiation, Hargreaves and FAO-Blaney-Criddle were used. He reported that all combination methods performed better compared to the radiation methods and it was also found that among the different methods Penman-Monteith equation gave the best result.

Changming *et al*. (2002) conducted a study for determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter at Luancheng Station in the North China Plain. They concluded that water consumption for winter grown wheat and maize was found to be 453 and 423mm respectively and the crop coefficient values were 0.93 and 1.1 respectively.

Hossein *et al*. (2004) assessed the ET estimation models in semiarid environments and experimentally verified with drainage type lysimeter. The results showed that, Penman-Monteith model performed well in semiarid environment where as Pan Evaporation method produced best results in humid temperate region.

Xu and Chen (2005) conducted a study to evaluate seven evapotranspiration models and their performance was verified with water balance studies using lysimeter measurements. Out of the seven evapotranspiration models, three models calculated actual evapotranspiration directly using the balancing relationship approach, i.e. the CRAE model of Morton, the advection–aridity (AA) model of Brutsaert and Stricker, Granger and Gray model (GG). The rest four models calculated initial potential evapotranspiration and then actual evapotranspiration by considering the soil moisture condition. Two of the four potential evapotranspiration models belong to the temperature-based category, i.e. the Thornthwaite model and the Hargreaves model and the other two models are radiation-based category, i.e. the Makkink model and the Priestley–Taylor model. The results showed that, the GG model and the Makkink were highly correlated with lysimeter measurements than the other models.

Benli *et al*. (2006) conducted a study for determination of evapotranspiration and basal crop coefficient of alfalfa with a weighing lysimeter. He concluded that, in a semi-arid climate condition for estimating the reference evapotranspiration of alfalfa, the following methods performed satisfactorily viz. Penman–Monteith, Makkink and FAO-Penman. The measured evapotranspiration rates were 1470, 1557 and 1161mm during the years 1995, 1996 and 1997 respectively. For alfalfa, crop coefficients for initial, mid and late seasons of an individual cutting period at the four growth stages were 0.71, 1.78 and 1.51 respectively.

Urrea *et al*. (2006) conducted a study to test evapotranspiration models with lysimeter observations in a semiarid climate. FAO-56 Penman–Monteith, FAO-24 Corrected Penman (I) and (II), FAO-24 Blaney–Criddle and FAO-24 Radiation and Hargreaves models were used in the study. It was concluded, that FAO-56 Penman–Monteith method was the most adequate, when compared to lysimeter measurements. The Hargreaves model was the second most precise, even in its simplicity. The FAO-24 Radiation model also gave good performance, although it produced a small overestimation. The FAO-24 Penman (I) and (II) models and especially the FAO-24 Blaney–Criddle model significantly overestimated the lysimeter measurements, while the Penman model considerably underestimated ETo.

Casanova *et al*. (2009) organised a study to estimate lettuce evapotranspiration in greenhouse conditions in the central zone of chile to evaluate five methods. These methods were compared with water balance measurements in lysimeter. The methods used were Class A pan, Andersson evaporimeters, Piche atmometers and FAO-Penman-Monteith and FAO-Radiation equations. The results showed that Piche atmometers performed best with other methods in the order Andersson evaporimeters < Class A pan < FAO-Radiation < FAO-Penman-Monteith < Piche atmometers.

A study was conducted to determine growth-stage-specific Kc and crop water use for cotton (*Gossypiumhirsutum*) and wheat (*Triticumaestivum*) using Lysimeter and local weather data were used to compute the reference evapotranspiration (ETo). Seasonal total amounts of crop water use ranged from 689 to 830 mm for cotton and 483 to 505 mm for wheat. The Kc values determined over the growing seasons varied from 0.2 to 1.5 for cotton and 0.1 to 1.7 for wheat. Some of the values corresponded and some did not correspond to those from FAO-56. Development of regionally based and growth-stage-specific Kc would help in irrigation management and provided a precise water application for this region (Ko *et al*., 2009).

Mini-Lysimeters was fitted in a farm of Milano University to obtain direct measurement of evapotranspiration from reference crop. An indirect estimation of evapotranspiration has been carried out by means of micro meteorological algorithm of Penman–Monteith. Data produced by the Mini-Lysimeters has been compared with Penman-Monteith model. The results indicated that the two methods were closer to each other. The results of statistical indexes represented the same results for lysimeters and Penman-Monteith (Parisi *et al*., 2009).

Islam and Hossain (2010) conducted experiment on determination of crop co-efficient of hybrid maize by using lysimeter. Results obtained that the crop co-efficient values at initial, development, mid-season and late season stages of hybrid maize (variety: BARI Hybrid Maize-I) were determined as 0.38, 0.87, 1.36 and 0.75 respectively.

Bakhtiari *et al*. (2011) evaluated reference evapotranspiration models for a semiarid environment using lysimeter measurements. The study involves six grass evapotranspiration models such as Penman-Kimberly 1996, FAO-56 Penman–Monteith, FAO-24 Radiation, FAO-24 Blaney-Criddle, Hargreaves-Samani, Makkink and lysimetric data. The accuracy of different models were determined on the basis of root mean square error (RMSE) and index of agreement (d). Results indicated that FAO-24 Radiation equation was the most precise method, with a d- index of 0.78 and a RMSE of 1.63. The FAO-24 radiation equation was superior compared to the other methods during the high evaporative demand period (April to September 2004) for estimating ETo with a d-index of 0.45 and a low RMSE value of 1.86. Again, FAO-24 radiation equation was superior compared to the other methods during the low evaporative demand period, with d-index of 0.46 and RMSE of 1.30. In all of the three periods, the Makkink method assessed poor performance and could not be recommended for the region.

Fisher (2012) conducted experiments on lysimeters to measure water use and to develop crop-coefficient functions necessary for estimating ET. Lysimeter data for computing crop-water use of Cotton under local environmental conditions, ranged from 2 mm/day to 8 mm/day. The Kc values in the early season ranged from 0.2 to 0.6 and 1.1 to almost 1.3 during the peak period. The Kc curves varied greatly among the years, indicating the large differences in crop growth patterns among the years.

Tabari *et al.* (2013) conducted a study for comparative analysis of 31 reference crop evapotranspiration methods under humid conditions. In this research work, seven temperatures based, eight pan evaporation based, ten mass transfer-based methods and four radiation-based were evaluated against the FAO-56 Penman-Monteith model in the humid climate of Iran and from each group the best and worst methods were identified. In addition, by using air temperature and solar radiation data, two radiations based methods were derived on the basis of FAO-56 Penman-Monteith model as a reference. Among the temperature based and pan evaporation based methods, the Blaney–Criddle and Snyder methods yielded the best ETo estimates. The ETo values obtained from the radiation based equations newly developed were better than those calculated by existing radiation based methods. Among the mass transfer based methods the Romanenko equation was the best equation for estimating ETo.

Dewidar *et al.* (2015) conducted a study on lysimeter based water requirements and crop coefficient of surface drip-irrigated date palm in Saudi Arabia. Non-weighing lysimeters were used to grow alfalfa (*Mcdicagosativa*) and grass (*Cynodondactylon*) as a reference crops and date palm (*Phoenix dactylifera*) as experimental crop to obtain the daily water requirements and crop coefficient throughout productive cycle of date palm. The results showed that estimated potential evapotranspiration of alfalfa and grass crops throughout the experimental period were approximately 2185 and 2068 mm, with a daily average of 5.98 and 5.66 mm/day respectively. The date palm evapotranspiration increased from 3.09 mm/day in February at pollination stage to 8.25 mm/day in July at fruit maturity stage, and then dipped to 5.42 mm/day in September at the end of harvest. The average crop coefficient for the date palm productive cycle through the whole year was 0.83.

Daily lysimetric data were used to assess nine different grass evapotranspiration models including FAO-56 Penman–Monteith, Penman-Kimberly 1996, FAO-Penman equation, Blaney–Criddle, FAO-24 Radiation, Makkink, Turc, Priestley–Taylor and Hargreaves in Kermanshah western part of Iran with semiarid climate. They reported that the FAO-Penman-Monteith, Makkink and Hargreaves were the most appropriate models for the region (Ghamarnia *et al.,* 2015).

Mattar *et al.* (2016) carried a study for evaluating and calibrating reference evapotranspiration models using water balance under hyper-arid environment. This study investigated five reference evapotranspiration models (one temperature based model, three radiation based models and one combined model). By using the weekly water balance of alfalfa these models were evaluated and calibrated by EnviroSCAN to estimate the crop evapotranspiration (ETc). Based on the weekly water balance, calibration models were evaluated and validated using wheat and potatoes respectively. He reported that the FAO-56 Penman-Monteith model proved to be superior in estimating ETc with a slight underestimation of 2 per cent. Meanwhile, the Hargreaves-Samani model (temperature based) underestimated ETc by 20 per cent and the Priestley-Taylor and Makkink models (radiation based) had similar performances underestimating by up to 35 per cent of the measured ETc. Compared to other models the Turc model had the lowest performance, demonstrating values underestimated by up to 60 per cent of the measured ETc.

Mila *et al.* (2016) conducted a lysimeter study on sunflower to develop crop co-efficient values for different growth stages. The results revealed that irrigation at 15 days interval produced the highest yield and was considered suitable for estimating ETc and Kc. The seasonal total ETc was found as 270.89 mm, whereas the Kc values of sunflower under different ETo methods for initial, development, mid-season and late season ranged from 0.34 to 0.48, 0.80 to 1.10, 1.06 to 1.55 and 0.27 to 0.36 respectively. Radiation, temperature, Penman-Monteith and Hargreaves models were used to compare the lysimeter values. Among these methods, Penman-Monteith model gave relatively higher value than the other models.

2.6 Energy Balance Approaches

Hirschi *et al*. (2016) reported that the accurate determination of evapotranspiration is required for many meteorological, climatological, ecological, hydrological research and developments. Hence two well recognized approaches were used to decide evapotranspiration at the site level. One was based on lysimeter and the other one was eddy-10 covariance flux capacities. These measurements were compared on several time scales. Overall, the lysimeter and eddy-10 covariance measurements were highly correlated, particularly on the annual time scale.

Marras *et al*. (2016) used the residual energy balance "Eddy Covariance" data and direct measurement of latent heat flux for assessing evapotranspiration and crop coefficients in a Mediterranean vine yard. They concluded that the residual energy balance values were greater than daily observed values during periods with precipitation, but they were similar during dry periods.

2.7 CALIBRATION AND VALIDATION OF ET MODELS

Hajare *et al*. (2009) used Blaney-Criddle, Christiansen model, Hargreaves model, Modified Penman model, Radiation model and Thornthwaite model for evapotranspiration studies of Nagpur District. He made an attempt to develop the calibration coefficients for the above mentioned models with Modified Penman model. The results showed that in the absence of adequate climatic data for the use of Modified Penman model, Blaney-Criddle, Radiation model and

Thornthwaite models would be used because of the high correlation of these models.

Rao *et al*. (2012) conducted a study on potential evapotranspiration estimation for Indian conditions and to improve the accuracy through calibration coefficients. In this study seven methods were employed to estimate the PET and the resultant values were compared with Penman-Monteith estimated PET. The results revealed that, for an annual basis, Turc method resulted in more errors followed by Thornthwaite and Blaney-Criddle. During southwest monsoon period PET estimated from Open pan and Christiansen pan method resulted in more errors whereas during northeast monsoon season Hargreaves and Christiansen pan resulted in more errors. During summer, modified Penman and Hargreaves are the best methods to adopt. During winter modified Penman and PET from Open pan resulted in few errors. Hargreaves method resulted in more errors during winter season compared to summer. Calibration coefficients were evolved on annual and seasonal basis for different methods to reduce the errors in PET estimation in comparison to Penman-Monteith method. They concluded that the efficiency of these coefficients were determined using an independent data set which showed that the errors can be minimized to a great extent by applying these coefficients.

Fenga *et al*. (2016) conducted experiment on calibration of Hargreaves model for reference evapotranspiration estimation in Sichuan basin of southwest China. The present investigation calibrated the Hargreaves model using Bayesian theory at 19 meteorological stations in Sichuan basin of southwest China. The results confirmed that the locally calibrated Hargreaves model (with average RelRMSE and MAE 0.284 and 0.433) performed better than the original Hargreaves model (with average RelRMSE and MAE 0.567 and 0.959). The original Hargreaves model overestimated ETo at daily, monthly and annual time scale, but the calibrated Hargreaves model gives closer average values with Penman-Monteith ETo, which could confirm the good performances of the calibrated Hargreaves model. Therefore, the calibrated Hargreaves model could be highly recommended for estimating ETo when only temperature data is available.

2.8 ADVANTAGES AND DISADVANTAGES OF ET MODELS

The advantages and disadvantages of different categories of empirically derived ET models were reported by various researchers Jensen, 1966; Jensen *et al*, 1990; Amatya *et al*, 1995; Allen *et al*, 1998; Droogers and Allen, 2002; Irmak *et al*, 2003; Gavilan *et al*, 2006.

Table 2.1 Advantages and disadvantages of ET models

ETo models	**Advantages**	**Disadvantages**
Combination model	Under different climatic conditions it is well-documented model compared to lysimeters (Jensen *et al.*, 1990) Under a variety of climatic scenarios it yields good results (Allen *et al.*, 1998) It is predominantly physically based approach (Irmak *et al.*, 2003)	Many assumptions were fixed rs = 70 sec/m It requires many meteorological data Except temperature the data quality of all-weather parameters are poor (Droogers and Allen, 2002).
Radiation model	Requires temperature, radiation	It requires local calibration (Jensen, 1966) Lack of aerodynamic resistance Applicable for long period calculation (Amatya *et al.*, 1995) Less sensitive to the quality of input weather parameters.
Temperature model	Requires only temperature	Sensitive to sensible heat advection It requires local calibration (Gavilan *et al.*, 2006).

Materials and Methods

CHAPTER III

MATERIALS AND METHODS

This chapter explains the various materials used in the study, description of the study area, details of evapotranspiration models, construction of drainage type lysimeter and the meteorological data used for estimation and measurement of Evapotranspiration. It also explains the details of water balance study using lysimeter, development of inter-relationship between estimation models and actual lysimetric measurement. Each of these parts are discussed in detail under the following subheads.

3.1 SITE DESCRIPTIONS, SOIL TYPE AND CLIMATE

The lysimeter experiment was conducted in the E-block of KCAET instructional farm at Tavanur in Malappuram district. It is situated at 10^0 51' 18" north latitude and 75^0 59' 11'' east longitude. The total geographical area of the region is about 40.2 ha out of which the area selected for lysimeter experiment is 35 m^2. The study area contains sandy loam soil.

Agro-climatically, the area falls within the border line of northern hemisphere and central zone of kerala. Majority of the rainfall received in this region is from south-west monsoon. The average annual rainfall varies from 2500 mm to 2900 mm, the average maximum temperature of the area is 31^{o}C and the average minimum temperature is 26^{o}C.

3.2 FIELD INSTRUMENTATION AND MEASUREMENT

The field instrumentations and measurements to collect the data required for estimation and measurement of reference crop evapotranspiration is explained in this section.

3.2.1. Determination of Physical Properties of Soil

Soil is the reservoir in the water balance study. Therefore determination of soil physical properties and soil moisture content measurements are important. Soil samples were taken from the experimental plot at two levels one from the surface (0-10cm depth) and the other from 10-20 cm depth. They were mixed together to determine properties like soil texture, bulk density, particle density, field capacity, wilting point and available soil moisture content. The methods are explained as follows.

3.2.1.1 Sieve analysis

The complete sieve analysis can be divided into two parts. One is coarse analysis and second is fine analysis. An oven dried sample of soil is separated into two fractions by sieving it through a 4.75 mm IS sieve. The portion retained on it (+ 4.75 mm size) is termed as the gravel fraction and is kept for the coarse analysis, while the portion passing through it (-4.75 mm size) is subjected to fine sieve analysis. The following sets of sieves are used for coarse sieve analysis: IS: 100, 63, 20, 10 and 4.75 mm, the sieves used for fine sieve analysis are: 2 mm, 1 mm, 600, 425, 300, 212, 150 and 75 micron IS sieves.

Sieving was performed by arranging the various sieves one over the other in the order of their mesh openings. The largest aperture sieve being kept at the top and the smallest aperture sieve at the bottom. A receiver was kept at the bottom and a cover was placed at the top of the whole assembly. The soil sample was put on the top sieve and the whole assembly was fitted on a sieve shaking machine. The amount of shaking depends upon the shape and the number of particles. The portion of the soil sample retained on each sieve was weighed. The percentage of soil retained on each sieve was calculated on the basis of the total mass of soil sample taken and from these results; percentage passing through each sieve was calculated. The different sizes of particles retained on different sieves were shown in Plate 3.1.

Plate 3.1 Soil retained in different sieves

3.2.1.2 The core cutter method

A core cutter, consisting of a steel cutter, 10 cm in diameter and about 13 cm high and a 2.5 cm high dolly driven in the cleaned surface with the help of suitable hammer, till about 1 cm of the dolly protrudes above the surface. The cutter, containing the soil, was dug out of the ground, the dolly was removed and the excess soil was trimmed off. The mass of the soil in the cutter was found. The ratio of mass to the volume of the cutter gives the bulk density and then dry density is computed using following formulas.

$$\gamma = \frac{W}{V}$$

Where, γ = Bulk density of soil (g/cc), W = Total weight of soil (g) and V = Total volume of soil (cm^3).

$$\gamma_d = \frac{\gamma}{1+W}$$

Where, γ_d = Dry density of soil (g/cc) and W = Moisture content of soil (%).

Plate 3.2 Cylinder core cutter

3.2.1.3 Permanent wilting point and field capacity

A soil moisture characteristic was done with the pressure plate apparatus (Plate 3.3). The apparatus consists of ceramic pressure plate or membranes of high air entry values contained in airtight metallic chambers strong enough to withstand high pressure (15 bars or more). The apparatus enables the development of soil moisture characteristic curves in the higher range of matric potential (>1bar) which is not possible on suction plates.

The procedure for determining soil matric potential and water content relation involved first saturation of the porous plates and the soil sample (undisturbed or disturbed) and was placed on these plates. The plates were transferred to the metallic chambers. The chamber was closed with wrenches to tighten the nuts and bolts with the required torque for ceiling it. Pressure was applied from a compressor through control which helps in maintaining the desired two pressures 1/3atm & 15atm which were applied to get field capacity and permanent wilting point respectively. It was ensured that there was no leakage from the chamber. Water starts to flow out from saturated soil samples through outlet and continues to trickle till equilibrium against the applied pressure was achieved. After that the soil samples were taken out and oven dried for determining moisture content on volume basis (Michael, 2008). The data and calculations are given in Appendix I.

Plate 3.3 Soil samples in pressure plate apparatus

3.2.1.4 Soil moisture measurement

Gravimetric method was used to determine the soil moisture content. Basic measurements of soil moisture are made on soil samples of known weight or volume. Soil samples are collected with a soil auger. The samples were taken from the desired depth at several locations in the area. They were collected in air tight aluminium containers. The soil samples were weighed and then dried in an oven at 105^0c for about 24 hours, until all the moisture was driven off. After removing from oven they were cooled slowly to room temperature and weighed again. The difference in weight is the amount of moisture in the soil (Michael, 2008). The data and calculations are shown in Appendix I.

3.2.1.5 Weather data

Weather data was collected from the meteorological observatory RARS Pattambi, KAU from January 2011 to May 2017. Daily data was collected and it was converted into mean monthly average values. The meteorological data comprises the following parameters: maximum and minimum temperature, maximum and minimum relative humidity, wind speed, solar radiation and pan evaporation. By incorporating this data in the different models the reference crop evapotranspiration (ETo) was estimated. The mean monthly meteorological data for six year period is given in Table 3.1.

Table 3.1 Mean monthly weather data for the period January, 2011-December, 2016

Month	**Max temp (^{0}C)**	**Min temp (^{0}C)**	**Max RH (%)**	**Min RH (%)**	**Wind speed (k/h)**	**Sunshine hours**	**Pan Evaporation(mm)**
January	33.34	20.72	85.24	39.74	6.19	8.30	5.11
February	34.93	21.34	85.71	35.24	4.62	8.22	5.61
March	36.19	23.78	87.42	43.10	4.12	8.05	5.56
April	35.34	25.08	87.00	52.05	3.20	7.10	5.07
May	33.89	24.69	89.46	62.09	3.12	6.42	4.30
June	30.37	23.48	94.48	76.65	2.31	3.11	2.37
July	29.73	23.52	94.39	75.64	2.52	3.09	2.25
August	29.97	23.64	93.96	72.47	2.68	4.35	2.58
September	30.73	23.54	93.37	67.65	2.34	5.51	3.00
October	31.28	24.01	92.50	60.12	1.89	5.53	2.90
November	32.07	22.73	89.34	52.99	2.53	5.84	3.05
December	32.57	21.47	87.54	48.44	4.17	7.18	3.90

3.3 PERFORMANCE OF REFERENCE CROP EVAPOTRANSPIRATION MODELS (ETo_{EST})

Reference crop ET (ETo) is the potential evapotranspiration which is defined as “the rate of evapotranspiration from an extensive surface of 8 to 15cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water" (Doorenbos and Pruitt, 1977).

Direct measurement of evapotranspiration under field conditions is a very difficult task. Based on meteorological data many models have been developed for various climates to estimate reference crop evapotranspiration. Hence this research work evaluated ten different models which are relevant under Indian condition and widely used for the estimation of reference crop evapotranspiration. They are Thornthwaite (1948), Hargreaves *et al.,* (1985), Turc (1961), Christiansen (1968) Pan Evaporation, FAO-24 Blaney-Criddle (1977), FAO-24 Modified Penman (1977), FAO-24 Open Pan (1977), Preistly-Taylor (1972) and FAO-56 Penman-Monteith (1991) models. In recent years FAO-56 Penman-Montetith model which is more physically based provides superior results in both arid and humid regions and has been recommended as a new standard for reference crop Evapotranspiration estimates (Allen *et al*., 1998). For comparing the performance of these empirical models, FAO-56 Penman-Monteith model was used as the standard here. The various empirical models were evaluated using monthly average values of meteorological parameters measured for six years (January, 2011- December, 2016) at RARS, Pattambi. The performance of the models were evaluated in terms of established statistically quantitative measures such as coefficient of determination (R^2), mean bias error (MBE), root mean square error (RMSE) and relative root mean square error (RelRMSE). The formulae for RMSE, RelRMSE and MBE were explained in section 3.5.1.

The coefficient of determination is defined as the squared value of the Pearson correlation coefficient. The coefficient of determination is an estimate of the combined dispersion against the single dispersion of the observed and predicted values since it represents the squared ratio between the covariance and the multiplied standard deviations of the observed and predicted values (Krause *et al*., 2005). The coefficient has values ranging from zero to one representing how much of the observed dispersion is explained by the prediction. The closer the value of the correlation coefficient to one, the stronger the correlation is. A value of zero indicates no correlation between the observed and predicated values. The coefficient of determination alone is often an insufficient and misleading evaluation criterion since the magnitude of R^2 is not consistently related to the accuracy.

The other parameters such as RMSE describes the difference between the observed values and the model predictions in the unit of the variable (Licciardello *et al*., 2007) and RelRMSE is the ratio of the RMSE to the standard ETo values from FAO-56 PM. Mean bias error is the difference between estimated ETo using empirical models and the ETo from FAO-56 PM model were also used to test the accuracy of the empirical models.

3.3.1 Description of the Models Used in the Study (Source: FAO, 1992)

Thornthwaite (1948) model (THM)

$$ETo = 1.6\, l\, (10\, Tm / I)^{a}$$

Where, ETo = Adjusted reference crop evapotranspiration in mm (12 hrs, day time), Tm = Mean temperature in ^{o}C, I = Annual heat index = $\Sigma\, (t_1 / 5)^{1.514}$, a = An empirical exponent = $6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.792 \times 10^{-2} I + 0.49239$, l = Day length factor, which is computed as $l = (n/12)\,(D/30)$, where D is no. of days in a month.

Hargreaves et al., (1985) model (HAM)

$$ETo = 0.0023\, R_A\, T_D^{0.5}\, (Tm + 17.8)$$

Where, R_A = Extra-terrestrial radiation (mm/day), T_D = Difference between maximum and minimum temperature (^{o}C), Tm = Mean temperature (^{o}C) and the value of R_A on any given day can be deduced by using the relation presented under Turc (1961) method.

Turc (1961) model (TUM)

$ETo = 0.40\ Tm\ (Rs + 50) / (T + 15)$

Where, Tm = Mean air temperature (^{o}C), Rs = Solar radiation in langleys and the solar radiation (Rs) is in turn computed from the following expression.

$Rs = [0.25 + 0.5\ (n / N)]\ R_A$

Where, R_A = Extra-terrestrial radiation ($MJm^{-2}\ day^{-1}$), n = Actual hours of bright sunshine (hrs), N = Maximum possible hours of sunshine (hrs) and the extra-terrestrial radiation (R_A) is computed after Duffie and Beckman (1991) as

$R_A = (24 \text{ X } 60) / \pi\ GSc\ [dr\ [Ws \sin (LAT) \sin d + \cos (LAT) \cos (d) \sin Ws]]$

Where, GSc = Solar constant (0.82 $MJm^{-2}\ min^{-1}$), dr = Relative distance of the earth from the sun, d = Solar declination in radiance and the distance from the earth to sun is calculated as

$dr = 1 + 0.033 \cos (2\pi i / 365)$

Where, i = Julian day, Solar declination (d) is computed as $d = 0.4093 \sin (2\pi (284 + i) / 365)$. The sunset hour angle, Ws, in radians is calculated as Ws = arc cos (-tan (LAT) tan d). The maximum possible hours of sunshine (N) is simulated using the following function

$N = 2 / 15 \cos^{-1} (-\tan LAT \tan d)$

Where, $d = 23.45 \sin (360(284 + i) / 365)$ and LAT is latitude of the station

Christiansen (1968) Pan Evaporation model (CHM)

$ETo = 0.755\ E_O\ C_{T2}\ C_{W2}\ C_{H2}\ C_{S2}$

Where, E_O = Open pan evaporation (mm), $C_{T2} = 0.862 + 0.179\ (Tm / 20) – 0.041\ (Tm / 20)^2$. Where, Tm is the mean temperature in ^{o}C, $C_{W2} = 1.189 – 0.240$ (W /

6.7) + 0.051 (W / 6.7)^2. Where, W = Mean wind speed 2m above ground level in km per hour, C_{H2} = 0.499 + 0.620 (Hm / 0.60) – 0.119 (Hm / 0.60)^2. Where, Hm = Mean relative humidity, expressed decimally, C_{S2} = 0.904 + 0.0080 (S / 0.8) + 0.088 (S / 0.8)^2. Where, S is the percentage of possible sunshine, expressed decimally.

FAO-24 Blaney-Criddle (1977) model (BCM)

ETo = a + bf

f = p (0.46 T + 8.13)

a = 0.0043 RH_{min} – n / N – 1.41

b = a_o +a_1 RH_{min} + a_2 n / N + a_3U_d + a_4RH_{min} n / N + $a_5RH_{min}U_d$

Where, p = Mean daily percent of annual daytime hours (monthly p / (days/mo)), Tm = Mean air temperature (^{o}C), n / N = Ratio of possible to actual sunshine hours, RH_{min} = Minimum daily relative humidity in percentage and U_d = Daytime wind at 2 m height (ms^{-1}). Where, a_o = 0.81917, a_1 = 0.0040922, a_2 = 1.0705, a_3 = 0.065649, a_4 = 0.0059684 and a_5 = 0.0005967.

FAO-24 Modified Penman (1977) model (MPM)

ETo = [WR_n + (1-W) f (u) (e_a-e_d)] c

Where, ETo = Reference crop evapotranspiration (mm/day), W = Temperature related weighing factor, R_n = Net radiation (mm day^{-1}), f (u) = Wind related function, (e_a-e_d) = Difference between saturated vapour pressure at mean air temperature and mean actual vapour pressure of air (mb) and c = Correction factor. The saturation vapour pressure (e_a) is estimated as a function of temperature using the equation.

$$e_a = e^{(54.88 – 5.03 \log (Tm + 273) – 6791 / Tm + 273)}$$

Here, Tm = Daily mean air temperature (^{o}C) and the vapour pressure is simulated as a function of this saturation value and relative humidity as $e_d = e_a$ [RH / 100]

Where, RH = Relative humidity (percent), the temperature related weighing factor (W) is computed from the slope of saturation vapour pressure curve (d) and psychrometric constant (t_c) as $W = d / (d + t_c)$

The slope of the saturation vapour pressures curve is estimated with the following equation

$d = (e_a/ Tm + 273) (6791 / (Tm + 273) – 5.03)$

The psychrometric constant is computed with the following equation

$t_c = (6.6 X 10^{-4}) Pb$

Where, $Pb = (101.3 – 0.01152 Elev + 5.44 X 10^{-1} Elev^2) 10$

Where, Elev = Elevation of the location (m) and the wind related function (Fu) is computed using the expression $F (u) = 0.27 ((1 + 0.93 U_3) / 100))$

Where, U_3 = Wind speed at 3 m height in km day^{-1}, which is converted to wind speed at 2m height with the coefficient of 0.93. The net radiation (R_n) is computed with the expression $R_n = (R_{ns} – R_{nl}) 0.4081632$.

Where, R_{ns} = Net short wave radiation (MJ m^{-2} day^{-1}), R_{nl} = Net long wave radiation (MJ m^{-2} day^{-1}), the factor 0.4081632 converted MJ m^{-2} day^{-1} into mm of water per day. The net short wave radiation (R_{ns}) is computed as $R_{ns} = (1 – \alpha) R_s$

Where, α = Albedo (0.26), R_s = Solar radiation (MJ m^{-2} day^{-1}), the correction factor ‘c’ in the above relation is derived after Frevert *et al.,* (1983) as

$c = a_o + a_1RH_{Max} + a_2R_s + a_3U_d + a_4DN_r + a_5U_dDN_r + a_6RH_{Max}R_sU_d + a_7RH_{Max}R_sDNr$

Where, $a_o = 0.6817006$, $a_1 = 0.0027864$, $a_2 = 0.0181768$, $a_3 = -0.0682501$, $a_4 = 0.0126514$, $a_5 = 0.0097297$, $a_6 = 0.000043025$, $a_7 = -0.00000092118$ and DN_r = Ratio of day time tonight time wind speed.

$$U_d = \frac{DNr\ U2}{1+DNr}\frac{1000}{12.36}$$

Where, U_2 = Wind speed at 2 m height (kmday^{-1})

FAO-24 Open Pan (1977) model (OPM)

$$ETo = K_p\ E_p$$

Where, K_p = Pan coefficient, E_p = Measured open pan evaporation (mm).

Pan coefficient as computed by Allen and Pruitt (1991) for green and dry fetch is adopted in this study which is

Green Fetch

$$K_p = 0.108 - 0.000331\ U_2 + 0.0422\ln(\text{Fetch}) + 0.1434\ln(RH_{mean}) - 0.000631\ [\ln(\text{Fetch})]^2\ [\ln(RH_{mean})]$$

Dry Fetch

$$K_p = 0.61 + 0.00341\ RH_{mean} - 0.00000187\ U_2 RH_{mean} - 0.000000111\ U_2\ (\text{Fetch}) + 0.0000378\ U_2\ln(\text{Fetch}) - 0.0000332\ U_2\ln(U_2) - 0.0106\ [\ln(U_2)]\ [\ln(\text{Fetch})] + 0.00063\ [\ln(\text{Fetch})]^2\ [\ln(U_2)]$$

In the present study, green fetch coefficients were used during southwest monsoon and northeast monsoon seasons and dry fetch coefficients during winter and summer periods. A fetch of 10m during southwest monsoon and northeast monsoon periods and 100m during winter and summer periods were assumed.

FAO-56 Penman-Monteith (1991) model (PMM)

$$ETo = \frac{0.408\,\Delta\,(Rn - G) + \Upsilon \frac{900}{T+273} U2\ (ea - ed)}{\Delta + \Upsilon(1 + 0.34U2)}$$

Where, ETo = Reference crop evapotranspiration (mm/day), R_n = Net radiation at crop surface (MJ m^{-2} day^{-1}), G = Soil heat flux (MJ m^{-2} day^{-1}), T = Average temperature at 2 m height (^{o}C), U_2 = Wind speed measured at 2 m height (m s^{-1}), (e_a-e_d) = Vapour pressure deficit for measurement at 2 m height (K Pa), Δ = Slope vapour pressure curve (K Pa $^{o}C^{-1}$), ϒ = Psychrometric constant (K Pa $^{o}C^{-1}$), 900 = Coefficient for the reference crop (1 j^{-1} Kg K d^{-1}) and 0.34 = Wind coefficient for the reference crop (s m^{-1}).

The various components of the above relation are derived as

i) When solar radiation is available

$$Rn = 0.77\ Rs - (a_c \frac{Rs}{Rsc} + b_c)\ (a_1 + b_1\sqrt{ed})\ \sigma\ \frac{(T_{Kx}^4 + T_{Kn}^4)}{2}$$

Where, T_{kx} and T_{kn} is both set equal to mean hourly air temperature for hourly calculations. This is not employed in the present study as very few stations have the data on solar radiation.

ii) When only sunshine data is available

$$R_n = 0.77\ (0.25 + 0.50\ \frac{n}{N} + R_s) - 2.45 \times 10^{-9}\ (0.9\ \frac{n}{N} + 0.1)\ (0.34 - 0.14\sqrt{e_d})\ (T_{Kx}^4 + T_{Kn}^4)$$

$$G = 0.38\ (T_{day\ i} - T_{day\ i-1})$$

Where, $T_{day\,i}$= Mean daily air temperature and $T_{day\,i-1}$= Mean daily air temperature of preceding day.

iii) Vapour Pressure Deficit (VPD)

$$VPD = (e_a - e_d) = \frac{e^0(T_{max}) + e^0(T_{min})}{2} - e_d$$

Where, VPD = Vapour Pressure Deficit (K Pa), e^o (T_{max}) = Saturation vapour pressure at T_{max} (K Pa), e^o (T_{min}) = Saturation vapour pressure at T_{min} (K Pa), e_d = Actual vapour pressure (K Pa) and $e_a = e^o$ (T) = 0.611 exp $(\frac{17.27T}{T+237.3})$.

Where, e_a = Saturation vapour pressure (K Pa), e^o (T) = Saturation vapour pressure function (K Pa), T = Air temperature (°C) and $e_d = e^o\,(T_{min})\frac{RH_{max}}{100}$.

iv) Δ is slope of vapour pressure, computed as

$$\Delta = \left(\frac{e_a}{T_m+273}\right)\left(\frac{6791}{T_m+273} - 5.03\right)$$

Priestley-Taylor model (PTM)

$$ETo = \alpha \left(\frac{\Delta}{\Delta+\Upsilon}\right)(R_n\text{-}G)$$

Where, ETo = Reference crop evapotranspiration (mm/day), Δ = Slope of the vapour pressure curve (KPa^0C^{-1}), ϒ = Psychrometric constant (KPa^0C^{-1}), R_n = Net radiation (MJ m^{-2} day^{-1}) and G = Daily soil heat flux (mm/day).

Makkink model (MKM)

$$ETo = 0.61\left[\frac{\Delta}{\Delta+\Upsilon}\right]\frac{R_s}{2.45} - 0.12$$

Where, ETo = Reference crop evapotranspiration (mm/day), Δ = Slope of the vapour pressure curve (KPa^0C^{-1}), ϒ = Psychrometric constant (KPa^0C^{-1}) and R_s = Solar radiation (MJ m^{-2} day^{-1}).

In this research work the estimated values by different empirical models are referred as ETo_{THM}, ETo_{HAM}, ETo_{TUM}, ETo_{MPM}, ETo_{CHM}, ETo_{OPM}, ETo_{PMM}, ETo_{PTM} and ETo_{MKM} respectively.

3.4 MEASUREMENT OF ACTUAL EVAPOTRANSPIRATION BY LYSIMETER (ETo_{LYM})

3.4.1. Construction of Drainage Type Lysimeter

A plot of 5X7 m size was selected in the E-block of instructional farm KCAET, for installing the lysimeter. For constructing the lysimeter tank, a rectangular pit of cross sectional area 5.25m^2 and 1m depth was made (Plate 3.4). In this pit, a brick masonry tank of 2X2.5X1m with concrete bottom was constructed (Plate 3.5). The soil was filled to an effective depth of 60cm followed by 10cm thick river sand. Below the river sand layer, a 30 cm thick gravel pack layer (Plate 3.6) collected the excess percolating/drainage water from the upper zone and discharges into a drainage sump. A plastic container of diameter 40 cm and depth 27 cm with lid was provided for the collection of drainage water. The wall thickness of the tank was 12cm. The cross sectional view of lysimeter is shown in Fig. 3.1. Special precautions were taken to refill the top 60 cm soil in the lysimeter to its original status by restoring the correct soil profile and compaction to maintain its original density. A slope of 4 per cent was provided at the bottom surface. A drainage pipe of diameter 2.5cm with perforations was buried at the bottom to convey the drainage water into a sump outside the tank. A view of the lysimeter after filling all the media is shown in Plate 3.7.

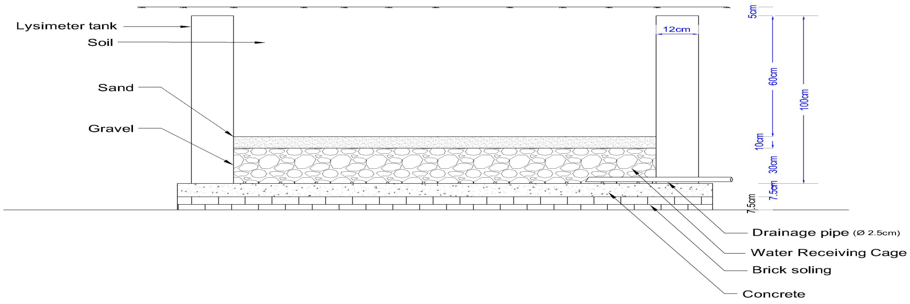

Fig 3.1 Cross sectional view of lysimeter

Plate 3.4 Pit for lysimeter installation

Plate 3.5 A view of lysimeter tank

Plate 3.6 Drainage media filling

Plate 3.7 Lysimeter in filled condition

3.4.2 Irrigation System

The irrigation was applied using drip system. The PVC pipe of diameter 30mm was used as the main and 25mm pipe was used as the sub main. There were 11number of low density polyethylene laterals of 5m length and drippers of 4lph were used for applying water. The lysimeter of 5m^2 area comprises of six laterals with 48 drippers (Plate 3.8). The evapotranspiration from a reference surface not short of water is called reference crop evapotranspiration. Hence irrigation was applied daily until an appreciable quantity of water has obtained as drainage. Accordingly irrigation was applied for 10min every morning at a rate of 32 litres per day. Uniform application of water was continued throughout the experiment.

3.4.3 Reference Grass

Congo signal grass (*Brachiaria ruziziensis*) belonging to the fodder variety was grown as the reference crop in the lysimeter as well as the area surrounding it to create the same microclimate. Grass slips were brought from the Live Stock Research Station, Thirivanzakonnu, KVASU. Planting was done on 3rd December and the initial stage of grass is shown in Plate 3.9. It is a creeping perennial with dense foliage and therefore can be used for soil conservation purpose as strip crop. It grows to a height of about 50 to 100 cm and the grass root depth of 50 cm. It prefers a warm moist tropical climate. It can be grown in almost all types of soils but cannot tolerate water logging. It also tolerates shade. The slips were planted at a spacing of 20cmX20cm in the lysimeter and the surrounding area and were irrigated by drip. It was also ensured to maintain the height of grass as 15-20cm throughout the experiment. A view of grass progressing in lysimeter with drainage provision is shown in Plate 3.10. After 28 days the grass completely covered the ground and fully established (Plate 3.11).

The lysimeter usually measures crop evapotranspiration (ETo) accurately and precisely. In this study, this measured value is hereafter depicted as ETo_{LYM}. Here the grass is grown in a totally controlled environment and the system is not affected by any other parameters such as surface runoff, interflow, deep percolation and groundwater contribution. Moreover lysimeter imitated the natural field conditions. Hence, it is recommended that no further replication is necessary (Mila *et al.*, 2016).

Plate 3.8 Drip irrigation in lysimeter

Plate 3.9 Initial stage of grass

Plate 3.10 Drainage provision

Plate 3.11Well watered and fully covered grass

3.4.4 Water Balance Model

ETo_{LYM} was calculated by using the water balance model. The water balance model involves four components. They are applied water, effective rainfall, change in soil water content (soil moisture storage) and deep percolation/drainage/seepage water to measure evapotranspiration as residuals. The water balance study was conducted in the lysimeter.

The field water balance model can be defined based on the conservation of mass as follows:

$$ETo_{LYM} = (W_a + EP) - (D_w \pm \Delta S_s)$$

Where, ETo_{LYM} = Reference crop evapotranspiration in mm for time, t, W_a = Applied water, mm for time, t, EP = Effective rainfall, mm for time, t, D_w = Drainage water, mm, for time, t and ΔS_s = Change in soil moisture storage, mm, for time, t.

The runoff component was not considered in the water balance equation since an outlet was provided for the seepage of water (Zhang *et al.*, 2004). But effective precipitation was considered, since there was a rainfall of 2.5 and 6.1 mm during April and May 2017. The various water balance components were monitored on weekly basis and are explained as follows.

Applied water

Quantity of water applied is an important component of water balance. The irrigation water was applied using drip irrigation. The quantity of water applied during irrigation was calculated as follows.

$$\text{Water applied (mm)} = \frac{\text{No of drippers X Each dripper capacity (lph)} \times \text{Applied time (min)}}{1000 \times 60 \times \text{Area of lysimeter } (\text{m}^2)}$$

Effective rainfall

The rainfall falling over a given area was measured by a rain gauge and 75 per cent of that was taken as the effective rainfall.

Drainage water (Seepage Water)

The slow movement of water through pores of unsaturated soil was measured as the percolated water/drainage water. Drainage water from lysimeters was collected in a plastic container with lid which prevents evaporation from the container and measured using a graduated cylinder.

Changes in Soil Moisture (Soil Moisture Storage)

Soil moisture storage is the total amount of water stored in the soil within the plant's root zone. Soil moisture was measured by gravimetric method on weekly basis. Soil moisture samples were collected at two different depths, one at 10cm depth and the other one at 20cm depth before irrigation to determine the change in soil moisture storage. Measured soil moisture in weight basis was converted into volume basis by using the following formula.

$$\Delta S_s = \sum_{i=1}^{n} \frac{M_{1i} - M_{2i}}{100} \times A_i \times D_i$$

Where, ΔS_s = Change in soil moisture storage, mm, for time, t, n = Number of soil layers in the root zone, M_{1i} = Moisture content at the time of first sampling in the i^{th} layer, M_{2i} = Moisture content at the time of second sampling in the i^{th} layer, A_i = Apparent specific gravity of i^{th} layer and D_i = Depth of i^{th} layer of the soil with root zone (mm).

3.5 COMPARISON OF ETo ESTIMATED (ETo_{EST}) WITH ETo MEASURED (ETo_{LYM})

Accurate estimation of ETo and conservation of water is of prime importance for irrigation of agriculture lands. Therefore weekly ETo values estimated by the different models were compared with actual field measurement in lysimeter. For this comparison current weekly meteorological data for the period from January, 2017 to May, 2017 (Table 3.2) was used for estimating ETo, as the lysimeter experiment was conducted during the same period.

Table 3.2 Mean weekly weather data for the period January-May, 2017

Weeks	**Max temp (^{0}C)**	**Min temp (^{0}C)**	**Max RH (%)**	**Min RH (%)**	**Wind speed (km/h)**	**Sunshine hours**	**Pan evaporation(mm)**
1st week	34.23	19.39	84.43	33.29	3.45	8.23	4.50
2nd week	33.83	19.71	72.71	43.00	3.54	8.19	4.47
3rd week	34.04	20.63	81.00	45.71	6.81	8.80	6.30
4th week	34.20	22.86	82.57	41.14	7.61	5.74	6.40
5th week	35.11	21.86	82.71	36.14	5.75	9.17	5.99
6th week	35.53	21.39	82.00	32.00	4.85	8.93	6.06
7th week	35.41	21.76	68.00	30.00	9.86	9.60	9.19
8th week	35.97	21.84	91.86	43.00	3.31	6.33	5.09
9th week	37.17	21.80	75.43	39.71	4.94	6.90	6.91
10th week	35.00	23.79	89.14	51.71	3.01	7.79	5.29
11th week	35.03	22.87	90.14	51.00	3.33	7.80	5.07
12th week	35.57	24.43	92.14	50.43	2.87	7.87	4.90
13th week	37.29	24.43	89.00	44.57	3.24	8.56	5.70
14th week	36.43	25.24	88.00	54.29	3.26	7.64	5.04
15th week	35.90	25.70	86.29	56.14	3.22	5.93	4.70
16th week	34.46	25.89	88.29	54.29	3.20	4.67	4.31
17th week	35.51	25.43	88.43	51.57	3.43	8.53	5.13
18th week	36.74	24.81	84.57	47.86	3.22	7.93	4.60
19th week	35.10	24.04	82.86	53.71	3.75	6.43	4.38
20th week	34.37	25.07	89.00	61.71	3.59	6.96	5.20
21st week	33.70	24.69	86.29	59.00	2.97	4.43	3.58

3.5.1 Statistical Analysis

The accuracy of each method in comparison with lysimeter was analysed by using simple regression analysis and a series of statistical parameters such as R^2, root mean square (RMSE), Relative RMSE and mean bias error (MBE) values as proposed by Willmott (1982).

$$\text{RMSE} = [N^{-1}\textstyle\sum_{i-1}^{N}(P_i - O_i)^2]^{0.5}$$

$$\text{RelRMSE} = \left(\frac{RMSE}{O_{avg}}\right)$$

$$\text{MBE} = [\textstyle\sum(P_i - O_i) / n]$$

Where, RMSE is root mean square error, MBE is mean bias error, N is the numbers of observations P_i are estimated ETo values (mm/day), O_i are ETo values measured (ETo_{LYM}) by the lysimeter (mm/day) and O_{avg} is the average value of measured ETo values.

3.6 RELATIONSHIP OF MODEL VALUES (ETo_{EST}) WITH LYSIMETER VALUES (ETo_{LYM})

Majority of the Indian locations have only rainfall and air temperature data. This requires the application of temperature based or other simple methods in the ETo estimation. However, these simple methods do not account for major weather parameters which affect the value of ETo. Hence, local calibration is necessary. By using lysimeter the empirical methods can be calibrated or validated for new locations (Urrea *et al.,* 2006).

Allen *et al.* (1983) suggested the use of following relation at locations with limited data to marginalize errors as:

$ETo_{LYM} = b\ ETo_{EST}$ or $ETo_{LYM} = a + b\ ETo_{EST}$

Where, ETo_{LYM} = ETo measured from the lysimeter and ETo_{EST} = ETo estimated by using empirical models.

Kashyap and Panda (2001) used lysimeter to calibrate coefficients for various empirical models for semiarid region. The utility of this method in narrowing down the errors in ETo estimation by different approaches for a coastal location of Andhra Pradesh was demonstrated in a study by Rambabu and Rao (1999). By selecting the empirical model as an independent variable and lysimeter observations as a dependent variable, calibration/adjustment coefficients were evolved by using linear regression techniques to improve the predictability of each of these ten models selected in this study.

The coefficient of determination (R^2), MBE, RMSE and RelRMSE values indicate the accuracy of the relation developed between the ETo estimated by empirical models and ETo measured from the lysimeter. To evaluate the performance of the different models discussed in this research the statistical criteria (quantitative) and graphical display (qualitative) approaches were used. The combined approach is useful in making comparative evaluations of model performance between lysimeter and models (Loague and Green, 1991).

Results and Discussion

CHAPTER IV
RESULTS AND DISCUSSION

Estimation of reference crop evapotranspiration (ETo) for a particular region has immense relevance in crop planning, water management and irrigation design. There are a number of methods available for estimation of ETo. But only a very few scientific studies related to water management have been taken up in this humid tropical region. Hence this study evaluated the performance of ten most widely used empirical models for Indian conditions and they were compared with the recent FAO-56 Penman-Monteith model which is more physically based and provides superior results in both arid and humid regions all over the world. In order to get higher accuracy of estimate and to select the best method for estimating ETo in this region another comparative study was conducted with actual field measurement using lysimeter. The local calibration of estimated model had been done with lysimetric data to find the relationship between them. The results pertaining to these aspects are discussed in the following sub titles.

4.1 DETERMINATION OF PHYSICAL PROPERTIES OF SOIL

The physical properties of soil required for the lysimeter water balance study were determined and presented in Table 4.1.

Table 4.1 Physical properties of soil

Sl. No.	Soil Properties	Values
1	Coarse sand (%)	99.4
2	Fines (%)	0.6
4	Bulk density (g/cc)	1.63
5	Dry bulk density (g/cc)	1.52
6	Field capacity (%)	21.01
7	Permanent wilting point (%)	15.74
8	Available soil moisture content (%)	5.26

4.2. ESTIMATION OF REFERENCE CROP EVAPOTRANSPIRATION (ETo) USING EMPIRICAL MODELS

Methods of direct measurements are often very expensive and cumbersome. Hence reference evapotranspiration is commonly computed from weather data. However no single existing method using meteorological data is universally adoptable under all climatic regions. Therefore use of specific method is limited by the conditions in which they have been developed. Large data requirement is also limits the application of many of the methods. Hence by determining the inter relationship between the methods enable the user to easily convert the values obtained from different methods. In recent years FAO-56 Penman-Montetith model which is more physically based provides superior results in both arid and humid regions and has been recommended as a new standard for reference crop evapotranspiration estimates.

In this research reference crop evapotranspiration (ETo) was calculated using ten empirical models which are widely used in Indian conditions. They are Thornthwaite (1948), Hargreaves *et al.,* (1985), Turc (1961), Christiansen (1968) Pan Evaporation, FAO-24 Blaney-Criddle (1977), FAO-24 Modified Penman (1977), FAO-24 Open Pan (1977), Priestly-Taylor, Makkinik and FAO-56 Penman-Monteith (1991). These ten models are here after represented as THM, HAM, TUM, CHM, BCM, MPM, OPM, PTM, MKM and PMM respectively for convenience. Out of the above models, two were combination models (MPM and PMM), two were temperature models (THM and BCM), three were radiation models (TUM, PTM and MKM) and two were evaporation models (CHM and OPM). The FAO-56 PMM was used as the standard for comparing the performance of these models. The monthly ETo estimated using the meteorological data for the period, 2011-2016 by the ten empirical models were presented in Table 4.2 and Fig. 4.1.

Table 4.2 ETo values obtained from different empirical models in mm/day

MONTH	ETo THM	ETo HAM	ETo TUM	ETo BCM	ETo MPM	ETo CHM	ETo PMM	ETo OPM	ETo PTM	ETo MKM
January	9.98	5.24	15.10	9.12	9.21	3.73	4.48	4.31	0.72	3.05
February	9.27	5.53	15.26	9.24	9.18	4.16	4.60	4.75	0.79	3.06
March	10.36	5.92	15.72	9.89	9.36	4.32	4.65	4.81	0.87	3.06
April	8.90	5.56	15.62	10.05	8.43	4.13	3.99	4.47	0.79	2.69
May	8.14	5.08	15.29	9.82	7.61	3.60	3.45	3.83	0.70	2.40
June	3.63	4.11	14.31	8.07	4.15	2.11	1.78	1.97	0.37	1.07
July	3.69	3.89	14.25	8.00	4.12	1.98	1.81	1.88	0.38	1.06
August	5.22	4.00	14.52	8.43	5.36	2.25	2.38	2.15	0.50	1.54
September	6.43	4.24	14.76	9.02	6.45	2.62	2.80	2.49	0.60	1.99
October	6.75	4.06	14.81	8.45	6.49	2.51	2.66	2.39	0.56	2.01
November	6.85	4.32	14.69	8.03	6.76	2.53	2.75	2.5	0.53	2.12
December	8.63	4.43	14.72	8.73	7.98	3.04	3.43	3.36	0.61	2.62
Average	7.32	4.70	14.92	8.90	7.09	3.08	3.23	3.24	0.62	2.22

From Table 4.2 it was seen that the ETo values obtained from the Turc model was the highest (14.92 mm/day) and Priestly-Taylor model was the lowest (0.62 mm/day). Thornthwaite, Blaney-Criddle and Modified Penman models gave closer values to each other 7.32, 8.90 and 7.09 mm/day respectively. While Christiansen, Penman-Monteith, Open pan and Makkinik models gave values like 3.08, 3.23, 3.24 and 2.22 mm/day respectively which were slightly lower than the ETo values obtained from the Hargreaves model (4.7 mm/day). It was observed from Fig 4.1 that the ETo values obtained from the different models were highest in the summer months March and April and remained lowest in the monsoon months June and July. The various calculations and estimation of ETo using the empirical models were illustrated in appendix II.

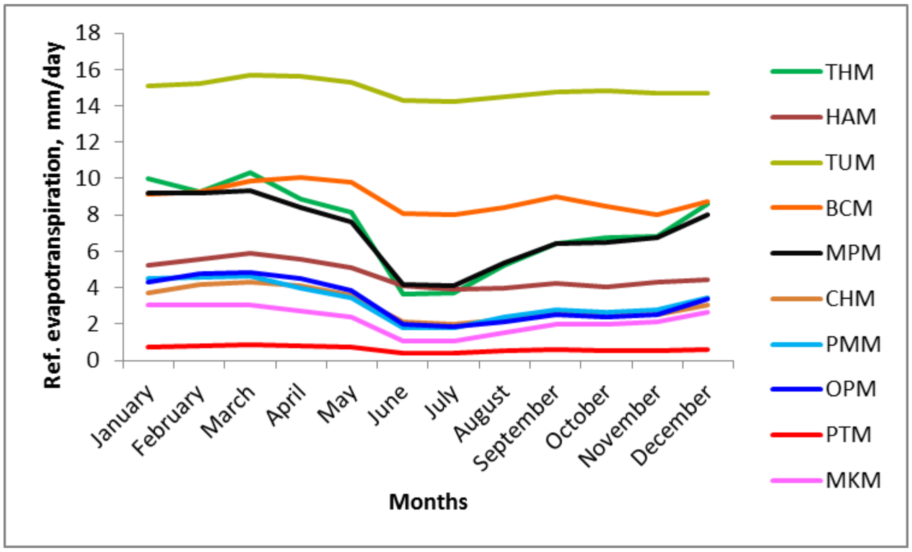

Fig.4.1 Variation of Monthly ETo values estimated from different models

4.3 PERFORMANCE OF REFERENCE CROP EVAPOTRANSPIRATION MODELS (ETo_{EST})

In recent years FAO-56 Penman-Monteith model which is more physically based provides superior results in both arid and humid regions and it has been recommended as a new standard for reference crop evapotranspiration estimates (Allen *et al.*, 1998). Hence in this study a statistical comparison was made by considering FAO-56 PMM as the standard using the six years (2011-2016) average monthly climate data.

Table 4.3 showed Percentage variation of ETo of different models compared with FAO-56 PMM. It is evident that Christiansen, Open pan, Priestly-Taylor and Makkinik models gave an average of 2.85, 0.12, 80.48 and 31.56 per cent lower values of ETo than Penman-Monteith model. While Thornthwaite, Hargreaves, Turc, Blaney-Criddle and Modified Penman models gave an average of 126.46, 54.56, 407.48, 199.09 and 123.10 per cent higher ETo values than Penman-

Monteith model respectively. From this it is clear that the models Christiansen, Open pan, Makkinik and Hargreaves models were very near to Penman-Monteith estimation.

Table 4.3 Percentage variation of ETo of different models from FAO-56 PMM.

Months	**THM OVER PMM**	**HAM OVER PMM**	**TUM OVER PMM**	**BCM OVER PMM**	**MPM OVER PMM**	**CHM OVER PMM**	**OPM OVER PMM**	**PTM OVER PMM**	**MKM OVER PMM**
January	122.69	16.84	236.88	103.41	105.60	-16.83	-3.85	-84.01	-31.92
February	101.30	20.11	231.54	100.65	99.41	-9.65	3.25	-82.91	-33.41
March	122.86	27.40	238.14	112.67	101.33	-7.00	3.37	-81.36	-34.10
April	122.99	39.21	291.44	151.80	111.30	3.60	12.06	-80.22	-32.47
May	136.09	47.48	343.58	184.85	120.81	4.54	11.07	-79.64	-30.35
June	103.80	130.62	703.70	353.48	133.33	18.50	10.93	-79.03	-39.86
July	103.99	115.03	687.25	341.90	127.67	9.60	3.68	-79.23	-41.64
August	119.25	67.98	509.86	254.12	125.28	-5.60	-9.77	-78.87	-35.30
September	129.89	51.40	427.45	222.23	130.49	-6.46	-10.86	-78.62	-28.90
October	153.46	52.28	455.94	217.11	143.46	-5.65	-10.26	-78.99	-24.49
November	149.53	57.22	434.79	192.43	145.98	-7.81	-9.04	-80.61	-22.73
December	151.67	29.13	329.24	154.43	132.50	-11.43	-1.97	-82.30	-23.53
Average	126.46	54.56	407.48	199.09	123.10	-2.85	-0.12	-80.48	-31.56

Table 4.4 showed the statistical comparison of different models by considering FAO-56 PMM as the standard model using simple regression analysis, MBE, RMSE and RelRMSE.

Table 4.4 Evaluation of the different empirical models in comparison with FAO-56 PMM.

SI. No.	**Estimation Models**	**Regression line slope**	**Regression line intercept**	**R^2**	**MBE**	**RMSE**	**RelRMSE**
1	THM	2.14	0.37	0.94	4.09	4.28	1.32
2	HAM	0.64	2.60	0.86	1.47	1.53	0.47
3	TUM	0.41	13.59	0.78	11.69	11.71	3.62
4	BCM	0.56	7.06	0.63	5.67	5.70	1.76
5	MPM	1.77	1.35	0.96	3.86	3.95	1.22
6	CHM	0.80	0.48	0.92	-0.15	0.33	0.10
7	OPM	1.07	-0.23	0.94	0.01	0.26	0.08
8	PTM	0.14	0.13	0.91	-2.61	2.75	0.85
9	MKM	0.68	0.01	0.95	-1.01	1.06	0.33

The positive values of MBE indicated overestimation and negative value underestimation of ETo values. The best model was the one that had the lowest RMSE and the highest R^2. Accordingly the models were ranked from best to the worst as follows. The Modified Penman model gave the best performance with R^2 of 0.96, RMSE 3.95 and RelRMSE 1.22. This is similar to results obtained by Meshram *et al.* (2010). The next best performance was given by Hargreaves model with RMSE 1.53, RelRMSE 0.47 and R^2 0.86. This is in conformity with the findings of Moroozeh and Bansouleh (2015). The Open pan model ranked the third with RMSE 0.26, RelRMSE 0.08 and R^2 0.94. The models that gave underestimations were Christiansen, Priestly-Taylor and Makkinik with MBE 0.15, 2.61 and 1.01 and the corresponding RelRMSE 0.10, 0.85 and 0.33 and R^2 of 0.92, 0.91 and 0.95 respectively. The Thornthwaite, Turc and Blaney-Criddle models provide overestimation with regression line slope of 2.14, 0.41 and 0.56 and regression line intercept of 0.37, 13.59 and 7.06 and R^2 of 0.94, 0.78 and 0.63 respectively.

4.4 MEASUREMENT OF ACTUAL EVAPOTRANSPIRATION BY LYSIMETER (ETo_{LYM})

Table 4.5 represented the actual reference evapotranspiration measured by weekly water balance in lysimeter (ETo_{LYM}). Since the reference crop was grass, the ETo values were almost steady during the entire period of study.

Table 4.5 Actual evapotranspiration by lysimeter (ETo_{LYM})

Weeks	Applied water (mm)	Drainage (mm)	Change in soil water storage (mm)	ETo_{LYM} (mm)	ETo_{LYM} (mm/day)
1st Week	44.80	11.48	3.16	30.16	4.31
2nd Week	44.80	11.39	-1.74	35.15	5.02
3rd Week	44.80	11.33	0.22	33.25	4.75
4th Week	44.80	11.25	-0.77	34.32	4.90
5th Week	44.80	11.14	0.73	32.93	4.70
6th Week	44.80	10.96	1.39	32.45	4.64
7th Week	44.80	10.84	1.46	32.50	4.64
8th Week	44.80	10.71	2.19	31.90	4.56
9th Week	44.80	10.64	2.58	31.58	4.51
10th Week	44.80	10.59	0.72	33.49	4.78
11th Week	44.80	10.47	-2.08	36.41	5.20
12th Week	44.80	10.4	-0.4	34.80	4.97
13th Week	44.80	10.32	-1.31	35.79	5.11
14th Week	44.80	10.19	1.35	33.26	4.75
15th Week	44.97	9.99	-0.6	35.58	5.08
16th Week	44.80	9.72	0.63	34.45	4.92
17th Week	45.00	9.59	-0.5	35.91	5.13
18th Week	45.10	9.46	-0.58	36.22	5.17
19th Week	44.80	9.32	1.65	33.83	4.83
20th Week	44.80	9.55	3.17	32.08	4.58
21st Week	44.90	9.72	4.94	30.24	4.32

4.5 COMPARISON OF MEASURED ETo (ETo_{LYM}) WITH ESTIMATED ETo (ETo_{EST}).

The weekly values of ETo measured from the lysimeter water balance and that estimated values from the different empirical models were compared. Weekly average ETo values for the twenty one weeks during which the lysimeter study conducted was also determined from the ETo models. The measured and the estimated ETo values were presented in Table 4.6 and Fig.4.2. It was evident from the results that the ETo values obtained from the different models showed deviation from the measured values. Turc model was the highest deviated (15.43 mm/day) and Priestly-Taylor the lowest (0.67 mm/day). Thornthwaite (5.01 mm/day), Hargreaves (5.61 mm/day), Christiansen (4.12 mm/day), Open pan (4.45 mm/day) and Penman-Monteith (3.88 mm/day) were found very close to measured values (4.96 mm/day). However Blaney-Criddle (9.86 mm/day) and Modified Penman (8.50 mm/day), models overestimated the measured value and Makkinik (2.87 mm/day) model underestimated. The calculations of weekly estimated ETo and measured ETo were illustrated in appendix III.

Table 4.6 Weekly estimated ($\mathrm{ETo}_{\mathrm{EST}}$) and measured ($\mathrm{ETo}_{\mathrm{LYM}}$) values of ETo.

Weeks	**ETo LYM**	**ETo THM**	**ETo HAM**	**ETo TUM**	**ETo BCM**	**ETo MPM**	**ETo CHM**	**ETo OPM**	**ETo PMM**	**ETo PTM**	**ETo MKM**
1st week	4.31	2.22	5.65	15.04	8.40	8.13	3.39	3.67	3.79	0.65	3.04
2nd week	5.02	4.42	5.51	15.03	8.88	8.38	3.34	3.63	3.80	0.66	3.05
3rd week	4.75	7.22	5.44	15.24	9.93	9.67	4.52	5.08	4.66	0.74	3.36
4th week	4.90	6.45	5.13	14.97	8.41	7.61	4.49	5.10	4.16	0.55	2.21
5th week	4.70	2.57	5.50	15.48	10.22	9.64	4.30	4.78	4.71	0.74	3.47
6th week	4.64	5.01	5.68	15.43	9.69	9.34	4.38	4.83	4.55	0.72	3.41
7th week	4.64	8.10	5.60	15.56	10.62	10.85	5.69	6.84	6.23	0.76	3.73
8th week	4.56	7.18	5.73	15.11	8.69	7.54	4.07	4.30	3.41	0.60	2.46
9th week	4.51	1.98	6.52	15.44	9.26	7.95	5.01	5.52	4.07	0.60	2.61
10th week	4.78	4.46	5.56	15.57	10.12	8.76	4.35	4.54	3.64	0.72	2.99
11th week	5.20	6.64	5.74	15.49	10.01	8.88	4.13	4.34	3.73	0.72	3.02
12th week	4.97	9.16	5.61	15.69	10.20	9.27	4.07	4.23	3.81	0.76	3.13
13th week	5.11	2.54	6.30	15.98	11.08	9.45	4.58	4.81	4.09	0.77	3.32
14th week	4.75	4.53	5.87	15.82	11.04	8.92	4.15	4.33	3.76	0.73	2.98
15th week	5.08	5.27	5.60	15.52	9.95	7.39	3.87	4.04	3.18	0.60	2.32
16th week	4.92	5.46	5.07	15.20	8.86	6.22	3.55	3.71	2.72	0.50	1.81
17th week	5.13	2.51	5.47	15.85	11.42	9.56	4.17	4.38	4.00	0.78	3.29
18th week	5.17	4.70	5.98	15.80	10.83	9.03	3.69	3.88	3.90	0.74	3.10
19th week	4.83	5.55	5.62	15.35	9.95	7.76	3.49	3.70	3.41	0.62	2.49
20th week	4.58	8.04	5.17	15.46	10.72	8.49	4.32	4.52	3.48	0.69	2.75
21th week	4.32	1.26	5.03	14.96	8.70	5.64	2.98	3.11	2.44	0.45	1.63

Average	4.80	5.01	5.61	15.43	9.86	8.50	4.12	4.45	3.88	0.67	2.87

It was seen from Fig.4.2 that ETo values obtained from the different models followed same trend of variation except Turc, Priestly-Taylor and Thornthwaite. Since grass was used as the reference crop there was not much variation in the weekly ETo values and it showed steady values throughout the different weeks of the study period. However a decreasing trend was observed during the 16th week due to rainfall and after that values showed an increasing trend due to the high temperature prevailed during those days.

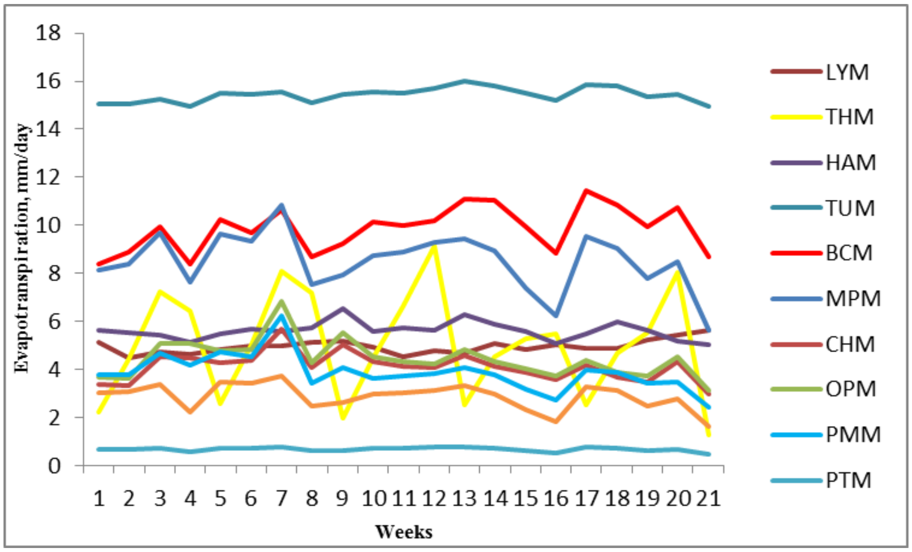

Fig.4.2 Comparison of ETo_{LYM} and $ETo_{EST.}$

The statistical comparison between ETo values estimated from the models and the ETo values measured from lysimeter was done with simple regression analysis. The estimation model values were taken as the independent variables and measured values from lysimeter were taken as the dependent variables. The per cent deviation of mean weekly estimated ETo by different empirical models from measured ETo, R^2, RMSE, MBE and RelRMSE were presented in Table 4.7.

Table 4.7 Comparative evaluation of ETo_{EST} with $ETo_{LYM.}$

Models	**Percent deviation from measured values**	**R^2**	**MBE**	**RMSE**	**RelRMSE**
Thornthwaite	1.97	0.14	0.06	2.27	0.46
Hargreaves	13.59	0.83	0.65	0.82	0.17
Turc	212.33	0.03	10.47	10.48	2.11
Blaney-Criddle	99.58	0.77	4.90	5.00	1.01
Modified Penman	72.58	0.56	3.54	3.79	0.76
Christiansen	-16.45	0.60	-0.83	1.09	0.22
Open Pan	-9.88	0.51	-0.51	1.02	0.21
Penman-Monteith	-21.14	0.43	-1.07	1.40	0.28
Priestly-Taylor	-86.36	0.57	-4.28	4.30	0.87
Makkinik	-41.76	0.43	-2.09	2.21	0.45

The results of evaluation of ten empirical methods with lysimeter measurement showed that the Hargreaves model gave the best performance with R^2 0.83 and the RMSE 0.82. This result was similar to the study conducted by Kashyap and Panda (2001) and Urrea *et al*. (2006) in which the Hargreaves model gave the best performance in sub humid and semiarid regions with R^2 0.70 and 0.84 and the corresponding RMSE 0.35 and 0.90 respectively. The ETo values by Turc method was highly over estimated with insignificant R^2 (0.03) and RMSE (10.48). Results were similar to Kashyap and Panda (2001), in which the Turc model has little over estimation with R^2 0.70 and the RMSE 0.26. But, the Blaney-Criddle model overestimated ETo values with R^2 0.76 and the RMSE 4.99. This is also in conformity with the findings of Urrea *et al*. (2006). Modified Penman model also over estimated with R^2 0.55 and RMSE 3.78 in this study. This was similar to the results of Benli *et al.* (2006).

The Penman-Monteith model underestimated the ETo values with R^2 0.42 and the RMSE 1.39. Priestly-Taylor underestimated with R^2 0.56 and the RMSE 4.29. This is in accordance with studies of Kashyap and Panda (2001) in which the Priestly-Taylor model underestimated the ETo values measured from the lysimeter. Makkinik model also underestimated the ETo values with R^2 0.42 and RMSE 2.20. This is similar to the findings Benli *et al.* (2006) in which Makkinik model gave under estimation.

The statistical analysis revealed that among the different models, Hargreaves, Open pan and Christiansen were found to be the best models for this region. However, in case of limited data availability the Hargreaves, Open Pan and Christiansen models are preferred.

4.6 RELATIONSHIP OF VARIOUS ETo ESTIMATION MODEL VALUES WITH LYSIMETRIC DATA (LOCAL CALIBRATION).

In the present research work, lysimeter was used to measure the actual ETo values (ETo_{LYM}). Then ETo_{LYM} was used to develop relationship with other models such as Thornthwaite, Hargreaves, Blaney-Criddle, Christiansen, Penman-Monteith, Modified Penman, Open Pan, Turc, Priestly-Taylor and Makkinik models. As lysimeter study is very cumbersome and expensive it is not always possible to conduct experiments in lysimeter. Hence, it is necessary to find the relationship between selected model output and the lysimetric data. To develop the interrelationship between the model values and the lysimetric data, linear regression analysis had been done by using Microsoft excel statistics and the scatter plot is depicted in (Fig.4.3).

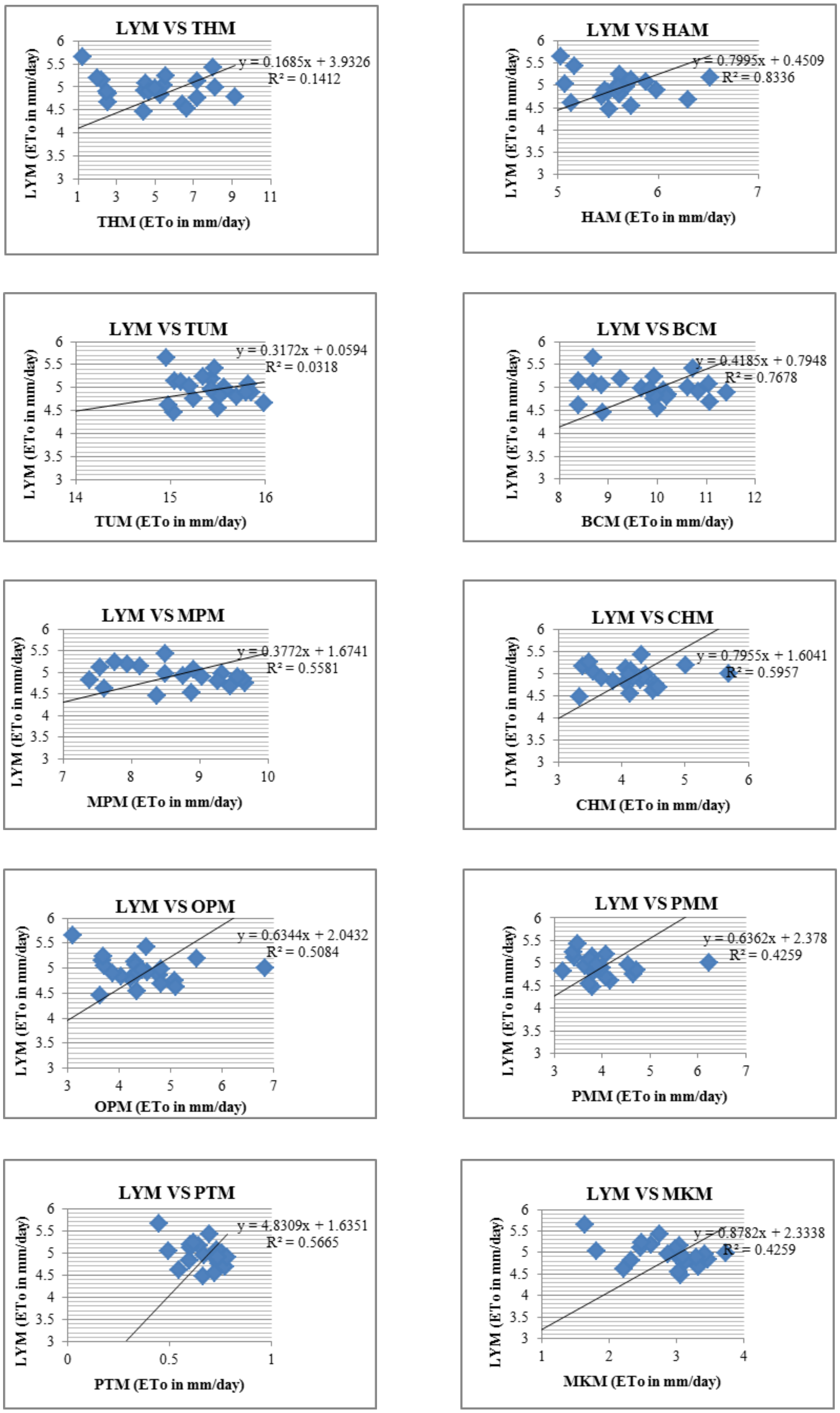

Fig.4.3. Scatter plot between ETo estimated by empirical models vs ETo lysimeter

Lysimetric data was used to calibrate the empirical models locally. Utility of this method helps in narrowing down the errors. Local calibration or adjustment coefficients were evolved by linear regression technique with lysimetric data as the dependent variable and the empirical model values as the independent variable. The equations showing relationships of various models with lysimetric data were given in Table 4.8. It can be noted that the models which has higher coefficient of correlation were Hargreaves, FAO-24 Open Pan and Christiansen and hence these three models were recommended to be suitable for this region.

Table 4.8 Relationship between Lysimeter and Model ETo Values.

Sl. No.	Models	Relation	Regression line slope (m)	Regression line intercept (c)	R^2
1	Thornthwaite	LYM = 0.16 THM + 3.93	0.16	3.93	0.14
2	Hargreaves	**LYM = 0.79 HAM + 0.45**	0.79	0.45	0.83
3	Turc	LYM = 0.31 TUM + 0.05	0.31	0.05	0.03
4	Blaney-Criddle	LYM = 0.41 BCM + 0.79	0.41	0.79	0.77
5	Modified Penman	LYM = 0.37 MPM + 1.67	0.37	1.67	0.56
6	Christiansen	**LYM = 0.79 CHM + 1.60**	0.79	1.60	0.60
7	Open Pan	**LYM = 0.63 OPM + 2.04**	0.63	2.04	0.51
8	Penman-Monteith	LYM = 0.63 PMM + 2.37	0.63	2.37	0.43
9	Priestly-Taylor	LYM = 4.83 PTM + 1.63	4.83	1.63	0.57
10	Makkinik	LYM = 0.87 MKM + 2.33	0.87	2.33	0.43

This inter-relationship would help us to estimate ETo in the absence of Lysimetric data and non-availability of all required data. However this has to be validated with another crop experiment in lysimeter to test its accuracy.

Summary and Conclusion

CHAPTER V

SUMMARY AND CONCLUSION

The changing global climate has significant effect on evapotranspiration and hence there is a need to estimate continually updated evapotranspiration. In the present research work, the reference crop evapotranspiration (ETo) is estimated by using ten empirical models which are widely used in Indian conditions namely, Thornthwaite (1948), Hargreaves *et al.,* (1985), Turc (1961), Christiansen (1968) Pan Evaporation, FAO-24 Blaney-Criddle (1977), FAO-24 Modified Penman (1977), FAO-24 Open Pan (1977), Preistly-Taylor, Makkinik and FAO-56 Penman-Monteith (1991) models. These ten models are here after represented as THM, HAM, TUM, CHM, BCM, MPM, OPM, PTM, MKM and PMM respectively for convenience. The primary objective of this study was to assess the performance of these reference evapotranspiration models for the humid tropical region. This was achieved by comparing it with FAO 56 Penman-Monteith which is recommended as the new standard for reference crop evapotranspiration estimates in all climates all over the world. The model computation was accomplished by using six years (January, 2011-December, 2016) average meteorological data. After the preliminary comparison with FAO-56 Penman-Monteith, all these ten models were validated with lysimetric data. Weekly water balance was conducted in lysimeter to find the actual reference evapotranspiration for the period January-May, 2017. For comparison, weekly reference evapotranspiration was estimated using the weekly values of meteorological data for the same period during which the lysimeter experiment was conducted. Then best fit relations were developed between the estimated values (ETo_{EST}) and observed values (ETo_{LYM}).

The results pertaining to the comparison of ET models using the meteorological data for the period Januay, 2011-December, 2016 were as follows. Among the different models, the monthly ETo values obtained from the Turc model showed the highest (14.92 mm/day) and Priestly-Taylor model the lowest (0.62 mm/day). Thornthwaite, Blaney-Criddle and Modified Penman models gave closer values to each other 7.32, 8.90 and 7.09 mm/day respectively. While Christiansen, Penman-Monteith, Open pan and Makkinik models gave values like 3.08, 3.23, 3.24 and 2.22 mm/day respectively which were slightly lower than the values obtained from the Hargreaves model (4.7 mm/day).

The statistical comparison was made by considering FAO-56 Penman-Monteith model as the standard. The Modified Penman model gave the best performance with R^2 of 0.96 with RMSE 3.95 and RelRMSE 1.22 followed by Hargreaves model with RMSE 1.53, RelRMSE 0.47 and R^2 0.86. The Open Pan method ranked the third one with RMSE 0.26, RelRMSE 0.08 and R^2 0.94. While the models, Christiansen, Priestly-Taylor and Makkinik were underestimated with MBE 0.15, 2.61 and 1.01, RelRMSE 0.10, 0.85 and 0.33 and R^2 of 0.92, 0.91 and 0.95 respectively. The Thornthwaite, Turc and Blaney-Criddle models showed overestimation with regression line slope of 2.14, 0.41 and 0.56 and line intercept of 0.37, 13.59 and 7.06 and R^2 of 0.94, 0.78 and 0.63 respectively.

For validation of the models, a weekly ETo estimated from models (ETo_{EST}) using the meteorological data for the period January-May, 2017 was compared with ETo observed from lysimeter (ETo_{LYM}). The ETo values obtained from the different models showed deviation from the actual measured values. Turc model was the highest deviated (15.43 mm/day) and Priestly-Taylor the lowest (0.67 mm/day). Thornthwaite (5.01 mm/day), Hargreaves (5.61 mm/day), Christiansen (4.12 mm/day), Open Pan (4.45 mm/day) and Penman-Monteith (3.88 mm/day) were found very close to the measured values (4.96 mm/day). However Blanny-Criddle (9.86 mm/day) and Modified Penman (8.50 mm/day) models overestimated the measured values and Makkinik (2.87 mm/day) model underestimated.

The ETo values estimated by the ten models and the ETo values measured from lysimeter were statistically compared for assessing the performance. The Hargreaves model gave the best performance with R^2 0.83 and RMSE 0.82. The Turc model was highly over estimated with insignificant R^2 (0.03) and the RMSE

(10.48). The Blaney-Criddle model overestimated with R^2 0.76 and RMSE 4.99. The Modified Penman model slightly over estimated with R^2 0.55 and RMSE 3.78. But, the Penman-Monteith and Makkinik models slightly underestimated the ETo values with R^2 0.42, 0.42 and the RMSE 1.39, 2.20 respectively. Priestly-Taylor highly underestimated with R^2 0.56 and RMSE 4.29. Hence it is concluded that Hargreaves, Open Pan and Christiansen models were found to be in close agreement with lysimetric data and hence these models were suggested for use in this humid tropical region.

In order to find the best fit empirical models in areas of limited data availability, local calibration of models was done with lysimetric data (ETo_{LYM}). The relationships were developed between the observed and estimated values. Accordingly the models which are more suitable for the area such as Hargreaves (HAM), Christiansen (CHM) and Open Pan (OPM) models were taken to find the relationship. This would facilitate to calculate ETo in case of non-availability of all required data. The equations developed were as follows: $ETo_{LYM} = 0.79HAM + 0.45$, $ETo_{LYM} = 0.79CHM + 1.60$ and $ETo_{LYM} = 0.63OPM + 2.04$.

Finally the results of this research can be recommended for humid tropical region for irrigation scheduling, selection of cropping pattern, optimum allocation of water resources and efficient use of water.

Further scope of research

- The accuracy of equations developed by using weekly data is to be validated with another lysimeter experiment in another crop.
- There is a scope for calibration of actual model coefficients by optimization technique by choosing the least square error as an optimal parameter to determine the level of dispersion
- The importance of developing a regional scale crop coefficient values for various crops in this humid tropical environment are reflected in this research.

- A need of conducting the experiment in a weighing type lysimeter is crucial for accurate measurement of ET on daily basis
- Impact of ET models on yield of the crop regionally can be studied
- Since FAO-56 Penman-Monteith proved to be superior in estimating reference ET all over the world, the best models found in the study has to be retested over long term period to obtain an average calibrated coefficient for the region.

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Appendices

APPENDIX I

Physical properties of soil by Core cutter method

Calculations

Weight of core soil (W) : 1472.5 g

Volume of core soil (V) : 900.20 cm^3

Weight of moisture container (W_1) : 334.5 g

Weight of moist soil + Moisture container weight (W_2) : 1806.5 g

Weight of dry soil + Moisture container weight (W_3) : 1704 g

Moisture content of soil (ω) : 7.48 %

Bulk density and particle density of soil were determined by using the following formulas

Bulk density of the soil (g/cm^3) $\gamma = \frac{W}{V}$

$= 1472.5/900.20$

$= 1.63$ g/cc

Particle density of the soil (g/cm^3) $\gamma_d = \frac{\gamma}{1+\omega}$

$= 1.63/(1+0.0748)$

$= 1.52$ g/cc

Coarser and Finer particles of soil

IS Sieve	Particle size (mm)	mass of each sieve (g)	mass of each sieve + retained soil	mass of soil retained (g)	percentage on each sieve	cumulative percent retained	% finer
2 mm	2	359.5	1044.0	684.5	50.3	50.3	49.7
1mm	1	368.5	481.0	112.5	8.3	58.6	41.4
600 µ	0.6	332.0	433.0	101.0	7.4	66.0	34.0
425 µ	0.425	335.5	402.0	66.5	4.9	70.9	29.1
300 µ	0.3	344.5	476.0	131.5	9.7	80.6	19.4
212 µ	0.212	340.5	556.0	215.5	15.8	96.4	3.6
150 µ	0.15	333.5	351.0	17.5	1.3	97.7	2.3
75 µ	0.075	297.5	320.0	22.5	1.7	99.4	0.6
Final Sieve	<75 micron	256.0	264.5	8.5	0.6	100.0	0.0
Sum				1360.0			

Field capacity, Available moisture content and Permanent wilting point of soil.

Samples	Soil constants	Mass of container (g)	Mass of wet soil (g)	Mass of dry soil (g)	Moisture content (%)	Available water (%)
1	FC	24.63	46.32	42.50	21.38	5.37
	PWP	27.48	55.60	51.72	16.01	
2	FC	22.50	51.14	46.24	20.64	5.16
	PWP	28.84	49.50	46.73	15.48	

Soil moisture measurements

Weeks	Surface layer(10 cm)	$((M_{bi-}M_{ei})/100)*(A_i*D_i)$ (1)	Deep layer (10 cm)	$((M_{bi}-M_{ei})/100)*(A_i*D_i)$ (2)	Soil moisture Storage (Δs) Ly=(1)+(2)
1	18.77	-0.03	25.51	3.19	3.16
2	18.79	1.55	23.56	-3.29	-1.74
3	17.84	-1.16	25.58	1.38	0.22
4	18.56	1.19	24.73	-1.96	-0.77
5	17.83	-0.99	25.93	1.72	0.73
6	18.43	1.5	24.88	-0.11	1.39
7	17.51	-0.54	24.95	2.01	1.46
8	17.85	0.74	23.72	1.45	2.19
9	17.39	1.01	22.83	1.58	2.58
10	16.78	1.96	21.87	-1.24	0.72
11	15.58	-1.75	22.63	-0.33	-2.08
12	16.65	-0.94	22.83	0.54	-0.4
13	17.22	3.29	22.51	-4.6	-1.31
14	15.21	-2.37	25.32	3.72	1.35
15	16.66	-0.87	23.05	0.27	-0.6
16	17.19	0.44	22.88	0.19	0.63
17	16.92	-1.38	22.77	0.88	-0.5
18	17.76	1.76	22.23	-2.35	-0.58
19	16.69	0.68	23.67	0.98	1.65
20	16.27	-0.38	23.07	3.55	3.17
21	16.5	3.63	20.9	1.31	4.94

APPENDIX II

Estimated six years monthly average ETo by Thornthwaite model

		Thornthwaite model			
Months	Tmean	I	a	L	ETo
Jan	27.034	12.874	0.712	0.715	9.980
Feb	28.135	13.677	0.725	0.647	9.265
Mar	29.985	15.061	0.747	0.693	10.359
Apr	30.208	15.235	0.750	0.592	8.899
May	29.290	14.539	0.739	0.553	8.140
Jun	26.925	12.797	0.710	0.259	3.628
Jul	26.622	12.578	0.707	0.266	3.693
Aug	26.805	12.709	0.709	0.375	5.218
Sep	27.133	12.945	0.713	0.459	6.434
Oct	27.642	13.315	0.719	0.477	6.752
Nov	27.400	13.139	0.716	0.487	6.853
Dec	27.022	12.865	0.712	0.618	8.633

Estimated six years monthly average ETo by Hargreaves model

		Hargreaves model		
Months	Tmean	TD^.5	Ra	ETo
Jan	27.034	3.551	14.300	5.236
Feb	28.135	3.686	14.200	5.528
Mar	29.985	3.522	15.300	5.922
Apr	30.208	3.204	15.700	5.555
May	29.290	3.031	15.500	5.085
Jun	26.925	2.610	15.300	4.106
Jul	26.622	2.490	15.300	3.893
Aug	26.805	2.514	15.500	3.998
Sep	27.133	2.679	15.300	4.237
Oct	27.642	2.638	14.700	4.057
Nov	27.400	3.054	13.600	4.318
Dec	27.022	3.332	12.900	4.430

Estimated six years monthly average ETo by Turc model

			Turc model			
Months	Tm	N	n/N	Ra	Rs	ETo
Jan	27.034	11.600	0.715	14.300	8.689	15.098
Feb	28.135	11.800	0.697	14.200	8.498	15.261
Mar	29.985	12.000	0.671	15.300	8.957	15.718
Apr	30.208	12.300	0.577	15.700	8.457	15.620
May	29.290	12.600	0.510	15.500	7.826	15.293
Jun	26.925	12.700	0.245	15.300	5.701	14.308
Jul	26.622	12.600	0.245	15.300	5.700	14.251
Aug	26.805	12.400	0.351	15.500	6.593	14.515
Sep	27.133	12.100	0.455	15.300	7.309	14.762
Oct	27.642	11.800	0.469	14.700	7.122	14.811
Nov	27.400	11.600	0.504	13.600	6.824	14.688
Dec	27.022	11.500	0.624	12.900	7.251	14.725

Estimated six years monthly average ETo by Blaney-Criddle model

		Blaney-Criddle model			
Months	P	a	b	f	ETo
Jan	0.260	-1.954	2.070	5.347	9.116
Feb	0.270	-1.955	1.967	5.690	9.236
Mar	0.270	-1.895	1.991	5.919	9.886
Apr	0.280	-1.763	1.915	6.167	10.048
May	0.280	-1.653	1.897	6.049	9.821
Jun	0.290	-1.326	1.579	5.950	8.073
Jul	0.290	-1.330	1.578	5.909	7.999
Aug	0.280	-1.449	1.723	5.729	8.429
Sep	0.280	-1.575	1.835	5.771	9.019
Oct	0.270	-1.621	1.789	5.628	8.448
Nov	0.260	-1.686	1.803	5.391	8.032
Dec	0.260	-1.826	1.974	5.346	8.728

Estimated six years monthly average ETo by Modified Penman model

					Modified Penman model					
Months	Tmean	RH mean	F(u)	w	1-W	ea	ed	ea-ed	Rn	ETo
Jan	27.03	62.49	0.25	0.75	0.24	35.35	22.10	13.25	9.97	9.21
Feb	28.13	60.47	0.18	0.76	0.23	37.65	22.76	14.89	10.01	9.17
Mar	29.98	65.26	0.16	0.77	0.22	41.10	26.80	14.30	10.24	9.35
Apr	30.20	69.52	0.13	0.77	0.22	42.29	29.38	12.90	9.35	8.43
May	29.29	75.77	0.12	0.77	0.22	39.38	29.79	9.58	8.57	7.61
Jun	26.92	85.56	0.09	0.75	0.24	36.29	31.05	5.23	4.81	4.15
Jul	26.62	85.01	0.10	0.75	0.24	34.65	29.44	5.20	4.78	4.12
Aug	26.80	83.21	0.11	0.75	0.24	34.82	28.97	5.85	6.22	5.36
Sep	27.13	80.51	0.09	0.75	0.24	36.05	29.02	7.02	7.53	6.45
Oct	27.64	76.30	0.07	0.76	0.23	36.57	27.90	8.67	7.48	6.48
Nov	27.40	71.16	0.10	0.76	0.24	36.05	25.64	10.40	7.73	6.75
Dec	27.02	67.98	0.17	0.75	0.24	35.35	24.05	11.29	8.94	7.97

Estimated six years monthly average ETo by Christiansen Pan Evaporation model

		Christiansen model				
Months	EVAPORATION (mm)	CT2	CW2	CH2	CS2	ETo
Jan	5.111	1.029	1.019	1.015	0.906	3.727
Feb	5.605	1.033	1.048	1.003	0.906	4.159
Mar	5.559	1.038	1.061	1.032	0.906	4.323
Apr	5.074	1.039	1.086	1.058	0.905	4.134
May	4.295	1.036	1.089	1.092	0.905	3.604
Jun	2.367	1.029	1.112	1.141	0.904	2.110
Jul	2.248	1.028	1.106	1.138	0.904	1.984
Aug	2.577	1.028	1.102	1.130	0.905	2.247
Sep	3.001	1.029	1.112	1.117	0.905	2.618
Oct	2.895	1.031	1.125	1.095	0.905	2.513
Nov	3.047	1.030	1.106	1.067	0.905	2.532
Dec	3.895	1.029	1.060	1.048	0.905	3.038

Estimated six years monthly average ETo by Penman-Monteith model

			Penman-Monteith model				
Months	U2	Tmean	Δ	ϒ	es-ea	Rn-G	ETo
Jan	1.584	27.034	0.210	0.067	1.725	10.028	4.482
Feb	1.181	28.135	0.222	0.067	1.998	10.853	4.603
Mar	1.055	29.985	0.243	0.067	1.893	11.686	4.648
Apr	0.819	30.208	0.246	0.067	1.584	10.617	3.991
May	0.798	29.290	0.235	0.067	1.170	9.544	3.448
Jun	0.592	26.925	0.208	0.067	0.588	5.224	1.780
Jul	0.644	26.622	0.205	0.067	0.592	5.283	1.810
Aug	0.686	26.805	0.207	0.067	0.672	7.050	2.380
Sep	0.598	27.133	0.211	0.067	0.814	8.360	2.799
Oct	0.483	27.642	0.216	0.067	1.026	7.769	2.664
Nov	0.646	27.400	0.213	0.067	1.270	7.418	2.746
Dec	1.067	27.022	0.209	0.067	1.425	8.500	3.430

Estimated six years monthly average ETo by Open Pan method

	Open Pan Method		
		Dry Fetch	
Months	EVAPORATION(mm)	Kp	ETo
Jan	5.111	0.842	4.309
Feb	5.605	0.850	4.752
Mar	5.559	0.864	4.805
Apr	5.074	0.883	4.472
May	4.295	0.896	3.829
Dec	3.895	0.867	3.363
		Green Fetch	
Jun	2.367	0.834	1.975
Jul	2.248	0.834	1.877
Aug	2.577	0.833	2.148
Sep	3.001	0.831	2.495
Oct	2.895	0.827	2.391
Nov	3.047	0.820	2.498

Estimated six years monthly average ETo by Priestly Taylor model

		Priestly Taylor model							
Months	Tmean	Δ	ϒ	Rn-G	λ	albedo	1/λ	Δ/(Δ+ϒ)	ETo
Jan	27.034	0.210	0.067	10.028	2.437	0.230	0.410	0.757	0.717
Feb	28.135	0.222	0.067	10.853	2.435	0.230	0.411	0.767	0.787
Mar	29.985	0.243	0.067	11.686	2.430	0.230	0.411	0.784	0.866
Apr	30.208	0.246	0.067	10.617	2.430	0.230	0.412	0.785	0.789
May	29.290	0.235	0.067	9.544	2.432	0.230	0.411	0.777	0.702
Jun	26.925	0.208	0.067	5.224	2.437	0.230	0.410	0.756	0.373
Jul	26.622	0.205	0.067	5.283	2.438	0.230	0.410	0.753	0.376
Aug	26.805	0.207	0.067	7.050	2.438	0.230	0.410	0.755	0.503
Sep	27.133	0.211	0.067	8.360	2.437	0.230	0.410	0.758	0.598
Oct	27.642	0.216	0.067	7.769	2.436	0.230	0.411	0.763	0.560
Nov	27.400	0.213	0.067	7.418	2.436	0.230	0.410	0.761	0.533
Dec	27.022	0.209	0.067	8.500	2.437	0.230	0.410	0.757	0.607

Estimated six years monthly average ETo by Makkinik model

		Makkinik model				
Months	Δ	ϒ	Δ + ϒ	Rs	Δ/(Δ + ϒ)	ETo
Jan	0.209	0.067	0.276	16.823	0.757	3.051
Feb	0.221	0.067	0.288	16.672	0.767	3.064
Mar	0.243	0.067	0.310	16.321	0.783	3.063
Apr	0.246	0.067	0.313	14.396	0.785	2.694
May	0.235	0.067	0.302	13.025	0.777	2.401
Jun	0.208	0.067	0.275	6.3135	0.756	1.070
Jul	0.205	0.067	0.272	6.262	0.753	1.056
Aug	0.207	0.067	0.274	8.818	0.755	1.540
Sep	0.210	0.067	0.277	11.174	0.758	1.989
Oct	0.216	0.067	0.283	11.221	0.762	2.011
Nov	0.213	0.067	0.280	11.843	0.760	2.122
Dec	0.209	0.067	0.276	14.554	0.757	2.623

APPENDIX III

Estimated weekly average ETo by lysimeter

	Lysimeter								
Weeks	Applied water/ Grass (I) in mm	Drainage (D) in mm	Surface layer(10 cm)	$((M_{bi}-M_{ei})/100)*(A_i*D_i)$ (1)	Deep layer (10 cm)	$((M_{bi}-M_{ei})/100)*(A_i*D_i)$ (2)	Soil moisture Storage (Δs) Ly=(1)+(2)	ET=I-D±Δs	ETo Average
1	44.80	11.48	18.77	-0.03	25.51	3.19	3.16	30.16	4.31
2	44.80	11.39	18.79	1.55	23.56	-3.29	-1.74	35.15	5.02
3	44.80	11.33	17.84	-1.16	25.58	1.38	0.22	33.25	4.75
4	44.80	11.25	18.56	1.19	24.73	-1.96	-0.77	34.32	4.90
5	44.80	11.14	17.83	-0.99	25.93	1.72	0.73	32.93	4.70
6	44.80	10.96	18.43	1.5	24.88	-0.11	1.39	32.45	4.64
7	44.80	10.84	17.51	-0.54	24.95	2.01	1.46	32.50	4.64
8	44.80	10.71	17.85	0.74	23.72	1.45	2.19	31.90	4.56
9	44.80	10.64	17.39	1.01	22.83	1.58	2.58	31.58	4.51
10	44.80	10.59	16.78	1.96	21.87	-1.24	0.72	33.49	4.78
11	44.80	10.47	15.58	-1.75	22.63	-0.33	-2.08	36.41	5.20
12	44.80	10.4	16.65	-0.94	22.83	0.54	-0.4	34.80	4.97
13	44.80	10.32	17.22	3.29	22.51	-4.6	-1.31	35.79	5.11
14	44.80	10.19	15.21	-2.37	25.32	3.72	1.35	33.26	4.75
15	44.97	9.99	16.66	-0.87	23.05	0.27	-0.6	35.58	5.08
16	44.80	9.72	17.19	0.44	22.88	0.19	0.63	34.45	4.92
17	45.00	9.59	16.92	-1.38	22.77	0.88	-0.5	35.91	5.13
18	45.10	9.46	17.76	1.76	22.23	-2.35	-0.58	36.22	5.17
19	44.80	9.32	16.69	0.68	23.67	0.98	1.65	33.83	4.83
20	44.80	9.55	16.27	-0.38	23.07	3.55	3.17	32.08	4.58
21	44.90	9.72	16.5	3.63	20.9	1.31	4.94	30.24	4.32

Estimated weekly average ETo by Thornthwaite model

		Thornthwaite model			
Weeks	Tmean	I	a	L	PET
1	26.807	12.710	0.709	0.160	2.224
2	26.771	12.684	0.709	0.318	4.421
3	27.336	13.091	0.715	0.513	7.220
4	28.529	13.965	0.729	0.447	6.454
5	28.486	13.934	0.729	0.178	2.574
6	28.457	13.912	0.729	0.347	5.009
7	28.586	14.008	0.730	0.560	8.103
8	28.907	14.247	0.734	0.492	7.175
9	29.486	14.681	0.741	0.134	1.982
10	29.393	14.611	0.740	0.303	4.464
11	28.950	14.279	0.735	0.455	6.639
12	30.000	15.070	0.747	0.612	9.156
13	30.857	15.727	0.758	0.166	2.540
14	30.836	15.710	0.758	0.297	4.535
15	30.800	15.683	0.757	0.346	5.272
16	30.171	15.201	0.749	0.363	5.456
17	30.471	15.430	0.753	0.166	2.508
18	30.779	15.666	0.757	0.308	4.698
19	29.571	14.746	0.742	0.375	5.552
20	29.721	14.859	0.744	0.541	8.039
21	29.193	14.461	0.737	0.086	1.264

Estimated weekly average ETo by Hargreaves model

	Hargreaves model			
Weeks	Tmean	TD^.5	Ra	ETo
1	26.807	3.853	14.300	5.652
2	26.771	3.757	14.300	5.507
3	27.336	3.663	14.300	5.437
4	28.529	3.368	14.300	5.132
5	28.486	3.641	14.200	5.504
6	28.457	3.761	14.200	5.682
7	28.586	3.696	14.200	5.599
8	28.907	3.759	14.200	5.734
9	29.486	3.921	15.300	6.524
10	29.393	3.349	15.300	5.561
11	28.950	3.487	15.300	5.736
12	30.000	3.338	15.300	5.615
13	30.857	3.586	15.700	6.300
14	30.836	3.345	15.700	5.874
15	30.800	3.194	15.700	5.605
16	30.171	2.928	15.700	5.072
17	30.471	3.176	15.500	5.465
18	30.779	3.454	15.500	5.981
19	29.571	3.325	15.500	5.616
20	29.721	3.050	15.500	5.166
21	29.193	3.002	15.500	5.030

Estimated weekly average ETo by Turc model

			Turc model			
Weeks	Tm	N	n/N	Ra	Rs	PET
1	26.807	11.600	0.709	14.300	8.647	15.042
2	26.771	11.600	0.706	14.300	8.621	15.028
3	27.336	11.600	0.759	14.300	8.999	15.238
4	28.529	11.600	0.495	14.300	7.115	14.973
5	28.486	11.800	0.777	14.200	9.068	15.477
6	28.457	11.800	0.757	14.200	8.922	15.434
7	28.586	11.800	0.814	14.200	9.326	15.564
8	28.907	11.800	0.536	14.200	7.358	15.105
9	29.486	12.000	0.575	15.300	8.224	15.437
10	29.393	12.000	0.649	15.300	8.788	15.570
11	28.950	12.000	0.650	15.300	8.798	15.492
12	30.000	12.000	0.656	15.300	8.843	15.691
13	30.857	12.300	0.696	15.700	9.386	15.984
14	30.836	12.300	0.621	15.700	8.803	15.824
15	30.800	12.300	0.482	15.700	7.709	15.523
16	30.171	12.300	0.380	15.700	6.906	15.204
17	30.471	12.600	0.677	15.500	9.121	15.847
18	30.779	12.600	0.629	15.500	8.752	15.800
19	29.571	12.600	0.510	15.500	7.829	15.347
20	29.721	12.600	0.552	15.500	8.154	15.459
21	29.193	12.600	0.351	15.500	6.599	14.955

Estimated weekly average ETo by Blaney-Criddle model

		Blaney-Criddle model			
Weeks	P	a	b	f	PET
1	0.260	-1.989	1.953	5.320	8.403
2	0.260	-1.941	2.035	5.316	8.878
3	0.260	-1.981	2.213	5.383	9.931
4	0.260	-1.732	1.835	5.526	8.406
5	0.270	-2.059	2.141	5.733	10.216
6	0.270	-2.054	2.050	5.729	9.690
7	0.270	-2.118	2.217	5.745	10.619
8	0.270	-1.775	1.809	5.785	8.689
9	0.270	-1.844	1.896	5.857	9.259
10	0.270	-1.869	2.051	5.846	10.121
11	0.270	-1.871	2.052	5.791	10.012
12	0.270	-1.877	2.040	5.921	10.200
13	0.280	-1.969	2.088	6.251	11.082
14	0.280	-1.845	2.063	6.248	11.043
15	0.280	-1.686	1.864	6.243	9.954
16	0.280	-1.582	1.694	6.162	8.858
17	0.280	-1.936	2.153	6.201	11.415
18	0.280	-1.898	2.040	6.241	10.833
19	0.280	-1.740	1.920	6.085	9.947
20	0.280	-1.749	2.043	6.105	10.724
21	0.280	-1.545	1.696	6.036	8.695

Estimated weekly average ETo by Modified Penman model

				Modified Penman model						
Weeks	Tmean	RH mean	F(u)	w	1-W	ea	ed	ea-ed	Rn	PET
1	26.80	58.85	0.14	0.75	0.25	33.65	19.80	13.84	9.20	8.13
2	26.77	57.85	0.14	0.75	0.25	33.65	19.46	14.18	9.47	8.38
3	27.33	63.35	0.27	0.75	0.25	35.70	22.61	13.08	10.51	9.66
4	28.52	61.85	0.30	0.77	0.23	37.80	23.38	14.41	7.66	7.61
5	28.48	59.42	0.23	0.77	0.23	37.80	22.46	15.33	10.31	9.64
6	28.45	57.00	0.19	0.77	0.23	37.80	21.54	16.25	10.06	9.33
7	28.58	49.00	0.39	0.77	0.23	37.80	18.52	19.27	10.51	10.84
8	28.90	67.42	0.13	0.77	0.23	37.80	25.48	12.31	8.40	7.53
9	29.48	57.57	0.20	0.77	0.22	40.10	23.08	17.01	8.33	7.95
10	29.39	70.42	0.12	0.77	0.22	40.10	28.24	11.85	9.85	8.76
11	28.95	70.57	0.13	0.77	0.22	37.85	26.71	11.13	9.97	8.88
12	30.00	71.28	0.11	0.78	0.22	42.40	30.22	12.17	10.39	9.26
13	30.85	66.78	0.13	0.78	0.22	42.40	28.31	14.08	10.48	9.44
14	30.83	71.14	0.13	0.78	0.22	42.40	30.16	12.23	9.93	8.92
15	30.80	71.21	0.13	0.78	0.22	42.40	30.19	12.20	8.15	7.39
16	30.17	71.28	0.13	0.78	0.22	42.00	29.94	12.06	6.80	6.21
17	30.47	70.00	0.14	0.78	0.22	42.10	29.47	12.63	10.63	9.55
18	30.77	66.21	0.13	0.78	0.22	42.40	28.07	14.32	9.99	9.03
19	29.57	68.28	0.15	0.77	0.22	40.10	27.38	12.71	8.53	7.75
20	29.72	75.35	0.14	0.77	0.22	40.10	30.21	9.882	9.54	8.49
21	29.19	72.64	0.12	0.77	0.22	40.10	29.13	10.97	6.22	5.64

Estimated weekly average ETo by Christiansen Pan Evaporation model

		Christiansen (1968) Pan Evaporation model				
Weeks	EVAPORATION (mm)	CT2	CW2	CH2	CS2	PET
1	4.500	1.028	1.079	0.993	0.906	3.389
2	4.471	1.028	1.076	0.986	0.906	3.337
3	6.300	1.030	0.998	1.021	0.906	4.522
4	6.400	1.034	0.982	1.012	0.905	4.493
5	5.986	1.034	1.021	0.996	0.906	4.305
6	6.057	1.034	1.042	0.981	0.906	4.376
7	9.186	1.034	0.946	0.926	0.906	5.694
8	5.086	1.035	1.083	1.045	0.905	4.073
9	6.914	1.037	1.040	0.984	0.905	5.015
10	5.286	1.037	1.091	1.063	0.906	4.345
11	5.071	1.035	1.082	1.064	0.906	4.132
12	4.900	1.038	1.095	1.068	0.906	4.068
13	5.700	1.041	1.085	1.042	0.906	4.584
14	5.043	1.041	1.084	1.067	0.906	4.149
15	4.700	1.040	1.085	1.067	0.905	3.871
16	4.314	1.039	1.086	1.068	0.905	3.550
17	5.129	1.040	1.080	1.060	0.906	4.174
18	4.600	1.040	1.085	1.038	0.906	3.688
19	4.383	1.037	1.071	1.050	0.905	3.494
20	5.200	1.037	1.075	1.090	0.905	4.321
21	3.583	1.036	1.093	1.075	0.905	2.979

Estimated weekly average ETo by FAO-24 Open Pan method

	FAO-24 Open Pan (1977) Method		
Weeks	EVAPORATION(mm)	Kp	PET
1	4.500	0.815	3.668
2	4.471	0.811	3.626
3	6.300	0.806	5.081
4	6.400	0.797	5.103
5	5.986	0.799	4.783
6	6.057	0.797	4.826
7	9.186	0.744	6.838
8	5.086	0.846	4.302
9	6.914	0.798	5.518
10	5.286	0.859	4.543
11	5.071	0.856	4.343
12	4.900	0.864	4.234
13	5.700	0.844	4.813
14	5.043	0.859	4.332
15	4.700	0.860	4.041
16	4.314	0.860	3.711
17	5.129	0.853	4.377
18	4.600	0.843	3.877
19	4.383	0.844	3.701
20	5.200	0.870	4.524
21	3.583	0.868	3.109

Estimated weekly average ETo by FAO-24 Penman-Monteith model

		FAO-24 Penman-Monteith (1991) model					
Weeks	U2	Tmean	Δ	ϒ	es-ea	Rn-G	ETo
1	0.882	26.807	0.207	0.067	1.972	9.069	3.794
2	0.906	26.771	0.207	0.067	1.815	9.333	3.797
3	1.741	27.336	0.213	0.067	1.678	10.375	4.656
4	1.947	28.529	0.226	0.067	1.825	7.520	4.164
5	1.470	28.486	0.226	0.067	2.033	10.176	4.707
6	1.241	28.457	0.225	0.067	2.197	9.923	4.548
7	2.523	28.586	0.227	0.067	2.430	10.372	6.226
8	0.847	28.907	0.230	0.067	1.797	8.262	3.412
9	1.264	29.486	0.237	0.067	2.230	8.191	4.070
10	0.770	29.393	0.236	0.067	1.517	9.711	3.644
11	0.853	28.950	0.231	0.067	1.517	9.837	3.734
12	0.735	30.000	0.243	0.067	1.558	10.257	3.809
13	0.829	30.857	0.254	0.067	1.934	10.344	4.090
14	0.835	30.836	0.254	0.067	1.583	9.795	3.756
15	0.823	30.800	0.253	0.067	1.522	8.019	3.178
16	0.817	30.171	0.245	0.067	1.442	6.663	2.724
17	0.876	30.471	0.249	0.067	1.588	10.498	3.997
18	0.823	30.779	0.253	0.067	1.854	9.855	3.897
19	0.959	29.571	0.238	0.067	1.565	8.392	3.408
20	0.917	29.721	0.240	0.067	1.214	9.400	3.483
21	0.759	29.193	0.234	0.067	1.285	6.089	2.438

Estimated weekly average ETo by Priestly-Taylor model

			Priestly-Taylor model						
Weeks	Tmean	Δ	ϒ	Rn-G	λ	albedo	1/λ	Δ/(Δ+ϒ)	ETo
1	26.807	0.207	0.067	9.069	2.438	0.230	0.410	0.755	0.646
2	26.771	0.207	0.067	9.333	2.438	0.230	0.410	0.755	0.665
3	27.336	0.213	0.067	10.375	2.436	0.230	0.410	0.760	0.744
4	28.529	0.226	0.067	7.520	2.434	0.230	0.411	0.771	0.548
5	28.486	0.226	0.067	10.176	2.434	0.230	0.411	0.771	0.741
6	28.457	0.225	0.067	9.923	2.434	0.230	0.411	0.770	0.722
7	28.586	0.227	0.067	10.372	2.434	0.230	0.411	0.771	0.756
8	28.907	0.230	0.067	8.262	2.433	0.230	0.411	0.774	0.605
9	29.486	0.237	0.067	8.191	2.431	0.230	0.411	0.779	0.604
10	29.393	0.236	0.067	9.711	2.432	0.230	0.411	0.778	0.715
11	28.950	0.231	0.067	9.837	2.433	0.230	0.411	0.775	0.720
12	30.000	0.243	0.067	10.257	2.430	0.230	0.411	0.784	0.761
13	30.857	0.254	0.067	10.344	2.428	0.230	0.412	0.791	0.775
14	30.836	0.254	0.067	9.795	2.428	0.230	0.412	0.791	0.734
15	30.800	0.253	0.067	8.019	2.428	0.230	0.412	0.790	0.600
16	30.171	0.245	0.067	6.663	2.430	0.230	0.412	0.785	0.495
17	30.471	0.249	0.067	10.498	2.429	0.230	0.412	0.788	0.783
18	30.779	0.253	0.067	9.855	2.428	0.230	0.412	0.790	0.738
19	29.571	0.238	0.067	8.392	2.431	0.230	0.411	0.780	0.619
20	29.721	0.240	0.067	9.400	2.431	0.230	0.411	0.781	0.695
21	29.193	0.234	0.067	6.089	2.432	0.230	0.411	0.777	0.447

Estimated weekly average ETo by Makkinik model

			Makkinik model			
Weeks	Δ	ϒ	Δ + ϒ	Rs	Δ/(Δ + ϒ)	ETo
1	0.207	0.067	0.274	16.793	0.755	3.037
2	0.207	0.067	0.274	16.878	0.755	3.052
3	0.213	0.067	0.280	18.374	0.760	3.357
4	0.226	0.067	0.293	12.162	0.771	2.214
5	0.226	0.067	0.293	18.717	0.771	3.471
6	0.225	0.067	0.292	18.409	0.770	3.410
7	0.227	0.067	0.294	20.044	0.771	3.730
8	0.230	0.067	0.298	13.403	0.774	2.464
9	0.237	0.067	0.304	14.082	0.779	2.612
10	0.236	0.067	0.303	16.053	0.778	2.991
11	0.231	0.067	0.298	16.286	0.775	3.021
12	0.243	0.067	0.310	16.670	0.784	3.133
13	0.254	0.067	0.321	17.464	0.791	3.318
14	0.254	0.067	0.321	15.758	0.791	2.982
15	0.253	0.067	0.320	12.378	0.790	2.316
16	0.245	0.067	0.313	9.893	0.785	1.814
17	0.249	0.067	0.316	17.405	0.788	3.293
18	0.253	0.067	0.320	16.348	0.790	3.096
19	0.238	0.067	0.305	13.422	0.780	2.487
20	0.240	0.067	0.307	14.734	0.781	2.746
21	0.234	0.067	0.301	9.038	0.777	1.628

Abstract

ASSESSMENT OF EVAPOTRANSPIRATION MODELS FOR THE HUMID TROPICAL REGION OF TAVANUR

by

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ABSTRACT OF THE THESIS

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ABSTRACT

World is facing an acute water crisis due to the increase of world population, droughts, land degradation, and food demand. This increases the concern over conservation of water. One of the most important factors related to water management is crop evapotranspiration. In the present research work, the reference crop evapotranspiration (ETo) is estimated by using ten empirical models which are widely used in Indian conditions namely, Thornthwaite (1948), Hargreaves *et al.,* (1985), Turc (1961), Christiansen (1968) Pan Evaporation, FAO-24 Blaney-Criddle (1977), FAO-24 Modified Penman (1977), FAO-24 Open Pan (1977), Preistly-Taylor, Makkinik and FAO-56 Penman-Monteith (1991).

The accuracy of these reference evapotranspiration models were evaluated by comparing it with FAO-56 Penman-Monteith using six years monthly average meteorological data for the period January, 2011-December, 2016. Then the models were validated with lysimetric data. The weekly water balance studies were conducted in lysimeter to find the actual reference evapotranspiration. The model values were estimated using weekly meteorological data for the period January-May 2017 during which the lysimeter study was conducted. Then best fit relations were developed between the estimated values (ETo_{EST}) and observed values (ETo_{LYM}) for the humid tropical region.

Among the different empirical models, Turc model showed the highest ETo value (14.92 mm/day) while the Priestly-Taylor showed the lowest (0.62 mm/day). Thornthwaite, Blaney-Criddle and Modified Penman model gave closer values to each other 7.32, 8.9 and 7.09 mm/day respectively. While Christiansen, Penman-Monteith, Open Pan and Makkinik models gave values like 3.08, 3.23, 3.24 and 2.22 mm/day respectively which were slightly lower compared to the values obtained from the Hargreaves model (4.7 mm/day). The statistical comparison was made by considering FAO-56 PMM as the standard model using six year average monthly meteorological data. The Modified Penman model gave

the best performance with R^2 of 0.96 with RMSE 3.95 and RelRMSE 1.22 followed by Hargreaves model. The Open Pan method ranked the third one. The models, Christiansen, Priestly-Taylor and Makkinik were underestimated while Thornthwaite, Turc and Blaney-Criddle models overestimated.

For validation of the models, weekly ETo estimated from models were compared with ETo observed from lysimeter for the period January-May, 2017. The Hargreaves model showed the best performance with R^2 0.83 and RMSE 0.82. The Turc model was highly over estimated while Blaney-Criddle and Modified Penman models were only slightly overestimated. The Penman-Monteith and Makkinik models were slightly underestimated while Priestly-Taylor highly underestimated with R^2 0.56 and the RMSE 4.29. Hence it is concluded that Hargreaves (HAM), Open Pan (OPM) and Christiansen (CHM) models were found to be in close agreement with lysimetric data and hence these models were suggested for use in this humid tropical region. Therefore relationships were developed between these empirical model output and the lysimetric data (LYM). The relationships developed were as follows: ETo_{LYM} = 0.79HAM + 0.45, ETo_{LYM} = 0.79CHM + 1.60 and ETo_{LYM} = 0.63OPM + 2.04.

Finally the results of this research can be recommended for humid tropical region for irrigation scheduling, selection of cropping pattern, optimum allocation of water resources and efficient use of water.