Modeling of Moisture Movement and Irrigation Scheduling under Drip Irrigation in High Density Apple (*Malus domestica*) Orchard

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(2014-AE-18-M)

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Thesis

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“Parents”

Someone who embrace us in arms as we enter this world
Someone who always persuade us with their loving words of praise
Someone who constantly stand by us
Someone who listens tolerantly to all our qualms and stresses
Someone who’s eyes shine with pride and contentment at our every little Achievement

DEDICATE MY THESIS

To the most beautiful creatures of Allah

“MY BELOVED PARENTS

(Mrs. & Mr. Aftab Ahmed Shah)”

Sher-e-Kashmir
University of Agricultural Sciences and Technology of Kashmir
Faculty of Horticulture, Division of Agricultural Engineering

Certificate – I

This is to certify that the thesis entitled, **“Modeling of Moisture Movement and Irrigation Scheduling under Drip Irrigation in High Density Apple (*Malus domestica*) Orchard”** submitted in partial fulfillment of the requirements for the award of the degree of **Master of Technology in Agricultural Engineering (Soil and Water Engineering)**, to the **Faculty of Horticulture, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir** is a record of bonafide research work carried out by **Er. Mehlath Shah (Regd. No. 2014-AE-18-M)** under my supervision and guidance. No part of the thesis has been submitted for any other degree or diploma.

It is further certified that information received during the course of investigation has duly been acknowledged.

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We, the members of the Advisory Committee of **Er. Mehlath Shah (Regd. No. 2014-AE-18-M),** a candidate for the degree of **Master of Technology in Agricultural Engineering (Soil and Water Engineering)** have gone through the manuscript of the thesis entitled, **"Modeling of Moisture Movement and Irrigation Scheduling under Drip Irrigation in High Density Apple (*Malus domestica*) Orchard"** and recommend that it may be submitted by the student in partial fulfillment of the requirements for the award of the degree.

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Certificate – III

This is to certify that the thesis entitled, **“Modeling of Moisture Movement and Irrigation Scheduling under Drip Irrigation in High Density Apple (*Malus domestica*) Orchard”** submitted by **Er. Mehlath Shah (Regd. No. 2014-AE-18-M)** to the **Faculty of Horticulture, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir** in partial fulfillment of the requirements for the award of the degree of **Master of Technology in Agricultural Engineering (Soil and Water Engineering)** was examined and approved by the Advisory Committee and External Examiner on …………….. .

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ABSTRACT

In order to determine the moisture depletion pattern and water requirement for apple tree, field experiment was conducted in high density Apple (Var. Gala Red Lum) orchard at experimental farm, Shalimar, SKUAST-Kashmir during April-July, 2016. Soil moisture sensors were used to measure the daily soil water potential which was later converted to moisture content. It was found that maximum depletion of soil moisture took place in the top most layer of crop root zone *i.e.* 15 cm. Six different reference evapotranspiration models were used to identify the most suitable reference evapotranspiration model for the local agro-climatic conditions. The crop coefficient values recommended by FAO were modified for local agro-climatic conditions and their values for initial, mid and end stages of crop were found to be 0.65, 1.00, and 0.75 respectively. It was found that Modified Penman equation best matched with Penman-Monteith equation which was taken as standard. The statistical errors of crop evapotranspiration were found as R^2: 0.98, RMSE: 0.07 mm/day and MBE: 0.16 mm/day which shows good agreement. The analysis indicated that the Blaney-Criddle equation had the second best performance (R^2 = 0.97, RMSE = 0.14 mm/day and MBE = 0.22

mm/day) among the other methods. The crop water requirement was also determined using CROPWAT model and it showed that the model simulated the crop evapotranspiration with reasonable accuracy, RMSE: 0.18 mm/day, R^2: 0.99 and MBE: 0.15 mm/day and can be used for estimating crop water requirement which help in irrigation scheduling. Irrigation scheduling chart was designed which revealed that the maximum crop water requirement was in the month of June (315.2 liters). Crop evapotranspiration was later partitioned into evaporation and transpiration which revealed that transpiration rates were minimum in initial months and increased towards end stage due to increase in canopy cover.

Key words: Crop evapotranspiration, Crop coefficient, CROPWAT, Evapotranspiration, Irrigation Scheduling, Partitioning of evapotranspiration, Soil moisture depletion, Soil water potential, Transpiration.

Signature of Student

Dated____________

Signature of Major Advisor

Dated _________________

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Mehlath Shah

Place: Shalimar, Srinagar
DATE: _______________

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Notations used in reference ET models:

ET_o = Reference evapotranspiration (mm/day)
R_n = Net radiation at the crop surface (MJ/m^2 per day)
G = Soil heat flux density (MJ/m^2 per day)
T = Mean daily air temperature (°C)
u_2 = Wind speed at 2 m height (m/sec)
e_s = Saturation vapour pressure (kPa)
e_a = Actual vapour pressure (kPa)
$e_s - e_a$ = Saturation vapour pressure deficit (kPa)
Δ = Slope of saturation vapour pressure curve at temperature T (kPa/°C)
γ = Psychrometric constant (kPa/°C)
T_{mean} = Mean daily temperature (°C)
T_{max} = Mean daily maximum temperature (°C)
T_{min} = Mean daily minimum temperature (°C)
$e°(T_{max})$ = Saturation vapour pressure at the maximum air temperature (kPa)
$e°(T_{min})$ = Saturation vapour pressure at the minimum air temperature (kPa)
T = Mean air temperature (°C)
exp[..] = 2.7183 (base of natural logarithm) raised to the power [..]
$e°\ (T_{min})$= Saturation vapour pressure at daily minimum temperature (kPa)
$e°\ (T_{max})$= Saturation vapour pressure at daily maximum temperature (kPa)
RH = average relative humidity, %
RH_{max} = Maximum relative humidity (%)
RH_{min} = Minimum relative humidity (%)
R_n = Net radiation (MJ/m^2 per day)
R_{ns} = Net incoming shortwave radiation (MJ/m^2 per day)
R_{nl} = Net outgoing longwave radiation (MJ/m^2 per day)
R_s = Solar or shortwave radiation (MJ/m^2 per day)
n = Actual sunshine hours (hour)
N = Maximum possible duration of sunshine hours or daylight hours (hour)
n/N = Relative sunshine duration
R_a = Extraterrestrial radiation (MJ/m^2 per day)
R_{so} = Clear sky solar radiation (MJ/m^2 per day)
z = Station elevation above sea level (m)
σ = Stefan-Boltmann constant (4.903×10^{-9} MJ/K^4 per m^2 per day)
T_{max}, K = Maximum absolute temperature during the 24-hour period (K)
T_{min}, K = Minimum absolute temperature during the 24-hour period (K)
K = °C + 273.16
R_s/R_{so} = Relative shortwave radiation (limited ≤ 1)
S_0 = Average daily astronomic possible sunshine duration of time interval, h

S_{year} = Yearly sum of astronomic possible sunshine duration, h (here, 4378.5 h)

TD = The difference between maximum and minimum daily temperature in ^{o}C

α = Priestley-Taylor parameter (α= 1.26)

L = Special heat of evaporation = 2.45 $MJ/m^2/hr/mm$

Chapter - 1

INTRODUCTION

Water is most abundant and, at the same time, the most limiting resource, that plants need to grow and function for the best efficiency or productivity in terms of biomass. It is most precious gift of nature and plays an important role for plant growth (Clothier, 1990; Kumar *et al.*, 2012). Water is important to the physiology of plants due to its crucial role in all physiological processes and due to the large quantities that are required. Although, India is not a water poor country, due to growing human population, severe neglect and over-exploitation of this resource, water is becoming a scarce commodity. India is more vulnerable because of the growing population and in-disciplined lifestyle. This calls for immediate attention by the stakeholders to make sustainable use of the available water resources. 70% of the earth surface is covered with water, which amounts to 1400 million cubic kilometers. However, 97.5% of this water being sea water, it is salty. Fresh water availability is only 35 million cubic kilometers and only 40% of this can be used by human beings. Out of the total fresh water, 68.7% is frozen in ice caps, 30% is stored underground and only 0.3% water is available on the surface of the earth. Out of the surface water, 87% is stored in lakes, 11% in swamp and 2% in rivers (Panchal and Shah, 2013).

An understanding of crop root distributions and water uptake patterns has become important. Modern and environmentally friendly practices involving high frequency irrigation and fertilization are being developed (Clothier and Green, 1994). Information about the structure and function of crop root systems is essential for matching irrigation system design and management with crop requirement. Additionally, irrigation scheduling schemes that rely on monitoring soil water status must consider the influences of root water extraction patterns on soil water dynamics (Coelho, 1996, 1999). It has been estimated that over 70% of the irrigation water is wasted by depriving irrigation to other dry areas. Farmers in India have been traditionally practicing flow irrigation which is resulting in huge wastage of water, while causing severe soil erosion, leaching of fertilizers, increasing the infestation of pests, diseases and weeds and suppressing the crop yields. Nevertheless, farmers as well as policy makers are not serious about the discontinuation of this unscientific practice. Immediate attention is needed to shift from flood irrigation to micro irrigation and to increase the water use efficiency, which can ease the water scarcity to a great extent (Rosegrant *et al.,* 2002).

Sound irrigation management requires information about crop water requirement and root water uptake pattern of different crops. Water is useful in the process of plant growth. Deficiency of water in the root zone of soil results in reduced plant growth and affects the crop yield, thus objective of irrigation is to maintain adequate moisture content in the root zone, such that crop yield is not affected adversely (Green *et al.*, 2006; Kumar *et al.*, 2013; Kumar *et al.*, 2014). Agriculture sector is the largest user (almost 80%) of water resources in India (Kumar *et al.*, 2012). Innovative water conservation practices/techniques need to be adopted for conservation and uniform distribution of water in the field leading to higher productivity and better quality of produce (Schwartzman and Zur, 1986; Bhatnagar and Srivastava, 2003).

Drip irrigation system is one of the most economical and efficient methods of irrigating various crops. The adoption of drip irrigation has significant positive impact on the cost of cultivation and cost of production (Kumar and Palanisami, 2010). In drip irrigation, uniform distribution of water may ensure good crop yield and quality of produce and lead to reduction in soil degradation (Kumar *et al., 2013).* Application of irrigation water through this method helps in achieving saving in irrigation water, increased water-use efficiency, decreased tillage requirement, higher quality products, increased crop yields and higher fertilizer-use efficiency (Qureshi *et al.*, 2001; Sivanappan, 2002).

Water uptake by plant roots greatly influences transport of water and chemicals in soil-plant systems. The transport process has critical effects on crop yields, as well as the quality and quantity of infiltration recharge to groundwater systems under croplands (Schmidhalter *et al.*, 1994; Wallach, 1990). Enormous effort has been made to simulate soil water movement with water uptake by roots, using microscopic and macroscopic approaches. The microscopic approach (Gardner, 1960) simulates water flow into individual roots. This method needs detailed information on the geometry of root systems, which is practically impossible to acquire. Most models simulating soil water movement with plant water uptake adopt a macroscopic approach, in which water extraction by plant roots is treated as a sink term distributed in the root zone. The sink term is incorporated into Richards' equation that describes water movement in variably saturated soils (Richards, 1952; Jury *et al.*, 1991).

The unsaturated zone of the soil profile embodies many complex processes such as infiltration, evaporation, soil moisture storage, root water uptake and others. Hydrological perspective, water uptake by root systems and their spatial distribution exert a large degree of control on the water fluxes to the atmosphere and the groundwater (Canadell *et al.*, 1996). For understanding of the magnitude of these fluxes, accurate estimates of the temporal and spatial root water uptake patterns are needed. Spatial and temporal characterization of soil water is important for optimization of water use. Plant root water uptake rate depends upon transpiration rate, root distribution, soil hydraulic properties and water availability (Feddes, 2001).

During the past few decades, many hydrologic models have been developed to simulate water flow in the subsurface, utilizing different techniques to couple the atmospheric evaporative demand with the resulting extractions of evapotranspiration from the canopy and subsurface (Kumar *et al.,* 2012). A commonly used approach to determine the water lost to the atmosphere is to specify the evapotranspiration within the model and use soil moisture, water-table depth, and/or canopy characteristics to estimate the actual evapotranspiration.

Accurate evapotranspiration estimates are needed to determine the water requirement of crops for irrigation scheduling. Field measurement of evapotranspiration is rarely available and actual crop evapotranspiration (ET_c) is usually determined from reference crop evapotranspiration (ET_o) using the crop factor method, which consists of multiplying ET_o with crop specific coefficients (K_c) to obtain ET_c. Over the years, many methods have been developed, revised, and recommended for estimation of ET_o for different types of weather parameters and climatic conditions (Allen *et al.*, 1998). The Food and Agriculture

Organization (FAO) recommends the use the FAO-56 Penman Monteith method for estimating reference evapotranspiration (ET_o) (Allen *et al.,* 1998; Allen *et al.*, 2006). This method is the most widely used in the world and has been proven to accurately estimate ET in different climates (Allen *et al.*, 1998; De Bruin and Stricker, 2000; Hussein and Al-Ghobari, 2000; Smith, 2000; Walter *et al.*, 2000; Kashyap and Panda, 2001).

Apple (*Malus domestica*), is a typical temperate tree fruit, it gives the highest yield of good quality fruits in regions having long day hours with high light intensity and relatively warm days with cool nights and low relative humidity during the growing season and dormant, chilling, winter season below 7°C. The area under apple cultivation in India has increased by 24% from 1.95 lakh ha in 1991-92 to 2.42 lakh ha in 2001-02 although production increased by less than 1% (*i.e.* from 11 to 12 lakh tones) (Horticulture Department of Kashmir*)*. It is the principle fruit crop of Jammu & Kashmir with 1.61 lakh hectare under its cultivation with a production of 16.47 lakh tonnes (Horticulture Department of Kashmir, 2013). Apple industry is considered to be the backbone of the economy of Kashmir valley that provides employment to about 60% of the population. It is the main source of livelihood of many households of the region. Kashmir Valley, also known as fruit bowl of India, offers several variety of apple. Some of the prominent varieties are Ambri, Delicious, American Teral, Maharaji, Piazratbali, Ke-sari, and Royal Misri. As per the data by Kashmir Horticulture department, total apple production in 2013-14 has been recorded at 16, 33, 349.0 metric tons.

Apple (*Malus domestica*) trees are particularly sensitive to low soil moisture supply, water stress during growing season reduces number and size of fruits. Irrigation required for maintaining adequate soil moisture usually results in increased yield, decreased incidence of skin cracking. Severe water deficiency adversely affects flower formation. It is necessary to irrigate the plant during the period June/July to September (Zeliha *et al.*, 2012). Apple tree water use has a good correlation to leaf area (Angelocci and Valancogen, 1993). Trees with many shaded leaves will have lower water use efficiency because the interior shaded leaves still transpire, although their photosynthetic rate is low due to reduced light. Marangoni *et al.* (1992) showed that the stomatal conductance of shaded leaves may be up to 60% of that of exposed leaves. In apple trees in the field, it appears that stomata are well coupled with photosynthesis; usually not opening more than needed to maintain a constant internal CO_2 (Lakso, 1994). This means factors affecting photosynthesis will also affect water loss.

The scope of the present study stretches out in the direction of the optimal utilization of water resources through optimum irrigation scheduling i.e., determination of accurate crop water requirement.

The present study is aimed to evaluate different reference evapotranspiration models. In Kashmir, apple (*Malus domestica*) is one of the most widely cultivated temperate climate fruit-trees. With increasing interest in commercial production of apples, physiological responses to factors limiting growth and yield need to be studied. The moisture depletion is important aspect and the corresponding crop water requirement is determined. Keeping the above facts in view, the present study was undertaken with the following objectives:

- To study water movement at different depth using different capacity emitter.
- Comparative study of different reference evapotranspiration models for computation of daily crop evapo-transpiration for agro-climatic conditions of study area.
- To study partition of crop evapotranspiration into evaporation and transpiration.

Organization of the dissertation

The dissertation has been divided into five chapters.

Chapter 1 describes the general introduction; background; problem definition and objectives.

Chapter 2 gives the literature review of modeling root moisture uptake, crop evapotranspiration and partition of evapotranspiration into evaporation and transpiration.

Chapter 3 highlights the methodology adopted for the study to achieve the different objectives and gives detail of the field experiment.

Chapter 4 discusses the results obtained in the field experiment of high density apple.

Chapter 5 contains summary and conclusions from this research. It also highlights recommendations for follow-up research.

Chapter - 2

REVIEW OF LITERATURE

2.1 General

Water scarcity is one of the important concerns nowadays. It is important to find ways for optimal utilization of water. Water being the critical issue of the 21th century, has been labeled as 'blue gold' (Green *et al.*, 2006). Irrigation is responsible for 80% of the world-wide spending of 'blue gold' (Huffaker and Hamilton, 2007). Optimal utilization of irrigation water can be achieved only by adopting suitable irrigation practices. Drip irrigation is one of those irrigation practices which have helped significantly to conserve water by providing only that volume of water to plant as needed by it. The amount of irrigation optimization is crop-dependent and generally governed by amount of water extracted by plant roots (Ahmedi *et al.*, 2011).

Depending on the characteristic of model being used, optimization methods are chosen. Widespread literature review on the subject gives an idea about different factors affecting root water uptake and moisture depletion in root zone which will be discussed extensively. The flow of water in soil is driven by water potential gradient. The chapter will also discuss different studies carried out to estimate of crop evapotranspiration using various models. Different literature has also been cited to get a clear idea about irrigation scheduling patterns.

2.2 Moisture depletion/uptake studies

Root water uptake is an important process, determining the transport of water between soil and atmosphere and influencing plant productivity and crop yield. A wealth of studies using both models and observations deal therefore with understanding root water uptake, that is, to learn where plants take up water (Doussan *et al.*, 2006; Javaux *et al.*, 2008; Schneider *et al.*, 2010).

Nimah and Hanks (1973a) compared early numerical models and divided root models into two types: microscopic studies, such as the analyses of Philip (1957) and Gardner (1960), which consider radial flow of water to a single root; macroscopic models, which consider removal of water by the root zone as a whole, without considering explicitly the effect of individual roots. Nimah and Hanks (1973a) developed a numerical model to predict water content profiles, evapotranspiration, water flow from or to the water table, root extraction, and root-water potential under transient field conditions. They modified the flow equation by adding an extraction term, following modifications made earlier by Whisler *et al.* (1968) and Molz and Remson (1970). The scheme predicted changes in root extraction, evapotranspiration, and drainage due to the variations in pressure head-water content relations and root depth. The model was tested over 2 years with alfalfa (*Medicago sativa* L.). Predicted and computed water content-depth profiles showed best agreement 48 h after any water addition. The poorest agreement for all crops tested was right after irrigation (Nimah and Hanks, 1973b). Cardon and Letey (1992) reviewed the literature on mathematical models that simulate water and solute movement through the soil, and coupled with simultaneous water uptake by plant roots.

Wu *et al.* (1999) evaluated a root water extraction model to incorporate the effect of soil water deficit and plant root distributions on plant transpiration of annual crops. For several annual crops, normalized root density distribution functions were established to characterize the relative distributions of root density at different growth stages. The ratio of actual to potential cumulative transpiration was used to determine plant leaf area index under water stress from measurements of plant leaf area index at optimal soil water condition. The root water uptake model was implemented in a numerical model. The numerical model was applied to simulate soil water movement with root water uptake and simulation results were compared with field experimental data. The simulated soil matric potential, soil water content and cumulative evapotranspiration had reasonable agreement with the measured data.

Gui-Rui Yu *et al.* (2007) measured the effect of vertical root distribution on root water uptake and the resulting changes of profile soil water. The observations indicate that depth of the most densely rooted soil layer was more important than the maximum rooting depth for increasing the ability of plants to cope with the shortage of water occurrence of most densely rooted layer at or below 30 cm soil depth. In the soil layers colonized most densely by roots day time effect soil water saturation always dropped dramatically due to the high efficient local water depletion.

Ojha *et al.* (2009) carried out a study to observe the performance of different root-water extraction models using available data as well as data generated under controlled conditions. Data pertaining to moisture uptake in respect to two crops: wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) along with soil-water characteristics were monitored at the Indian Institute of Technology Roorkee, agricultural farm. For this purpose, a numerical model was also formulated by incorporating different moisture extraction terms as sink terms in the Richards equation. A nonlinear root-water uptake model selected as the base model was evaluated for its moisture uptake efficiency. The study established the merits of the base model over other extraction terms considered, particularly constant and linear extraction terms in predicting the soil moisture depletion in the root zone. The study also stresses the nonlinearity parameter of the base model, which is capable of defining crop specific nonlinearity in the plant moisture uptake.

Quijano *et al.* (2012) reviewed the modelling approach to understand the interaction between below ground and above ground ecohydrologic dynamics as facilitated by hydraulic redistribution. The results indicate that deep layer uptake of water by the tall vegetation and its release in the shallow layers enhances the productivity of the understory vegetation during the summer. The presence of small vegetation reduces direct soil-evaporative loss making more moisture available for vegetation which enhances the total ecosystem productivity.

Guohua *et al.* (2013) carried out a field experiment to research the effect of soil temperature distribution on root water uptake in soil water simulation. Soil temperature distribution patterns under border irrigation and surface drip irrigation were researched. The root water uptake model was modified based on the effect of soil temperature on root water uptake. Results showed soil temperature profile distribution was greatly influenced by irrigation method. The modification of the root water uptake model as affected by temperature profile distribution, the value of the root mean square error between the simulated and observed soil water decreased from approximately 0.04 to 0.02 in the top layer under border irrigation, but showed no obvious difference under surface drip irrigation. When soil temperature differed greatly in the top layer from the deep layer, the root water uptake model considering soil temperature could improve the precision of soil water simulation. The results indicated that the modified root water uptake model could be used to simulate soil water dynamics.

Kumar *et al.* (2013) developed and validated a root uptake model for a uniform crop root zone in a semiarid agro-climate. They tested for its efficacy in predicting moisture depletion in a multilayer crop root zone in a sub-temperate, sub-humid agro-climate. Evaluation of moisture uptake prediction efficiency of model in uniform, vis-à-vis multilayer crop root zone, done on the basis of secondary experimental data of three crops, indicated significant improvement in predicted moisture uptake when a multilayered crop root zone was considered. To validate the enhanced prediction efficiency of the model, in the case of a multilayer crop root zone, field experiments on two Indian crops, i.e., Indian mustard (*Brassica Juncea*) and Wheat (*Triticum-aestivum*), were conducted in the sub-temperate, sub-humid agro-climate of Solan, Himachal Pradesh, India. Model performance indicators exhibited good agreement between model-predicted soil-moisture parameters and experimental results.

Shankar *et al.* (2013) conducted a study to extend the Ojha-Rai model to other crops without requiring detailed and time-consuming experiments. Two important dimensionless numbers (specific transpiration, T_s, and specific root water uptake, T) were identified based on readily available plant parameters. Data for determining the relationship between these numbers were obtained by minimizing the deviations between the field-observed moisture depletions of 28 crops reported in literature and the numerically simulated soil moisture depletions. Field experiments on three Indian crops-maize, Indian mustard, and wheat-were used for validation of the proposed empirical relationship. This relationship showed promise for use in the Ojha-Rai (1996) model for root water uptake for a variety of crops.

Hildebrandt *et al.* (2016) evaluated and thermodynamics formulation of root water uptake. It was described that how energetics involved in root water uptake can be quantified. The illustration was done using as simple, four box model of soil root system to represent heterogeneity and parameterization in which root water uptake is driven by xylem potential of a plant with fixed flux boundary conditions.

2.3 Crop evapotranspiration

For a given set of conditions, evapotranspiration depends on availability of water. The crop evapotranspiration under standard conditions, denoted as ET_c, is the evapotranspiration from disease-free, well-fertilized crops, grown in large fields under optimum soil water conditions and achieving full production under the given climatic conditions. The amount of water required to reimburse the evapotranspiration loss from the cropped field is defined as crop water requirement. Under the same climatic conditions ET_o differs from ET_c because the former depends on climatic data and the later depends on ETo and Kc, which changes for a given crop from sowing to harvesting period.

2.3.1 Measurement of evapotranspiration

Estimation of evapotranspiration is not easy at all. The measurements of evapotranspiration for given vegetation type can be carried out in two ways: either by using lysimeters or by the use of field plots. To determine evapotranspiration in lysimeters accurate measurement of various physical parameters or the soil water balance are required. The methods are often expensive and challenging in terms of accuracy of measurement and can only be fully exploited by well-trained research personnel. These methods are unsuitable for routine measurements but remain important for the evaluation of ET estimates obtained by more indirect methods. Apart from these methods, meteorological data can also be used to determine the evapotranspiration and is discussed below:

2.3.1.1 ET computed from meteorological data

The meteorological factors determining evapotranspiration are weather parameters which, represents energy for vaporization and remove water vapour from the evaporating surface. There are number of climatic parameters that affect the rate of evaporation. Owing to the difficulty of obtaining accurate field measurements, ET is commonly computed from weather data. A large number of empirical or semi-empirical equations have been developed for assessing crop or reference crop evapotranspiration from meteorological data.

Various researchers have evaluated the performance of the different calculation methods for different locations. As a result of an expert consultation held in May 1990, the FAO Penman-Monteith method is now recommended as the standard method for the definition and computation of the reference evapotranspiration, ET_o. The ET from crop surfaces under standard conditions is determined by crop coefficients (K_c) that relate ET_c to ET_o.

2.3.2 Crop coefficient approach

In the crop coefficient approach the crop evapotranspiration, ET_c is calculated by multiplying the reference crop evapotranspiration, ET_o, by a crop coefficient, K_c (Allen *et al.*, 1998).

$$ET_C = K_c \times ET_o$$

The K_c in the above equation predicts ET_c under standard conditions. This represents the upper envelope of crop evapotranspiration and represents conditions where no limitations are placed on crop growth or evapotranspiration due to water shortage, crop density, or disease, weed, insect or salinity pressures.

The ET_c predicted by K_c is adjusted if necessary to non-standard conditions, $ET_{c\ adj}$, where any environmental condition or characteristic is known to have an impact on or to limit ET_c. Most of the effects of the various weather conditions are incorporated into the ET_o estimate. Therefore, as ET_o represents an index of climatic demand, while K_c varies predominately with the specific crop characteristics and only to a limited extent with climate. This enables the transfer of standard values for K_c between locations and between climates. This has been a primary reason for the global acceptance and usefulness of the crop coefficient approach and the K_c factors developed in past studies (Allen *et al.*, 1998).

2.4 Evapotranspiration (ET)

ET rate depends on weather conditions, water availability, vegetation characteristics, management and environmental constraints. The main weather variables affecting ET are temperature, solar radiation, wind speed and vapour pressure. Accurate estimation of evapotranspiration (ET) in the field is difficult, due to its dependence on variety of parameters, which are difficult to obtain. Moisture uptake from the root zone of a cropped area represents ET very well.

2.4.1 Reference evapotranspiration (ET_o)

Reference evapotranspiration is the evaporation from a reference surface of the earth and it depends on weather conditions. The reference surface can be an open water surface (open pan) or it can be related to weather variables (temperature, radiation, sunshine hours, wind speed, air humidity etc.) and is denoted as $ET_{o.}$ A large number of methods have been developed over the last 50 years by numerous scientists and specialists throughout the world to estimate the evapotranspiration from different climatic variables. Several models of varying complexity have been developed for its estimation of ET_o as its quatity varies with meteorological variables (Doorenbos and Pruitt, 1977; Burnman *et al.*, 1980; Sharma, 1985).

A specific input data is used as input in these models to estimate the maximum evapotranspiration rate from a cropped surface under conditions of unlimited moisture availability, hence also referred to potential evapotranspiration (PET). Doorenbos and Kassam (1979) have evaluated ET_o of crop by the calculations of PET of the reference crop. The reference evapotranspiration estimation methods vary from empirical relationships to complex methods such as the Penman combination method (Penman, 1948) based on physical processes. These methods can be grouped into combination theory types (Penman Monteith, FAO 24 corrected Penman, Kimberley-Penman), temperature-based (Thornwaite, SCS Blaney-Criddle, FAO-24 Blaney Criddle, Hargreaves) radiation-based (Turc, Jensen-Haise, Priestly-Taylor and FAO-24 radiation) mass-transfer, (e) water budget, respectively (Xu and Singh, 2002).

The performance of different reference evapotranspiration estimation methods varies with climatic conditions and availability of data, and the data requirements vary from method to method. The ET_o estimations depend upon the quality of the meteorological data, therefore, it is very difficult to decide upon an appropriate ET_o estimation method among different available methods for a particular station given the available data. Over the years, many methods have been developed, revised, and recommended for estimation of ET_o for different types of weather data and climatic conditions. Numerous studies have revealed a widely varying performance of the different equations and acknowledged that Penman Monteith and all other methods require local calibration (George *et al.*, 2002).

Jensen and Allen (2000) gave a good overview of the evolution of practical ET_o estimation methods including theoretical and empirical equations. The theoretical methods in common use include the original Penman method (Penman, 1948) and its variations such as the FAO-24 Penman (Doorenbos and Pruitt, 1977) and the Kimberly Penman (Wright, 1982). The Penman methods combine an energy balance with expressions that describe heat fluxes to derive a method to estimate vapor flux from a vegetated surface.

Many researchers evaluated the performance of the various methods for different locations (Subramaniam and Rao, 1985; Allen *et al.*, 1989; Mall and Gupta, 2002; Nandagiri and Kovoor, 2004; Yoder *et al.*, 2005) and it was found that the proposed methods did not behave the same way in different locations around the world. Differences among methods often reach hundreds of millimeters per growing season (Federer *et al.*, 1996), and accuracy of a given method depends heavily on the climatic conditions of the study site.

The Penman-Monteith equation has been extensively evaluated and compared with measured lysimeter ET under different climatic conditions. Jensen *et al.* (1990) analyzed the performance of 20 different methods against lysimeter measured ET_o for 11 stations located in different climatic zones around the world. The Penman-Monteith method ranked as the best method for all climatic conditions. Allen *et al.* (1994) also showed that ET_o computed using the Penman-

Monteith equation yielded estimates close to measured ETo values. Following these studies, the FAO-56 Penman-Monteith method (Allen *et al.*, 1998) was adopted as the standard method for definition and computation of ET_o from a grass reference surface (cool season grass). Several other works have confirmed the validity of the Penman-Monteith equation (De Souza and Yoder, 1994; Chiew *et al.*, 1995; Howell *et al.*, 1997, 2000; Oliveria and Yoder, 2000; Itenfisu 2003).

Based on decades of statistics and knowledge gained, the FAO (United Nations Food and Agricultural Organization) suggested that Penman-Monteith method gives more consistent ET_o estimates and has shown to perform better than other methods when compared with Lysimeter data (Smith *et al.*, 1992). The meteorological data needed for Penman-Monteith equation are vast and are not always readily available. Nandagiri and Kovoor (2006) observed that the temperature based FAO-56 Hargreaves and FAO-24 Blaney-Criddle methods provide acceptable ET_o estimates for semi-arid climate of India. many studies carried out in India have identified the FAO-24 Penman combination method (Doorenbos and Pruitt, 1977) to be the most accurate one (Subramaniam and Rao, 1985; Mall and Gupta, 2002).

2.3.2 Crop coefficient (K_c)

The crop coefficient represents crop-specific water use and is required for accurate estimation of irrigation requirements. Doorenbos and Pruitt (1977) suggested that the K_c values need to be derived empirically for each crop based on lysimeter data and local climatic conditions. Crop coefficient values for a number of crops grown under different climatic conditions were suggested by Doorenbos and Pruitt (1977). These values are commonly used in places where local data are not available. However, they emphasized the strong need for local calibration of crop coefficients under given climatic conditions (Shankar, 2007; Shankar *et al.*, 2012). Wright (1982) also presented crop coefficients for a few crops. Since, localized K_c values are not always available in many parts of India and due to lack of locally determined crop water use data, the values of K_c as suggested by Food and Agricultural Organization of the United Nations (Allen *et al.*, 1998; Doorenbos and Kassam, 1979) are being widely used to estimate crop water requirement.

Crop coefficient is a noteworthy parameter for indirect assessment of crop evapo-transpiration, because it can provide various effects on water requirement of crop, for instance, biological distinctiveness of crops, level of crop yield, conditions of soil tillage etc. (Wright, 1982; Liu and Pereira, 1998; Ma and Jiao, 2006).

A list of growth stage specific crop coefficients is provided by Allen *et al.* (1998). These crop coefficients have been calibrated for a typical agro-climate, and hence a detailed route has been outlined to modify the crop coefficients for a particular study area. The crop coefficients provided by FAO, have been calibrated, under highly controlled conditions, hence their modified values can well represent the local crop water requirement (Allen *et al.*, 1998).

2.5 Estimation of evapotranspiration

A large number of studies have been conducted for many years, which have shown that there is a close relationship between the net radiant energy received by an irrigated crop of wet soil and the rate of evapotranspiration. Basically two approaches have been used for estimating the evapotranspiration *i.e.* aerodynamic approach and the energy balance approach.

Penman (1948) was the first scientist who combined the aerodynamic and the energy balance approach to develop equation for estimating evapotranspiration. Therefore, the equation for estimating evapotranspiration is called combination equation.

Blaney and Criddle (1962) developed a simplified empirical formula to compute evapotranspiration using correlation, which utlilsed mean monthly air temperature, amount of daylight and a crop factor showing seasonal variation. They noted that the efficient design and operation of water supply project depend on an awareness of the quantity of water that is lost through the process of evapotranspiration.

Monteith (1965) introduced modifications to the original Penman equation by incorporating a stomatal resistance term resulting in the well-known Penman-Monteith equation. For a number of years, the FAO-24 Penman method was used as a standard equation for estimating ET_o when all weather data (temperature, humidity, wind, and solar radiation) were available. However, recent studies have revealed the FAO-24 Penman method to lack proven global validity and interest has shifted to the Penman-Monteith equation (Jensen *et al.*, 1990; Allen *et al.*, 1994; Allen *et al.*, 1998; Walter *et al.*, 2001). The Penman-Monteith equation has been extensively evaluated and compared with measured lysimeter ET under different climatic conditions.

Jensen *et al.* (1990) analyzed the performance of 20 different methods against lysimeter measured ET_o for 11 stations located in different climatic zones around the world. The Penman-Monteith method ranked as the best method for all climatic conditions.

Amatya *et al.* (1995) evaluated the reliability of the Hargreaves and Samani, Makkink, Priestly-Taylor, Turc, and Thornwaite ET_o estimation methods by comparing the estimates with results from the Penman-Monteith method for conditions in eastern North Carolina, and found that Turc's method gave the best daily ET_o estimates.

Chin and Zhao (1995) developed a methodology to assess the relative merits of using evaporation-pan network and semi empirical function to estimate reference crop evapotranspiration (ET_c). Study concluded that pan-based estimates of reference crop evapotranspiration are preferable to semi empirical evapotranspiration function in south Florida.

Wu (1997) evaluated six ET models (Penman, Revised Penman, Jensen-Haise, Hargreaves, Kohler, and Taylor) to determine daily ET based on climatic data collected for three years by an automatic weather station at the CTAHR Waimanalo Research Station, Hawaii. The results showed that the correlation between daily readings was not as good as expected; however, excellent correlations were found for all ET models, except the Kohler model, when a 7-day or longer moving average of daily readings was used. The regression coefficient (R^2) was only about 0.64 for daily readings but increased to nearly 0.90 when the 7-day moving average was used. A 15-day moving average analysis increased the R^2 to 0.94. The correlation results indicated that for fields in Hawaii the simple Hargreaves model can be used to estimate ET as accurately as the complicated Penman model.

Samani (2000) developed a method to estimate solar radiation and subsequently reference crop evapotranspiration using minimum climatological data. A modification was made to the original equation that uses minimum and maximum temperature to estimate solar radiation reference crop evapotranspiration. The proposed modification allowed for the correction of the errors associated with indirect climatological parameters affecting the local temperature range.

Water Conservation Fact sheet (2001) introduced by British Columbia Ministry of Agriculture, Food and Fisheries provides information on selecting the crop coefficient that should be used. Crop coefficients for tree fruits and grapes have been segregated into months. The absence of a cover crop will lower the crop coefficients. The cover crop draws water from the soil storage reservoir and therefore increases water use. If there is no cover crop or grass between the tree or plant rows the crop coefficients will be about 10% lower in May, September and October and 20% lower in June, July and August.

Jacobs *et al.* (2004) carried out a study on wet prairie community in Central Florida, USA, and found that a calibrated Penman-Monteith model gave good results for PET, that the Priestley-Taylor and the Penman models overestimated PET, and that the uncalibrated, simpler Turc and Makkink methods performed nearly as well as the Penman-Monteith method.

Dragoni *et al.* (2004) estimated actual transpiration in an apple orchard in cool, humid climate (New York, USA), showed a significant overestimation (over 15%) of basal crop coefficients by the FAO 56 method compared to measurements (sap flow).

Sanij *et al.* (2004) conceded a study to (i) assess the estimates of ET_o obtained using six models against experimentally determined values in a semi-arid environment, Karaj in Iran; (ii) assess the usefulness of short-term weather data in the computation of ET_o estimates for forecasting purposes; and (iii) compare ET_o computed for a semi-arid environment with that of a humid temperate environment, Tottori in Japan. In-field lysimeter experiments were conducted in 1993 and 1994 in Karaj to compute daily ET_o from water-balance data and a similar experiment was conducted in 1972 and 1973 in Tottori. The ET_o estimates were obtained using the Penman (PE), Penman-Monteith (PM), Wright-Penman (WP), Blaney-Criddle (BC), Radiation balance (RB), and Hargreaves (HG) models. The results showed that: (i) PM model produced best ET_o estimates for semi-arid environment whereas the PE model produced the best ET_o estimates for humid temperate environment; and (ii) 8-year weather data and 2-year return period approach produced most reliable ETo estimates for forecasting purposes.

Chen *et al.* (2005) used the Penman-Monteith equation to estimate potential evapotranspiration occurring in Taiwan. In this study, various empirical equations from different theoretical models for calculating potential evapotranspiration were compared with the Penman-Monteith equation based on daily meteorological data from four meteorological stations in Taiwan. Monthly potential evapotranspiration was estimated using equations developed by Blaney-Criddle (1950), Hargreaves-Samani (1985), Kharrufa (1985), Makkink (1957), Priestley-Taylor (1972), and Hargreaves (1975). The results revealed that the Hargreaves-Samani equation and the Priestley-Taylor equation overestimated the 5-year (1998-2002) potential evapotranspiration, but the Blaney-Criddle equation, the Kharrufa equation, the Makkink equation and the Hargreaves equation underestimated the data.

Lu *et al.* (2005) studied six potential evapotranspiration methods for regional use in the southeastern United States. Three temperature based (Thornthwaite, Hamon, and Hargreaves-Samani) and three radiation based (Turc, Makkink, and Priestley-Taylor) PET methods were compared. The study found that PET values calculated from the six methods were highly correlated (Pearson correlation coefficient 0.85 to 1.00). Multivariate statistical tests, however, showed that PET values from different methods were significantly different from each other. Greater differences were found among the temperature based PET methods than radiation based PET methods. In general, the Priestley-Taylor, Turc, and Hamon methods performed better than the other PET methods. Based on the criteria of availability of input data and correlations with AET values, the Priestley-Taylor, Turc, and Hamon methods are recommended for regional applications in the southeastern United States.

Sumner and Jacobs (2005) studied a non-irrigated pasture site in Florida, USA, and found that both Penman-Monteith and a modified Priestley-Taylor methods required seasonal calibration parameters.

Yoder *et al.* (2005) compared different methods for estimating daily reference crop evapotranspiration at a site in the humid southeast United States. Pairwise comparisons were made between daily ET_o estimated from eight different ET_o equations and ET_o measured by lysimeter to provide information helpful in selecting an appropriate ET_o equation. Based on the standard error of the estimate (Syx), the relationship between the estimated and measured ET_o was the best using the FAO−56 Penman-Monteith equation (coefficient of determination (r^2) = 0.91, Syx = 0.31mm d^{-1}, and a coefficient of efficiency (E) = 0.87), followed by the Penman (1948) equation (r^2 = 0.91, Syx = 0.34 mm d^{-1}, and E = 0.88), and Turc's equation (r^2 = 0.90, Syx = 0.36 mm d^{-1}, and E = 0.88). The FAO-24 Penman and Priestly-Taylor methods overestimated ET_o, while the Makkink equation underestimated ET_o. The results for the Hargreaves−Samani equation showed low correlation with lysimeter ET_o data (r^2 = 0.51, Syx = 0.68 mm d^{-1}, and E = 0.20), while those for the Kimberly Penman were reasonable (r^2 = 0.87, Syx = 0.40 mm d^{-1}, and E = 0.87). These results supported the adoption of the FAO−56 Penman−Monteith equation for the climatological conditions occurring in the humid Southeast. However, Turc's equation could be an attractive alternative to the more complex Penman-Monteith method as it requires fewer input parameters.

Katerji and Rana (2006) computed K_c by comparison two methods of determining ET_c for six species cultivated in the Mediterranean region. The first one is direct and uses a model proposed by Katerji and Perrier (1983). The second one is indirect and adopted the approach proposed by Allen *et al.* (1989) in the bulletin FAO 56. In all the analyzed situations the direct method gave more accurate estimation of ET_c. The lower performance of the indirect model was analyzed in detail by Katerji and Rana (2006). They found that the accuracy of ET_c values indirectly determined depends on two factors. Firstly, it depends on the accuracy of the determination of ET_o; then, on the accuracy of the K_c values used. On the other hands, the direct evaluation of ET_c uses the one step approach instead of the two steps approach. This one step approach, since it is based on lower number of computation steps and on a lower number of error sources, can provide a more accurate estimation of ET_c. For this reason the recent scientific literature underlines the interest of developing methods permitting the direct calculation of ET_c (Testi *et al.*, 2004; Orgaz *et al.*, 2005).

Petillo and Castel (2007) calculated the actual evapotranspiration (ET_c) of mature 'Valencia' orange trees [*Citrus sinensis* (L.) Osb.], drip-irrigated and non-irrigated, using the water balance method, over three years. Annual ET_c was 24% higher from irrigated trees that from non-irrigated trees (767 and 620 mm year^{-1}, respectively). Maximum monthly average ET_c was 3.3 mm day^{-1} or 80 L tree^{-1} day^{-1} (trees were spaced at 6 × 4 m). Generally ET_c rate was reduced in January, the month of maximum atmospheric demand, compared with December, even under fully irrigated trees. The average annual value of the crop coefficient (K_c) for irrigated trees was 0.69. Monthly K_c values also showed a clear seasonal trend, with minimum values in summer (0.60), intermediate values in autumn and spring (0.77 and 0.80, respectively) and maximum values in winter (0.87).

Wang *et al.* (2007) calculated ET_o using Penman-Monteith, Blaney-Criddle, and Hargreaves methods in their study for determination of a reference model to estimate evapotranspiration in Burkina Faso. It was observed that for most of the time, the Penman-Monteith ET_o value is ranged between Blaney-Criddle and Hargreaves. Therefore, the model using the mean equation of (Blaney-Criddle + Hargreaves)/2 was proposed as it may produce the best estimation when assessed by the root mean square error. The present proposed model offered the most satisfactory alternatives to standard Penman-Monteith method for a reliable monthly ET_o estimation, and provided a valuable reference for the studied area.

Gong *et al.* (2007) carried out field experiments to investigate the effects of leaf area index and soil moisture content on evapotranspiration and its components within an apple orchard in northwest China for 2 years. Evapotranspiration in the non-rainfall period was estimated using two approaches: the soil water balance method based on tube-type time-domain reflection measurements, and sap flow plus micro-lysimeter methods. The two methods were in good agreement, with differences usually less than 10%. The components of evapotranspiration varied with canopy development. During spring and autumn, soil evaporation was dominating as result of low leaf area index. In summer, plant transpiration became significant, with an average transpiration to evapotranspiration ratio of 0·87. The crop coefficient K_c showed a strong linear dependence on leaf area index. The water stress coefficient K_s was around 1·0 when soil moisture was above 23% and started to decrease linearly after that. This study demonstrated that prediction of evapotranspiration in apple orchards can be made using the Food and Agriculture Organization's crop coefficient method from commonly available meteorological data in the area.

Weib and Menzel (2008) evaluated four different potential evapotranspiration equations according to Priestley Taylor, Kimberly Penman, Penman Monteith (FAO-56) and Hargreaves on a global basis to demonstrate their difference, and assessed their impact on the calculation of stream flows. The various equations of potential evapotranspiration showed great differences in magnitude. But due to the limited availability of validation data, it was difficult to assess which method is the physically most reasonable to be applied. According to this study, the radiation-based Priestley Taylor equation proved to be most suitable for a global application. For the calculation of stream flows, however, the processes involved in the derivation of actual evapotranspiration values from potential evapotranspiration values appear more relevant than the absolute value of the potential evapotranspiration itself.

Douglas *et al.* (2009) observed daily evapotranspiration (DET) at 18 sites having measured DET and ancillary climate data and then used these data to compare the performance of three common methods for estimating potential evapotranspiration (PET): the Turc method (Tc), the Priestley-Taylor method (PT) and the Penman-Monteith method (PM). The sites were distributed throughout the State of Florida and represent a variety of land cover types: open water (3), marshland (4), grassland/pasture (4), citrus (2) and forest (5). The performance of the three methods when applied to conditions close to PET (Bowen ratio ≤ 1) was used to judge relative merit. Under such PET conditions, annually aggregated Tc and PT methods performed comparably and outperformed the PM method, possibly due to the sensitivity of the PM method to the limited transferability of previously determined model parameters. At a daily scale, the PT performance appears to be superior to the other two methods for estimating PET for a variety of land covers in Florida.

Er-Raki *et al.* (2009) measured actual evapotranspiration using the FAO-56 single crop coefficient approaches over an irrigated citrus orchard under drip and flood irrigations in Marrakech (Morocco). The results shows that, by using crop coefficients suggested in the FAO-56 paper, the performance of both approaches was poor for two irrigation treatments. While, after the determination of the appropriate values of K_c based on ET_c measurements by eddy covariance, the performance of both approaches greatly improved. The obtained K_c values were lower than the FAO-56 values by about 20%. The lower K_c values obtained that K_c FAO reflect the practice of drip irrigation for one field and the low value of cover fraction for the other field. Additionally, the efficiency of the irrigation practices was investigated by comparing the measured *Kc* for two fields. The results showed that a considerable amount of water was lost by direct soil evaporation from the citrus orchard irrigated by flooding technique.

Benli *et al.* (2010) evaluated the performance of six commonly used reference evapotranspiration estimation methods with different data requirements (Penman-Monteith-FAO56, Priestley-Taylor, Radiation-FAO24, Hargreaves, Blaney-Criddle, Class A pan) using weighing lysimeter data from a semiarid highland environment. The RMS errors (RMSE) and index of agreement for the daily data and the monthly averages as well as the mean absolute error (MAE) for the seasonal totals were computed to compare these methods. The Penman-Montheith-FAO56 method with the full data set, with replacement of wind speed, and with replacement of relative humidity took the top three spots, with MAEs for the seasonal totals ranging between 40 and 70 mm. The Hargreaves method came in fourth (MAE 54 mm), followed by the Penman-Montheith-FAO56 method with replacement of all three parameters (MAE 57 mm). The RMSE for the monthly average ET_o was 0.43 and 0.50 mm·days^{-1} for the Penman-Monteith-FAO56 without and with replacement of all three parameters and 0.48 mm·days^{-1} for

Hargreaves. Thus, it was found that if only temperature data would be available, Hargreaves method would be preferred above the Penman-Montheith-FAO56 equation with replacement of humidity, radiation, and wind speed data, for this semiarid highland environment.

Raja (2010) evaluated the validation of CROPWAT 8.0 for estimation of reference evapotranspiration using limited climatic data under temperate conditions of Kashmir found that the ET_o estimated from limited data i.e. daily air temperature with annual mean wind speed of location (0.625 m/s) through CROPWAT had good agreement with that of ET_o estimated from full set of climatic data. The root mean square error (RMSE) and mean bias error (MBE) values were less than 0.260 mm/day and 0.150 mm/day, respectively. The pan evaporation method was also acceptable to estimate ET_o, because when compared to ET_o estimate with full set of climatic data have RMSE value less than 250 mm/day and MBE value near to zero.

Rao *et al.* (2011) recognized appropriate PET models for two small forested watersheds in the humid Appalachians in the southeastern United States. They compared three common PET models (FAO-56 grass reference ET, Hamon PET, and Priestley-Taylor PET) with measured AET at monthly and annual temporal scales, and also derived correction factors for the FAO-56 grass reference ET and Hamon PET models at the monthly scale using the Priestley-Taylor equation as the standard method for estimating forest PET. They found that different PET models gave significantly different PET estimates. The Priestley-Taylor equation gave the most reasonable estimates of forest PET for both watersheds and found that the uncorrected Hamon and FAO PET methods would cause large underestimates of forest PET.

Mohawesh (2011) studied daily outputs from eight evapotranspiration models against reference evapotranspiration (ET_o) data computed by FAO-56PM to assess the accuracy of each model in estimating ET_o. Models were compared at eight stations across Jordan. Results showed that Hargreaves modified models were the best in light of mean biased error (MBE), root mean square error (RMSE) and mean absolute error (MAE). The study also suggested that local calibration was needed for the models or linear regression could be used to calculate the ET_o.

Darshana *et al.* (2012) simulated CROPWAT model for estimation of the crop water requirement, time and depth. The study area encompassed three command areas, i.e. farm A, farm B and Tsedey State Farm, and five different type of crops, i.e. potato, tomato, apple, peach and winter wheat. The simulation results of the CROPWAT model illustrated that crop water requirement for apple was highest (993 mm), followed by peach (908 mm), tomato (470 mm), potato (443 mm) and wheat (294 mm). The study reveals that fruit crops have more crop water requirements than cereals.

Hu *et al.* (2012) modified the crop coefficient in each growing period of jujube, and established a function relationship between crop coefficients, days after sprouting and LAI. The crop coefficient of jujubes from this study provided a scientific basis for the water management of jujubes under drip-irrigation in Loess Plateau of China.

Kumar *et al.* (2012) analyzed different evapotranspiration models in different agro-climatic regions for efficient water management of crops and suggested suitable model for sub-temperate and sub-humid region. They suggested various models/approaches varying from empirical to physically based, available for the estimation of reference evapotranspiration. They found Penman Monteith model as best suitable for sub-temperate, sub-humid region.

Heydari *et al.* (2013) computed evapotranspiration (ET_o) by several models for Naein city in Isfahan province (center of Iran) from 1993-2006. Outputs were obtained from IMO (Iran Meteorological Organization) weather station, located in the Naein, for all of these years. FAO Penman Monteith (FAO-56 PM) method has been accepted by many researchers and international institutes as the reference and Standard method. Accurate different methods were compared with FAO-56 PM method. Results show that Blaney-Criddle (BC) model were the best in light of mean biased error (MBE), root mean square error (RMSE) and maximum absolute error (MAXE).The mean values MBE, RMSE and MAXE computed -0.554, 0.690 and 1.429 $mm.d^{-1}$ for BC, respectively. For all the years,

ET_0 rates were low in winter and fall and highest during the summer. Also, the maximum and minimum annual ET_0 estimations by Blaney-Criddle and FAO-56 PM methods was in 2001 and 1996, respectively.

Racz *et al.* (2013) performed descriptive statistical and sensitivity analysis of 10 commonly used estimation models - one of them with two variants. Correlation between modelled and measured evapotranspiration data series was assessed. The magnitude of the model outputs, their variability and responses to the changes of selected atmospheric parameters were evaluated. Priestley-Taylor, Penman-Monteith-FAO-56, Shuttleworth-Wallace (parameterized with alternative radiation balance), Szasz and Makkink proved to be the most sensitive methods. As regards the systematic error, Makkink and Shuttleworth-Wallace showed the best agreement with pan evaporation, while Shuttleworth-Wallace, Blaney-Criddle and Makkink models were found to be the closest to the Penman-Monteith-FAO-56 method as a reference value.

Al-Khalifa *et al.* (2014) conducted a study to estimate the crop coefficients (Kc) values for the different growth stages of banana under Gezira conditions. The study showed the calculated K_c values were found to be 0.5, 0.8 and 1.1 for $K_{c\ ini}$, $K_{c\ dev}$ and $K_{c\ mid}$ respectively, in the first year, but in the second year it was constant at value 1.2. The crop water requirement of the mother banana plant and first ratoon crops was 30336 m^3/ha from transplanting to harvest.

Almsaraf (2014) estimated the crop coefficient for cherries plants in Michigan State. The crop coefficients for cherries were modified accordingly to the actual measurements of soil moisture content. Actual evapotranspiration (consumptive use) were measured by the soil moisture readings using Time Domain Reflectometers (TDR), and compared with the actual potential evapotranspiration that calculated by using modified Penman-Monteith equation which depends on metrological station and by using pan evaporation method. Absolute error techniques showed that the predicted crop coefficient by Michigan State University should be modified and changed from 1.0 to 1.20 during June, and from 1.02 during July and August to 1.2 to reduce the crop water stress and give better water management and perfect schedule for irrigation process.

Gupta *et al.* (2016) carried out a study with the objective to compare the performance of Energy-Balance, Aerodynamic, Penman, Priestley-Taylor and Stephen-Stewart methods for the hilly and plain regions of north India for estimation of reference evapotranspiration with data intensive Modified Penman-Monteith (PENMON) method using the daily weather data acquired from automatic weather station during 2013-14 and 2014-15. The performance evaluation of selected methods was carried out using linear regression and simple Statistical analysis. The Most suitable method was compared with the methods reported for the various hilly and plain regions of the north India to suggest a substitute of PENMON method for estimation of reference evapotranspiration using minimal climatic parameters which are easily available. It was observed that the Penman method performed the best for hilly as well as for the plain regions and was in line with estimated ET0 by PENMON method with coefficient of determination (R2) of 0.95 and 0.89 and root mean square error (RMSE) 0.60 mm day-1 and 0.58 mm day-1 during 2013-14 and 2014-15, respectively. However, as compared to plain regions the value of ET0 estimated by Penman method was observed to be less for the hilly regions.

2.6 Partitioning of evapotranspiration

It is important to quantify the partitioning of ET and its control for accurate prediction of climatic responses of ecosystem. By far the most abundant partitioning studies are short term campaigns that range for eight days to four months. However, several studies revealed the use of isotope measurements along with the “Keeling” relationship for water vapor to partition ET along with sap flow measurements (William *et al.*, 2004; Yepez *et al.*, 2003; Snyder & Maxwell, 2005). Many studies also indicated that E/ET, the indicator of ET partitioning, was controlled by canopy conductance at the diurnal timescale and by leaf area index (LAI) at the seasonal timescale (Sakuratani, 1987; Liu et al., 2002; Kato et al., 2004; Scott et al., 2006; Sauer et al., 2007).

Merta (2002) developed a function for evaporation to evapotranspiration ratio based on results of Wheat and Maize which indicated that the transpiration achieves the highest portion of the total evapotranspiration (dense agricultural crops nearly 100%). The results obtained in the study indicated that 'E_s/ET_c' is mainly controlled by Leaf Area Index (LAI).

Zhang *et al.* (2004) carried out a study to partition reference evapotranspiration into evaporation and transpiration, on the basis of the fact that ratio of reference of evaporation to reference evapotranspiration depends on the development stage of leaf canopy.

Zhongmin et al. (2009) studied the partitioning of evapotranspiration in four grassland ecosystems. Results of the study indicated that monthly E/ET ranged from 12% to 56% in the peak growing seasons and the annual E/ET ranged from 51% to 67% across the four ecosystems. Canopy stomatal conductance controlled E/ET at the diurnal timescale, and the variations and magnitude of leaf area index (LAI) explained most of the seasonal, annual, and site-to-site variations in E/ET. A simple linear relationship between growing season LAI and E/ET explained ca. 80% of the variation observed at the four sites for the 10 modeled site-years. Our work indicated that the daily E/ET decreased to aminimum value of ca. 10% for values of LAI greater than 3 m2 m_2 at the ecosystem with a dense canopy. The sensitivities of E/ET to changes in LAI increased with the decline in water and vegetation conditions at both the seasonal and the annual time scales, i.e., the variations in LAI could cause stronger effects on E/ET in the sparse-canopy ecosystems than in the dense-canopy ecosystems.

Simic *et al.* (2014) carried out a study which indicated that leaf area index (LAI) is a critical variable of evapotranspiration calculation. According to the results LAI results in the reduction of annual groundwater recharge at the average precipitation due to increased evapotranspiration. It also results in reduction of runoff due to increase in evapotranspiration and infiltration.

2.7 Closure

The study focuses on the moisture extraction pattern in the root zone. Well renowned methodologies can be used to attain various soil and crop parameters. It is evident from the review of different models of evapotranspiration that different investigators have developed many models of evapotranspiration under different climatic conditions during last many years. It may be noted that a single model does not essentially predict the accurate results in all type of climatic conditions. It is enviable to develop appropriate models for reliable assessment of evapotranspiration of crops in temperate climatic conditions.

Chapter - 3

MATERIALS AND METHODS

3.1 General

The present study was conducted to evaluate the use of different capacity emitter's *i.e.* 2 lph, 4 lph and 8 lph Apple trees under local climatic conditions. The following parameters were measured/estimated during field experiments of study: (i) soil moisture depletion (ii) plant parameters such as plant height, root depth (iii) soil parameters such as soil texture, bulk density, particle density and hydraulic conductivity (iv) Crop evapotranspiration and modification of crop coefficient. The detailed field experiment is discussed in following sections.

3.2 Experimental site

The study was conducted in a high density apple orchard at Sher-e-Kashmir University of Agricultural Sciences and Technology, Shalimar Research Farm. It is located at 34.14^{o} N latitude and 74.87^{o} E longitude and 1606 m above mean sea level. The experimental farm is laid out with high density apples under drip irrigation system. The variety selected for the present study is Gala Red Lum with root stock M9T337. The spacing between the rows and plant to plant is 3 and 1.5 m respectively. Three lines of the same variety were selected and emitters of 2 lph, 4 lph and 8 lph capacity were placed on each line per tree. There were two drippers per tree. The layout of experimental plot is shown in Plate 3.1.

3.3 Collection of meteorological data

The meteorological data on temperature, humidity, rainfall, sunshine, wind speed, etc. was collected from the Division of Agronomy, SKUAST-Kashmir. Other data was calculated from the empirical formulas given in the FAO-56 manual.

3.4 Hydraulic characteristics of soil

3.4.1 Texture

The most important and permanent feature of a soil is texture. Many physical, chemical, and biological characteristics of soil are related to texture,

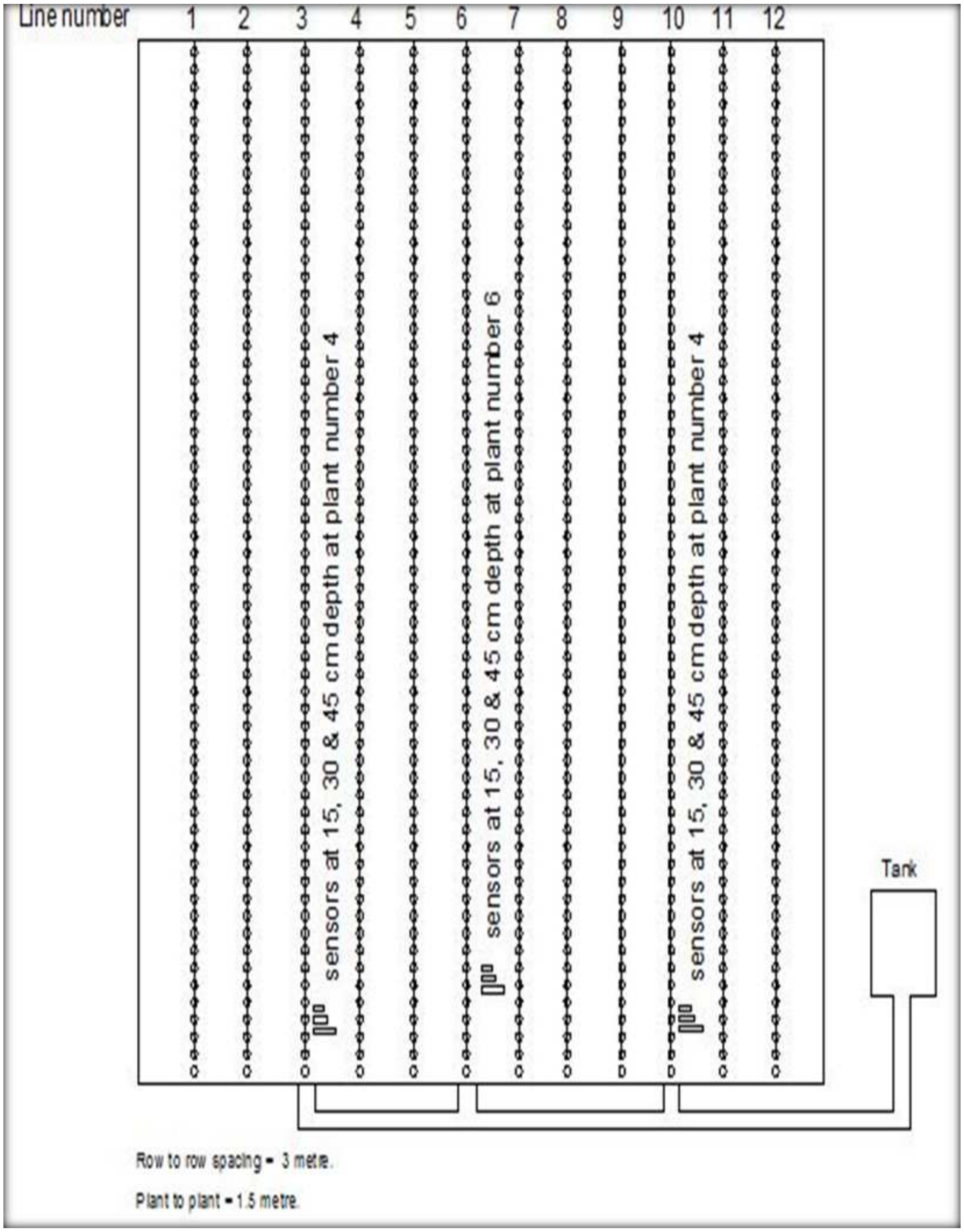


Plate 3.1: Layout of experimental plot

making textural determination one of the most basic of soil analysis. Soil texture describes the size distribution of individual soil particles. However, texture is generally used to reference the proportions of sand, silt, and clay. The method used in the study is the United States Department of Agriculture (USDA) Triangle method.

Soil samples were collected from the experimental farm and detailed grain size was analyzed using a set of sieves and a calibrated hydrometer, followed by the methodology suggested by Trout *et al.* (1982). The details of textural classification and other hydraulic properties of the soil are summarized in Table 3.1.

Table 3.1: Soil textural properties

Soil Type	**Silty clay loam**
Sand	19.6%
Silt	48.0%
Clay	32.4%
Bulk density	1.41 mg/m^3
Particle density	2.58 mg/m^3
Hydraulic conductivity	0.6 cm/hr
Field Capacity	0.45 cm^3-cm^3

3.4.2 Bulk density (mg/m^3)

Undisturbed soil samples were obtained using core sampler from the experimental site. Bulk density, which is defined as the mass of solids per unit volume of dry soil, has been determined by the procedure adopted by Trout *et al.* (1982).

3.4.3 Particle density (mg/m^3)

The particle density of soil represents the density of soil solids and is defined as the mass of soil solids per unit volume of soil solids. The pycnometer method (Trout *et al.*, 1982) has been used to determine the bulk density of the soil samples. The particle density has been shown in Table 3.1 which is typical for silty clay loam soils.

3.4.4 Saturated hydraulic conductivity (cm/hr)

The field saturated hydraulic conductivity (K_c) is the most important factor governing water transmission in unsaturated soils (Rawls *et al.,* 1982). Hydraulic conductivity is the measure of the ability of a soil to conduct water under a unit hydraulic potential gradient. Field saturated hydraulic conductivity refers to the saturated hydraulic conductivity of the soil containing entrapped air. The hydraulic conductivity is measured using falling head permeameter (Plate 3.2). It consists of a metallic mould, 100 mm internal diameter, 127.3 mm effective height and 1000 ml capacity according to IS: 2720. The mould is provided with a detachable extension collar, 100 mm diameter and 60 mm high. The soil ring and specimen with ring are placed. on bottom porous stone. Upper plate is placed on the permeameter and fastened securely to the base with 3 nuts to ensure ring seal.

Top porous stone and piston was inserted and a 6.0 kPa pressure was applied on the specimen. Initial reading was noted to determine subsequent change in specimen height for unit weight calculations due to increase in load increment. It is imperative that all air bubbles be flushed out of the system.

The bleeding valve in the base of apparatus was closed. Initial reading was recorded, then load was applied again and the final reading recorded.

Standpipe was filled and the height of water in the tube noted. Above steps were repeated several times to establish an average hydraulic conductivity for the sample.

The hydraulic conductivity was calculated from the following formula:

$$K = 2.3\ (aL/At)\ \log_{10}(h_1/h_2) \qquad \ldots (3.1)$$

Plate 3.2: Falling head permeameter

Where:

K = hydraulic conductivity, cm/sec;

a = cross-sectional area of the standpipe, cm^2;

L = average height of the sample for the load increment, cm;

A = cross-sectional area of the sample, cm^2;

t = elapsed time increment, seconds;

h_1 = height of water at the beginning of time increment, millimeters and

h_2 = height of water at the end of time increment, millimeters.

3.4.5 Electrical conductivity (Ec)

Electrical conductivity of the suspension liquid of 1:2.5 soil: water suspension was determined with the solu bridge conductivity meter at 25°C (Jackson, 1979).

3.4.6 Root depth (cm)

The root depth is one of the important parameters in the present study. The amount of soil moisture that is available to a plant is determined by the moisture characteristics of the soil, the depth to which the plant roots extend and the proliferation or density of the roots. To utilize effectively the moisture stored in the soil profile, roots must continue to proliferate into unexploited zones throughout the plant's growth cycle. The root depth varies from crop to crop and also from time to time during growth. During favorable growth periods, roots often elongate so rapidly that satisfactory moisture contacts can be maintained even when the soil moisture content declines. Soil texture and structure also affect the depth of root to a great extent. For measuring the rooting depth, trench profile method has been used and the root zone depth was found out to be around 45 cm.

3.5 Crop parameters

The crop parameters have a dominating role in predicting the moisture uptake. There are number of plant factors involved in the process of moisture uptake and accurate determination of these factors is quite complicated. Root depth and plant height has been recorded for the Apple crop in the experimental field.

3.5.1 Crop growth stages

As the crop develops, the ground cover, crop height and the leaf area change. Due to differences in evapotranspiration during the various growth stages, the crop coefficient (K_c) for a given crop will vary over the growing period. The growing period can be divided into four distinct growth stages: initial, crop development, mid-season and late season. The duration of crop stages have been considered on the basis of study by Doorenbos and Pruitt (1977).

3.5.1.1 Initial stage

The initial stage runs from planting date to approximately 10% ground cover. The length of the initial period is highly dependent on the crop, the crop variety, the planting date and the climate. The end of the initial period is determined as the time when approximately 10% of the ground surface is covered by green vegetation. During the initial period, the leaf area is small, and evapotranspiration is predominately in the form of soil evaporation. Therefore, the K_c during the initial period ($K_{c\ ini}$) is large when the soil is wet from irrigation and rainfall and is low when the soil surface is dry (Doorenbos and Pruitt, 1977).

3.5.1.2 Crop development stage

The crop development stage runs from 10% ground cover to effective full cover. Effective full cover for many crops occurs at the initiation of flowering. As the crop develops and shades more and more of the ground, evaporation becomes more restricted and transpiration gradually becomes the major process. During the crop development stage, the K_c value corresponds to amounts of ground cover and plant development.

3.5.1.3 Mid-season stage

The mid-season stage starts from effective full cover and ends at the start of maturity. In the maturity stage of crop, the degree of evapotranspiration which is relative to ET_o is reduced because of the beginning of the ageing, yellowing or senescence of leaves, leaf drop, or the browning of fruit. The mid-season stage is the longest stage for perennials and for many annuals, but it may be relatively short for vegetable crops that are harvested fresh for their green vegetation. The value for K_c ($K_{c\ mid}$) is relatively constant for most growing and cultural conditions and reaches its maximum value at the mid season stage.

3.5.1.4 Late season stage

The late season stage extents from the start of maturity to harvest or full senescence. There is no need to compute K_c and ET_c towards the end when the crop is harvested as it dries out naturally and reaches full senescence, or experiences leaf drop. The K_c value at the end of the late season stage ($K_{c\ end}$) reflects crop and water management practices. If adequate irrigation is given to crop until it is harvested, the $K_{c\ end}$ value reaches its maximum value at end stage of crop.

3.5.2 Crop height

Plant height is a parameter which directly represents the growth of crop. Height of selected plants is measured and an average height is recorded. It has been observed that the plant height increases rapidly during development and mid-season growth stage and reaches its maximum in the mid-season stage of crop. The average plant height during the study period was found to be 3 meters.

3.6 Soil moisture distribution

Soil moisture readings before and after irrigation was taken at 15, 30 & 45 cm soil depths, to characterize the soil water distribution pattern.

3.6.1 Irrigation System

Drippers were installed in the experimental site. Three types of emitters were selected for the study *i.e.* 2 lph, 4 lph and 8 lph. In line three, 2 lph drippers were installed while as in line six and line ten emitters of capacity 4 lph and 8 lph were installed respectively. Different capacity emitters and their installation are shown in Plate 3.3 and Plate 3.4.

3.6.2 Soil moisture Depletion

In order to study moisture depletion in the Apple plant, sensors were installed at different depths to record soil water potential which is later converted to daily available moisture content and moisture depletion rate during the cropping period. Van-Genuchten (1980) equation was adopted to convert soil matric potential to soil moisture content as the parameters involved are widely available in literature. These are as follows:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha_v h|^{n_v})^{m_v}} \text{ for } h < 0 \qquad \text{...2a}$$

$$= \theta_s \text{ for } h \geq 0 \qquad \text{...2b}$$

where α_v, and n_v are curve fitting parameters and m_v is given by

$$m_v = 1 - \frac{1}{n_v} \qquad \text{...2c}$$

Moisture depletion gives us an idea about the moisture absorbed by plant from the soil since the previous sampling occasion. The period of moisture depletion commences with a uniform distribution of available moisture in the soil profile, which approximates to the field capacity. Occurrence of rain between two sampling occasions, results in predominance of moisture in the soil layers. This is the intrinsic short coming of this method.

3.6.3 Watermark soil moisture sensor

The soil acts as a reservoir to store water between irrigations or rainfall events, so that it is available to the crop or plants as needed for healthy growth. The purpose of using sensors to measure soil water potential is to give a better understanding of how fast water is being depleted in the different areas of field. By reading the sensors 2-3 times between irrigations, an accurate picture of this process over the time is gained, and accordingly an irrigation scheduling pattern can be developed that meets crop need for water. This eliminates the guesswork, results in water savings, lower pumping costs and eliminate excess leaching of nitrogen due to over irrigation.

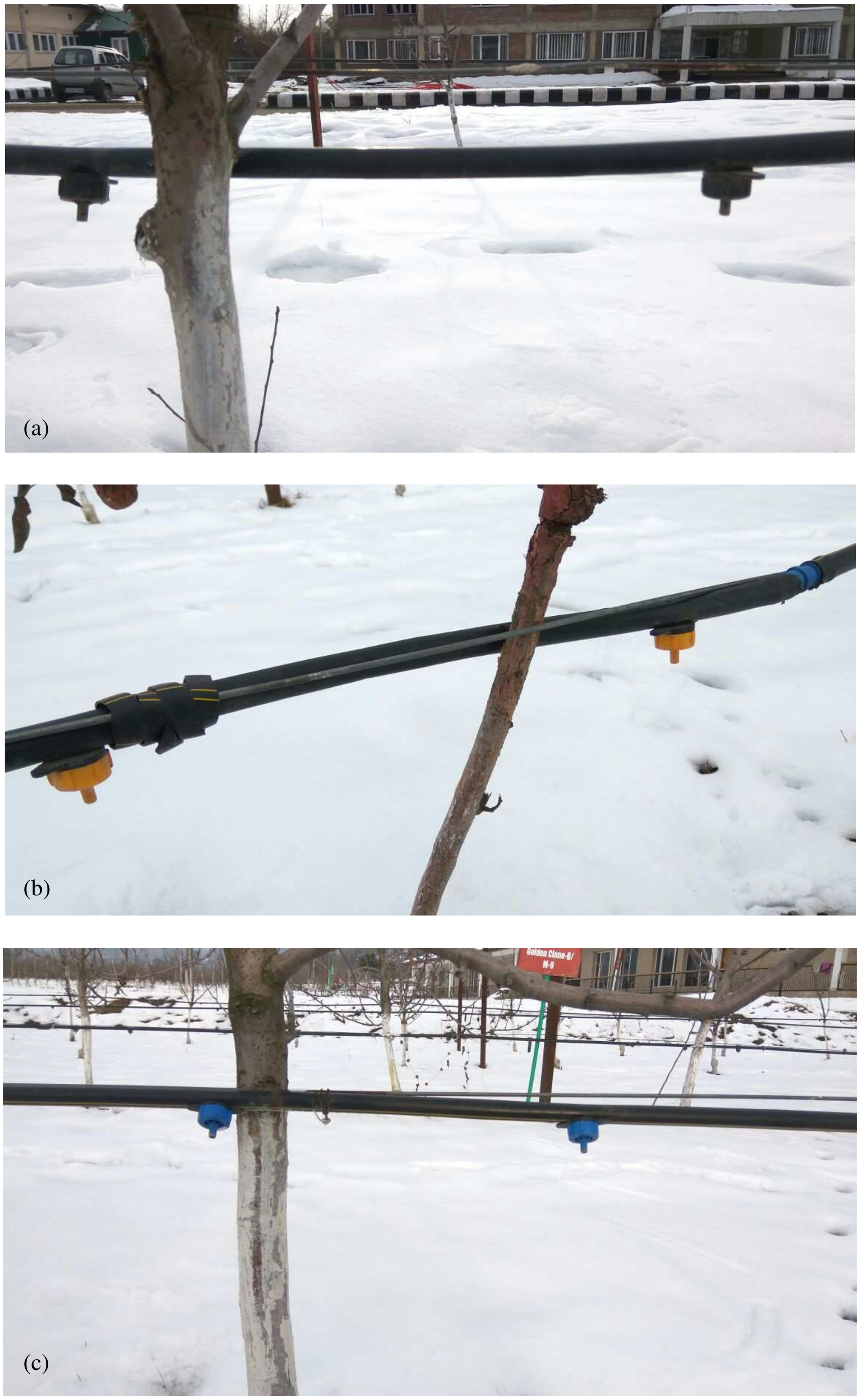


Plate 3.3 (a-c): Emitters of capacity (a)2 lph, (b)4 lph and (c) 8lph

Plate 3.4: Installation of different capacity emitters

3.6.4 Sensor installation

More than one sensor should be frequently placed at given location, at varying depths. For instance, one sensor is installed in the upper layer of plants effective root zone and other sensors installed deeper in the root zone profile. Before installing a sensor, it should be soaked overnight in the irrigation water. Make a access hole in the soil for the sensor to the desired depth with the rod. Fill the hole with the water and push the sensor inside the hole. A length of "½ class 315 or ¾ PVC" will tightly fit over sensors collar and can be used to push the sensor inside the soil. A close fitting of sensor in the soil is very important. The sensors wire should be pegged up for easy access. Fill the hole with the slurry and install the sensor. This will "grout in" the sensor to ensure close fit. The installation procedure and position of sensor is shown in Plate 3.5 to 3.7.

3.6.5 Measuring meter

For measurement of soil suction head an advanced system of the sensors (Watermark, Irrometer Company, Inc. Reverside CA), has been installed. These sensors can measure soil suction head observations ranging from 0-199 centibars. In the experimental field sensors are installed near three plants in three different lines at depths 15, 30, and 45 cm during cropping period. The sensors are connected with wire lead, which can be connected to Watermark meter with alligator clips. The moisture meter directly gives the soil water potential. The watermark meter and measurement of soil suction head in Apple tree is shown in Plate 3.8 and Plate 3.9.

3.7 Reference crop evapotranspiration

The evapotranspiration from a reference surface is called the reference crop evapotranspiration and is denoted by ET_o. The reference surface is a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sm^{-1} and an albedo of 0.23. ET_o is also defined as the rate at which readily available soil water is vaporized from specified vegetated surfaces (Jensen *et al.,* 1990). In other words reference evapotranspiration is the *ET* rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an

Plate 3.5: Sensors wetted before installing in soil

Plate 3.6: Installation of sensors in soil

Plate 3.7: Position of sensors installed

Plate 3.8: Watermark meter

Plate 3.9: Measurement of soil suction head in apple tree

expanse of at least 100 m of the same or similar vegetations (Allen *et al.,* 2005). The concept of the ET_o was introduced to study the evaporative demand of the atmosphere independent of crop type, crop development, and management practices. ET_o values measured or calculated at different locations or in different seasons are comparable as they refer to the *ET* from the same reference surface. The only factors affecting ET_o are climatic parameters The reference ET_o was computed using daily values of the climatic parameters obtained from the meteorological station of the Division of Agronomy, SKUAST-K from January, 2016 - July, 2016. Six different models were used to calculate the reference evapotranspiration which are:

3.7.1 Penman Monteith model

The Penman-Monteith Equation is given by the following equation (FAO, 1998).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_{2})} \qquad ----(3.1)$$

The equation uses standard climatological records of solar radiation (sunshine), air temperature, humidity and wind speed for daily, weekly, ten-day or monthly calculations. The other parameters are calculated using empirical equations.

3.7.1.1 Psychometric constant (γ)

The psychometric constant relates the partial pressure of water in air to the air temperature so that vapor pressure can be estimated using paired dry and wet thermometer bulb temperature readings. Another way to describe the psychometric constant is the ratio of specific heat of moist air at constant pressure (Cp) to latent heat of vaporization. For details on the psychometric constant (γ) the FAO, 1998 is referred which summarizes the values of γ as a function of altitude. For our location the value of γ is found out to be 0.056.

3.7.1.2 Air temperature

The (average) daily maximum and minimum air temperatures in degrees Celsius (°C) are required. Where only (average) mean daily temperatures are available, the calculations can still be executed but some underestimation of ETo will probably occur due to the non-linearity of the saturation vapor pressure - temperature relationship (Allen *et al.* 1998). Air temperature is also needed for the calculation of the slope of saturation pressure curve, and is given by the following equation:

$$T_{mean} = \frac{T_{max} + T_{min}}{2} \qquad ------(3.2)$$

3.7.1.3 Mean saturation vapour pressure (e_s)

The mean saturation vapor pressure for a day, week, decade, or month should be computed as the mean between the saturation vapor pressure at the mean daily maximum and minimum air temperatures for that period. As the saturation vapour pressure is related to the air temperature, it can be calculated from the air temperature.

$$e^{o}(T) = 0.6108\exp\left(\frac{17.27T}{T + 237.3}\right) \qquad ------(3.3)$$

Due to the non-linearity of the above equation, the mean saturation vapour pressure for a day, week, decade or month should be computed as the mean between the saturation vapour pressure at the mean daily maximum and minimum air temperatures for that period:

$$e_s = \frac{e^{o}(T_{max}) + e^{o}(T_{min})}{2} \qquad ------(3.4)$$

3.7.1.4 Slope of saturation vapour pressure curve (Δ)

For the calculation of evapotranspiration, the slope of the relationship between saturation vapor pressure and temperature, Δ, is required. The value of Δ is a function of the mean air temperature and is calculated using the following equation:

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T + 237.3}\right)\right]}{(T + 237.3)^2} \qquad ------(3.5)$$

3.7.1.5 Actual vapour pressure (e_a)

The actual vapor pressure can also be calculated from the relative humidity. Depending on the availability of the humidity data, different equations should be used. It can be derived from the dew point temperature data or from the relative humidity (RH) data.

$$e_a = \frac{e^0(T_{min})\frac{RH_{max}}{100} + e^0(T_{max})\frac{RH_{min}}{100}}{2} \qquad ----(3.6)$$

3.7.1.6 Vapour pressure deficit (e_s - e_a)

The vapour pressure deficit is the difference between the mean saturation vapour pressure (e_s) and the actual vapour pressure (e_a) for a given time period.

3.7.1.7 Net radiation (R_n)

One of the major inputs to the FAO Penman-Monteith Equation is the net radiation at the crop surface (R_n). The net radiation is the difference between the incoming net shortwave radiation (R_{ns}) and the outgoing net longwave radiation (R_{nl}):

$$R_n = R_{ns} - R_{nl} \qquad ------(3.7)$$

For R_n determination it is important to first explain some concepts and define certain parameters in the process of deriving the inputs of equation for the calculation of R_s.

3.7.1.8 Extraterrestrial radiation (R_a)

Extraterrestrial radiation (R_a) is the solar radiation received at the top of the earth's atmosphere on a horizontal surface. The local intensity of the radiation is determined by the angle between the direction of the sun's rays and the normal (perpendicular) to the surface of the atmosphere. This angle will change during the day and will be different at different latitudes and in different seasons. The angle is zero, if the sun is directly overhead. As seasons change, the position of the sun, the length of the day and, hence, R_a change. R_a for each day of the year and for different latitudes can be estimated by using equations:

$$R_a = \frac{24\,(60)}{\pi} G_{sc} d_r [\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\sin(\omega_s)] \qquad ----(3.8)$$

Where R_a = extraterrestrial radiation [MJ m^{-2} day^{-1}]

G_{sc} = solar constant [0.0820 MJ m^{-2} min^{-1}]

d_r = inverse relative distance Earth-Sun

ω_s = sunset hour angle [radian]

φ = latitude [radian]

δ = solar declination [radian]

R_a is expressed in the above equation in MJ m^{-2} day^{-1}. The corresponding equivalent evaporation in mm day^{-1} is obtained by multiplying R_a by 0.408.

The inverse relative distance Earth-Sun, d_r and the solar radiation, δ are given by:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \qquad ------(3.9)$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \qquad ----(3.10)$$

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

3.7.1.9 Solar or shortwave radiation (R_s)

Part of the extraterrestrial radiation (R_a) is scattered, reflected or absorbed in the process of entering the atmosphere. The amount of radiation that reaches the earth's surface is called solar radiation (R_s). It depends on R_a and the transmission through the atmosphere, which is largely dependent on cloud cover. It is calculated through the use of an equation which relates solar radiation to extraterrestrial radiation and relative sunshine duration.

$$R_s = \left(a_s + b_s \frac{n}{N}\right) R_a \qquad -----(3.11)$$

Where, R_s = solar or shortwave radiation [MJ m^{-2} day^{-1}]

n = actual duration of sunshine [hour]

N = maximum possible duration of sunshine or daylight hours [hour]

n/N = relative sunshine duration [-1]

R_a = extraterrestrial radiation [MJ m^{-1} day^{-2}]

a_s = regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days (n=0).

$a_s + b_s$= fraction of extraterrestrial radiation reaching the earth on clear days (n=N).

The maximum duration of sunshine (N) can be calculated using different equations. The actual duration of sunshine (n) is recorded with a sunshine recorder and is part of the climatological data of weather station.

3.7.1.10 Net solar or shortwave radiation (R_{ns})

The net solar or shortwave radiation, resulting from the balance between incoming and reflected solar radiation, is given by:

$$R_{ns} = (1 - \alpha)\, R_s \qquad ------(3.12)$$

Where, R_{ns} = net solar or net wave radiation [MJ m^{-2} day^{-1}]

α = albedo or canopy refection coefficient, which is 0.23 for the hypothetical grass reference crop [dimensionless]

R_s = incoming solar radiation [MJ m^{-2} day^{-1}]

3.7.1.11 Clear sky radiation (R_{so})

The calculation of the clear-sky radiation R_sO, n = N, is required for computing net long wave radiation.

i. **For near sea level or when calibrated values for a_s and b_s are available:**

$$R_{so} = (a_s + b_s)R_a \qquad ------(3.13)$$

Where, R_{so} = clear-sky solar radiation [MJ m^{-2} day^{-1}]

a_s and b_s = fraction of extraterrestrial radiation reaching the earth on clear-sky days (n = N)

ii. **When calibrated values for a_s and b_s are not available:**

$$R_{so} = (0.75 + 2 \times 10^{-5} z)\ R_a \qquad ------(3.14)$$

Where, z is the station elevation above sea level [m].

3.7.1.12 Net longwave radiation (R_{nl})

The rate of long wave radiation emission is proportional to the absolute temperature (Kelvin) of the surface raised to the fourth power. R_{nl} is calculated using the following expression:

$$R_{nl} - \sigma \left[\frac{T_{max,K}{}^4 + T_{min,K}{}^4}{2}\right] \left(0.34 - 0.14\sqrt{e_a}\right) \left(1.35\frac{R_s}{R_{so}} - 0.35\right) - - - (3.15)$$

Where, R_{nl} = net outgoing long wave radiation [MJ m^{-2} day^{-1}]

σ = Stephan-Boltzmann constant [4.903×10^{-9} MJ K^{-4} m^{-2} day^{-1}]

$T_{max,K}$= maximum absolute temperature during the 24-hour period [K= °C+273.16]

$T_{min,K}$= minimum absolute temperature during the 24-hour period [K= °C+273.16]

e_a = actual vapour pressure [kPa]

R_s/R_{so} = relative short wave radiation (limited to $\leq$ 1.0)

R_s = measured or calculated solar radiation (equation 16) [MJ m^{-2} day^{-1}]

R_{so} = calculated (equation 17 or 18) clear sky radiation [MJ m^{-2} day^{-1}]

The term $\left(0.34 - 0.14\sqrt{e_a}\right)$ expresses the correction for air humidity, and will be smaller if the humidity increases. The effect of cloudiness is expressed by $\left(1.35\frac{R_s}{R_{so}} - 0.35\right)$.

3.7.1.13 Soil heat flux (G)

The soil heat flux (G) is another input required in the FAO Penman-Monteith equation. G is the energy that is utilized in heating the soil and it is a component of the energy balance equation and should be considered when making estimates of evapotranspiration. The size of the soil heat flux beneath the grass reference surface for one-day and ten-day periods is relatively small and it may be ignored for all practical purposes. Hence, in ET_o calculations using the FAO Penman-Monteith equation G is considered to be zero.

$$G_{day} \approx 0 \qquad ------(3.16)$$

3.7.1.14 Wind speed (u_2)

For input into the FAO Penman-Monteith Equation, the average daily wind speed in meters per second (m s^{-1}) measured at 2 m above the ground level is required. It is important to verify the height at which wind speed is measured, as wind speeds measured at different heights above the soil surface differ. This is provided in the meteorological data.

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)} \qquad ------(3.17)$$

Where;

u_2 = wind speed 2 m above the ground surface, m s^{-1};

u_z = measured wind speed 2 m above the ground surface, m s^{-1};

h = height of the measurement above the ground surface, m.

3.7.2 Other Reference Evapotranspiration Models

Many investigators have developed various models for predicting reference crop evapotranspiration using meteorological data. For present study following six models (Table 3.2) were used. For testing of these reference evapotranspiration models, using local climatic data and modified crop coefficient value, reference evapotranspiration have been calculated for each crop.

Table 3.2: Reference crop evapotranspiration models

S. No.	Method of ET_0 Estimation	Equations Used	Basic Reference	Required Meteorological Data
1.	FAO-24 corrected Penman (c = 1), (F c P-Mon)	$ET_0 = c\left[\frac{\Delta}{\Delta+\gamma}(R_n - G) + \frac{\gamma}{\Delta+\gamma} 2.7 W_f (e_a - e_d)\right]$	Doorenbos and Pruit (1977)	Net radiation, vapour pressure deficit and wind velocity
2.	Priestley-Taylor (P-T)	$ET_0 = \alpha \frac{\Delta}{\Delta+\gamma}(R_n - G)$	Shuttleworth (1992)	Net radiation, soil heat flux and vapour pressure deficit
3.	FAO-24 Blaney-Criddle, (F B-C)	$ET_0 = a + b\left[p\left(0.46\bar{T} + 8.13\right)\right]$	Doorenbos and Pruit (1977)	Annual day time hours, temperature and wind velocity
4.	Hargreaves-Samani (H-S)	$ET_0 = 0.0135(KT)(R_a)(TD^{1/2})(TC + 17.8)$ $KT = 0.00185(TD)^2 - 0.0433TD + 0.4023$	Hargreaves and Samani (1982, 85)	Net radiation, min/max temperature
5.	FAO Pan Evaporation (F E-Pan)	$ET_0 = K_p \ E_{pan}$	Allen *et al.* (1998)	Pan evaporation
6	Penman Monteith (P-M)	$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$	Allen *et al.* (1998)	Vapour pressure deficit, radiation flux, wind velocity, temperature and soil heat flux.

The notation of parameters used for computation of ET_o are shown in Table 3.3:

ET_o	Reference Evapotranspiration (mm day^{-1})	Δ	Slope of vapor pressure (kPa $^oC^{-1}$)
a	Priestly-Taylor coefficient ranges from 1.08-1.34 depending upon crop and location.	G	Soil heat flux density (Mj m-2 day-1)
P	Mean daily percentage of annual day time hours.	a & b	Regression Coefficients
TC	Average daily temperature	TD	Tmax-Tmin (^{o}C)
T_{min}	Minimum Temperature (^{o}C)	T_{max}	Maximum Temperature (^{o}C)
e_s	Saturation vapor pressure (kPa)	e_a	Actual vapor pressure (kPa)
(e_s-e_a)	Saturation vapor pressure deficit (kPa)	u_2	Wind speed at 2m height (ms^{-1})
W_f	Wind function	γ	Psychrometric constant
R_n	Net radiation at crop surface (Mj m^{-2} day^{-1})	R_s	Extraterristrial radiation (mm day^{-1})
E_{pan}	Potential Evapotranspration (mm day-1)	K_{pan}	Pan coefficient

3.8 Crop coefficient

The concept of K_c was introduced by Jensen (1968) and further developed by the other researchers (Doorenbos and Pruitt, 1975, 1977; Burman *et al.*, 1980a,

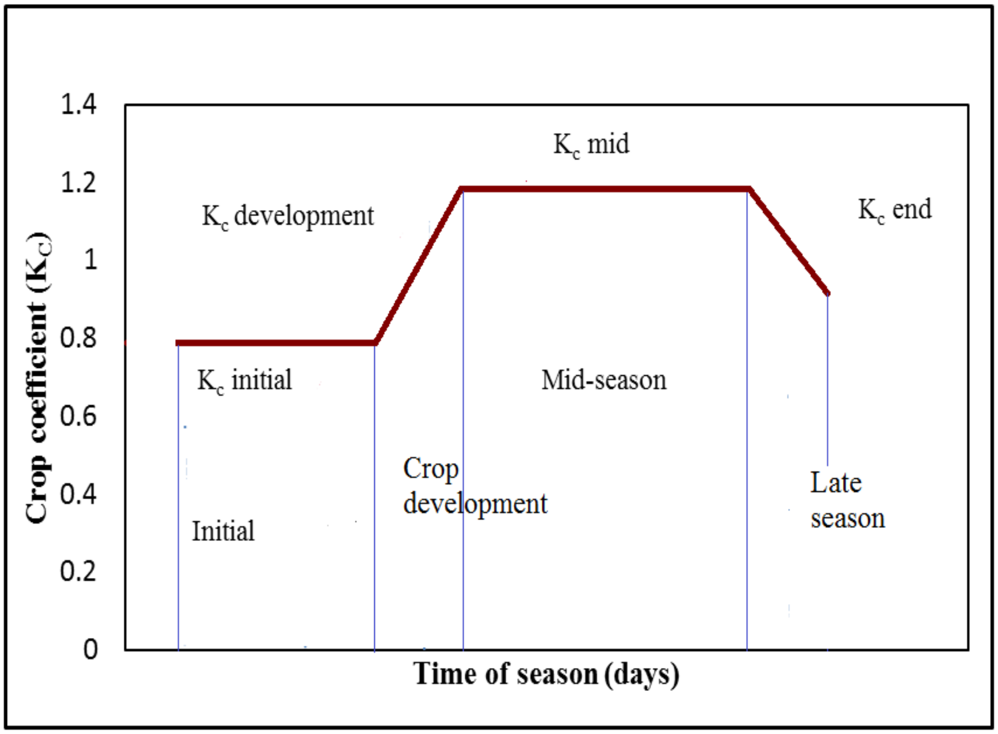


Plate 3.10: FAO suggested general crop coefficient curve (Allen *et al.,* 1998)

Burman *et al.*, 1980b; Allen *et al.*, 1998). The crop coefficient is the ratio of the actual crop evapotranspiration (ET_c) to reference crop evapotranspiration (ET_o). Crop coefficient varies with the changes in vegetation and ground cover of the crop during the growing period. The trends in K_c during the growing period are represented in the crop coefficient curve. The values for K_c which are required to describe and construct the crop coefficient curve are the initial stage ($K_{c\ ini}$), the mid-season stage ($K_{c\ mid}$) and the end stage (K_{cend}). FAO suggested general trend of crop coefficient in different growth stages of the crops as shown in Plate 3.10.

The FAO proposed crop coefficient values for initial, mid and end stages of growth for Apple are $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ which are 0.6, 1.20 and 0.85, respectively. These values have been modified for the local agro-climatic conditions, soil characteristics and crop according to the procedure given in FAO 56 guidelines (Allen *et al.,* 1998).

The crop coefficient values suggested by FAO can be modified using the different equations for initial, mid and end stages of growth for Apple. Accurate estimates of $K_{c\ ini}$ can be obtained by considering the time interval between wetting events, the evaporation power of the atmosphere (ET_o) and the magnitude of the wetting event. Hence, the following equation (Allen *et al.*, 1998) is used.

$$K_{cini} = K_{ciniFAO} + \frac{(1-10)}{(40-10)}\left[K_{cini(heavywetting)} - K_{cini(lightwetting}\right] \quad \dots (3.18)$$

Where I is the average infiltration depth in mm based on the magnitude of the wetting events. Subscripts FAO, heavy wetting and light wetting refer to the FAO recommended value, $K_{c\ ini}$ derived from the FAO-curve corresponding to the heavy wetting and $K_{c\ ini}$ derived from the FAO-curve corresponding to light wetting for the corresponding parameters.

The value of $K_{c\ mid}$ varies with the climatic conditions and the crop height. More arid climates and conditions of greater wind speed will have higher values of $K_{c\ mid}$. More humid climates and conditions of lower wind speed will have lower values of $K_{c\ mid}$. The values of $K_{c\ end}$ reflects crop and water management practices. If the crop is irrigated frequently until harvested fresh, the top soil remains wet and $K_{c\ end}$ value will be relatively high. Consequently both the soil surface and vegetation are dry and the value for $K_{c\ end}$ will be relatively small.

More arid climates and conditions of greater wind speed will have higher values for $K_{c\ end}$. More humid climates and conditions of lower wind speed will have lower values for $K_{c\ end}$. For specific adjustment in climates where minimum relative humidity differs from 37 per cent or where u_2 is larger or smaller than 2.0 m s^{-1}, $K_{c\ mid/end}$ value is determined from the following equation:

$$K_{cmid/end} = K_{cmid/end(table)} + \left[0.04(u_2 - 2) - 0.0004(RH_{\min} - 45)\right]\left(\frac{h}{3}\right)^{0.3} \quad \ldots (3.19)$$

Where,

$K_{c\ mid/end\ (table)}$ = tabulated value of $K_{c\ mid/end}$

u_2 = mean value of daily wind speed at 2.0 m height over grass during the mid-season growth stage/late season stage (ms^{-1}) for $1ms^{-1} < u_2 < 6\ ms^{-1}$,

RH_{min} = mean value of daily minimum relative humidity during the mid-season growth stage/late season stage (per cent) for $20\% < RH_{min} < 80\%$

H = mean plant height during the mid-season stage/late season stage (m) for $0.1\ m < h < 10\ m$

3.9 Crop evapotranspiration

The FAO recommended K_c values for different growth stages (Allen *et al.*, 1998) of apple, have been modified as discussed in previous section 3.7. The crop coefficient values were modified for local climatic conditions. Crop evapotranspiration represents crop water requirement, which is determined as product of K_c values of particular period and corresponding reference evapotranspiration (ET_o).

3.10 Overview of CROPWAT

CROPWAT is a Windows based decision support system designed as a tool to help agro-meteorologists, agronomists, and irrigation engineers carry out standard calculations for evapotranspiration and crop water use studies, particularly the design and management of irrigation schemes. It allows the development of recommendations for improved irrigation practices, the planning of irrigation schedules under varying water supply conditions, and the assessment of production under rain fed conditions or deficit irrigation.

The programme uses daily/monthly climatic data (temperature, relative humidity, wind speed, sunshine hours, and rainfall) for the calculation of reference evapotranspiration. It can calculate effective rainfall using four different methods but calculation was done using USDA Soil Conservation method. The input data used for model are crop coefficient for growth stages (K_c), root zone depth and allowable soil moisture depletion the programme calculated the crop water requirements on a decade (10-day) basis.

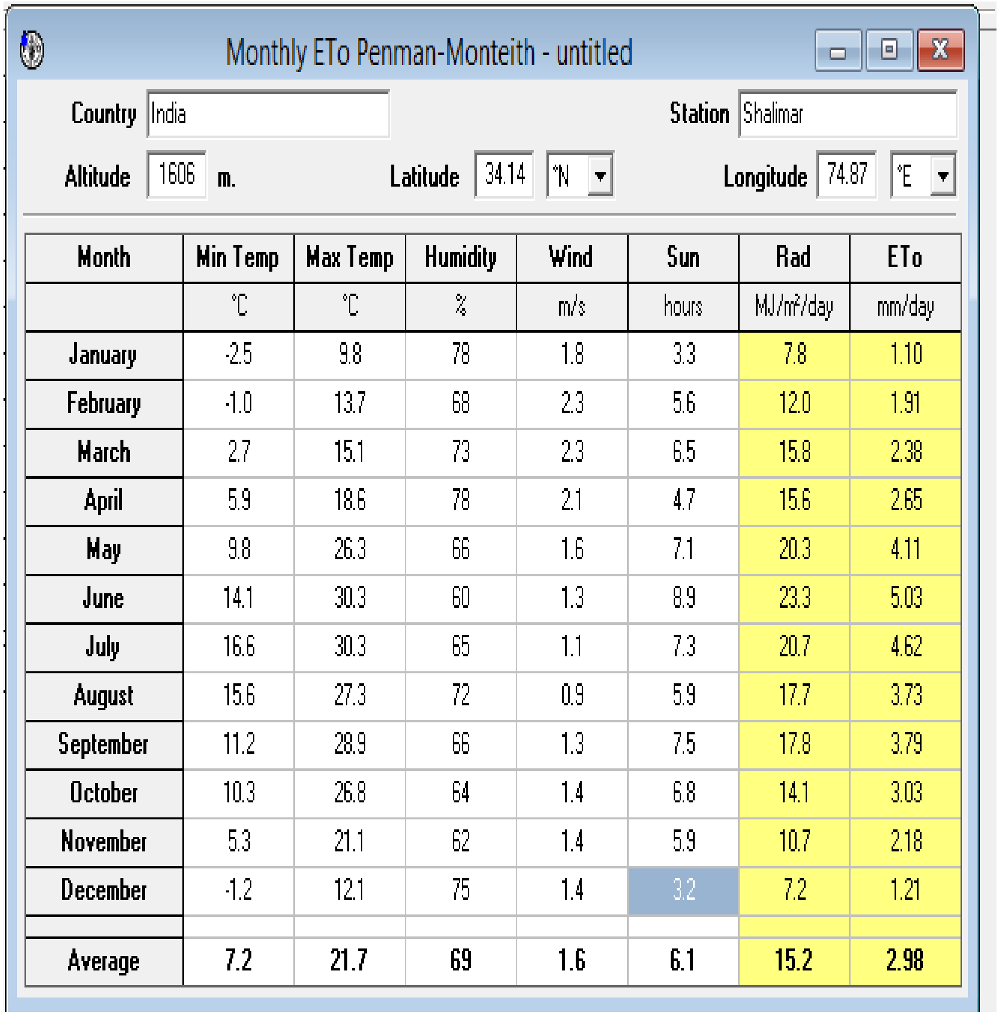
3.10.1 Reference crop evapotranspiration (ET_o) and the effective rainfall

The software calculated reference evapotranspiration and effective rainfall using input meteorological data and different crop input. This software uses FAO Penman-Monteith equation for determining reference evapotranspiration. Effective rainfall is defined as that part of the rainfall which is effectively used by the crop after rainfall losses due to surface run off and deep percolation have been accounted. The effective rainfall is the rainfall ultimately used to determine the crop irrigation requirements.

3.10.2 Crop water requirement

Based on the cropping programme adopted, crop data and soil data is entered into CROPWAT to enable the programme to calculate the crop water requirements for the crop. The crop data required are crop planting dates, the crop coefficient (K_c) values at the different growth stages, the length of growth stages, the crop rooting depth at the different growth stages, the allowable soil moisture depletion levels and the yield response factors (K_y). The soil parameters required for irrigation scheduling using the FAO CROPWAT programme are total available soil moisture content, maximum rooting, maximum rain infiltration rate, initial soil moisture depletion and initial available soil moisture.

After the input of the crop and soil data, CROPWAT proceeds to calculate the crop water and irrigation requirements of the given cropping pattern, using the entered data. The climate input file, rainfall input file, soil input file and crop input file are illustrated in Plate 3.11-3.13, respectively.



Country: India

Station: Shalimar

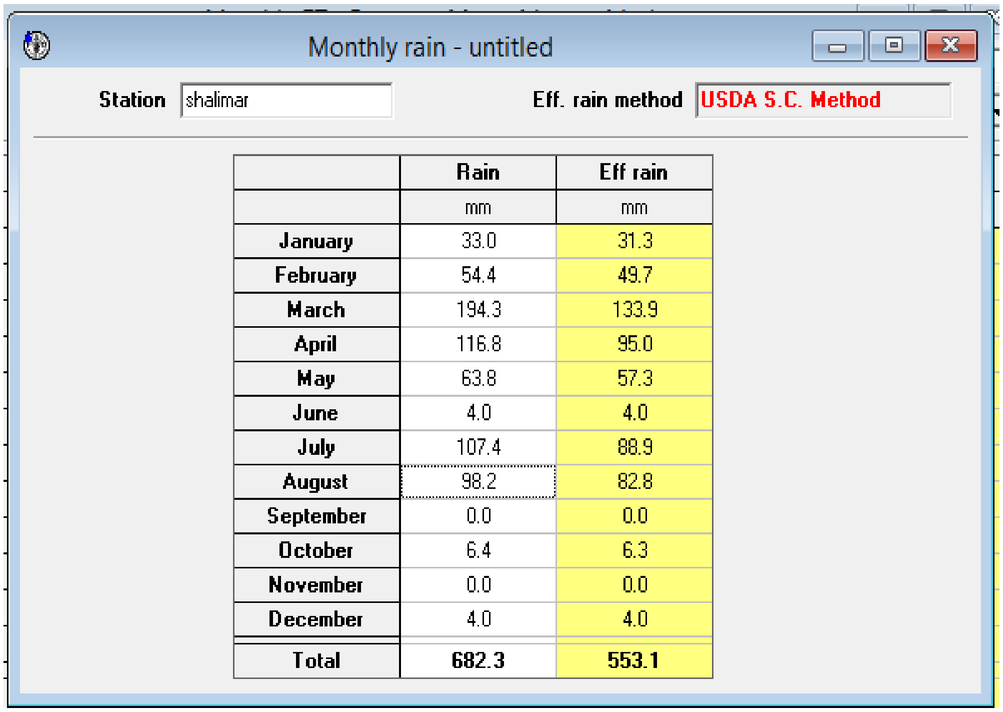
Altitude: 1606 m.

Latitude: 34.14 °N

Longitude: 74.87 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	m/s	hours	MJ/m²/day	mm/day
January	-2.5	9.8	78	1.8	3.3	7.8	1.10
February	-1.0	13.7	68	2.3	5.6	12.0	1.91
March	2.7	15.1	73	2.3	6.5	15.8	2.38
April	5.9	18.6	78	2.1	4.7	15.6	2.65
May	9.8	26.3	66	1.6	7.1	20.3	4.11
June	14.1	30.3	60	1.3	8.9	23.3	5.03
July	16.6	30.3	65	1.1	7.3	20.7	4.62
August	15.6	27.3	72	0.9	5.9	17.7	3.73
September	11.2	28.9	66	1.3	7.5	17.8	3.79
October	10.3	26.8	64	1.4	6.8	14.1	3.03
November	5.3	21.1	62	1.4	5.9	10.7	2.18
December	-1.2	12.1	75	1.4	3.2	7.2	1.21
Average	7.2	21.7	69	1.6	6.1	15.2	2.98

Plate 3.11: Climate input file for CROPWAT

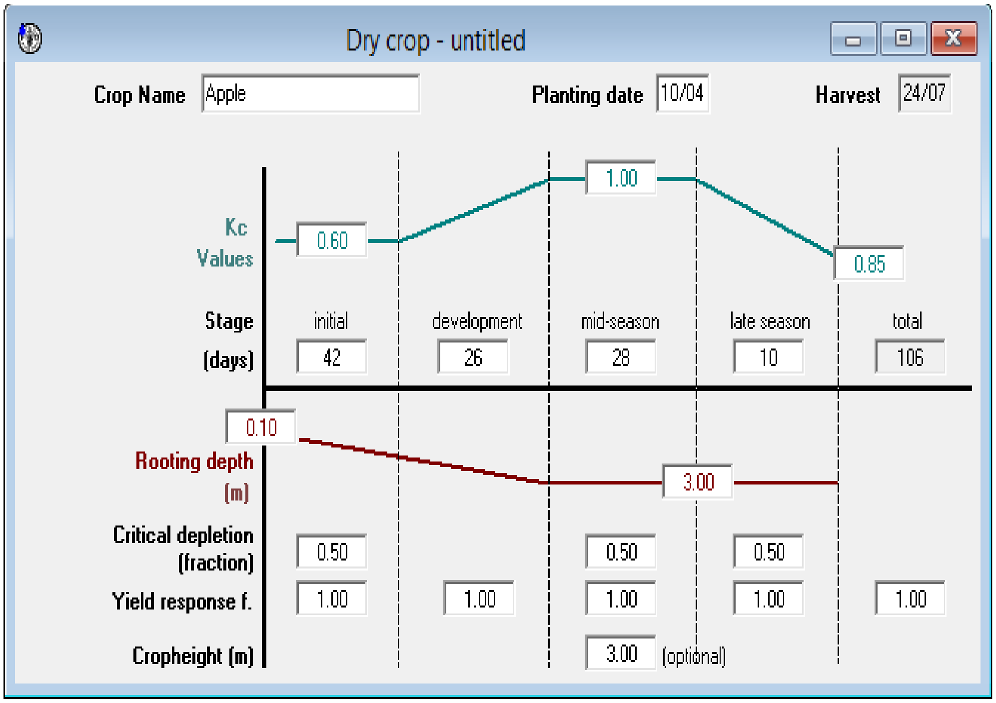


Station shalimar

Eff. rain method USDA S.C. Method

	Rain	Eff rain
	mm	mm
January	33.0	31.3
February	54.4	49.7
March	194.3	133.9
April	116.8	95.0
May	63.8	57.3
June	4.0	4.0
July	107.4	88.9
August	98.2	82.8
September	0.0	0.0
October	6.4	6.3
November	0.0	0.0
December	4.0	4.0
Total	**682.3**	**553.1**

Plate 3.12: Rainfall input file for CROPWAT



Crop Name Apple

Planting date 10/04

Harvest 24/07

	initial	development	mid-season	late season	total
Kc Values	0.60		1.00		0.85
Stage (days)	42	26	28	10	106
Rooting depth (m)	0.10			3.00	
Critical depletion (fraction)	0.50		0.50	0.50	
Yield response f.	1.00	1.00	1.00	1.00	1.00
Cropheight (m)			3.00 (optional)		

Plate 3.13: Crop input file for CROPWAT

3.11 Partitioning of evapotranspiration

Crop evapotranspiration consists of three components, which are interception, evaporation and transpiration. During the initial stage of crop, soil is bare. In the development and end stages, soil is covered by plants only partly; however, during the middle stage soil is fully covered with the plant canopy. These conditions play an important role in partitioning of evapotranspiration into its components. The separation of soil evaporation and plant transpiration fluxes from evapotranspiration is essential to understanding the water economy of both agricultural and natural ecosystems (Paruelo *et al.*, 1991). In order to comprehend the relative importance and functioning of key ecosystem components and their responses to climate forcing in open canopy systems, information about partitioning of fluxes is often required (Scott *et al.*, 2003). When the presence of woody-plant species within a landscape influences the volume of root systems, evaporative leaf area, and duration of physiological activity, a shift in the ratio of transpiration to evapotranspiration can be expected (Huxman *et al.*, 2005). Partitioning equation based on leaf area index has been used in the present study to partition soil evaporation and plant transpiration (Allen, 1990; Zhang *et al.*, 2004 and Shankar *et al.*, 2012).

The equation used is given below:

$$\frac{E_s}{ET_c} = \mathrm{EXP}(-\delta * \mathrm{LAI}) \qquad \ldots (3.20)$$

Where δ is dimensionless canopy extinction coefficient, whose value is 0.6 for apple (Jackson 1979, 1980).

3.11.1 Soil evaporation

Evaporation can be defined as the process where liquid water is transformed into a gaseous state. Evaporation can only occur when water is available. It also requires that the humidity of the atmosphere be less than the evaporating surface (at 100% relative humidity there is no more evaporation). The evaporation process requires large amounts of energy. Evaporation of water from the soil is controlled by the availability of energy and the rate of water conduction to the soil surface. As the soil dries, energy availability becomes less important and the rate of soil water conduction becomes more important (Ziemer, 1979).

3.11.2 Plant transpiration

Transpiration consists of the vaporization of liquid water contained in plant tissues and the vapor removal to the atmosphere. Crops usually lose their water through stomata. Transpiration rate is influenced by characteristics of crop, environmental aspects and cultivation practices adopted. Transpiration rates vary with different plants. While assessing transpiration, not only the type of crop but also the crop development and local climatic conditions should be considered. Under favorable conditions with ample water supply, when leaves are photosynthesizing at a high rate, plants transpire at a rate similar to evaporation from free body of water at the same temperature, covering the same land area as canopy. This rate may be referred to as the potential transpiration, evaporation or evapotranspiration (Xu. *et al*, 2006).

3.11.3 Leaf area index

Leaf area index is a dimensionless variable and was first defined as the total one sided area of photosynthetic tissues per unit ground surface area (Watson, 1947). LAI is a dynamic parameter as it changes day to day. There are two main methods to measure LAI, direct and indirect (Gower *et al.*, 1999). Direct measurements consists of methods measuring leaf area index directly from field collected data and indirect methods include methods where LAI is derived from more easily measurable parameters (Gower *et al.*, 1999).

3.11.3.1 Leaf area index measurement

Leaf area was measured in the leaf area meter present in the laboratory of Vegetable Science, SKUAST-Kashmir. The instrument is non-portable type and is equipped with a sensor and read out unit. It consists of discs of various sizes to calculate the area of leaves ranging from large to small sized ones. It employs destructive method for measuring of leaf areas as leaves have to be separated from plants. The leaf area meter and measurement of leaf area is shown in Plate 3.14 and Plate 3.15.

Plate 3.14: Leaf area meter

Plate 3.15: Measurement of leaf area

3.12 Statistical analysis

The collected data was statistically analyzed using several statistical parameters *i.e.* root mean square error (RMSE), coefficient of determination (R^2), percent error (PE) and mean bias error (MBE). The statistical indicators are determined using following equations:

3.12.1 Root mean square error (RMSE)

This is an index of the actual error produced by the model and is calculated as (Thomann, 1982):

$$RMSE = \sqrt{\Sigma_{i=1}^{n} \frac{1}{n} (P_i - O_i)^2} \qquad \ldots (3.21)$$

3.12.2 Coefficient of determination (R^2)

Coefficient of determination gauges well data fit a statistical model. This coefficient usually ranges from zero to one. It is calculated as (Bansal *et al.,* 1991):

$$R^2 = \frac{[\Sigma_{i=1}^{n} (O_i - O) \Sigma_{i=1}^{n} = 1(P_i - P)]^2}{\sqrt{\Sigma_{i=1}^{n} (O_i - O)^2 \Sigma_{i=1}^{n} (P_i - P)^2}} \qquad \ldots (3.22)$$

$$\frac{\qquad\qquad}{\mathrm{O_i}}$$

3.12.3 Mean bias error (MBE)

It is the difference between the expected value and the true value of the parameter being estimated. It is calculated as:

$$MBE = \frac{1}{N} \Sigma_{i=1}^{n} (P_i - O_i) \qquad \ldots (3.23)$$

3.13 Closure

This chapter presents different reference evapotranspiration equations and also provides the laboratory and field experiment details carried out to record the important field data needed for study of Apple trees and its soil type. The experiments involve the measurement of soil physical properties, leaf area, canopy cover and soil moisture depletion. The laboratory and field experiments were conducted on the basis of standard procedures provided in the literature cited.

Chapter - 4

RESULTS AND DISCUSSIONS

In this study, daily moisture depletion was recorded at regular intervals for the cropping period (April-July) of apple tree and different models were used to estimate the crop evapotranspiration of apple trees. Further crop evapotranspiration was later partitioned into evaporation and transpiration. The result and discussion of the study are described under following headings:

4.1 Soil matric potential and soil moisture depletion

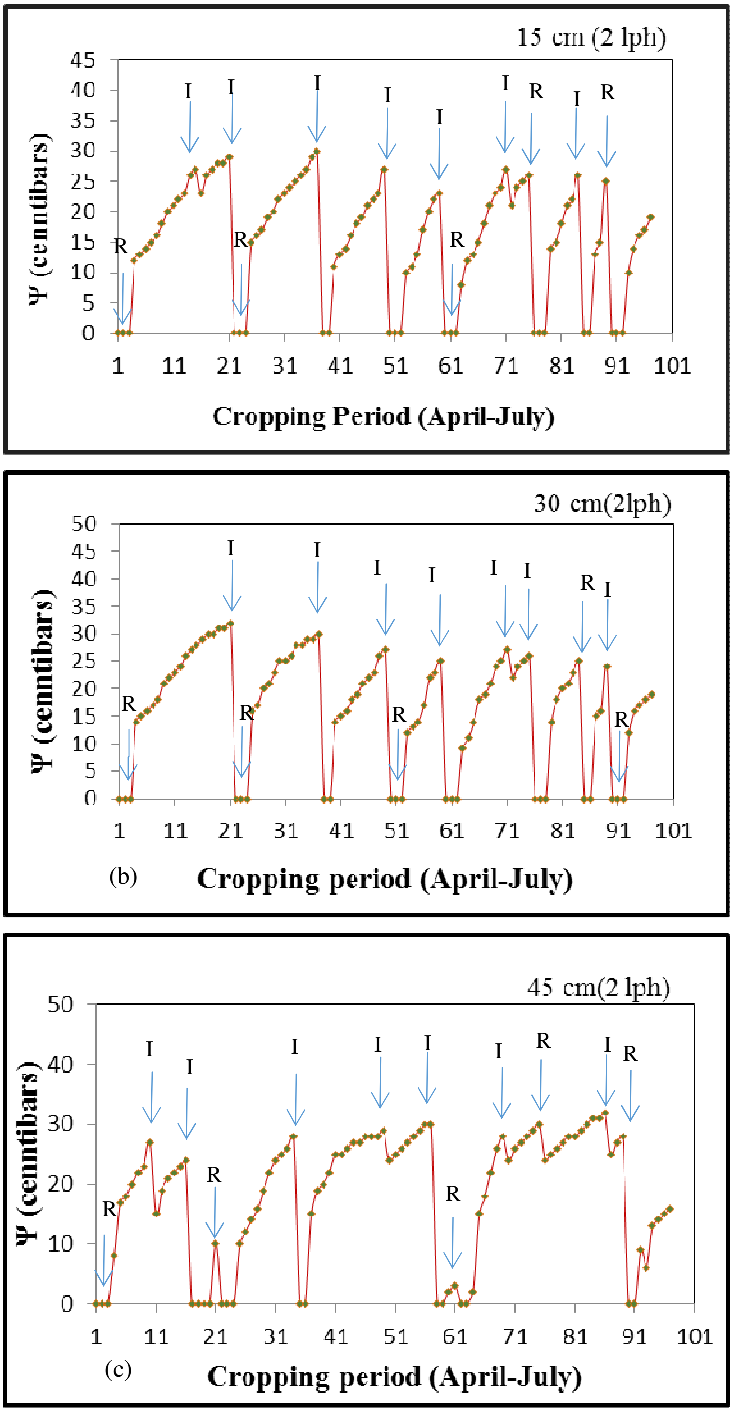
4.2 Crop evapotranspiration

4.3 Partitioning of crop evapotranspiration

4.1 Soil matric potential and Soil moisture depletion

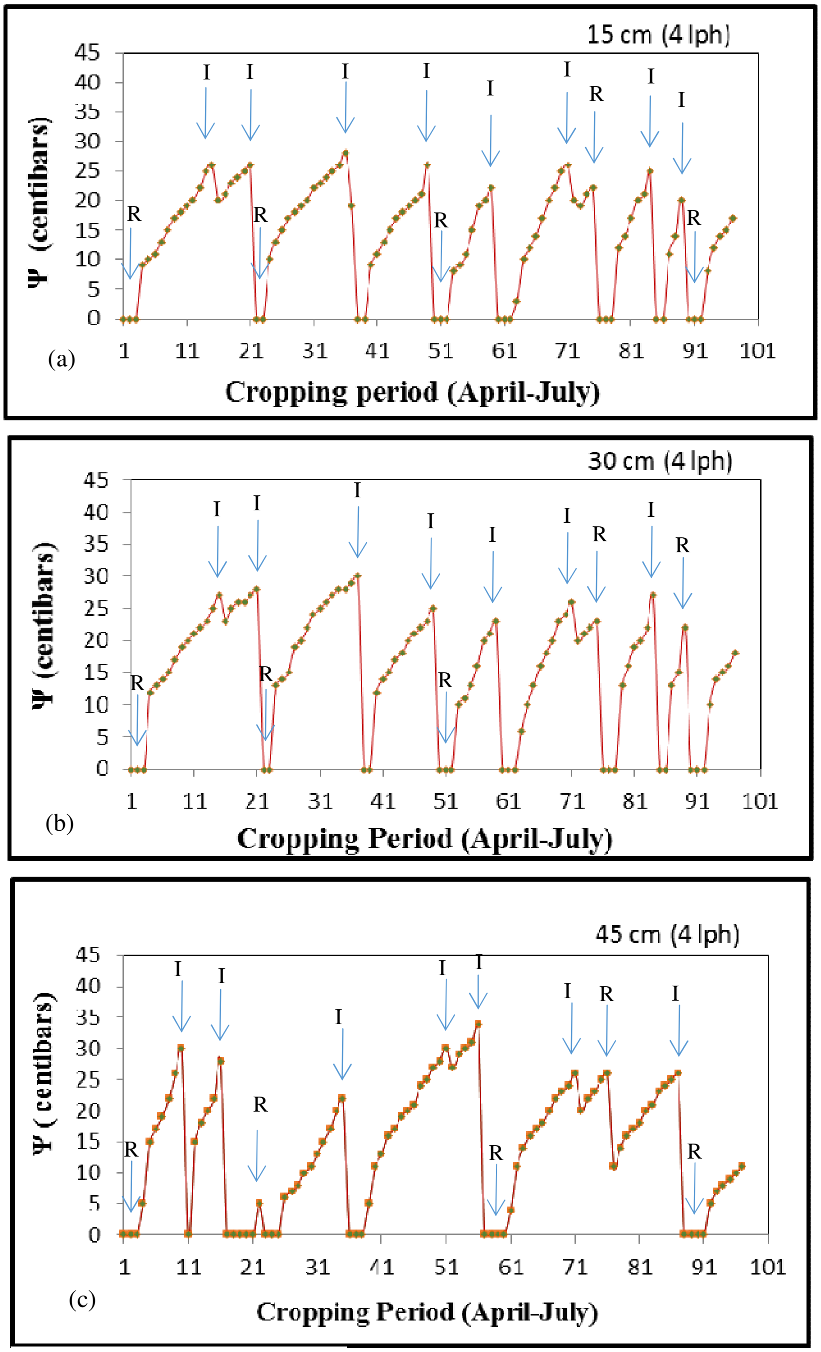
4.1.1 Soil matric potential (Ψ)

Soil moisture sensors were installed at depths of 15, 30 and 45 cm of the root zone of the plant. These sensors gave the soil water potential at different depths. Soil water potential was recorded between two irrigations or between two rainfall events. The graph plotted between soil water potential and duration of crop is shown in Fig. 4.1 (a-c) - 4.3 (a-c) for 2, 4 and 8 lph dripper capacity, respectively. It is evident from Fig. 4.1- 4.3 that soil water potential reading was zero on the day of applied irrigation and rainfall showing that soil is fully saturated. As the time elapsed the water potential reading increased. It is illustrated in graphs that irrigation was applied when the water potential reading vary in the range of 25-35 centibars. It is evident from Fig. 4.1(a-c) that the soil water potential was observed to be highest on 27th May, 2016 at 15 cm depth. Whereas, soil matric potential was observed to be highest on 11th May, 2016 and 15th July, 2016 at 30 cm and 45 cm soil depths respectively. The highest values were attained by Soil water potential due to no rainfall and long irrigation intervals on these days, because of which soil was completely dry and in urgent need of moisture. Since, the moisture depletes very fast in upper part of root zone, it was observed that water potential reached its maximum value at the 15 cm soil depth much earlier than deeper layers *i.e.* 30 cm and 45 cm where water remains



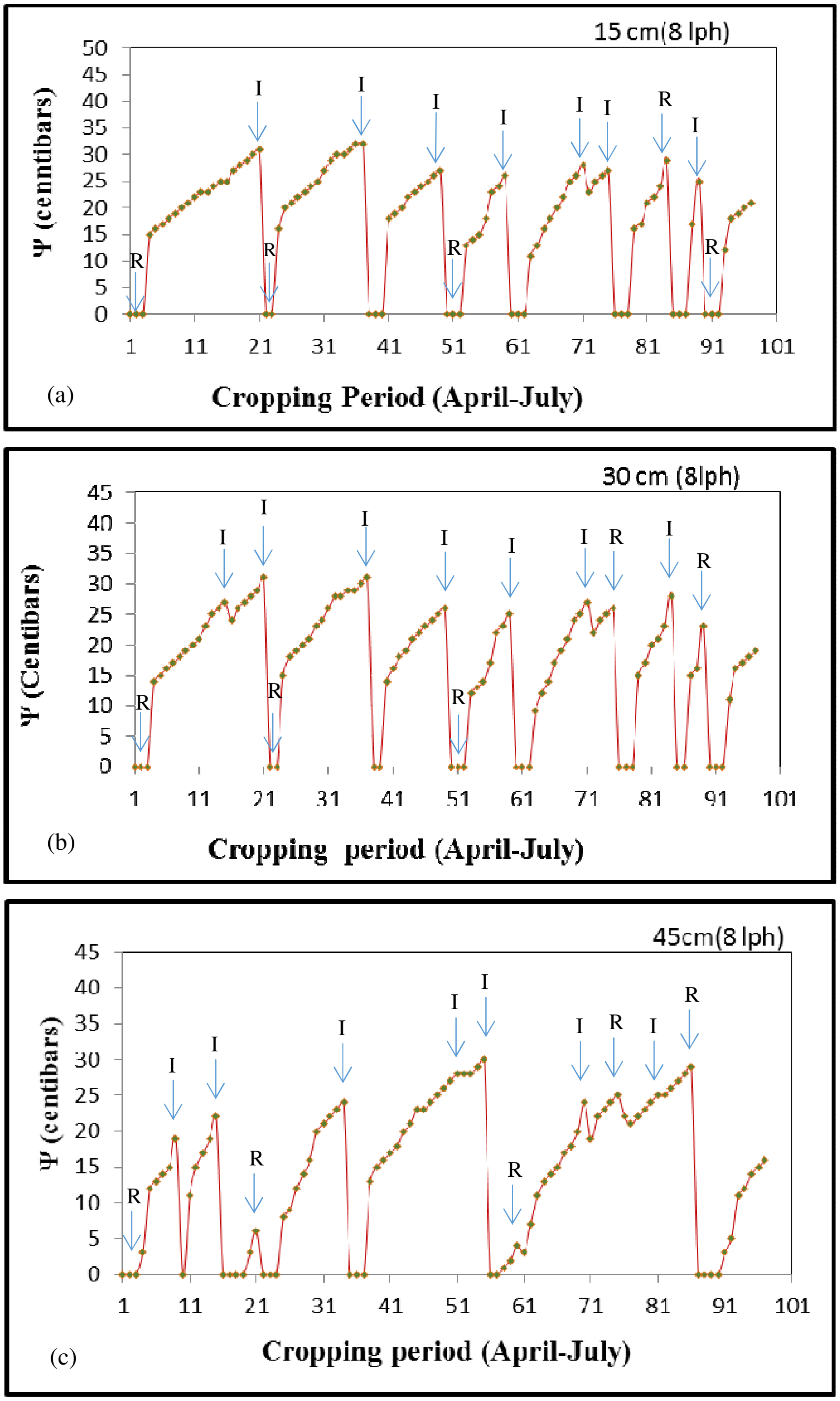
I = Irrigation; R : Rain

Fig. 4.1(a-c): **Soil water potential fluctuation using 2 lph capacity emitter during an irrigation season as measured using sensors install at (a) 15, (b) 30 and(c) 45cm**



I = Irrigation; R : Rain

Fig. 4.2(a-c): Soil water potential fluctuation using 4 lph capacity emitter during an irrigation season as measured using sensors installed at (a) 15, (b) 30 and(c) 45 cm



I = Irrigation; R : Rain

Fig 4.3(a-c): **Soil water potential fluctuation using 8 lph capacity emitter during an irrigation season as measured using sensors installed at (a) 15, (b) 30 and (b) 45 cm**

available to plant for longer duration and depletes slowly The results illustrated in the graph also shows that during development and fruiting stages of crop soil suction reading has increased *i.e*. moisture depletion is more during that period.

It is evident from Fig. 4.2 (a-c) that the highest soil water potential was observed on 23rd May, 2016 at 15 cm depth. Whereas, soil matric potential was observed to be highest on 29th May, 2016 at 30 cm soil depth. Soil matric potential was found to be highest on 17th June, 2016 at 45 cm soil depth. Soil potential reached its highest values on these days due to no rainfall and long irrigation intervals because of which soil was completely dry and in urgent need of moisture.

It is illustrated from Fig. 4.3 (a-c) that the highest soil water potential was observed on 22th May, 2016 at 15 cm depth. Whereas, soil matric potential was observed to be highest on 28th May, 2016 and 15th June, 2016 at 30 and 45 cm soil depth, respectively. Soil potential reached its highest values on these days due to no rainfall and long irrigation intervals because of which soil was completely dry and in urgent need of moisture.

4.1.2 Moisture depletion

Idea about availability of moisture for plant uptake is given by soil moisture status at different root depths in the root zone. It indicates the part of crop root zone, most susceptible to moisture depletion. The duration between two rainfall events, and two irrigation events was selected for computing moisture depletion for the study area. The graph was plotted between the volumetric moisture content (θ_s) and days after planting (DAP) as shown in Fig. 4.4-4.6.

It is evident from Fig 4.4 that on using 2 lph capacity emitter, minimum moisture depletion occurs in the initial months of the study period due to lesser plant canopy (Shankar *et al.*, 2012; Kumar *et al.*, 2013). Moisture depletion increases considerably in the development stage due to rise in temperature and maturity attained by plant. Since in the month of July the canopy reaches 80-90% of the full shape and fruits begin to develop intensively, the water use of apple tree reaches its maximum value.

It is evident from Fig.4.5 that on using 4 lph capacity emitter, minimum

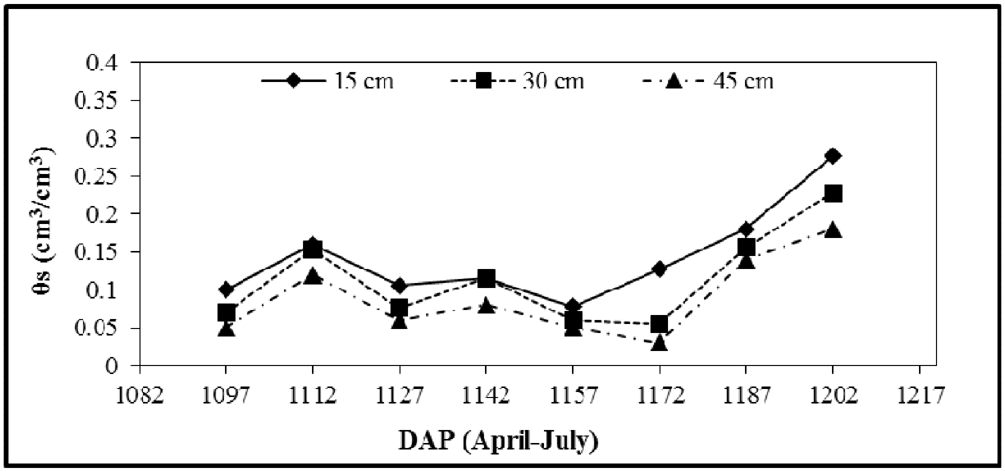


Fig 4.4: Soil moisture status for the crop period using 2 lph emitter for Apple at different depth

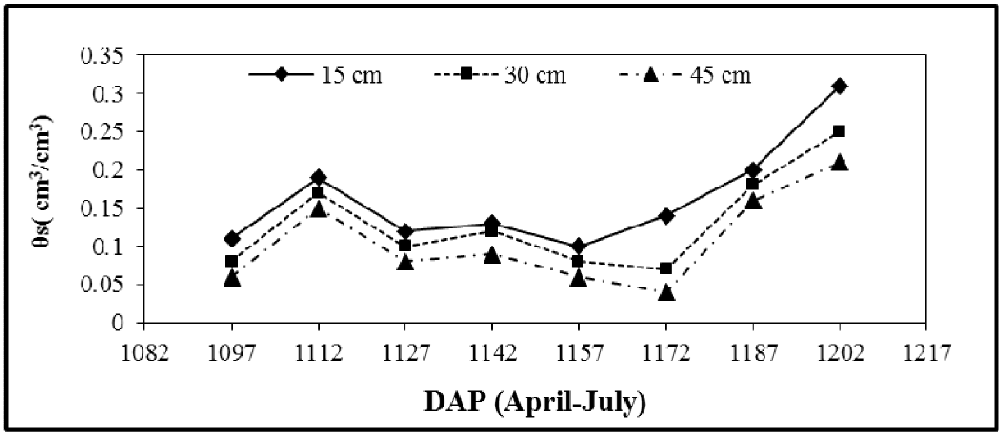


Fig. 4.5: Soil moisture status for the crop period using 4 lph emitter for Apple at different depth

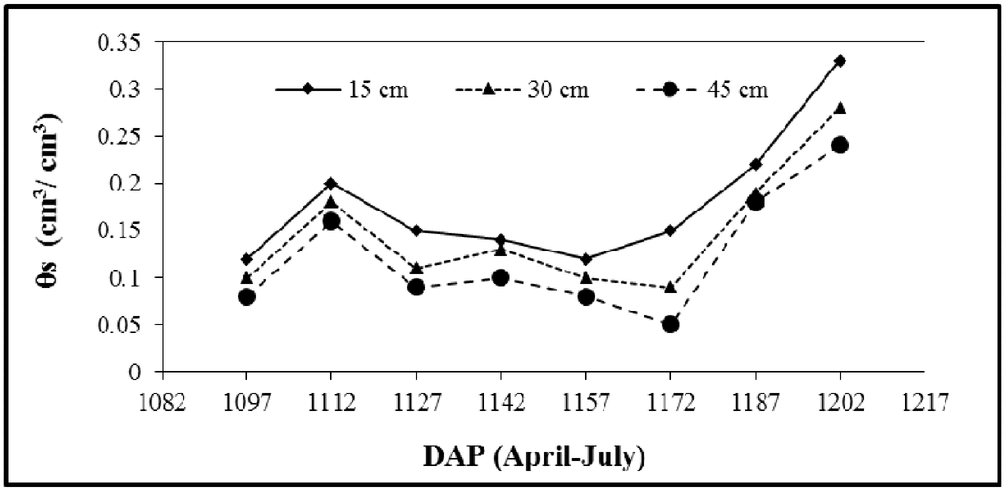


Fig. 4.6: **Soil moisture status for the crop period using 8 lph emitter for Apple at different depth**

depletion of moisture occurs in the initial months of the study period due to lesser plant canopy. There is a considerable increase in the moisture depletion in the development stage as the temperature has started rising and the plant has attained maturity. In the month of July the water use of apple trees is the largest because the canopy has reached the 80-90 percent of the full shape and the fruit begin to develop very intensively.

Fig 4.6 clearly indicates that water requirement of apple tree is less in initial months which results in minimum moisture depletion during this period. In the development stage when the temperature starts rising and the plant attain maturity, there is a considerable increase in moisture depletion which is due to the increase in water use of apple trees.

Moisture depletion along the depth was also determined for the study period. The variation of moisture depletion for 1097-1202 DAP (April-July) is shown in Fig. 4.7-4.10. It illustrated from Fig. 4.7 that the maximum depletion of moisture takes place in the top 15 cm layers of soil and is considerably less in the lower layers. Similar trend is observed over the entire study period. In the upper part of the root zone where root density is high, moisture depletes very fast, whereas in the lower part of the root zone sufficient moisture for the plant is continuously available (Shankar *et al.*, 2012; Kumar *et al.*, 2013).

Fig 4.7-4.10 shows a constant trend in moisture depletion pattern along the whole crop period using different capacity emitters. Although, the same volume of water is given to each tree through 2, 4 and 8 lph capacity emitters at different time intervals, maximum moisture depletion is observed to occur on using the 8 lph drippers at 15, 30 and 45 cm soil depth. This is due to the reason that more amount of water remains available to plant.

4.1.3 Crop water requirement

4.1.3.1 Reference evapotranspiration

Different models viz: Penman Monteith, Blaney-Criddle, Modified Penman, Hargreaves-Samani, Priestly Taylor and Open pan were used to estimate reference evapotranspiration. These models performed on the basis of climatic data and modified crop coefficient.

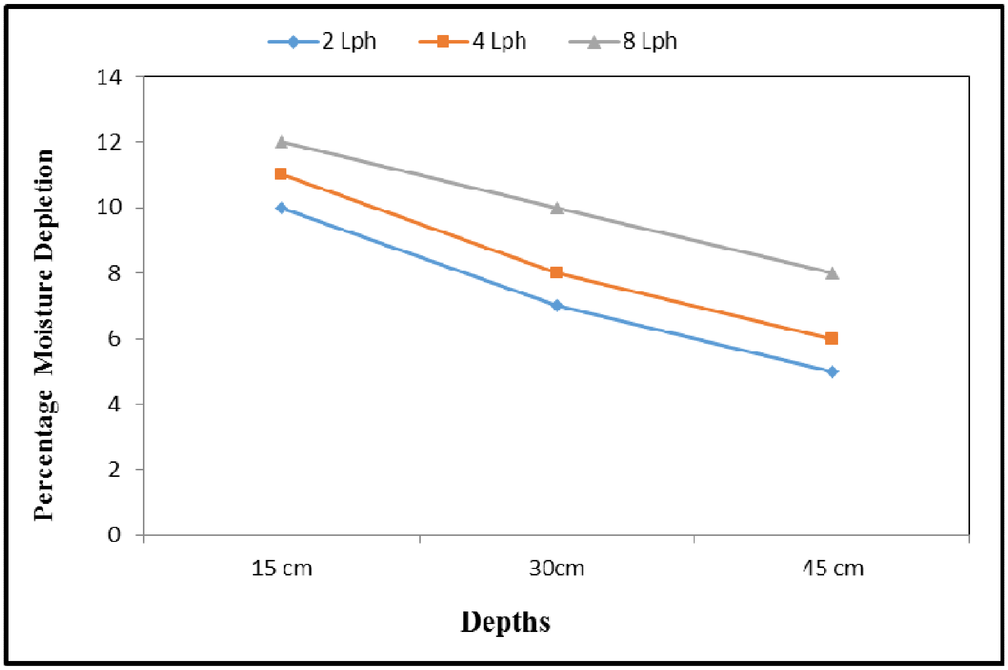


Fig. 4.7: Moisture depletion for the period 1097-1112 DAP (April) for apple

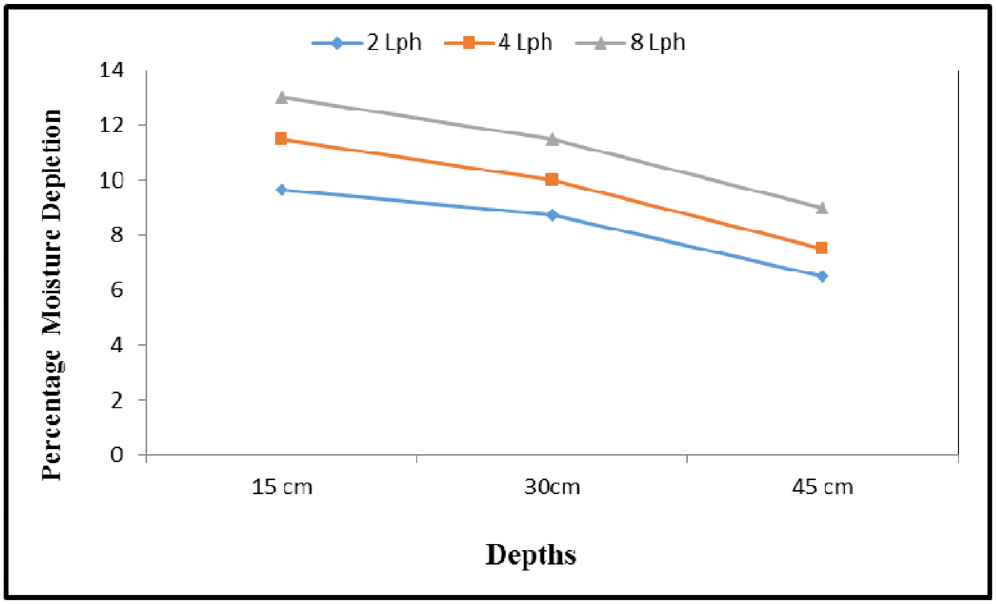


Fig. 4.8: Moisture depletion for the period 1127-1142 DAP (May) for apple

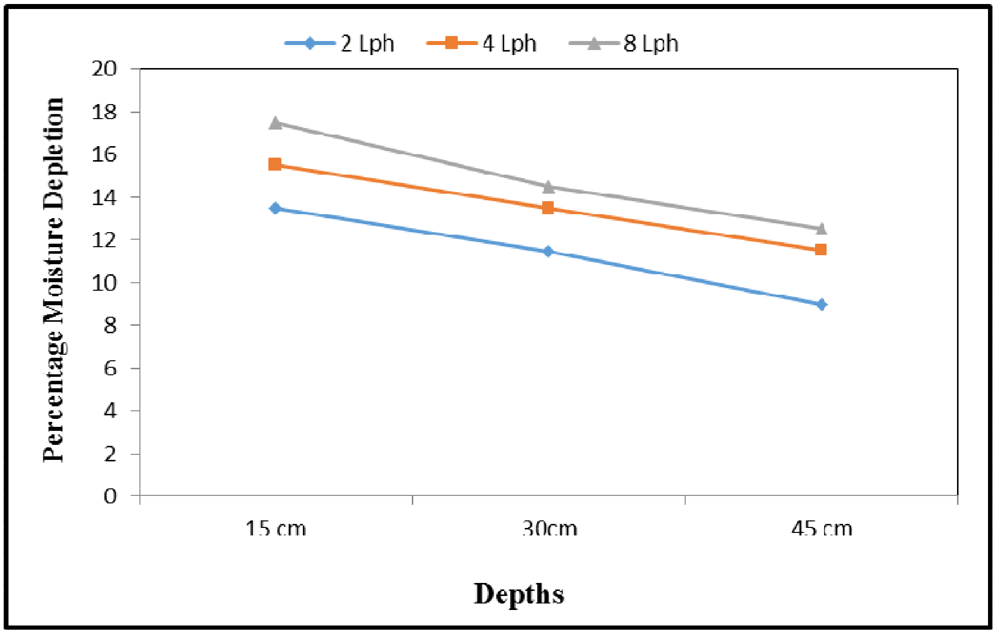


Fig. 4.9: Moisture depletion for the period 1157-1172 DAP (June) for apple

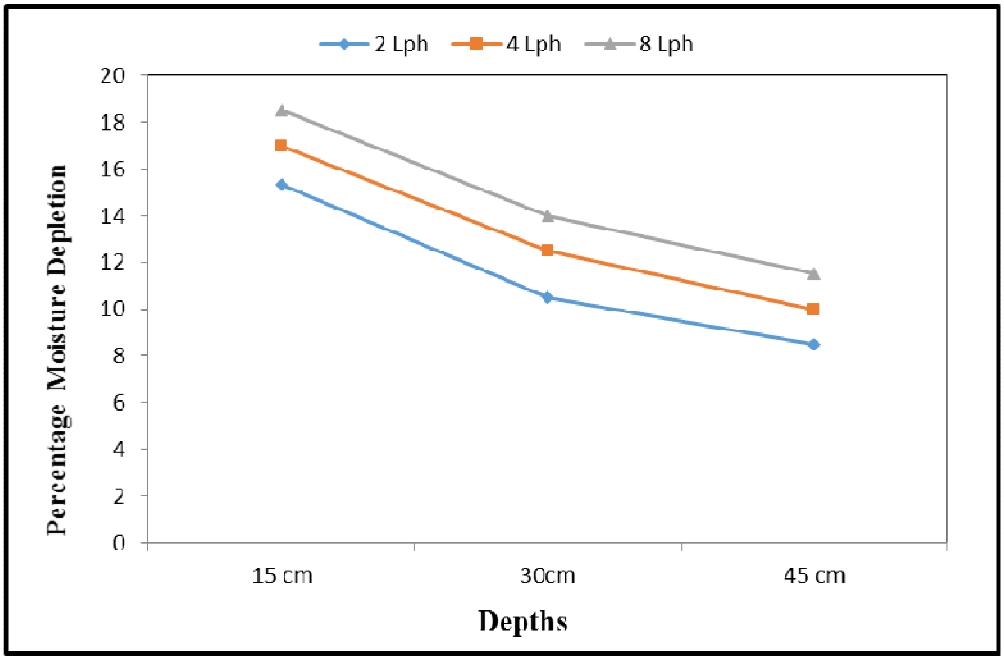


Fig. 4.10: Moisture depletion for the period 1187-1202 DAP (July) for apple

The results of reference evapotranspiration during the cropping period (April-July) of Apple are summarized in Table 4.1 and illustrated in Fig. 4.11 and 4.12. The monthly and average ET_o are shown in Fig. 4.11 and Fig 4.12. It is evident from Fig 4.11 that maximum evapotranspiration occurs during the months of May-July and starts decreasing August onwards. Difference in ET_o is attributed to combined effect of temperature, radiation, wind speed, sunshine hours and humidity.

Table 4.1: Reference evapotranspiration (ET_o) for the year 2016

Months	Models					
	Modified Penman	Hargreaves-Samani	Blaney-Criddle	Priestly-Taylor	FAO Penman-Monteith	Open Pan
	mm/day					
January	1.0	1.3	0.4	1.1	0.8	0.6
February	1.8	2.1	1.4	2.0	1.5	1.3
March	2.4	2.6	1.8	0.7	2.0	1.2
April	2.8	3.6	1.9	1.2	2.4	1.9
May	4.1	5.5	3.7	0.9	3.6	2.4
June	5.1	6.3	5.0	0.9	4.5	3.8
July	4.7	5.8	4.7	0.9	4.1	3.6
August	3.8	4.6	3.6	4.6	3.4	3.3
September	3.5	4.7	3.7	6.7	3.1	3.1
October	3.4	4.4	3.4	6.3	2.9	3.0
November	1.0	2.3	1.5	3.2	1.1	0.9
December	1.3	2.1	1.3	3.1	0.8	0.6

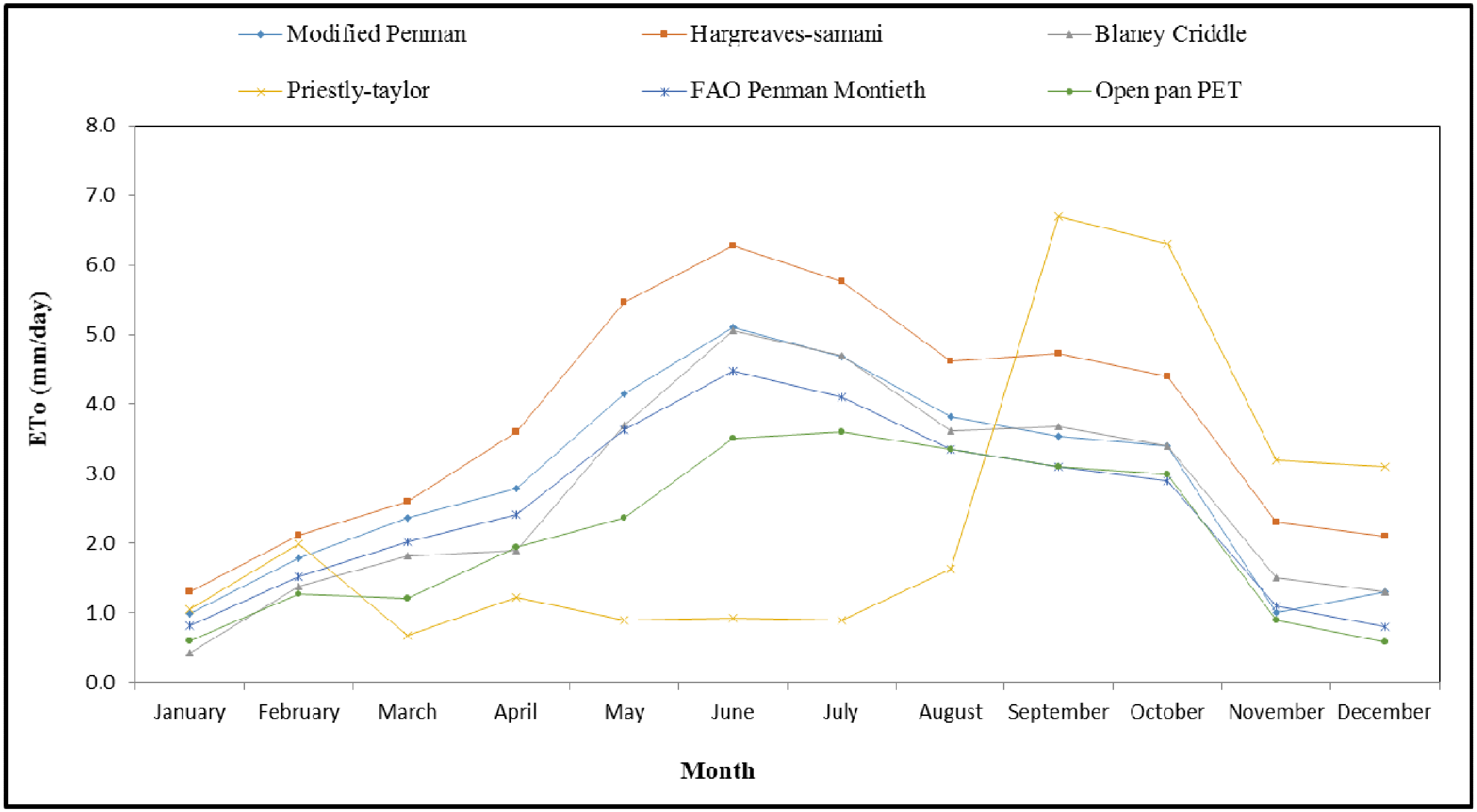


Fig. 4.11: Monthly average reference evapotranspiration (ET_o) from Jan-Dec 2016

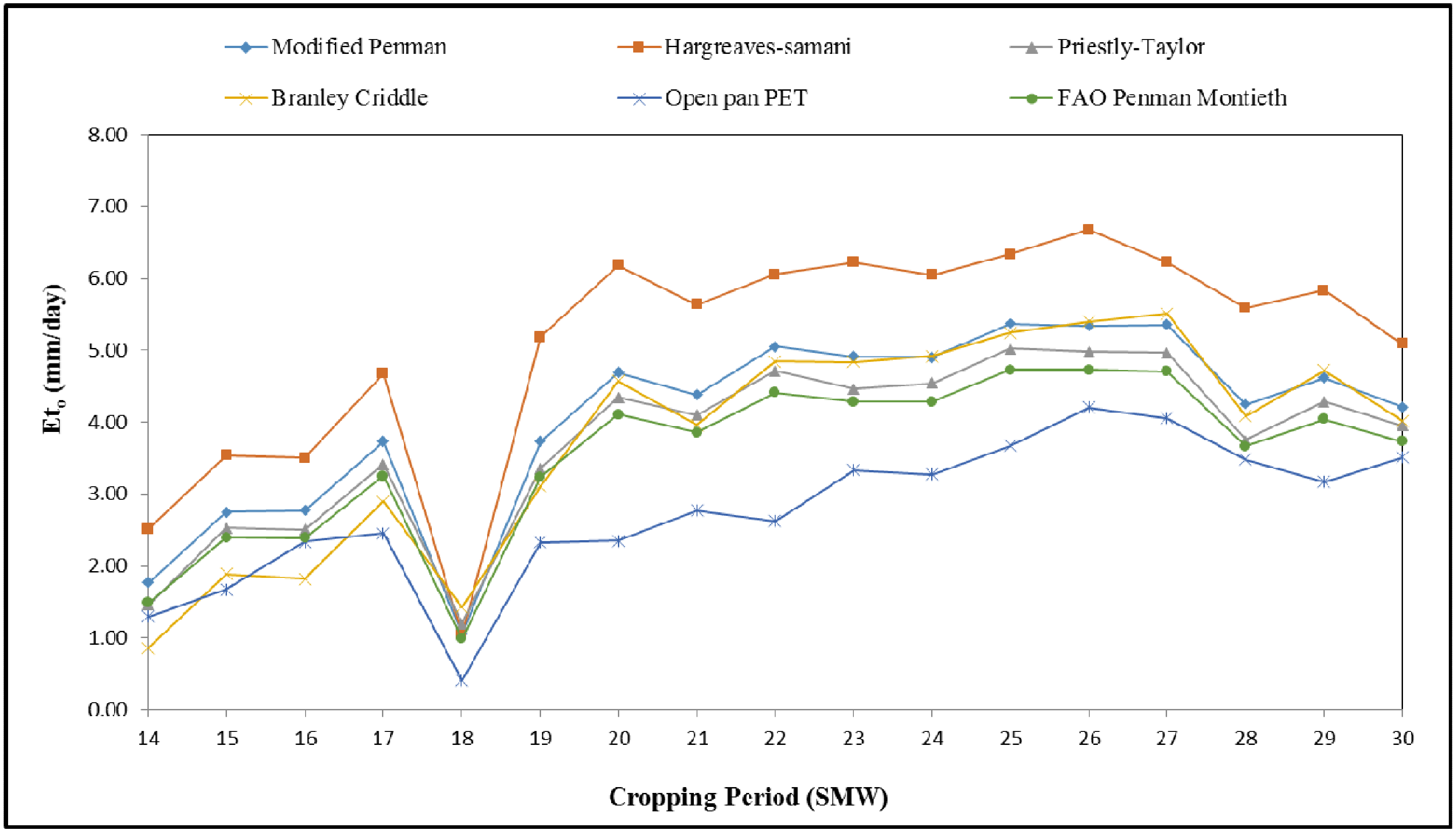


Fig. 4.12: Weekly average reference evapotranspiration (ET$_o$) for the cropping period (April-July) of apple

4.1.3.2 Crop coefficient

The crop coefficient was modified for the local conditions using the FAO recommended procedure (Allen *et al.,* 1998). Crop coefficient curve for the local conditions was developed for Apple according to the FAO-56 method. The FAO-56 recommended curve is based on the estimated values of crop coefficients. Crop coefficient is measured for different stages of Apple viz: initial, mid and end which are denoted as $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ respectively.

The modified crop coefficient curve developed for local conditions of Apple is shown in Fig. 4.13. It is evident from the Fig. 4.13 that modified crop coefficient for initial, mid and end stages of Apple are 0.6, 1.00 and 0.75 respectively. The details of recommended and modified K_c values are shown in Table 4.2.

Table 4.2: Modified values of FAO recommended crop coefficients for local conditions

Crop	Crop Coffecient								
Apple	$K_{c\ ini}$			$K_{c\ mid}$			$K_{c\ end}$		
	FAO Value	**Modifying Parameters**	**Modified Value**	**FAO Value**	**Modifying Parameters**	**Modified Value**	**FAO Value**	**Modifying Parameters**	**Modified Value**
	0.6	$K_{c\ ini}$ (heavy wetting=1.20 $K_{c\ ini}$ (light wetting)=0.85	0.65	1.2	U2= 2.07 m s^{-1} RH_{min}= 56.32 H=2.6 m	1.00	0.85	U2= 2.07 m s^{-1} RH_{min}= 54.64 H=3.1 m	0.75

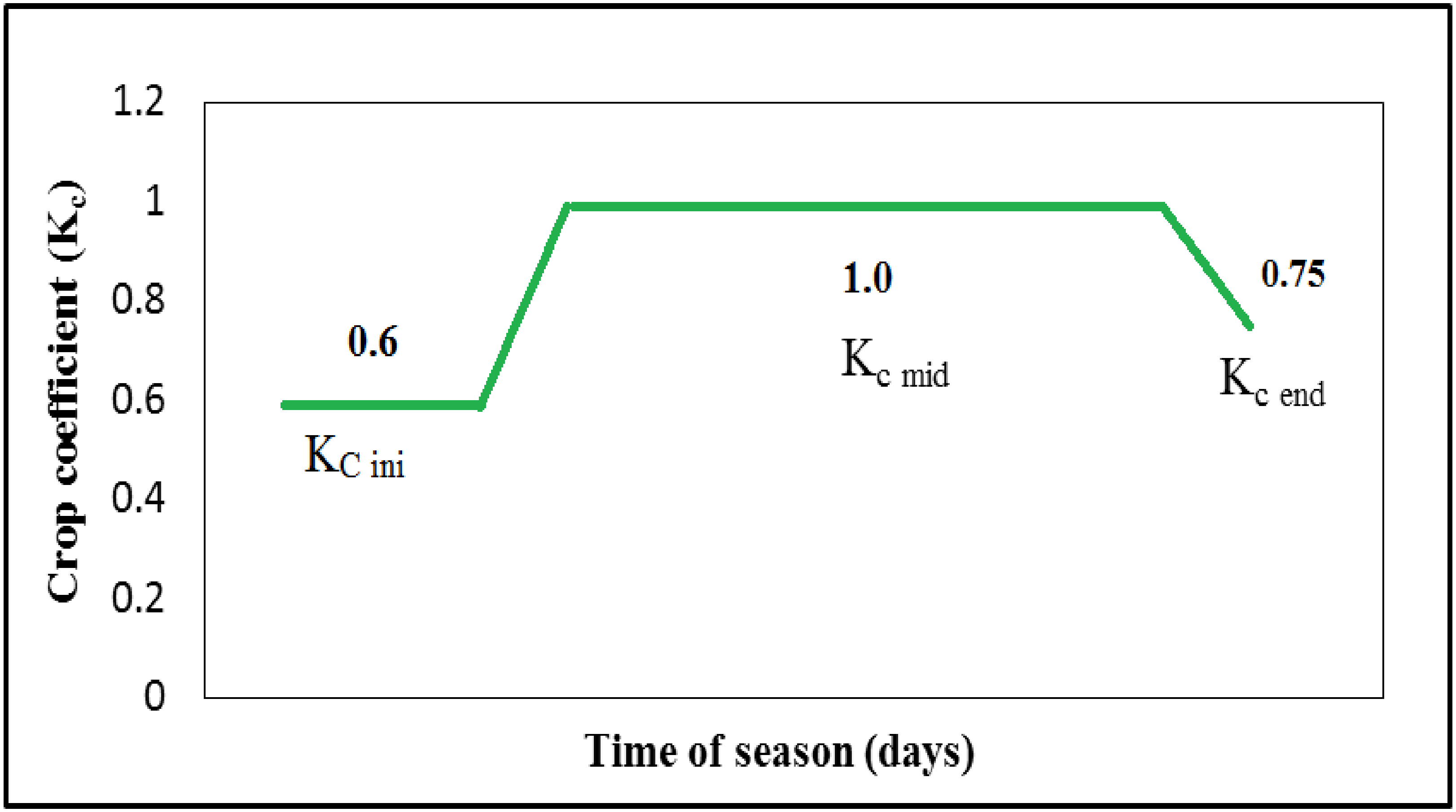


Fig. 4.13: Modified crop coefficient curve

4.2 Crop evapotranspiration

The crop evapotranspiration was calculated by multiplying the reference ET value obtained from the reference ET models with the crop coefficient, from 21st April, 2016 - 30th July, 2016. The crop evapotranspiration with modified K_c value for the year 2016 is shown in Table 4.3 and illustrated in Fig. 4.14-4.15. It was observed that the crop evapotranspiration is lower during the initial months of planting and its value increases as the plant growth progresses. It is clearly evident from Fig. 4.14-4.15 that the maximum water requirement of crop is observed during the months of May-July. In order to find out the best suited crop evapotranspiration model for the local agro-climatic conditions the FAO Penman-Monteith model was taken as standard.

It is evident from Table 4.3 that water requirement of crop was low in initial months of growth stage, increased towards development stage, reached maximum values of 3.2 mm/day in May 2016, 4.0 mm/day in June 2016 and 3.3 mm/day in July 2016.

In case of the apple tree, comparison between cumulative crop evapotranspiration obtained from different models have been shown in Fig. 4.16. It is evident that, crop evapotranspiration computed using Open Pan and Hargreaves-Samani overestimate as compared to Penman-Monteith values of stage wise crop evapotranspiration. The cumulative evapotranspiration corresponding to Open Pan and Hargreaves-Samani show higher difference with Penman-Monteith values, whereas, Priestley Taylor, Modified Penman and Blaney-Criddle show smaller difference.

Table 4.3: Crop evapotranspiration (ET_C) for the year 2016

Months	**Models**					
	Modified Penman	**Hargreaves-Samani**	**Blaney-Criddle**	**Priestly-Taylor**	**FAO Penman-Monteith**	**Open Pan**
	mm/day					
January	0.6	0.8	0.3	0.6	0.5	0.4
February	1.1	1.3	0.8	1.2	0.9	0.8
March	1.4	1.6	1.1	0.4	1.2	0.7
April	2.6	3.4	1.8	1.2	2.3	1.8
May	3.9	5.2	3.5	0.9	3.4	2.2
June	4.9	6.0	4.8	0.9	4.3	3.3
July	3.5	4.6	4.2	0.9	3.5	3.2
August	2.9	3.5	2.7	1.2	2.5	2.8
September	2.7	3.5	2.8	3.0	2.3	2.3
October	2.6	3.3	2.6	3.1	2.2	2.2
November	0.8	1.7	1.1	2.4	0.8	0.7
December	0.9	1.6	1.0	2.3	0.6	0.4

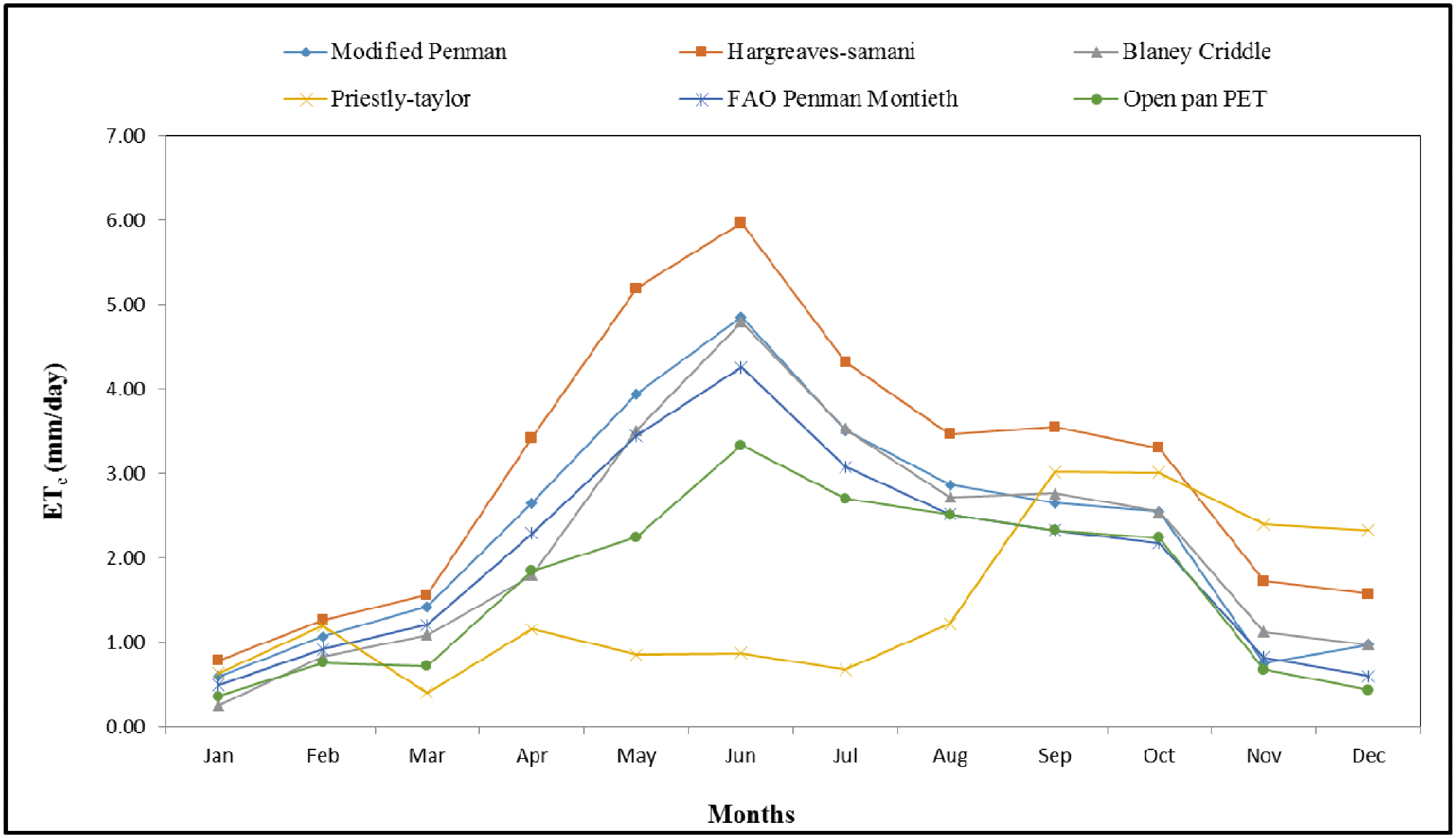


Fig. 4.14:Monthly average crop evapotranspiration (ET_c) for the cropping period (April-July) of apple

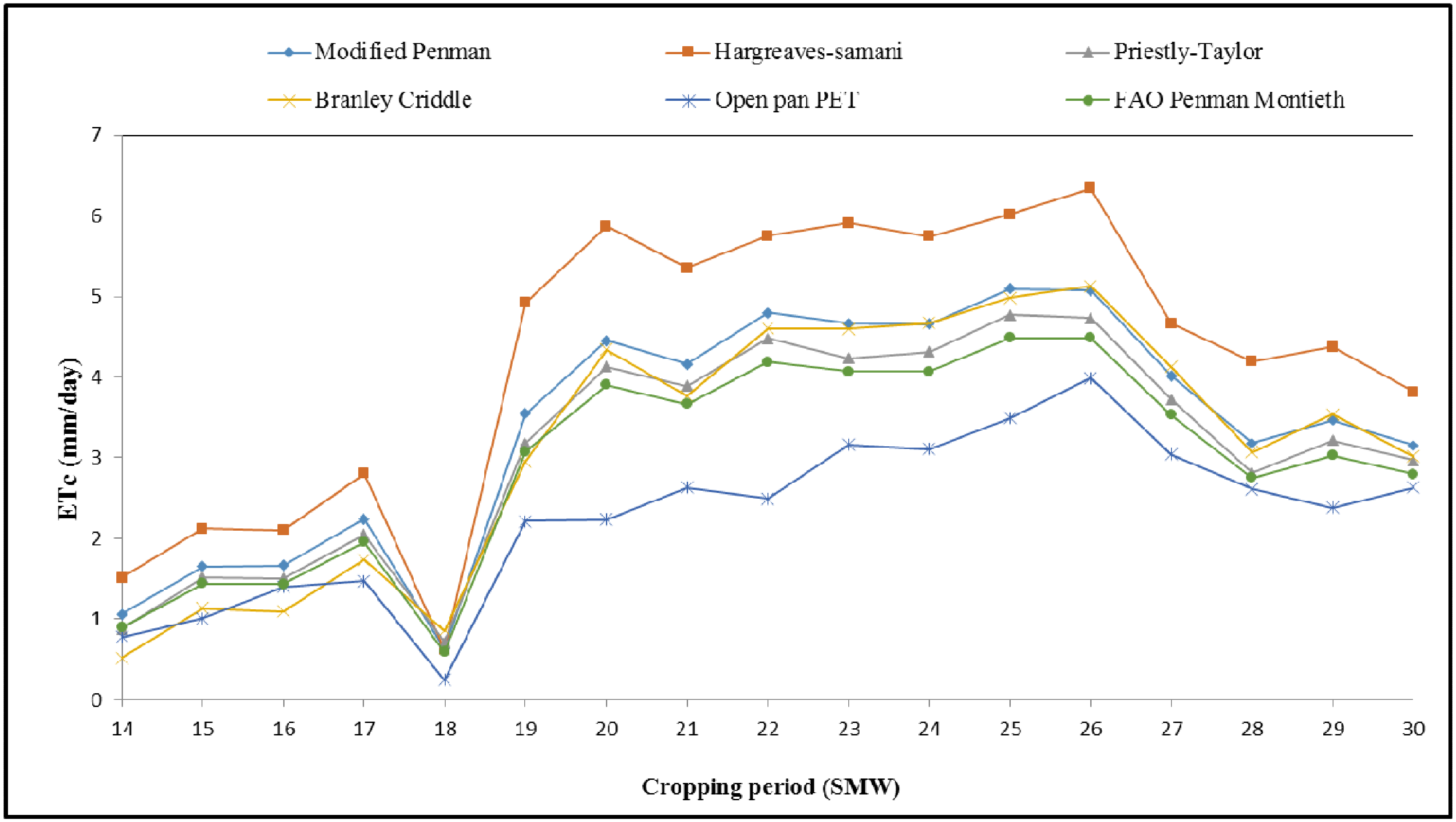


Fig. 4.15: Weekly average crop evapotranspiration (ET_c) for the cropping period (April-July) of apple

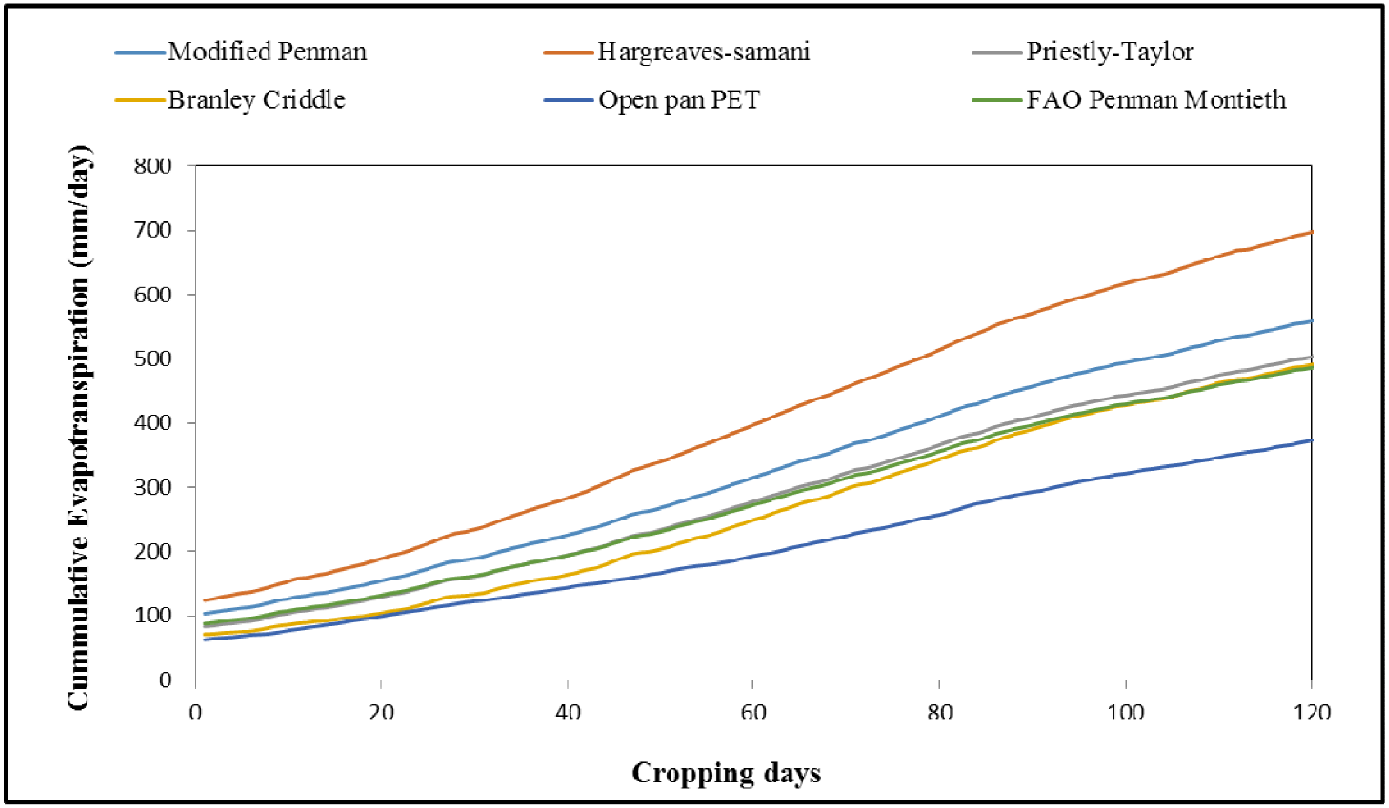


Fig. 4.16 Cumulative crop evapotranspiration for apple

Table 4.4: Statistical analysis of crop ET with field observed value

ET Models	R^2	RMSE (mm/day)	MBE (mm/day)
Modified Penman	0.98	0.07	0.16
Hargreaves-Samani	0.78	0.45	1.28
Priestly-Taylor	0.96	0.19	0.42
Blaney-Criddle	0.97	0.14	0.22
Open Pan	0.86	0.27	0.67

It is illustrated from Table 4.4 that the Modified Penman equation shows close agreement with observed value as compared other models. The Penman Monteith model gives R^2: 0.98, RMSE: 0.07 mm/day and MBE: 0.16 mm/day. Similar results have been obtained by Allen *et al.*, 1994; Itenfisu 2003; Kumar *et al.*, 2012. The results of Blaney-Criddle model has shown second best performance (R^2 = 97, RMSE = 0.14 mm/day and MBE: 0.22 mm/day) among the other methods. Hargreaves equation is not suitable method for estimation of crop evapotranspiration for present location due to the high overestimations and RMSE 0.45 mm/day.

4.2.1 Crop water requirement using CROPWAT

Models play a very important role in developing practical recommendations for optimizing crop production under conditions of scarce water supply. CROPWAT model was used to simulate the crop water requirement for Apple. The input files were used to calculate the reference evapotranspiration and effective rainfall in the first step. The model calculated the crop water requirement on the basis of the crop and soil data. The variation of reference evapotranspiration with different climatic parameters is shown in Fig. 4.17-4.20.

It is evident from Fig. 4.17 that temperature has a significant effect on reference evapotranspiration. Higher temperature gives higher evapotranspiration. Fig. 4.18 indicates a strong relationship between sunshine hours and evapotranspiration. With the increase in sunshine hours there is the corresponding increase in evapotranspiration. It is found in Fig. 4.19 that low evapotranspiration corresponds to higher relative humidity. From Fig. 4.20, we conclude that wind

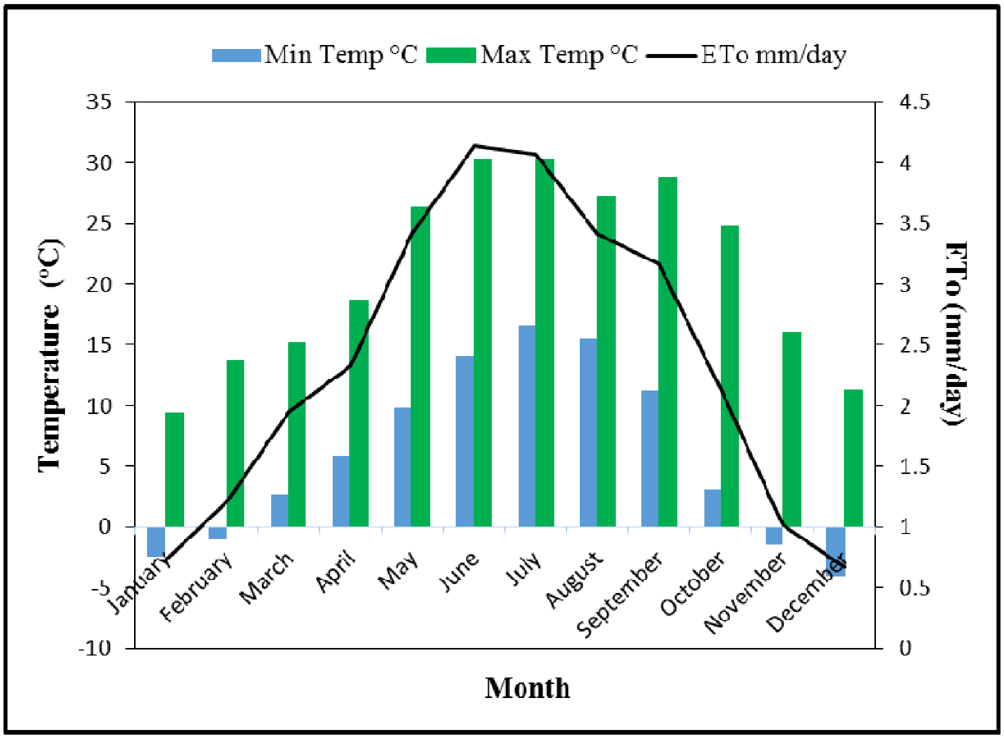


Fig. 4.17: Reference evapotranspiration with minimum and maximum temperature variation

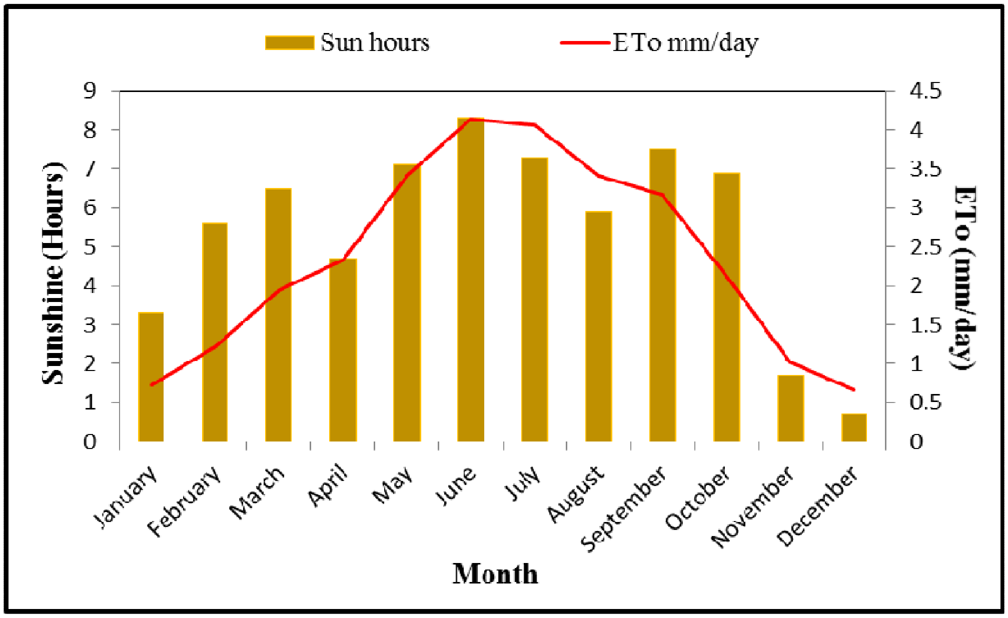


Fig. 4.18: Reference evapotranspiration with sunshine hours

speed does not have any effect on evapotranspiration as it ranges from low to moderate for the study area (Abdalla *et al.*, 2009).

CROPWAT uses Penman-Monteith equation for calculating reference evapotranspiration. The reference evapotranspiration obtained from CROPWAT is illustrated in Fig. 4.21. It is evident from Fig. 4.20 that evapotranspiration was low during the January-April months of 2016, increased in May-July for the study area. The reference ET reached maximum value of 4.14 mm/day in the month of June, 2016 and declined in October-December months. It can clearly be observed that evapotranspiration is low in rainy seasons and high in dry seasons (Abdalla *et al.*, 2009). The variation in ET_O is due to combined effect of changes in climatic data.

The details of irrigation requirement and crop ET are illustrated in Fig. 4.22. It is indicated in Fig. 4.22 that maximum crop evapotranspiration was found to be 43.5 mm/decade during the month of august with corresponding irrigation requirement 40.75 mm/decade. The irrigation requirement for the entire crop period is 1155.75 mm/dec.

The observed crop evapotranspiration calculated by multiplying Penman-Monteith equation with modified Kc values, and simulated evapotranspiration are illustrated in Fig. 4.23. Fig. 4.23 indicates the close relationship between observed and simulated values of reference ET.

The scatter plot (Fig. 4.24) between the observed and simulated values of crop evapotranspiration shows that the data points are even and closely distributed along the 1:1 line.

The statistical analysis of crop water requirement using CROPWAT model is shown in Table 4.5 which shows that there is a really close agreement between simulated and observed values of crop evapotranspiration with values of R^2, RMSE, percent error and MBE equal to 0.99, 0.18 mm/day, 9.90 and 0.15 mm/day, respectively. Overall CROPWAT model was found suitable for simulation of crop water requirement in the given agro climatic conditions of the study area.

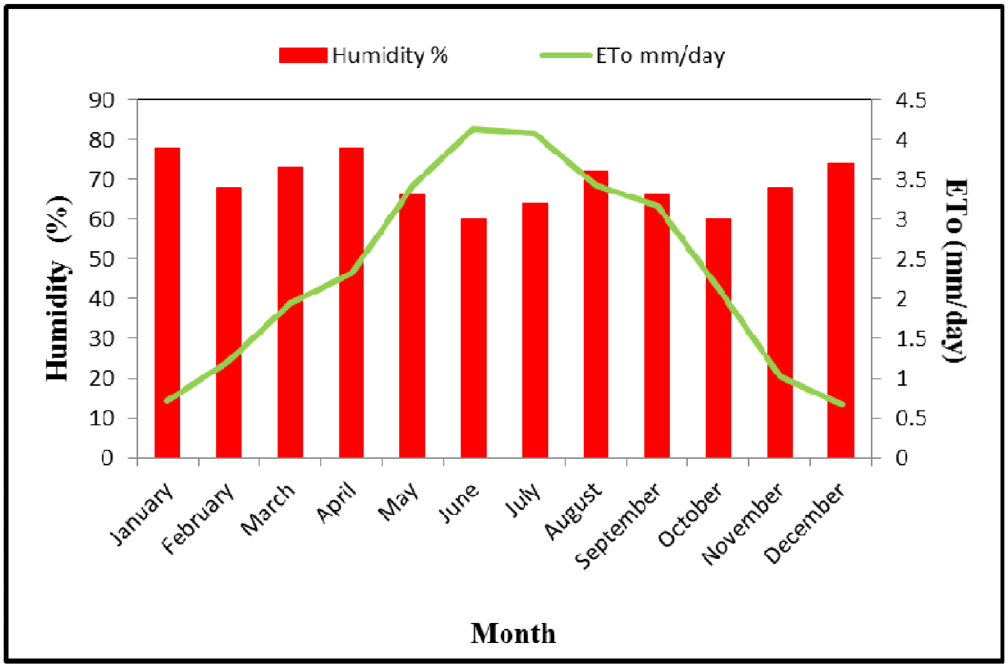


Fig. 4.19: Reference evapotranspiration with relative humidity

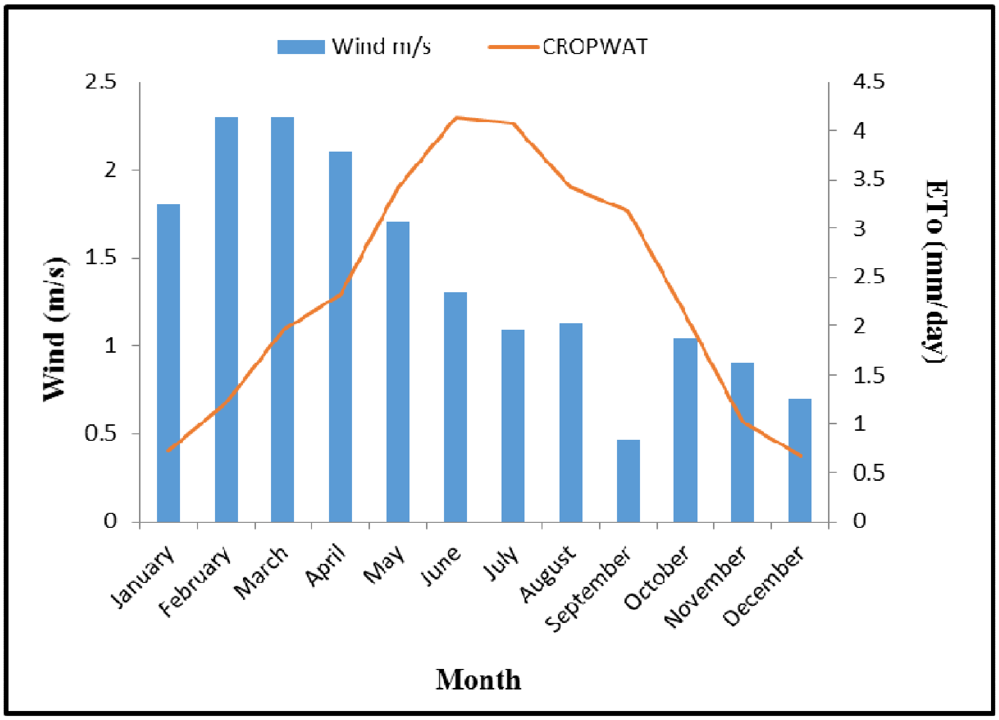


Fig. 4.20: Reference evapotranspiration with wind speed

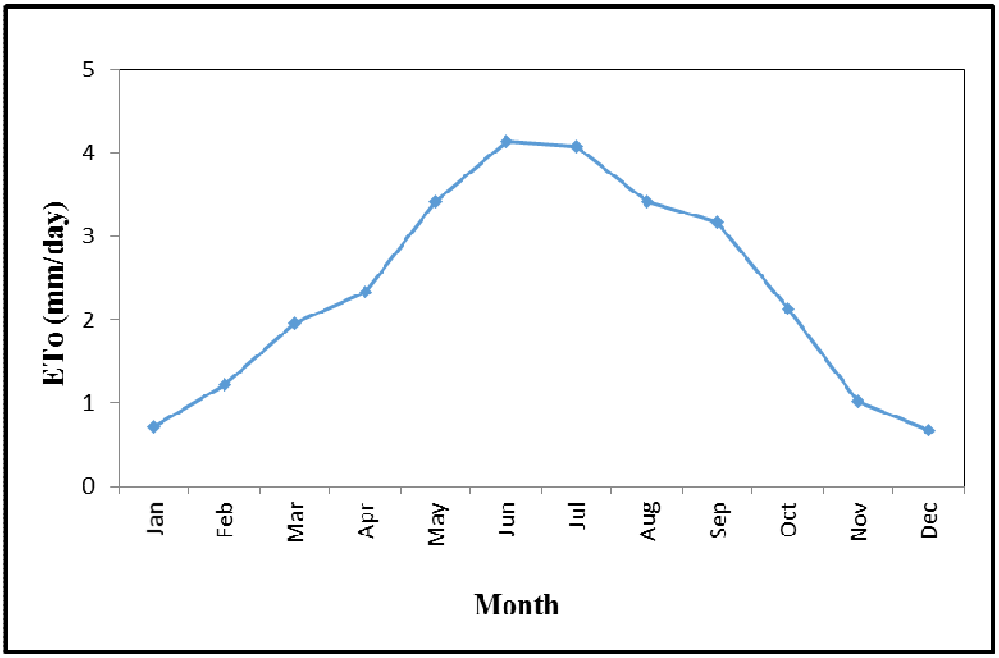


Fig. 4.21: Reference evapotranspiration for 2016 from CROPWAT model

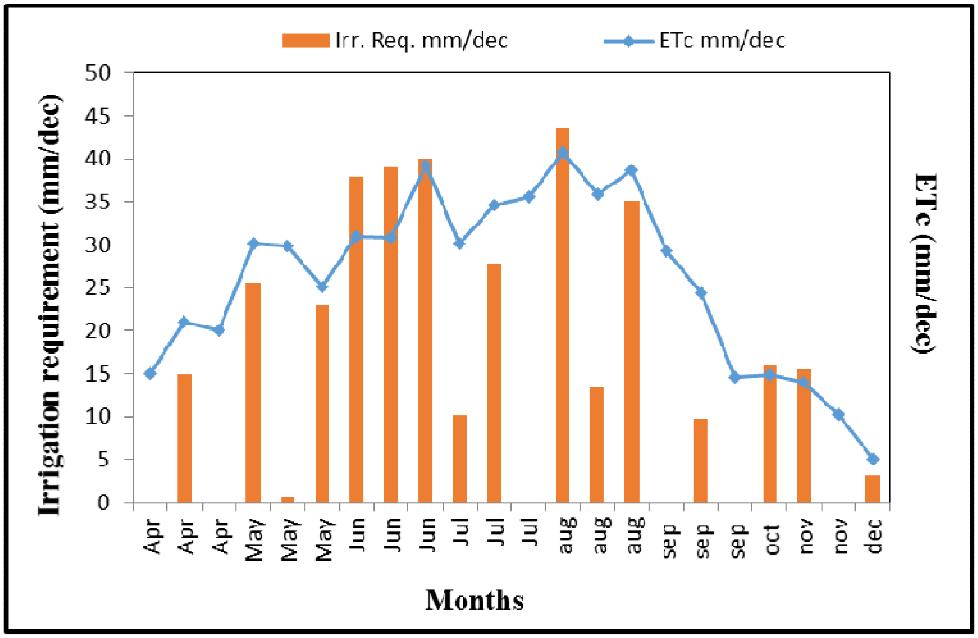


Fig. 4.22: Crop water requirement and irrigation requirement for 2016

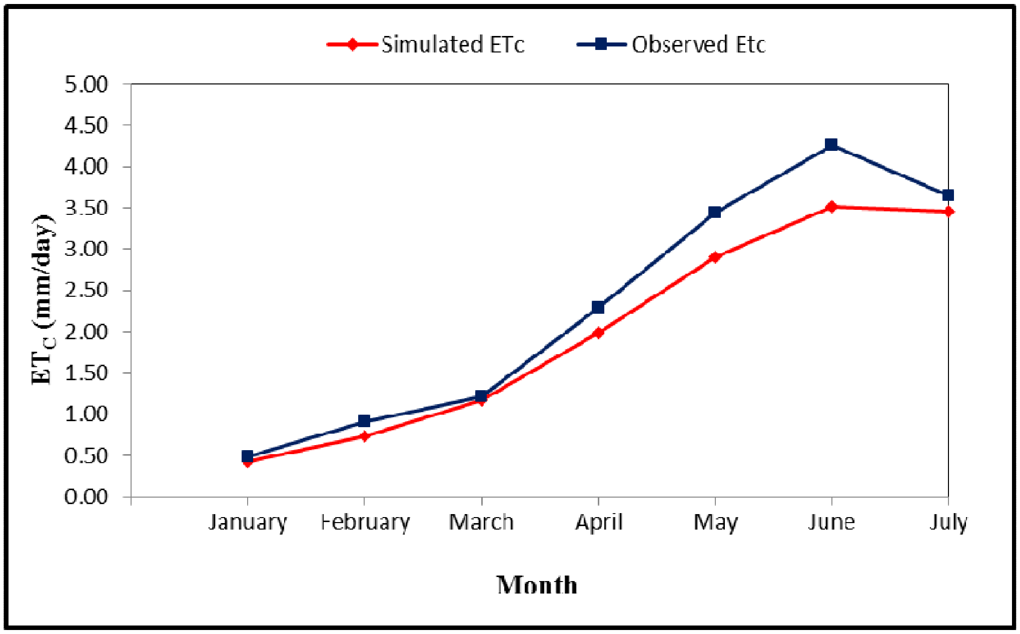


Fig. 4.23: Observed and CROPWAT simulated crop evapotranspiration for 2016

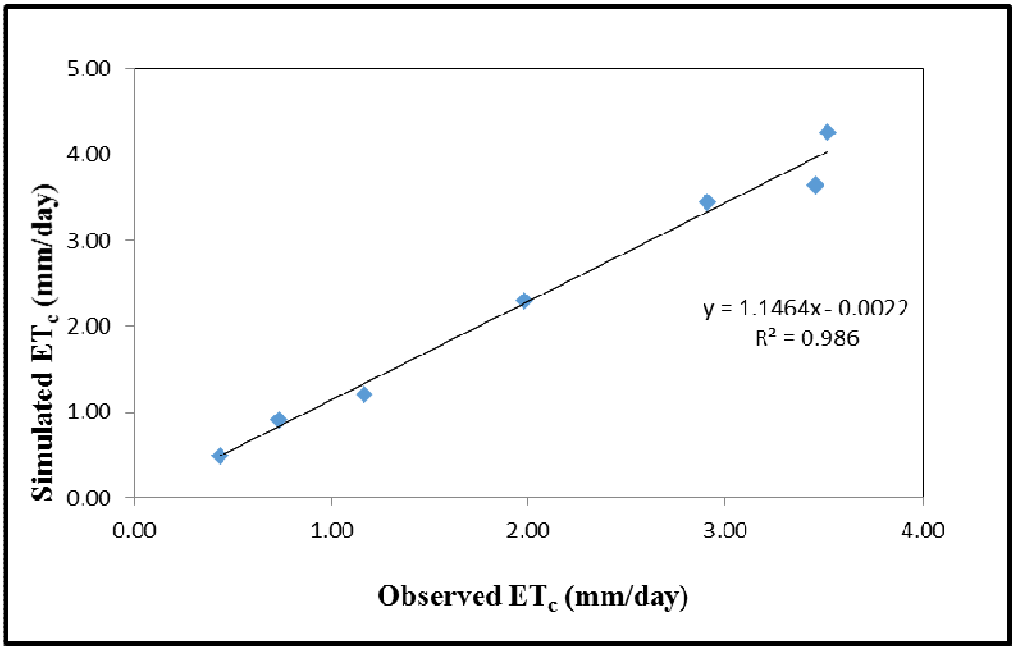


Fig. 4.24: Comparison between observed and simulated crop evapotranspiration

Table 4.5: Statistical analysis of crop water requirement using CROPWAT

Statistical parameter	Value
R^2	0.99
RMSE	0.18 mm/day
MBE	0.15 mm/day

4.2.2 Irrigation scheduling

An attempt was made to design charts for irrigation scheduling for Gala Red variety of Apple for the year 2016 without rainfall. When moisture depletion in the silty clay loam soil reaches 50 per cent, irrigation is to be done. The amount of water to be applied and time of irrigation depends on the crop water requirement and the wetted area. Since in the previous section 4.2.3 and 4.2.4 it was found that crop evapotranspiration is low in the months of January-March and October-December, therefore, no irrigation is required in these months. However, it was found that crop water requirement is high in the months of April-July because of which irrigation is considered particularly for these months. The volume of water to be applied was calculated by multiplying ET_c with wetted area.

It is evident from the Table 4.6 the water to be applied in the months of April, May, June and July is 109, 160, 315.12, 204.15 liters, respectively.

Table 4.6: Irrigation schedule chart for year 2016 from April-July

Month	Volume (lt.)
April	109.00
May	160.00
June	315.12
July	204.15

4.3 Partitioning of crop evapotranspiration

Crop evapotranspiration generally consists of evaporation, interception and transpiration. Among the three components interception is insignificant and is neglected in the present study. The other two components *i.e.* evaporation and transpiration are significant for prediction of moisture uptake in plants. Plants draw water from the soil via the roots and release this water as vapour into the air via the leaves. If the plant (or crop) has a large amount of fresh, green leaves, then water use will be higher. High water use is a desirable characteristic, since yields are well correlated with water use. Soon after emergence a crop has only a small amount of leaf material, so water use is relatively low, while water use will be highest when the crop reaches maximum leaf area. The crop factoris a number used to calculate the water use. It accounts for the crop leaf area. As discussed in chapter 3, partitioning equation based on leaf area index has been used in the present study to partition soil evaporation and plant transpiration.

$$\frac{E_s}{ET_c} = EXP(-\delta * LAI) \qquad \ldots.(4.1)$$

Where δ is dimensionless canopy extinction coefficient, whose value is 0.6 for apples (Jackson 1979, 1980). Daily evapotranspiration and its components evaporation and transpiration for the crop period of apple are shown in Fig. 4.25.

It is evident from Fig. 4.25 that transpiration rate is minimum in the initial months and increases as the leaf area increases towards the mid growth stage of crop. When plants are in their initial stage leaf area is less because of which soil is bare and evaporation rate in soil is more than transpiration rate of leaves. As the crop matures, leaf area increases thus, resulting in an increase in transpiration rate. The maximum value of transpiration rate is recorded as 0.98 mm/day on 87th day. It can be observed from the Fig. 4.25 that maximum transpiration rate occurs in the mid season stage of crop , at the same time when the root depth is maximum, similar to that observed by Ojha *et al.* (2009) and Shankar *et al.* (2012). However, in maturity stage of crop, ET decreases.

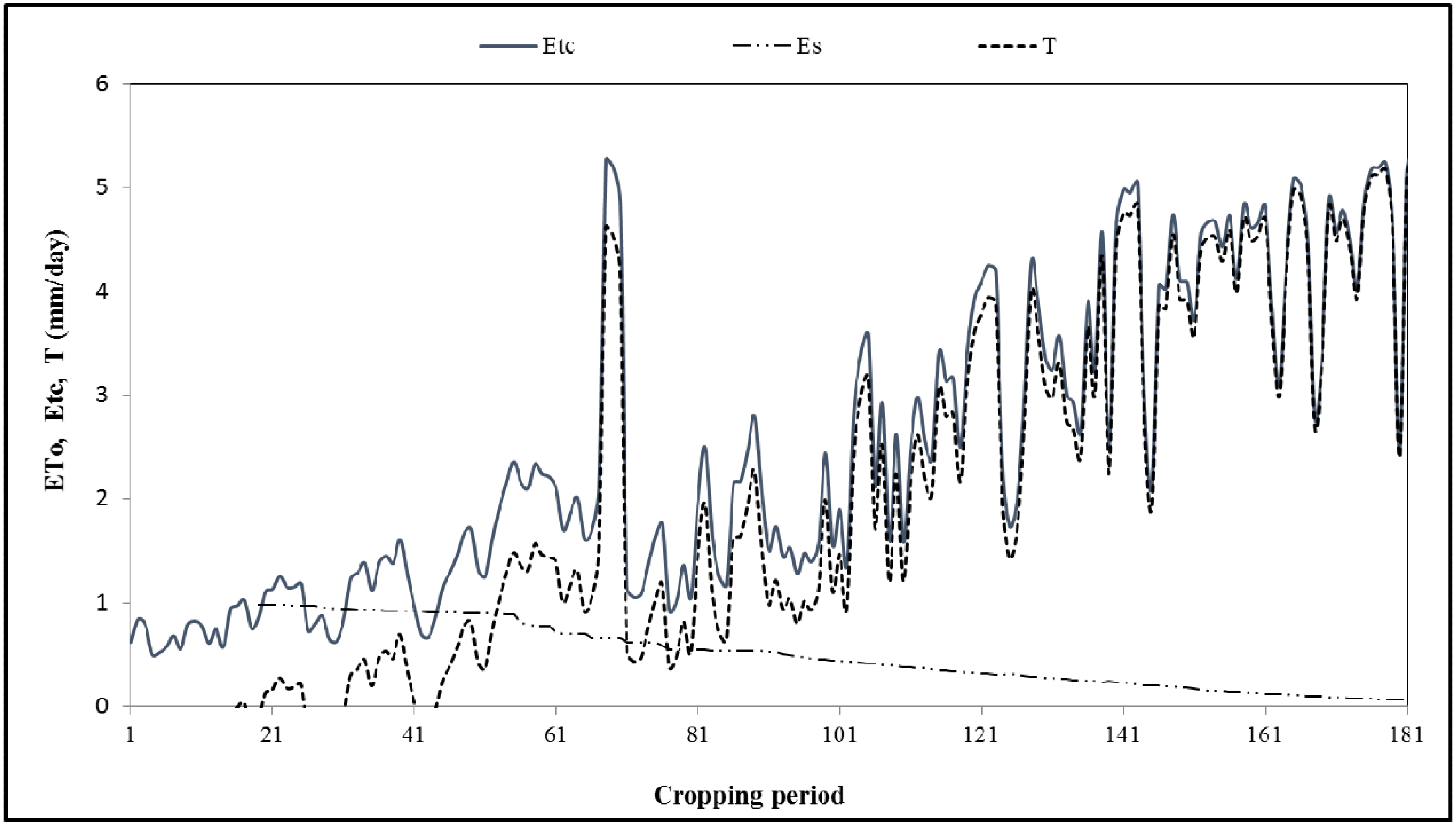


Fig. 4.25: Daily evapotranspiration, evaporation and transpiration for apple trees during crop period

4.4 Closure

The present chapter discussed the soil moisture potential at different crop stages of Apple trees. It also described the moisture depletion in different layers of root zone for the entire crop period. Outputs of different reference evapotranspiration models, modification of crop coefficient, crop evapotranspiration and its partition are also discussed here. The time of occurrence of maximum transpiration rate in the crop satisfies the assumption Ojha et al. (2009) and Shankar et al (2012) that, the maximum transpiration occurs at maximum root depth. Irrigation scheduling for different months of crop period are also described in the chapter.

Chapter - 5

SUMMARY AND CONCLUSION

5.1 General

The objective of this study is modeling of moisture movement and irrigation scheduling in high density Apple (*Malus domestica*) orchard. It gives us an insight into crop water requirement of Apple trees and also gives information on the temporal and spatial behavior of plant-soil-atmosphere continuum, thus, helps us in understanding movement of water in root zone of plant. For this purpose, moisture movement at different depths (15, 30 & 45 cm) of apple was studied using soil moisture sensors. The field experiment was conducted in high density Apple Orchard at SKUAST-Kashmir experimental farm. The experiment under drip irrigation was installed with 2 lph, 4lph & 8 lph capacity discharge emitters. Reference evapotranspiration for local conditions was calculated using different models and crop evapotranspiration has been calculated accordingly using modified crop coefficients for local conditions. Crop evapotranspiration which is pre requisite for precise estimation of moisture uptake has been obtained as product of crop coefficient and reference evapotranspiration.

5.2 Conclusion

The conclusions drawn from the study are summarized as follows:

1. Soil water potential was found to be zero on the days of irrigation and rainfall showing that soil is fully saturated or wet and as the time elapsed the water potential reading increased. Irrigation was applied to the apple crop when the sensor reading varied between 25-30 centibars.
2. Moisture depletion showed a non linear trend during the whole crop period of Apple in all three types of drippers (2 lph, 4 lph and 8 lph). In the upper part of root zone where root density is high, moisture depletes very fast whereas, in the lower part of root zone moisture depletes slowly as sufficient amount of water is continuously available.
3. Six different models have been used to calculate the reference evapotranspiration viz: Penman Monteith, Blaney Criddle, Penman

FAO 24, Hargreaves-Samani, Priestly Taylor and Open pan models. FAO recommended crop coefficients were modified for local agro-climatic conditions using the procedure outlined by FAO. Modified value of $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ are found 0.6, 0.95 and 0.75, respectively for climatic region of study area.

4. Crop evapotranspiration (ETc) calculated by FAO Penman-Monteith equation was found to be 0.5-1.1 mm/day during the months of January-March, 2.3-3.5 mm/day during April-July and 2.5-0.6 during August-December. The difference in ET_o was due to combined effect of change in climatic conditions.
5. The crop evapotranspiration calculated by the Modified Penman equation best matched with Penman-Monteith which is taken as standard equation with the R^2= 0.98, RMSE = 0.07 mm/day and MBE = 0.16 mm/day). Whereas, Blaney- Criddle equation had the second best performance (R^2 = 0.97, RMSE = 0.14 mm/day and MBE = 0.22 mm/day) among the other methods.
6. CROPWAT model values for crop evapotranspiration compared with Observed values showed close agreement with R^2 of 0.99, RMSE of 0.18 mm/day and MBE of 0.15 mm/day. Thus, the model can be used for estimating crop water requirement and can help in irrigation scheduling.
7. The maximum amount of water was found to be applied on 9th July *i.e.* 28.39 litres. Whereas, minimum volume for water was found to be applied on 14th August *i.e.* 9.89 litre.
8. The total volume of water to be applied was found to be 1058.2 litres using different capacity emitters (2 lph, 4 lph and 8 lph).Partitioning of evapotranspiration indicated that transpiration rate is minimum in the initial months and increases as the leaf area increases towards the mid growth stage of crop. Soil evaporation and transpiration reached its maximum value i.e. 0.98 mm and 4.83 mm on 19th January 2016 and 22nd May 2016, respectively.

5.3 Scope for future research

The present work has focused only on moisture depletion pattern. There are certain issues which are worth mentioning for future investigations. The available data was scarce as the study period was confined to a limited time period. Based on the findings of the present study, it is suggested to concentrate future investigations on the following aspects:

- Data of moisture depletion of previous year was not available which could be used to validate the observed results.
- Other reference evapotranspiration models/equations need to be investigated for their applicability in the given agro-climatic conditions.
- A model other than CROPWAT can be used to estimate the crop water requirement of Apple trees.
- Partitioning of evapotranspiration can be done using methods other than Leaf area index method.

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CERTIFICATE

Certified that all the corrections/amendments as suggested by External Examiner Dr. Deepak Jhajaria, Associate Professor, Department of Soil and Water Engineering, College of Agriculture Engineering and Post Harvest Technology, Ranipool, Gangtok (Sikkim) during thesis Viva-Voce examination held on 27th of April have been incorporated in the final manuscript entitled , **"Modeling of Moisture Movement and Irrigation Scheduling under Drip Irrigation in High Density Apple (*Malus domestica*) Orchard"** submitted by **Er. Mehlath Shah (Regd. No. 2014-AE-18-M) of Soil and Water Engineering discipline.**

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