CROP WATER MANAGEMENT IN SEMI-ARID CLIMATIC ZONE OF WESTERN MAHARASHTRA

Submitted by:

SUKHADEO TUKARAM DHOTRE

(2008RCE101)

Civil Engineering Department

Under the Supervision of:

Prof. Gunwant Sharma
Prof. Rohit Goyal
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Submitted

in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

DEPARTMENT OF CIVIL ENGINEERING
MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY
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ABSTRACT

Water is a significant and valuable resource for sustenance of life on the planet of the earth. A crop/ plant gets its water by root uptake. Irrigation (application of water) is required when the soil is unable to supply moisture to it. The main objective of water management in agriculture is to improve water use efficiency and its sustainability. Efficient soil water management for optimum crop production requires a thorough knowledge of the moisture characteristic of soil profile or soil medium through which the crops get their requirement of moisture and other nutrients for growth. The availability of soil moisture influences almost all the biochemical and physiological processes in crops/ plant which in turn affect the morphology of the crops/ plant.

A number of researchers have investigated the soil moisture models. Literature review indicates that there are two types of water up take models. One is water budget model and second one is dynamic model. Water budget models are the simplest types of soil moisture models which treat the soil profile or medium as a bucket. The concepts of field capacity and wilting point are important key parameters to soil moisture budget models. One of the strength is that these types of models require a minimum amount of data, namely field capacity, wilting point, daily precipitation and evapotranspiration. The amount of irrigation water required for a crop in the field depend on the rooting pattern of that crop and the layer-wise distribution of soil moisture in the root zone profile. There has been continuing interest in developing physical parameter based mathematical models which are classified as dynamic models.

The first quantitative description of water flow through a porous medium was developed by Henri Darcy, in the course of his classic investigation of seepage rates through sand filters in the city of Dijon. The actual geometry of soil pores and flow pattern in soil medium is complicated to describe in microscopic details. For this reason flow through complex medium is generally described in terms of a macroscopic flow velocity vector. In macroscopic view the detailed flow pattern is ignored and conducting soil medium is treated as though it were a uniform medium, with assuming the flow spread out over the entire cross section.

Darcy’s law is not valid for all conditions of liquid flow. Richards extended the Darcy’s law for unsaturated flow with provision that the hydraulic conductivity is the function of the matric suction or suction. To obtain the generalised flow equation and account for transient as well as a steady flow process, continuity equation is needed to be introduced which embodies the law of conservation of mass in mathematical form. The transient state of this flow equation is commonly known as Richards’ equation. One dimensional form equation considered for this study area. The finite element approach for one dimensional flow is considered and computer software is developed for this study area. The software developed is useful for monotonic drying case only.

For soil moisture analysis four research stations namely Sholapur, Pune, Kolhapur and Ahmednagar have been selected. This area falls in the semi-arid climatic zone of western Maharashtra, India. The Van Genuchten parameters m, n and α, are soil parameters which are needed to run the dynamic model. The depthwise soil moisture characteristic curves (SMCC) are prepared from observed data for research area. The soil moisture parameters are established from SMCC by using Van Genuchten model with some variation for the study area. The sensitivity analysis has been carried out for this study area for finding out suitability of models. Richards’ equation is coupled with sink. In the study sink model is used with some modification in it. Here Borg and Grimes suggested sinusoidal simple root growth model is used in governing model.

The methods for evaluating reference evapotranspiration require various parameters. Some of these parameters are directly recorded in weather stations while some parameters are derived with the help of a direct or empirical relationship. Hargreaves model is an alternative and simple approach used where only maximum, minimum temperature and extra-terrestrial radiation are required. The original Hargreaves equation has a tendency to under-predict under high wind conditions and to over-predict under conditions of high relative humidity. To overcome this error Hargreaves introduced the modified Hargreaves equation which can be used alternatively. However, this modified Hargreaves model needs some modification with respect to local condition.

The developed Hargreaves model is proposed for the study area. In this research work reference evapotranspiration is estimated by FAO-56 model and Hargreaves model with modification for the study area. Irrespective of any method or model used in crop water management, estimation of reference evapotranspiration is must. It play important role in water budget model as well as in dynamic models.

In this research work Pearl Millet is considered as the crop for the study area. The rainfall and evapotranspiration data has been analyzed for finding out the sowing week for Pearl Millet and assessing the severity of drought on weekly basis. The analysis of weekly rainfall data reveals the severity of drought during the crop growth period. The climatological data has been analyzed on the weekly basis, for finding out suitability of various evapotranspiration methods for this region. From the crop coefficient data, the consumptive use requirement for the Pearl Millet crop during the crop growth period has been estimated for this region. The analysis of rainfall and, climatological data for drought analysis of crop helped in understanding the hydro-meteorology of the semi-arid regions of the Maharashtra.

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LIST OF ABBREVIATIONS USED

Symbols		Description
α	:	Van Genuchten parameter
B	:	Model parameter
Γ	:	Psychrometric constant, kPa/ °C1
Δ	:	Slope of the saturation vapour pressure curve.
Έ	:	Ratio molecular weight of water vapour/dry
θ	:	Volumetric soil moisture (L^3/ L^3)
Θ	:	Effective saturation or water retention properties of soil
θ_r	:	Residual water content (L^3/ L^3)
θ_s	:	Saturated water content (L^3/ L^3)
Λ	:	Latent heat of vaporization
Ψ	:	Suction or matric potential of soil (L)
ψ^*	:	Threshold value of soil water pressure at which root up take water is not reduced
ψ_1	:	Anaerobiosis point at which deficient aeration conditions exist
Ψ_2	:	Pressure head values at optimal water uptake rate
Ψ_3	:	Pressure head values at optimal water uptake rate. Varies with evaporation demand of the atmosphere
Ψ_4	:	Wilting point" pressure head at which plants can no longer extract water from the soil
ψ_{50}	:	The soil water pressure head at which $\phi_{(\psi)}$is reduced by 0.50
ψ_{max}	:	Second threshold value pressure head values beyond which the change of pressure head no longer influence the relative transpiration significantly
ω_s	:	Sunset hour angle
Ə	:	Albedo or canopy reflection coefficient
$\phi_{(\psi)}$	:	Dimensionless soil water availability (stress response)
ϕ_0	:	Relative transpiration at ψ_{max}
Δ	:	Slop vapour pressure curve (kPa/^{o}C)
AE		Average Error
a_g and b_g	:	Coefficient that depend on the growth stages
$C_{(\psi)}$	:	Differential soil water capacity (1/L)
c_p	:	Specific heat at constant pressure
CV		Coefficient of Variation
$D(\theta)$	:	Soil moisture diffusivity (L^2/ T)

DAP : The days after planting
d_r : Inverse relative distance Earth-Sun
DTM : Days to maturity for the plant
E_a : Actual vapour pressure (kPa)
E_p : Potential Evaporation rate from soil surface(L/T)
E_s : Saturation vapour pressure (kPa)
E_s-E_a : Saturation vapour pressure deficit (kPa)
ET_o : Reference Evapotranspiration rate (L/T)
ET_p : Potential Evapotranspiration rate(L/T)
G : Soil heat flux density (MJ/ m^2d)
G(z) : Root distribution function (L^{-1})
G_{sc} : Solar constant
H : Total pressure head
H_L : Latent heat of vaporisation of water per unit mass(J/kg)
J : Number of days in the year
K : Hydraulic conductivity
$K(\theta)/K(\psi)$: Unsaturated hydraulic conductivity (L/T)
K_c : Crop coefficient
K_r : Relative hydraulic conductivity
K_s : Saturated hydraulic conductivity (L/T)
L : Depth of soil profile (root zone)
LAI : Leaf Area Index (LAI**)** (L^2/ L^2)
L_m : Maximum root depth
L_r (t) : Root length at a particular growth stage / root depth; (L)
m : Curve Fitting Parameters(empirical hydraulic shape parameters) or Van Genuchten parameter
n : Curve Fitting Parameters (empirical hydraulic shape parameters) or Van Genuchten parameter
n_a : Actual duration of sunshine, [h]
N_m : Maximum possible duration of sunshine or daylight hours, [h]
n_a/N_m : Relative sunshine duration
P : Atmospheric pressure, kPa
R^2 Coefficient of Efficiency
R(z) : Root density distribution
R_1, R_2, R_3, R_4 : Polynomial coefficients

R_a : Extraterrestrial radiation, (MJ/ m^2 d)

r_{ec} : Radiation extinction coefficient

RE : Relative Error

RMSE Root Mean Square Error

R_n Net solar radiation at crop surface (MJ/ m^2 day)

R_{nl} : Net long wave radiation

$R_{nrd}(z_r)$: Normalized distribution function of relative root density

R_{ns} : Net solar (or net shortwave) radiation

R_s : Solar (or shortwave) radiation, (MJ/ m^2 day)

R_{so} : Clear sky radiation

$S(\Psi, z, t)$: Soil moisture uptake rate per unit volume of soil by plant root (Sink) (L^3 L^{-3} T^{-1})

S_c : Soil cover

SD Standard Deviation

S_{max} : Maximum(potential) root water uptake rate (L^3 L^{-3} T^{-1})

SMCC : Soil Moisture Characteristic Curve

t : Time(s)

T_{max} : Maximum daily air temperature, (ºC)

T_{mean} : Mean daily air temperature, (ºC)

T_{min} : Minimum daily air temperature, (ºC)

T_j : Transpiration on jth day

T_p : Potential plant transpiration rate (L/T)

U_2 : Wind speed at 2 m above the ground surface, m s^{-1}

U_z : Measured wind speed at z meter above the ground surface, (m /s)

z : Depth/ Height

$z_r =(z/L_r)$: Normalized depth ranging from 0 to 1

z_{rj} : Root depth on jth day

z_{rmax} : Maximum root depth

CHAPTER - 1
INTRODUCTION

1.1 INTRODUCTION

Application of irrigation water to the crop is the most important recurring aspect in crop water management which needs careful consideration. A crop gets its water by its roots. Irrigation water is required when the soil is unable to supply moisture to the crop. The main objective of irrigation is to keep sufficient water supply available to crop. If water is in short supply, whatever is available needs to be supplied most effectively and efficiently (Miller and Donahue, 1997). Determination of an irrigation schedule or time of application of water is a tedious process. The evolutions in computer programs have made it simple and easy. Water can be applied to farm fields according to the water requirement of the crops. In the beginning the amount of water supplied is small as root depth is in developing stage. During the mid-season, the irrigation water applied need to be larger as root depth is deep. Thus, it reveals that irrigation water depth and the irrigation interval varies with the crop development stages. In arid and semi-arid regions, where rainfall is scarce, providing irrigation system is very critical. There is no substitute for water. It is indispensable for human, animal and plant life. Hence, it is necessary to develop, conserve, utilise and manage this precious resource economically and efficiently so as to meet the growing demand for agriculture and other human developmental activities. The main challenge for irrigation engineers and water management department in semi-arid region is to improve water use and its application efficiency. Several irrigation scheduling means are available now a days to assist in irrigation scheduling. Some of the few techniques are as follows:

- Soil moisture probes
- Soil moisture sensors in the field
- Crop water use estimators
- Computerized daily soil water balance
- Physically based models for estimating soil moisture status

1.2 SOIL MOISTURE

The state and movement of water or moisture in the soil is a complex phenomenon since it is affected by variety of factors and properties like physical, biological and chemical, and, processes that interact with each other (Jenson, 1981). The soil water (moisture) is depleted due to evaporation from soil surface, transpiration through the plant and deep percolation into the soil beyond the root zone. Root elongation is reduced due to high resistance of dry soil. Irrigation provide favourable environment for crop growth and produce (Reddy and Reddi, 1992). Proper soil water management for optimum crop yield requires a knowledge of the moisture characteristics of soil profile or medium through which the crops absorbs their requirement of moisture as well as other nutrients required for their growth. The availability of moisture in the soil influences all the biochemical and physiological processes in crop. This in turn affect the morphology of the crop and plants. All the crop and plants have an optimal moisture requirement and any deviation from the optimum results in adverse effect leading to poor growth, yields and the quality of the produce (Singh, 1988).

An accurate quantification of moisture uptake by plants under different environmental conditions is essential for deciding efficient irrigation scheduling. There are several approaches and methods that are available for deciding irrigation water application scheduling. They can be broadly classified as follows:

- Plant/ crop based method
- Soil moisture based

Plant/ crop based method is very accurate but at the same time it is finding difficult in measuring or determining plant/ crop water stress therefore second method of soil moisture based irrigation scheduling method is more popular. Yadav and Mathur (2008) state water uptake by crop roots is a dynamic and non-linear process. This process influences by variety of crop, soil medium properties in which it sowen, and the existing climatic conditions

Soil moisture definition is available in all standard text. It can be defined in a simple way as the amount of water contained in the soil pores in the vadoze zone that is available for plants to use or evaporate into the atmosphere. Moisture movement in this vadoze zone is intricate because soil-pores contain gas and water. The parameter, which is necessary to estimate moisture content, hydraulic conductivity is hydraulic constant in saturated systems turn into hydraulic function in unsaturated condition. As per Dane and Wierenga (1975) the rate at which moisture moves into soil profile depends on the soil matric suction and conductivity. Schwartz and Zang (2003) views that the governing equation for the moisture estimation becomes more complicated to solve because parameters turn into non-linear functions. An estimate of the spatial distribution and temporal variation of soil moisture content of vadoze zone is widely recognized as a key parameter in the following disciplines:

- Agriculture
- Meteorology
- Ecology
- Hydrology
- Environmental studies

All processes involving in soil-water interaction in the field take place while the soil profile is in an unsaturated condition. The unsaturated flow process is in general complicated and difficult to describe accurately, as this flow process often changes in the state and content of soil water during flow. Such change involves complicated relations among the variables like soil wetness, suction and conductivity. Their inter-relations further become intricate by hysteresis. The formulation and solution of unsaturated flow problem requires the use of indirect method of analysis like numerical techniques. Hillel (1982) says the development in theoretical and experimental method for treating these problems was rather late; in recent decades, unsaturated flow has become one of the most important and active topic of research in soil physics, agriculture and irrigation engineering.

1.3 PLANT WATER REQUIREMENT

The irrigation engineers and farmers are well accustomed and think that each crop has its own water requirement. As per the simple laws of physics, that water requirement for all crops must be the same, if they were grown on the same soil zone and in the same growing season. Plants can readily use soil water held with matric suction approaching -1500 kPa (-15 bar), most of the plant available water is held in high matric suction from -33 to -100 kPa (-1/3 to -1 bar). As per Miller and Donahue (1997) the irrigation water application is recommended when about 50% of crop available water has been used or exhausted in the zone of maximum root activity, probably within the 15 to 60 cm depth; except in ripening seed crop or sugarcane crops. The moisture contained in soil should never approach the permanent wilting point unless rapid maturing is needed. The moisture retained at -1/3 bar is often represented as field capacity. Immediately after irrigation water application soil is at saturation, at this stage soil pore spaces are filled completely with water and very little air remain in soil pores. After drainage, water is drained away from the large size pore spaces and some air begins to enter in the soil pores. This process takes nearly about 48 hours, depending on the soil medium and its constituents. Once the soil medium has drained out by gravity in around 48 hours, remaining moisture is held by matric suction around the soil particles, and no further drainage will be taking place. This condition is known as soil at field capacity, and at this condition soil is holding as much water as it can. The condition at which matric suction is – 15 bars is called wilting point. As the soil dries out, plant root requires to work harder to get moisture from soil around. The moisture is extracted by the plant root from the soil until a point is reached when the roots are unable to obtain moisture from the soil. This is called the wilting point for that soil. At this stage soil is not totally dry, but the remaining moisture is held so tightly that the roots cannot obtain it. As a soil approaches wilting point the plant growth decreases. Plants do not sustain in a soil at wilting point and will die if water is not applied. There are various views about these correlations. The amount and rate of water uptake depend on the ability of the roots to absorb water from the soil with which they are in contact, as well as on the ability of the soil to supply and transmit water toward the roots at a rate sufficient to meet transpiration requirement. These depend on properties of the plants like root density, root depth and rate of root growth, as well as the physiological ability of the plant to continue to extract water from the soil medium at the rate needed to avoid wilting. As per Hillel (1982) properties of the soil medium like hydraulic conductivity, matric suction, their relationship and meteorological conditions control the rate at which the plant is required to transpire and hence the rate at which it must extract water from the soil in order to maintain its own hydration. Generally limits like field capacity and wilting point have been accepted as upper and lower limits of available water to the crops by irrigation engineers.

1.4 INTERVAL OF WATER APPLICATION

The interval between irrigation water application and the amount of water needed to apply at each irrigation time depend on how much moisture is held in the root zone and how fast it is used by the crop. This can be judged by following factors.

- Soil texture: - It refers to the size and range of soil particles in the soil profile. The particles are universally named as sand, silt and clay. The procedure and mechanism of separating out these fractions and of measuring their proportion is called mechanical analysis. The sand and silt are inert materials and are called skeleton and clay is called the flesh of soil. Together all three fractions of the solid phase, are combined in various configuration, constitute the matrix of the soil.
- Soil structure: - The arrangement and organisation of the particles (sand, silt and clay) in the soil profile is called soil structure. Soil particles are differing in dimension (shape and size) and orientation. They can be variously associated and inter linked. The mass of it can form complex and irregular in configuration. The soil structure determines the total porosity as well as the shape of the individual pores and their size distribution. In general soil structure is recognised as three broad categories as single grained, massive and aggregated. In single grained or structureless categories the particles are entirely unattached to each other. The structure is completely loose e.g., Coarse granular or unconsolidated deposit of the desert dust. In massive structure soil is tightly packed in large cohesive blocks. Whereas, in case of aggregates or peds soil particles are associated in small clods. This condition is most desirable condition for plant growth.

- Depth of effective root zone: - The quantity and rate of water uptake depend on the ability of the root to absorb water from the soil medium around with it and in contact. It also depends on the condition of the soil that how much amount of moisture release and transmit toward the roots at a rate sufficient to meet transpiration requirement or not. These in turn also depend on properties and characteristic of the plants like rooting density, rooting depth and rate of root extension.
- The stage of development of the crop: - During the life cycle of crop, there are some stages in the life cycle of it, when it is in need of water. Allowing water stress beyond certain limit during these stages causes a definite set back to the growth process and the yield is affected. These stages are referred to as the critical stages of water requirement. A crop in young stage needs frequent irrigation water; at this stage it is very susceptible to water stress, because root system is not deep and extensive.

1.5 MODELS

Models have been developed in research with a large variation in degree of complexity. Empirical models display simple relationship between input and output, this model is treated as “black box” model. Other types of model are mechanistic models which simulate physical, chemical and physiological processes that take place within the system. De Jong and Kabat (1990) says that in practice, mechanistic models make use of empirical functions when and where knowledge about a given process is lacking. The selection of the most appropriate method that balances the mechanistic-empirical character of the model is controlled by model objectives. The improving of irrigation water management in the areas of dry weather conditions during the growing period is achieved only by modeling the irrigation water application schedule. Dejong and Kabat (1990) state that the mathematical models which simulate the physical processes of the crop-soil irrigation systems are rarely duplicate their prototype in every detail; physical models may look like scaled down version of real system, but the grain and pore size distribution and their distribution within the porous media will not be scaled version of their counterparts in the prototype. As per Hillel (1971) mathematical models of soil moisture can usually be constructed only after making several simplifying assumptions.

1.6 NECESSITY FOR THE STUDY

Management of irrigation describes the interaction between the people responsible for irrigating and the equipment that administers irrigation water. Those responsible for managing irrigation water supply gather information to support their decisions about irrigation water application frequency, timing, and amount. Information gathering may be done by human senses (the feel of the soil and appearance of the crop) and consideration of weather. Irrigation managers may use instruments to more accurately gather relevant information about soil moisture, weather, and crop development. Allen et al. (1998) carefully detailed the combination of crop coefficients and simulated reference evapotranspiration for the purpose of managing irrigation.

Soil moisture is directly measured by soil moisture measuring instrument. Direct soil moisture measurement is easy to use and relatively accurate but expensive to implement because of soil heterogeneity requiring multiple soil measure sensor to capture spatial and temporal variation. Soil moisture reserve status (SMR) and its spatial and temporal coverage can be made available by using models (water budget and physical) which estimate soil moisture changes from readily available meteorological data, soil and vegetative characteristic.

The role of soil moisture in the top vadoze zone is very important and controls the success of agriculture. The top zone also regulates partitioning of precipitation into runoff and infiltration and groundwater storage. Soil water retention and its rate of movement in the soil are the important aspect in irrigation water application scheduling, and hence it is felt that there is a need to undertake the studies on the aspect furthermore.

1.7 OBJECTIVES AND SCOPE

The principal objective of this research is to develop a methodology for making improved estimates of soil moisture reserve (SMR). The objectives can be listed as follow.

- To evolve/ develop crop water management models for study area.

- To develop a forecasting model for reference evapotranspiration.
- To compare the model with the existing water budget model in use in the area.

1.8 COMPONENT OF CONCEPTUAL MACROSCOPIC MODEL

Hillel (1982) stated that the movement of water in the field can be characterised as a continuous cycle, repetitive sequence of process, without beginning or end. However, we can conceive of the cycle as if it starts with entry of water into the soil by the process of infiltration, continues with the temporary storage of water in the soil, ends with its removal from the soil by drainage, evaporation and plant uptake. It can be represented these processes by field water cycle as shown in Figure. 1.1. The water table is deep in Maharashtra and groundwater, doesn't contribute in root zone water except in waterlogging area. Modeling has emerged as an important tool in all branches of science. Models are conceptual description tools that represent and describe an approximation of a field situation and real system or natural phenomena. They are not exact descriptions of physical systems or processes but are mathematically representing a system. The differential equations are developed from analyzing process. The reliability or utility of model predictions depend on how well the model approximates the actual/ natural situation in the study area. Certainly, simplifying assumptions are made in order to construct a model, because the field situations are usually too complicated to be simulated exactly.

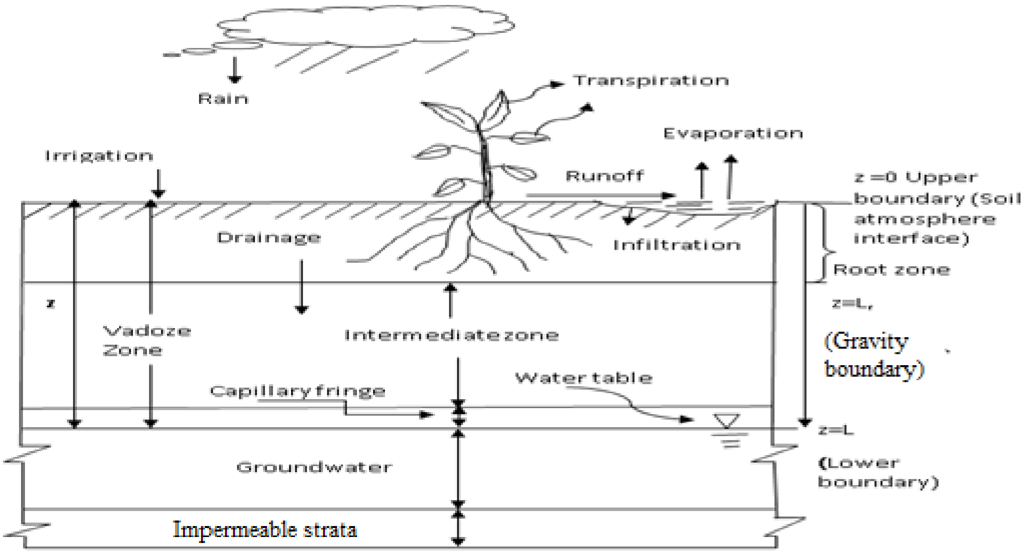


Figure 1.1: Component of macroscopic root system

1.9 METHODOLOGY AND MODEL DEVELOPMENT STEPS

Numerical solution of the mathematical equation gives approximate solution to the problem, i.e. the unknown variable is solved at discrete points in space (Steady-State flow) and time (Transient flow). Numerical models are used to solve the more complex equations of multi-dimensional soil water flow. Analytical solutions are not available for many problems of practical interest while the numerical methods allow us to solve the governing equation. The most popular techniques are as the Finite Difference Method (FDM) and Finite Element Method (FEM). In our study finite element method (FEM) is adopted. The steps for development of model considered are represented in structural diagram shown in Figure1.2 as follows:

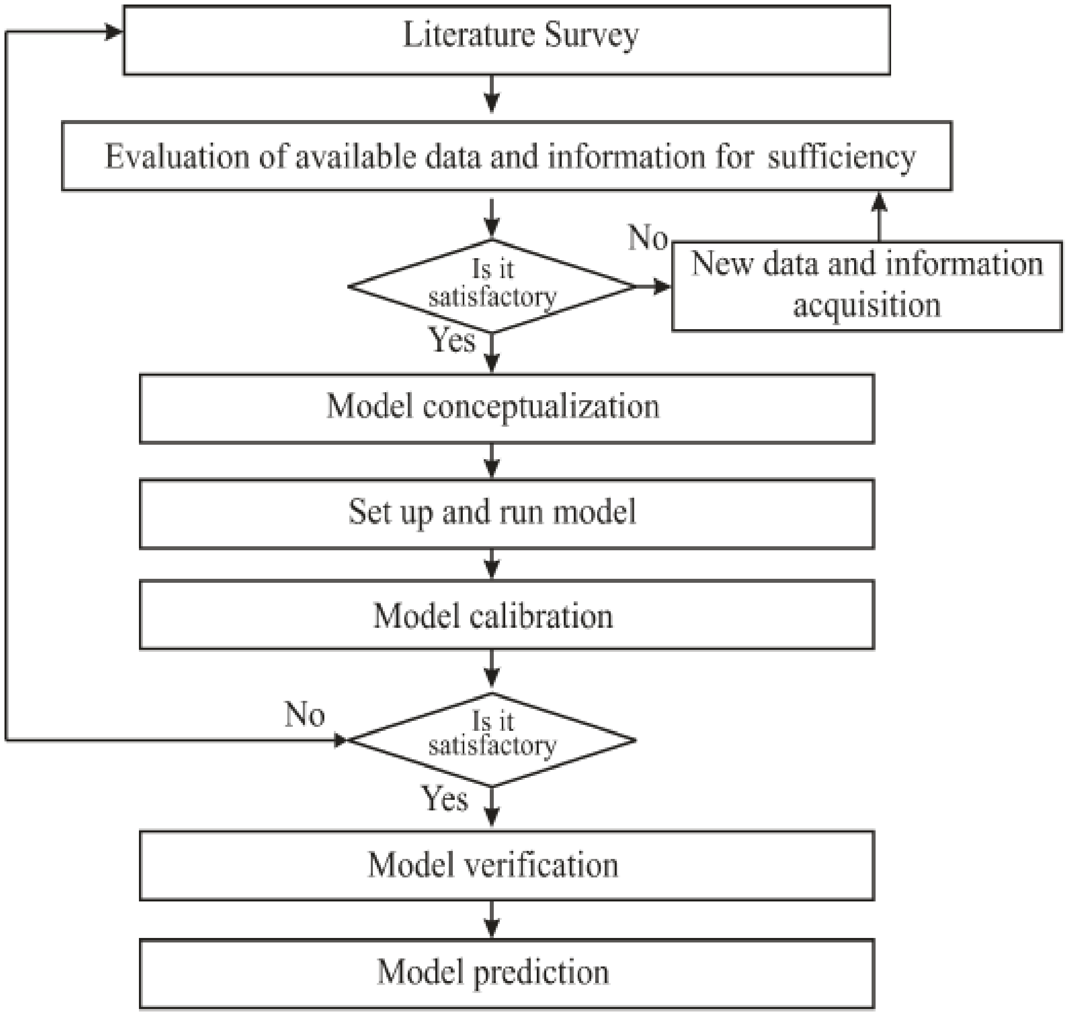


Figure 1.2: Structural diagram of steps followed in model development

1.10 POTENTIAL BENEFITS OF STUDY

The potential benefits of studying the current status of soil moisture in vadoze zone or investigating the root zone depth are numerous as listed below:

- Efficient irrigation scheduling can be achieved.
- Proper crop selection (Al- Hamdan et al. 2010) can be ensured.
- Increased crop yield or output through optimal soil moisture conditions at sowing and during the growing period (De Jong and Bootsma, 1996) could be initiated.
- Economical and water conservation benefits through rational irrigation scheduling could be made possible.
- Management of efficient agricultural practices can be ensured.
- Decision about trafficability in the fields can be taken.
- Early drought prediction can be achieved. Drought monitoring and evaluation (Akinremi et al. 1996) of drought impact on agricultural production for management of rural subsidy schemes can be ensured.
- Economical and environmental benefits from selective application of pesticides for soil moisture dependent insects and diseases can be made possible.
- Improved soil erosion prediction can be carried out through improved hydrological modelling and the relationship between erosion and runoff producing zones can be developed.
- Design of drainage system (Clemente et al. 1994) and minimising drainage can be ensured.
- Minimizing the leaching losses can be achieved.
- Better estimation of groundwater recharges (Martinez et al. 2009) can be done.
- The monitoring of global climate change through persistence of high or low soil moisture content can be achieved.

1.11 ORGANISATION OF THESIS

In semi-arid climatic area, the cropping choice is restricted due to moisture stress and lack of assured sources of irrigation. Pearl millet is a crop that thrive even in adverse agro-ecological situations, making them less risky for producers. Pearl millet is widely cultivated during the rainy and post-rainy seasons in central western Maharashtra. Besides grain, pearl millet is an important feed for livestock, especially in the dry months when other feed resources are in short supply, hence this crop is considered for study.

Present Thesis has been divided into eight Chapters. Chapter1 outline the introduction and main objectives of present study. The components of models are described in brief. The potential benefits of studying the current status of soil moisture in vadoze zone or investigating are listed. Several irrigation scheduling means which are available now days to assist in irrigation managers and farmers are discussed in this Chapter.

In Chapter 2 Literature review including concepts used in irrigation methods, soil moisture models available for estimation and their evolution have been presented. Evapotranspiration, its measurement, and estimation as well as other relevant literature is also discussed here.

Chapter 3 provides an insight into the model and its formulation. The application of Darcy’s law and Richards equation with parameters required for developing governing model have been discussed in detail. The reference evapotranspiration model and required parameters are discussed in detail.

In Chapter 4 detailed information on element library for formulation and idealization for practical problem is given. Finite Element Method for one-dimensional flow is dealt in detail. The governing model is validated with Celia et al. (1990) model and software listing has been given in Appendix - A.

Chapter 5 gives details for the estimation of soil parameters needed for soil moisture model. The soil moisture data analysis for study area is performed and presented in this Chapter.

In Chapter 6 the data collected from four research station has been analyzed for reference evapotranspiration estimation. The model developed for the study area has been compared with FAO-56 model and sensitivity analysis has also been carried out and results are presented in this Chapter.

Chapter7 gives the crop water management for pearl millet crop and result of week-wise drought analysis has also been carried out.

In Chapter 8 Conclusions have been drawn and recommendations are given. Suggestion for the future scope of the research work are also given.

CHAPTER-2

LITERATURE REVIEW

2.1 INTRODUCTION

Water management is a sub-set of water cycle management. Agriculture is the largest user of fresh water resources, consuming around 70 percent of it. Ideally the main challenge confronting water management in agriculture is to improve water use efficiency and its sustainability. Water crisis is not primarily due to a lack of water availability, but rather arises from mismanagement of available resources (http://www.cseindia.org/taxonomy/term/20248/menu). Crop water management can be achieved through following measures.

- Different irrigation technologies
- Use of soil moisture estimating models
- Soil moisture estimation by feel and appearance
- Planning and scheduling by using crop Indicator
- Soil Moisture measuring instruments
- Quantifying evapotranspiration
- Decrease in water losses from crop-growing areas by selecting Cropping pattern and farming practices

2.2 DIFFERENT IRRIGATION TECHNOLOGIES

An adequate water supply is important for plant and crop growth. When rainfall is not sufficient, the plants and crop must get required water from irrigation. The various methods of irrigation are available to use. Each method has its own advantages and disadvantages. These advantages and disadvantages should be considered while choosing the method of irrigation best suited to the local circumstances. Literature review reveals that there are four methods of irrigation (Singh, 1988; Reddy and Reddi, 1992; Suresh, 2008).

- Surface irrigation
- Sprinkler irrigation
- Drip or trickle irrigation
- Sub-irrigation

2.2.1 Surface Irrigation

Surface irrigation is the application of water by gravity flow over the surface of the field. In this method entire field is flooded (basin irrigation) or the water is fed into small channels (furrows) or strips of land (borders). In the surface irrigation water flows directly over the surface of the soil (Singh, 1988; Reddy and Reddi, 1992).

2.2.1.1 Basin Irrigation

Basin irrigation is the common form of surface irrigation. It is suitable in regions with layouts of small fields. The field is leveled in all directions, and is encompassed by a dyke to prevent runoff. This type of irrigation is used for rice crop on flat lands or in terraces on hillsides in Konkan region of Maharashtra. Orchid is also being grown in basins. In this method one tree is planted in the centre of a small basin. The basin method is used for crops which can sustain standing water for long duration.

2.2.1.2 Border Irrigation

Border irrigation method is an extension of basin irrigation method. Its field is sloping, long rectangular or contoured shapes, with free draining conditions at the lower or tail end. This type of irrigation is generally best suited to larger farms. It is designed to produce long uninterrupted field lengths for ease of mechanical or equipment operations. Borders can be prepared up to 800 m depending upon field conditions, or even more in length. The width can be kept 3 to 30 m depending on a variety of factors. This type is generally considered less suitable to small-scale field where hand labour or animal is used for cultivation methods. In this method, irrigation is done by diverting a flow of water from the channel to the upper end of the border. When the desired amount of water has been given to the border, the flow is turned off; Sometime this may occur before the water has reached the end of the border. There are no specified rules for controlling this decision. If the flow is stopped too early there may not be enough water in the border to complete the irrigation at the tail end. If supply is kept running for too long time, then water may overflow the end of the border and loss of water occur.

2.2.1.3 Furrow Irrigation

Furrow irrigation method avoids flooding the entire field surface as in basin irrigation. The water flow is guided and channelized along the primary direction of the field using furrows or corrugations. Water seeps through the wetted perimeter, moves vertically and horizontally and get stored in soil reservoir. Furrows are some time, employed in basins and borders to reduce the effect of topographical variation and crusting. The main feature of furrow irrigation is that the flow into each furrow is independently decided and controlled as opposed to furrowed borders and basins, where the flow is set and controlled on a border by border and basin by basin basis. This method provide better on-farm water management and flexibility under many surface irrigation situations. The advantages of this irrigation method are as follows:

- The discharge per unit width of the field is reduced
- A smaller wetted area reduces evaporation losses
- The farmer has more opportunity to achieve higher efficiencies
- Application efficiency higher than that in other irrigation methods (borders and basins)
- This method is suitable for crops like sorghum, maize, cotton, tobacco, tomato, potato, sugarcane

The disadvantages of furrow irrigation are as listed below:

- Possibility in accumulation of salinity
- Tail water losses
- Difficulty in moving farm equipment in the field
- Erosive possibility of the flow in furrows
- Efficient labour is required to operate
- Difficulty, in regard to regulating equal discharge in each furrow

2.2.1.4 Flooding Irrigation

In this method the water is flooded in the field without constructing ridges or bunds to guide the flow of water. Suresh (2008) listed the following disadvantages:

- Percolation losses are more
- Waterlogging problem
- Method is unsuitable where there is scarcity of water
- Water application efficiency reduces

2.2.2 Sprinkler Irrigation

Water is sprayed through the air from pressurized nozzles, and falls like rain on the crop. Water is supplied through a system of pipe network by pumping. Water then comes out through sprinklers in such way that it breaks up into small water drops which fall on the surface like a rain. This is suitable for almost all field crops like wheat, gram, vegetables, Cotton, Soyabean, Tea, Coffee, and other fodder crops. Sprinkler irrigation is known since 1946, but it is only since 1980 widely known to farmers of India (Reddy and Reddi, 1992). Jain Irrigation system (http: //www.jains.com) developed following type of sprinkler system.

- **Rainport Sprinkler System**

Rainport is a mini irrigation system. Laterals and sprinklers are easily shifted from one place to other. Re-installation of the system is easy and it consumes or requires less time and labour.

- **Overhead Sprinkler System**

Overhead sprinklers are designed for a wide range of general field conditions. The system is portable, semi-portable and solid set systems.

- **Raingun and long Range Sprinkler System**

This system is recommended for field crops like sugarcane, pulses, oil seeds, cereals, tea, coffee, and vegetables.

2.2.3 Trickle or Drip Irrigation

Trickle or drip irrigation system supplies water directly to the root zone below the soil surface through emitters that control water flow. This type of irrigation was introduced in India in early seventies, significant development has taken place only in the eighties (Reddy and Reddi, 1992). Now, a wide variety of quality products are available to make drip irrigation reliable and easy to use. By use of this system water is saved because now control is possible onto keep runoff and evaporation losses within limit. Suresh (2008) concluded that initial investment is more in procuring sprinkler and drip irrigation system, but now a days these are adopted in places where there is scarcity of water and labour.

2.2.4 Sub-irrigation

In sub-irrigation, the water table is artificially raised either through blocking ditches or by supplying water through the perforated pipes. It refers to the application of water below the top soil. The application of water through open ditch system consists of construction of open ditches at an interval of 15 to 30 m, depth from 30 to 100 cm and the spacing is used in such a way that the water can be spread adequately throughout the area between two ditches. It also drains the excess water (Suresh, 2008).

2.3 USE OF SOIL MOISTURE ESTIMATING MODELS

The soil moisture has an effects on crop growth. It is important and needs to be considered in agricultural management. In the semi-arid climatic zone the main constraint to crop cultivation is less rainfall and its extreme variability. The study of soil moisture condition in agricultural crop is very important in semi-arid region. The soil moisture contents are varying in response to soil factors and weather events. It is not economical to monitor soil moisture extensively by field measurements. Therefore, soil moisture estimating models are needed. Recently many researchers have developed moisture models, De Jong and Bootsma (1996) reviewed literature and revealed that there are three types of models as follow:

- Water budget models
- Semi dynamic models
- Dynamic models

Mahdian and Gallichand (1996) classified of soil moisture models into two categories.

- Water balance models (Models follow the budget approach)
- Numerical models (Model based on Richards' partial differential equation)

2.3.1 Water Budget Models

Water budget models are the simplest types of soil moisture flow models used in irrigation water application. In this method soil medium profile is treated as bucket. This bucket is assumed to have fixed water capacity. The assumed bucket is filled with precipitation or on application of irrigation water and emptied with evaporation or evapotranspiration. The excess water above its water capacity is assumed as loss (runoff/ drainage). These types of models ignore the vertical moisture distribution in the root zone and assume that the losses by evapotranspiration and deep infiltration are a function of the average degree of soil saturation. As per the views of Anderson and Harding (1991) and Yadav et al. (2009 a & b) the spatial and temporal distributions of soil moisture regime calculated by using water budget models are not so accurate to quantify moisture flow and solute transport in the vadoze zone. The concepts of field capacity and wilting point are central and important in water budget models. A drawback of water budget models is that redistribution of water (except for the recharge to field capacity) is not considered. De Jong and Bootsma (1996) put forward that these models are restricted to free draining soils with a deep water table only. These models do not consider capillary rise of groundwater penetrating into the root zone. The strength of these types of models is that these models require a less amount of data, namely field capacity, wilting point, daily precipitation and evapotranspiration.

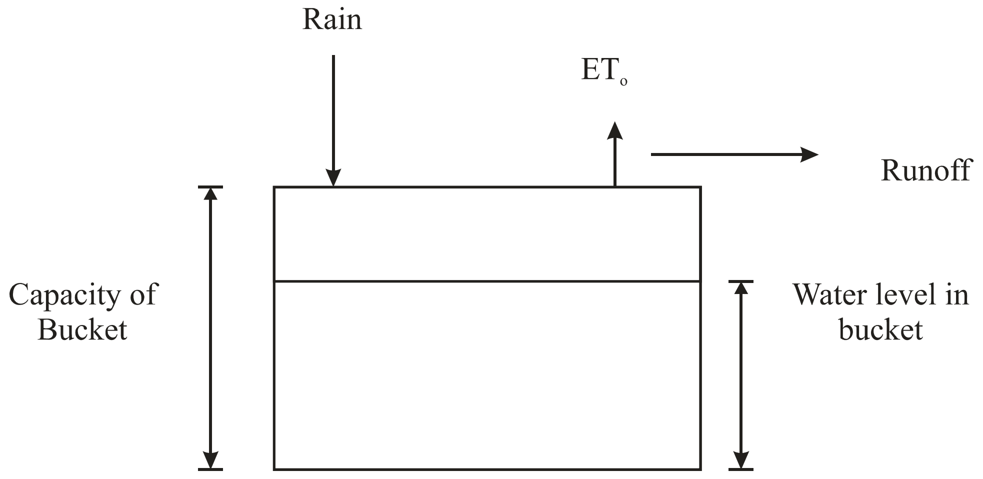


Figure 2.1: Bucket model

2.3.1.1 Niwa Model

Niwa model is a simple bucket model as shown in Figure 2.1. It uses only one parameter, the soil moisture storage capacity (S_{max}). Rainfall or irrigation water is infiltrating into, a soil store and moisture is reducing by evapotranspiration. At the stage when soil store is full, it is assumed to be saturated or at field capacity and the excess rainfall water is treated as runoff. Evapotranspiration is treated to be continued at its potential rate till the soil water store drops to half of its field capacity or S_{max}. The evapotranspiration decreases linearly to zero when store is empty. Kandel et al. (2005) used S_{max} value 150 mm for all modeling grids in their study.

2.3.2 Semi-Dynamic Models

Semi-dynamic models uses the multi-layer concept. They combine water budget procedure with a more dynamic methodology. In these models daily application of water is stored in the uppermost soil layer, until this layer reaches its upper limit. The excess water from first layer start to cascade into lower layers, until sufficient storage is reached. This process continues to consequent layers. This subsequent redistribution and drainage is estimated by using a Darcy-type unsaturated flow computation equation. These models split ET_o between potential crop transpiration and soil evaporation on the basis of ground cover and the leaf area index (LAI). As per De Jong and Bootsma (1996) Semi-dynamic models provide a more detailed description of water movement through the soil than water budget models.

2.3.2.1 Versatile Soil Moisture Budget (VSMB) Model

Bier and Robertson (1966) state that in Versatile Soil Moisture Budget (VSMB) model, infiltration is distributed over six soil zones as a function of infiltration depth, relative water content in each zone, and a percolation coefficient. The latter determines the fraction of the infiltration water which percolates to the next zone before field capacity is reached. In another version of VSMB model described by Dyer and Mack (1984), each zone can be filled to its saturation water content, rather than field capacity.

2.3.3 Dynamic Models

In dynamic models infiltration and redistribution of water are controlled by the physical factors governing water movement in soil. The knowledge of the availability of soil moisture is an important factor in relation to crop production. The amount of irrigation water for a crop field is dependent on the rooting pattern of that crop and the layer-wise distribution of soil moisture in the root zone profile. As the measurement of soil moisture at regular intervals is not economical and time consuming, there has been continuing interest in developing physical parameter based mathematical models.

2.3.3.1 Types of Dynamic Models

Molz and Remson (1970) have classified the dynamic models in two major groups as follows:

- Microscopic (Single Root) Dynamic Models
- Macroscopic (Root System) Dynamic Models

Feddes and Raats (2004) in their literature considered following types.

- Local scale (micro scale, mesoscale and macro scale),
- Field scale
- Regional scale to Global scale

2.3.3.2 Microscopic (Single Root) Dynamic Models

The water uptake by plant root has been mathematically described by single root models. In this model the root is assumed to be a line sink of with following properties (Taylor and Klepper, 1975):

- Infinite length
- Uniform radius
- Uniform absorption

These Microscopic, bottom up approach dynamic models, deal with the radial flow of water to an individual (single) root. The driving force for the uptake of water into the root is the difference in water potential that exists between the soil solution adjacent to the root and the root xylem as described by Taylor and Klepper (1975) and Yadav and Mathur (2008).

According to Molz and Remson (1970) soil moisture flow equation is generally written in cylindrical coordinates and solved with appropriate boundary conditions at the root surface and at some distance, r_{max} from the root. In many studies r_{max} is taken to be infinite.

Chang and Corapcioglu (1997) found that this approach is more useful in its understanding of the root extraction process than in its interpretation of field data collected under heterogeneous condition over a period of root development. As cited by Rao and Mathur (1994), Mathur and Rao (1999) and Raat (2007) Phillip (1957) was the first researcher (pioneer) who developed microscopic approach. Microscopic analyses of the root extraction process have also been presented by Gardner (1960), Molz et al. (1968) and Taylor and Klepper (1975).

2.3.3.2.1 Limitation of Microscopic Models

Microscopic models are not effective due to the following reasons:

- According to Molz (1981), Rao and Mathur (1994), Mathur and Rao (1999) and Yadav and Mathur (2008) steady-state conditions hardly exist. The living root system is a dynamic system. The detailed geometry of the root system is practically impossible to measure. The permeability of the root varies with position along the root.
- Hillel (1975) and Mathur and Rao (1999) concluded that the root water uptake is the most effective in young root material. Since the length of young root is not directly related to the total length, there will be differential absorption activities depending upon the age and location of the roots while using the microscopic approach.
- Hillel (1975) found that the experimental evaluation of root properties is not practical because of the space time involved.
- Taylor and Klepper (1975) and Mathur and Rao (1999) stated that the main limitation of the microscopic models is that they cannot be experimentally tested and boundary conditions cannot be easily defined and applied to such models.
- Molz and Remson (1970) found that in some of the microscopic studies there may be a tendency to presume uniform extraction even at moderate or low root densities.

2.3.3.3 Macroscopic (Root System) Dynamic Models

These macroscopic dynamic models are top-down approach models which eliminate the need for obtaining soil and plant parameters. The flow to individual roots is ignored and the overall root system is considered to uptake moisture from each layer of the root zone at some rate. This rate depends on position of depth point in a coordinate system, existing moisture content, and time from initial condition. Chang and Corapcioglu (1997) assumed the following boundary conditions:

- Top soil surface as upper boundary
- Lower boundary as the water table boundary
- Gravity flow condition boundary (where water table boundary is not considered)

2.3.4 Other Developments in Macroscopic Dynamic Models

Chang and Corapcioglu (1997) expressed that all models calculate soil moisture flow by numerical solution to Darcy - Richards equation coupled with water extraction by root system, assuming incompressible soil matrix and applying continuity equation. Gardner (1964*)* proposed a macroscopic mathematical model to describe the water uptake by a non-uniform root system. The main thrust in this study was to determine the rooting distribution associated with each depth increment rather than integrating it over the entire root zone as a continuum. Similarly, Whistler et al. (1968) considered the surface area of the roots per unit volume of soil and an effective distance over which the water moves toward the root (a kind of root density function). Nimah and Hanks (1973) further extended this concept and considered the root distribution function, RDF $_{(z)}$, which is the proportion of total active roots in depth increment, Δz. This RDF is dependent upon time as well as depth, for nine day interval and they assumed it as constant with time. They determined this function by sampling the soil profile in the field assuming value of the effective water potential in the root depended on following factors:

- RDF
- Climatic condition
- Soil conditions

They calculated the root extraction per unit depth (S) from the difference between root and soil potentials multiplying by the soil hydraulic conductivity and a root distribution function estimated from measurements of root weight. The model was later modified by Feddes et al. (1974) in which it was shown that the root effectiveness function is proportional to root mass and that both vary nearly exponentially with depth. This study suggested that this function can be found by sampling the root mass with depth and determining the proportionality constant from the model calibration. This model made the assumption that the potential at the root surface is constant throughout the root system. This assumption would only be valid if the root resistance is always small compared to that in the soil and that this is not always the case as described by Rowse et al. (1978). They calculated weekly water content profiles which did not agree completely with those measured in the field. Feddes et al. (1976) stated that the determination of the root effectiveness function would take lot of work or may need careful and expensive experimentation. For this reason they proposed different approach in which water uptake by root is considered as a function of the water content of the soil. They introduced a simpler extraction function.

The literature review reveals that the use of this macroscopic water uptake by roots category is favoured in most of the root water uptake models. These models either ignore the impact of soil moisture deficit or do not consider the non-homogeneity of root density distribution throughout the soil depth. In arid and semi-arid climatic regions, crop is subjected to varying levels of moisture stress in different parts of the root zone, which in turn results in the reduction of moisture uptake by plants. To overcome this lacuna, Feddes et al. (1978) developed a model by introducing a reduction factor for plant water extraction to incorporate the impact of soil moisture availability. This modified water extraction term suggests that potential transpiration is distributed homogeneously over the rooting depth and moisture uptake is reduced during water shortage. Molz (1981) suggested that models of soil moisture would be further improved if information on growth, development on root system and increasing amount of agronomic data are incorporated in flow models.

Molz and Remson (1970) proposed a linear model to fit an empirical rule that 40, 30, 20 and 10 %, respectively, of the total transpiration requirement comes from each successively deeper quarter of the root zone. Feddes et al. (1978) developed a model which assumes that the entire depth of root zone has a constant rate of extraction. Since at the tip of the root system this can be expected to be zero and that near the surface where root density is maximum rate of extraction would be high. These models show some deviation from the result in order to rectify this, Prasad (1988) proposed a linear water uptake model that takes into account the nonhomogeneous distribution of roots in the soil by assuming that the root density, and consequently water uptake by roots decreases linearly with the root zone depth.

Borge and Grime (1986) reviewed the depth development of roots of 48 crop species, by analysing 135 reported field observation under favourable environmental conditions. He proposed sinusoidal root growth model.

Marino and Tracy (1988) developed another model taking the root extraction term as a function of the water pressure gradient across the root-soil interface as well as soil and root parameters. This water flow model coupled with partial differential equation describes the macroscopic movement of water through a root-soil system. Malik et al. (1989) developed model utilizing either observed or generated root length densities incorporating factors which account for the decreased rate of water uptake by plant roots due to following reasons:

- Diminishing soil moisture during the drying cycles and
- Decreasing root effectiveness during crop growth period.

The soil moisture contents simulated by their model using observed and generated root length densities were overestimated by 6.0 % and 9.6 % on an overall basis, respectively in comparison to observed soil moisture contents. These variations were due to following reasons:

- Assuming soil profile to be homogeneous
- Neglecting hysteresis effect
- Assuming a multiplicative soil moisture dependent function
- Root effective function causing less water uptake by plant roots

Gardener (1991) considered a moving sink model to predict water uptake by roots. However, according to his study, the moving sink method does not explicitly explain the observed uptake patterns completely.

Ojha and Rai (1996) improved the linear water uptake model proposed by Prasad (1988) with a nonlinear root uptake model. Wu et al. (1999) subdivided these water uptake models into two categories. Models by Nimah and Hanks (1973) and Hillel et al. (1976a, b) were categorised in the first categories. In this the water potential and hydraulic parameters inside the plant roots which are difficult to quantify, were considered. The second category models were using the potential transpiration rate, soil moisture availability, and the plant root density distribution. Feddes et al. (1974 and 1978), Gardner (1983), Molz and Remson (1970) and Prasad (1988) were used this type of approach. The parameters required for this category were relatively easy to obtain.

Ojha et al. (2009) validated Ojha and Rai (1996) model by conducting experiment and found that their model performed better.

Input soil parameters, m, n and α are necessary for running governing models. These parameters are evaluated by Van Genuchten model. The Van Genuchten model is complex in form and relies on a greater number of fitting parameters than the other available models. However, it yields a continuous output in the unsaturated zone and provides a good description of the soil moisture characteristic curve under all circumstances (Song et al. 2013)

Knowledge of a soil's unsaturated hydraulic conductivity or relative permeability is critical for describing the flow of fluids and solutes in the vadose zone. The water flows through the pore space (voids) in the soil profile. The permeability of soil is affected by changes in this space. In the saturated soil, void space is completely filled with moisture and coefficient of permeability is correlated to the void ratio of the soil. The resistance of water movement in a saturated soil is primarily a function of soil particle size and their arrangement and distribution of pores. All the pores are essentially filled with moisture in a saturated soil. In other words, water flows through all the pore channels under fully saturated conditions. As a result, the coefficient of permeability of a saturated soils is considered to be a function of void ratio and assumed to be constant value.

In the unsaturated soil, the void space is partly filled with water and air. The permeability of water in unsaturated soil is affected not only by the void ratio, pore size distribution, voids distribution and dry density but also by the degree of saturation. The coefficient of permeability is a function of the combined changes in the void ratio and the degree of saturation. The amount of pore space available for water to flow through soil decreases as a result of air entry into the soil. The reduction in degree of saturation of soil associated with an in increase in air content. This results in an increase in the matric suction or suction of the soil. Since the permeability of unsaturated soil is influenced by the degree of saturation, the soil moisture characteristic curve (SMCC) is used to predict the permeability coefficient. The major advantage of using the SMCC is that the moisture suction relationship can be easily obtained experimentally than the moisture-permeability relationship. It is common practice to express the permeability coefficient of water phase in unsaturated soil (K) as a scalar product of saturated permeability (K_s) and relative permeability (K_r). Kuang and Jiao (2011) and Ghanbarian et al. (2016) state that accurate prediction of the relative permeability to water under partially saturated condition has broad applications and has been studied intensively since the 1940s by petroleum, chemical, agriculture and civil engineers, as well as hydrologists and soil scientists. Experimental procedures are also available to directly measure the coefficient of permeability of unsaturated soils. They are time consuming, difficult, and costly. Hence much of research focus has been towards developing semi-empirical procedures to predict the unsaturated coefficient of permeability using the saturated coefficient of permeability and the soil-water characteristic curve.

2.4 SOIL MOISTURE ESTIMATION BY FEEL AND APPEARANCE

United States Department of Agriculture (USDA) has presented detailed information (*http: //www.nrcs. usda.gov /wps/ portal/nrcs/detail/wy/soils/?cid=nrcs142p2_026830*) on their website about feel and appearance method. This information can be used in irrigation water application scheduling. Feel and appearance method involves the following steps:

- Firstly, the soil sample is collected from field by using a probe, auger or a shovel.
- Second activity is firmly squeezing collected sample in a hand several times to form an irregularly shaped ball.
- Third step is to form ribbon by squeezing sample between thumb and forefinger.

- Following observation are noted:
    - Soil texture
    - Ability to form ribbon
    - Firmness
    - Surface roughness of ball
    - Water glistening
    - Loose soil particles
    - Soil/ water staining on fingers
    - Soil colour
- At last observations are compared with available charts and photographs to estimate the water available and the soil moisture in mm depleted below the field capacity.

2.5 SCHEDULING BY USING CROPPING PATTERN AS INDICATOR

Al-Kaisa and Broner (2001) suggested quick soil moisture assessment method. Crop appearance is one of the many field indicators that can be used in irrigation water application scheduling. A crop suffering from water stress has a darker color and exhibits curling or wilting. This indicator, now days, is considered inferior for modern agriculture due to the inability to determine the actual crop water use. The main advantage of this indicator is that it provides direct and visual feedback. Different Crops have different water requirements and they respond differently to water stress.

2.6 SOIL MOISTURE MEASURING DEVICES

At present several instruments and devices are available for monitoring or measuring soil moisture. The most commonly used in the field are tensiometers, moisture blocks and various electronic soil probes.

2.6.1 Tensiometers

A tensiometer is a device sealed water-filled tube with a porous ceramic tip on the lower end and a vacuum gauge on the upper end. It is installed in the soil profile with the ceramic tip placed at the desired root zone depth and with the gauge above ground. In dry soil water comes out of the instrument. The depleting water in the tube creates a partial vacuum. This vacuum is registered on the gauge. The drier the soil, the higher is the reading. When the soil receives water or moisture the action is reversed.

2.6.2 Electrical Resistance Meters

Electrical resistance meters determine soil moisture by measuring the electrical resistance between two wire grids embedded in a block of gypsum or similar material. These are permanently embedded in the field. The electrical resistance varies with its moisture content. As the soil dries, the block loses water and the electrical resistance increases. The resistance changes within the block is measured by the meter and interpreted in terms of soil water content.

2.7 EVAPOTRANSPIRATION

To schedule irrigation properly, farmer must know the environmental demand for surface water. The surface water loss occurs through evapotranspiration (ET). Fontenot (2004) has expressed that it is simply the amount of water returned to the atmosphere through evaporation and transpiration. Additionally, Dingman (1994) and Allen et al. (1998) have also observed that the evapotranspiration (ET) is a function of following factors:

- Temperature
- Solar radiation
- Humidity
- Wind
- Characteristics of the vegetation

The process known as evapotranspiration (ET) is used in many disciplines as listed below:

- Irrigation system design
- Irrigation scheduling
- Hydrologic and drainage studies

Verstraete (1987) has stated that ET is a combined process of both evaporation from soil surface and plant surfaces and transpiration through plant canopies. In this process the water is transferred from the soil medium and plant surfaces into the atmosphere in the form of vapour. Reference, potential and actual evapotranspiration are distinguishing terms which are commonly used, with some differences in their meaning.

2.7.1 Potential Evapotranspiration (ET_p)

The potential evapotranspiration concept was first introduced in the late 1940s and 1950s by Penman as stated by Irmak and Haman (2015). Its definition is available in standard text books. In the definition the evapotranspiration rate is not related to specific crop. As per the view of Irmak and Haman (2015) the main confusion with this definition is that there are many types of horticultural and agronomical crops that fit into the definition of short green crops. As per FAO researcher the definition confuses as to which crop should be selected and used as a short green crop.

2.7.2 Reference Evapotranspiration (ET_o)

In the reference evapotranspiration definition ambiguity about the crop is removed. The grass is specifically defined as the reference crop and this crop is assumed to be free of water stress and diseases. The terms reference evapotranspiration and reference crop evapotranspiration both represent the same meaning. The reference evapotranspiration concept was introduced by irrigation engineers and researchers in the late 1970s and early'80s to avoid ambiguities that existed in the definition of potential evapotranspiration. By considering the reference crop as grass, it has become simple and practicable to use proper crop coefficients. Two main crops have been used as the reference crops which are grass and alfalfa. Alfalfa has the physical characteristics closer to many crops than grass. Literature review reveals that researchers mostly agree with a clipped grass which provides a better representation of reference evapotranspiration than alfalfa.

Irmak and Haman (2015) have stated the important differences between the potential and reference evapotranspiration. According to that the weather data collection site is well defined in reference evapotranspiration. The reference evapotranspiration concept has been gaining significant acceptance by the engineers and scientists throughout the world because specific equations and standardized procedures being available for its estimates. The International Commission for Irrigation and Drainage (ICID) and the Food and Agriculture Organization (FAO) recommended that Penman-Monteith equation (FAO-56) be considered as the standard method for its estimation.

Reliable estimates of ET can provide estimates of water need through irrigation. There are several methods to measure evapotranspiration directly. For instance, a lysimeter is used to measure ET by routinely measuring the change in soil moisture of known volume of soil that is covered with vegetation. Fontenot (2004) remarked that lysimeter is expensive both in economically and in time investments to install, check, and maintain the equipment. He also pointed that evaporation pans measure the loss of a known quantity of water through evaporation. It does not measure transpiration directly. Therefore, it must be adjusted by using pan coefficients to represent ET_o. This indicates that the direct measurement of ET_o is difficult.

As per FAO-56, Penman-Monteith model is the standard for ET_o estimation. This method do not need plant and soil factors to be collected. ET_o calculation is simplified by using crop coefficients for varieties of crops. This model is a variant of the original 1948 Penman model. It accounts for aerodynamic resistance (R_a) and bulk surface resistance (R_s). These terms have modified the original equation. Allen et al. (1998) reported that the R_a term describes the physical resistance in transporting moisture from the evaporating surface (i.e. plant leaf) into the atmosphere. Fontenot (2004) stated that these two terms allow the original Penman model to better approximate the actual processes of evapotranspiration from a vegetated surface.

A major difficulty in modeling ET_o is the requirement for meteorological data of study area. All needed data may not be easily available everywhere. This restricts the use of more accurate model, and necessitates use of models that have less demanding data requirements. The limitation of reliable data availability in study area prompted Hargreaves et al. (1985) to develop an alternative approach where only maximum, minimum temperature and extraterrestrial radiation are required. As per the views of Allen et al. (1998) the Hargreaves model has a tendency to under-predict under high wind conditions ($U_2 > 3$ m/s) and to over-predict under conditions of high relative humidity.

Hargreaves (1994) introduced modified Hargreaves Equation which can be used alternatively where accurate data collection is difficult.

2.8 CROP EVAPOTRANSPIRATION

Subramaniam (1989) expressed that information on evapotranspiration of crops and water requirements of a region are needed for design and operation of irrigation projects. Crop evapotranspiration is calculated by multiplying ET_o by Crop coefficient (K_c) for the crop of interest. The concept of K_c was introduced and further developed by the researchers Doorenbos and Pruitt (1975) and Allen et al. (1998). FAO 56 gave detailed information on crop coefficient. The crop coefficient can be either single coefficient, or split into two/ dual coefficients. Dual coefficient describe separately the differences in evaporation and transpiration. The selection of coefficient depends on the purpose of the estimation, the precision, the data available and the time step with which the calculations are executed. Soil evaporation fluctuates daily and the single crop coefficient expresses only the time-averaged effects of crop evapotranspiration. If dual crop coefficient is considered the effects of crop transpiration and soil evaporation are estimated separately. The calculation for crop evapotranspiration consists of following steps (Subramaniam, 1989):

- Finding the crop growth stages
- Determining their lengths
- Selecting and applying the corresponding crop coefficients
- Adjusting the selected coefficients according to climatic conditions during these stages

CHAPTER - 3

MODEL FORMULATION

3.1 GOVERNING EQUATION

Soil water is dynamic and it moves constantly in the soil medium. The downward and horizontal movements of water occur during or after irrigation water application or rainfall. The upward movements take place when upper soil layers start drying up on owing to evaporation or evapotranspiration. As per Hubbert (1956) the first quantitative description of water flows through a porous medium was developed by Darcy in 1856, in the course of his classic investigation of seepage rates through sand filters in the city of Dijon France. He discovered the following equation.

$$q = \frac{K\Delta H}{L} \tag{3.1}$$

Where,

$\frac{\Delta H}{L}$ = hydraulic gradient or potential gradient,

K = hydraulic conductivity,

q = (Q/A) flux density or specific discharge,

Q = volume flowing through the column per unit time,

A = flow cross-sectional area.

Darcy's law is applicable for saturated (i.e. steady) flow only. In steady state flow the water volume incoming equals the water volume outgoing in the soil medium considered for study. The soil pores are generally highly irregular, intricate and tortuous. The flow through these soil pores is restricted by numerous hindrances like constriction and occasionally dead end spaces. The actual geometry of soil profile and flow pattern is complicated to describe in microscopic details. For this reason flow through complex medium is generally considered in terms of a macroscopic flow velocity vector. The detailed flow pattern is ignored and the conducting soil profile or medium is treated as though it were a uniform soil medium. The flow is assumed to be spread out over the entire cross-section of medium.

Darcy's law is not valid for all conditions of liquid flow. It is applied only when flow is laminar and where soil water interaction does not result in change of fluidity or permeability with a change in gradient. The laminar flow occurs only in silty and clayey soils. Majority of study indicate that hydraulic gradient more than unity may result in non-laminar flow. Darcy's law applied as long as the velocity of flow and the sizes of particles are such that the values of Reynold number remains below one. This type of condition is however valid in most cases of water flow through soil medium. Due to the small size of soil pores, flow through soil is generally considered as laminar

Hillel (1982) observed that majority of the soil water flow processes occur when the soil is in an unsaturated condition. Darcy's law is not directly applicable to these circumstances. In case the flow is unsteady, the flux changes with time. The hydraulic head may not decrease linearly along the direction of flow. The hydraulic gradient or the conductivity is variable in this situation. The localised gradient, flux and conductivity values are considered rather than the overall values for the soil system as a whole. Slichter in 1899 generalised Darcy's law for porous media into three dimensional macroscopic differential forms as follows:

$$q = -K\nabla H \tag{3.2}$$

Where, $\nabla = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}$ and ∇H = hydraulic gradient.

The divergence of vector (∇) gives at a point the rate per unit volume at which the physical entity issuing from that point (Remson et al. 1971). Richards (1931) extended the Darcy's law for unsaturated flow with provision that the conductivity is a function of matric suction or suction (ψ).

$$q = -K(\psi)\nabla H \tag{3.3}$$

The equation (3.3) is also written in another form with provision that the conductivity is a function of moisture content or water content (θ).

$$q = -K(\theta)\nabla H \tag{3.4}$$

Where, ψ = suction and θ = water content.

Equation (3.3) and (3.4) represents the movement of water in unsaturated soils. These are nonlinear and partials difference equations. These equations are difficult to approximate as they do not have a closed form analytical solution. To obtain a generalised flow equation and to account for transient condition, as well as, steady flow process, the continuity equation is needed to be introduced which embodies the conservation of mass law in mathematical form (Hillel, 1982). Richards applied a continuity requirement and obtained a general partial differential equation describing water movement in unsaturated non-swelling soils as follow:

$$\frac{\partial \theta}{\partial t} = -\nabla . q \tag{3.5}$$

The relation between θ and Ψ is experimentally obtained in two ways. Firstly in the desorption case, saturated soil sample is taken and gradually suction is increased and the successive measurement of wetness versus suction is observed. Secondly in the sorption case, a dry soil sample is wetted gradually with decreasing suction and the successive measurement of wetness versus suction is observed. Each of the practical method yields separate soil moisture continuous curve. This curves are known as Soil Moisture Characteristic Curves (SMCC).

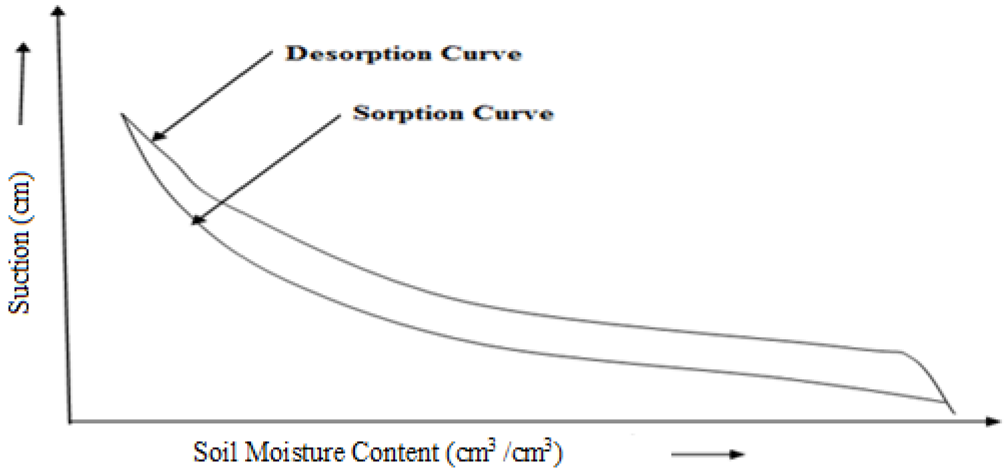


Figure 3.1: Soil Moisture Characteristic Curves (SMCC)

On observing these two curves, it is found that the two curves are not identical. This different nature of curve is called as hysteresis (Hillel, 1971 and 1982; Kirkham and Powers, 1972; Dane and Wierenga, 1975). The θ and ψ depend on whether the soil is wetting or drying. As per Braddock et al. (2001) this hysteresis arises from the differences in the processes of filling or emptying of pores in the soil. The relation between conductivity to suction depends on whether the soil is wetting or drying. Hillel (1982) explained that at a given suction, a drying soil contains more moisture than in wetting. In our study drying curve is considered. The equation (3.5) can be written in the following form.

$$\frac{\partial \theta}{\partial t} = -\nabla.[K(\psi)\nabla H] \tag{3.6}$$

Total hydraulic head (H) is the sum of the pressure and the gravitational heads (H = ψ – z). Putting H = ψ – z, Richards Equation has been written in most widely accepted mathematical form as follows:

$$\frac{\partial \theta}{\partial t} = -\nabla.[K(\psi)\nabla(\psi - z)] \tag{3.7}$$

∇z is zero for horizontal flow (as there is no change in gravitational head in horizontal direction) and unity for vertical flow (Gravitational head decreasing at the rate of 1 cm with each centimetre of vertical depth below the surface) (Hillel, 1982).

$$\frac{\partial \theta}{\partial t} = -\left[\frac{\partial}{\partial x}\left(K(\psi)\frac{\partial \psi}{\partial x}\right)\right] - \left[\frac{\partial \psi}{\partial y}\left(K(\psi)\frac{\partial \psi}{\partial y}\right)\right] - \left[\frac{\partial}{\partial z}\left(K(\psi)\frac{\partial \psi}{\partial z}\right) - \left(\frac{\partial K(\psi)}{\partial z}\right)\right] \tag{3.8}$$

The flow process may occur in which ∇z or gravity gradient is negligible compared to strong suction, then above equation changes in the following form which is known as mixed form equation.

$$\frac{\partial \theta}{\partial t} = -\left[\frac{\partial}{\partial x}\left(K(\psi)\frac{\partial \psi}{\partial x}\right)\right] - \left[\frac{\partial \psi}{\partial y}\left(K(\psi)\frac{\partial \psi}{\partial y}\right)\right] - \left[\frac{\partial}{\partial z}\left(K(\psi)\frac{\partial \psi}{\partial z}\right)\right] \tag{3.9}$$

To simplify the mathematical and experimental treatment of unsaturated flow process, it is often advantageous to change the flow equation into a form analogous to the equation of diffusion and heat conduction, for which ready solution are easily available. To transform the flow equation, it is sometimes possible to relate the flux to the water content gradient rather than to the suction gradient so the suction gradient $\frac{\partial \psi}{\partial x}$ can be expanded by the chain rule as follows:

$$\frac{\partial \psi}{\partial x} = \left(\frac{\partial \psi}{\partial \theta}\right)\left(\frac{\partial \theta}{\partial x}\right), \frac{\partial \psi}{\partial y} = \left(\frac{\partial \psi}{\partial \theta}\right)\left(\frac{\partial \theta}{\partial y}\right) \text{ and } \frac{\partial \psi}{\partial z} = \left(\frac{\partial \psi}{\partial \theta}\right)\left(\frac{\partial \theta}{\partial z}\right)$$

Where, $\frac{\partial\theta}{\partial x}, \frac{\partial\theta}{\partial y}$ and $\frac{\partial\theta}{\partial z}$ are wetness gradient and $\frac{\partial\theta}{\partial\psi} = \mathrm{C}(\theta) =$ specific water capacity. This specific water capacity is slope of the soil moisture characteristic curve (SMCC) at any particular value of wetness θ (Feddeset al. 1978; Hillel, 1982; Belmans et al. 1983; Clemente et al. 1994). Using the chain rule equation (3.9) will be transformed in θ-based form as follows.

$$\mathrm{C}(\theta)\frac{\partial\theta}{\partial t} = -\left[\frac{\partial}{\partial x}\left(\mathrm{K}(\theta)\frac{\partial\theta}{\partial x}\right)\right] - \left[\frac{\partial}{\partial y}\left(\mathrm{K}(\theta)\frac{\partial\theta}{\partial y}\right)\right] - \left[\frac{\partial}{\partial z}\left(\mathrm{K}(\theta)\frac{\partial\theta}{\partial z}\right)\right] \qquad (3.10)$$

If the soil wetness θ and ψ are uniquely related then the left hand term of above equation (3.10) can be written in a ψ - based form with considering
$\frac{\partial\theta}{\partial t} = \left(\frac{\partial\theta}{\partial\psi}\right)\left(\frac{\partial\psi}{\partial t}\right)$ as follows:

$$\mathrm{C}(\psi)\frac{\partial\psi}{\partial t} = -\left[\frac{\partial}{\partial x}\left(\mathrm{K}(\psi)\frac{\partial\psi}{\partial x}\right)\right] - \left[\frac{\partial}{\partial y}\left(\mathrm{K}(\psi)\frac{\partial\psi}{\partial y}\right)\right] - \left[\frac{\partial}{\partial z}\left(\mathrm{K}(\psi)\frac{\partial\psi}{\partial z}\right)\right] \qquad (3.11)$$

In a steady, isotropic, homogeneous and stable medium, if there is no change of moisture (water) content with respective time. $\frac{\partial\theta}{\partial t} = 0$, then K (θ) or K (ψ) would be K. The equation would change as follows:

$$0 = \frac{\partial^2 \mathrm{H}}{\partial x^2} + \frac{\partial^2 \mathrm{H}}{\partial y^2} + \frac{\partial^2 \mathrm{H}}{\partial z^2} \quad \text{or } \nabla^2 \mathrm{H} = 0 \qquad (3.12)$$

Hillel (1982) stated that in virtually all type of studies the equations derived for fluid motions were used in various forms. Celia et al. (1990) gave three forms of equation for fluid motions:

- ψ-based,
- θ -based
- Mixed form

These three types of equations are also used in one, two or three dimensional forms. In general, from a macroscopic point of view, nearly all form of models calculate soil moisture flow by numerical solution of the Darcy- Richards Equation coupled with water extraction by root system (i.e. sink). For study area one dimensional ψ - based model is considered which is written as follows:

$$\frac{\partial}{\partial z}\left(K(\psi)\frac{\partial\psi}{\partial z}+1\right) = C(\psi)\frac{\partial\psi}{\partial t} \tag{3.13}$$

As per the study of Clement et al. (1994), the mixed and θ-based forms are best for conservation of mass, particularly when sharp moisture gradients are present, and the mixed and ψ - based forms are necessary for saturated conditions and layered soil profiles. If the sink term R_s (θ, ψ, z, t) is considered then model would change as follows:

$$\frac{\partial}{\partial z}\left(K(\psi)\frac{\partial\psi}{\partial z}+1\right) + R_s\,(\theta,\psi,z,t) = C(\psi)\frac{\partial\psi}{\partial t} \tag{3.14}$$

Kumar et al. (2013), used mixed form Richards' 1-dimensional model in their study.

3.2 PARAMETERS ESTIMATION FOR GOVERNING EQUATION

After flux (q), the hydraulic conductivity K and moisture content θ are important parameters in the governing equation. As per Bouwer (1978), moisture movement in this vadoze zone is complicated. The soil-pores contain air and water. Parameter like hydraulic conductivity which is a hydraulic constant in saturated systems, becomes a hydraulic functions in unsaturated soils. Dane and Wierenga (1975) stated that the rate at which moisture moves in soil depends on the soil moisture suction and hydraulic conductivity. Schwartz and Zang (2003) expressed that governing equation for the flow becomes more complicated to solve because parameters turn into nonlinear functions. The hydraulic behavior of unsaturated soils is presented by means of the soil–water retention curve or Soil Moisture Characteristic Curve (SMCC). The soil–water retention curve and the unsaturated hydraulic conductivity are very important input parameters for the governing models for the simulation. The ultimate goal, during the soil hydraulic parameter evaluation, is to obtain parameters that are the closest and are representative the flow process. Van Genuchten (1980), De Jong (1982) and Birle et al. (2008) concluded that the experimental procedure for the determination of the unsaturated hydraulic conductivity is complex and time consuming, hence it is practicable that the unsaturated hydraulic conductivity is to be estimated from SMCC curves using empirical models. It is also an established fact that soil water retention data are more easily measured than hydraulic conductivity data in the laboratory. Van Genuchten (1980) remarked that the most applied conductivity models are based on the Burdine or Mualem theory. Mualem (1976) cited the following equation of Burdine.

$$\mathrm{K}_r(\theta\mathrm{e}) = \frac{\Theta^2 \int_0^{\theta_e} \frac{d\theta_e}{\psi 2}}{\int_0^{\theta_s} \frac{d\theta_e}{\psi 2}} \tag{3.15}$$

Where,

$\Theta = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} =$ effective saturation ($\theta_r \leq \theta \leq \theta_s$),

θ_e = effective moisture content= $\theta - \theta_r$,

θ_r = residual moisture content,

θ = actual moisture content,

θ_s = moisture content at saturation,

K_r = relative hydraulic conductivity.

Mualem (1976) equation was given by Van Genuchten (1980) as follows.

$$\mathrm{K}_r(\Theta) = \Theta^{1/2}\left[\frac{\int_0^{\Theta} \frac{d\Theta}{\psi}}{\int_0^{1} \frac{d\Theta}{\psi}}\right]^2 \tag{3.16}$$

Van Genuchten (1980) derived a closed form analytical expression from the soil water retention curves based on Mualem (1976) theory as follows.

$$\Theta(\psi) = \left\{\frac{1}{[1+(\alpha\psi)^n]}\right\}^m \tag{3.17}$$

Where α, m and n are soil parameters. Gardner (1983) showed that parameter n increases with increasing coarseness of texture, being of the order 1.5 to 2 for clays and loams to as high as 5 or 10 for sands; m is usually less than one.

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1+(\alpha\psi)^n]^m} \tag{3.18}$$

Here $m = 1 - 1/n$ (The soil-hydraulic properties derived and obtained by assuming that $k = m - 1 + \left(\frac{1}{n}\right) = 0$

$$K_r(\psi) = \frac{\{1-(\alpha\psi)^{n-1}[1+(\alpha\psi)^{n}]^{-m}\}^2}{[1+(\alpha\psi)^{n}]^{\frac{m}{2}}} \tag{3.19}$$

$$K_r(\Theta) = \Theta^{\frac{1}{2}}\left[1-\left(1-\Theta^{\frac{1}{m}}\right)^{m}\right]^2 \tag{3.20}$$

K_s = hydraulic conductivity at saturation and $K_r = K/K_s$

$$\mathrm{K}(\Theta) = K_s\left[1-\left(1-\Theta^{1/m}\right)^{m}\right]^2\Theta^{1/2} \tag{3.21}$$

$$\mathrm{K}(\psi) = K_s\,\frac{\{1-(\alpha\psi)^{n-1}[1+(\alpha\psi)^{n}]^{-m}\}^2}{[1+(\alpha\psi)^{n}]^{m/2}} \tag{3.22}$$

There are so many models available for finding out soil parameters. Generally for finding out soil parameters Van Genuchten model is used and computer program is prepared for it and available soil moisture data is analysed. Leiz et al. (1997) studied fourteen models for determining Θ (ψ), four models for K_r (ψ) and seven models for K_r (Θ). It means fourteen for Θ (ψ), and eleven for K_r. Leiz et al. (1997) also studied the combination of these water retention and conductivity models. They found Van Genuchten models were most appropriate for finding unsaturated hydraulic conductivity and water retention. Mirjat et al. (2005) established SMCC curve for various depths in free draining sandy loam soil with deep water table in the laboratory and 0.2 to 2 m depth in the field. Based on the results of his study, he has suggested that Van Genuchten model be used. Most of the studies show that the Van Genuchten predictive model based on SMCC perform reasonably well. This model is valid for monotonic wetting or drying only. In our study monotonic drying case is considered.

3.3 DEVELOPMENT OF MACROSCOPIC SINK TERM R_S (Ψ, z, θ, t)

The sink term R_s, for water uptake by plants is needed to estimate when Richards equation is coupled with sink. Feddes et al. (1978) proposed a semi empirical root extraction term which depends on soil water potential, and the maximum extraction rate, S_{max}. Most of the macroscopic models are developed on the basis of Feddes et al. (1978) model.

$$R_s(\Psi, \mathrm{z}, \theta, \mathrm{t}) = \phi(\psi)S_{max}(0 \le \phi(\psi) \le 1) \tag{3.23}$$

However, the above model was written in a different way by Perrochet (1987) as follows:

$$R_s(\Psi, z, \theta, t) = \phi(\psi)\, G(z)\, S_{max} \tag{3.24}$$

Where,

G (z) = root distribution function,

R_s (Ψ, z, θ, t) = soil moisture uptake rate per unit volume of soil by plant root,

S_{max} = maximum specific moisture extraction rate,

Φ (ψ) = reduction term.

3.3.1 Development of Reduction (ψ) Term

As per Levin et al. (2007), under water stress conditions the plant roots may not supply the maximum moisture required for potential transpiration, S_{max}. This lack of available moisture in the soil root zone causes most plants to biologically react by closing stomata, reducing transpiration, and reducing metabolic reactions. Various studies show that this reduction in transpiration rate is modelled by a limiting function. This limiting function determines the percentage decrease in the plants ability to draw moisture as the soil moisture suction increases in the vadoze zone. In such case, often the plant transpiration starts to decrease below the field capacity and ceases when the soil suction reaches the wilting point. To account for such conditions, it is acceptable to relate the actual evapotranspiration to the potential evapotranspiration (Levin et al. 2007). Homaee et al. (2002a, 2002b) studied various soil moisture reduction models, and evaluated using the experimental data. In many root uptake models, the following [Feddes et al. (1978)] piecewise linear reduction function is used widely.

$$\phi_{(\psi)} = \begin{cases} 0 \text{ for } \Psi_1 \leq \Psi \\ (\Psi_1 - \Psi)/(\Psi_1 - \Psi_2) \text{ for } \Psi_1 \geq \Psi \geq \Psi_2 \\ 1 \quad \text{ for } \Psi_2 \geq \Psi \geq \Psi_3 \\ 0 \text{ for } \Psi \geq \Psi_4 \end{cases} \tag{3.25}$$

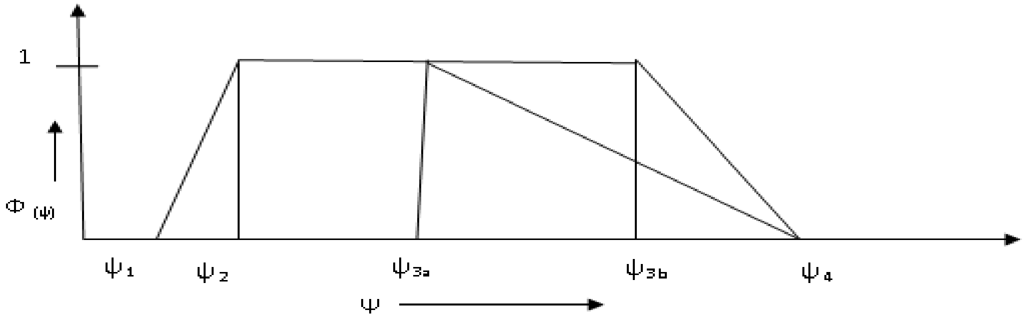


Figure 3.2: Dimensionless piecewise linear reduction function model (Feddes et al. 1978)

Feddes and Raats (2004) have given a table of critical suction head values for various crops. These values depend on various factors.

ψ_1 = anaerobiosis point at which deficient aeration conditions exist,

ψ_2 = values at optimal water uptake rate,

ψ_3 = suction values at optimal water uptake rate and varies with evaporation demand of the atmosphere,

ψ_4 = Wilting point pressure head at which plants can no longer extract water from the soil.

Table: 3.1 Critical Matric suction for various crops (cm)

Sr. No.	Crop	Ψ_1	Ψ_2	Ψ_{3a}	Ψ_{3b}	Ψ_4
01	Potato	-10	-25	-320	-600	-16000
02	Sugar beet	-10	-25	-320	-600	-16000
03	Wheat	0	-1	-500	-900	-16000
04	Pasture	-10	-25	-200	-800	-8000
05	Corn	-10	-25	-325	-600	-15000

De Jong and Kabat (1990) used the suction limit $\psi_1 = -1$ kPa; $\psi_2 = -2.5$ kPa; $\psi_{3a} = -20$ kPa; $\psi_{3b} = -80$ kPa; $\psi_4 = -800$ kPa. Mahdian and Gallichand (1996) used the suction limits $\psi_1 = -0.05$ m; $\psi_2 = -0.5$ m; $\psi_{3a} = -4$ m; $\psi_{3b} = -6$ m; $\psi_4 = -150$ m. Van Genuchten 1987 proposed reduction function for water stress and for salinity stress. Reduction function became $\phi_{(\Psi,\ \Psi_o)}$ (Feddes et al. 2001; Feddes and Raats 2004). Following three reduction terms discussed in detail by Homaee et al. (2002) and Feddes and Raats (2004)

$$\left.\begin{aligned}\Phi(\psi) &= \frac{1}{\left\{1 + \left(\frac{\psi}{\psi 0.5}\right)^{\mathrm{p}}\right\}}\\ \Phi(\psi_o) &= \frac{1}{\left\{1 + \left(\frac{\psi_o}{\psi_o 0.50}\right)^{\mathrm{po}}\right\}}\end{aligned}\right\} \text{Van Genuchten (1987) reduction function} \qquad (3.26)$$

$$\left.\begin{aligned}\Phi(\psi) &= \frac{1}{\left\{1 + \left(\frac{\psi* - \psi}{\psi* - \psi_o.50}\right)^{\mathrm{p}}\right\}}\\ \Phi(\psi_o) &= \frac{1}{\left\{1 + \left(\frac{\psi_o* - \psi_o\psi}{\psi_o* - \psi_o 0.50}\right)^{\mathrm{p}}\right\}}\end{aligned}\right\} \text{Dirksen et al. (1993) reduction function} \qquad (3.27)$$

$$\left.\begin{aligned}\Phi(\psi) &= \frac{1}{\{1 + \{[\frac{(1-\Phi_{\max})}{\Phi_{\max}}]\,[\frac{(\psi*-\psi)}{(\psi*-\psi_{max})}]^{\mathrm{p}}\}\}}\\ \Phi(\psi_o) &= \frac{1}{\{1 + \{[\frac{(1-\Phi_{o\max})}{\Phi_{o\max}}]\,[\frac{(\psi_o*-\psi_o)}{(\psi_o*-\psi_{o\,max})}]^{\mathrm{p}}\}\}}\end{aligned}\right\} \text{Homaee (2002 a) Model} \qquad (3.28)$$

Where, $\mathrm{p} = \frac{\psi_{max}}{(\psi_{max} - \psi*)}$

3.3.2 Development of Potential Transpiration Term (S_{max})

Most of the models found in the literature are similar in approach, but these models use different root extraction functions. Empirical equations have been developed by various researchers to predict the root growth with time. Some of these empirical equation required detailed information on the root to predict the growth rate of the root at microscopic scale. Such equations are impractical to use due to the requirement of extensive data. On the other hand simpler models, which are less accurate but use less information, are more practicable to use. Rao and Mathur

(1994), Chang and Corapcioglu (1997) classified two broad categories of root growth models. The first category assumes that root density changes with depth and not with time. In this approach an exponential function for the root growth is used. Second category assumes root distribution to be a function of time and soil moisture suction. The root growth equation is described in terms of root elongation minus the death rate of roots. Ojha and Rai (1996) critically reviewed Molz and Remson (1970), Feddes et al. (1978) and Prasad (1988) models. They suggested that root density is a nonlinear function of soil depth and they developed following model.

$$S_{max} = \left\{ \left[\frac{T_p}{L_r}\right] [\beta + 1] \left[1 - \left(\frac{z}{L_r}\right)\right]^{\beta} \right\} \tag{3.29}$$

Where,

T_p= transpiration on jth day,
L_r = root depth on jth day.

When β = 0, Ojha and Rai model becomes model which is suggested by Feddes et al. (1978) i.e. constant rate extraction model. For β = 1 Ojha and Rai model becomes model which is suggested by Prasad (1988) i.e. linear rate extraction model. Ojha et al. (2009) conducted a study to examine the performance of three models with Ojha and Rai (1996) and other two exponential root water uptake models. They concluded that further work is necessary to establish the value of $\beta_{optimal}$ for a variety of crops.

Table 3.2: Coefficient (β) for different crops with depth

Sr. No.	Depth	Cabbage	Wheat	Sorghum	Cotton
01	0.00	0.32	0.80	0.40	0.53
02	0.50	0.74	0.97	0.89	0.88
03	0.75	0.83	0.95	0.97	0.94
04	1.0	0.90	0.89	0.99	0.96
05	1.25	0.95	0.78	0.97	0.94
06	1.50	0.98	0.67	0.91	0.89
07	2.0	0.99	0.42	0.77	0.75

3.3.3 Root Distribution Function, G(z)

Perrochet (1987) introduced root distribution function in Feddes et al. (1978) reduction model.

$$S_{max} = \mathrm{G(z)}T_p \tag{3.30}$$

Wu et al. (1999) developed S_{max} equation (3.31) by introducing normalised distribution function of relative root density. The numerical model was applied to simulate soil moisture movement with root water uptake. The simulation results were compared with field experimental data. The simulated soil suction, soil moisture content and cumulative evapotranspiration had reasonable agreement with the measured data.

$$S_{max} = \frac{[R_{nrd}(Z_r)T_p]}{L_r} \tag{3.31}$$

Where,

R_{nrd} (z_r) = normalized distribution function of relative root density,

z_r = (z/ L_r) = normalized depth ranging from 0 to 1.

$$\mathrm{R_{nrd}}(Z_r) = \mathrm{R_0} + \mathrm{R_1}(Z_r) + \mathrm{R_2}(Z_r)^2 + \mathrm{R_3}(Z_r)^3 \tag{3.32}$$

Where, R_0, R_1, R_2 and R_3 are polynomial coefficients.

Wu et al. (1999) and Yadav et al. (2009) proved that if root density distribution function assumes the value of unity, the Wu et al. (1999) model would change to that suggested by Feddes et al. (1978). And similarly taking a linear reduction of root density distribution with depth and assuming a zero density at the bottom of the root zone, the model changes to the one similar to Prasad (1988). Wu et al. (1999) considered R_{nrd} (z_r) to be a nonlinear function determined from root density data.

Table 3.3: Polynomial coefficient R_{nrd} (z_r) for some crops

Sr. No.	Name of the crop	R_0	R_1	R_2	R_3
1	Wheat	2.21	-3.72	3.46	-1.87
2	Maize	2.15	-1.67	-2.36	1.88
3	Cotton	1.46	-.18	-0.62	-0.66
4	Bean	1.44	-.14	-0.61	-0.69

3.3.3.1 Root Growth Model, L_r

Wu et al. (1999) and Yadav et al. (2009) described the plant growth over a generation. They typically characterized it by a sigmoidal function. It comprises four growth stages; the growth in the initial stage is represented by an exponential growth rate, followed by a linear growth period with a relatively constant rate and subsequently the growth becomes progressively less until a steady state is attained. The equation used by Yadav et al. (2009) in their study describes the sigmoidal growth and dynamics of root depth as follows:

$$L_r(\mathrm{t}) = L_m \left\{ \left[\frac{1 + a_g}{a_g \left(1 + a_g \mathrm{e}^{-\mathrm{bg}\left(\frac{\mathrm{DAP}}{\mathrm{DTM}}\right)} \right)} \right] - \left[\frac{1}{a_g} \right] \right\} \tag{3.33}$$

Where,

a_g and b_g= Coefficient that depend on the growth stages or empirical growth parameters,

DAP = days after planting,

DTM = days to maturity for the plants,

L_m = maximum root depth.

Borg and Grimes (1986) reviewed the depth development of roots of 48 crop species by analysing 135 reported field observation under generally favourable environmental conditions and derived a sinusoidal simple root growth model as follows:

$$L_r(\mathrm{t}) = L_m \left(0.5 + \left(0.5 \sin \left(3.303 \left(\frac{\mathrm{DAP}}{\mathrm{DTM}} \right) - 1.47 \right) \right) \right) \tag{3.34}$$

3.3.3.2 Transpiration Model, T_p

Perrochet (1987), Babajmopoulos et al. (1995) and Wu et al. (1999) gave transpiration model as follow

$$T_p = ET_o - E_p \tag{3.35}$$

Where,

ET_o = reference evapotranspiration,

E_P = potential evaporation rate from soil surface.

Allen et al. (1998) state that when crop is small, applied water or available moisture losses are by evaporation only because the soil surface is not covered by the plant. Once the crop is well developed and completely covers the soil surface, transpiration become the main process. FAO Irrigation and Drainage Paper No. 24 Expert Group recommended four methods for estimating ET_o for different regions. They were as follows:

- Blaney-Criddle Method
- Radiation Method
- Pan evaporation Method
- Modified Penman Method

The selection of the method depends on the availability of data and amount of accuracy needed in study. As per Reddy and Reddi (2008) possible errors for first three methods were 15 %, 20 %, and 25 % respectively. FAO 56 recommends Penman-Monteith Equation as the sole standard method for the definition and computation of the reference evapotranspiration.

$$ET_o = \frac{\{(0.408\Delta\,(R_n - \mathrm{G})) + \left(\gamma\left(\frac{900}{\mathrm{T}+273}\right)(U_2(E_S - E_a))\right)\}}{\{\Delta + \gamma(1 + 0.34U_2)\}} \tag{3.36}$$

Where,

ET_o = reference evapotranspiration (mm/day),

R_n = net radiation at crop surface (MJ/ m^2 day),

G = soil heat flux density (MJ/ m^2 day),

T = mean daily air temperature at 2 m height (^{0}C),

U_2 = wind speed at 2m height (m/s),

E_s = saturation vapour pressure (kPa),

E_a = actual vapour pressure (kPa),

E_s - E_a = saturation vapour pressure deficit (kPa),

Δ = slope of the vapour pressure curve (kPa/ ^{0}C),

γ = psychrometric constant (kPa/^{0}C).

Mayber and Gale (1972) state that most of the water applied by irrigation method is lost in the process of transpiration. The water stress develops in the plant when the rate of transpiration exceeds that of the available water supply for the plant. The E_p estimation steps as suggested, by De Jong and Kabat (1990) are as follows:

$$E_p = ET_o(-0.21 + 0.70(\mathrm{LAI})^{\frac{1}{2}} \text{ If LAI} < 3 \qquad (3.37)$$

$$E_\mathrm{p} = ET_\mathrm{o} \qquad \text{If} \quad \text{LAI} > 3 \qquad (3.38)$$

Where, LAI = leaf area index.

Belman et al. (1983) and Feddes and Bastiaanssen (1992) calculated E_p as follows:

$$E_p = ET_o \exp(-0.6\mathrm{LAI}) \quad \text{where} \quad \mathrm{LAI} = \mathrm{a}S_c + \mathrm{b}{S_c}^2 + \mathrm{c}{S_c}^3 \qquad (3.39)$$

Where, S_c = Soil cover.

Wu et al. (1999) used E_p in their model as follows:

$$E_p = \left[\frac{\delta}{(\delta+\gamma)H_l}\right]\left[R_n \mathrm{e}^{(-0.39\mathrm{LAI})}\right] \qquad (3.40)$$

Where,

δ = saturation vapour pressure curve slope.

γ = psychrometric constant,

R_{ne} = net solar radiation flux,

H_L= latent heat of vaporisation of water per unit mass.

Babajimopoulos et al. (1995) have put forward a simple equation.

$$E_p = ET_o \exp(-0.623 \text{ LAI}) \tag{3.41}$$

Studies indicate that the difference in leaf anatomy, stomata characteristic, aerodynamic properties and even albedo cause the crop evapotranspiration to differ from the reference crop evapotranspiration under the same climatic conditions. Martinez et al. (2009) considered the following equation:

$$E_p = ET_o \exp(-r_{ec} \text{LAI}) \tag{3.42}$$

r_{ec}= 0 .4 = radiation extinction coefficient.

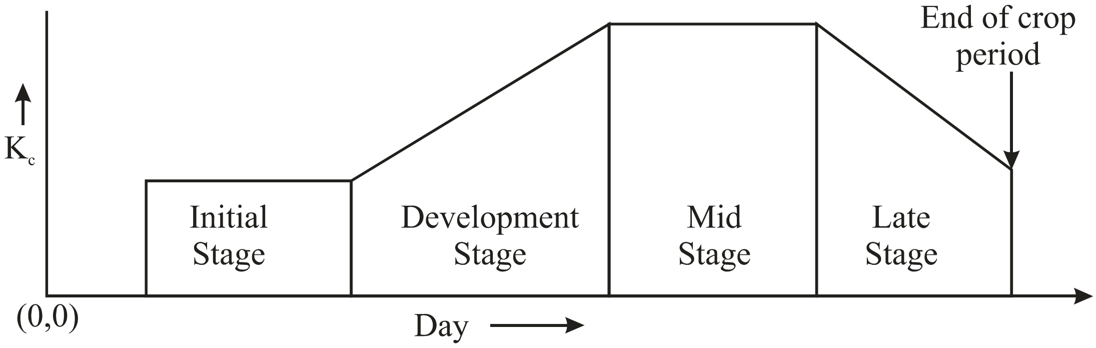


Figure 3.3: Crop Coefficient (K_c) Curve (Allen et al. 1998)

CHAPTER 4

PHENOMENON FOR ONE DIMENSIONAL UNSATURATED SOIL

4.1 INTRODUCTION

The phenomenon of water movement through unsaturated soil mass, in essence, happens to be a kind of logical extension to the phenomenon of water movement through saturated soil mass. The unsaturated flow processes are in general complicated and difficult to describe quantitatively, since they often entail changes in state and content of soil water during flow. Such changes involve complex relation among the variable soil wetness, suction and conductivity. This interrelation may be further complicated by hysteresis. The saturated soil-water flow is caused by driving force from potential gradient. This means the flow takes place from higher potential to lower potential. This principle applies in unsaturated, as well as saturated soil mass. The moving force in saturated soil mass is a gradient of positive pressure potential. On the other hand, water in an unsaturated soil mass is subject to a sub atmospheric pressure or suction which is equivalent to a negative pressure potential. The gradient of this potential likewise constitutes a moving force. As far as the finite element analysis for flow through unsaturated soil is concerned the main effect would be changed in the conductivity $K_x = K_y = K$. there are various empirical equations have been proposed in respect of ‘K’.

4.2 MODELING

Celia et al. (1990) state that in virtually all studies of unsaturated zone, the fluid motion is assumed to obey the classical Richards Equation. This equation is written in several forms, with either total head ψ [L] or moisture content θ [L^3/L^3] as dependent variable. The constitutive relationship between θ and ψ allows for conversion of one form of the equation to another. Three standard forms of unsaturated flow equation may be identified: ψ - based form, the θ - based form and the mixed form. These equations are written as follows:

$$\nabla . K(h)\, \nabla(\psi) + \frac{\partial \mathrm{K}}{\partial \mathrm{z}} = \mathrm{C(h)}\, \frac{\partial \mathrm{h}}{\partial \mathrm{t}} \qquad (4.1a)$$

$$\nabla . D(\theta)\nabla(\theta) + \frac{\partial K}{\partial z} = \frac{\partial \theta}{\partial t} \tag{4.1b}$$

$$\nabla . K(\psi)\nabla h + \frac{\partial K}{\partial z} = \frac{\partial \theta}{\partial t} \tag{4.1c}$$

In Equation 4.1 the term $\frac{\partial K}{\partial z}$ is indicative of non-homogeneity of the soil mass. In some studies this $\frac{\partial K}{\partial z}$ is removed from the equation. Thus the final form of equation may be considered as shown in the following equation.

$$\nabla . K(\psi)\nabla \psi = C(h)\frac{\partial \psi}{\partial t} \tag{4.2a}$$

$$\nabla . D(\theta)\nabla(\theta) = \frac{\partial \theta}{\partial t} \tag{4.2b}$$

$$\nabla . K(\psi)\nabla = \frac{\partial \theta}{\partial t} \tag{4.2c}$$

Where,

$C\ (\psi) = \frac{\partial \theta}{\partial \psi}$ = specific moisture capacity [1/L],

K (ψ) = unsaturated hydraulic conductivity [L/T],

$D(\theta) = \frac{K(\theta)}{C(\theta)}$ = unsaturated diffusivity [L^2/T].

In the above equation the porous medium is assumed to be isotropic. It is also assumed that appropriate constitutive relationships between θ and ψ or K and θ are available. It may be observed that the left hand side in Equations 4.2 have character identical to that of steady state phenomenon. However, the right hand side of the equation being non-zero the software for the steady state analysis needs to be coupled with the requirement of the right hand side requirement. The details of modeling and estimating needed parameters for it, are dealt in four chapters. These are:

a) Determination of soil moisture parameters of an actual site (Van Genuchten parameters), are analyzed in Chapter 5.

b) Determination of reference evapotranspiration (ET_o) from data collected for an actual site, are analyzed in Chapter 6.

c) Using water budget model and dynamic model are discussed in Chapter 7.

d) The element library for a formulation, finite element idealizations and Finite element solution for a practically important problem are discussed in present chapter.

4.3 ELEMENT LIBRARY

The proposed investigation is supposed to be carried out through the finite element solution technique. For this the idealization has the character of semi-discretization. This is because the idealization for the soil continuum in (x, y, z) is carried out through well-established finite element idealization process. The time dimension in which theory is extended upto infinity is represented through a finite difference technique. In view of this, the details of type of elements need to be enumerated. The element types available in literature are quite huge. The practically useful elements for the proposed investigation are included in the element library of the analysis software. Following are the details of element which are incorporated in the analysis software.

4.3.1 One Dimensional Elements

The one dimensional elements are having two nodes in case of first order elements and three nodes in case of second order elements. These are shown in Figure, 4.1 as follows:

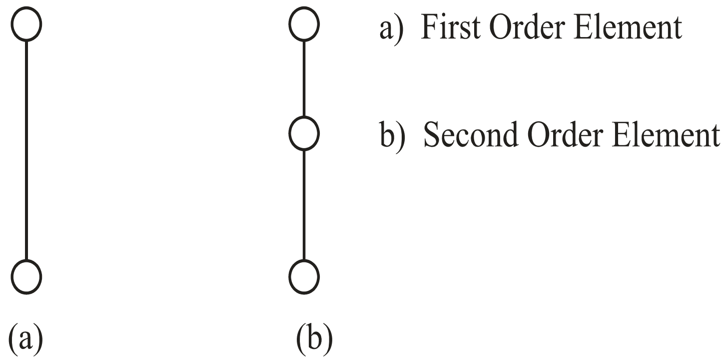


Figure 4.1: One Dimensional Element

4.3.2 Two Dimensional Elements

The two dimensional elements having four nodes in case of first order element and eight nodes in case of second order elementary shown in Figure, 4.2.

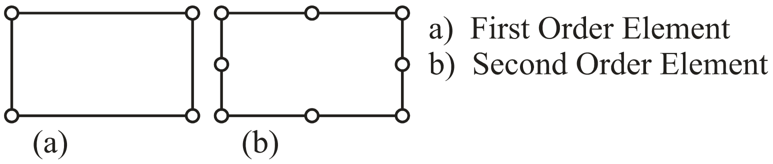


Figure 4.2: Two Dimensional Elements

4.3.3 Three Dimensional Elements

The three dimensional elements having eight nodes in case of first order element and twenty nodes in case of second order elementary shown in Figure, 4.3.

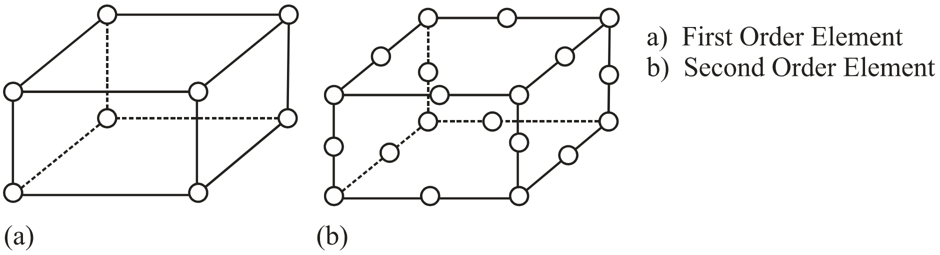


Figure 4.3: Three Dimensional Elements

NOTE: The elements shown above are referred to a natural co-ordinate system. In the actual analysis having Cartesian reference system, required element characteristics are derived through technique of Jacobian transformations coupled with the Gauss quadrature numerical integrations. The relevant details are presented in the sections to follow while dealing with the actual problem areas.

4.4 ONE DIMENSIONAL PROBLEMS

Considering the flow potential through a parameter Φ. The one dimensional flow confined to vertical direction represents a problem having application to the crop water management system. The finite element analysis for such problem is conducted by adopting one dimensional element for the purpose of finite element idealization.

4.4.1 First Order Element

A two nodded line element referred to a natural co-ordinate system (Figure, 4.4 a), and Cartesian co-ordinate system (Figure, 4.4 b), constitute a first order one dimensional element. The element is an isoparametric element which details are as shown in Figure, 4.4.

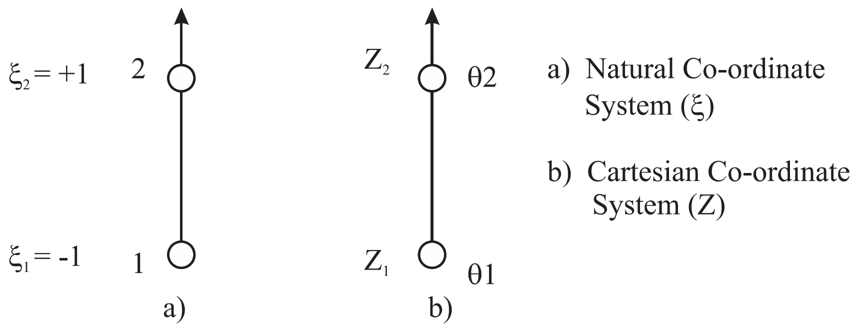


Figure 4.4: Details of First Order One Dimensional Isoparametric Element

The characteristics of the elements are derived as follows:

a) Interpolation Functions:

(N1, N2) interpolation functions are:

$$N_1 = \frac{(1-\xi)}{2} \tag{4.3a}$$

$$N_2 = \frac{(1+\xi)}{2} \tag{4.3b}$$

Flow potential φ is given by

$$\Phi = N_1\Phi_1 + N_2\Phi_2$$

$$= [N][\Phi_e] \tag{4.4}$$

Where,

$$[N] = \begin{bmatrix} N1 & N2 \end{bmatrix} \tag{4.5}$$

$$[\theta e] = \begin{bmatrix} \theta 1 \\ \theta 3 \end{bmatrix} \tag{4.6}$$

b) Flow Gradient

$$i = -\frac{d\Phi}{dz} \tag{4.7a}$$

$$= -[B][\Phi_e] \tag{4.7b}$$

Where

$$[B] = \frac{dN_1}{dz} \tag{4.8}$$

$$\frac{dN_1}{dZ} = \frac{dN_1}{d\xi} \cdot \frac{d\xi}{dZ} = -\frac{1}{2}\frac{d\xi}{dZ} \tag{4.9}$$

$$\frac{dN_2}{dZ} = \frac{dN_2}{d\xi} \cdot \frac{d\xi}{dZ} = \frac{1}{2}\frac{d\xi}{dZ} \tag{4.10}$$

$$Z = N_1 Z_1 + N_2 Z_2 \tag{4.11}$$

$$\frac{dZ}{d\xi} = \frac{dN_1}{d\xi} Z_1 + \frac{dN_2}{d\xi} Z_2 \tag{4.12}$$

$$= -\frac{1}{2} Z_1 + \frac{1}{2} Z_2 \tag{4.13}$$

$$= \frac{1}{2}(Z_1 - Z_2) = \frac{L}{2} \tag{4.14}$$

Here, ‘L’ is the length of the element

$$\frac{d\xi}{dZ} = \frac{2}{L} \tag{4.15}$$

Therefore

$$\frac{dN_1}{dZ} = -\frac{1}{L} \tag{4.16a}$$

$$\frac{dN_2}{dZ} = \frac{1}{L} \tag{4.16b}$$

And

$$[B] = 1/L \begin{bmatrix} -1 & 1 \end{bmatrix} \tag{4.17}$$

c) Seepage stiffness

Seepage stiffness matrix $[S_e]$ is given by

$$[S_e] = K \int_{Z_1}^{Z_2} [B]^T \, [B] dZ \tag{4.18}$$

Here, K is the hydraulic conductivity

$$dZ = \frac{L}{2} d\xi \tag{4.19}$$

Hence,

$$[S_e] = K \int_{-1}^{1} [B]^T \, [B] \frac{L}{2} d\xi \tag{4.20a}$$

$$[S_e] = \frac{K}{L^2} \int_{-1}^{1} [B]^T \, [B] d\xi \tag{4.20b}$$

$$= K/L \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \tag{4.20c}$$

d) Consistent Mass

Consistent mass matrix $[M_e]$ is given by

$$[M_e] = \int_{Z_1}^{Z_2} [N]^T \, [N] dZ \tag{4.21a}$$

$$[M_e] = \frac{L}{2} \int_{-1}^{1} [N]^T \, [N] d\xi \tag{4.21b}$$

$$= L/2 \begin{bmatrix} 2/3 & 1/3 \\ 1/3 & 2/3 \end{bmatrix} \tag{4.21c}$$

4.4.2 Second Order Element

A three noded line element referred to a natural co-ordinate system (Figure, 4.5a) and Cartesian co-ordinate system (fig. 4.5b) constitutes a second order one dimensional element. The element is an isoparametric element and its characteristics are derived as follows:

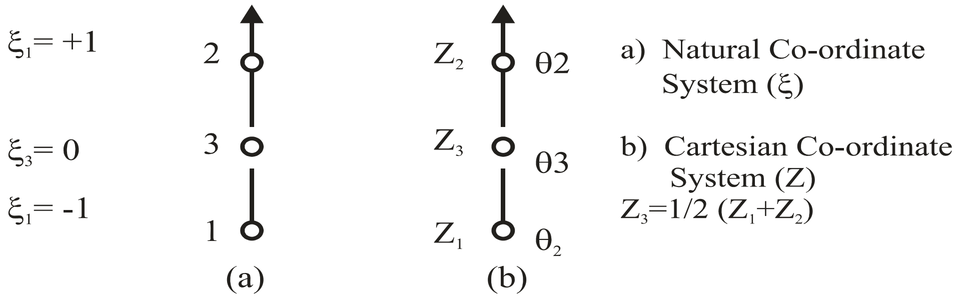


Figure 4.5: Details of a Second Order One Dimensional Element

a) Interpolation Function

(N_1, N_2, N_3) interpolation functions are

$$N_1 = -\frac{\xi(1-\xi)}{2} \tag{4.22a}$$

$$N_2 = \frac{\xi(1+\xi)}{2} \tag{4.22b}$$

$$N_3 = (1-\xi^2) \tag{4.22c}$$

Flow Potential Φ is given by

$$\varphi = N_1\varphi_1 + N_2\varphi_2 + N_3\varphi_3 \tag{4.23}$$

$$= [N][\varphi_e] \tag{4.24}$$

Where

[N]= (4.25)

N_1	N_2	N_3

[Φe]= (4.26)

[Φ1]
[Φ2]
[Φ3]

b) Flow Gradient

Flow gradient i is given by

$$i = -[B][\varphi_e] \tag{4.27}$$

Where

[B]= (4.28)

$\frac{dN_1}{dz}$	$\frac{dN_2}{dz}\frac{dN_2}{dz}$	$\frac{dN_3}{dz}$

$$\frac{dN_1}{dZ} = \frac{dN_1}{d\xi}\cdot\frac{d\xi}{dZ} = \frac{(-1+2\xi)}{2}\frac{d\xi}{dZ} \tag{4.29}$$

$$\frac{dN_2}{dZ} = \frac{dN_2}{d\xi}\cdot\frac{d\xi}{dZ} = \frac{(1+2\xi)}{2}\frac{d\xi}{dZ} \tag{4.30}$$

$$\frac{dN_2}{dZ} = \frac{dN_3}{d\xi}\cdot\frac{d\xi}{dZ} = -2\xi\frac{d\xi}{dZ} \tag{4.31}$$

$$Z = N_1 Z_1 + N_2 Z_2 \; + N_3 Z_3 \tag{4.32}$$

$$\frac{dZ}{d\xi} = \frac{(-1+2\xi)}{2} Z_1 + \frac{(1+2\xi)}{2} Z_2 - 2\xi Z_3 = \frac{L}{2} \tag{4.33}$$

Where $L = Z_2 - Z_1$

'L' is length of the element therefore

$$\frac{d\xi}{dZ} = \frac{2}{L} \tag{4.34}$$

Thus

$$[B]= \begin{array}{|c|c|c|} \hline -1+2\xi & 1+2\xi & -4\xi \\ \hline \end{array} \tag{4.35}$$

c) Moisture movement stiffness

Stiffness matrix $[S_e]$ is given by

$$[S_e] = K \int_{Z_1}^{Z_2} [B]^T \, [B] dZ \tag{4.36}$$

Here, K is the hydraulic conductivity

$$dZ = \frac{L}{2} d\xi \tag{4.37}$$

Therefore

$$[S_e] = \frac{KL}{2} \int_{-1}^{1} [B]^T \, [B] dz \tag{4.38}$$

It can be shown that

$$[S_e] = \frac{K}{6L} \begin{array}{|c|c|c|} \hline 14 & 2 & -16 \\ \hline 2 & 14 & -16 \\ \hline -16 & -16 & 32 \\ \hline \end{array} \tag{4.39}$$

d) Consistent Matrix

Consistent mass matrix $[M_e]$ is given by

$$[M_e] = \int_{Z_1}^{Z_2} [N]^T \, [N] dZ \tag{4.40}$$

$$[M_e] = \frac{L}{2} \int_{-1}^{1} [N]^T \, [N] d\xi \tag{4.41a}$$

Therefore,

$$[M_e] = \frac{L}{2} \begin{bmatrix} \frac{4}{15} & \frac{-1}{15} & \frac{2}{15} \\ \frac{-1}{15} & \frac{4}{15} & \frac{2}{15} \\ \frac{2}{15} & \frac{2}{15} & \frac{16}{15} \end{bmatrix} \tag{4.41b}$$

4.5 TEST PROBLEM

Data and results of one dimensional problem which are available in literature (Parikh, 1995) is taken up as a test problem for the finite element algorithm developed. Here problem is as defined in Equation 4.42.

$$K \frac{d^2\psi}{dz^2} = \frac{d\psi}{dt} \tag{4.42}$$

The problem is solved by finite difference technique, by taking four equal division in z direction and 20 equal divisions on the time axis. For the finite element solution of the same problem four equal divisions with each division of one unit in z direction leads to an idealization system comprising five nodes and four elements as shown in the following Figure, 4.6. Twenty division for time increment with each increment of 0.25 seconds. Taking the value of K = unity. The governing finite element equation had the two noded element. The details are given in the following Equation 4.43.

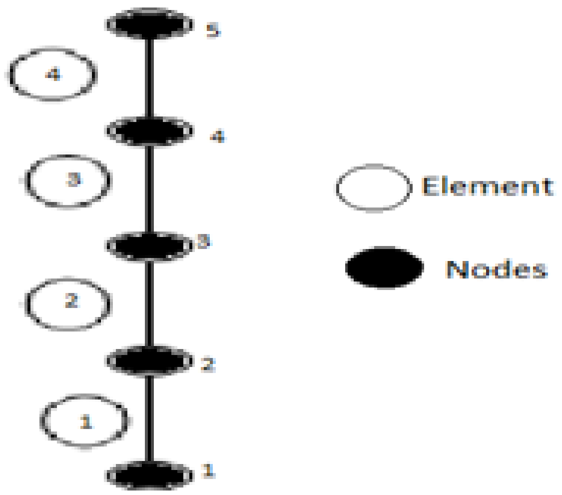


Figure 4.6: Finite Element Idealisation

$$\{[S_e] + [M_e]\}\, [H_e]^{t+\Delta t} = [R_e]^t \qquad (4.43)$$

Where, $[R_e] = L[N]^T[H_e]$

The data is as given below:

1) At t = 0 for all the nodes, H =100

2) For t > 0 at node 1 and 5,H =0

This boundary condition is given in which t = 0 the value of H at nodes 1 and 5 equal to 50 [(100+0)/2]. The solution is undertaken by employing the frontal solution technique. The elements are tackled sequentially. The complete solution details along with those available from the finite different solution are presented in following Figure, 4.7.

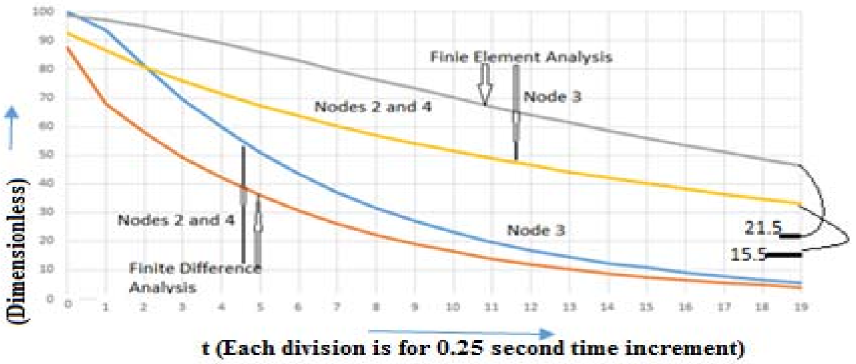


Figure 4.7: Solution Details

It is found that the finite element solution follows the trend similar to that of finite difference solution. The convergence is quite slow. It is well known that a finite element solution will be improved by refinement of idealization. The mesh dimension is reduced in z direction to half of the original size. The time increment reduced to 0.1 second at the end point of time period. The values obtained are indicated in Figure, 4.7. It proved that by making the refinement the convergence is very significant. In fact from the published literature it follows that, extremely fine mesh accompanied by very small size of time increment the ultimate solution is achieved.

4.6 VALIDATION FOR ONE DIMENSIONAL ANALYSIS SOFTWARE

In Section 4.5, success of the analysis of software was demonstrated by comparing the trend of the result with available finite different solution (Parikh, 1995). With a view to the validation of the software, the problem of Celia et al. (1990) is taken up from the available details and key features. The problem is reproduced herein. The various types of governing model have been already presented in Section 4.2. However for sake of ready reference relevant details are reproduced herein again.

4.6.1 Modeling Richards Equation for Vertical Unsaturated Flow

The vertical water flow in unsaturated soil mass is simulated by combination of Darcy's Law and mass conservation equation which is generally known Richards Equation. This governing model used in the study is expressed as follows:

$$\frac{\partial}{\partial z}\left(K(\psi)\frac{\partial \psi}{\partial z}+1\right) = C(\psi)\frac{\partial \psi}{\partial t} \tag{4.44a}$$

Where,

$C(\psi)$ is soil moisture specific/ differential capacity i.e. the change in moisture content in a unit volume of soil per unit change in matric suction. It is mathematically represented as $C(\psi) = \frac{d\theta}{d\psi}$,

$$\frac{d\theta}{d\psi} = \frac{-\alpha m\,(\theta_s-\theta_r)}{1-m}\,\Theta^{\frac{1}{m}}\left(1-\Theta^{\frac{1}{m}}\right)^{m} \qquad (4.44b)$$

Where, $\Theta = \frac{(\theta-\theta_r)}{(\theta_s-\theta_r)}$ & K(ψ)= hydraulic conductivity.

$$K(\psi) = K_s\,\frac{\{1-(\alpha\psi)^{n-1}[1+(\alpha\psi)^{n}]^{-m}\}^{2}}{[1+(\alpha\psi)^{n}]^{m/2}} \qquad (4.44c)$$

By this Van Genuchten equation α, m and n (fitting parameters) are established by using Soil Moisture Characteristic Curve (SMCC). The software listing of V G model is provided in appendix.

4.6.2 Numerical Data

The problem, considered for validation of the model is taken from Celia et al. (1990). The relevant material properties used here are as follows:

$\alpha = 3.35\ m^{-1}$,

$n = 2$,

$K_s = 9.22\text{x}10^{-5} m/s$,

$\theta_s = 0.368$,

$\theta_r = 0.102$.

The length (L) of the soil sample is 1m. The initial and boundary conditions are given as follows:

$t = 0$	$\psi = -10m$	$0 \le Z \le 1m$
$t > 0$	$\psi = -10m$	$Z = 0$
$t > 0$	$\psi = -0.75$	$Z = 1m$

The problem is simulated using the above mentioned model by employing a finite element idealization with 2 noded elements. Here θ_s, θ_r, α, m and n are Van Genuchten parameters. For analyzing the soil properties, the Van Genuchten model is used and results are presented graphically as follows:

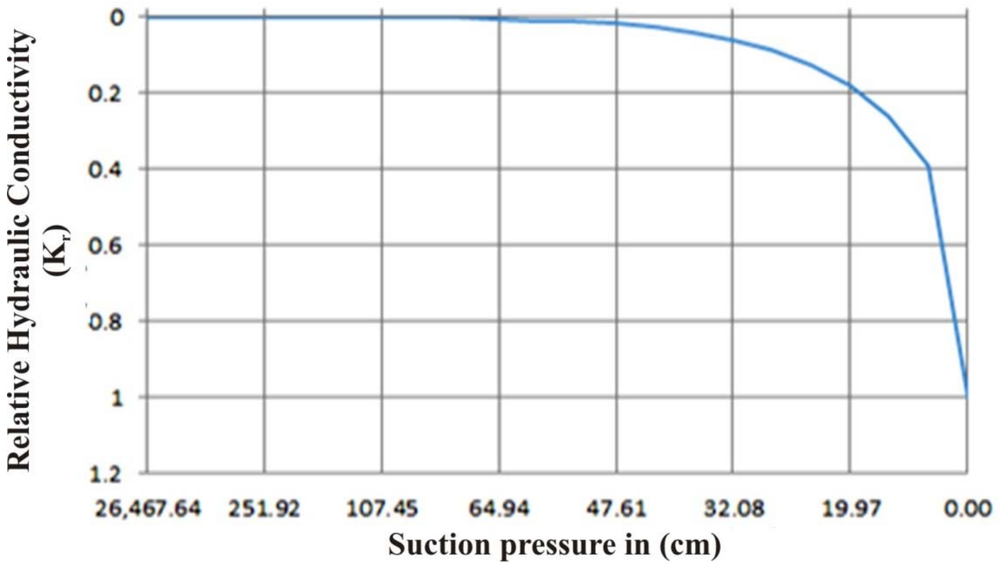


Figure 4.8: Typical Plot Relative Hydraulic Conductivity versus Suction

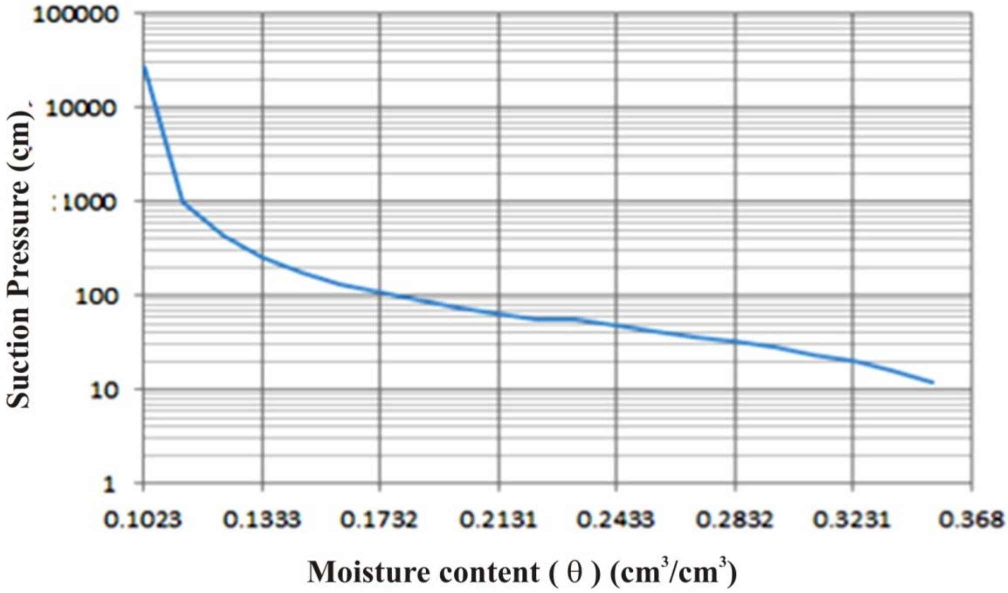


Figure 4.9: Typical Moisture Retention Curve (SMCC)

4.6.3 Validation

Celia et al. (1990) obtained results using finite element and finite difference solution using $\Delta z = 2.5$ cm grid size with different time steps. For validation of our selected model (ψ - based) time step is fixed as one hour, i.e., $\Delta t = 1$hr. The varying space grid sizes (i.e., $\Delta z = 2.5$ cm, $\Delta z = 2$ cm and $\Delta z = 1$ cm) are used. The results obtained are presented graphicaly as follows:

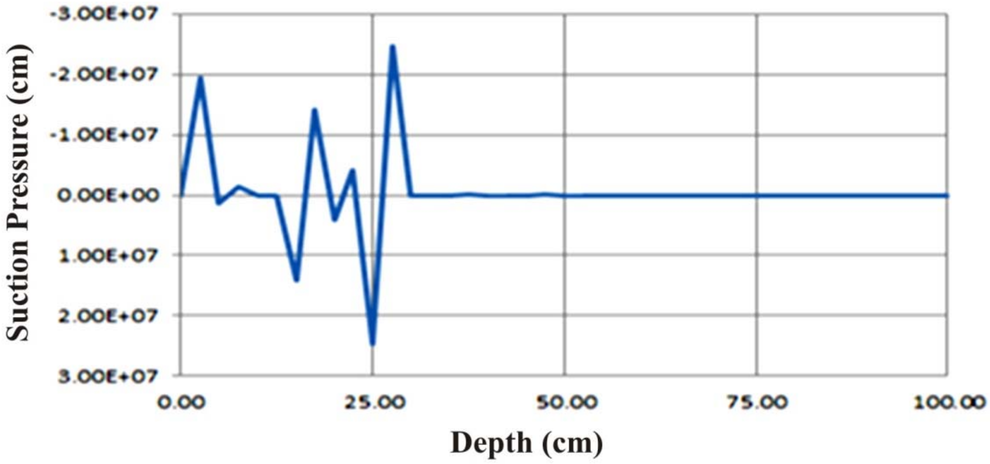


Figure 4.10: Unstable Solution at Δt = 1 Hr & Δz =2.5 cm

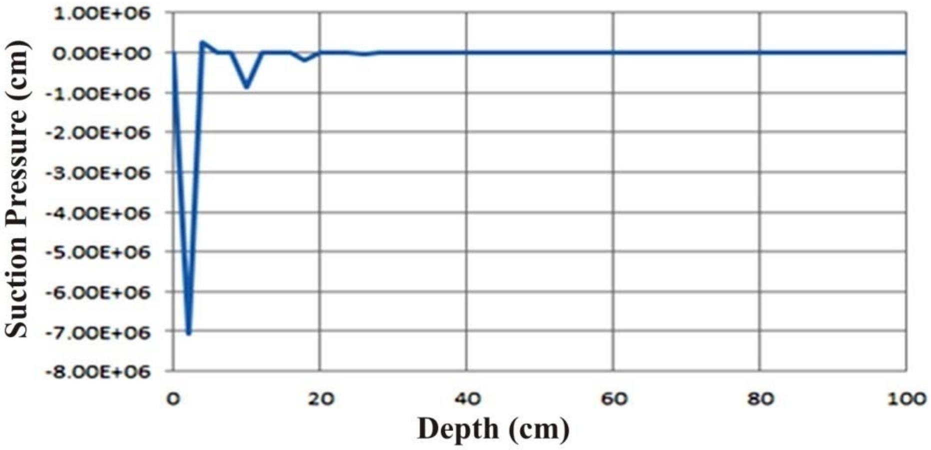


Figure 4.11: Unstable Solution at Δt = 1 Hr & Δz = 2 cm

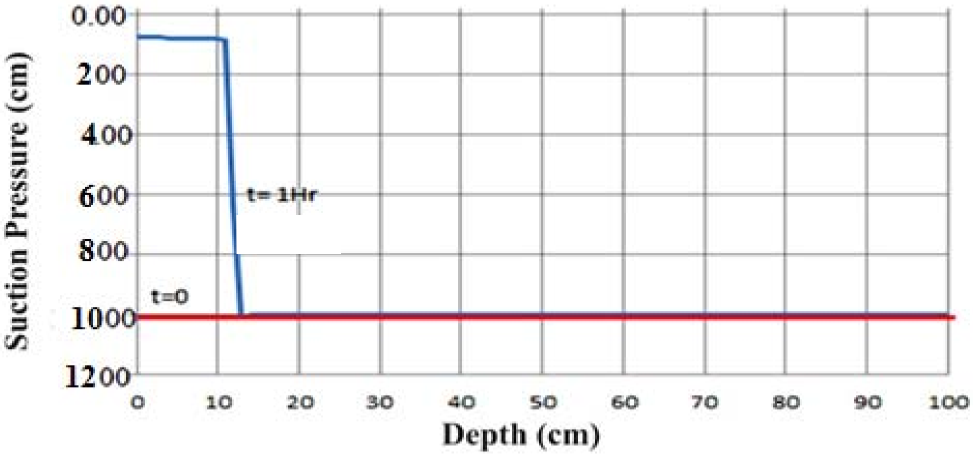


Figure 4.12: Stable Solution at Δt = 1 Hr & Δz = 1 cm

4.7 ALGORITHM FOR THE ANALYSIS OF SOFTWARE

The algorithm for the problems of flow through the unsaturated soil has two components. One is space component and another is time component. Algorithm is presented below.

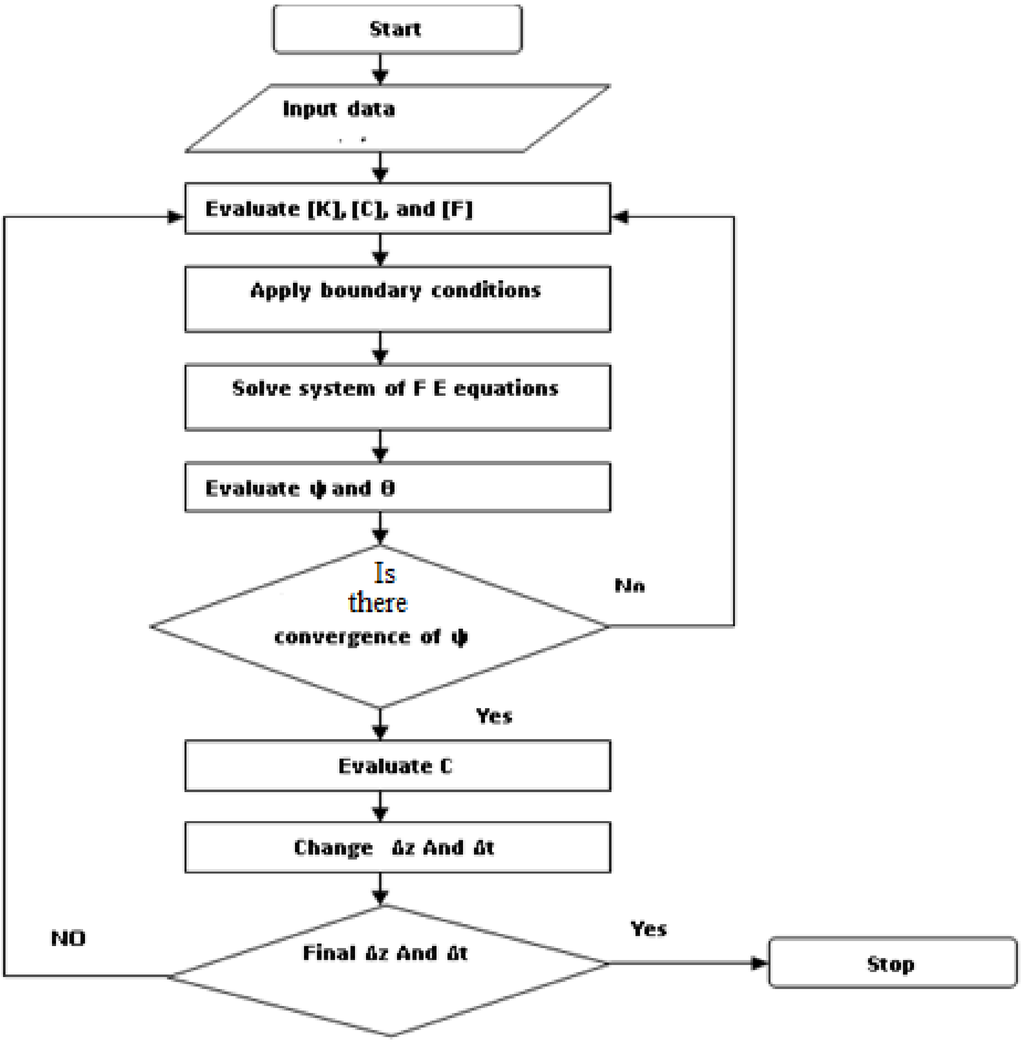


Figure 4.13: Algorithm for the Developed Software

4.8 PRACTICAL APPLICATION

The problem considered for validation had totally homogenous characteristics. For example the material parameters and initial suction pressure were kept identical throughout the domain of analysis. In practice such ideal condition are seldom encountered. In fact the soil mass would in general be heterogeneous. Whereby, the material property as well as initial suction pressures would display random characteristics. The software developed however, caters to various variability such as those encountered in practical field. It would therefore be of interest to analyze a typical situation offered by practical field data. The practical field data concerning the site at Sholapur, Maharashtra is taken. There, full computational details dealing with derivation of soil parameters required for the application of the developed software have been included.

4.8.1 Estimating Hydraulic coefficient K(ψ) and C(ψ)

The required formulae for calculating K(ψ) and C(ψ) of the element already been provided earlier. However same are reproduced for ready reference.

$$K(\psi) = Ks\frac{\{1-(\alpha\psi)^{n-1}[1+(\alpha\psi)^{n}]^{-m}\}^{2}}{[1+(\alpha\psi)^{n}]^{m/2}} \tag{4.45}$$

$$C(\psi) = \frac{-\alpha m(\theta_s-\theta_r)}{1-m}\Theta^{\frac{1}{m}}\left(1-\Theta^{\frac{1}{m}}\right)^{m} \tag{4.46}$$

These formulae are used for the purpose of computing initial values of K(ψ) and C(ψ) as well as while conducting finite element analysis where solution process at each step derives the modified value of suction pressure ψ.

4.8.2 Solution Details

The finite element idealisation adopted for the analysis has the following features.

Table 4.1: Soil parameters used (Sholapur)

Depth	Moisture at saturation θ_s	Residual Moisture θ_r	Parameters established			Hydraulic Conductivity K_s (cm/ hr)
			n	m	α	
0 to 15 cm	0.6264	0.2172	1.66	0.40	0.009	0.175
15 to 30 cm	0.615	0.209	1.63	0.39	0.0096	0.114
30 to 60 cm	0.613	0.2018	1.61	0.38	0.0118	0.171

(a) Each segment is of size 1cm. The total one dimensional two noded element in respect of the depth of 60 cm considered are equal to 60.

(b) The above details give rise to 61 nodes.

(c) In absence of possible field boundary condition data arbitrary values of ψ at base node 1 and top node 61 have been assumed.

(d) The time increment is kept equal one hour i.e. Δt =1 hr.

(e) 24 solution steps are performed to derive the state of affairs at the end of 24 hours. That means one day.

(f) The variation of ψ with depth at the end of 24 hours is shown over the graph Figure, 4.14.

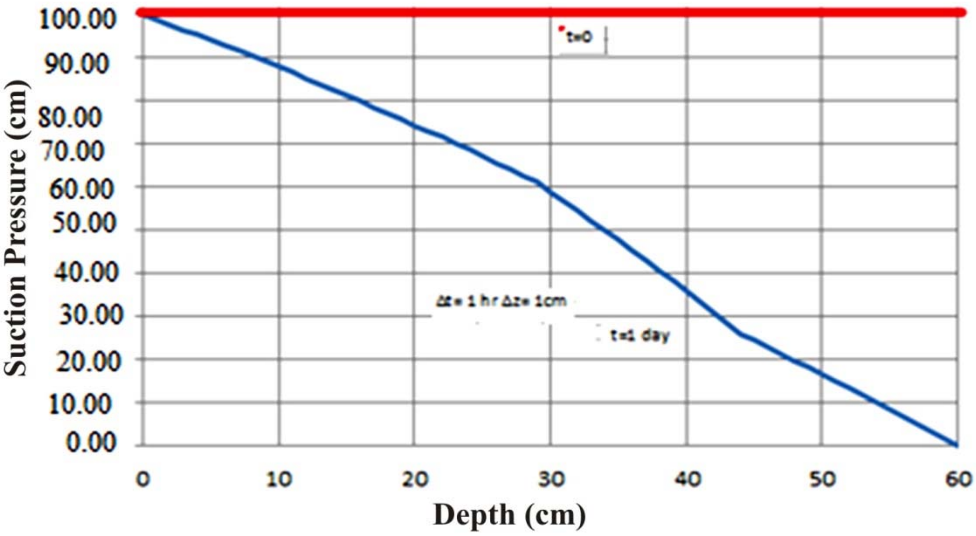


Figure 4.14: Variation of Suction Pressure with Time

It may be noted that rather than displaying continuous variation of ψ with depth, a small kink is displayed at the intermediate depth, which is indicative of influence of heterogeneity of soil mass. This software is ready to use in the field for crop water management.

Similarly, the soil parameters were estimated by Van Genuchten (VG) and Modified VG Modelsfor Pune, Ahmednagar, Kolhapur and Sholapur research stations are presented in Table, 5.45.

CHAPTER- 5

SOIL MOISTURE ANALYSIS IN THE STUDY AREA

5.1 INTRODUCTION

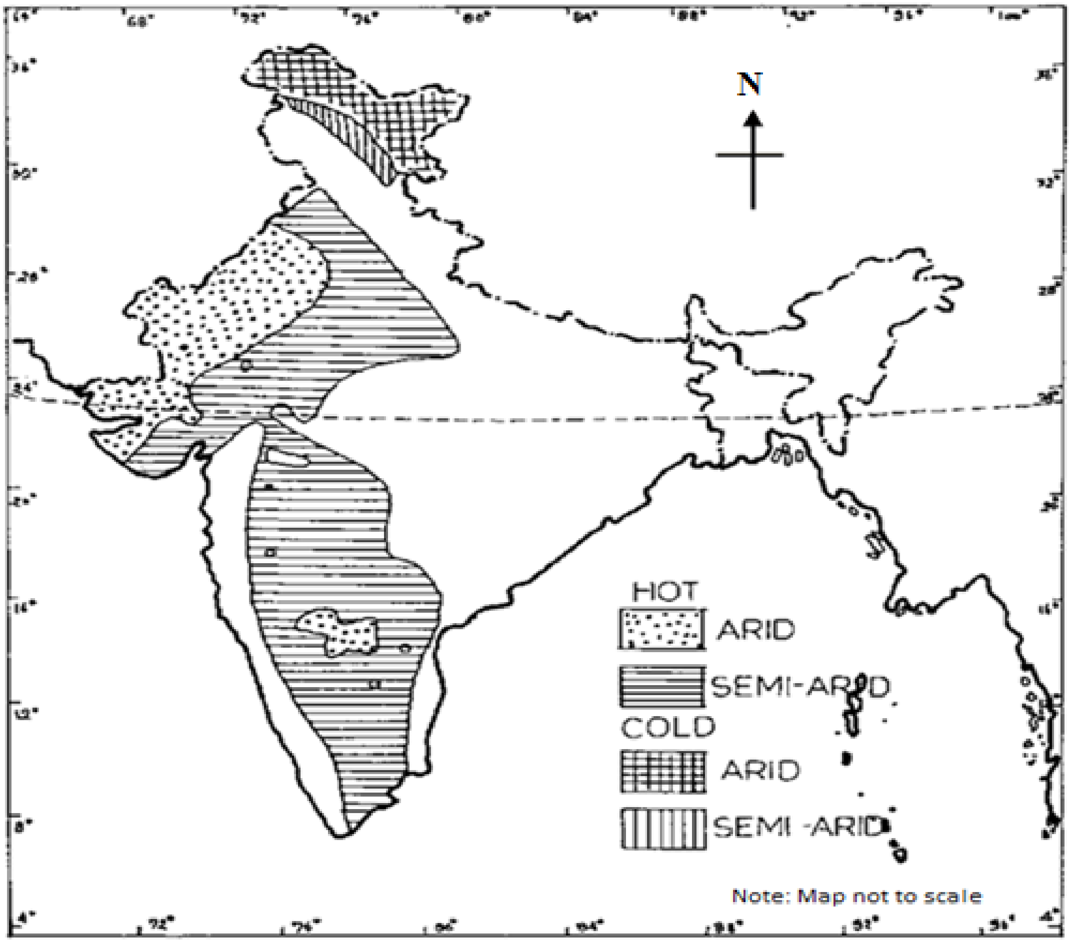


Figure 5.1: Map of India Showing Arid and Semi-Arid Zones

(Source: fao.org)

Maharashtra is one of the states of India which occupies the western and central parts of the country. The present state of Maharashtra was formed on 1 May 1960. Gujarat state is on the north. Madhya Pradesh is in the north and east. Karnataka and erstwhile Andhra Pradesh states are on the south. The state lies between the latitudes 15.6 ° N and 22.1° N and longitudes 72.6° E and 80.9 ° E. This state consists of 36 districts, and they are grouped into six revenue divisions and nine agro-climatic zones as shown in following Table and Figure.

Table 5.1: Districts of Maharashtra

Sr. No.	Division	District Name
1.	Amravati	Amravati, Akola, Buldhana, Washim and Yavatmal.
2.	Aurangabad	Jalna, Latur, Nanded, Osmanabad, Aurangabad, Beed, Hingoli, and Parbhani.
3.	Konkan	Mumbai City, Mumbai Suburban, Palghar, Raigad, Ratnagiri, Sindhudurg and Thane.
4.	Nashik	Nashik, Dhule, Jalgaon, Ahmednagar and Nandurbar.
5.	Nagpur	Nagpur, Gadchiroli, Gondiya, Bhandara, Chandrapur and Wardha.
6.	Pune	Pune, Kolhapur, Sangli, Satara and Sholapur.

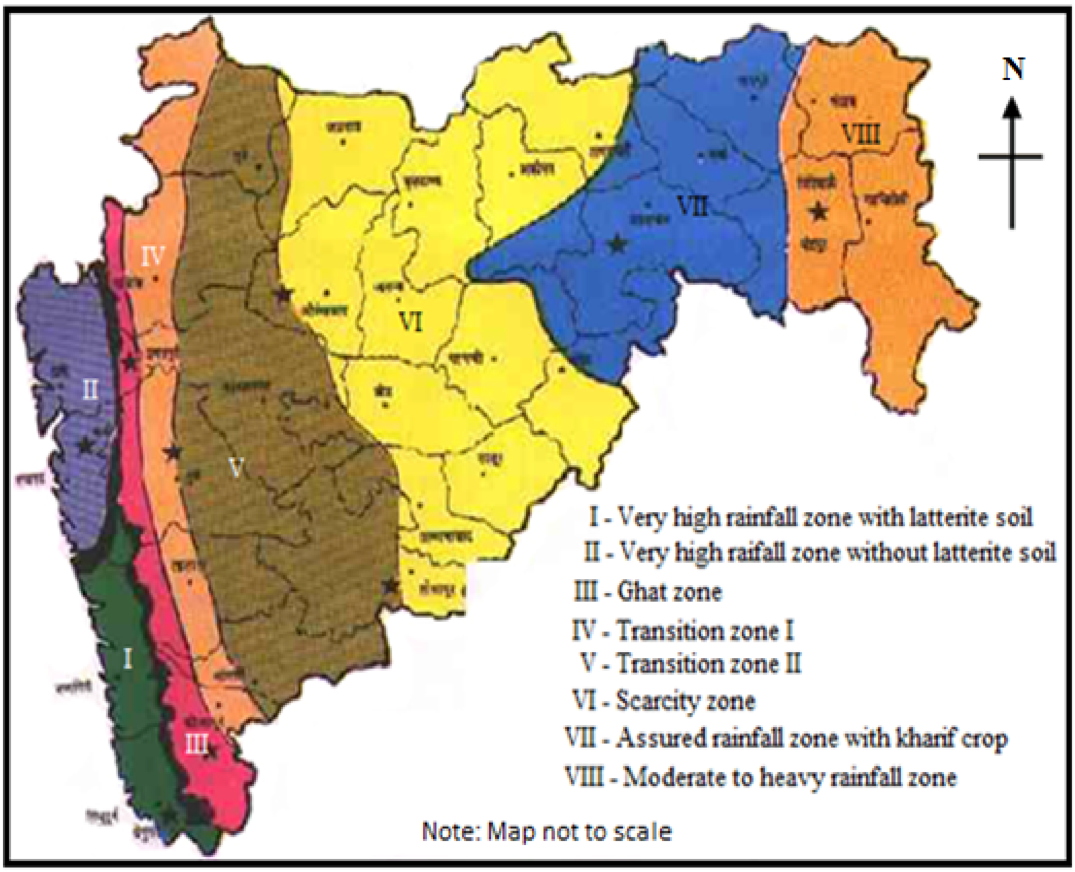


Figure 5.2: Rainfall Zone Wise Map of Maharashtra

Table 5.2: Agro climatic zones of Maharashtra

Zone No.	Agro-Climatic Zone	Area Covered	Soil type	Agricultural Crops	Remarks
1	Very high rainfall zone with lateritic soil.	Ratnagiri, Sindhudurg and Southern portion of Raigad District.	Lateritic, highly permeable, medium to deep, free from calcium carbonate, slightly acidic and soil colloid complex is low in bases. Well supplied with nitrogen but poor availability of phosphate and potash.	Paddy is the major crop and finger millet and other coarse hill millets forms the other secondary crops. The area is ideally suited for tropical fruits such as mango, cashew, coconut, betel nut, jack fruit, etc.	Heavy downpours results in severe soil erosion. Severe drought problem even with little break in the rains. Coastal saline soils due to inundation of sea water. These soils are derived from basalt on account of forest vegetation and warm humid climate, these basalt have given rise to lateritic soil.
2	Very high rainfall zone without lateritic soil.	Thane, Palghar and northern part of Raigad District.	Soils are neutral in reaction, loamy textured, and colloids are nearly saturated. Well supplied with nitrogen. Better retention of moisture as compared to those in Zone 1.	Same as above.	The extent of coastal saline soils is comparatively more in this zone.
3	Ghat Zone.	Narrow strip covering portion of Nashik, Pune, Satara and Kolhapur on the eastern side and Raigad and Ratnagiri on the western side of Sahyadri range.	The soils are shallow to medium deep with neutral pH, well supplied with phosphate and potash but low in nitrogen. Soils are red to reddish brown with light texture.	Area is suited for growing grasses and developing forestry, paddy and hill millets are the important crops.	Since the soils in this zone are developed on higher altitudes coupled with heavy rainfall (more than 3000mm) they are subjected to heavy soil erosion.
4	Transition Zone 1.	Comprises a stretch of areas adjacent to the Ghat zone on the eastern side of the same districts.	The soils are shallow to deep, dark brown gravelly loams with pH ranging from 7.8 to 8.2. Well supplied with nitrogen. Soils are red to reddish brown.	Paddy and coarse hill millets	Rainfall between 1750 to 2500mm. These soils are derived from basalt.
5	Transition Zone 2.	Ahmednagar, Sangli and central tehsils of Nashik, Pune, Satara and Kolhapur Districts.	It has deeper fertile soils. The pH ranges from 7.5 to 8. Fair in nitrogen, phosphate and potash content. The soils formed from trap rock are predominantly greyish black and varying texture depending on the local topography.	Bajra, groundnut, cotton, jowar, paddy etc.	Rainfall between 700 to 1750mm. The soils are brown to dark.

Table 5.2 (Continued)

Sr. No.	Agro-Climatic Zone	Area Covered	Soil type	Agricultural/ Horticulture Crops	Remarks
6	Scarcity zone.	Sholapur, Ahmednagar and eastern parts of the Pune, Satara, Sangli, Kolhapur, Dhule, Nashik and western parts of Aurangabad, Beed and Usmanabad Districts.	The major portions of the soils are moisture retentive. Soils are neutral to slightly alkaline, pH is 7.8 to 8.5. Moderate calcium carbonates, low in nitrogen and moderate in phosphates. The soils are mostly derived from Deccan trap. They are mostly clayey in nature. The soil is under laid with murum.	Jowar is the major food crop and the largest area under rabi crop, gram and wheat are other important rabi crops. About 20 to 25 percent area is covered by kharif crop such as Bajra, redgram, horsegram and groundnut.	This area is considered as traditionally famine area. This zone covers 1/5 of the total area of state. The rainfall is scanty (500 to 700 mm). Soil erosion poses a serious problem because of intense showers during September.
7	Assured rainfall zone mainly with kharif cropping.	This comprises of whole of Vidarbha (except Chandrapur, Bhandara, Gadchiroli, and Gondiya Districts) and major portion of Marathwada.	Soils are medium deep to deep slightly alkaline in reaction. pH is 7.00 to 8.5. Fair amount of calcium carbonate. Soils are generally deficient in nitrogen and moderate in phosphate and potash.	Jowar, cotton and groundnut are main crop in kharif and wheat in rabi.	The rainfall range from 700 to 900 mm. and is well distributed. The comparatively deeper and clayey soils pose problem of restricted drainage during certain parts of the monsoon.
8&9	Moderate to heavy rainfall zone.	Chandrapur, Bhandara, Gadchiroli, Gondiya and Nagpur Districts.	Soils derived from parent rock like granite, gneisses, and schists.	Cotton, Kh. Jowar, Tur, Wheat, Pulses and Oilseeds. Paddy is predominant crop in Bhandara.	950 to 1250 mm on western side and 1700 mm on eastern side.

5.2 STUDY AREA

The study area comprises six districts. The data records considered for analysis are of four district places Ahmednagar, Pune, Sholapur, and Kolhapur. The data is collected from the research stations which are shown in the following map. All the data required for analysis is not available from all the District places. Only four research stations are considered for study. The temporal and spatial variation of data is not considered for district. Only available data from particular research station are used. The national normal average rainfall for India is 1083 mm (http://data.worldbank.org/indicator/AG.LND.PRCP.MM).The average annual rainfall for study area which are below normal average rainfall are marked bold in rainfall data Table. The area where rainfall is high, the rice is grown as kharif main crop. Some parts or tehsils where rainfall is less bajra is cultivated as main crop in rainy session.

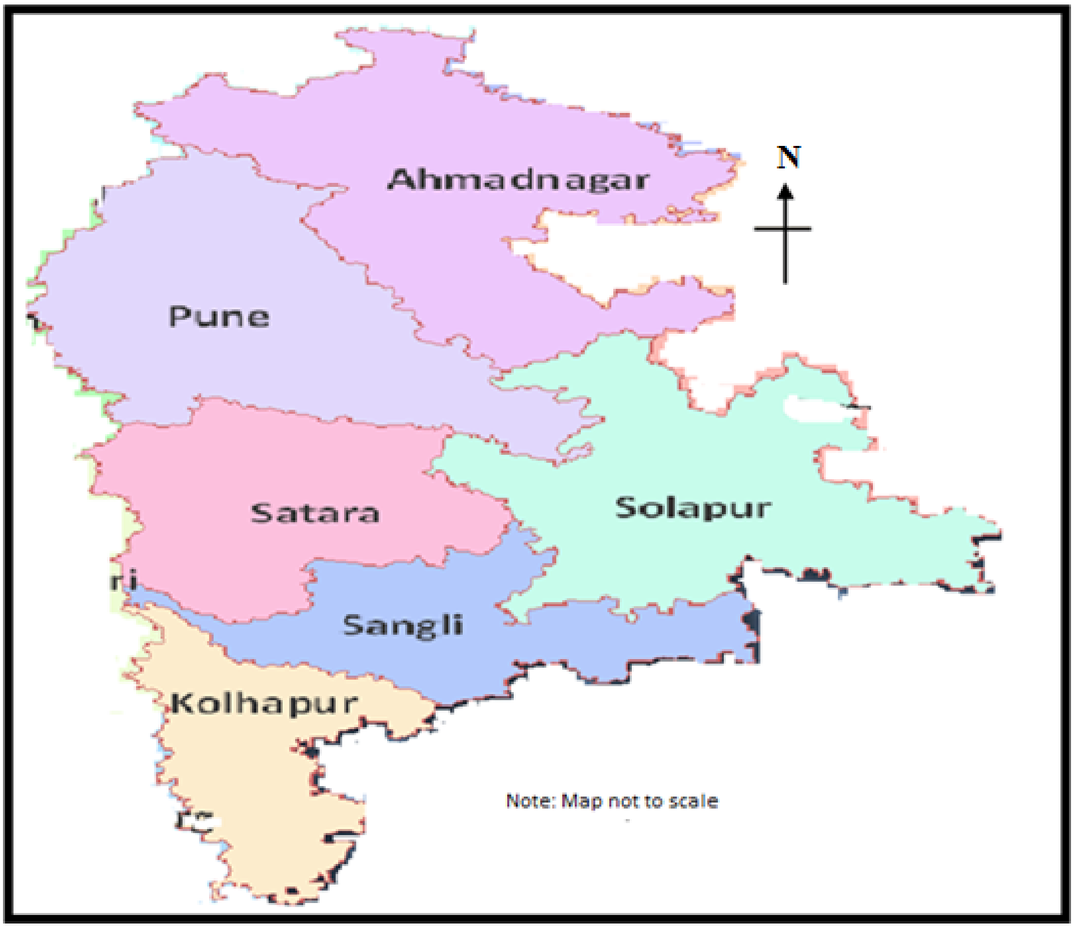


Figure 5.3: Map of Western Maharashtra

5.2.1 Sholapur District, Maharashtra, India

Sholapur district is famous for chadder, hand-loom, and power-loom industries in Maharashtra. Its area is 14844.6 sq.kms. This district consist of 11 tehsils (blocks). This district is surrounded by Ahmednagar and Usmanabad districts on the north, Sangli district on south and Pune and Satara district in the west side. Geographical Location of district is in between 17.10^o to 18.32^o N and 74.42^o to 76.15^o E. The maximum temperature in summer cross 46^o Celcius and touch minimum 9^o Celsius in winter. This district stands last in rainfall amount. The total net cultivated area for Bajra is 88174 Hectares. This district area is classified as semi-arid tropical. The soils of this area are derived from the igneous rocks (i.e., basalt). The soil colour is brown to very dark greyish brown. The soils of this area can be classified into broad categories according to depth as follows:

- Very shallow (depth < 7.5 cm)
- Shallow (7.5 cm < depth < 22.5 cm)
- Medium deep soil (22.5 cm < depth < 45 cm)
- Deep soil (45 to 90 cm depth)

The infiltration rate is moderately low. Kharif crops are grown in rainy season (June to September period). The kharif cops grown in this area are: pearl millet, redgram, groundnut, horsegram, mothbean, sunflower, greengram, blackgram etc.

Table 5.3: Rainfall Data for Sholapur (mm) Tehsilwise.

(http://Sholapur.gov.in/htmldocs/rain.pdf)

S. No	**Tehsils**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**Average**
1	Sholapur(N)	**586.3**	**629.8**	**582.3**	**300.2**	**603.8**	**697.6**	**453.1**	**582.9**	**634.3**	**680.9**	**756.2**	**610.2**	**472.8**	**534.7**	**393.9**	**567.9**
2	Sholapur(S)	**586.3**	**629.8**	**582.3**	**300.2**	**603.8**	**697.6**	**453.1**	**582.9**	**634.3**	**680.9**	**756.2**	**610.2**	**472.8**	**502.4**	**387.6**	**565.4**
3	Akkalkot	**745.0**	**568.0**	**516.0**	**344.0**	**445.7**	**588.6**	**551.1**	**542.4**	**424.8**	**567.2**	**717.2**	**618.0**	**556.3**	**601.4**	**433.3**	**547.9**
4	Barshi	**782.4**	**601.0**	**480.7**	**338.4**	**488.9**	**757.5**	**659.6**	**916.3**	**670.3**	**706.9**	**1030.3**	**505.6**	**551.6**	**540.1**	**392.2**	**628.1**
5	Pandharpur	**554.2**	**545.8**	**403.3**	**254.6**	**532.8**	**519.7**	**474.8**	**605.3**	**469.2**	**730.8**	**672.1**	**395.8**	**361.8**	**566.2**	**371.3**	**497.2**
6	Mangalwedha	**372.6**	**454.1**	**583.0**	**322.2**	**711.4**	**656.4**	**623.9**	**954.7**	**529.5**	**736.9**	**604.9**	**309.0**	**287.5**	**437.9**	**373.0**	**530.5**
7	Sangola	**505.9**	**482.8**	**642.0**	**377.8**	**379.0**	**369.6**	**560.6**	**716.5**	**499.3**	**683.6**	**615.9**	**330.1**	**393.8**	**463.5**	**492.9**	**500.9**
8	Malshiras	**263.0**	**371.0**	**296.0**	**107.0**	**388.5**	**324.3**	**437.2**	**651.1**	**596.5**	**788.7**	**719.2**	**436.8**	**350.0**	**589.5**	**326.0**	**443.0**
9	Madha	**630.7**	**367.0**	**355.0**	**308.9**	**469.0**	**631.0**	**487.3**	**617.4**	**600.3**	**632.8**	**1118.7**	**389.5**	**434.5**	**591.3**	**340.4**	**531.6**
10	Mohol	**652.9**	**519.0**	**415.1**	**217.6**	**429.5**	**538.2**	**588.1**	**638.0**	**595.0**	**519.1**	**948.8**	**508.6**	**318.1**	**527.0**	**335.0**	**516.7**
11	Karmala	**940.0**	**472.0**	**364.0**	**194.9**	**522.4**	**571.3**	**508.8**	**340.2**	**715.7**	**556.3**	**963.4**	**538.9**	**258.7**	**510.0**	**384.6**	**522.7**
Average		**601.8**	**512.8**	**474.5**	**278.7**	**506.8**	**577.4**	**527.1**	**649.8**	**579.0**	**662.2**	**809.4**	**477.5**	**405.3**	**533.1**	**384.6**	**532.0**

Note: Data marked bold shows the average rainfall lies below National normal average rainfall

Table 5.4: Rainfall and Evapotranspiration Data for Sholapur

Sr. No.	Week No.	Rainfall (mm)	Evapotranspiration (mm)
1	27	42.65	33.34
2	28	13.17	33.26
3	29	27.18	31.33
4	30	25.50	28.42
5	31	36.75	29.35
6	32	18.10	27.11
7	33	8.43	30.31
8	34	37.23	28.25
9	35	26.60	32.38
10	36	35.38	29.96
11	37	32.45	30.15
12	38	16.03	31.13
13	39	27.13	27.49
Total		303.97	359.73

The paucity of the total amount of rainfall and large variations, both in extent and distribution in different years. The average annual rainfall in the district is 742 mm.

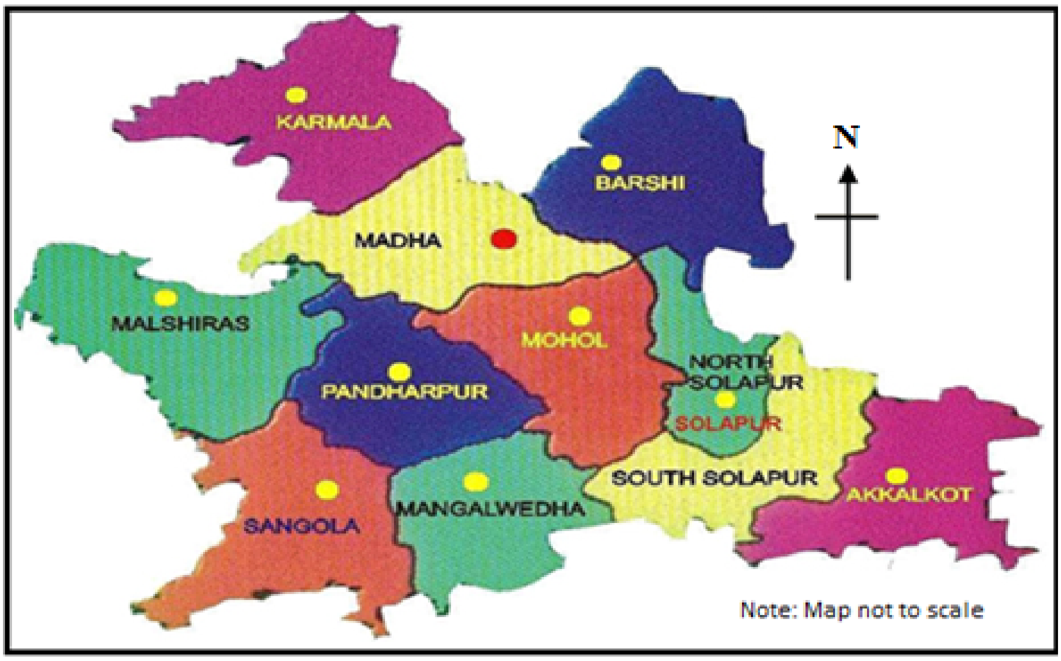


Figure 5.4: Map of Sholapur District (Source: zpsholapur.gov.in)

5.2.2 Study Area Pune District, Maharashtra, India.

Geographical location of Pune district is between 17° 54’ and 19° 24’ North latitudes and 73° 19’ and 75° 10’ East longitudes. The area of district is 15,642 sq.km. It is surrounded by the Ahmednagar district on the North-East side, Sholapur district on the South-East side, Satara district on the South side, Raigad district on the West and Thane district on the North-West side. The climate of the western region of Pune is cool, whereas the eastern region is hot and dry. The rainfall pattern is not same for all tehsils or blocks. Velhe tehsil receives the maximum rainfall (>1500mm) followed by Mulshi and Maval tehsils which have rainfall is between 1001 and 1500mm. The annual rainfall is between 801 and 1000 mm for Bhor, whereas 601 and 800 mm for Junnar and Ambegaon. The Khed, Haveli, Pune-city, Purandhar, Shirur and Indapur receive comparatively low rainfall i.e., ranging from 401 to 600 mm. The lowest rainfall (<400mm) occurs in Baramati and Daund tehsils. Among the cereals and pulses bajra (538 ha) and rice (599 ha) are main crops.

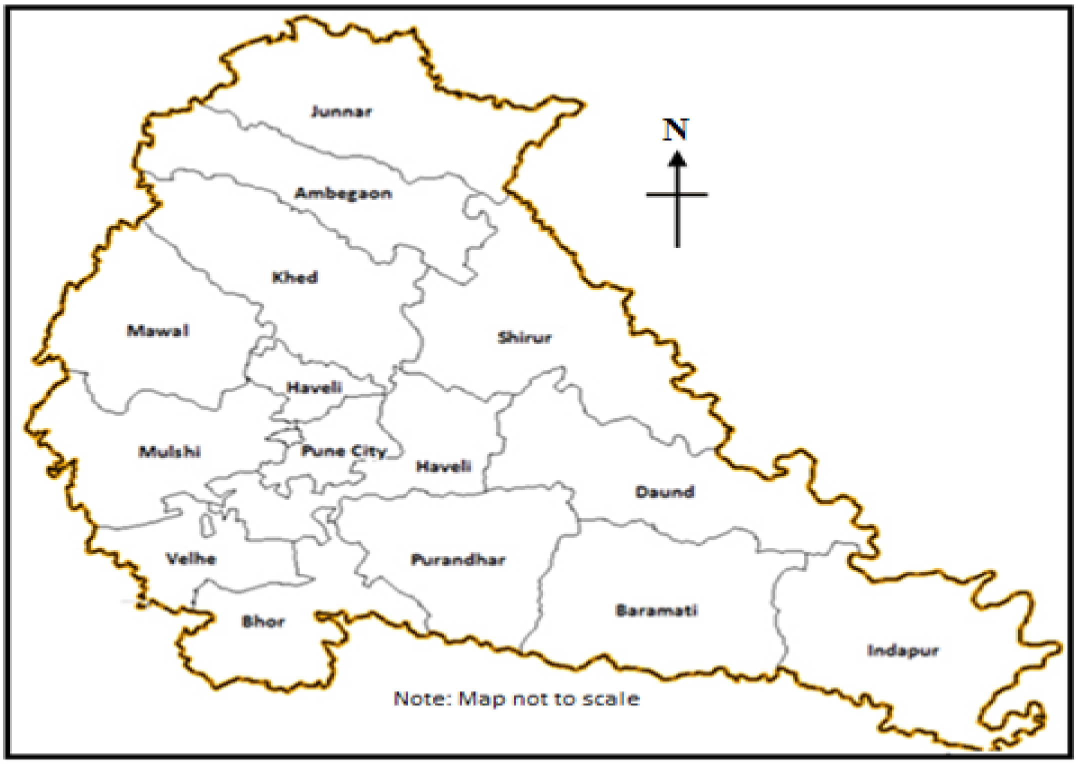
Table 5.5: Rainfall Data for Pune District (Tehsilwise) (mm) (Mishra, 2013)

Year **Tehsil**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**Average**
Pune City	**335.3**	**652.4**	1239.5	1246	**779.44**	**689.29**	**909.7**	1169	**979.9**	**492.7**	**849.32**
Haveli	**452.2**	**890.6**	1250.36	1247.5	**859.04**	**706.09**	**938.3**	1147.8	**979.6**	**505.4**	**897.67**
Mulshi	1251	1878	2875.8	2804	1834	1602	1836.7	1592	1792	1438	1890.35
Bhor	**712**	1380.1	1714	1762	1429.4	**998**	1213	1121	1129.3	**833**	1229.18
Maval	**1026**	1466	2561	2252	1442.6	1399.5	1364.8	1168	1482	**1013**	1571.14
Velhe	1420	2054.4	6320.6	3997	3263	2409	1405	2043	2695.1	2070.4	2667.7
Junnar	**648.2**	**771.8**	**1344.4**	**1237**	**880**	**747.4**	**706**	**862.3**	**769**	**557.1**	**852.32**
Khed	**386.2**	**775**	973.1	1461.1	**756.5**	**692.66**	**639.6**	1018.4	**637.7**	**436.2**	**777.65**
Ambegaon	**421.8**	**735.1**	1025	1338.3	**830.9**	**735**	**732.3**	**823.4**	**836**	**616.6**	**809.44**
Shirur	**266**	**374**	**460**	**760**	**674**	**492**	**859.6**	**849.5**	**441.8**	**321**	**549.69**
Baramati	**113.2**	**521**	**711**	**567**	**622**	**454**	**738.8**	**804.6**	**291**	**235**	**505.76**
Indapur	**163.3**	**651.9**	**696.1**	**668**	**640.3**	**345.4**	**932.4**	**805.8**	**399**	**250.6**	**555.28**
Daund	**156.3**	**522**	**742.2**	**594**	**604.85**	**326.7**	**474.3**	**639.3**	**347.6**	**337.4**	**474.46**
Purandhar	**215**	**710**	1158	1476	**519**	**497**	**806**	**602**	**609.4**	**371**	**696.34**
Average	**540.5**	**955.9**	1647.9	1529.3	**1081.1**	**863.9**	**968.3**	1046.2	**956.4**	**677.0**	

Note: Data marked bold shows the average rainfall lies below National normal average rainfall

Table 5.6: Rainfall and Evapotranspiration Data for Pune

Sr. No.	Week No	Rainfall (mm)	Reference Evapotranspiration (mm)
1	27	42.65	21.01
2	28	13.17	27.70
3	29	27.18	29.96
4	30	25.50	21.21
5	31	36.75	17.57
6	32	18.10	19.10
7	33	8.43	20.21
8	34	37.23	23.92
9	35	26.60	28.92
10	36	35.38	26.72
12	37	32.45	23.51
13	38	16.03	23.45
14	39	27.13	26.64
Total		346.62	309.92



Note: Map not to scale

Figure 5.5: Map of Pune District (Source: maharashtra.gov.in)

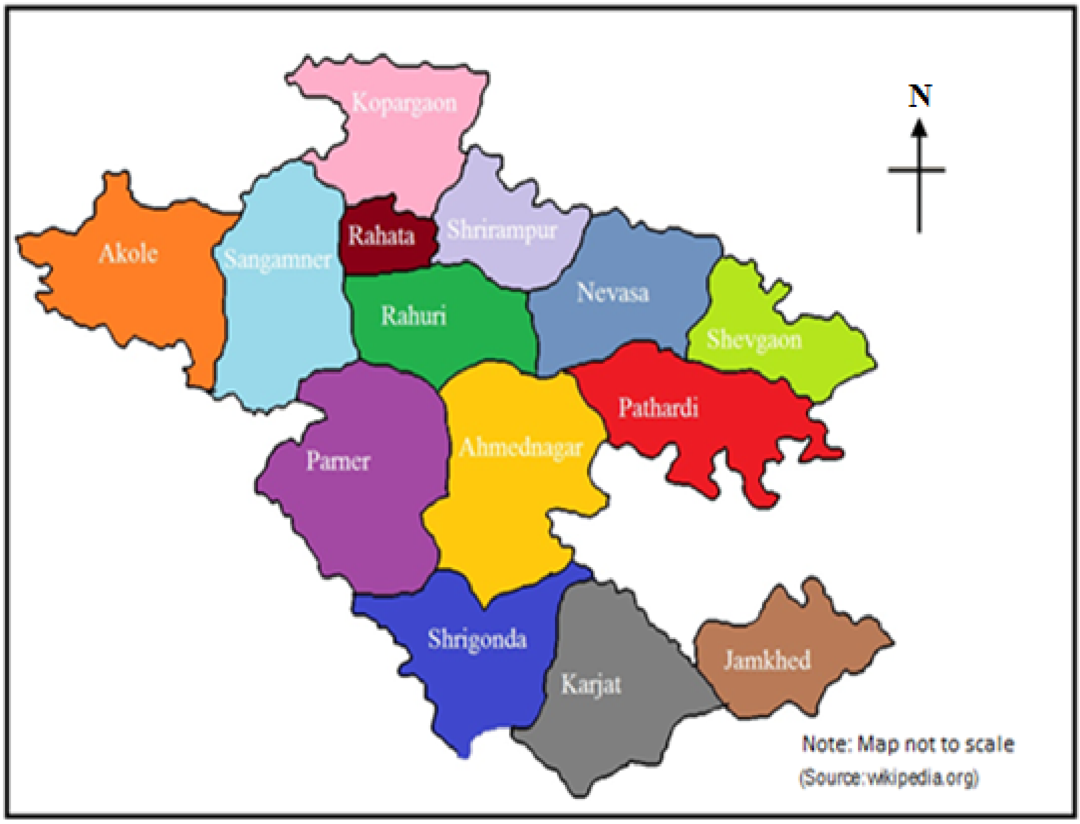
5.2.3 Ahmednagar District, Maharashtra, India

Ahmednagar is the largest district in the Maharashtra state. The district is surrounded by Sholapur (South-East), Aurangabad (North-East), Nashik (North-West) and Pune (South-West). This district consists of fourteen tehsils. The climate of the district is hot in the summer and general dryness during major part of the year. The district mostly is in rain shadow to the east of Western Ghats. There is a meteorological observatory in the district at Ahmednagar city. The area of the district is 17034 sq.kms. The tehsils of this districts are Nagar, Parner, Pathardi, Shewgaon, Karjat, Shreegonda, Jamkhed, Shrirampur, Nevasa, Akole, Sangamner, Kopergaon, Rahuri and Rahta. Main kharif Crops of districts are Bajra (202271 ha) sugar cane (57748 ha), Cotton (69153ha) and soyabean (55099ha). The latitude19° 05' 0" N and longitude N, 74° 48' 0" E.

Table 5.7: Rainfall Data for Ahmednagar District (Tehsilwise) (mm) (Vijesh, 2014)

Year **Taluka**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**Average**
Akola	**476.3**	**502.0**	1354.0	1084.0	1130.0	**871.0**	**1006.0**	**830.0**	**1041.0**	**500.0**	**879.4**
Jamkhed	**502.0**	**516.0**	**686.0**	**634.0**	**1020.0**	**614.0**	**729.0**	**714.0**	**839.0**	**712.0**	**696.6**
Karjat	**525.5**	**328.0**	**635.0**	**606.0**	**785.0**	**416.1**	**794.0**	**775.0**	**752.0**	**413.0**	**603.0**
Kopargaon	**337.0**	**341.0**	**479.0**	**406.0**	**571.0**	**596.0**	**401.0**	**493.0**	**760.0**	**455.0**	**483.9**
Nagar	**400.0**	**214.0**	**556.0**	**500.0**	**809.0**	**648.0**	**693.0**	**625.0**	**832.0**	**374.0**	**565.1**
Nevasa	**344.0**	**265.0**	**568.0**	**479.0**	**629.0**	**368.0**	**603.0**	**527.0**	**904.0**	**474.0**	**516.1**
Parner	**517.2**	**190.0**	**759.0**	**531.0**	**852.0**	**389.9**	**389.0**	**581.0**	**676.0**	**368.0**	**525.3**
Pathardi	**559.0**	**544.0**	**681.0**	**451.0**	**804.0**	**443.9**	**687.0**	**727.0**	**932.0**	**614.0**	**644.3**
Rahta	**475.9**	**263.0**	**557.0**	**601.0**	**690.0**	**462.0**	**385.0**	**447.0**	**926.0**	**395.0**	**520.2**
Rahuri	**325.0**	**313.0**	**575.0**	**465.0**	**796.0**	**745.5**	**671.0**	**686.0**	**886.0**	**589.0**	**605.2**
Sangamner	**492.0**	**489.0**	**650.0**	**529.0**	**589.0**	**485.7**	**487.0**	**452.0**	**692.0**	**240.0**	**510.6**
Shevgaon	**476.3**	**362.0**	**785.0**	**465.0**	**759.0**	**450.0**	**520.0**	**729.0**	**824.0**	**741.0**	**611.1**
Shrigonda	**421.0**	**110.0**	**574.0**	**484.0**	**523.0**	**752.0**	**448.0**	**651.0**	**739.0**	**326.0**	**502.8**
Shrirampur	**308.5**	**259.0**	**553.0**	**550.0**	**788.0**	**613.9**	**521.0**	**650.0**	**932.0**	**636.0**	**581.1**
Average	**440.0**	**335.4**	**672.3**	**556.1**	**767.5**	**561.1**	**595.3**	**634.8**	**838.2**	**488.4**	**588.9**

Note: Data marked bold shows the average rainfall lies below National normal average rainfall



Note: Map not to scale
(Source: wikipedia.org)

Figure 5.6: Map of Ahmednagar District

5.2.4 Kolhapur District, Maharashtra, India

The Kolhapur district is Southern-most district in Maharashtra state. The Kolhapur is the district headquarter which is an ancient city. The geographical area of Kolhapur district is 7746 sq. kms. There are twelve tehsils in Kolhapur district namely Ajara, Chandgad, Karveer, Radhanagari, Gaganbawada, Bhudargad, Gadhinglaj, Hatkangale, Kagal, Panhala, Shirol and Shahuwadi. It lies between 15^0 43’ to 17^0 17’ North latitude and 73^0 40’ to 78^0 42’, East longitude. The length of the district South to North is 160 Kms. and East to west is 60 Kms. Generally Monsoon begins in the first week of June. The average annual rainfall in the district is 1025 mm, but there is unevenness in the annual rainfall in the district. In the tehsils Gaganbawada, Radhangari, Chandgad and Ajara the average rainfall is 6000 mm. In South-East regions of Shirol and Hatkangale the rainfall is 550 mm. The main crops of district are bajra (32570 ha), Jowar and Sugarcane etc.

Table 5.8: Rainfall Data for Kolhapur District (Tehsilwise) (mm)

(http://shodhganga.inflibnet.ac.in)

Sr. No.	Tehsil	Rainfall (mm)
1	Shahuwadi	3820
2	Panhala	2080
3	Hatkanangale	**525**
4	Shirol	**585**
5	Karveer	**1070**
6	Gaganbavada	6230
7	Radhanagari	3480
8	Kagal	**817**
9	Bhudargad	1570
10	Ajra	3140
11	Gadhinglaj	**965**
12	Chandagad	2700

Note: Data marked bold shows the average rainfall lies below National normal average rainfall

Note: Map not to scale
(Source: mapsofindia.com)

Figure 5.7: Map of Kolhapur District

5.3 SOIL MOISTURE DATA ANALYSIS BY Van Genuchten Model.

Soil and meteorological data collected from India Metrological Department (IMD) Pune, Durgude et al. (1996), Mungare (1979) and Mahatma Phuley Krishi Vidyapit (MPKV) Rahuri. Analysis for four research stations namely Sholapur, Pune, Ahmednagar and Kolhapur have been selected. These area fall in the semi-arid zone of western Maharashtra, India. The Van Genuchten (VG) model is used for soil moisture analysis with some modification in obtaining the results.

$$\Theta(\psi) = \left\{\frac{1}{[1+ (\alpha\psi)^{n}]}\right\}^{m} \tag{5.1}$$

Algorithm for curve fitting and finding Van Genuchten parameters:

- Input number of data points (N)
- Initialize sumx, sumy, sumxy and sumx^2 as zero
- For i = 1 to N, increment by 1
- Input x and y values
- Calculate Y= logy and X = logx
- For fitting the curve $y = a\ e^{bx}$
- Calculate sumx, sumy, sumxy and sumx^2
- For fitting the curve $y = a\ x^{b}$
- Calculate, sumXY and sum X^2
- End loop
- Construct coefficient matrix and solution matrix
- Find solution matrix
- Plot the graph
- Calculate m, n, α from fitted graph
- Smoothen the values

The complete listing for used software is given in Appendix-A. At the outset depthwise Soil Moisture Characteristic Curve (SMCC) for each research station were prepared from available record data (Figures: 5.1, 5.14, 5.19 etc.). The suction values (ψ or Y), where soil moisture contents (θ or X) were recorded, are 100 cm, 330 cm, 500 cm, 1000 cm, 5000 cm, 10000 cm & 15000 cm. The soil parameters m, n and α were evaluated by using three curve fitting methods for each SMCC.

- $Y = a_1 e^{b_1 X}$
- $Y = a_2 X^{b_2}$
- $Y = a_3 {b_3}^X$

The sensitivity analysis is performed for each one curve fitting method. The results are presented in Tables: 5.9, 5.11, 5.13, 5.15, 5.17, 5.19, 5.21, 5.23, 5.25, 5.27, 5.29, 5.31, 5.33, 5.35, 5.37, 5.39, 5.41 and 5.43. The most suitable curve fitting method's m, n and α values were considered for simulation. These obtained curve fitting parameters or soil parameters are known as Van Genuchten parameters. The moisture content x_1 is simulated by Equation, 5.1. The statistical analysis is performed for x_1 values with comparing X values (Tables: 5.10, 5.12, 514, 5.16, 5.18, 5.20, 5.22, 5.24, 5.26, 5.28, 5.30, 5.32, 5.34, 5.36, 5.38, 5.40, 5.42 and 5.44). The coefficient of efficiency for this model found nearly about 80 %. To increase the coefficient of efficiency the m values were need to increase with corresponding change in n and α values. In the analysis m values were increased up to 40 %. This 40 % increases in m bring the simulated SMCC nearer to original SMCC (Figures: 5.12, 5.17, 5.22, 5.27, 5.32, 5.37, 5.41, 5.45, 5.49, 5.53, 5.57, 5.61, 5.64, 5.65, 5.66, 5.67, 5.68 and 5.69). The sensitivity analysis for both methods is presented in Tables: 5.10, 5.12, 514, 5.16, 5.18, 5.20, 5.22, 5.24, 5.26, 5.28, 5.30, 5.32, 5.34, 5.36, 5.38, 5.40, 5.42 and 5.44. The soil moisture x_2 values were simulated by using new curve fitting parameters. The estimated soil moisture content x_1 and x_2 are given in column no 4 and 7 in Tables: 5.10, 5.12, 514, 5.16, 5.18, 5.20, 5.22, 5.24, 5.26, 5.28, 5.30, 5.32, 5.34, 5.36, 5.38, 5.40, 5.42 and 5.44.

5.3.1 SMCC Analysis for Sholapur Research Station

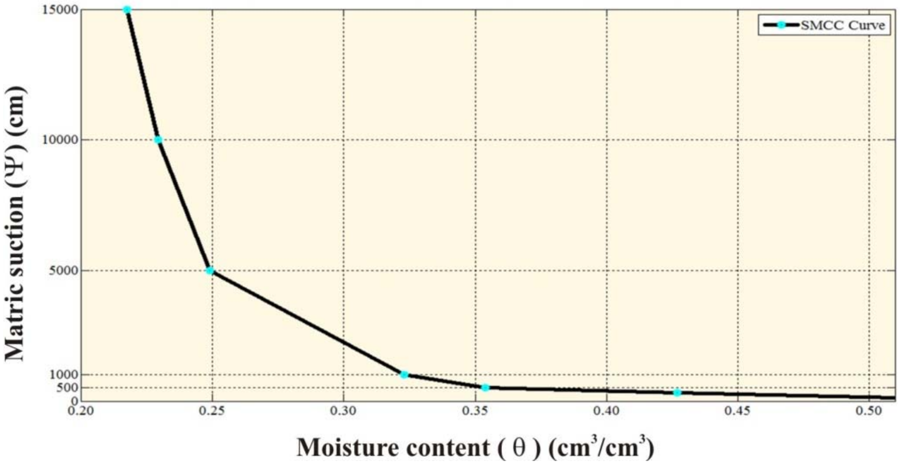


Figure 5.8: SMCC at a Soil Depth of 0 to 15 cm for Sholapur

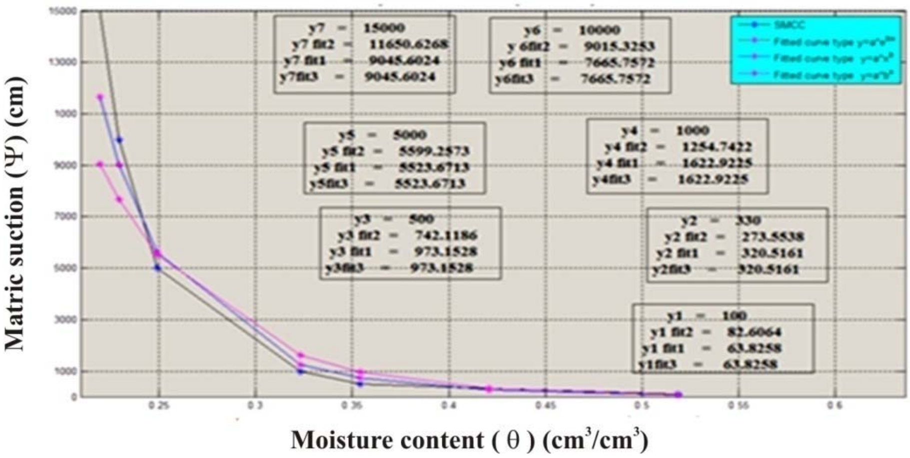


Figure 5.9: Curve Fitting for SMCC at a Soil Depth of 0 to 15 cm for Sholapur

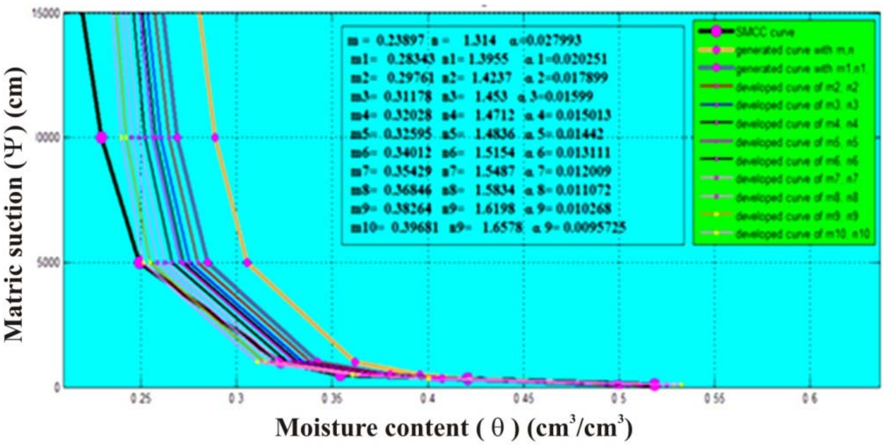


Figure 5.10: SMCC and Curves Generated with Established Parameters by Second Method for Sholapur

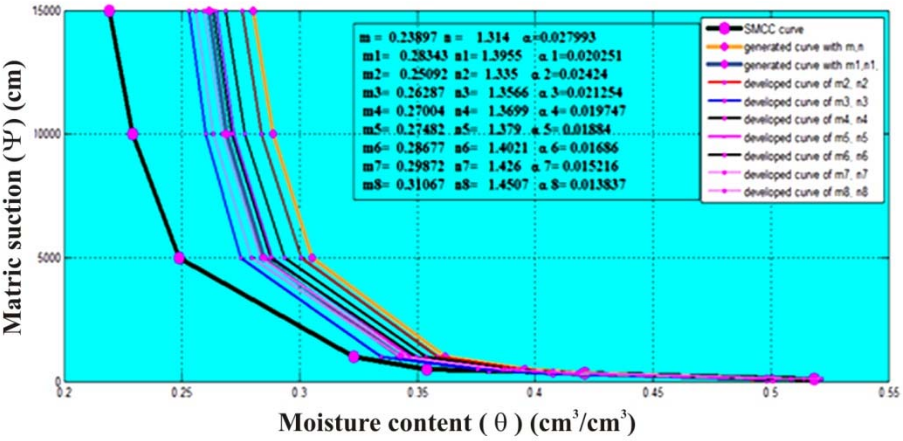


Figure 5.11: SMCC and Generated Curve with Established Parameters by First Method for Sholapur

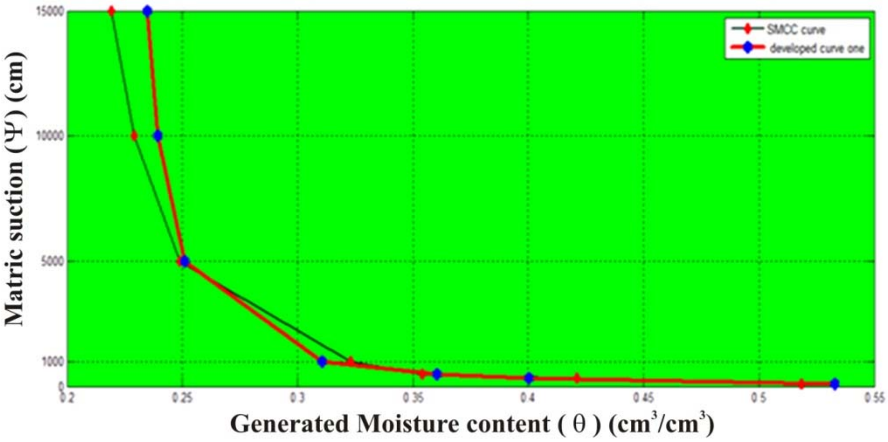


Figure 5.12: Original SMCC and Curve Generated by Parameter Selected at a Soil Depth of 0 to 15 cm for Sholapur

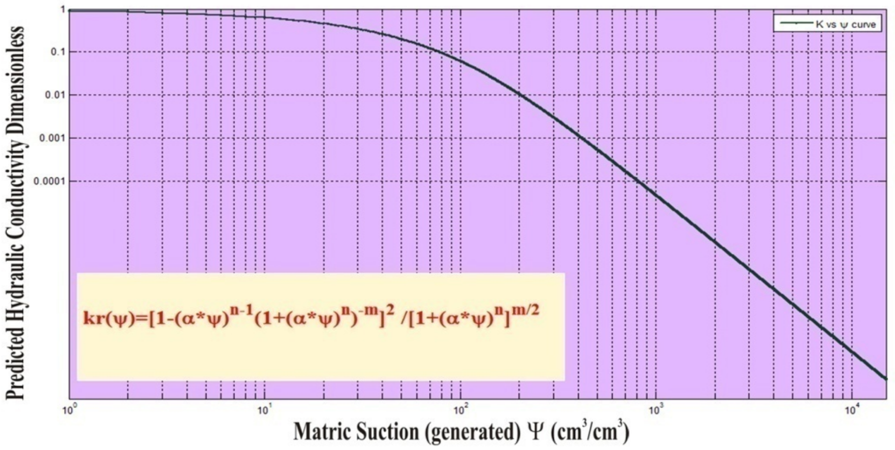


Figure 5.13: Hydraulic Conductivity vs Matric Suction at a Soil Depth of 0 to 15 cm for Sholapur

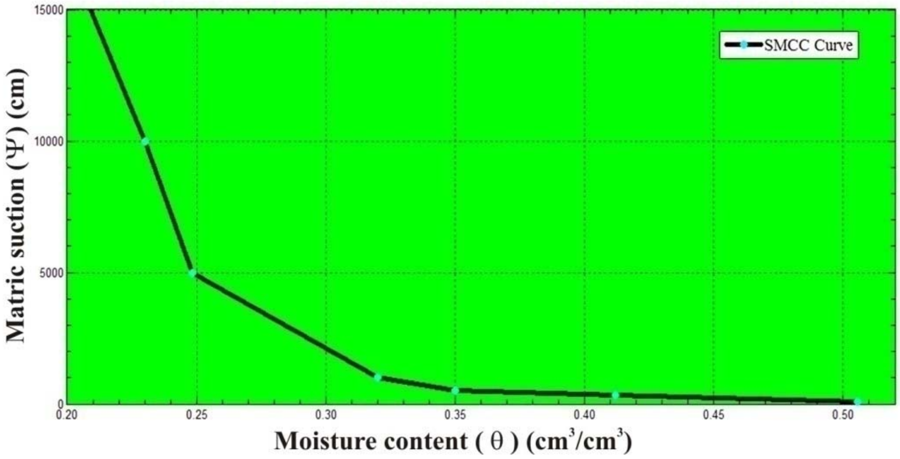


Figure 5.14: SMCC at a Soil Depth 15 to 30 cm for Sholapur

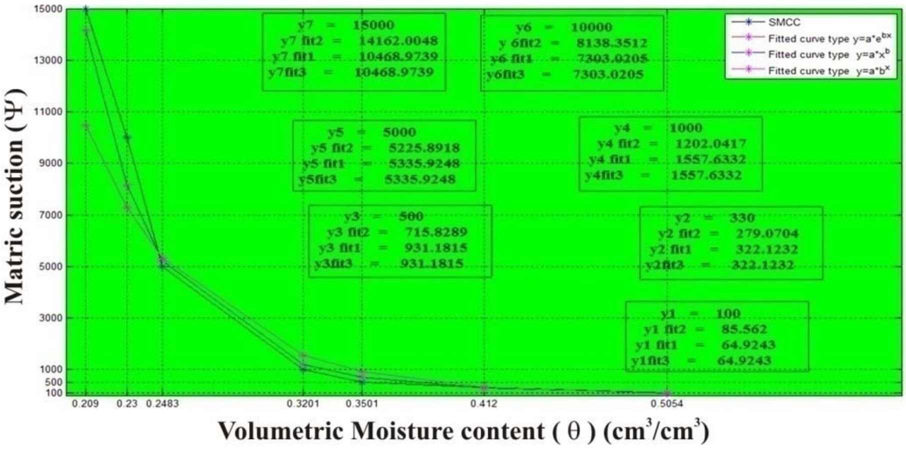


Figure 5.15: Curve fitting for SMCC at a Soil Depth of 15 to 30 cm for Sholapur

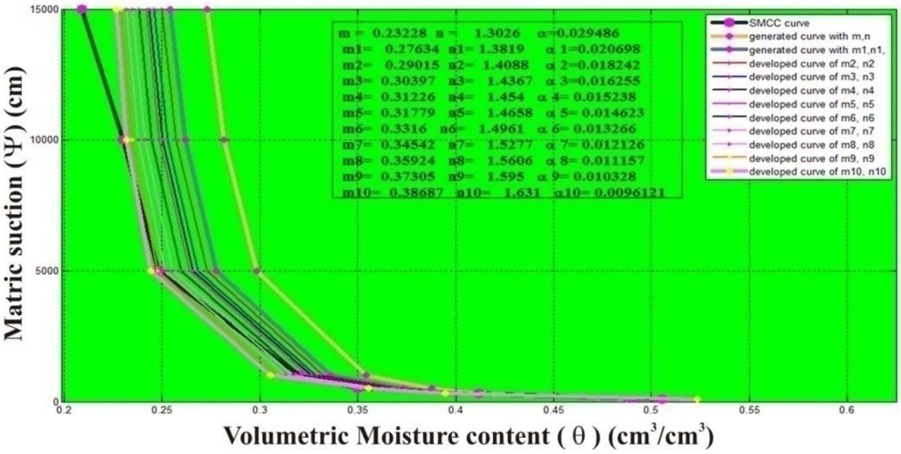


Figure 5.16: SMCC and Generated Curves at a Soil Depth of 15 to 30 cm for Sholapur

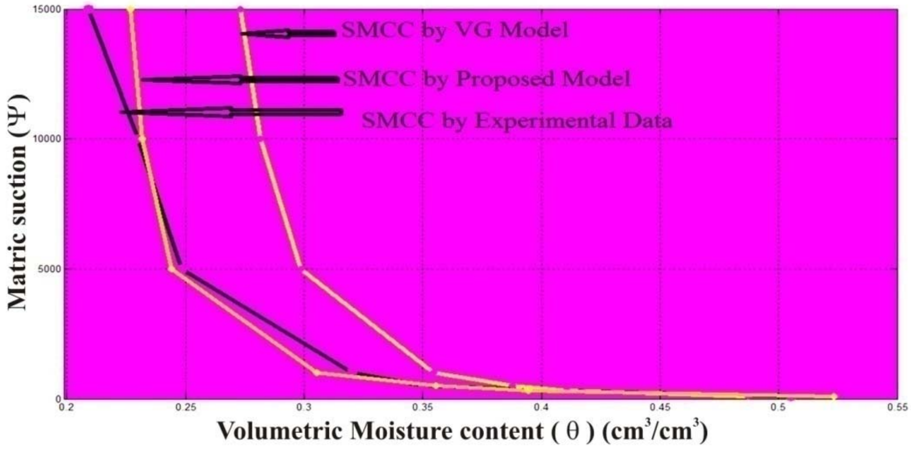


Figure 5.17: SMCC and Generated Curves of Selected Parameters at a Soil Depth of 15 to 30 cm for Sholapur

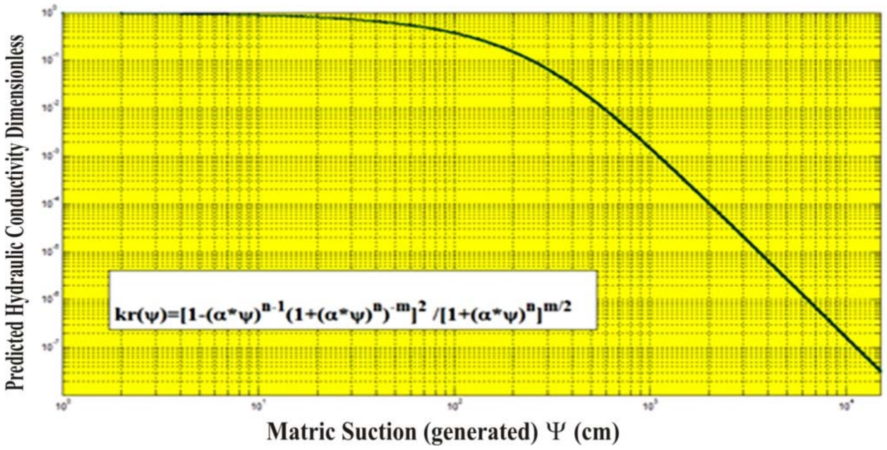


Figure 5.18: Hydraulic Conductivity vs Matric Suction at a Soil Depth of 15 to 30 cm for Sholapur

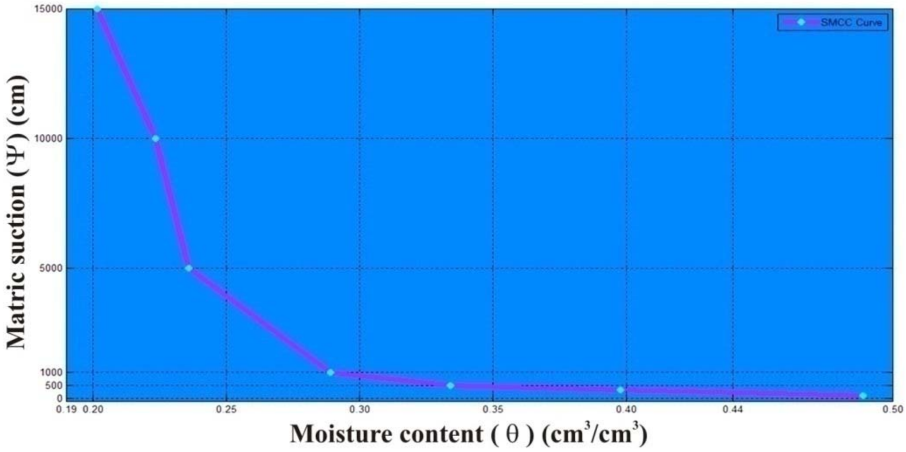


Figure 5.19: SMCC at a Soil Depth 30 to 60 cm for Sholapur

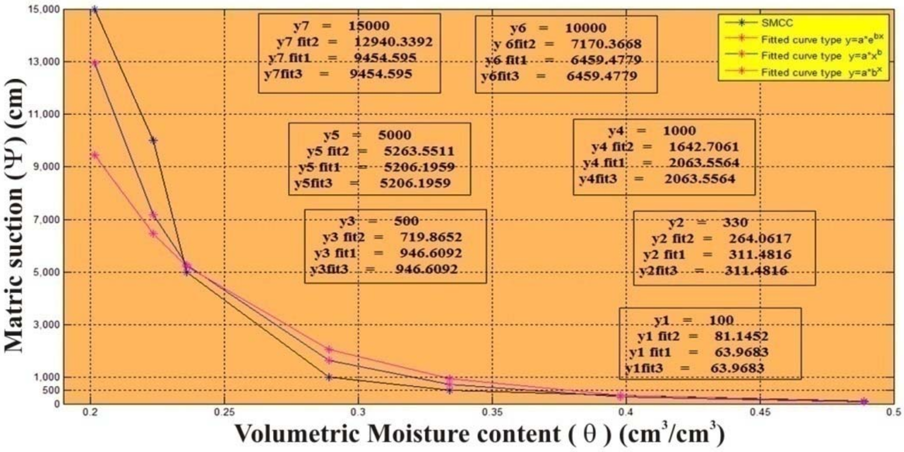


Figure 5.20: Curve fitting for SMCC at a Soil Depth of 30 to 60 cm for Sholapur

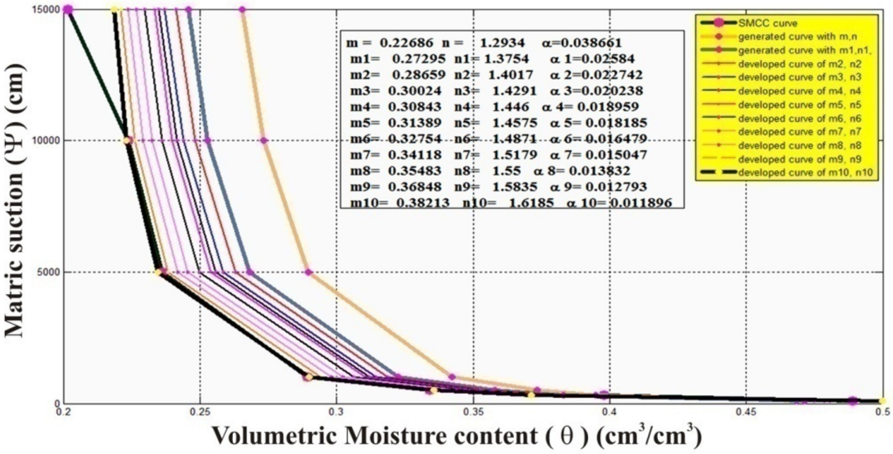


Figure 5.21: SMCC and Generated Curve at a Soil Depth of 30 to 60 cm for Sholapur

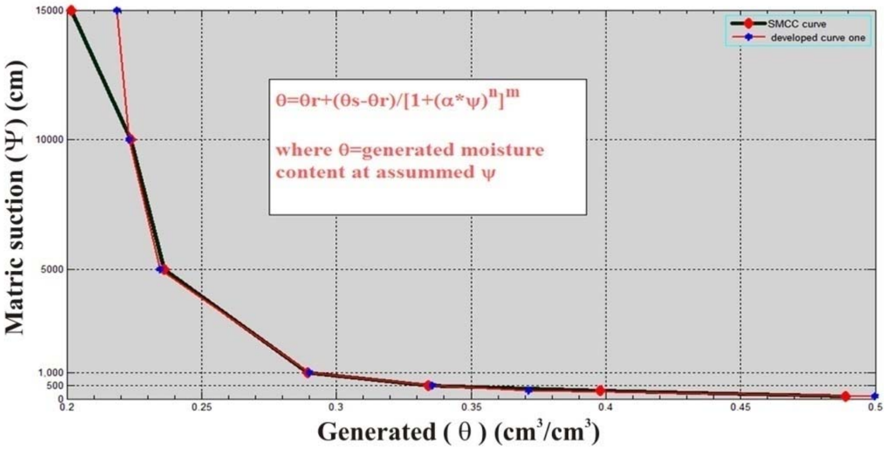


Figure 5.22: SMCC and Generated Curve of Selected parameters at a Soil Depth of 30 to 60 cm for Sholapur

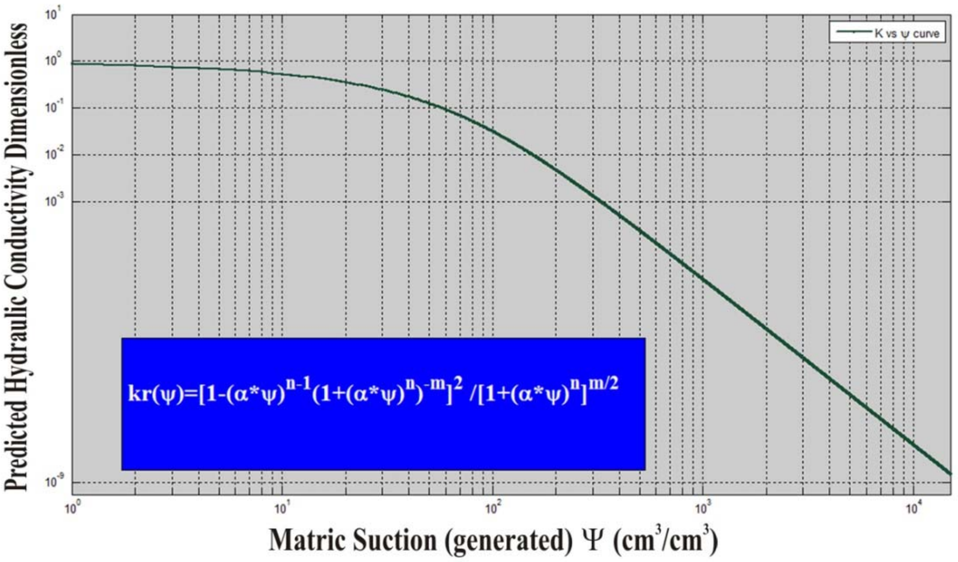


Figure 5.23: Hydraulic Conductivity vs Matrix Suction at a Soil Depth of 30 to 60 cm for Sholapur

The soil moisture analysis for Solapur research station is performed by VG model and proposed model. The obtained results were presented in above graph figures. A knowledge of soil moisture relationships or desorption curves help in formulating a suitable strategy for proper crop water management. The soil moisture characteristic curves (SMCC) depict the moisture release patterns in the soil profile. The quantum of the moisture held in the soils decreases with the increase in suction, and vice-versa. The trend of SMCC is similar to the infiltration curve. It is also important for the analysis of groundwater recharge. It is used to predict soil-water storage. These relationships are also of considerable value to geotechnical and geo-environmental engineering practices. The most fundamental approach to assessing model performance in terms of behaviour is through visual inspection of the simulated and observed curves. On observing SMCC, it shows most of moisture i.e. nearly up to 50 % was released rapidly when suction increases from o to 1000 cm. The rate of release of soil moisture also depends on texture of soils. The moisture content in soil from suction 100 to 300 cm is generally known as field capacity. On observing SMCC it indicate that the moisture from saturation to field capacity is of limited use to crop as it drained out rapidly from the soil pores. The soil moisture available at suction between 100 cm to 15000 cm is useful for plant growth. The soil moisture present at suction 15000 cm is called permanent wilting point as suction increases very rapidly. The quantity of moisture in the soil between the limits of field capacity and permanent wilting point is called available soil water. The crop can get moisture without much effort in this range (available soil moisture range). The soil depth considered for study were 0 to 15 cm, 15 to 30 cm and 30 to 60 cm for Sholapur research station. There are certain physical implications for each model parameter estimated by VG model and proposed model. It can be seen that α is approximately equivalent to the air-entry value of SMCC. Furthermore, n is related to the pore size distribution which controls the gradient of the linear portion of SMCC, i.e., how fast the soil is wetted-up or dried out subject to a change of suction. In order to evaluate the quality of the fitting of Van Genuchten model and proposed model, the significant tests were carried out using the statistical parameters based on experimental/ recorded (observed) and estimated (simulated) water content values. This test criteria's are mathematical measures of how well a model simulation fits the available observations. In general, many efficiency criteria contain a summation of the error term (difference between the simulated and the observed values) normalized by a measure of the variability in the observations. To avoid the canceling of errors of opposite sign, the summation of the absolute or squared errors is often used for many efficiency criteria. These criteria's are: Average Error, Relative Error, Standard Deviation, Root Mean Square Error, Coefficient of Variation and Coefficient of Efficiency.

- **Average Error (AE)**

Average Error is a measure of how far of simulated moisture content is from a recorded moisture content. It may be used to express the inaccuracy in simulated or estimated moisture content. The formulae used for AE is as follows:

$$\mathrm{AE} = (\text{Average of Observed Moisture Content } - \text{Average of Estimated Moisture Content}) \quad (5.2)$$

- **Relative Error (RE)**

Relative Error expresses how large the Average Error is compared with the total size of the object you are measuring. Relative Error is fraction or is multiplied by 100 and expressed as a percent.

$$\mathrm{RE} = \frac{\text{Average Error}}{\text{Known Value}} \qquad (5.3)$$

- **Standard Deviation**

Standard Deviation is the measure of spread or variability of the data in a set of data from its mean value.

$$SD = \sqrt{\frac{1}{N}\left(\sum_{1}^{N}(Y_i - \overline{Y_i})^2\right)} \qquad (5.4a)$$

Or

$$SD = \sqrt{\frac{1}{N}\left(\sum_{1}^{N}(X - \overline{X_i})^2\right)} \qquad (5.4b)$$

- **Root Mean Square Error (RMSE)**

Root Mean Square Error (RMSE) (also known as Root Mean Square Deviation) is one of the most widely used statistics in hydrology and water management. RMSE measures how much error there is between two datasets**.** It usually compares a predicted value and an observed value.

$$RMSE = \sqrt{\left(\frac{1}{N}\sum_{i}^{N}(Yfit_i - Y_i)^2\right)} \qquad (5.5a)$$

$$RMSE = \sqrt{\left(\frac{1}{N}\sum_{i}^{N}(x_i - X_i)^2\right)} \qquad (5.5b)$$

- **Coefficient Variation (CV)**

A Coefficient of Variation (CV) is a statistical measure of the dispersion of data points in a data series around the mean. The coefficient of variation represents the ratio of the standard deviation to the mean, and it is a useful statistic for comparing the degree of variation from one data series to another, even if the means are drastically different from one another. It is calculated as follows:

$$\mathrm{CV} = \frac{\text{Standard Deviation}}{\text{Mean of the Observed Values}} \tag{5.6}$$

- **Coefficient of Efficiency (R^2)**

The Coefficient of Efficiency or Nash-Sutcliffe coefficient is an indicator of the model's ability to predict about the 1:1 line between experimental and simulated moisture content.

$$R^2 = 1 - \frac{\sqrt{\left(\frac{1}{N}\sum_i^N (Y_i - Yfit_i)^2\right)}}{\sqrt{\left(\frac{1}{N}\sum_i^N (Y_i - Y_{avg})^2\right)}} \qquad (5.7a)$$

$$R^2 = 1 - \frac{\sqrt{\left(\frac{1}{N}\sum_i^N (X_i - x_i)^2\right)}}{\sqrt{\left(\frac{1}{N}\sum_i^N (X_i - X_{avg})^2\right)}} \qquad (5.7b)$$

The coefficient of efficiency ranges from −1 to 1. A value of 1 implies that a linear equation describes the relationship between observed and simulated perfectly while −1 implies that there is perfectly opposite relation. A value of 0 implies that there is no correlation. Using above statistic parameters the VG model and proposed models were tested and results are presented in following Tables, 5.9 to 14.

Table 5.9: Sensitivity Analysis for Soil Depth 0 to 15 cm (Comparing Three Methods) (Sholapur)

	Ψ=Y	**θ=X**	**yfit$_1$**	**yfit$_2$**	**yfit$_3$**	**(yfit$_1$-Y)^2**	**(yfit$_2$-Y)^2**	**(yfit$_3$-Y)^2**	**(y$_{avg}$-Y)^2**
Y_7	15000	0.2172	9045.6	11650	9045.6	3.5E+07	1.1E+07	3.5E+07	1.09E+08
Y_6	10000	0.2292	7665.8	9015.3	7665.8	5448717	969584	5448717	29578055
Y_5	5000	0.2490	5523.7	5599.3	5523.7	274232	359109	274232	192344.5
Y_4	1000	0.3230	1622.9	1254.7	1622.9	388032	64893.6	388032	12683777
Y_3	500	0.3539	973.15	742.12	973.15	223874	58621.4	223874	16495206
Y_2	330	0.4270	320.52	273.55	320.52	89.9444	3186.17	89.9444	17904991
Y_1	100	0.5185	63.826	82.606	63.826	1308.57	302.537	1308.57	19904349
Total	31930	2.3178	25215	28618	25215	4.2E+07	1.3E+07	4.2E+07	2.06E+08
Average (y$_{avg}$)	4561.43	0.3311	3602.2	4088.2	3602.2	5970158	1811171	5970158	29388927
Std Dev	5855.52	0.1118	3740.6	4718.1	3740.6				
Average Error			-959.2	-473.2	-959.2				
Relative Error			-0.21	-0.104	-0.21				
Root Mean Square Error						2443.39	1345.8	2443.39	
Coefficient of Variation						0.5357	0.2950	0.5357	
Coefficient of Efficiency (R^2)						0.7969	0.9384	0.7969	

Table 5.10: Sensitivity Analysis for Selected m, n and α values for Soil Depth 0 to 15 cm (Sholapur)

	Ψ=Y	**θ=X**	**x_1(θ generated) (by VG Model)**	**(x_1-X)^2**	**(x_{avg}-X)^2**	**x_2 (θ generated) (by Proposed Model)**	**(x_2-X)^2**	**(x_{avg}-X)^2**
Y_7	15000	0.21722	0.2782	0.0037	0.0130	0.2330	0.0002	0.0130
Y_6	10000	0.2292	0.2865	0.0033	0.0104	0.2378	0.0001	0.0104
Y_5	5000	0.2490	0.3034	0.0030	0.0067	0.2499	0.0000	0.0067
Y_4	1000	0.3230	0.3600	0.0014	0.0001	0.3114	0.0001	0.0001
Y_3	500	0.3539	0.3941	0.0016	0.0005	0.3632	0.0001	0.0005
Y_2	330	0.4270	0.4178	0.0001	0.0092	0.4041	0.0005	0.0092
Y_1	100	0.5185	0.4973	0.0004	0.0351	0.5379	0.0004	0.0351
Total	31930	2.3178	2.5373	0.0135	0.0750	2.3372	0.0014	0.0750
Average (x_{avg})	4561.4286	0.3311	0.3625	0.0019	0.0107	0.3339	0.0002	0.0107
Std Dev	5855.5171	0.1118	0.0802			0.1113		
Average Error			0.0314			0.0028		
Relative Error			0.0947			0.0084		
Root Mean Square Error				0.0439			0.0144	
Coefficient of Variation				0.1349			0.0442	
Coefficient of Efficiency (R^2)				0.8203			0.9807	

Table 5.11: Sensitivity Analysis for Soil Depth 15 to 30 cm (Comparing Three Methods) (Sholapur)

	Ψ=Y	θ=X	yfit$_1$	yfit$_2$	yfit$_3$	(yfit$_1$-Y)^2	(yfit$_2$-Y)^2	(yfit$_3$-Y)^2	(y$_{avg}$-Y)^2
Y$_7$	15000	0.209	10468.97	14162	10468.97	20530198	702244	20530198	1.09E+08
Y$_6$	10000	0.23	7303.021	8138.351	7303.021	7273698	3465736	7273698	29578055
Y$_5$	5000	0.2483	5335.925	5225.892	5335.925	112845.5	51027.11	112845.5	192344.5
Y$_4$	1000	0.3201	1557.633	1202.042	1557.633	310954.8	40820.85	310954.8	12683777
Y$_3$	500	0.3501	931.1815	715.8289	931.1815	185917.5	46582.11	185917.5	16495206
Y$_2$	330	0.412	522.1232	279.0704	522.1232	36911.32	2593.824	36911.32	17904991
Y$_1$	100	0.5054	64.9243	85.502	64.9243	1230.305	210.192	1230.305	19904349
Total	31930	2.2749	26183.78	29808.69	26183.78	28451755	4309214	28451755	2.06E+08
Average	4561.429	0.324986	3740.54	4258.384	3740.54	4064536	615602	4064536	29388927
Average (y$_{avg}$)	5855.517	0.10734	4021.49	5310.534	4021.49				
Std Dev			-820.888	-303.045	-820.888				
Relative Error			-0.1799	-0.0664	-0.1799				
Root Mean Square Error						2016.07	784.6031	2016.07	
Coefficient of Variation						0.4420	0.1720	0.442-	
Coefficient of Efficiency (R^2)						0.8617	0.9791	0.8617	

Table 5.12: Sensitivity Analysis for Selected m, n and α values for Soil Depth 15 to 30 cm (Sholapur)

Ψ=Y	θ=X	x_1(θ generated) (by VG Model)	(x_1-X)^2	$(x_{avg}-X)$^2	x_2 (θ generated) (by Proposed Model)	(x_2-X)^2	$(x_{avg}-X)$^2	$(x_{avg}-X)$^2
Y_7	15000	0.2090	0.2733	0.0041	0.0135	0.2266	0.0003	0.0135
Y_6	10000	0.2300	0.2817	0.0027	0.0090	0.2318	0.0000	0.0090
Y_5	5000	0.2483	0.2986	0.0025	0.0059	0.2443	0.0000	0.0059
Y_4	1000	0.3201	0.3544	0.0012	0.0000	0.3055	0.0002	0.0000
Y_3	500	0.3501	0.3876	0.0014	0.0006	0.3556	0.0000	0.0006
Y_2	330	0.4120	0.4106	0.0000	0.0076	0.3946	0.0003	0.0076
Y_1	100	0.5054	0.4872	0.0003	0.0325	0.5235	0.0003	0.0325
Total	31930	2.2749	2.4934	0.0122	0.0691	2.2819	0.0012	0.0691
Average (x_{avg})	4561.4286	0.3250	0.3562	0.0017	0.0099	0.3260	0.0002	0.0099
Std Dev	5855.5171	0.1073	0.0784			0.1083		
Average Error			0.0312			0.0010		
Relative Error			0.0960			0.0031		
Root Mean Square Error				0.0418			0.0131	
Coefficient of Variation				0.1286			0.0403	
Coefficient of Efficiency (R^2)				0.8229			0.9826	

Table 5.13: Sensitivity Analysis for Soil Depth 30 to 60 cm (Comparing Three Methods) (Sholapur)

	Ψ=Y	**θ=X**	**yfit$_1$**	**yfit$_2$**	**yfit$_3$**	**(yfit$_1$-Y)^2**	**(yfit$_2$-Y)^2**	**(yfit$_3$-Y)^2**	**(y$_{avg}$-Y)^2**
Y_7	15000	0.2018	9054.595	12940.34	9054.595	35347841	4242203	35347841	1.09E+08
Y_6	10000	0.2237	6459.478	7170.367	6459.478	12535297	8006824	12535297	29578055
Y_5	5000	0.2361	5206.196	5263.551	5206.196	42516.75	69459.18	42516.75	192344.5
Y_4	1000	0.2893	2063.556	1642.706	2063.556	1131152	413071.1	1131152	12683777
Y_3	500	0.3341	946.6092	719.8652	946.6092	199459.8	48340.71	199459.8	16495206
Y_2	330	0.398	311.4816	264.0617	311.4816	342.9311	4347.859	342.9311	17904991
Y_1	100	0.489	63.9683	81.1452	63.9683	1298.283	355.5035	1298.283	19904349
Total	31930	2.172	24105.88	28082.04	24105.88	49257907	12784601	49257907	2.06E+08
Average	4561.429	0.3102	3443.698	4011.719	3443.698	7036844	1826372	7036844	29388927
Average (y$_{avg}$)	5855.517	0.1044	3489.439	4782.037	3489.439				
Std Dev			-1117.73	-549.709	-1117.73				
Relative Error			-0.2450	-0.1205	-0.2450				
Root Mean Square Error						2652.705	1351.433	2652.705	
Coefficient of Variation						0.5816	0.2963	0.5816	
Coefficient of Efficiency (R^2)						0.7606	0.9379	0.7606	

Table 5.14: Sensitivity Analysis for Selected m, n and α values for Soil Depth 30 to 60 cm (Sholapur)

	Ψ=Y	**θ=X**	**x_1(θ generated) (by VG Model)**	**$(x_1\text{-}X)$^2**	**$(x_{avg}\text{-}X)$^2**	**x_2 (θ generated) (by Proposed Model)**	**$(x_2\text{-}X)$^2**	**$(x_{avg}\text{-}X)$^2**
Y_7	15000	0.2090	0.2733	0.0041	0.0135	0.2266	0.0003	0.0135
Y_6	10000	0.2300	0.2817	0.0027	0.0090	0.2318	0.0000	0.0090
Y_5	5000	0.2483	0.2986	0.0025	0.0059	0.2443	0.0000	0.0059
Y_4	1000	0.3201	0.3544	0.0012	0.0000	0.3055	0.0002	0.0000
Y_3	500	0.3501	0.3876	0.0014	0.0006	0.3556	0.0000	0.0006
Y_2	330	0.4120	0.4106	0.0000	0.0076	0.3946	0.0003	0.0076
Y_1	100	0.5054	0.4872	0.0003	0.0325	0.5235	0.0003	0.0325
Total	31930	2.2749	2.4934	0.0122	0.0691	2.2819	0.0012	0.0691
Average (x_{avg})	4561.429	0.3250	0.3562	0.0017	0.0099	0.3260	0.0002	0.0099
Std Dev	5855.517	0.1073	0.0784			0.1083		
Average Error			0.0312			0.0010		
Relative Error			0.0960			0.0031		
Root Mean Square Error				0.0418			0.0131	
Coefficient of Variation				0.1286			0.0403	
Coefficient of Efficiency (R^2)				0.8229			0.9826	

The evaluation of model behavior and performance is commonly made and reported through comparisons of simulated and observed values. Often, comparisons are made between simulated and recorded values by efficiency criteria. It provide an objective assessment of the closeness of the simulated behaviour to the observed or recorded measurements. There are a few efficiency criteria such as the Nash-Sutcliffe efficiency or coefficient of determination. There are a large number of other efficiency criteria too. The criteria's were discussed in detail at the outset of sensitivity analysis tables in this section. The curve fitting method one and third are not found suitable as their R^2 values are not encouraging.

For depth 0 to 15 cm $R_1^2 = 0.80$, $R_2^2 = 0.94$ and $R_3^2 = 0.80$.
For depth 15 to 30 cm $R_1^2 = 0.86$, $R_2^2 = 0.98$ and $R_3^2 = 0.86$.
For depth 30 to 60 cm $R_1^2 = 0.76$, $R_2^2 = 0.93$ and $R_3^2 = 0.76$.

The second curve fitting method is used for simulating soil moisture parameters. The soil moisture parameters were estimated by VG and proposed model. The R^2 values of proposed methods found suitable.
For depth 0 to 15 cm $R_1^2 = 0.82$ and $R_2^2 = 0.98$.
For depth 15 to 30 cm $R_1^2 = 0.82$ and $R_2^2 = 0.98$.
For depth 30 to 60 cm $R_1^2 = 0.82$ and $R_2^2 = 0.90$.

The model efficiency of proposed model (R_2^2) is more than 90 % and the efficiency of VG model (R_1^2) is less than 83 %. The established soil moisture parameters are presented in Table: 5.45 for ready reference. The other parameters of sensitivity analysis for curve fitting and soil moisture parameter estimation are presented in Tables: 5.9 and 5.14. The visual observation and mathematical analysis supports the above conclusion for Sholapur research station.

5.3.2 SMCC Analysis for Pune Research Station

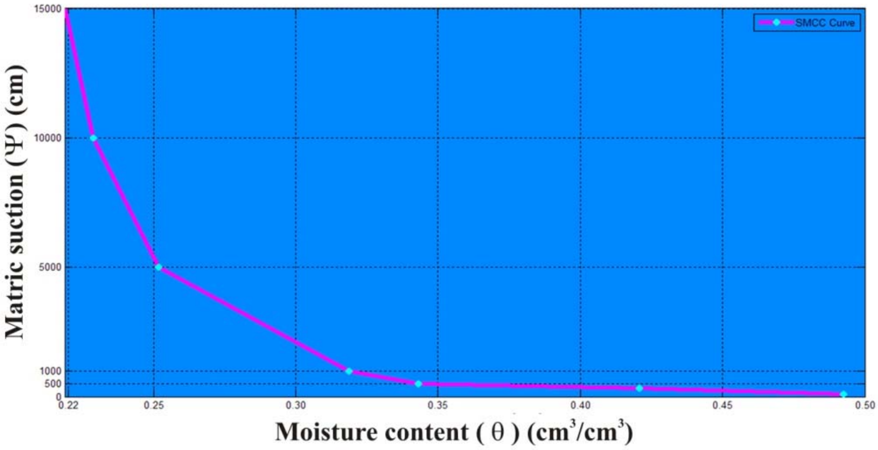


Figure 5.24: SMCC at a Soil Depth 0 to 15 cm for Pune

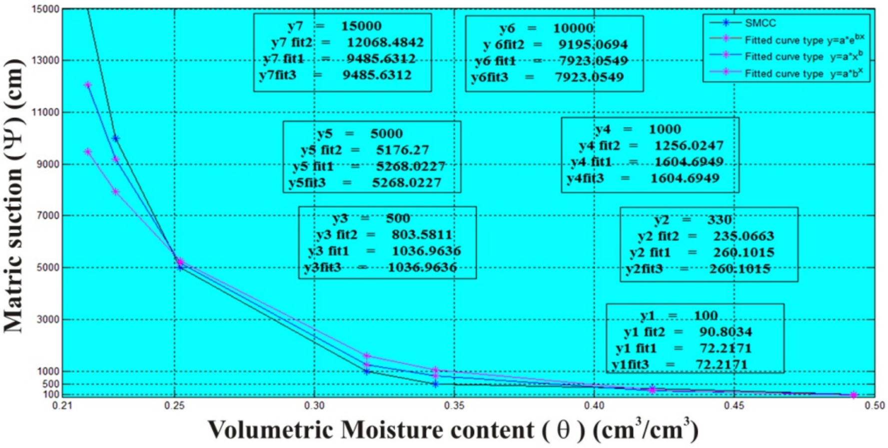


Figure 5.25: Curve fitting for SMCC at a Soil Depth of 0 to 15 cm for Pune

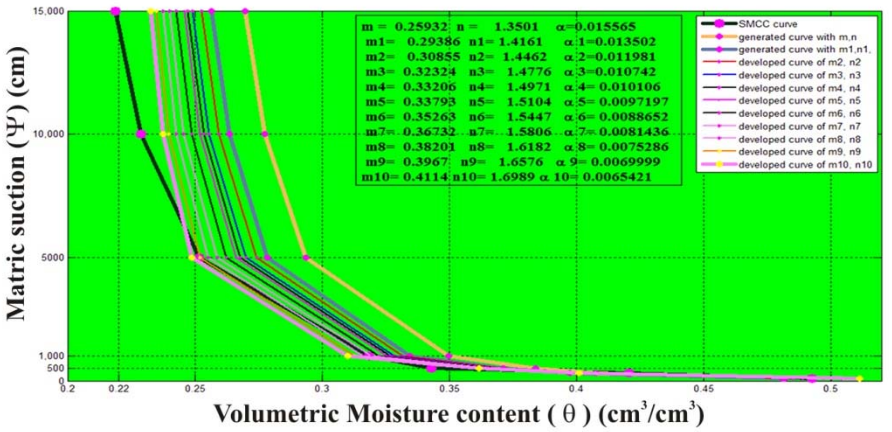


Figure 5.26: SMCC and Generated Curves at a Soil Depth of 0 to 15 cm for Pune

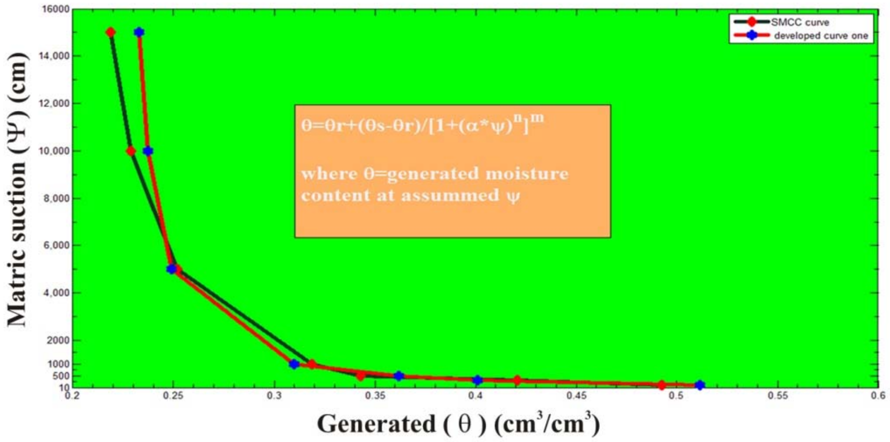


Figure 5.27: SMCC and Selected Curve at a Soil Depth of 0 to 15 cm for Pune

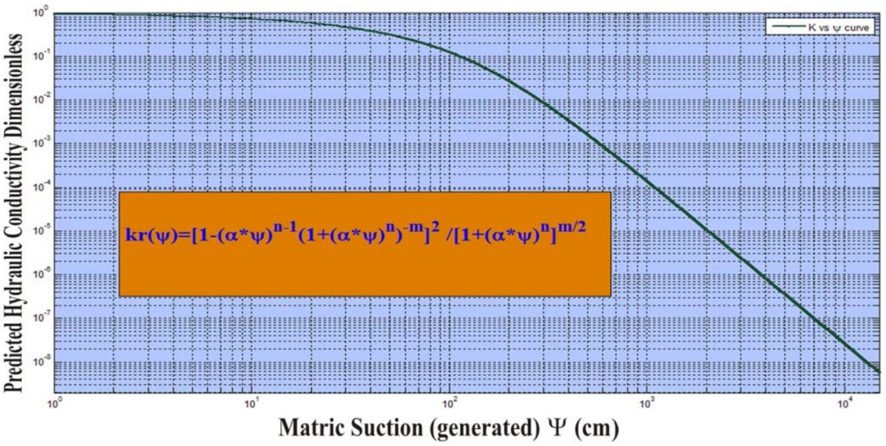


Figure 5.28: Hydraulic Conductivity vs Matrix Suction at a Soil Depth of 0 to 15 cm for Pune

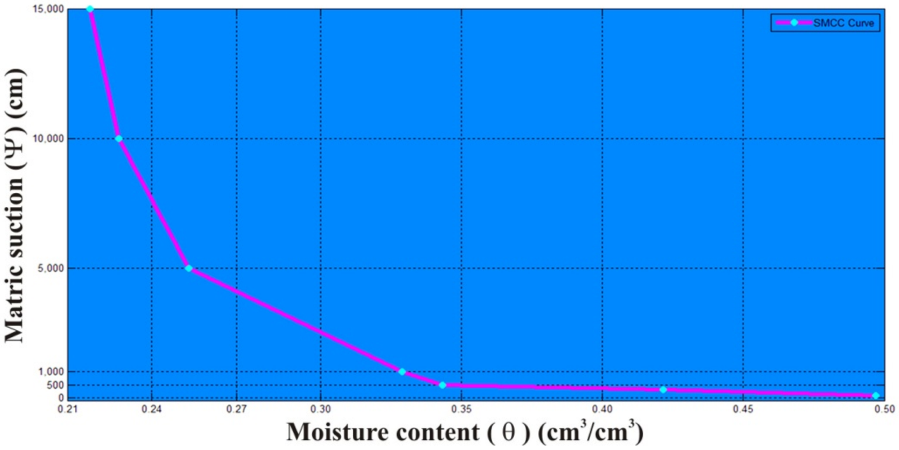


Figure 5.29: SMCC at a Soil Depth 15 to 30 cm for Pune

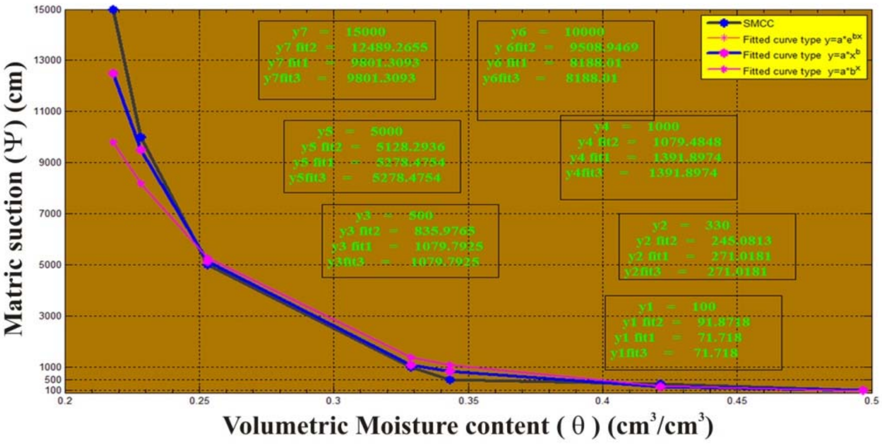


Figure 5.30: Curve Fitting for SMCC at a Soil Depth of 15 to 30 cm for Pune

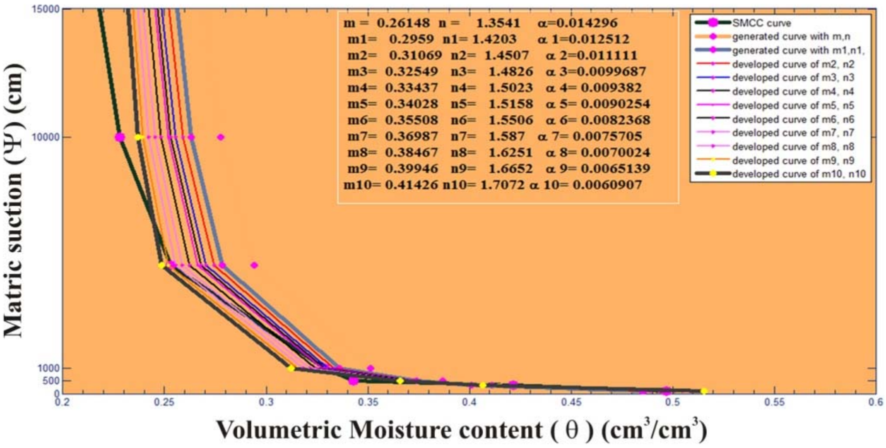


Figure 5.31: SMCC and Generated Curves at a Soil Depth of

15 to 30 cm for Pune

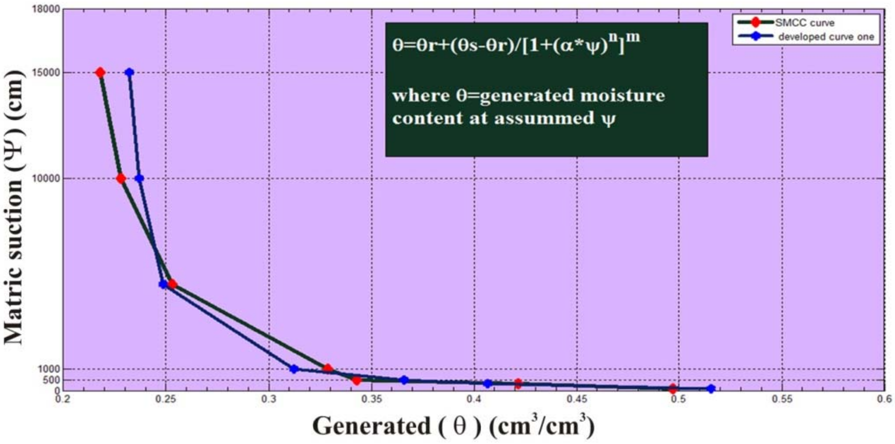


Figure 5.32: SMCC and Selected Curve at a Soil Depth of 15 to 30 cm for Pune

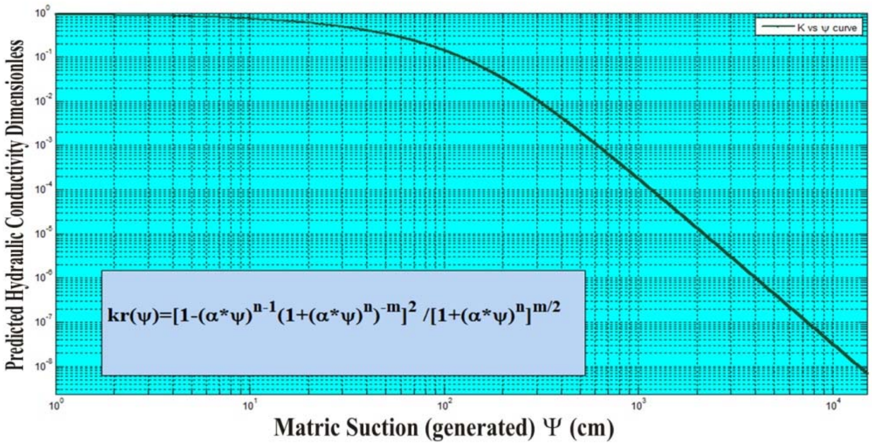


Figure 5.33: **Hydraulic Conductivity vs Matrix Suction at a Soil Depth of 15 to 30 cm for Pune**

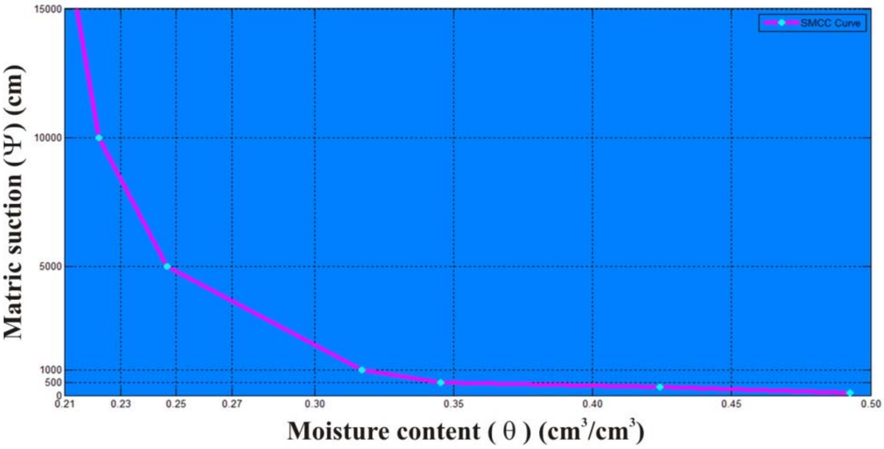


Figure 5.34: SMCC at a Soil Depth of 30 to 60 cm for Pune

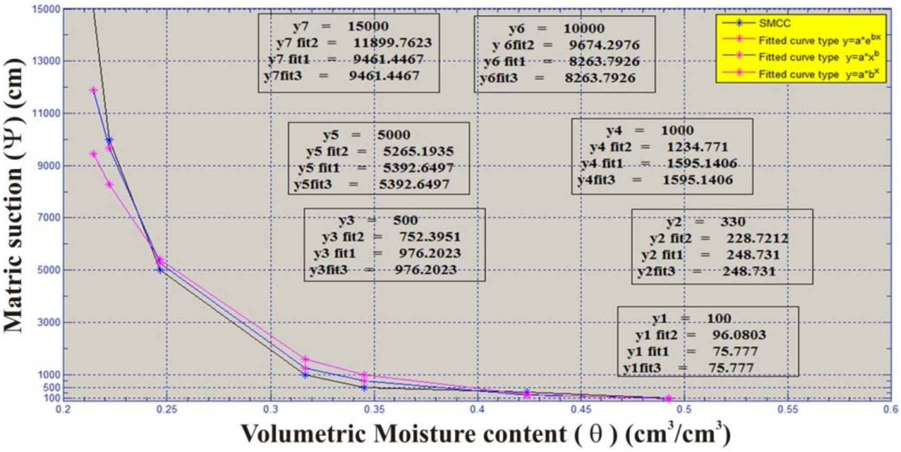


Figure 5.35: Curve Fitting for SMCC at a Soil Depth of 30 to 60 cm for Pune

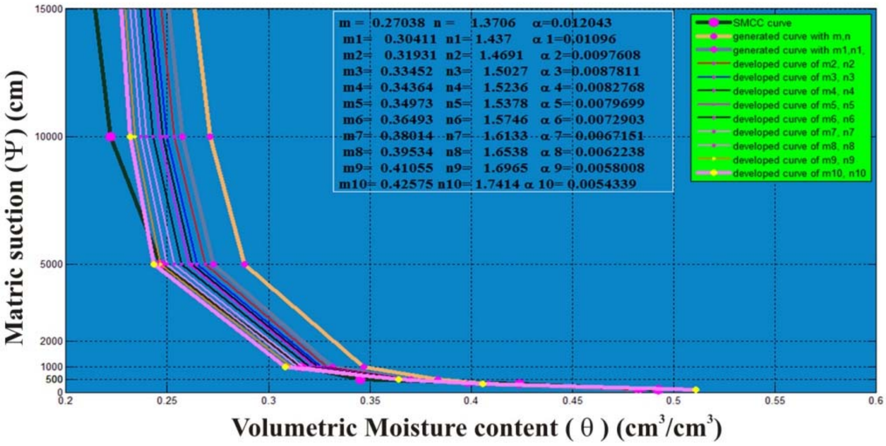


Figure 5.36: SMCC and Generated Curves at a Soil Depth of 30 to 60 cm for Pune

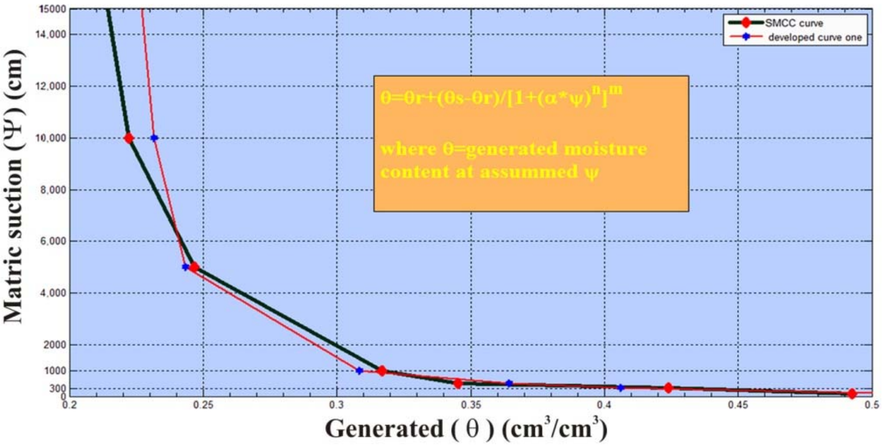


Figure 5.37: SMCC and Selected Curve at a Soil Depth of 30 to 60 cm for Pune

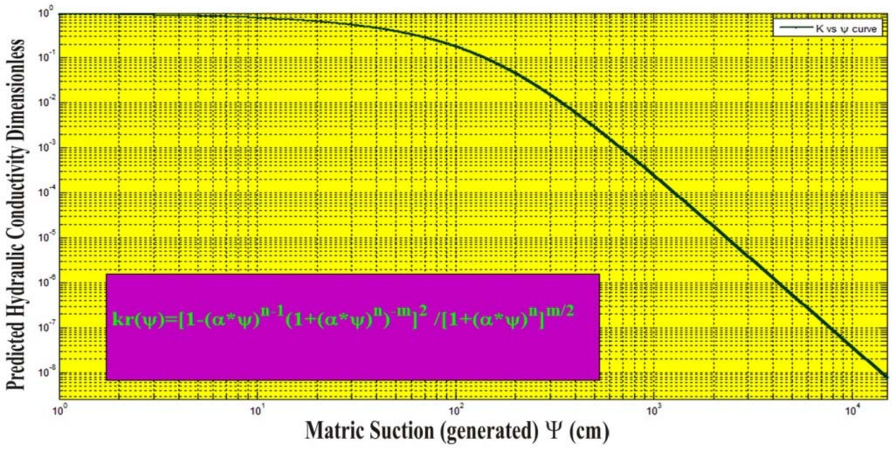


Figure 5.38: Hydraulic Conductivity vs Matrix Suction at a Soil Depth of 30 to 60 cm for Pune

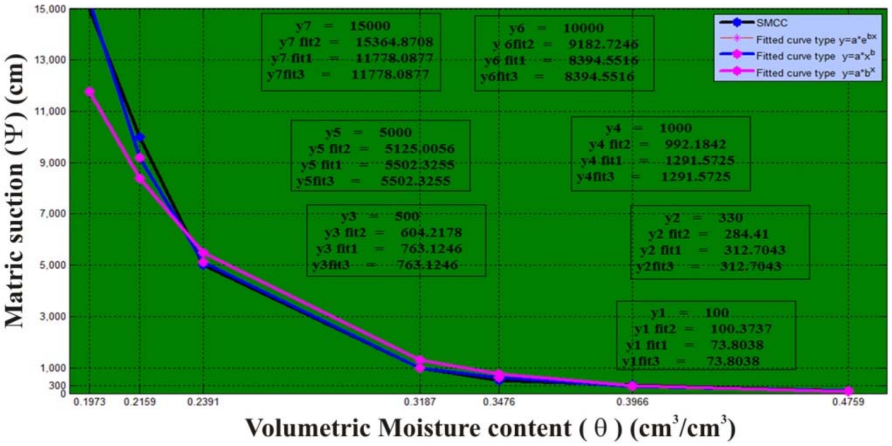


Figure 5.39: Curve Fitting for SMCC at a Soil Depth of 60 to 90 cm for Pune

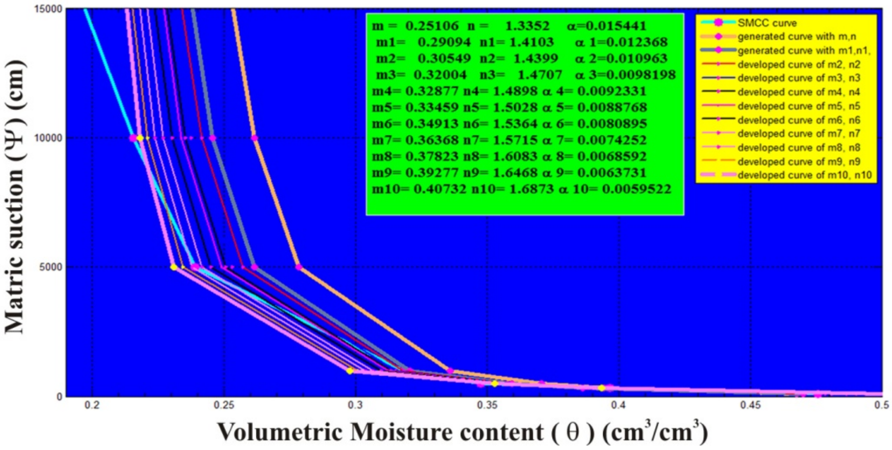


Figure 5.40: SMCC and Generated Curves at a Soil Depth of 60 to 90 cm for Pune

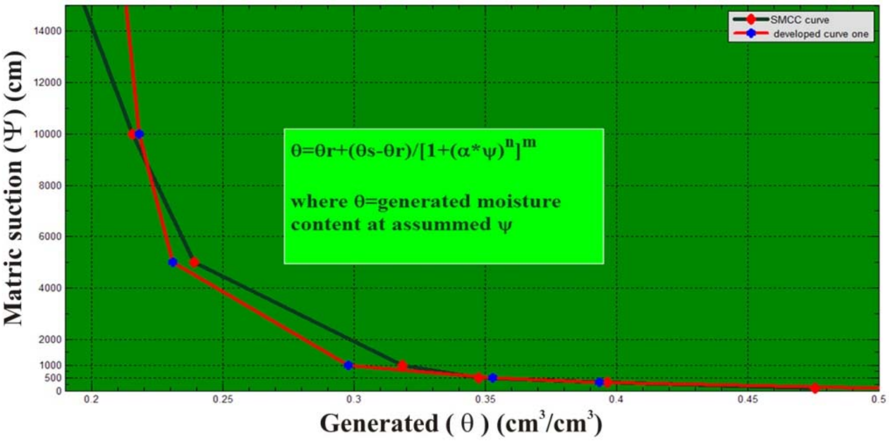


Figure 5.41: SMCC and Selected Curve at a Soil Depth of 60 to 90 cm for Pune

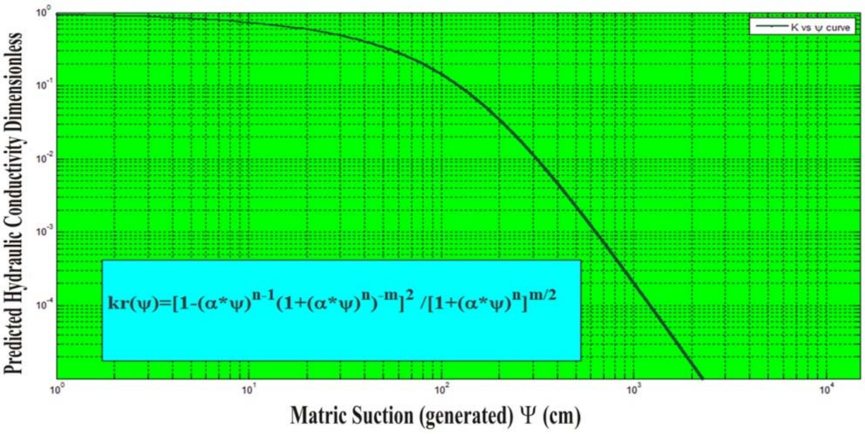


Figure 5.42: Hydraulic Conductivity vs Matrix Suction at a Soil Depth of 60 to 90 cm for Pune

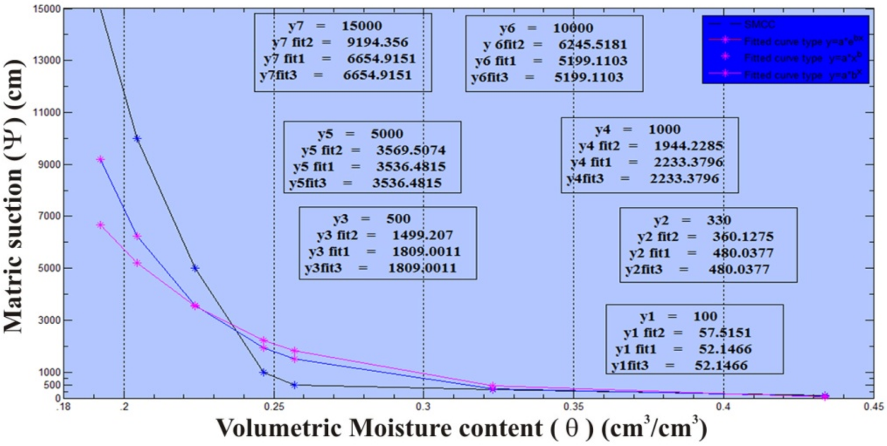


Figure 5.43: Curve Fitting for SMCC at a Soil Depth of 90 to 120 cm for Pune

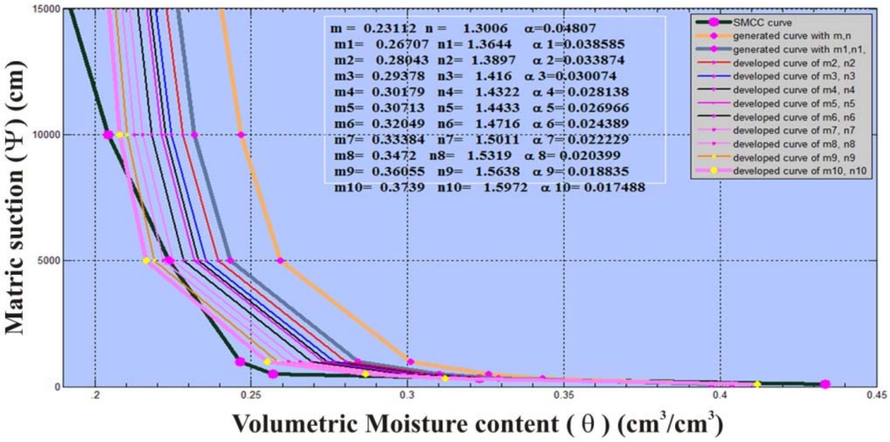


Figure 5.44: SMCC and Generated Curves at a Soil Depth of 90 to 120 cm for Pune

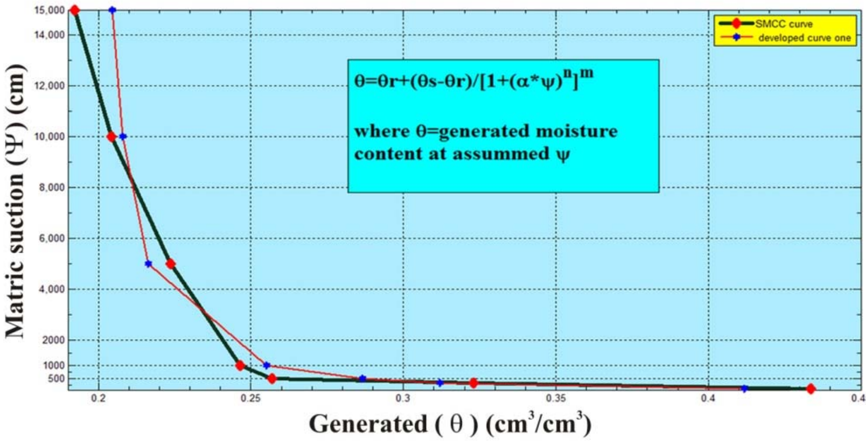


Figure 5.45: SMCC and Selected Curve at a Soil Depth of 90 to 120 cm for Pune

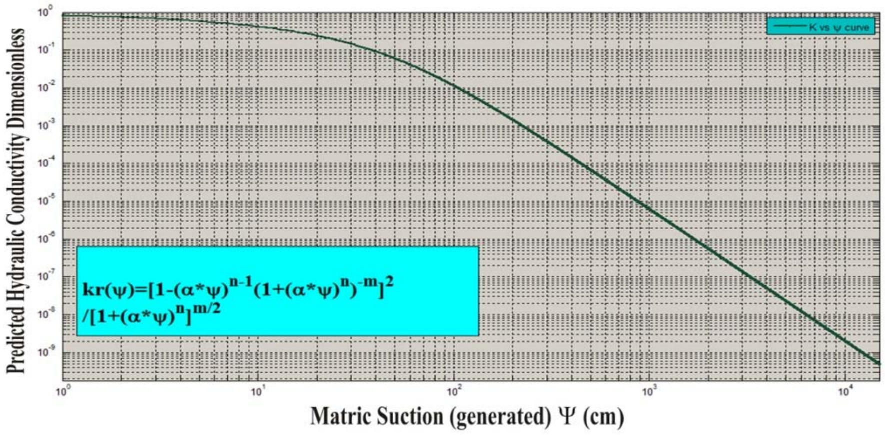


Figure 5.46: Hydraulic Conductivity vs Matrix Suction at a Soil Depth of 90 to 120 cm for Pune

The soil moisture analysis for Pune research station is performed by VG model and proposed model. The results were presented in above graph figures. The trend of SMCC is similar to the trend of Sholapur research station. The model performance in terms of visual inspection of the SMCC simulated and SMCC observed shows most of moisture i.e. nearly up to 50 % was released rapidly when suction increases from o to 1000 cm. The soil depth considered for study were 0 to 15 cm, 15 to 30 cm, 30 to 60 cm, 60 to 90 cm and 90 to 120 cm for Pune research station. The physical parameters were simulated by VG model and proposed model. In order to evaluate the quality of the fitting of Van Genuchten model and proposed model, the significant tests were carried out. The curve fitting method one and third are not found suitable as their R^2 (coefficient of efficiency) values are not encouraging. The second curve fitting method is found suitable as their R^2 values are more than 0.95 or model efficiency is 95 %. For soil depth 0 to 15 cm $R_1^2 = 0.83$, $R_2^2 = 0.95$ and $R_3^2 = 0.83$. For soil depth 15 to 30 cm $R_1^2 = 0.85$, $R_2^2 = 0.97$ and $R_3^2 = 0.85$. For soil depth 30 to 60 cm $R_1^2 = 0.83$, $R_2^2 = 0.95$ and $R_3^2 = 0.83$. For soil depth 60 to 90 cm $R_1^2 = 0.94$, $R_2^2 = 0.99$ and $R_3^2 = 0.94$. For soil depth 90 to 120 cm $R_1^2 = 0.52$, $R_2^2 = 0.75$ and $R_3^2 = 0.83$. The coefficient of efficiency for VG model is 0.66 to 0.86, while coefficient of efficiency for proposed model is 0.95 to 0.98. The sensitivity analysis is presented in detail in following Tables, 5.15 to 5.24. The proposed model found most suitable.

Table 5.15: Sensitivity Analysis for Soil Depth 0 to 15 cm (Comparing Three Methods) (Pune)

	Ψ=Y	θ=X	yfit$_1$	yfit$_2$	yfit$_3$	(yfit$_1$-Y)^2	(yfit$_2$-Y)^2	(yfit$_3$-Y)^2	(y$_{avg}$-Y)^2
Y$_7$	15000	0.2189	9485.6312	12068.4842	9485.6312	30408263.26	8593784.886	30408263.26	108963764.5
Y$_6$	10000	0.229	7923.0549	9195.0694	7923.0549	4313700.948	647913.2708	4313700.948	29578054.52
Y$_5$	5000	0.2519	5268.0227	5176.27	5268.0227	71836.16772	31071.1129	71836.16772	192344.522
Y$_4$	1000	0.3186	1604.6949	1256.0247	1604.6949	365655.9221	65548.64701	365655.9221	12683776.52
Y$_3$	500	0.3431	1036.9636	803.5811	1036.9636	288329.9077	92161.48428	288329.9077	16495205.52
Y$_2$	330	0.4207	210.1015	235.0663	210.1015	14375.6503	9012.407396	14375.6503	17904991.38
Y$_1$	100	0.4926	72.2171	90.8034	72.2171	771.8895324	84.57745156	771.8895324	19904348.72
Total	31930	2.2748	25600.6859	28825.2991	25600.6859	35462933.75	9439576.386	35462933.75	205722485.7
Average (y$_{avg}$)	4561.429	0.3250	3657.241	4117.899871	3657.240843	5066133.393	1348510.912	5066133.393	29388926.53
Std Dev	5855.517	0.1028	3885.355	4840.429214	3885.354649				
Average Error			-904.1877	-443.5287	-904.1877				
Relative Error			-0.1982	-0.0972	-0.1982				
Root Mean Square Error						2250.8073	1161.2540	2250.8073	
Coefficient of variation						0.4934	0.2546	0.4934	
Coefficient of Efficiency (R^2)						0.8276	0.9541	0.8276	

Table 5.16: Sensitivity Analysis for Selected m, n and α values for Soil Depth 0 to 15 cm (Pune)

	Ψ=Y	**θ=X**	**x_1(θ generated) (by VG Model)**	**$(x_1\text{-}X)$^2**	**$(x_{avg}\text{-}X)$^2**	**x_2 (θ generated) (by Proposed Model)**	**$(x_2\text{-}X)$^2**	**$(x_{avg}\text{-}X)$^2**
Y_7	15000	0.2189	0.2560	0.0014	0.0113	0.2329	0.0002	0.0113
Y_6	10000	0.2290	0.2617	0.0011	0.0092	0.2374	0.0001	0.0092
Y_5	5000	0.2519	0.2734	0.0005	0.0053	0.2489	0.0000	0.0053
Y_4	1000	0.3186	0.3145	0.0000	0.0000	0.3100	0.0001	0.0000
Y_3	500	0.3431	0.3404	0.0000	0.0003	0.3617	0.0003	0.0003
Y_2	330	0.4207	0.3589	0.0038	0.0092	0.4011	0.0004	0.0092
Y_1	100	0.4926	0.4252	0.0045	0.0281	0.5114	0.0004	0.0281
Total	31930	2.2748	2.2301	0.0113	0.0634	2.3035	0.0014	0.0634
Average x_{avg})	4561.4286	0.3250	0.3186	0.0016	0.0091	0.3291	0.0002	0.0091
Std Dev	5855.5171	0.1028	0.0615			0.1032		
Average Error			-0.0064			0.0041		
Relative Error			-0.0197			0.0126		
Root Mean Square Error				0.0402			0.0143	
Coefficient of Variation				0.1235			0.0440	
Coefficient of Efficiency (R^2)				0.8221			0.9774	

Table 5.17: Sensitivity Analysis for Soil Depth 15 to 30 cm (Comparing Three Methods) (Pune)

	$\Psi=Y$	**$\theta=X$**	**yfit$_1$**	**yfit$_2$**	**yfit$_3$**	**(yfit$_1$-Y)^2**	**(yfit$_2$-Y)^2**	**(yfit$_3$-Y)^2**	**(y$_{avg}$-Y)^2**
Y_7	15000	0.218	9801.309	12489.27	9801.309	27026385	6303788	27026385	1.09E+08
Y_6	10000	0.2282	8188.01	9508.947	8188.01	3283308	241133.1	3283308	29578055
Y_5	5000	0.2531	5278.475	5128.294	5278.475	77548.55	16459.25	77548.55	192344.5
Y_4	1000	0.3287	1391.897	1079.485	1391.897	153583.6	6317.833	153583.6	12683777
Y_3	500	0.3431	1079.793	835.9765	1079.793	336159.3	112880.2	336159.3	16495206
Y_2	330	0.4215	271.0181	245.0813	271.0181	3478.865	7211.186	3478.865	17904991
Y_1	100	0.4969	71.718	91.8718	71.718	799.8715	66.06764	799.8715	19904349
Total	31930	2.2895	26082.22	29378.92	26082.22	30881263	6687855	30881263	2.06E+08
Average (y$_{avg}$)	4561.429	0.327071	3726.032	4196.989	3726.032	4411609	955407.9	4411609	29388927
Std Dev	5855.517	0.104213	4020.162	5022.132	4020.162				
Average Error			-835.397	-364.44	-835.397				
Relative Error			-0.1831	-0.0799	-0.1831				
Root Mean Square Error						2100.383	977.4497	2100.383	
Coefficient of Variation						0.4605	0.2143	0.4605	
Coefficient of Efficiency (R^2)						0.8499	0.9675	0.8499	

Table 5.18: Sensitivity Analysis for Selected m, n and α values for Soil Depth 15 to 30 cm (Pune)

	Ψ=Y	**θ=X**	**x_1(θ generated) (by VG Model)**	**$(x_1\text{-}X)^2$**	**$(x_{avg}\text{-}X)^2$**	**x_2 (θ generated) (by Proposed Model)**	**$(x_2\text{-}X)^2$**	**$(x_{avg}\text{-}X)^2$**
Y_7	15000	0.2180	0.2695	0.0027	0.0119	0.2322	0.0002	0.0119
Y_6	10000	0.2282	0.2775	0.0024	0.0098	0.2368	0.0001	0.0098
Y_5	5000	0.2531	0.2940	0.0017	0.0055	0.2487	0.0000	0.0055
Y_4	1000	0.3287	0.3515	0.0005	0.0000	0.3123	0.0003	0.0000
Y_3	500	0.3431	0.3868	0.0019	0.0003	0.3660	0.0005	0.0003
Y_2	330	0.4215	0.4111	0.0001	0.0089	0.4065	0.0002	0.0089
Y_1	100	0.4969	0.4859	0.0001	0.0288	0.5153	0.0003	0.0288
Total	31930	2.2895	2.4762	0.0094	0.0652	2.3179	0.0017	0.0652
Average (x_{avg})	4561.43	0.3271	0.3537	0.0013	0.0093	0.3311	0.0002	0.0093
Std Dev	5855.52	0.1042	0.0799			0.1054		
Average Error			0.0267			0.0041		
Relative Error			0.0815			0.0124		
Root Mean Square Error				0.0367			0.0154	
Coefficient of Variation				0.1127			0.0473	
Coefficient of Efficiency (R^2)				0.8557			0.9746	

Table 5.19: Sensitivity Analysis for Soil Depth 30 to 60 cm (Comparing Three Methods) (Pune)

	Ψ=Y	**θ=X**	**yfit$_1$**	**yfit$_2$**	**yfit$_3$**	**(yfit$_1$-Y)^2**	**(yfit$_2$-Y)^2**	**(yfit$_3$-Y)^2**	**(y$_{avg}$-Y)^2**
Y_7	15000	0.2143	9461.447	11899.76	9461.447	30675573	9611474	30675573	1.09E+08
Y_6	10000	0.2221	8263.793	9674.298	8263.793	3014416	106082.1	3014416	29578055
Y_5	5000	0.2467	5392.65	5265.194	5392.65	154173.8	70327.59	154173.8	192344.5
Y_4	1000	0.3169	1595.141	1234.771	1595.141	354192.3	55117.42	354192.3	12683777
Y_3	500	0.3452	976.2023	752.3951	976.2023	226768.6	63703.29	226768.6	16495206
Y_2	330	0.424	248.731	228.7212	248.731	6604.65	10257.4	6604.65	17904991
Y_1	100	0.4925	75.777	96.0803	75.777	586.7537	15.36405	586.7537	19904349
Total	31930	2.2617	26013.74	29151.22	26013.74	34432315	9916977	34432315	2.06E+08
Average (y$_{avg}$)	4561.429	0.3231	3716.249	4164.46	3716.249	4918902	1416711	4918902	29388927
Std Dev	5855.517	0.105893	3953.51	4893.394	3953.51				
Average Error			-845.18	-396.968	-845.18				
Relative Error			-0.1852	-0.0870	-0.1852				
Root Mean Square Error						2217.86	1190.257	2217.86	
Coefficient of Variation						0.4862	0.2609	0.4862	
Coefficient of Efficiency (R^2)						0.8326	0.9518	0.8326	

Table 5.20: Sensitivity Analysis for Selected m, n and α values for Soil Depth 30 to 60 cm (Pune)

	Ψ=Y	θ=X	x_1(θ generated) (by VG Model)	$(x_1-X)^2$	$(x_{avg}-X)^2$	x_2 (θ generated) (by Proposed Model)	$(x_2-X)^2$	$(x_{avg}-X)^2$
Y_7	15000	0.2143	0.2634	0.0024	0.0118	0.2273	0.0002	0.0118
Y_6	10000	0.2221	0.2714	0.0024	0.0102	0.2319	0.0001	0.0102
Y_5	5000	0.2467	0.2880	0.0017	0.0058	0.2437	0.0000	0.0058
Y_4	1000	0.3169	0.3471	0.0009	0.0000	0.3091	0.0001	0.0000
Y_3	500	0.3452	0.3838	0.0015	0.0005	0.3656	0.0004	0.0005
Y_2	330	0.4240	0.4089	0.0002	0.0102	0.4077	0.0003	0.0102
Y_1	100	0.4925	0.4837	0.0001	0.0287	0.5139	0.0005	0.0287
Total	31930	2.2617	2.4462	0.0093	0.0673	2.2991	0.0015	0.0673
Average (x_{avg})	4561.429	0.3231	0.3495	0.0013	0.0096	0.3284	0.0002	0.0096
Std Dev	5855.517	0.1059	0.0816			0.1074		
Average Error			0.0264			0.0053		
Relative Error			0.0816			0.0166		
Root Mean Square Error				0.0364			0.0145	
Coefficient of Variation				0.1118			0.0447	
Coefficient of Efficiency (R^2)				0.8624			0.9781	

Table 5.21: Sensitivity Analysis for Soil Depth 60 to 90 cm (Comparing Three Methods) (Pune)

	Ψ=Y	**θ=X**	**yfit$_1$**	**yfit$_2$**	**yfit$_3$**	**(yfit$_1$-Y)^2**	**(yfit$_2$-Y)^2**	**(yfit$_3$-Y)^2**	**(y$_{avg}$-Y)^2**
Y$_7$	15000	0.1973	11778.09	15364.87	11778.09	10380719	133130.7	10380719	1.09E+08
Y$_6$	10000	0.2159	8394.552	9182.725	8394.552	2577465	667939.1	2577465	29578055
Y$_5$	5000	0.2391	5502.326	5125.006	5502.326	252330.9	15626.4	252330.9	192344.5
Y$_4$	1000	0.3187	1291.573	992.1842	1291.573	85014.52	61.08673	85014.52	12683777
Y$_3$	500	0.3476	763.1246	604.2178	763.1246	69234.56	10861.35	69234.56	16495206
Y$_2$	330	0.3966	312.7043	284.41	312.7043	299.1412	2078.448	299.1412	17904991
Y$_1$	100	0.4759	73.8038	100.3737	73.8038	686.2409	0.139652	686.2409	19904349
Total	31930	2.1911	28116.17	31653.79	28116.17	13365749	829697.2	13365749	2.06E+08
Average (y$_{avg}$)	4561.429	0.3130	4016.596	4521.97	4016.596	1909393	118528.2	1909393	29388927
Std Dev	5855.517	0.1025	4634.83	5844.804	4634.83				
Average Error			-544.833	-39.459	-544.833				
Relative Error			-0.1194	-0.0087	-0.1194				
Root Mean Square Error						1381.808	344.2792	1381.808	
Coefficient of Variation						0.3029	0.0755	0.3029	
Coefficient of Efficiency (R^2)						0.9350	0.9960	0.9350	

Table 5.22: Sensitivity Analysis for Selected m, n and α values for Soil Depth 60 to 90 cm (Pune)

	Ψ=Y	**θ=X**	**x_1(θ generated) (by VG Model)**	**$(x_1\text{-}X)^2$**	**$(x_{avg}\text{-}X)^2$**	**x_2 (θ generated) (by Proposed Model)**	**$(x_2\text{-}X)^2$**	**$(x_{avg}\text{-}X)^2$**
Y_7	15000	0.1973	0.25367	0.00318	0.01339	0.21332	0.00026	0.01339
Y_6	10000	0.2159	0.26187	0.00211	0.00943	0.21846	0.00001	0.00943
Y_5	5000	0.2391	0.27872	0.00157	0.00546	0.23134	0.00006	0.00546
Y_4	1000	0.3187	0.33616	0.00030	0.00003	0.29830	0.00042	0.00003
Y_3	500	0.3476	0.37083	0.00054	0.00120	0.35345	0.00003	0.00120
Y_2	330	0.3966	0.39455	0.00000	0.00699	0.39424	0.00001	0.00699
Y_1	100	0.4759	0.46776	0.00007	0.02654	0.50556	0.00088	0.02654
Total	31930	2.1911	2.3635	0.0078	0.0630	2.2147	0.0017	0.0630
Average (x_{avg})	4561.429	0.3130	0.3376	0.0011	0.0090	0.3164	0.0002	0.0090
Std Dev	5855.517	0.1025	0.0791			0.1088		
Average Error			0.0246			0.0034		
Relative Error			0.0787			0.0108		
Root Mean Square Error				0.0333			0.0154	
Coefficient of Variation				0.1025			0.0473	
Coefficient of Efficiency (R^2)				0.8766			0.9737	

Table 5.23: Sensitivity Analysis for Soil Depth 90 to 120 cm (Comparing Three Methods) (Pune)

	Ψ=Y	**θ=X**	**yfit$_1$**	**yfit$_2$**	**yfit$_3$**	**(yfit$_1$-Y)^2**	**(yfit$_2$-Y)^2**	**(yfit$_3$-Y)^2**	**(y$_{avg}$-Y)^2**
Y_7	15000	0.1921	6654.915	9194.356	6654.915	69640442	33705502	69640442	1.09E+08
Y_6	10000	0.2044	5199.11	6245.518	5199.11	23048542	14096134	23048542	29578055
Y_5	5000	0.2236	3536.482	3569.507	3536.482	2141886	2046309	2141886	192344.5
Y_4	1000	0.2465	2333.38	1944.229	2333.38	1777901	891567.5	1777901	12683777
Y_3	500	0.257	1809.001	1499.207	1809.001	1713484	998414.6	1713484	16495206
Y_2	330	0.3231	480.0377	360.1275	480.0377	22511.31	907.6663	22511.31	17904991
Y_1	100	0.4337	52.1466	57.5151	52.1466	2289.948	1804.967	2289.948	19904349
Total	31930	1.8804	20065.07	22870.46	20065.07	98347057	51740640	98347057	2.06E+08
Average (y$_{avg}$)	4561.429	0.268629	2866.439	3267.209	2866.439	14049580	7391520	14049580	29388927
Std Dev	5855.517	0.084508	2424.196	3359.617	2424.196				
Average Error			-1694.99	-1294.22	-1694.99				
Relative Error			-0.3716	-0.2837	-0.3716				
Root Mean Square Error						3748.277	2718.735	3748.277	
Coefficient of Variation						0.8217	0.5960	0.8217	
Coefficient of Efficiency (R^2)						0.5219	0.7485	0.5219	

Table 5.24: Sensitivity Analysis for Selected m, n and α values for Soil Depth 90 to 120 cm (Pune)

	$\Psi=Y$	$\theta=X$	x_1	(x_1-X)^2	$(x_{avg}-X)$^2	x_2	(x_2-X)^2	$(x_{avg}-X)$^2
Y_7	0.19210	0.24036	0.00233	0.00585	0.20468	0.00016	0.00585	0.19210
Y_6	0.20440	0.24661	0.00178	0.00412	0.20812	0.00001	0.00412	0.20440
Y_5	0.22360	0.25924	0.00127	0.00203	0.21633	0.00005	0.00203	0.22360
Y_4	0.24650	0.30086	0.00296	0.00049	0.25523	0.00008	0.00049	0.24650
Y_3	0.25700	0.32577	0.00473	0.00013	0.28687	0.00089	0.00013	0.25700
Y_2	0.32310	0.34316	0.00040	0.00297	0.31229	0.00012	0.00297	0.32310
Y_1	0.43370	0.40369	0.00090	0.02726	0.41258	0.00045	0.02726	0.43370
Total	31930	1.8804	2.1197	0.0144	0.0429	1.8961	0.0018	0.0429
Average (x_{avg})	4561.428571	0.2686	0.3028	0.0021	0.0061	0.2709	0.0003	0.0061
Std Dev	5855.517138	0.0845	0.0596			0.0748		
Average Error			0.0342			0.0022		
Relative Error			0.1273			0.0083		
Root Mean Square Error				0.0453			0.0158	
Coefficient of Variation				0.1393			0.0487	
Coefficient of Efficiency (R^2)				0.6647			0.9590	

5.3.3 SMCC Analysis for Kolhapur Research Station

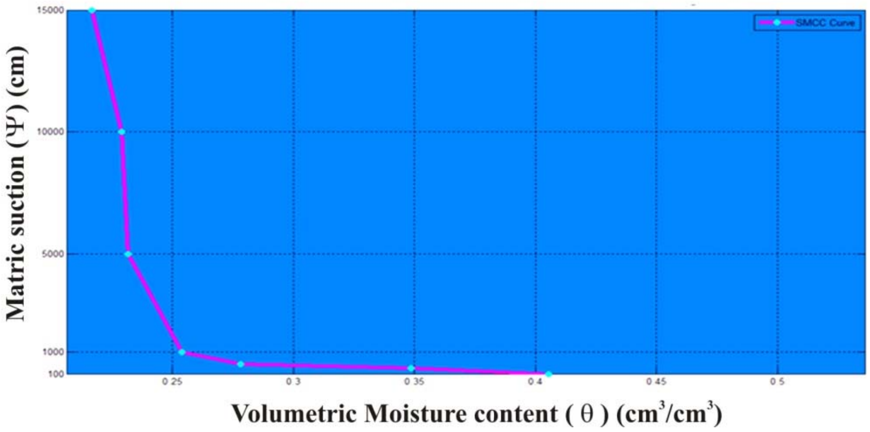


Figure 5.47: SMCC at a Soil Depth of0 to 15 cm for Kolhapur

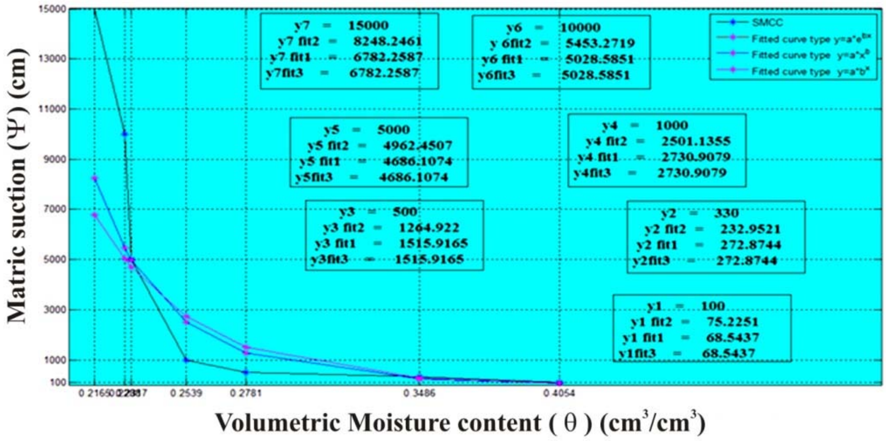


Figure 5.48: Curve Fitting for SMCC at a Soil Depth of 0 to 15 cm Kolhapur

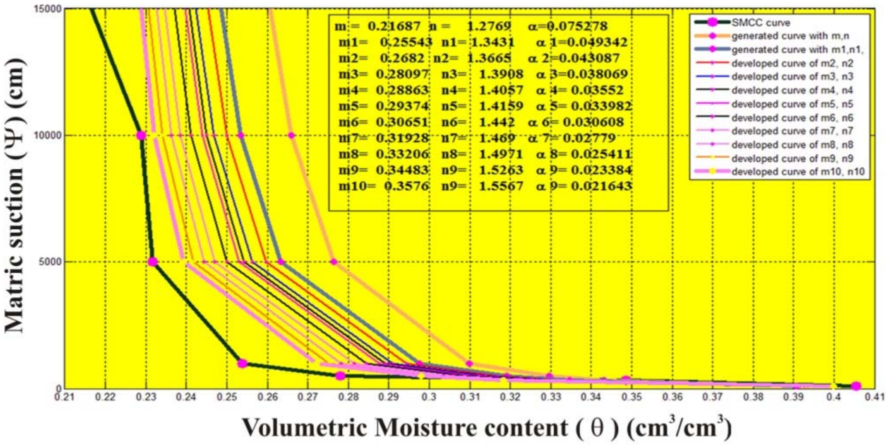


Figure 5.49: SMCC and Generated Curves at a Soil Depth of 0 to 15 cm for Kolhapur

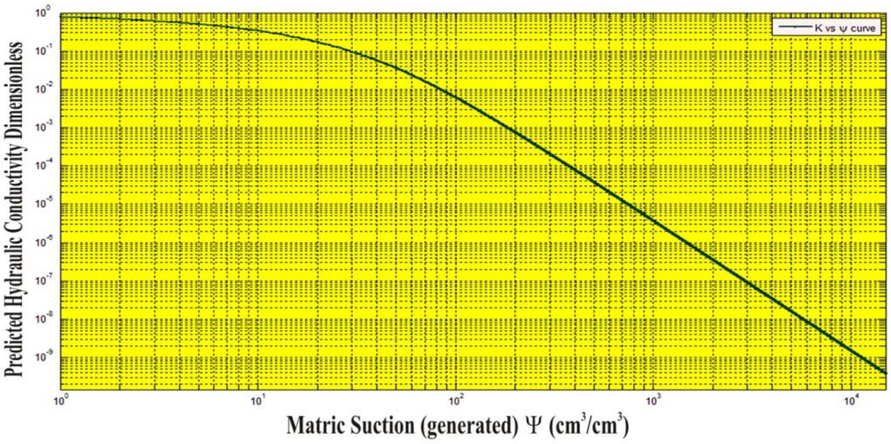


Figure 5.50: Hydraulic Conductivity vs Matrix Suction at a Soil Depth of 0 to 15 cm for Kolhapur

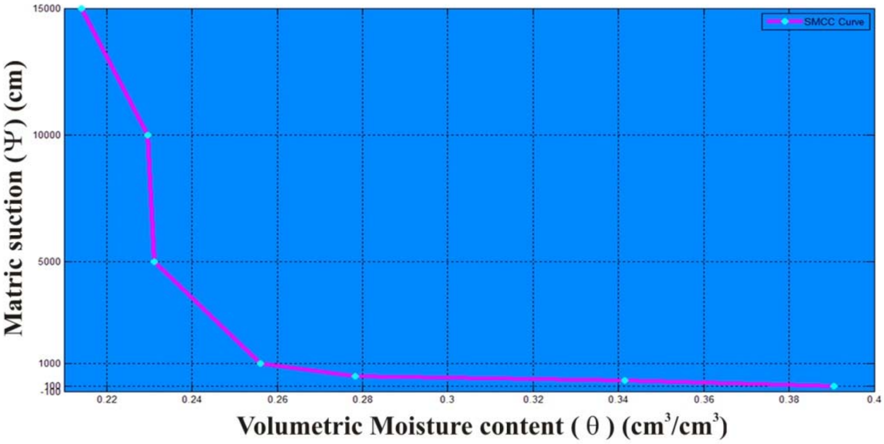


Figure 5.51: SMCC at a Soil Depth of 15 to 30 cm for Kolhapur

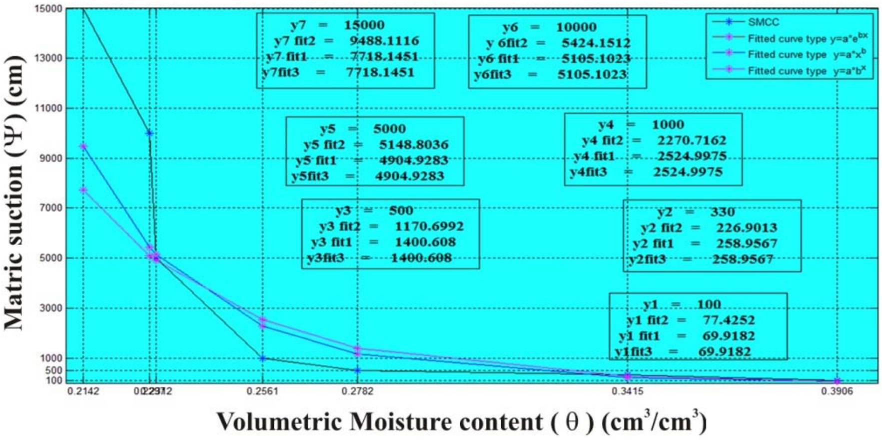


Figure 5.52: Curve Fitting for SMCC at a Soil Depth of 15 to 30 cm for Kolhapur

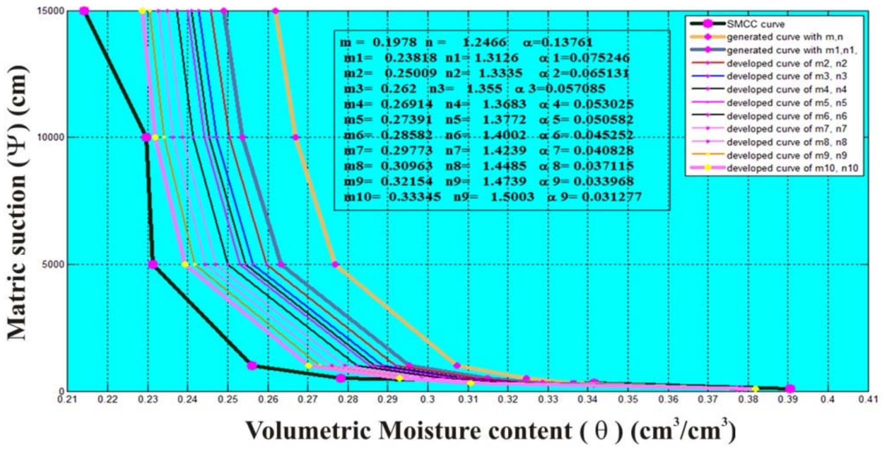


Figure 5.53: SMCC and Generated Curves at a Soil Depth of 15 to 30 cm for Kolhapur

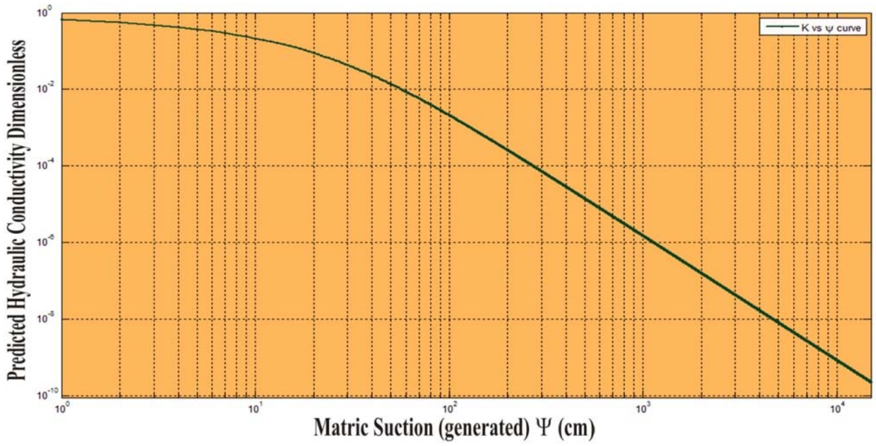


Figure 5.54: Hydraulic Conductivity vs Matrix Suction at a Soil Depth of 15 to 30 cm for Kolhapur

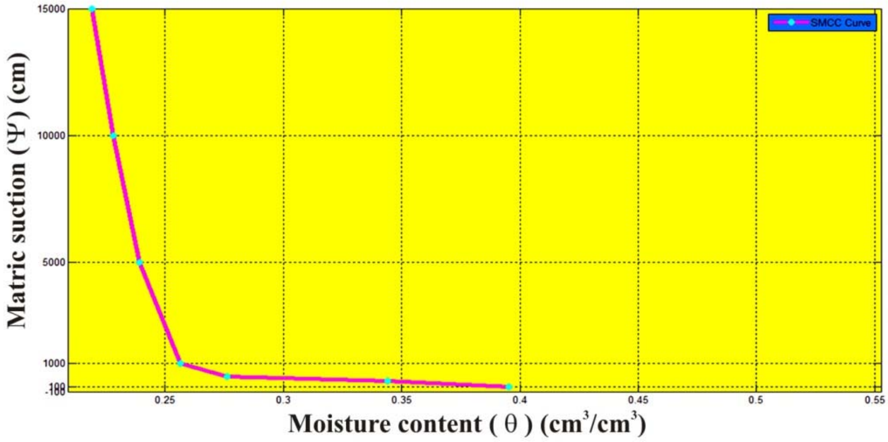


Figure 5.55: SMCC at a Soil Depth of30 to 60 cm for Kolhapur

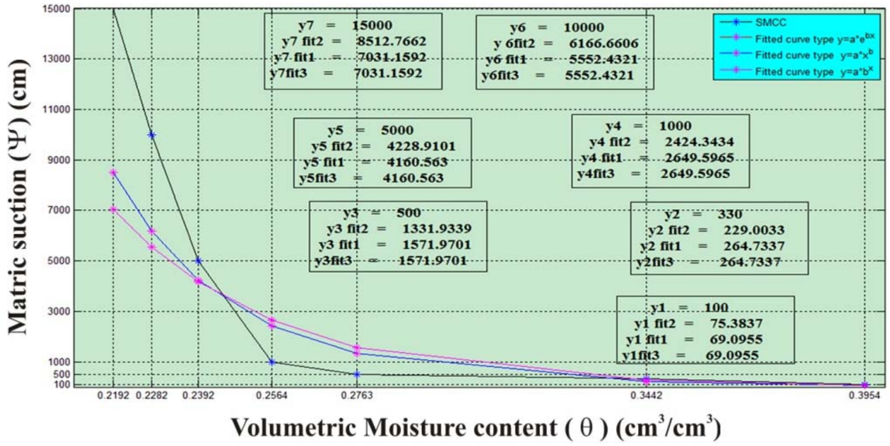


Figure 5.56: Curve Fitting of SMCC at a Soil Depth of 30 to 60 cm for Kolhapur

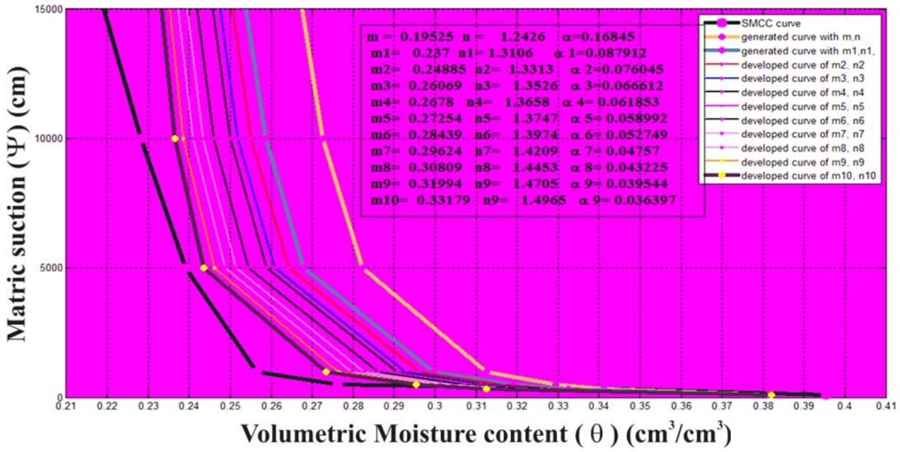


Figure 5.57: SMCC and Generated Curves at a Soil Depth of 30 to 60 cm for Kolhapur

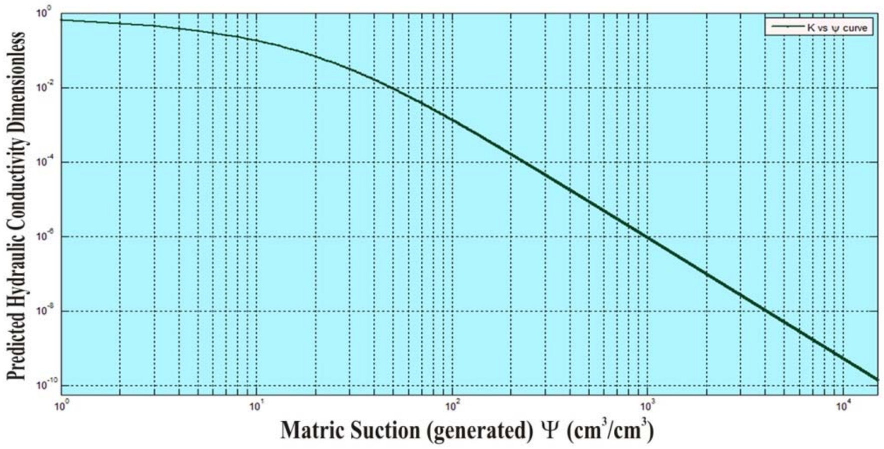


Figure 5.58: Hydraulic Conductivity vs Matrix Suction at a Soil Depth of 30 to 60 cm for Kolhapur

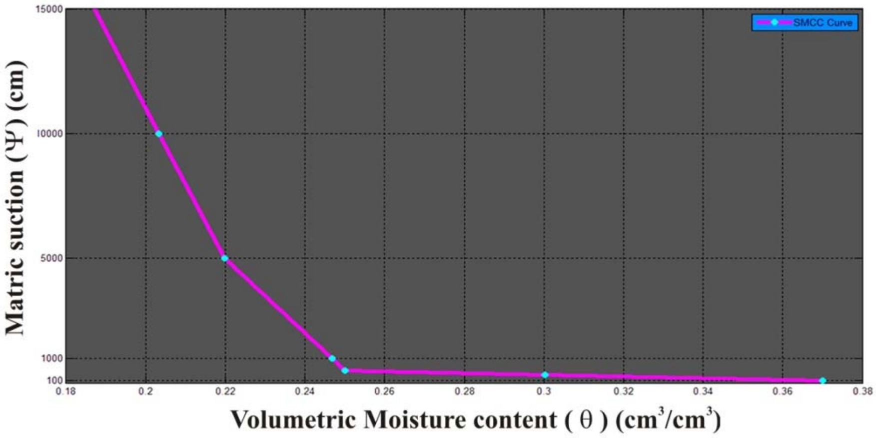


Figure 5.59: SMCC at a Soil Depth 60 to 90 cm for Kolhapur

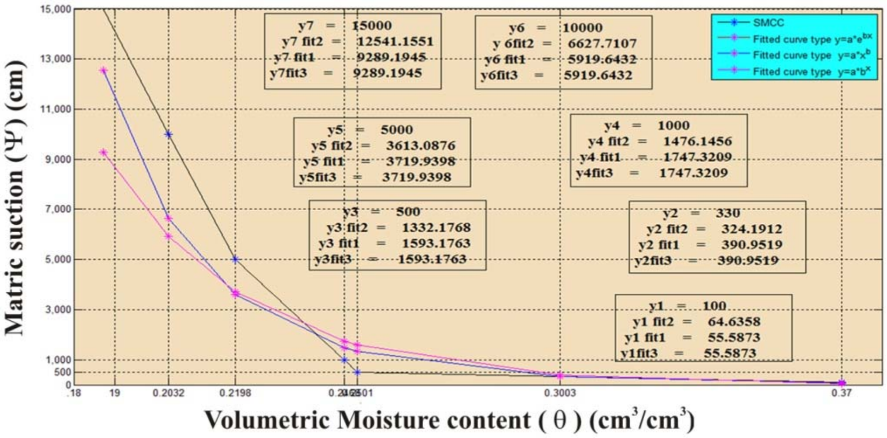


Figure 5.60: Curve Fitting for SMCC at a Soil Depth of 60 to 90 cm Kolhapur

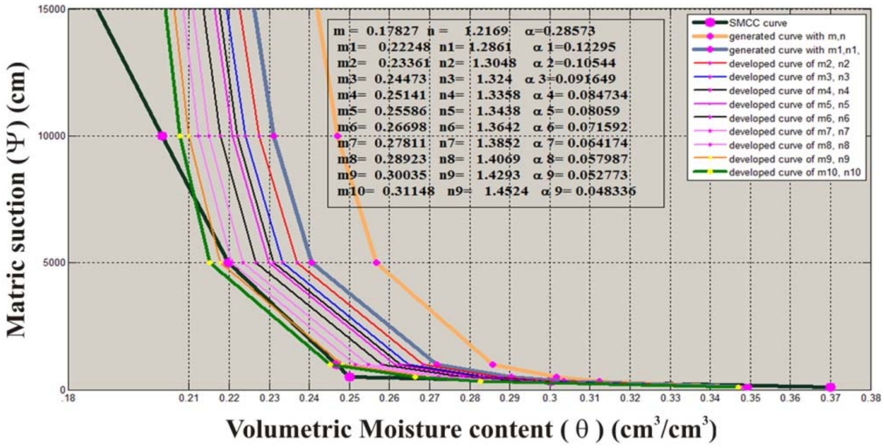


Figure 5.61: SMCC and Generated Curves at a Soil Depth of 60 to 90 cm for Kolhapur

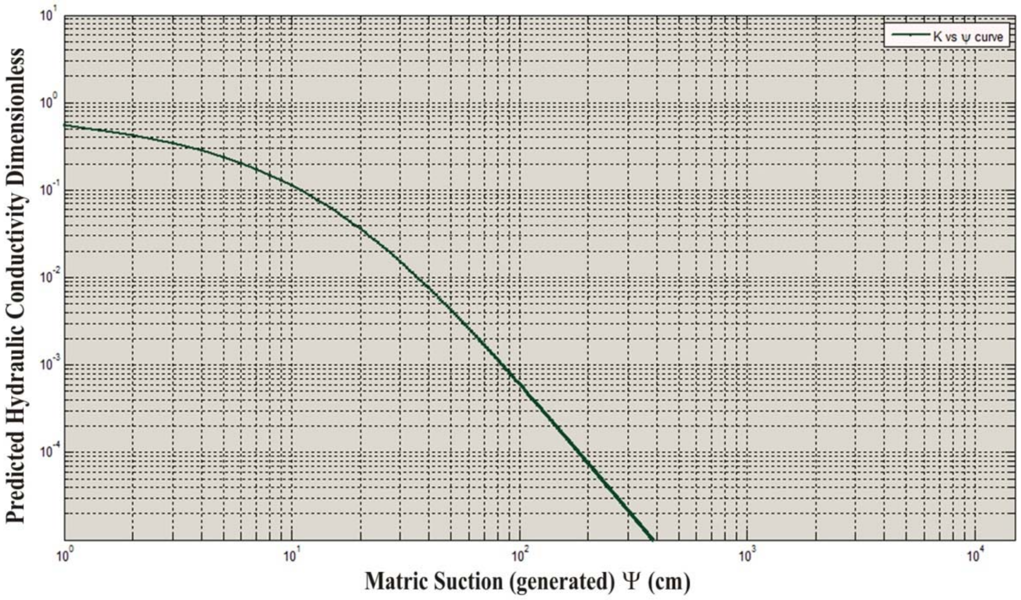


Figure 5.62: Hydraulic Conductivity vs Matrix Suction at a Soil Depth of 60 to 90 cm for Kolhapur

Table 5.25: Sensitivity Analysis for Soil Depth 0 to 15 cm (Comparing Three Methods) (Kolhapur)

	Ψ=Y	**θ=X**	**yfit$_1$**	**yfit$_2$**	**yfit$_3$**	**(yfit$_1$-Y)^2**	**(yfit$_2$-Y)^2**	**(yfit$_3$-Y)^2**	**(y$_{avg}$-Y)^2**
Y$_7$	15000	0.2165	6782.3	8248.2	6782.3	67531272	45586181	67531272	108963764.5
Y$_6$	10000	0.2288	5028.6	5453.3	5028.6	24714966	20672736	24714966	29578054.52
Y$_5$	5000	0.2317	4686.1	4962.5	4686.1	98528.564	1409.95	98528.564	192344.522
Y$_4$	1000	0.2539	2730.9	2501.1	2730.9	2996042.2	2253408	2996042.2	12683776.52
Y$_3$	500	0.2781	1515.9	1264.9	1515.9	1032086.3	585105.7	1032086.3	16495205.52
Y$_2$	330	0.3486	272.87	232.95	272.87	3263.3342	9418.295	3263.3342	17904991.38
Y$_1$	100	0.4054	68.544	75.525	68.544	989.49881	599.0207	989.49881	19904348.72
Total	31930	1.963	21085	22739	21085	96377148	69108858	96377148	205722485.7
Average (y$_{avg}$)	4561.43	0.2804	3012.2	3248.4	3012.2	13768164	9872694	13768164	29388926.53
Std Dev	5855.52	0.0708	2568	3067.3	2568				
Average Error			-1549	-1313	-1549				
Relative Error			-0.34	-0.288	-0.34				
Root Mean Square Error						3710.5477	3142.084	3710.5477	
Coefficient of Variation						0.8135	0.6888	0.8135	
Coefficient of Efficiency (R^2)						0.5315	0.6641	0.5315	

Table 5.26: Sensitivity Analysis for Selected m, n and α values for Soil Depth 0 to 15 cm (Kolhapur)

	Ψ=Y	**θ=X**	**x_1(θ generated) (by VG Model)**	**(x_1-X)^2**	**(x_{avg}-X)^2**	**x_2(θ generated) (by Proposed Model)**	**(x_2-X)^2**	**(x_{avg}-X)^2**
Y_7	15000	0.2165	0.3740	0.0248	0.0041	0.2289	0.0002	0.0041
Y_6	10000	0.2288	0.3803	0.0229	0.0027	0.2320	0.0000	0.0027
Y_5	5000	0.2317	0.3916	0.0256	0.0024	0.2393	0.0001	0.0024
Y_4	1000	0.2539	0.4208	0.0279	0.0007	0.2723	0.0003	0.0007
Y_3	500	0.2781	0.4348	0.0246	0.0000	0.2981	0.0004	0.0000
Y_2	330	0.3486	0.4436	0.0090	0.0047	0.3186	0.0009	0.0047
Y_1	100	0.4054	0.4701	0.0042	0.0156	0.4000	0.0000	0.0156
Total	31930	1.9630	2.9151	0.1389	0.0301	1.9893	0.0019	0.0301
Average (x_{avg})	4561.4	0.2804	0.4164	0.0198	0.0043	0.2842	0.0003	0.0043
Std Dev	5855.5	0.0708	0.0358			0.0615		
Average Error			0.1360			0.0038		
Relative Error			0.4850			0.0134		
Root Mean Square Error				0.1409			0.0164	
Coefficient of Variation				0.4333			0.0506	
Coefficient of Efficiency (R^2)				-3.6154			0.9371	

Table 5.27: Sensitivity Analysis for Soil Depth 15 to 30 cm (Comparing Three Methods) (Kolhapur)

	Ψ=Y	**θ=X**	**$yfit_1$**	**$yfit_2$**	**$yfit_3$**	**$(yfit_1-Y)^2$**	**$(yfit_2-Y)^2$**	**$(yfit_3-Y)^2$**	**$(y_{avg}-Y)^2$**
Y_7	15000	0.2142	7718.145	9488.112	7718.145	53025411	30380914	53025411	108963765
Y_6	10000	0.2297	5105.102	5424.151	5105.102	23960023	20938392	23960023	29578054.5
Y_5	5000	0.2312	4904.928	5148.804	4904.928	9038.628	22142.51	9038.628	192344.522
Y_4	1000	0.2561	2524.998	2270.716	2524.998	2325617	1614720	2325617	12683776.5
Y_3	500	0.2782	1400.608	1170.669	1400.608	811094.8	449797.2	811094.8	16495205.5
Y_2	330	0.3415	258.9567	226.9013	258.9567	5047.15	10629.34	5047.15	17904991.4
Y_1	100	0.3906	69.9182	77.4252	69.9182	904.9147	509.6216	904.9147	19904348.7
Total	31930	1.9415	21982.66	23806.78	21982.66	80137137	53417104	80137137	205722486
Average (y_{avg})	4561.429	0.2774	3140.379	3400.968	3140.379	11448162	7631015	11448162	29388926.5
Std Dev	5855.517	0.0656	2859.648	3453.835	2859.648				
Average Error			-1421.05	-1160.46	-1421.05				
Relative Error			-0.3115	-0.2544	-0.3115				
Root Mean Square Error						3383.5130	2762.4290	3383.5130	
Coefficient of Variation						0.7418	0.6057	0.7418	
Coefficient of Efficiency (R^2)						0.6104	0.7403	0.6104	

Table 5.28: Sensitivity Analysis for Selected m, n and α values for Soil Depth 15 to 30 cm (Kolhapur)

	Ψ=Y	θ=X	x_1(θ generated) (by VG Model)	(x_1-X)^2	$(x_{avg}-X)$^2	x_2(θ generated) (by Proposed Model)	(x_2-X)^2	$(x_{avg}-X)$^2
Y_7	15000	0.2142	0.2620	0.0023	0.0040	0.2285	0.0002	0.0040
Y_6	10000	0.2297	0.2670	0.0014	0.0023	0.2317	0.0000	0.0023
Y_5	5000	0.2312	0.2768	0.0021	0.0021	0.2390	0.0001	0.0021
Y_4	1000	0.2561	0.3073	0.0026	0.0005	0.2698	0.0002	0.0005
Y_3	500	0.2782	0.3246	0.0021	0.0000	0.2926	0.0002	0.0000
Y_2	330	0.3415	0.3364	0.0000	0.0041	0.3104	0.0010	0.0041
Y_1	100	0.3906	0.3773	0.0002	0.0128	0.3815	0.0001	0.0128
Total	31930	1.9415	2.1513	0.0107	0.0258	1.9536	0.0017	0.0258
Average (x_{avg})	4561.429	0.2774	0.3073	0.0015	0.0037	0.2791	0.0002	0.0037
Std Dev	5855.517	0.0656	0.0421			0.0550		
Average Error			0.0300			0.0017		
Relative Error			0.1080			0.0063		
Root Mean Square Error				0.0391			0.0157	
Coefficient of Variation				0.1204			0.0482	
Coefficient of Efficiency (R^2)				0.5841			0.9334	

Table 5.29: Sensitivity Analysis for Soil Depth 30 to 60 cm (Comparing Three Methods) (Kolhapur)

	Ψ=Y	**θ=X**	**yfit$_1$**	**yfit$_2$**	**yfit$_3$**	**(yfit$_1$-Y)^2**	**(yfit$_2$-Y)^2**	**(yfit$_3$-Y)^2**	**(y$_{avg}$-Y)^2**
Y_7	15000	0.2192	7031.195	8512.761	7031.195	63501850	42084267	63501850	108963765
Y_6	10000	0.2282	5552.432	6166.661	5552.432	19780860	14694491	19780860	29578055
Y_5	5000	0.2392	4160.563	4228.91	4160.563	704654.5	594579.6	704654.5	192344.52
Y_4	1000	0.2564	2649.597	2424.343	2649.597	2721169	2028754	2721169	12683777
Y_3	500	0.2763	1571.97	1331.934	1571.97	1149120	692114	1149120	16495206
Y_2	330	0.3942	264.7731	229.0033	264.7731	4254.548	10200.33	4254.548	17904991
Y_1	100	0.3954	69.0955	75.2837	69.0955	955.0881	610.8955	955.0881	19904349
Total	31930	2.0089	21299.63	22968.9	21299.63	87862863	60105017	87862863	205722486
Average (y$_{avg}$)	4561.429	0.2870	3042.804	3281.271	3042.804	12551838	8586431	12551838	29388927
Std Dev	5855.517	0.0760	2656.227	3181.219	2656.227				
Average Error			-1518.62	-1280.16	-1518.62				
Relative Error			-0.3329	-0.2806	-0.3329				
Root Mean Square Error						3542.857	2930.261	3542.857	
Coefficient of Variation						0.7767	0.6424	0.7767	
Coefficient of Efficiency (R^2)						0.5729	0.7078	0.5729	

Table 5.30: Sensitivity Analysis for Selected m, n and α values for Soil Depth 30 to 60 cm (Kolhapur)

	Ψ=Y	θ=X	x_1(θ generated) (by VG Model)	$(x_1\text{-}X)^2$	$(x_{avg}\text{-}X)^2$	x_2(θ generated) (by Proposed Model)	$(x_2\text{-}X)^2$	$(x_{avg}\text{-}X)^2$
Y_7	15000	0.2192	0.2192	0.0000	0.0046	0.2330	0.0002	0.0046
Y_6	10000	0.2282	0.2192	0.0001	0.0035	0.2362	0.0001	0.0035
Y_5	5000	0.2392	0.2193	0.0004	0.0023	0.2433	0.0000	0.0023
Y_4	1000	0.2564	0.2199	0.0013	0.0009	0.2735	0.0003	0.0009
Y_3	500	0.2763	0.2209	0.0031	0.0001	0.2960	0.0004	0.0001
Y_2	330	0.3942	0.2220	0.0297	0.0115	0.3136	0.0065	0.0115
Y_1	100	0.3954	0.2303	0.0273	0.0118	0.3849	0.0001	0.0118
Total	31930	2.0089	1.5509	0.0618	0.0346	1.9805	0.0076	0.0346
Average (x_{avg})	4561.429	0.2870	0.2216	0.0088	0.0049	0.2829	0.0011	0.0049
Std Dev	5855.517	0.0760	0.0040			0.0545		
Average Error			-0.0654			-0.0041		
Relative Error			-0.2280			-0.0141		
Root Mean Square Error				0.0940			0.0329	
Coefficient of Variation				0.2890			0.1011	
Coefficient of Efficiency (R^2)				-0.7845			0.7818	

Table 5.31: Sensitivity Analysis for Soil Depth 60 to 90 cm (Comparing Three Methods) (Kolhapur)

	Ψ=Y	**θ=X**	**$yfit_1$**	**$yfit_2$**	**$yfit_3$**	**$(yfit_1-Y)^2$**	**$(yfit_2-Y)^2$**	**$(yfit_3-Y)^2$**	**$(y_{avg}-Y)^2$**
Y_7	15000	0.1871	9289.155	12541.49	9289.155	32613749	6044249	32613749	108963765
Y_6	10000	0.2032	5919.643	6627.711	5919.643	16649312	11372335	16649312	29578054.5
Y_5	5000	0.2198	3719.94	3613.088	3719.94	1638554	1923526	1638554	192344.522
Y_4	1000	0.2468	1747.321	1476.146	1747.321	558488.5	226714.6	558488.5	12683776.5
Y_3	500	0.2501	1593.176	1332.177	1593.176	1195034	692518.2	1195034	16495205.5
Y_2	330	0.3103	390.9519	324.1912	390.9519	3715.134	33.74216	3715.134	17904991.4
Y_1	100	0.3700	55.5873	64.6358	55.5873	1972.488	1250.627	1972.488	19904348.7
Total	31930	1.7873	22715.77	25979.44	22715.77	52660826	20260628	52660826	205722486
Average (y_{avg})	4561.429	0.2553	3245.111	3711.349	3245.111	7522975	2894375	7522975	29388926.5
Std Dev	5855.517	0.0644	3346.655	4507.665	3346.655				
Average Error			-1316.32	-850.08	-1316.32				
Relative Error			-0.2886	-0.1864	-0.2886				
Root Mean Square Error						2742.8042	1701.2864	2742.8042	
Coefficient of Variation						0.6013	0.3730	0.6013	
Coefficient of Efficiency (R^2)						0.7440	0.9015	0.7440	

Table 5.32: Sensitivity Analysis for Selected m, n and α values for Soil Depth 60 to 90 cm (Kolhapur)

	$\Psi=Y$	$\theta=X$	x_1(θ generated) (by VG Model)	$(x_1-X)^2$	$(x_{avg}-X)^2$	x_2(θ generated) (by Proposed Model)	$(x_2-X)^2$	$(x_{avg}-X)^2$
Y_7	15000	0.1871	0.2419	0.0030	0.0047	0.2042	0.0003	0.0047
Y_6	10000	0.2032	0.2469	0.0019	0.0027	0.2076	0.0000	0.0027
Y_5	5000	0.2198	0.2566	0.0014	0.0013	0.2152	0.0000	0.0013
Y_4	1000	0.2468	0.2857	0.0015	0.0001	0.2452	0.0000	0.0001
Y_3	500	0.2501	0.3016	0.0027	0.0000	0.2664	0.0003	0.0000
Y_2	330	0.3103	0.3124	0.0000	0.0030	0.2826	0.0008	0.0030
Y_1	100	0.3700	0.3491	0.0004	0.0132	0.3470	0.0005	0.0132
Total	31930	1.7873	1.9943	0.0109	0.0249	1.7681	0.0019	0.0249
Average (x_{avg})	4561.429	0.2553	0.2849	0.0016	0.0036	0.2526	0.0003	0.0036
Std Dev	5855.517	0.0644	0.0393			0.0514		
Average Error			0.0296			-0.0027		
Relative Error			0.1158			-0.0107		
Root Mean Square Error				0.0394			0.0165	
Coefficient of Variation				0.1212			0.0507	
Coefficient of Efficiency (R^2)				0.5632			0.9238	

The soil moisture analysis for Kolhapur research station is performed by VG model and proposed model. The results were presented in above graph figures. The model performance in terms of visual inspection of the SMCC simulated and SMCC observed shows most of moisture i.e. nearly up to 50 % was released rapidly when suction increases from o to 1000 cm. The soil depths considered for study were 0 to 15 cm, 15 to 30 cm, 30 to 60 cm and 60 to 90 for Kolhapur research station. The physical parameters were estimated by VG model and proposed model. In order to evaluate the quality of the fitting of Van Genuchten model and proposed model, the significant tests were carried out. The curve fitting method one and third are not found suitable as their R^2 (coefficient of efficiency) values are not satisfactory. The second curve fitting method is found suitable as their R^2 values are satisfactory. For soil depth 0 to 15 cm $R_1^2 = 0.53$, $R_2^2 = 0.66$ and $R_3^2 = 0.53$. For soil depth 15 to 30 cm $R_1^2 = 0.61$, $R_2^2 = 0.74$ and $R_3^2 = 0.61$. For soil depth 30 to 60 cm $R_1^2 = 0.58$, $R_2^2 = 0.71$ and $R_3^2 = 0.58$. For soil depth 60 to 90 cm $R_1^2 = 0.74$, $R_2^2 = 0.90$ and $R_3^2 = 0.74$. The Coefficient of Efficiency of VG model is poor while coefficient of efficiency for proposed model is satisfactory. For soil depth 0 to 15 cm $R_1^2 = -3.61$ and $R_2^2 = 0.94$. For soil depth 15 to 30 cm$R_1^2 = 0.58$ and $R_2^2 = 0.93$. For soil depth 30 to 60 cm $R_1^2 = -0.79$ and $R_2^2 = 0.78$. For soil depth 60 to 90 cm $R_1^2 = 0.56$ and $R_2^2 = 0.92$. The sensitivity analysis is presented in detail in above Tables, 5.25 to 5.32. The proposed model found most suitable.

5.3.4 SMCC Analysis for Ahmednagar Research Station

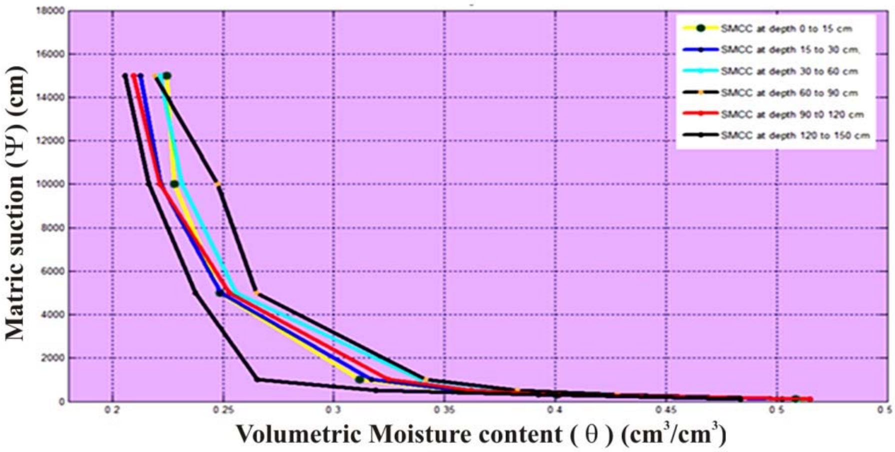


Figure 5.63: SMCC at various Soil Depth for Ahmednagar

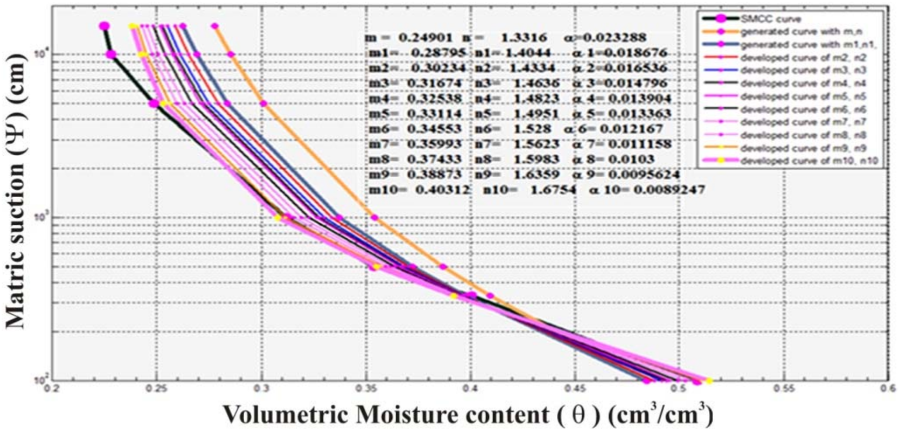


Figure 5.64: SMCC and Generated Curves at a Soil Depth of 0 to 15 cm for Ahmednagar

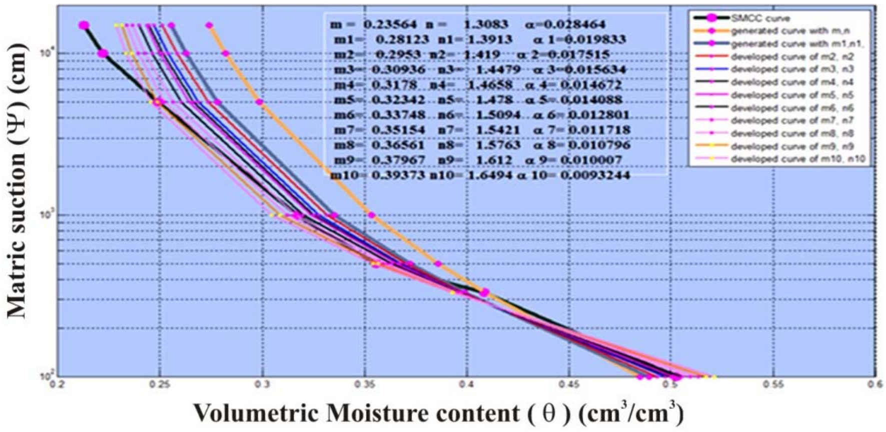


Figure 5.65: SMCC and Generated Curves at a Soil Depth of 15 to 30 cm for Ahmednagar

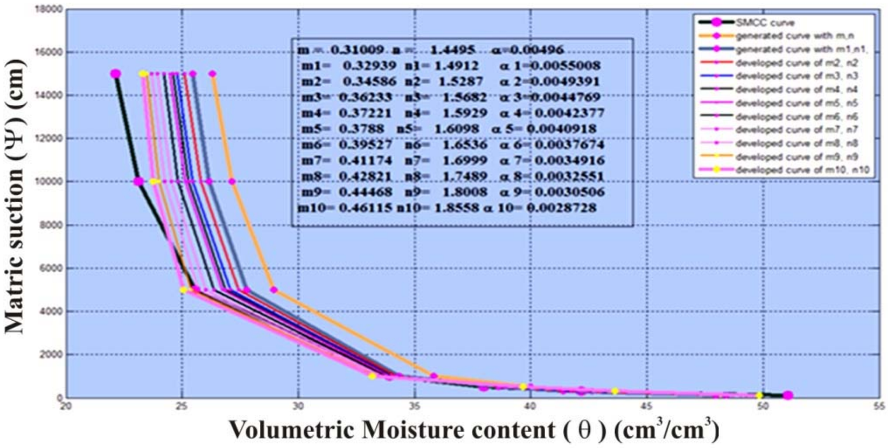


Figure 5.66: SMCC and Generated Curves at a Soil Depth of 30 to 60 cm for Ahmednagar

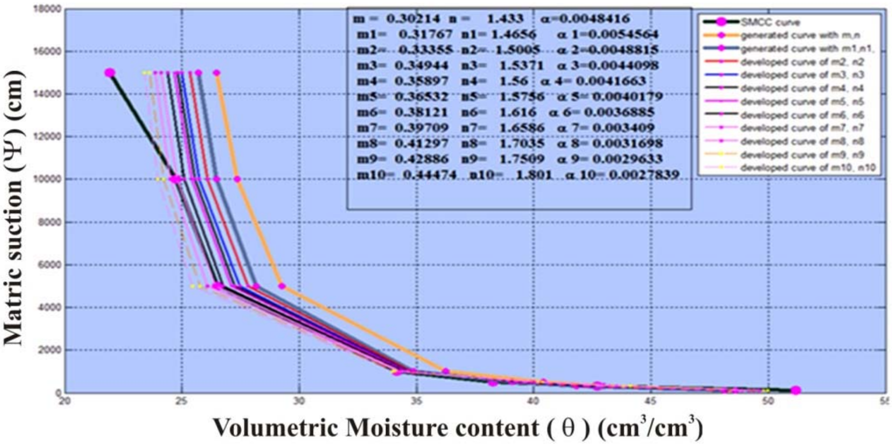


Figure 5.67: SMCC and Generated Curves at a Soil Depth of 60 to 90 cm for Ahmednagar

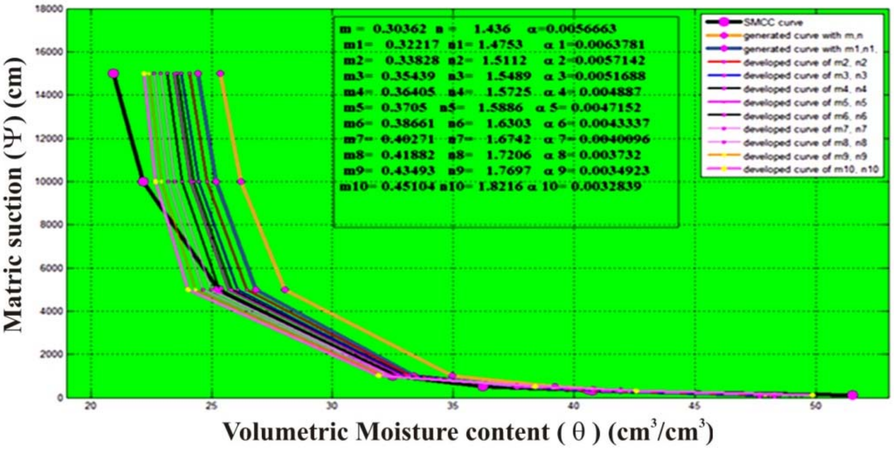


Figure 5.68: SMCC and Generated Curves at a Soil Depth of 90 to 120 cm for Ahmednagar

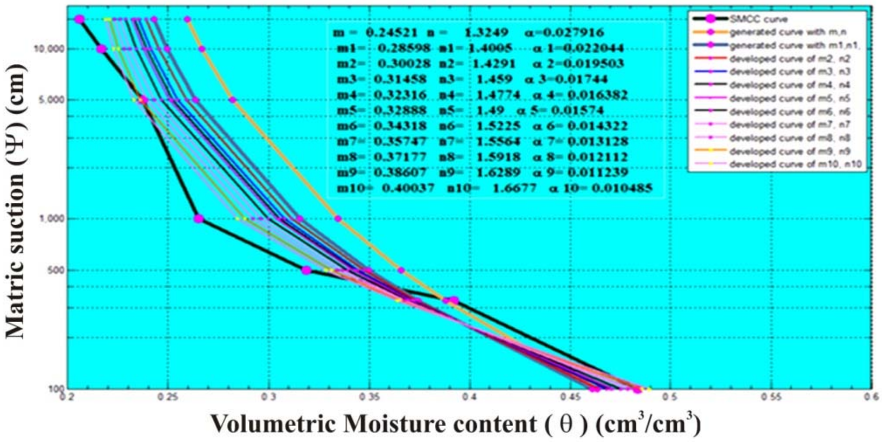


Figure 5.69: SMCC and Generated Curves at a Soil Depth of 120 to 150 cm for Ahmednagar

The soil moisture analysis for Ahmednagar research station is performed by VG model and proposed model. The results were presented in above graph figures. The model performance in terms of visual inspection of the SMCC simulated and SMCC observed shows most of moisture i.e. nearly up to 50 % was released rapidly when suction increases from o to 1000 cm. The soil depths considered for study were 0 to 15 cm, 15 to 30 cm, 30 to 60 cm and 60 to 90 cm for Ahmednagar research station. The physical parameters were estimated by VG model and proposed model. In order to evaluate the quality of the fitting of Van Genuchten model and proposed model, the significant tests were carried out. The curve fitting method one and third are not found suitable as their R^2 (coefficient of efficiency) values are not satisfactory. The second curve fitting method is found more suitable as their R^2 values are satisfactory. For soil depth 0 to 15 cm $R_1^2 = 0.53$, $R_2^2 = 0.66$ and $R_3^2 = 0.53$. For soil depth 15 to 30 cm $R_1^2 = 0.61$, $R_2^2 = 0.74$ and $R_3^2 = 0.61$. For soil depth 30 to 60 cm $R_1^2 = 0.58$, $R_2^2 = 0.71$ and $R_3^2 = 0.58$. For soil depth 60 to 90 cm $R_1^2 = 0.74$, $R_2^2 = 0.90$ and $R_3^2 = 0.74$. The coefficient of efficiency of VG model is poor while coefficient of efficiency for proposed model is satisfactory. For soil depth 0 to 15 cm $R_1^2 = - 3.61$ and $R_2^2 = 0.94$. For soil depth 15 to 30 cm$R_1^2 = 0.58$ and $R_2^2 = 0.93$. For soil depth 30 to 60 cm $R_1^2 = - 0.79$ and $R_2^2 = 0.78$. For soil depth 60 to 90 cm $R_1^2 = 0.56$ and $R_2^2 = 0.92$.The sensitivity analysis is presented in detail in below Tables, 5.33 to 5.44. The proposed model found most suitable in study area.

Table 5.33: Sensitivity Analysis for Soil Depth 0 to 15 cm (Comparing Three Methods)(Ahmednagar)

	$\Psi=Y$	$\theta=X$	yfit$_1$	yfit$_2$	yfit$_3$	(yfit$_1$-Y)^2	(yfit$_2$-Y)^2	(yfit$_3$-Y)^2	(y_{avg}-Y)^2
Y_7	15000	0.2247	8241.6	10400	8241.3	4.6E+07	2.1E+07	4.6E+07	1.09E+08
Y_6	10000	0.2279	7794.8	9550.2	7794.5	4862793	202335	4864227	29578055
Y_5	5000	0.2487	5425.7	5640.1	5425.3	181256	409698	180918	192344.5
Y_4	1000	0.3118	1807.7	1442.6	1807.4	652348	195869	651857	12683777
Y_3	500	0.3537	871.28	674.44	871.08	137849	30427.8	137699	16495206
Y_2	330	0.4008	383.58	317.36	383.46	2870.88	159.702	2858.46	17904991
Y_1	100	0.5085	58.767	75.557	58.739	1700.2	597.454	1702.45	19904349
Total	31930	2.2761	24584	28100	24582	5.2E+07	2.2E+07	5.2E+07	2.06E+08
Average (y_{avg})	4561.43	0.3252	3511.9	4014.3	3511.7	7359176	3142409	7359826	29388927
Std Dev	5855.52	0.1047	3558.2	4491.1	3558.1				
Average Error			-1049	-547.1	-1050				
Relative Error			-0.23	-0.12	-0.23				
Root Mean Square Error						2712.78	1772.68	2712.9	
Coefficient of Variation						0.5947	0.3886	0.5947	
Coefficient of Efficiency (R^2)						0.7496	0.8931	0.7496	

Table 5.34: Sensitivity Analysis for Selected m, n and α values for Soil Depth 0 to 15 cm (Ahmednagar)

	Ψ=Y	**θ=X**	**x_2(θ generated) (by Proposed Model)**	**(x_1-X)^2**	**(x_{avg}-X)^2**	**x_1(θ generated) (by VG Model)**	**(x_2-X)^2**	**(x_{avg}-X)^2**
Y_7	15000	0.2247	0.23836	0.00019	0.0101	0.277578	0.002796	0.0101
Y_6	10000	0.2279	0.24264	0.00022	0.00947	0.285205	0.003284	0.009467
Y_5	5000	0.2487	0.25327	2.1E-05	0.00585	0.300867	0.002721	0.005852
Y_4	1000	0.3118	0.30819	1.3E-05	0.00018	0.35433	0.001809	0.00018
Y_3	500	0.3537	0.35497	1.6E-06	0.00081	0.387002	0.001109	0.000812
Y_2	330	0.4008	0.39203	7.7E-05	0.00572	0.409785	8.07E-05	0.005715
Y_1	100	0.5085	0.51405	3.1E-05	0.0336	0.485245	0.000541	0.033599
Total	31930	2.2761	2.30351	0.00055	0.06573	2.500012	0.012341	0.065726
Average (x_{avg})	4561.4	0.32516	0.32907	7.8E-05	0.00939	0.357145	0.001763	0.009389
Std Dev	5855.5	0.10466	0.10061			0.076107		
Average Error			0.0039			0.0320		
Relative Error			0.0120			0.0984		
Root Mean Square Error				0.0088			0.0420	
Coefficient of Variation				0.0272			0.1291	
Coefficient of Efficiency (R^2)				0.9917			0.8122	

Table 5.35: Sensitivity Analysis for Soil Depth 15 to 30 cm (Comparing Three Methods) (Ahmednagar)

	Ψ=Y	θ=X	yfit$_1$	yfit$_2$	yfit$_3$	(yfit$_1$-Y)^2	(yfit$_2$-Y)^2	(yfit$_3$-Y)^2	(y$_{avg}$-Y)^2
Y$_7$	15000	0.2126	10175	14521	10175.1	23277669	229217.3	23279498	108963764.5
Y$_6$	10000	0.2219	8653.6	11217	8653.28	1812887	1481386	1813648	29578054.52
Y$_5$	5000	0.2490	5397.5	5599.2	5397.07	157976.5	359070.4	157661.2	192344.522
Y$_4$	1000	0.3171	1648.3	1303.2	1647.98	420254.1	91903.96	419877.7	12683776.52
Y$_3$	500	0.3560	837.06	648.58	836.867	113612	22077.32	113479.6	16495205.52
Y$_2$	330	0.4085	335.43	282.96	335.329	29.53453	2212.958	28.401	17904991.38
Y$_1$	100	0.5026	65.127	81.066	65.0975	1216.113	358.4989	1218.184	19904348.72
Total	31930	2.2677	27112	33653	27110.7	25783644	2186226	25785411	205722485.7
Average (y$_{avg}$)	4561.4	0.3240	3873.2	4807.6	3872.96	3683378	312318	3683630	29388926.53
Std Dev	5855.5	0.1069	4204.7	5894.3	4204.65				
Average Error			-688.25	246.19	-688.47				
Relative Error			-0.1509	0.054	-0.1509				
Root Mean Square Error						1919.213	558.8542	1919.279	
Coefficient of Variation						0.4207	0.1225	0.4208	
Coefficient of Efficiency (R^2)						0.8747	0.9894	0.8747	

Table 5.36: Sensitivity Analysis for Selected m, n and α values for Soil Depth 15 to 30 cm (Ahmednagar)

	Ψ=Y	**θ=X**	**x_2(θ generated) (by Proposed Model)**	**$(x_1$-X)^2**	**$(x_{avg}$-X)^2**	**x_1(θ generated) (by VG Model**	**$(x_2$-X)^2**	**$(x_{avg}$-X)^2**
Y_7	15000	0.2126	0.2291	0.0003	0.0124	0.2738	0.0037	0.0124
Y_6	10000	0.2219	0.2341	0.0001	0.0104	0.2819	0.0036	0.0104
Y_5	5000	0.2490	0.2461	0.0000	0.0056	0.2984	0.0024	0.0056
Y_4	1000	0.3171	0.3061	0.0001	0.0000	0.3533	0.0013	0.0000
Y_3	500	0.3560	0.3558	0.0000	0.0010	0.3861	0.0009	0.0010
Y_2	330	0.4085	0.3946	0.0002	0.0071	0.4088	0.0000	0.0071
Y_1	100	0.5026	0.5221	0.0004	0.0319	0.4847	0.0003	0.0319
Total	31930	2.2677	2.2879	0.0011	0.0686	2.4869	0.0123	0.0686
Average (x_{avg})	4561.43	0.3240	0.3268	0.0002	0.0098	0.3553	0.0018	0.0098
Std Dev	5855.52	0.1069	0.1070			0.0773		
Average Error			0.0029			0.0313		
Relative Error			0.0089			0.0967		
Root Mean Square Error				0.0127			0.0420	
Coefficient of Variation				0.0390			0.1290	
Coefficient of Efficiency (R^2)				0.9836			0.8203	

Table 5.37: Sensitivity Analysis for Soil Depth (30 to 60 cm) (Comparing Three Methods) (Ahmednagar)

	Ψ=Y	**θ=X**	**yfit$_1$**	**yfit$_2$**	**yfit$_3$**	**(yfit$_1$-Y)^2**	**(yfit$_2$-Y)^2**	**(yfit$_3$-Y)^2**	**(y$_{avg}$-Y)^2**
Y$_7$	15000	0.2213	10534	13086	10526	19942923	3664112.2	20020683	108963765
Y$_6$	10000	0.2314	8853	10070	8844.9	1316554.1	4897.5475	1334151	29578054.5
Y$_5$	5000	0.2557	5826	5604	5820.1	681633.21	364256.74	672487.6	192344.522
Y$_4$	1000	0.2392	7740	8289	7733	45426783	53132684	45333720	12683776.5
Y$_3$	500	0.3798	687.5	549.4	686.5	35144.728	2436.0293	34780.53	16495205.5
Y$_2$	330	0.4218	333.5	296.8	333.02	12.565475	1102.1441	9.120789	17904991.4
Y$_1$	100	0.5106	72.29	96.7	72.149	768.02308	10.91827	775.6707	19904348.7
Total	31930	2.2598	34046	37991	34015	67403818	57169500	67396608	205722486
Average (y$_{avg}$)	4561.43	0.3228	4864	5427	4859.3	9629116.9	8167071.4	9628087	29388926.5
Std Dev	5855.52	0.1144	4438	5275	4434.5				
Average Error			302.2	865.9	297.89				
Relative Error			0.066	0.19	0.0653				
Root Mean Square Error						3103.0818	2857.8088	3102.916	
Coefficient of Variation						0.6803	0.6265	0.6803	
Coefficient of Efficiency (R^2)						0.6724	0.7221	0.6724	

Table 5.38: Sensitivity Analysis for Selected m, n and α values for Soil Depth 30 to 60 cm (Ahmednagar)

	Ψ=Y	**θ=X**	**x_2(θ generated) (by Proposed Model)**	**$(x_1\text{-}X)$^2**	**$(x_{avg}\text{-}X)$^2**	**x_1(θ generated) (by VG Model)**	**$(x_2\text{-}X)$^2**	**$(x_{avg}\text{-}X)$^2**
Y_7	15000	0.2213	0.2361	0.0002	0.0103	0.2750	0.0029	0.0103
Y_6	10000	0.2314	0.2422	0.0001	0.0084	0.2857	0.0029	0.0084
Y_5	5000	0.2557	0.2591	0.0000	0.0045	0.3091	0.0028	0.0045
Y_4	1000	0.2392	0.3630	0.0153	0.0070	0.3976	0.0251	0.0070
Y_3	500	0.3798	0.4469	0.0045	0.0032	0.4517	0.0052	0.0032
Y_2	330	0.4218	0.4981	0.0058	0.0098	0.4856	0.0041	0.0098
Y_1	100	0.5106	0.5792	0.0047	0.0353	0.5609	0.0025	0.0353
Total	31930	2.2598	2.6247	0.0307	0.0785	2.7656	0.0455	0.0785
Average (x_{avg})	4561.4	0.3228	0.3750	0.0044	0.0112	0.3951	0.0065	0.0112
Std Dev	5855.5	0.1144	0.1369			0.1101		
Average Error			0.0521			0.0723		
Relative Error			0.1615			0.2238		
Root Mean Square Error				0.0662			0.0807	
Coefficient of Variation				0.2037			0.2481	
Coefficient of Efficiency (R^2)				0.6087			0.4195	

Table 5.39: Sensitivity Analysis for Soil Depth 60 to 90 cm (Comparing Three Methods) (Ahmednagar)

	$\Psi=Y$	$\theta=X$	$yfit_1$	$yfit_2$	$yfit_3$	$(yfit_1-Y)^2$	$(yfit_2-Y)^2$	$(yfit_3-Y)^2$	$(y_{avg}-Y)^2$
Y_7	15000	0.2192	12407	16380.2	12392.82	6723696	1904951	6797364	108963765
Y_6	10000	0.2475	7552.5	7866.87	7542.76	5990276	4550251	6038030	29578055
Y_5	5000	0.2651	5546.54	5195.19	5538.88	298704.7	38098.76	290392.2	192344.52
Y_4	1000	0.3416	1449.71	1123.44	1447.132	202239.8	15236.37	199927	12683777
Y_3	500	0.3827	705.019	565.628	703.6146	42032.97	4307.051	41458.9	16495206
Y_2	330	0.4279	319.072	288.196	318.3614	119.417	1747.533	135.4574	17904991
Y_1	100	0.5117	73.3737	97.846	73.17826	708.9605	4.639798	719.4057	19904349
Total	31930	2.3957	28053.2	31517.4	28016.75	13257777	6514596	13368027	205722486
Average (y_{avg})	4561.43	0.3422	4007.6	4502.48	4002.393	1893968	930656.6	1909718	29388927
Std Dev	5855.52	0.1063	4690.73	6013.28	4685.375				
Average Error			-553.828	-58.948	-559.036				
Relative Error			-0.1214	-0.0129	-0.1226				
Root Mean Square Error						1376.215	964.7054	1381.926	
Coefficient of Variation						0.3017	0.2115	0.3030	
Coefficient of Efficiency (R^2)						0.9356	0.9683	0.9350	

Table 5.40: Sensitivity Analysis for Selected m, n and α values for Soil Depth 60 to 90 cm (Ahmednagar)

	$\Psi=Y$	$\theta=X$	x_2(θ generated) (by Proposed Model)	$(x_1-X)^2$	$(x_{avg}-X)^2$	x_1(θ generated) (by VG Model)	$(x_2-X)^2$	$(x_{avg}-X)^2$
Y_7	15000	0.2192	0.2380	0.0004	0.0146	0.2782	0.0035	0.0146
Y_6	10000	0.2475	0.2453	0.0000	0.0086	0.2895	0.0018	0.0086
Y_5	5000	0.2651	0.2645	0.0000	0.0056	0.3139	0.0024	0.0056
Y_4	1000	0.3416	0.3738	0.0010	0.0000	0.4043	0.0039	0.0000
Y_3	500	0.3827	0.4560	0.0054	0.0018	0.4579	0.0057	0.0018
Y_2	330	0.4279	0.5042	0.0058	0.0077	0.4910	0.0040	0.0077
Y_1	100	0.5117	0.5796	0.0046	0.0295	0.5628	0.0026	0.0295
Total	31930	2.3957	2.6613	0.0172	0.0678	2.7977	0.0238	0.0678
Average (x_{avg})	4561	0.3422	0.3802	0.0025	0.0097	0.3997	0.0034	0.0097
Std Dev	5856	0.1063	0.1371			0.1100		
Average Error			0.0379			0.0574		
Relative Error			0.1109			0.1678		
Root Mean Square Error				0.0496			0.0583	
Coefficient of Variation				0.1524			0.1794	
Coefficient of Efficiency (R^2)				0.7463			0.6486	

Table 5.41: Sensitivity Analysis for Soil Depth 90 to 120 cm (Comparing Three Methods) (Ahmednagar)

	Ψ=Y	**θ=X**	**$yfit_1$**	**$yfit_2$**	**$yfit_3$**	**$(yfit_1$-Y)^2**	**$(yfit_2$-Y)^2**	**$(yfit_3$-Y)^2**	**$(y_{avg}$-Y)^2**
Y_7	15000	0.2090	10406.4	13943	10397	21101186	1116346	21183478	108963765
Y_6	10000	0.2216	8430.66	10017	8423	2462837	280.6405	2487021	29578054.5
Y_5	5000	0.2530	4988.73	4738	4983.5	127.0839	68815.28	271.1159	192344.522
Y_4	1000	0.3248	1502.91	1155	1500.9	252917.7	24011.45	250902.2	12683776.5
Y_3	500	0.3621	805.832	624.9	804.63	93533.08	15601.58	92800.43	16495205.5
Y_2	330	0.4075	377.376	320.6	376.74	2244.449	88.20012	2184.924	17904991.4
Y_1	100	0.5151	62.5049	85.31	62.373	1405.882	215.745	1415.827	19904348.7
Total	31930	2.2931	26574.4	30884	26549	23914251	1225358	24018073	205722486
Average (y_{avg})	4561.43	0.3276	3796.34	4412	3792.7	3416322	175051.2	3431153	29388926.5
Std Dev	5855.52	0.1108	4211.6	5519	4208				
Average Error			-765.09	-149	-768.8				
Relative Error			-0.1677	-0.03	-0.1685				
Root Mean Square Error						1848.329	418.3912	1852.337	
Coefficient of Variation						0.4052	0.0917	0.4061	
Coefficient of Efficiency (R^2)						0.8838	0.9940	0.8833	

Table 5.42: Sensitivity Analysis for Selected m, n and α values for Soil Depth 90 to 120 cm (Ahmednagar)

	Ψ=Y	θ=X	x_2(θ generated) (by Proposed Model)	$(x_1-X)^2$	$(x_{avg}-X)^2$	x_1(θ generated) (by VG Model)	$(x_2-X)^2$	$(x_{avg}-X)^2$
Y_7	15000	0.2090	0.2247	0.0002	0.0146	0.2618	0.0028	0.0146
Y_6	10000	0.2216	0.2308	0.0001	0.0118	0.2721	0.0026	0.0118
Y_5	5000	0.2530	0.2470	0.0000	0.0059	0.2945	0.0017	0.0059
Y_4	1000	0.3248	0.3439	0.0004	0.0000	0.3795	0.0030	0.0000
Y_3	500	0.3621	0.4237	0.0038	0.0010	0.4323	0.0049	0.0010
Y_2	330	0.4075	0.4749	0.0045	0.0060	0.4664	0.0035	0.0060
Y_1	100	0.5151	0.5652	0.0025	0.0343	0.5463	0.0010	0.0343
Total	31930	2.2931	2.5103	0.0116	0.0736	2.6530	0.0194	0.0736
Average (x_{avg})	4561.4	0.3276	0.3586	0.0017	0.0105	0.3790	0.0028	0.0105
Std Dev	5855.5	0.1108	0.1338			0.1086		
Average Error			0.0310			0.0514		
Relative Error			0.0947			0.1569		
Root Mean Square Error				0.0407			0.0527	
Coefficient of Variation				0.1251			0.1620	
Coefficient of Efficiency (R^2)				0.8427			0.7362	

Table 5.43: Sensitivity Analysis for Soil Depth 120 to 150 cm (Comparing Three Methods) (Ahmednagar)

	Ψ=Y	**θ=X**	**yfit$_1$**	**yfit$_2$**	**yfit$_3$**	**(yfit$_1$-Y)^2**	**(yfit$_2$-Y)^2**	**(yfit$_3$-Y)^2**	**(y$_{avg}$-Y)^2**
Y$_7$	15000	0.2058	7616.65	10069.6	7613.9	54513926	24308824	54553748	108963765
Y$_6$	10000	0.2166	6324.73	7519.27	6322.4	13507578	6154028	13524904	29578055
Y$_5$	5000	0.2375	4413.99	4443.71	4412.2	343407.8	309453.7	345524.4	192344.52
Y$_4$	1000	0.2653	2735.57	2361.81	2734.3	3012215	1854537	3007883	12683777
Y$_3$	500	0.3180	1104.48	839.318	1103.9	365395.3	115136.7	364665.3	16495206
Y$_2$	330	0.3920	309.077	254.169	308.87	437.7865	5750.398	446.5495	17904991
Y$_1$	100	0.4838	63.6699	76.444	63.617	1319.879	554.8861	1323.731	19904349
Total	31930	2.1190	22568.2	25564.3	22559	71744279	32748285	71798495	205722486
Average (y$_{avg}$)	4561.4	0.3027	3224.02	3652.05	3222.7	10249183	4678326	10256928	29388927
Std Dev	5855.5	0.1028	2987.23	3887.45	2986.2				
Average Error			-1337.4	-909.38	-1339				
Relative Error			-0.2932	-0.1994	-0.2935				
Root Mean Square Error						3201.434	2162.944	3202.644	
Coefficient of Variation						0.7018	0.4742	0.7021	
Coefficient of Efficiency (R^2)						0.6513	0.8408	0.6510	

Table 5.44: Sensitivity Analysis for Selected m, n and α values for Soil Depth 120 to 150 cm (Ahmednagar)

	Ψ=Y	**θ=X**	**x_2(θ generated) (by Proposed Model)**	**$(x_1\text{-}X)^2$**	**$(x_{avg}\text{-}X)^2$**	**x_1(θ generated) (by VG Model)**	**$(x_2\text{-}X)^2$**	**$(x_{avg}\text{-}X)^2$**
Y_7	15000	0.2058	0.2192	0.0002	0.0094	0.2593	0.0029	0.0094
Y_6	10000	0.2166	0.2233	0.0000	0.0075	0.2668	0.0025	0.0075
Y_5	5000	0.2375	0.2337	0.0000	0.0043	0.2822	0.0020	0.0043
Y_4	1000	0.2653	0.2868	0.0005	0.0014	0.3344	0.0048	0.0014
Y_3	500	0.3180	0.3322	0.0002	0.0002	0.3661	0.0023	0.0002
Y_2	330	0.3920	0.3685	0.0006	0.0079	0.3883	0.0000	0.0079
Y_1	100	0.4838	0.4939	0.0001	0.0327	0.4634	0.0004	0.0327
Total	31930	2.1190	2.1576	0.0016	0.0635	2.3605	0.0149	0.0635
Average (x_{avg})	4561.4	0.3027	0.3082	0.0002	0.0091	0.3372	0.0021	0.0091
Std Dev	5855.5	0.1028	0.0999			0.0746		
Average Error			0.0055			0.0345		
Relative Error			0.0182			0.1140		
Root Mean Square Error				0.0149			0.0461	
Coefficient of Variation				0.0458			0.1419	
Coefficient of Efficiency (R^2)				0.9755			0.7652	

5.4 SUMMARY OF RESULTS

In Section 5.3.1 soil parameters m, n and α were estimated by Van Genuchten method and proposed method. The results are presented in following Table 5.45. In analysis three curve fitting methods were used as follows:

$Y = a_1 e^{b_1 x}, Y = a_2 x^{b_2}$ *and* $Y = a_3 {b_3}^{x}$.

The abstract of sensitivity analysis of curve fitting is presented in Table 5.46, 5.48, 5.50 and 5.52.The parameters m, n and α estimated by Van Genuchten (VG) method were adjusted and sensitivity analysis for two methods are presented in Table 5.47, 5.49, 5.51 and 5.53.

Table 5.45: Estimated parameters for Various Stations in the Study Area by Van Genuchten (VG) & Modified VG Models

Sr. No.	Station	Depth	Moisture at saturation θ_s	Residual Moisture θ_r	Parameters established (VG)			Parameters Established (Modified VG)		
					n	m	α	n	m	α
1	Sholapur	0 to 15 cm	0.6264	0.2172	1.31	0.25	0.028	1.66	0.40	0.009
		15 to 30 cm	0.6150	0.2090	1.30	0.23	0.030	1.63	0.39	0.010
		30 to 60 cm	0.6130	0.2018	1.29	0.23	0.039	1.62	0.38	0.012
2	Pune	0 to 15 cm	0.5632	0.2189	1.35	0.26	0.016	1.70	0.41	0.006
		15 to 30 cm	0.5627	0.2180	1.35	0.26	0.014	1.70	0.41	0.006
		30 to 60 cm	0.5513	0.2143	1.37	0.27	0.012	1.74	0.43	0.005
		60 to 90 cm	0.5471	0.1973	1.36	0.26	0.015	1.69	0.41	0.006
		90 to 120 cm	0.5410	0.1921	1.30	0.23	0.048	1.60	0.37	0.018
3	Kolhapur	0 to 15 cm	0.5261	0.2165	1.28	0.22	0.075	1.56	0.34	0.022
		15 to 30 cm	0.5278	0.2142	1.25	0.20	0.138	1.50	0.33	0.031
		30 to 60 cm	0.5427	0.2192	1.25	0.20	0.169	1.50	0.33	0.036
		60 to 90 cm	0.5234	0.1871	1.22	0.18	0.286	1.45	0.31	0.048
4	Ahmednagar	0 to 15 cm	0.5938	0.2247	1.33	0.25	0.023	1.68	0.40	0.009
		15 to 30 cm	0.6091	0.2126	1.31	0.24	0.029	1.65	0.39	0.009
		30 to 60 cm	0.5924	0.2213	1.45	0.31	0.005	1.86	0.46	0.003
		60 to 90 cm	0.5924	0.2192	1.43	0.30	0.005	1.80	0.44	0.003
		90 to 120 cm	0.5858	0.2095	1.44	0.30	0.006	1.82	0.45	0.003
		120 to 150 cm	0.5860	0.2058	1.32	0.24	0.028	1.67	0.40	0.010

Table 5.46: Abstract of Sensitivity Analysis of Curve Fitting Parameters for Sholapur

Sr. No.	Depth (cm)	Method	Relative Error	Coefficient of Variation	Coefficient of Efficiency
1	0 to 15	1	-0.21	0.54	0.80
		2	-0.10	0.30	0.94
		3	-0.21	0.54	0.80
2	15 to 30	1	-0.18	0.44	0.86
		2	-0.07	0.17	0.98
		3	-0.18	0.44	0.86
3	30 to 60	1	-0.25	0.58	0.76
		2	-0.12	0.30	0.94
		3	-0.25	0.58	0.76

Table 5.47: Abstract of Sensitivity Analysis of Parameters Estimated for Sholapur

Sr. No.	Depth (cm)	Method	Relative Error	Coefficient of Variation	Coefficient of Efficiency
1	0 to 15	1	0.22	0.13	0.82
		2	0.02	0.04	0.98
2	15 to 30	1	0.10	0.13	0.82
		2	0.00	0.04	0.98
3	30 to 60	1	0.11	0.14	0.79
		2	0.00	0.04	0.98

Table 5.48: Abstract of Sensitivity Analysis of Curve Fitting Parameters for Pune

Sr. No.	Depth (cm)	Method	Relative Error	Coefficient of Variation	Coefficient of Efficiency
1	0 to 15	1	-0.20	0.49	0.83
		2	1.34	0.83	0.94
		3	-0.20	0.49	0.83
2	15 to 30	1	-0.18	0.46	0.85
		2	0.08	0.21	0.97
		3	-0.18	0.46	0.85
3	30 to 60	1	-0.19	0.49	0.83
		2	-0.09	0.26	0.95
		3	-0.19	0.49	0.83
4	60 to 90	1	-0.12	0.30	0.94
		2	-0.01	0.08	0.99
		3	-0.12	0.30	0.94
5	90 to 120	1	-0.37	0.82	0.52
		2	-0.28	0.60	0.75
		3	-0.37	0.82	0.52

Table 5.49: Abstract of Sensitivity Analysis of Parameters Estimated for Pune

Sr. No.	Depth (cm)	Method	Relative Error	Coefficient of Variation	Coefficient of Efficiency
1	0 to 15	1	-0.02	0.12	0.82
		2	0.01	0.04	0.98
2	15 to 30	1	0.08	0.11	0.86
		2	0.01	0.05	0.97
3	30 to 60	1	0.08	0.11	0.86
		2	0.02	0.04	0.98
4	60 to 90	1	0.08	0.10	0.88
		2	0.01	0.05	0.97
5	90 to 120	1	0.13	0.14	0.80
		2	0.01	0.05	0.97

Table 5.50: Abstract of Sensitivity Analysis of Curve Fitting Parameters for Kolhapur

Sr. No.	Depth (cm)	Method	Relative Error	Coefficient of Variation	Coefficient of Efficiency
1	0 to 15	1	-0.34	0.81	0.53
		2	-0.29	0.69	0.66
		3	-0.34	0.81	0.53
2	15 to 30	1	-0.31	0.74	0.61
		2	-0.25	0.61	0.74
		3	-0.31	0.31	0.61
3	30 to 60	1	-0.33	0.78	0.57
		2	-0.28	0.64	0.71
		3	-0.33	0.78	0.57
4	60 to 90	1	-0.29	0.60	0.74
		2	-0.19	0.37	0.90
		3	-0.29	0.60	0.74

Table 5.51: Abstract of Sensitivity Analysis of Parameters Estimated for Kolhapur

Sr. No.	Depth (cm)	Model	Relative Error	Coefficient of Variation	Coefficient of Efficiency
1	0 to 15	VG	0.49	0.43	-0.62
		Proposed	0.01	0.05	0.94
2	15 to 30	VG	0.11	0.12	0.58
		Proposed	0.01	0.05	0.93
3	30 to 60	VG	-0.23	0.29	-0.78
		Proposed	-0.01	0.10	0.78
4	60 to 90	VG	0.12	0.12	0.56
		Proposed	-0.01	0.05	0.92

Table 5.52: Abstract of Sensitivity Analysis of Curve Fitting Parameters for Ahmednagar

Sr. No.	Depth (cm)	Method	Relative Error	Coefficient of Variation	Coefficient of Efficiency
1	0 to 15	1	-0.23	0.59	0.75
		2	-0.12	0.39	0.89
		3	-0.23	0.59	0.75
2	15 to 30	1	0.15	0.42	0.87
		2	0.05	0.12	0.99
		3	-0.15	0.42	0.87
3	30 to 60	1	0.07	0.68	0.67
		2	0.19	0.63	0.72
		3	0.07	0.68	0.67
4	60 to 90	1	-0.12	0.30	0.94
		2	-0.01	0.21	0.97
		3	-0.12	0.30	0.94
5	90 to 120	1	-0.17	0.41	0.88
		2	-0.03	0.09	0.99
		3	-0.17	0.41	0.88
6	120 to 150	1	-0.29	0.70	0.65
		2	-0.20	0.47	0.84
		3	-0.29	0.70	0.65

Table 5.53: Abstract of Sensitivity Analysis of Parameters Estimated for Ahmednagar

Sr. No.	Depth (cm)	Model	Relative Error	Coefficient of Variation	Coefficient of Efficiency
1	0 to 15	VG	0.10	0.13	0.81
		Proposed	0.01	0.03	0.99
2	15 to 30	VG	0.10	0.13	0.82
		Proposed	0.01	0.04	0.98
3	30 to 60	VG	0.22	0.25	0.42
		Proposed	0.16	0.20	0.61
4	60 to 90	VG	0.17	0.18	0.65
		Proposed	0.11	0.15	0.75
5	90 to 120	VG	0.16	0.16	0.74
		Proposed	0.09	0.13	0.84
6	120 to 150	VG	0.11	0.14	0.77
		Proposed	0.02	0.41	0.98

The Van Genuchten model is complex in form and relies on a greater number of fitting parameters. The main advantage of this method is, it yields a continuous Soil Moisture Characteristic Curve (SMCC) in the unsaturated zone and provides a good description of the soil moisture characteristic and properties. It is known that the soil moisture parameter α is approximately equivalent to the air-entry value of SMCC while n is related to the pore size distribution which controls the gradient of the linear portion of SMCC, i.e., how fast the soil is wetted-up or dried-out subject to a change of suction. The parameter n increases with increasing coarseness of texture. The value of soil parameter m is related to the asymmetry of the model and is usually less than one.

The soil moisture characteristic curves obtained in this study were presented and various statistical measures were employed to compare the fitting accuracy of models. The sensitivity analysis is carried out depthwise for each research station. The RMSE statistic is an indicator of the overall error of the evaluated model function, with a value closer to zero indicating a better fit. In other words, the RMSE is a measure of the precision of the predicted parameters, and should be as small as possible for unbiased precise prediction. Generally the best indicator of fit quality, the coefficient of efficiency, statistic is a measure of the linearity between observed and fitted data, with a value approaching unity indicating that the fit explains most of the variability in the observed data. The sensitivity analysis for the three curve fitting method is presented. The RMSE values of the second method is associated with the lowest values, meaning that the fitted curve produced via this method had the highest correlation with the observed SMCC. The First and third method yield same results and performed the least well. A similar trend was observed in terms of coefficient of efficiency and other parameters of statistic values, with the second model again exhibiting the strongest linearity. Overall, the results indicate that the second curve fit method scores highest in the analysis of in terms of goodness of fit. The estimated soil parameters, m, n and α from second curve fitting methods were considered for generating the soil moisture content (x_1). The SMCC is plotted with new parameters shows some modification is necessary in obtained parameters. The m value is increased up to 40 %. This change shows good fit. Hence modification is made in the present model. The soil moisture parameters for all the four research stations were obtained by new model. The obtained parameters are presented in respective Tables. The coefficient of efficiency of VG model is nearly 80 % and for proposed model coefficient of efficiency is more than 95 %. On observing other parameters of sensitivity analysis proposed model found more suitable. The proposed methods result one research station to other analysis show very little variation hence this method can be used for other places of study area. The parameter obtained this Chapter are used in main governing model in Chapter 7.

CHAPTER-6

ESTIMATION OF EVAPOTRANSPIRATION

6.1 INTRODUCTION

In the literature review Chapter 2 and model formulation Chapter 3 the detailed discussion about evapotranspiration is done. For estimating evapotranspiration following type of parameters are required.

- Climatological
- Physical parameters

Some of these data are recorded directly in meteorological research stations available in study area. Some of the remaining parameters which are not recorded but are related to commonly observed data are derived with the help of a direct or empirical relationship. The FAO-56 Penman-Monteith Equation is used as one of the International Standard equation for comparing various methods. This International Standard equation used for estimating ET_o is as follows:

$$ET_o = \frac{\{(0.408\Delta\,(R_n - \mathrm{G})) + \left(\gamma\left(\frac{900}{\mathrm{T}+273}\right)\left(U_2(E_s - E_a)\right)\right\}}{\{\Delta + \gamma\,(1 + 0.34U_2)\}} \tag{6.1}$$

Where,

ET_o = reference evapotranspiration (mm/ day),

R_n = net radiation at crop surface (MJ/ m^2 day),

G = soil heat flux density (MJ/ m^2 day),

T= mean daily air temperature at 2 m height (^{0}C),

U_2= wind speed at 2m height (m/s),

E_s = saturation vapour pressure (kPa),

E_a = actual vapour pressure (kPa),

$E_s - E_a$ = saturation vapour pressure deficit (kPa),

Δ = slope of the vapour pressure curve (kPa/ ^{0}C),

γ = psychrometric constant (kPa/ ^{0}C).

6.2 REQUIRED PARAMETERS FOR ESTIMATION OF ET$_o$

6.2.1 Air Temperature

The daily maximum and minimum air temperatures data in degrees Celsius (°C) are required to calculate the mean temperature (T$_{mean}$).

$$T_{mean} = \frac{T_{min}+T_{max}}{2} \tag{6.2}$$

T $_{mean}$ = mean daily air temperature, ºC; T $_{max}$ = maximum daily air temperature, ºC; T $_{min}$ = minimum daily air temperature, ºC. The daily maximum and minimum temperature data is collected for all the four research stations, here only two stations data are graphically presented in following Figures 6.1 to 6.4.

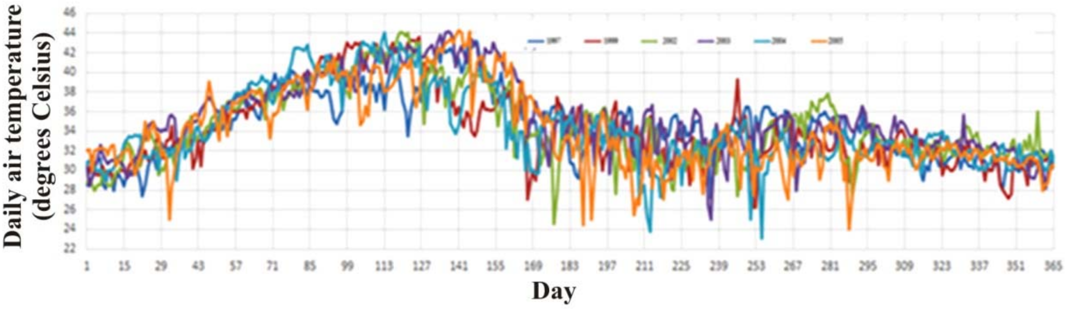


Figure 6.1: Daily Maximum Air Temperature for Sholapur

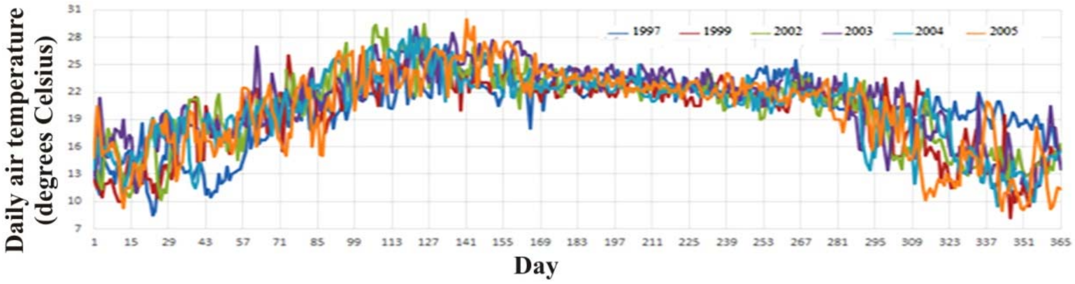


Figure 6.2: Daily Minimum Air Temperature for Sholapur

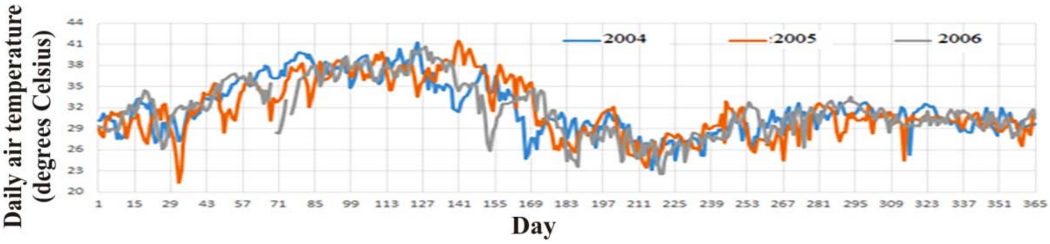


Figure 6.3: Daily Maximum Air Temperature for Pune

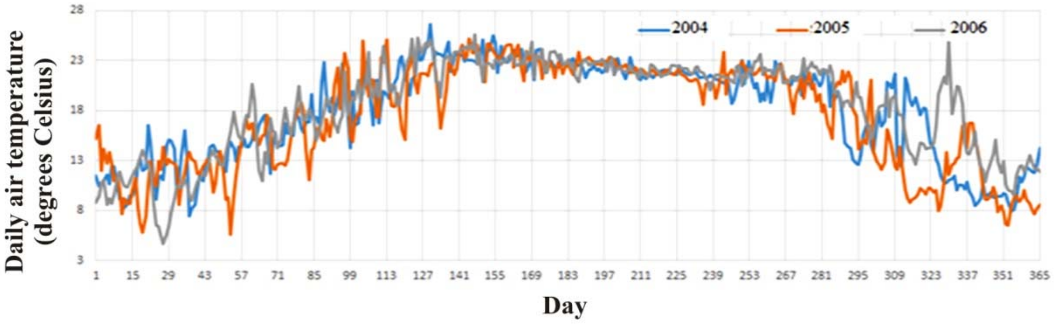


Figure 6.4: Daily Minimum Air Temperature for Pune

6.2.2 Mean Daily Solar Radiation

The average daily net radiation (MJ/ m^2 day) is important required parameter. A simple average of solar radiation values are available from observation station established by India Metrological Department (IMD) for the period of 24h. If the solar radiation is not recorded by IMD, then it can be evaluated with the help of following equation.

$$R_{so} = (0.75 + 2\,(10)^{-5}\mathrm{Z}\,)\,R_a \qquad (6.3)$$

This equation is used when calibrated values of a_s and b_s are not available.

R_{so} = clear sky radiation (MJ/ m^2 d),

R_a =extra-terrestrial radiation (MJ/ m^2 d),

Z = station elevation above sea level (m).

$$R_a = (24(60)/\pi)(G_{sc} d_r \omega_s\ (\sin(\varphi)\sin(\delta)) + \Big(\cos(\varphi)\big(\cos(\delta)\sin(\omega_s)\big)\Big) \qquad (6.4)$$

G_{sc} = Solar constant = 0.0820 (MJ/ m^2 min),

d_r = inverse relative distance factor between Earth-Sun.

$$d_r = 1 + \left(0.033\cos\left(2\,\pi\left(\frac{\mathrm{J}}{365}\right)\right)\right) \qquad (6.5)$$

J = number of days in the year.

The inverse relative distance factor between earth-sun is evaluated and presented graphically as follows:

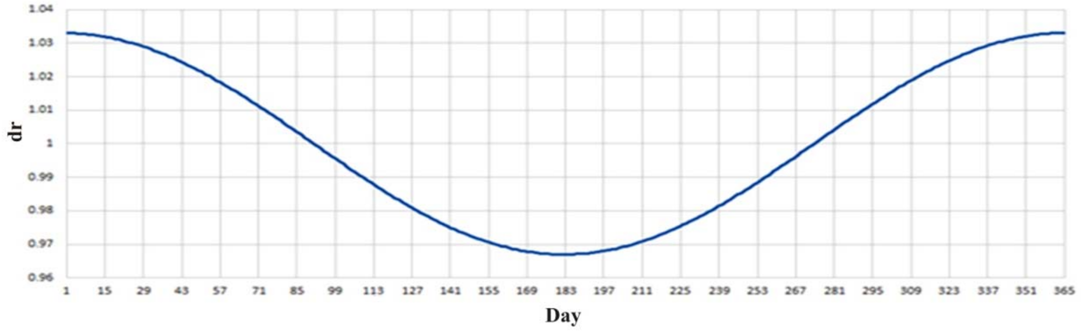


Figure 6.5: Inverse Relative Distance between Earth-Sun (d_r)

ω_s = sunset hour angle.

$$\omega_s = \arccos\left(-\tan(\varphi)\tan(\delta)\right) \tag{6.6}$$

Or

$$\omega_s = \left(\frac{\pi}{2}\right) - \left(\arctan\left(\frac{-\tan(\varphi)\tan(\delta)}{X^{0.5}}\right)\right) \tag{6.7}$$

$$X = 1 - \left(\tan(\varphi)^2\tan(\delta)^2\right) \tag{6.8}$$

X= 0.00001 if $X \leq 0$.

Here

$$\varphi = \text{lat(Rad)} = \left(\frac{\pi}{180}\right)(\text{latitude in decimal degree}) \tag{6.9}$$

For Sholapur research station where data is recorded latitude is 17 ^{0} 40$'$ then

$$\varphi = \left(\frac{\pi}{180}\right)\left(17 + \left(\frac{40}{60}\right)\right) = 0.3085 \text{ Rad.}$$

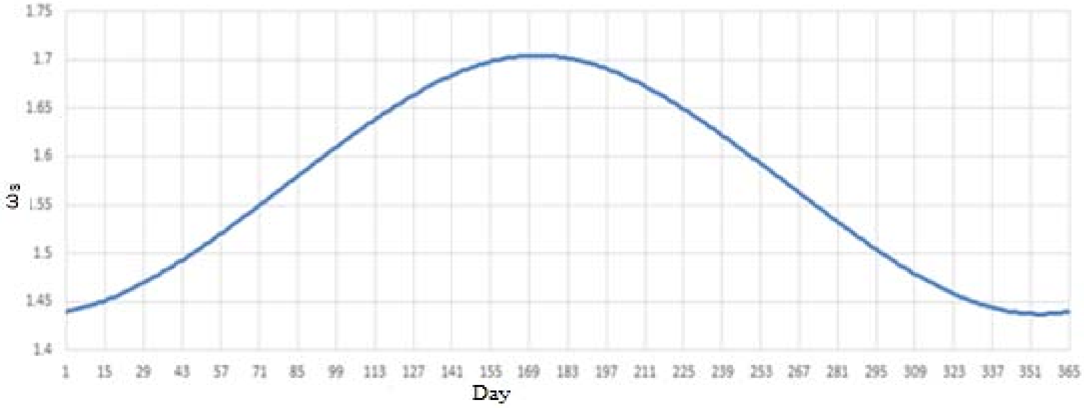


Figure 6.6: Sunset Hour Angle for all days in a Year for Sholapur

δ =solar declination (rad);

$$\delta = 0.409\left(\sin\left(\left(2\pi\left(\frac{J}{365}\right)\right) - 1.39\right)\right) \tag{6.10}$$

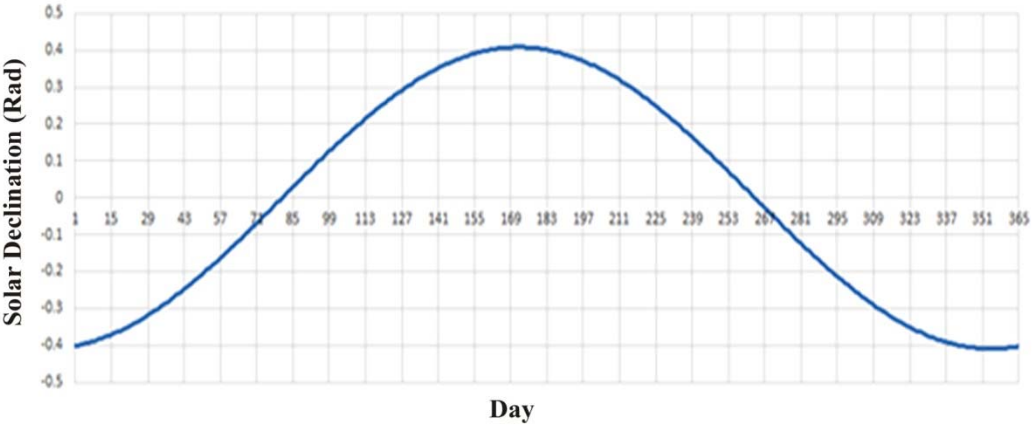


Figure 6.7: Solar Declination variation over a year

The R_a values for all the stations are obtained by using Equation 6.4. The obtained values of R_a are necessary for estimating reference evapotranspiration by FAO and other methods used in study. The evaluated values of R_a are represented in following Tables: 6.1, 6.3, 6.5, 6.6 and 6.7. The Ra values are graphically represented in appendix E.

Table 6.1: Monthwise Extra-Terrestrial Radiation (R_a) (MJ/ m^2 day) values for Sholapur

Date	Month											
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
1	27.4602	30.0558	33.6773	37.0828	38.6549	38.9078	38.7926	38.5289	37.3065	34.5119	30.6297	27.7705
2	27.5024	30.1747	33.8069	37.1643	38.6792	38.9053	38.7885	38.5104	37.2399	34.3942	30.5085	27.7127
3	27.5477	30.2952	33.9358	37.2437	38.7021	38.9026	38.7844	38.4908	37.1713	34.2754	30.3885	27.6578
4	27.5962	30.4170	34.0638	37.3211	38.7235	38.8996	38.7802	38.4702	37.1009	34.1555	30.2696	27.6060
5	27.6478	30.5401	34.1910	37.3964	38.7435	38.8965	38.7759	38.4484	37.0285	34.0346	30.1521	27.5572
6	27.7025	30.6644	34.3172	37.4696	38.7621	38.8931	38.7715	38.4255	36.9541	33.9127	30.0358	27.5114
7	27.7602	30.7899	34.4424	37.5407	38.7795	38.8896	38.7669	38.4013	36.8779	33.7899	29.9210	27.4688
8	27.8210	30.9165	34.5665	37.6097	38.7956	38.8859	38.7622	38.3760	36.7997	33.6662	29.8077	27.4294
9	27.8847	31.0440	34.6894	37.6767	38.8104	38.8821	38.7574	38.3493	36.7197	33.5418	29.6959	27.3931
10	27.9513	31.1725	34.8111	37.7416	38.8240	38.8782	38.7523	38.3213	36.6377	33.4166	29.5858	27.3600
11	28.0209	31.3018	34.9316	37.8044	38.8365	38.8742	38.7470	38.2920	36.5538	33.2908	29.4774	27.3301
12	28.0933	31.4318	35.0507	37.8651	38.8479	38.8702	38.7415	38.2613	36.4681	33.1644	29.3708	27.3035
13	28.1685	31.5625	35.1684	37.9238	38.8583	38.8661	38.7357	38.2292	36.3804	33.0375	29.2660	27.2801
14	28.2464	31.6938	35.2847	37.9805	38.8676	38.8619	38.7296	38.1956	36.2909	32.9102	29.1631	27.2601
15	28.3271	31.8255	35.3995	38.0352	38.8759	38.8578	38.7231	38.1605	36.1996	32.7825	29.0623	27.2433
16	28.4104	31.9577	35.5128	38.0879	38.8833	38.8536	38.7163	38.1239	36.1065	32.6545	28.9635	27.2298
17	28.4963	32.0902	35.6245	38.1386	38.8898	38.8494	38.7091	38.0857	36.0116	32.5263	28.8668	27.2196

Table 6.1 (Continued)

Date	Month											
	January	February	March	April	May	June	July	August	September	October	November	December
18	28.5848	32.2230	35.7345	38.1873	38.8955	38.8453	38.7014	38.0459	35.9148	32.3980	28.7724	27.2128
19	28.6757	32.3559	35.8429	38.2341	38.9003	38.8411	38.6933	38.0045	35.8164	32.2696	28.6802	27.2093
20	28.7691	32.4890	35.9495	38.2790	38.9044	38.8370	38.6847	37.9614	35.7162	32.1412	28.5903	27.2091
21	28.8649	32.6220	36.0544	38.3220	38.9078	38.8329	38.6756	37.9167	35.6144	32.0129	28.5027	27.2123
22	28.9629	32.7550	36.1575	38.3631	38.9105	38.8288	38.6659	37.8702	35.5109	31.8848	28.4177	27.2188
23	29.0632	32.8878	36.2587	38.4024	38.9125	38.8247	38.6555	37.8220	35.4058	31.7568	28.3351	27.2287
24	29.1657	33.0204	36.3581	38.4399	38.9139	38.8207	38.6446	37.7720	35.2991	31.6293	28.2550	27.2419
25	29.2703	33.1527	36.4556	38.4757	38.9148	38.8167	38.6329	37.7203	35.1909	31.5021	28.1776	27.2584
26	29.3769	33.2846	36.5511	38.5097	38.9151	38.8127	38.6205	37.6667	35.0812	31.3754	28.1028	27.2783
27	29.4855	33.4160	36.6447	38.5420	38.9149	38.8087	38.6074	37.6113	34.9701	31.2492	28.0307	27.3014
28	29.5961	33.5470	36.7364	38.5726	38.9143	38.8047	38.5935	37.5541	34.8575	31.1237	27.9614	27.3278
29	29.7084		36.8260	38.6016	38.9132	38.8007	38.5787	37.4951	34.7436	30.9989	27.8949	27.3576
30	29.8225		36.9137	38.6290	38.9117	38.7967	38.5630	37.4341	34.6284	30.8749	27.8313	27.3905
31	29.9383		36.9993		38.9099		38.5465	37.3713		30.7518		27.4267

Table 6.2: Monthwise Clear Sky Radiation (R_{so}) values for Sholapur

Date	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	20.8608	22.8325	25.5837	28.1708	29.3650	29.5572	29.4697	29.2694	28.3408	26.2178	23.2685	21.0965
2	20.8928	22.9229	25.6822	28.2327	29.3835	29.5553	29.4666	29.2553	28.2901	26.1284	23.1765	21.0526
3	20.9272	23.0144	25.7801	28.2930	29.4009	29.5532	29.4634	29.2404	28.2381	26.0381	23.0853	21.0109
4	20.9641	23.1069	25.8773	28.3518	29.4172	29.5510	29.4602	29.2247	28.1845	25.9470	22.9950	20.9715
5	21.0033	23.2005	25.9739	28.4090	29.4324	29.5486	29.4570	29.2082	28.1295	25.8552	22.9057	20.9344
6	21.0448	23.2949	26.0698	28.4646	29.4465	29.5460	29.4536	29.1908	28.0731	25.7626	22.8174	20.8997
7	21.0887	23.3903	26.1649	28.5186	29.4597	29.5433	29.4502	29.1725	28.0152	25.6693	22.7302	20.8673
8	21.1348	23.4864	26.2592	28.5711	29.4719	29.5405	29.4466	29.1532	27.9558	25.5753	22.6441	20.8374
9	21.1832	23.5833	26.3526	28.6219	29.4832	29.5377	29.4429	29.1329	27.8950	25.4808	22.5592	20.8098
10	21.2339	23.6809	26.4451	28.6712	29.4935	29.5347	29.4391	29.1117	27.8327	25.3857	22.4755	20.7847
11	21.2867	23.7791	26.5366	28.7189	29.5030	29.5317	29.4351	29.0894	27.7690	25.2901	22.3932	20.7620
12	21.3417	23.8779	26.6270	28.7651	29.5117	29.5286	29.4309	29.0661	27.7038	25.1941	22.3122	20.7417
13	21.3988	23.9772	26.7165	28.8097	29.5195	29.5255	29.4264	29.0417	27.6372	25.0977	22.2326	20.7240
14	21.4580	24.0769	26.8048	28.8528	29.5266	29.5223	29.4218	29.0162	27.5693	25.0010	22.1545	20.7087
15	21.5193	24.1770	26.8920	28.8943	29.5329	29.5192	29.4169	28.9895	27.4999	24.9040	22.0779	20.6960
16	21.5826	24.2774	26.9781	28.9343	29.5386	29.5160	29.4117	28.9617	27.4291	24.8068	22.0028	20.6857
17	21.6479	24.3781	27.0629	28.9728	29.5435	29.5129	29.4062	28.9327	27.3570	24.7094	21.9294	20.6780

Table 6.2 (Continued)

Date	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
18	21.7151	24.4789	27.1465	29.0098	29.5478	29.5097	29.4004	28.9024	27.2836	24.6119	21.8576	20.6728
19	21.7842	24.5799	27.2288	29.0454	29.5515	29.5065	29.3943	28.8710	27.2088	24.5144	21.7876	20.6702
20	21.8551	24.6810	27.3098	29.0795	29.5546	29.5034	29.3877	28.8383	27.1327	24.4168	21.7193	20.6700
21	21.9278	24.7820	27.3895	29.1121	29.5572	29.5003	29.3808	28.8043	27.0553	24.3193	21.6528	20.6725
22	22.0023	24.8830	27.4678	29.1434	29.5592	29.4972	29.3734	28.7690	26.9767	24.2220	21.5881	20.6774
23	22.0785	24.9840	27.5447	29.1733	29.5607	29.4941	29.3656	28.7324	26.8969	24.1248	21.5254	20.6849
24	22.1564	25.0847	27.6202	29.2017	29.5618	29.4910	29.3572	28.6944	26.8158	24.0279	21.4646	20.6949
25	22.2358	25.1852	27.6943	29.2289	29.5625	29.4880	29.3484	28.6551	26.7336	23.9313	21.4058	20.7075
26	22.3168	25.2854	27.7669	29.2547	29.5627	29.4849	29.3390	28.6144	26.6503	23.8351	21.3490	20.7225
27	22.3994	25.3852	27.8380	29.2793	29.5626	29.4819	29.3290	28.5723	26.5658	23.7392	21.2942	20.7401
28	22.4833	25.4847	27.9076	29.3025	29.5621	29.4788	29.3184	28.5289	26.4803	23.6439	21.2415	20.7602
29	22.5687		27.9757	29.3246	29.5613	29.4758	29.3072	28.4840	26.3938	23.5491	21.1910	20.7828
30	22.6554		28.0423	29.3454	29.5602	29.4728	29.2953	28.4377	26.3063	23.4549	21.1427	20.8078
31	22.7433		28.1073		29.5588		29.2827	28.3899		23.3613		20.8353

Table 6.3: Monthwise Extra-Terrestrial Radiation (R_a) (MJ/ m^2 day) values for Pune

Date	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	26.6533	29.3539	33.1793	36.8945	38.7624	39.2139	39.1265	38.7140	37.2118	34.1110	29.9743	26.9812
2	26.6968	29.4785	33.3179	36.9865	38.7953	39.2152	39.1203	38.6881	37.1349	33.9836	29.8468	26.9209
3	26.7437	29.6046	33.4558	37.0765	38.8266	39.2160	39.1139	38.6610	37.0561	33.8552	29.7205	26.8637
4	26.7939	29.7322	33.5930	37.1643	38.8563	39.2164	39.1072	38.6326	36.9754	33.7258	29.5956	26.8097
5	26.8473	29.8612	33.7295	37.2501	38.8846	39.2164	39.1002	38.6031	36.8927	33.5955	29.4720	26.7588
6	26.9039	29.9917	33.8650	37.3337	38.9113	39.2160	39.0930	38.5722	36.8080	33.4642	29.3499	26.7112
7	26.9637	30.1234	33.9996	37.4153	38.9366	39.2153	39.0854	38.5400	36.7215	33.3322	29.2294	26.6667
8	27.0267	30.2563	34.1332	37.4947	38.9605	39.2142	39.0774	38.5065	36.6329	33.1993	29.1105	26.6256
9	27.0927	30.3903	34.2657	37.5720	38.9830	39.2128	39.0691	38.4715	36.5425	33.0658	28.9933	26.5878
10	27.1618	30.5254	34.3971	37.6472	39.0042	39.2111	39.0605	38.4351	36.4501	32.9317	28.8778	26.5532
11	27.2340	30.6614	34.5273	37.7203	39.0241	39.2091	39.0514	38.3973	36.3559	32.7970	28.7642	26.5221
12	27.3091	30.7983	34.6563	37.7913	39.0428	39.2069	39.0419	38.3579	36.2597	32.6618	28.6525	26.4943
13	27.3871	30.9360	34.7839	37.8603	39.0602	39.2044	39.0319	38.3170	36.1617	32.5262	28.5428	26.4698
14	27.4680	31.0744	34.9102	37.9271	39.0765	39.2017	39.0215	38.2746	36.0618	32.3903	28.4352	26.4488
15	27.5518	31.2134	35.0350	37.9918	39.0916	39.1988	39.0105	38.2305	35.9601	32.2541	28.3297	26.4312
16	27.6384	31.3530	35.1583	38.0545	39.1057	39.1956	38.9990	38.1848	35.8566	32.1178	28.2264	26.4171
17	27.7277	31.4930	35.2801	38.1152	39.1187	39.1923	38.9869	38.1375	35.7514	31.9813	28.1253	26.4063

Table 6.3 (Continued)

Date	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
18	27.8196	31.6334	35.4003	38.1738	39.1307	39.1888	38.9742	38.0884	35.6444	31.8448	28.0266	26.3991
19	27.9142	31.7741	35.5189	38.2305	39.1418	39.1851	38.9609	38.0377	35.5356	31.7083	27.9302	26.3953
20	28.0114	31.9150	35.6358	38.2851	39.1519	39.1812	38.9469	37.9852	35.4252	31.5719	27.8363	26.3949
21	28.1110	32.0561	35.7510	38.3378	39.1611	39.1771	38.9322	37.9309	35.3132	31.4358	27.7449	26.3980
22	28.2131	32.1971	35.8644	38.3885	39.1694	39.1729	38.9167	37.8749	35.1995	31.2999	27.6561	26.4046
23	28.3176	32.3382	35.9761	38.4373	39.1770	39.1685	38.9005	37.8170	35.0842	31.1644	27.5699	26.4147
24	28.4244	32.4791	36.0859	38.4843	39.1837	39.1639	38.8835	37.7573	34.9674	31.0294	27.4864	26.4282
25	28.5335	32.6198	36.1938	38.5293	39.1898	39.1591	38.8657	37.6958	34.8492	30.8948	27.4056	26.4451
26	28.6447	32.7603	36.2998	38.5726	39.1951	39.1542	38.8469	37.6324	34.7295	30.7609	27.3276	26.4655
27	28.7580	32.9004	36.4039	38.6140	39.1997	39.1491	38.8273	37.5670	34.6083	30.6276	27.2525	26.4893
28	28.8734	33.0401	36.5060	38.6537	39.2037	39.1437	38.8067	37.4998	34.4859	30.4951	27.1802	26.5166
29	28.9908		36.6062	38.6916	39.2071	39.1382	38.7851	37.4307	34.3621	30.3634	27.1109	26.5472
30	29.1100		36.7043	38.7278	39.2099	39.1325	38.7625	37.3597	34.2371	30.2327	27.0445	26.5813
31	29.2311		36.8005		39.2122		38.7388	37.2867		30.1030		26.6187

Table 6.4: Monthwise Clear Sky Radiation values for Pune

Date	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	20.3268	22.3865	25.3038	28.1372	29.5617	29.9061	29.8395	29.5248	28.3792	26.0144	22.8596	20.5769
2	20.3601	22.4814	25.4095	28.2074	29.5868	29.9071	29.8347	29.5051	28.3206	25.9173	22.7624	20.5309
3	20.3958	22.5776	25.5147	28.2760	29.6107	29.9077	29.8298	29.4844	28.2605	25.8194	22.6661	20.4873
4	20.4341	22.6750	25.6194	28.3430	29.6334	29.9080	29.8247	29.4628	28.1989	25.7207	22.5708	20.4461
5	20.4748	22.7734	25.7234	28.4084	29.6549	29.9080	29.8194	29.4402	28.1358	25.6213	22.4765	20.4073
6	20.5180	22.8729	25.8268	28.4722	29.6753	29.9077	29.8139	29.4167	28.0713	25.5212	22.3834	20.3710
7	20.5636	22.9733	25.9295	28.5344	29.6946	29.9071	29.8081	29.3922	28.0053	25.4204	22.2915	20.3371
8	20.6116	23.0747	26.0314	28.5950	29.7128	29.9063	29.8020	29.3666	27.9377	25.3191	22.2008	20.3057
9	20.6620	23.1769	26.1324	28.6539	29.7300	29.9052	29.7957	29.3399	27.8688	25.2173	22.1114	20.2769
10	20.7147	23.2799	26.2326	28.7113	29.7462	29.9039	29.7891	29.3122	27.7983	25.1150	22.0234	20.2506
11	20.7697	23.3836	26.3319	28.7670	29.7614	29.9024	29.7821	29.2833	27.7264	25.0123	21.9367	20.2268
12	20.8270	23.4880	26.4303	28.8212	29.7756	29.9007	29.7749	29.2533	27.6531	24.9092	21.8516	20.2056
13	20.8865	23.5930	26.5276	28.8737	29.7889	29.8989	29.7673	29.2221	27.5784	24.8058	21.7679	20.1870
14	20.9482	23.6986	26.6239	28.9247	29.8013	29.8968	29.7593	29.1897	27.5022	24.7021	21.6858	20.1709
15	21.0121	23.8046	26.7191	28.9741	29.8129	29.8946	29.7510	29.1561	27.4246	24.5983	21.6054	20.1575
16	21.0781	23.9111	26.8131	29.0219	29.8236	29.8922	29.7422	29.1213	27.3457	24.4943	21.5266	20.1467
17	21.1462	24.0178	26.9060	29.0682	29.8335	29.8896	29.7330	29.0852	27.2654	24.3902	21.4495	20.1385

Table 6.4 (Continued)

Date	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
18	21.2164	24.1249	26.9977	29.1129	29.8427	29.8869	29.7233	29.0478	27.1838	24.2861	21.3742	20.1330
19	21.2885	24.2322	27.0881	29.1561	29.8511	29.8841	29.7131	29.0091	27.1009	24.1820	21.3007	20.1301
20	21.3626	24.3397	27.1773	29.1978	29.8588	29.8811	29.7024	28.9690	27.0167	24.0780	21.2291	20.1298
21	21.4386	24.4472	27.2651	29.2379	29.8658	29.8780	29.6912	28.9276	26.9312	23.9742	21.1594	20.1322
22	21.5165	24.5548	27.3517	29.2766	29.8722	29.8748	29.6795	28.8849	26.8445	23.8706	21.0917	20.1372
23	21.5962	24.6624	27.4368	29.3138	29.8779	29.8714	29.6671	28.8408	26.7566	23.7672	21.0259	20.1449
24	21.6776	24.7699	27.5205	29.3496	29.8831	29.8679	29.6541	28.7952	26.6676	23.6642	20.9622	20.1552
25	21.7608	24.8772	27.6028	29.3840	29.8877	29.8643	29.6405	28.7483	26.5774	23.5616	20.9006	20.1681
26	21.8456	24.9843	27.6837	29.4170	29.8917	29.8605	29.6262	28.6999	26.4861	23.4595	20.8411	20.1837
27	21.9320	25.0912	27.7631	29.4486	29.8953	29.8566	29.6112	28.6501	26.3937	23.3578	20.7838	20.2018
28	22.0200	25.1977	27.8410	29.4788	29.8983	29.8526	29.5955	28.5989	26.3003	23.2568	20.7287	20.2226
29	22.1095		27.9174	29.5078	29.9009	29.8484	29.5791	28.5462	26.2059	23.1564	20.6758	20.2460
30	22.2005		27.9922	29.5354	29.9030	29.8440	29.5618	28.4920	26.1106	23.0567	20.6252	20.2719
31	22.2928		28.0655		29.9048		29.5437	28.4363		22.9577		20.3005

Table 6.5: Monthwise Extra-Terrestrial Radiation (R_a) (MJ/ m^2 day) values for Kolhapur

Date	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	27.6599	30.2286	33.9258	37.2050	38.6465	38.8245	38.7023	38.4625	37.2624	34.4935	30.6712	27.9085
2	27.7017	30.3461	34.0524	37.2818	38.6673	38.8209	38.6987	38.4448	37.1964	34.3771	30.5528	27.8542
3	27.7466	30.4651	34.1781	37.3565	38.6866	38.8171	38.6951	38.4260	37.1285	34.2595	30.4355	27.8030
4	27.7947	30.5854	34.3029	37.4291	38.7046	38.8132	38.6915	38.4062	37.0587	34.1410	30.3194	27.7547
5	27.8458	30.7071	34.4268	37.4997	38.7212	38.8091	38.6878	38.3852	36.9870	34.0214	30.2047	27.7095
6	27.9000	30.8299	34.5496	37.5682	38.7366	38.8048	38.6840	38.3631	36.9133	33.9009	30.0913	27.6673
7	27.9572	30.9538	34.6713	37.6347	38.7507	38.8005	38.6801	38.3398	36.8377	33.7796	29.9794	27.6283
8	28.0174	31.0787	34.7918	37.6990	38.7636	38.7961	38.6761	38.3152	36.7603	33.6574	29.8690	27.5924
9	28.0805	31.2046	34.9111	37.7613	38.7754	38.7917	38.6720	38.2893	36.6809	33.5345	29.7603	27.5597
10	28.1466	31.3314	35.0291	37.8216	38.7861	38.7872	38.6676	38.2621	36.5996	33.4110	29.6532	27.5302
11	28.2155	31.4590	35.1457	37.8798	38.7957	38.7827	38.6631	38.2336	36.5165	33.2868	29.5478	27.5038
12	28.2872	31.5872	35.2610	37.9359	38.8042	38.7782	38.6583	38.2036	36.4314	33.1621	29.4443	27.4807
13	28.3616	31.7161	35.3748	37.9901	38.8118	38.7737	38.6533	38.1722	36.3446	33.0370	29.3427	27.4609
14	28.4388	31.8456	35.4871	38.0422	38.8184	38.7693	38.6479	38.1393	36.2558	32.9114	29.2430	27.4443
15	28.5187	31.9755	35.5978	38.0924	38.8242	38.7649	38.6423	38.1050	36.1653	32.7856	29.1454	27.4310
16	28.6012	32.1058	35.7069	38.1406	38.8291	38.7605	38.6363	38.0691	36.0730	32.6595	29.0499	27.4210
17	28.6862	32.2365	35.8144	38.1869	38.8332	38.7562	38.6299	38.0316	35.9788	32.5332	28.9565	27.4143

Table 6.5 (Continued)

Date	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
18	28.7738	32.3673	35.9202	38.2312	38.8365	38.7519	38.6231	37.9925	35.8830	32.4068	28.8653	27.4109
19	28.8638	32.4983	36.0242	38.2737	38.8391	38.7477	38.6158	37.9518	35.7854	32.2805	28.7764	27.4107
20	28.9562	32.6293	36.1265	38.3143	38.8410	38.7436	38.6080	37.9094	35.6861	32.1541	28.6899	27.4139
21	29.0510	32.7603	36.2270	38.3530	38.8423	38.7395	38.5997	37.8653	35.5852	32.0279	28.6058	27.4204
22	29.1480	32.8912	36.3256	38.3899	38.8429	38.7356	38.5909	37.8195	35.4826	31.9020	28.5241	27.4302
23	29.2472	33.0220	36.4224	38.4251	38.8430	38.7316	38.5814	37.7720	35.3785	31.7763	28.4450	27.4434
24	29.3486	33.1525	36.5173	38.4585	38.8426	38.7278	38.5713	37.7227	35.2728	31.6510	28.3684	27.4598
25	29.4520	33.2826	36.6102	38.4902	38.8417	38.7240	38.5605	37.6716	35.1656	31.5261	28.2944	27.4795
26	29.5575	33.4124	36.7012	38.5203	38.8403	38.7203	38.5490	37.6187	35.0570	31.4018	28.2232	27.5024
27	29.6649	33.5416	36.7902	38.5486	38.8385	38.7167	38.5367	37.5640	34.9469	31.2780	28.1546	27.5286
28	29.7742	33.6703	36.8772	38.5754	38.8364	38.7130	38.5236	37.5074	34.8355	31.1550	28.0888	27.5581
29	29.8853	33.7984	36.9622	38.6006	38.8338	38.7094	38.5097	37.4490	34.7227	31.0327	28.0258	27.5908
30	29.9981		37.0452	38.6243	38.8310	38.7059	38.4949	37.3887	34.6087	30.9113	27.9657	27.6267
31	30.1125		37.1261		38.8279		38.4791	37.3265		30.7907		27.6658

Table 6.6: Monthwise Extra-Terrestrial Radiation (R_a) (MJ/ m^2 day) values for Ahmednagar

Date	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	26.3474	29.0865	33.1290	36.9137	38.8328	39.3259	39.2394	38.7489	37.0895	33.8240	29.7240	26.6818
2	26.3915	29.2130	33.2703	37.0075	38.8673	39.3281	39.2321	38.7189	37.0068	33.6920	29.5942	26.6206
3	26.4390	29.3412	33.4109	37.0993	38.9002	39.3297	39.2244	38.6877	36.9222	33.5591	29.4656	26.5626
4	26.4897	29.4710	33.5508	37.1890	38.9315	39.3309	39.2164	38.6552	36.8357	33.4253	29.3384	26.5077
5	26.5438	29.6022	33.6898	37.2765	38.9613	39.3316	39.2081	38.6213	36.7471	33.2905	29.2127	26.4561
6	26.6011	29.7349	33.8279	37.3620	38.9896	39.3320	39.1993	38.5861	36.6567	33.1550	29.0884	26.4078
7	26.6617	29.8689	33.9650	37.4453	39.0164	39.3318	39.1902	38.5495	36.5643	33.1550	28.9658	26.3627
8	26.7254	30.0041	34.1011	37.5265	39.0418	39.3314	39.1806	38.5114	36.4699	33.0188	28.8448	26.3209
9	26.7923	30.1406	34.2361	37.6056	39.0659	39.3305	39.1705	38.4718	36.3737	32.8819	28.7256	26.2825
10	26.8623	30.2781	34.3699	37.6826	39.0886	39.3293	39.1600	38.4308	36.2755	32.7444	28.6082	26.2475
11	26.9354	30.4166	34.5025	37.7574	39.1100	39.3277	39.1490	38.3882	36.1755	32.6064	28.4927	26.2158
12	27.0115	30.5560	34.6338	37.8302	39.1301	39.3259	39.1375	38.3440	36.0736	32.4680	28.3792	26.1876
13	27.0906	30.6963	34.7638	37.9008	39.1490	39.3237	39.1254	38.2982	35.9699	32.3292	28.2677	26.1628
14	27.1726	30.8373	34.8923	37.9694	39.1667	39.3213	39.1127	38.2507	35.8643	32.1901	28.1583	26.1414
15	27.2575	30.9790	35.0194	38.0358	39.1833	39.3185	39.0994	38.2016	35.7569	32.0508	28.0511	26.1235
16	27.3452	31.1213	35.1450	38.1002	39.1988	39.3155	39.0855	38.1509	35.6478	31.9113	27.9461	26.1091
17	27.4357	31.2641	35.2690	38.1626	39.2132	39.3122	39.0709	38.0983	35.5369	31.7717	27.8434	26.0982

Table 6.6 (Continued)

Date	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
18	27.5290	31.4073	35.3914	38.2229	39.2265	39.3087	39.0556	38.0441	35.4244	31.6322	27.7431	26.0908
19	27.6249	31.5509	35.5121	38.2812	39.2389	39.3049	39.0396	37.9880	35.3101	31.4927	27.6453	26.0868
20	27.7235	31.6947	35.6312	38.3375	39.2503	39.3008	39.0228	37.9302	35.1942	31.3535	27.5499	26.0864
21	27.8245	31.8387	35.7485	38.3919	39.2609	39.2965	39.0052	37.8705	35.0768	31.2144	27.4571	26.0895
22	27.9281	31.9827	35.8640	38.4443	39.2705	39.2920	38.9868	37.8091	34.9577	31.0757	27.3669	26.1062
23	28.0341	32.1268	35.9777	38.4947	39.2793	39.2872	38.9675	37.7457	34.8372	30.9374	27.2794	26.1198
24	28.1425	32.2708	36.0895	38.5433	39.2872	39.2822	38.9473	37.6805	34.7152	30.7996	27.1946	26.1370
25	28.2532	32.4147	36.1994	38.5900	39.2944	39.2769	38.9261	37.6133	34.5917	30.6623	27.1126	26.1576
26	28.3661	32.5583	36.3074	38.6349	39.3009	39.2713	38.9040	37.5443	34.4669	30.5257	27.0334	26.1816
27	28.4812	32.7017	36.4135	38.6780	39.3066	39.2655	38.8809	37.4734	34.3407	30.3898	26.9571	26.2092
28	28.5983	32.8446	36.5176	38.7192	39.3117	39.2594	38.8567	37.4005	34.2133	30.2547	26.8838	26.2402
29	28.7175	32.9871	36.6196	38.7588	39.3162	39.2530	38.8315	37.3257	34.0847	30.1205	26.8134	26.2746
30	28.8387		36.7197	38.7966	39.3200	39.2464	38.8051	37.2489	33.9549	29.9873	26.7461	26.3124
31	28.9617		36.8177		39.3232		38.7776	37.1702		29.8551		26.3537

$$R_s = \left(a_s + \left(b_s\left(\frac{n_a}{N_m}\right)\right)\right)R_a \qquad (6.11)$$

R_s = solar (or shortwave) radiation (MJ/ m^2 d),

a_s = 0.25 and b_s = 0.50 are as recommended by FAO-56,

n_a = actual duration of sunshine, [hour],

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

n_a/N_m = relative sunshine duration.

$$R_{ns} = (1 - ə)R_s \qquad (6.12)$$

Where,

R_{ns}= net solar (or net short wave) radiation,

ə = albedo or canopy reflection coefficient = 0.23 for hypothetical grass (i.e., reference crop) (dimensionless).

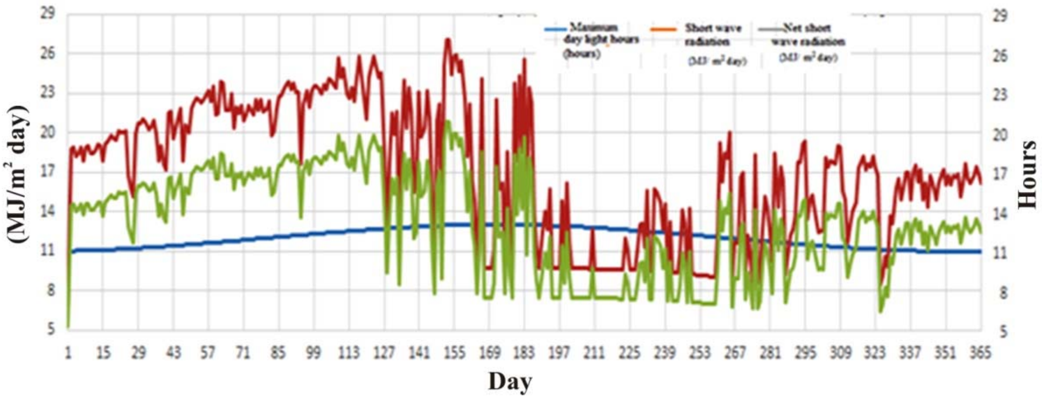


Figure 6.8: Typical Short Wave Radiation for the Year 1999 for Sholapur

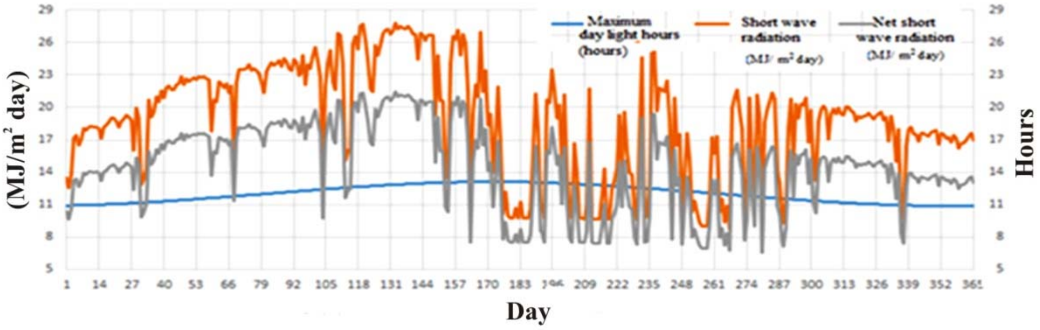


Figure 6.9: Typical Shortwave Radiation for the Year 2005 for Pune

Net long wave radiation R_{nl}

$$R_{nl} = \left(\frac{\sigma(T_{max}K^4 + T_{min}K^4)}{2}\right)(0.34 - 0.14\, E_a 0.5)\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \qquad (6.13)$$

R_{nl}= Net long wave radiation,

$T_{max}\,K^4$ = maximum absolute temperature during the 24-hour period [K = °C + 273.16],

$T_{min}\,K^4$ = minimum absolute temperature during the 24-hour period [K = °C + 273.16],

σ = Stefan-Boltzmann Constant [4.901 (10^{-9}) M J K^{-4} m^{-2} d^{-1}].

$$R_n = R_{ns} - R_{nl} \qquad (6.14)$$

R_n = net radiation at the crop surface.

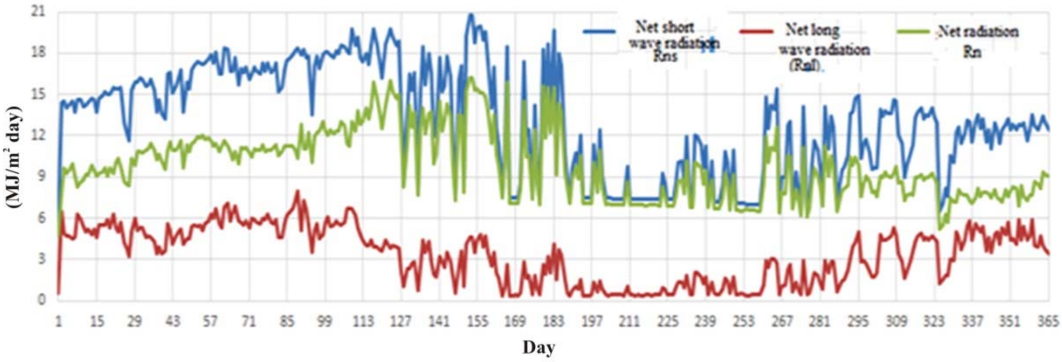


Figure 6.10: Typical Variation of R_{ns}, R_{nl} and R_n for the year 1999 for Sholapur

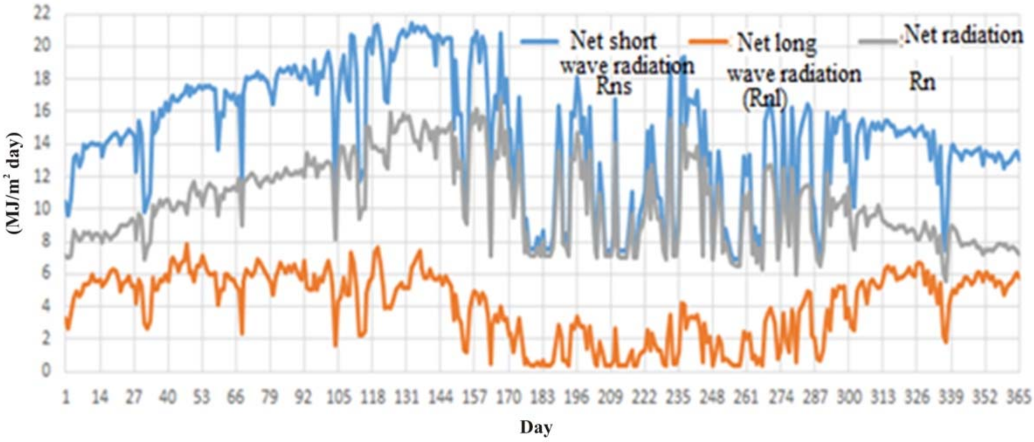


Figure 6.11: Typical Variation of R_{ns}, R_{nl} and R_n for the year 2005 for Pune

6.2.3 Wind Speed

The average daily wind speed (m s^{-1}) measured at 2 m above the ground level at the research station is required. It is important one to verify the height at which wind speed is measured in the study area, as wind speeds measured at different heights above the soil surface vary temporally in metrological station. The wind speed measured at heights other than 2 m need to be adjusted according to the following equation.

$$U_2 = U_z\left(\frac{4.87}{\text{In}(67.8\,\text{h}-5.42)}\right) \tag{6.15}$$

U_2 = wind speed at 2 m above the ground surface, m s^{-1},
U_z = measured wind speed at z m above the ground surface (m /s),
Z = height of the measurement location above the ground surface (m).

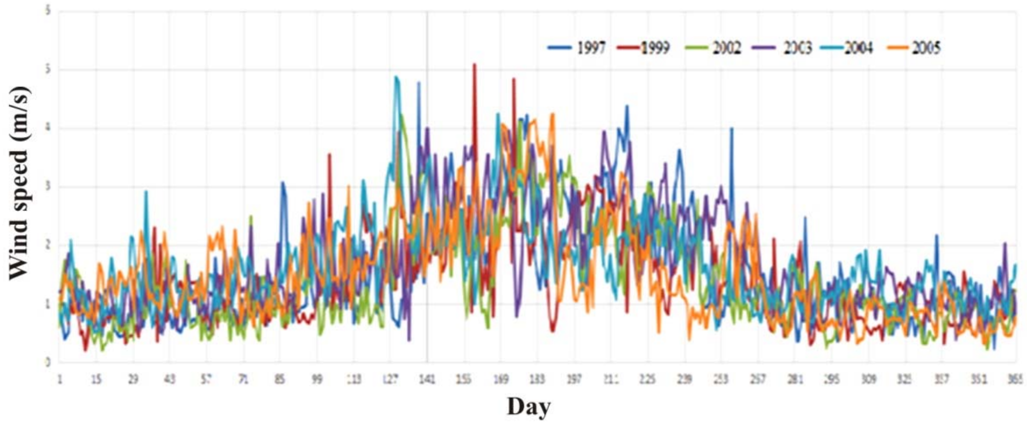


Figure 6.12: Wind Speed 2m above Ground Surface for Sholapur

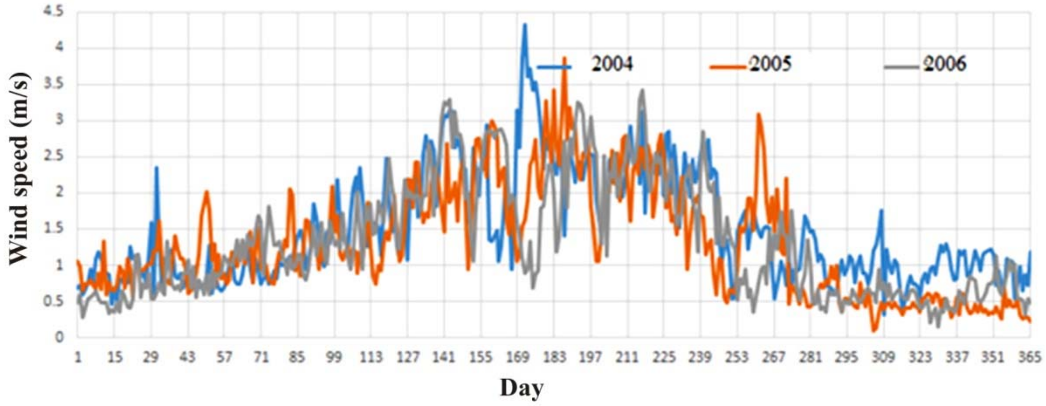


Figure 6.13: Wind Speed 2m above Ground Surface for Pune

6.2.4 Slope of The Saturation Vapour Pressure

For the calculation of evapotranspiration, the slope of the relationship between saturation vapour pressure and temperature is calculated as follows:

$$\Delta = 4098\left(\frac{0.6108\exp\left(\frac{17.27\,T_{mean}}{T_{mean}+237.3}\right)}{(T_{mean}+273.3)^2}\right) \tag{6.16}$$

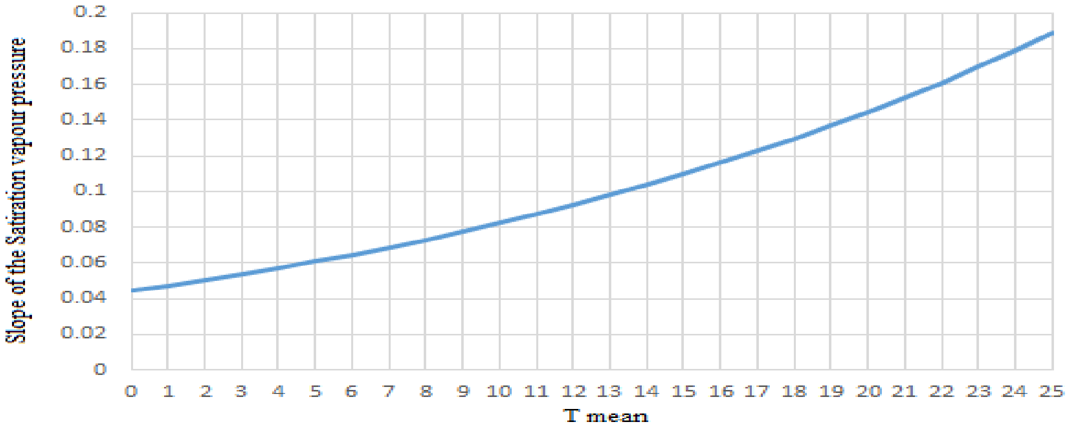


Figure 6.14: Slope of Saturation Vapour Pressure Verses T_{mean}

6.2.5 Atmospheric Pressure

The atmospheric pressure, P is calculated as follows:

$$P = 101.3\left(\frac{293-0.0065\,z}{293}\right)^{5.26} \tag{6.17}$$

Where, Z = elevation above mean sea level (m),

P = atmospheric pressure kPa.

For Pune, P = 94.04908 kPa;

For Sholapur, P = 95.7123 kPa;

For Ahmednagar, P = 93.8600 kPa;

For Kolhapur, P = 95.0103 kPa.

6.2.6 Psychrometric Constant

Psychrometric constant (γ) is calculated by the following equation.

$$\gamma = C_p \frac{P}{\varepsilon}\,\lambda = -0.000665\ 10^{-3}p \tag{6.18}$$

γ = psychrometric constant kPa/ °C,

P = atmospheric pressure kPa,

λ = latent heat of vaporization = 2.45 MJ /kg,

C_p = specific heat of water at constant pressure 1.013 (10^{-3}) MJ kg^{-1} $°C^{-1}$,

$\acute{\varepsilon}$ = ratio of molecular weight of water vapour to that of dry air = 0.622.

Estimated Psychrometric constant (γ) for Pune is 0.0625kPa/°C.

Estimated Psychrometric constant (γ) for Sholapur is 0.0636 kPa/°C.

Estimated Psychrometric constant (γ) for Ahmednagar is 0.0624 kPa/°C.

Estimated Psychrometric constant (γ) for Kolhapur is 0.0632 kPa/°C.

6.2.7 Actual Vapour Pressure (E_a)

$$E_a = \frac{E^0(T_{min})\left(\left(\frac{RH_{max}}{100}\right)\right) + \left(E^0(T_{max})\frac{RH_{min}}{100}\right)}{2} \tag{6.19}$$

$$E^0(T_{max}) = 0.6108\left(\exp\left(\frac{17.27\,T_{max}}{T_{max}+237.3}\right)\right) \tag{6.20}$$

$$E^0(T_{min}) = 0.6108\left(\exp\left(\frac{17.27\,T_{min}}{T_{min}+237.3}\right)\right) \tag{6.21}$$

6.2.8 Saturation Vapour Pressure (E_s)

As saturation vapour pressure is related to air temperature, it can be calculated from the air temperature.

$$E_s = \frac{E^0(T_{max}) + E^0(T_{min})}{2} \tag{6.22}$$

6.2.9 Vapour Pressure Deficit ($E_s - E_a$)

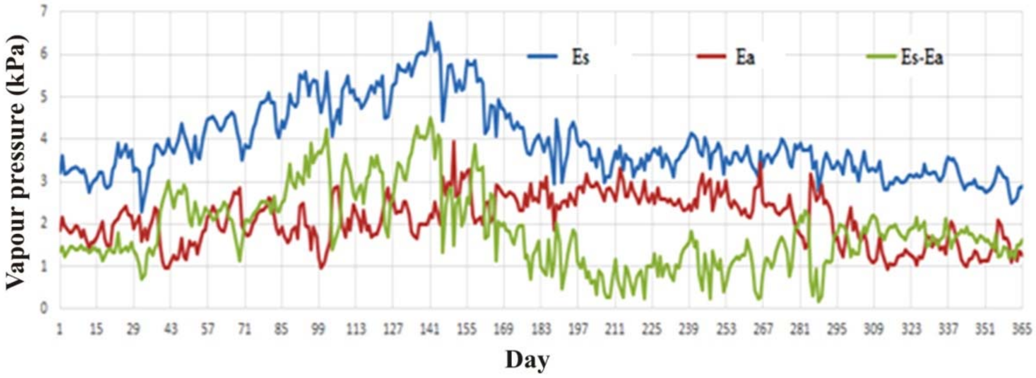


Figure 6.15: Saturation Vapour Pressure Deficit (kPa) for Sholapur (2005)

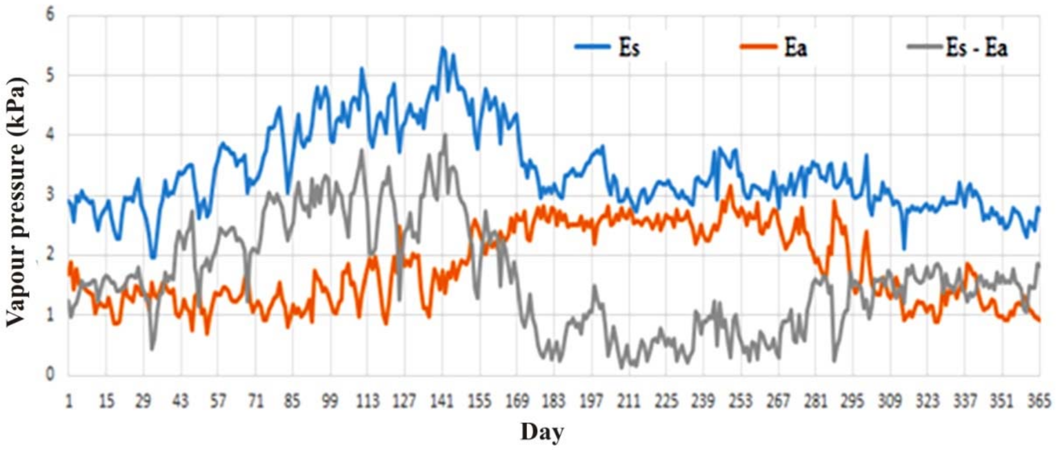


Figure 6.16: Saturation Vapour Pressure Deficit for Pune (2005)

6.2.10 Soil Heat Flux (G)

The soil heat flux (G) is small compared to R_n and is ignored.

6.3 OTHER IMPORTANT MODELS USED IN ET_o ESTIMATION

6.3.1 Hargreaves Method

Hargreaves et al. (1985) developed an alternative approach. The model requires only maximum, minimum temperature and extraterrestrial radiation. This type of models are used where data required for estimating ET_o by FAO is not available. The model used and developed by Hargreaves et al. (1985) is as follows:

$$ET_o = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}R_a \tag{6.23}$$

Allen et al. (1998) found that above equation has a tendency to under-predict under high wind conditions (U_2 > 3 m/s) and to over-predict under conditions of high relative humidity. To overcome this lacuna, Hargreaves (1994) developed the Modified Hargreaves Equation. This equation can be used where the accurate data collection is difficult.

$$ET_o = (0.0023)\ (0.408)\ (T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}R_a \tag{6.24}$$

The model proposed for Semi-Arid climatic zone of western Maharashtra is as follows:

$$ET_o = (0.0023)\ (0.3521)\ (T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}R_a \tag{6.25}$$

There are six districts in semi-arid zone of western Maharashtra. The climatological and physical parameters for Pune, Sholapur, Kolhapur and Ahmednagar were collected and analyzed.

The above discussed models (FAO-56), Original Hargreaves Method (OHAG), Modified Hargreaves Method (MHAG) and proposed Hargreaves Method (DHAG) are used to estimate ET_o.. The results for Pune, Sholapur, Ahmednagar and Kolhapur are presented graphically as below and the estimated values are presented in appendix-E in tabular form. The sensitivity analysis for this research stations are also performed and presented.

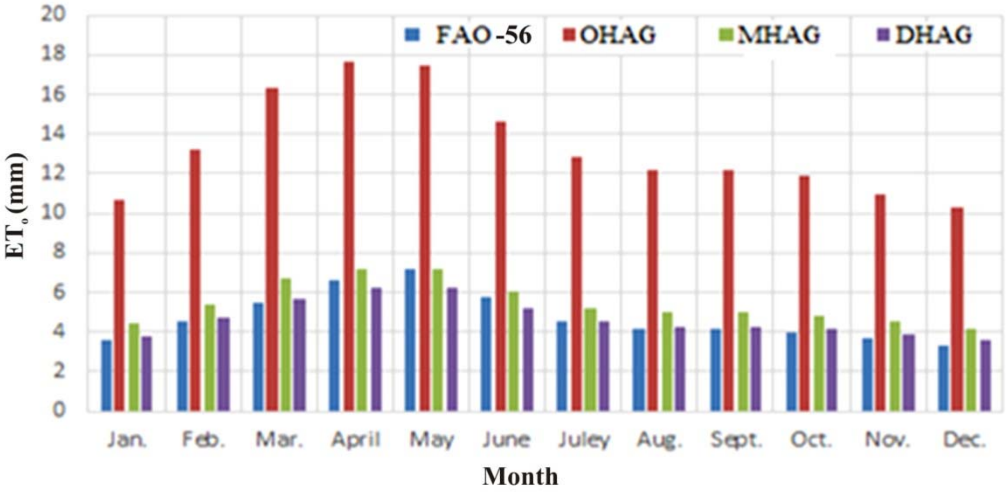


Figure 6.17: Monthly Mean ET_o for Sholapur

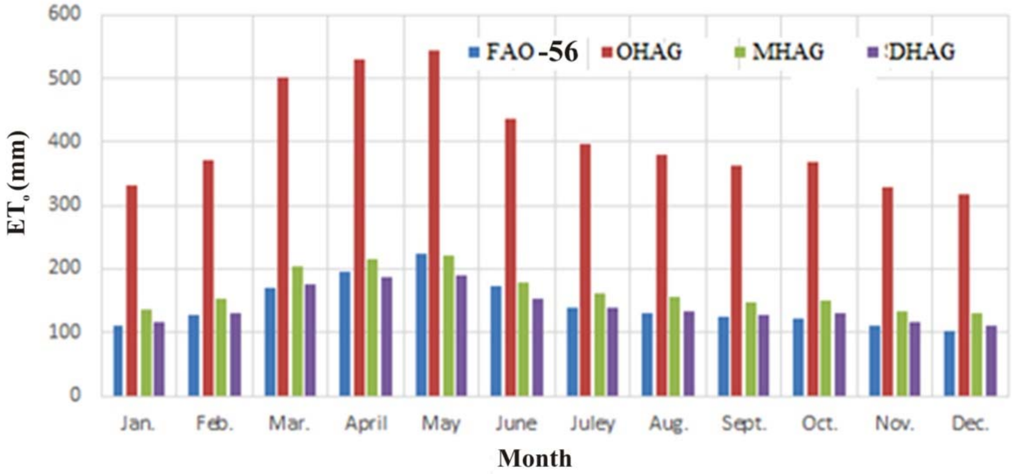


Figure 6.18: Monthly Total ET_o for Sholapur

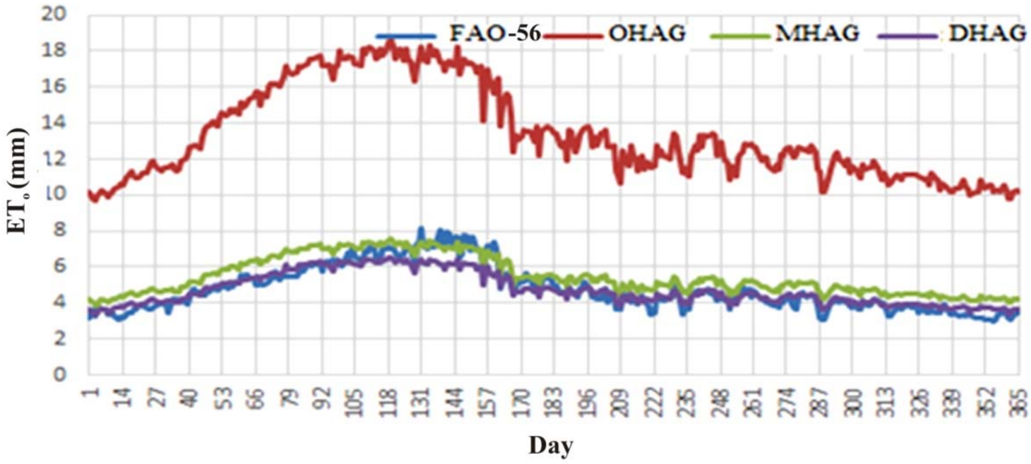


Figure 6.19: Mean Daily ET$_0$ Variation in a Year for Sholapur

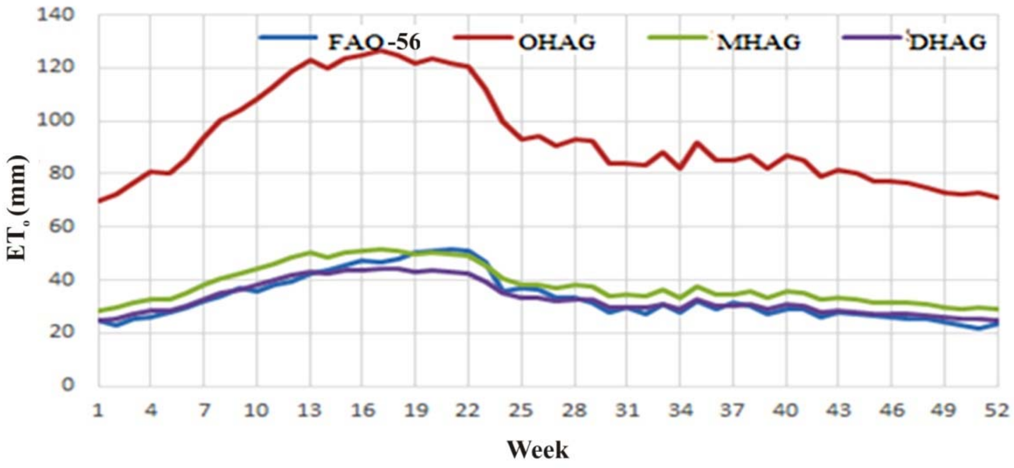
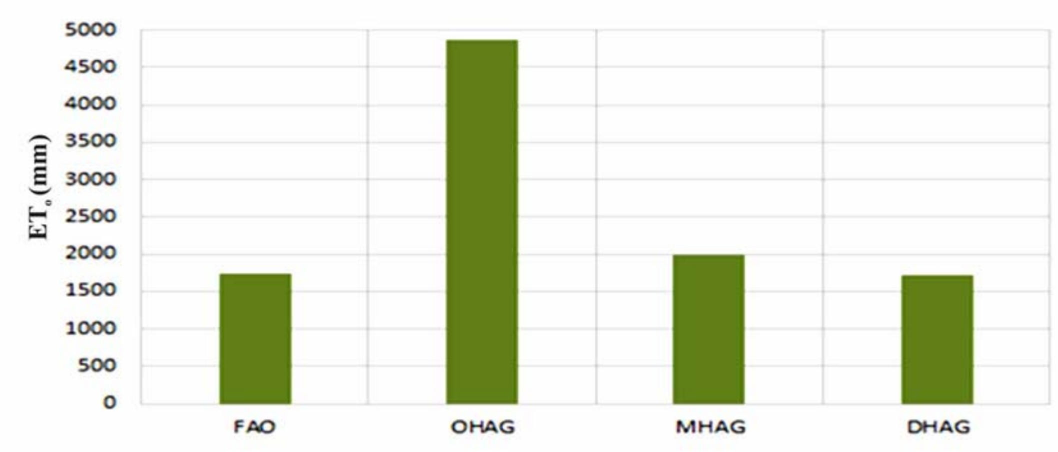


Figure 6.20: Weekly ET$_0$ for Sholapur



Models ⟶

Figure 6.21: Yearly Total ET$_0$ Estimation by Different Models for Sholapur

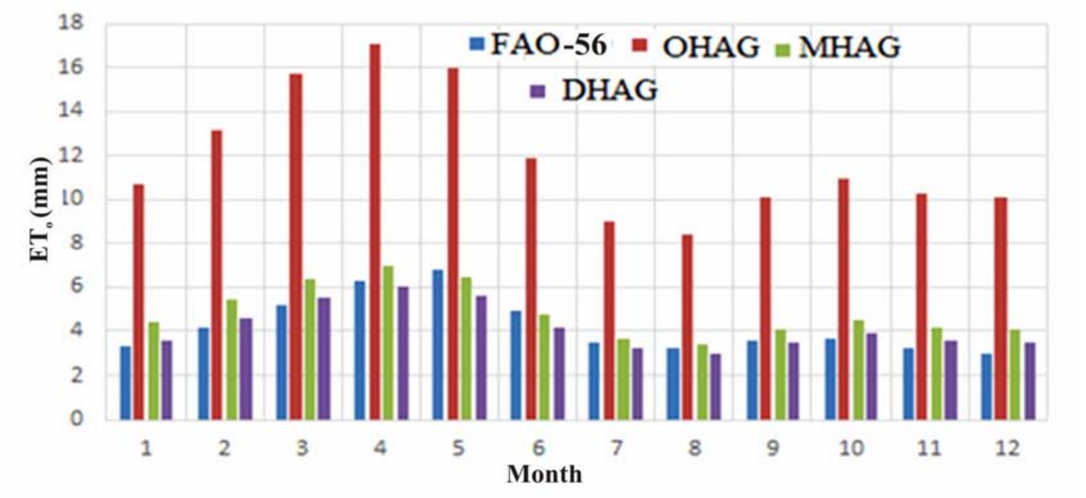


Figure 6.22: Monthly Mean ET$_o$ for Pune

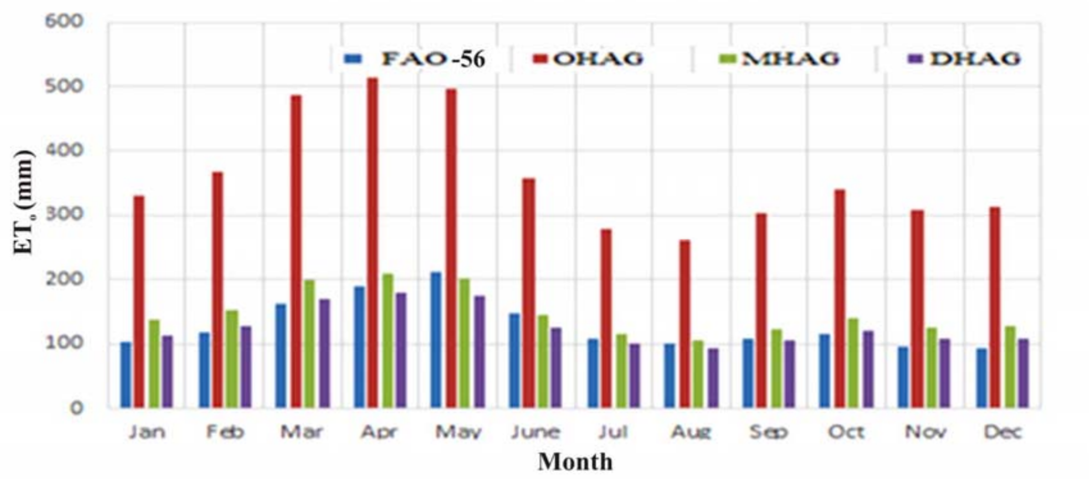


Figure 6.23: Monthly Total ET$_o$ for Pune

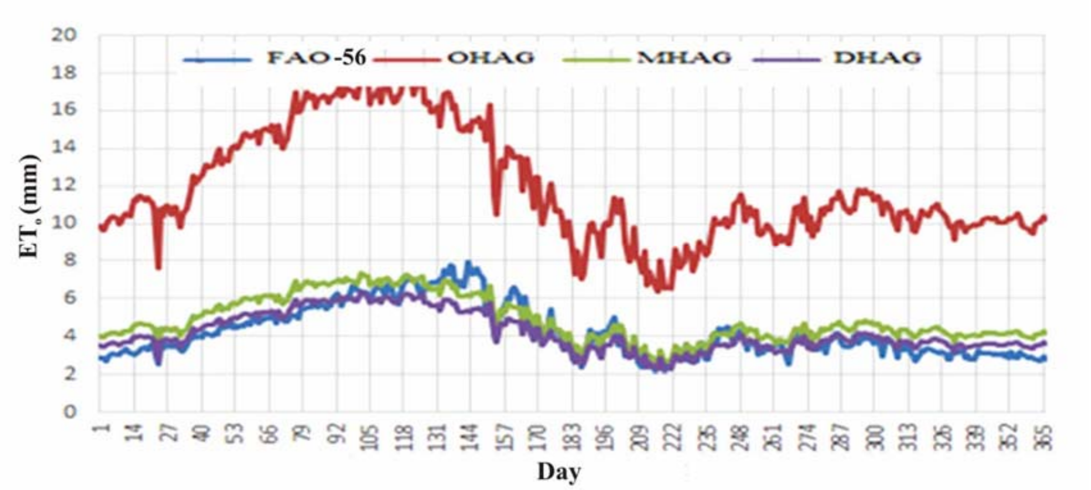


Figure 6.24: Mean Daily ET$_o$ Variation in a year for Pune

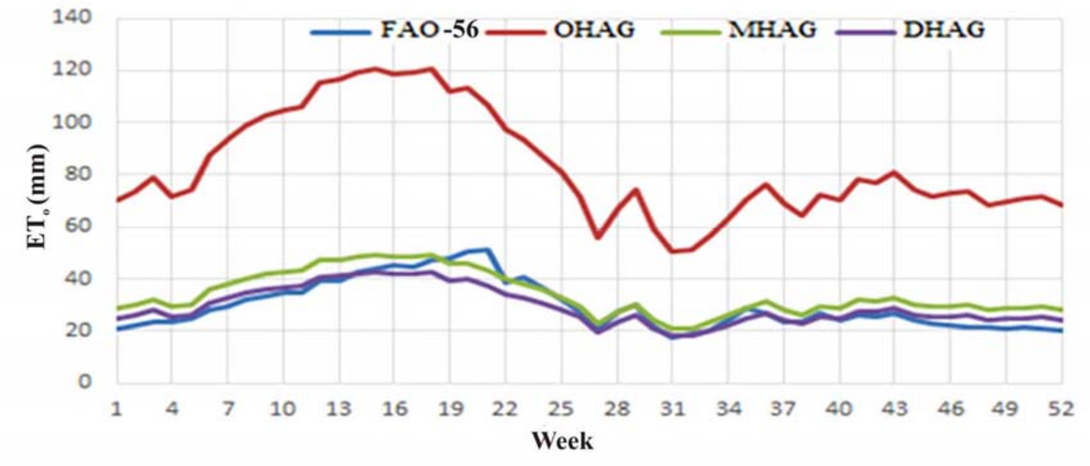
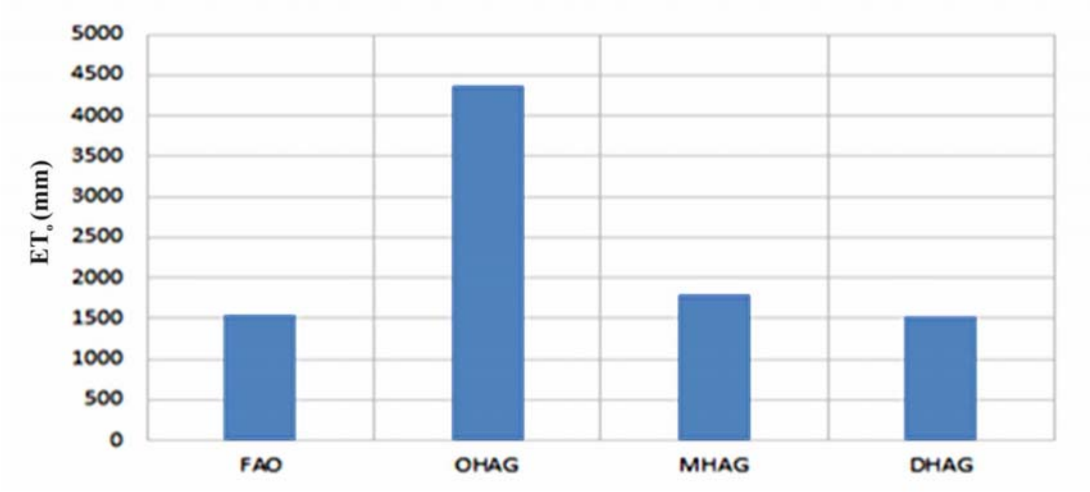


Figure 6.25: Weekly ET$_o$ for Pune



Models ⟶

Figure 6.26: Yearly Total ET$_o$ Estimated by Different Model for Pune

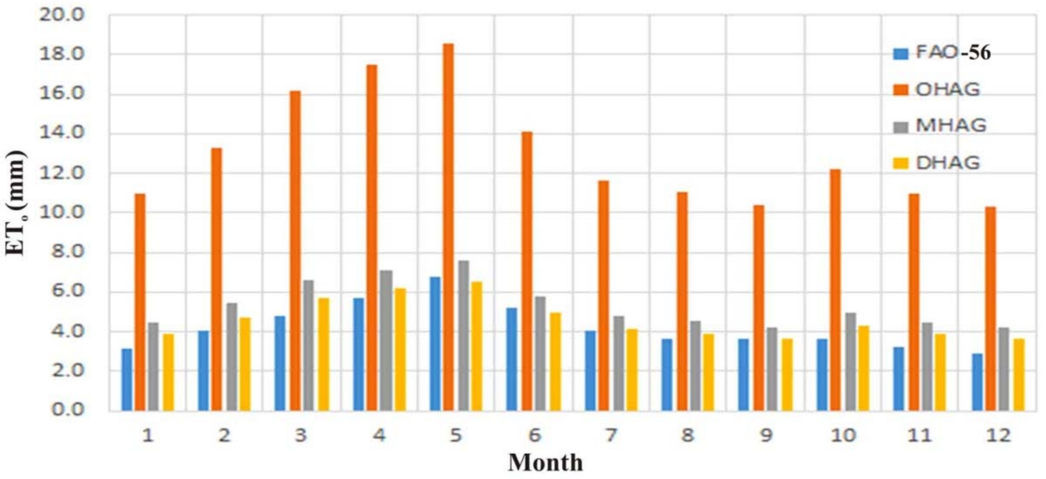


Figure 6.27: Monthly Mean ET$_o$ for Ahmednagar

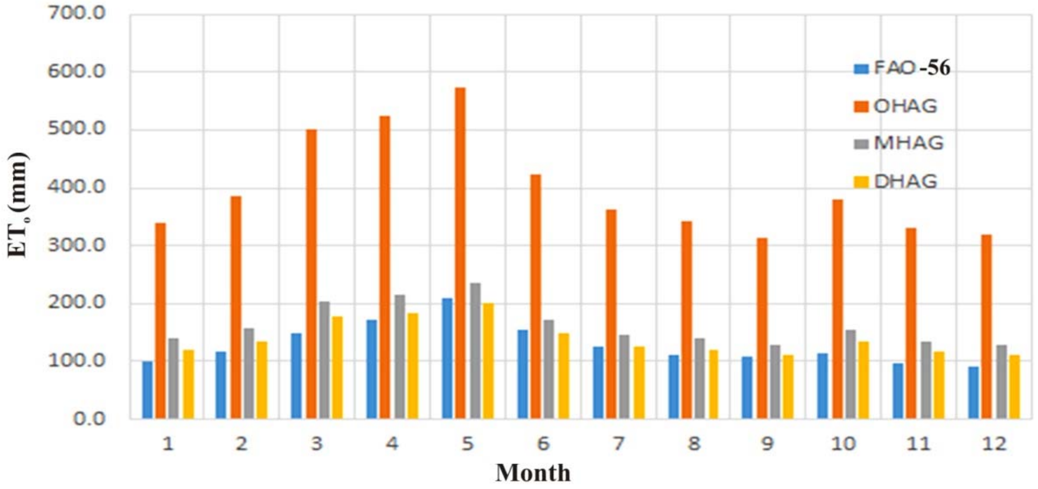


Figure 6.28: Monthly Total ET₀ for Ahmednagar

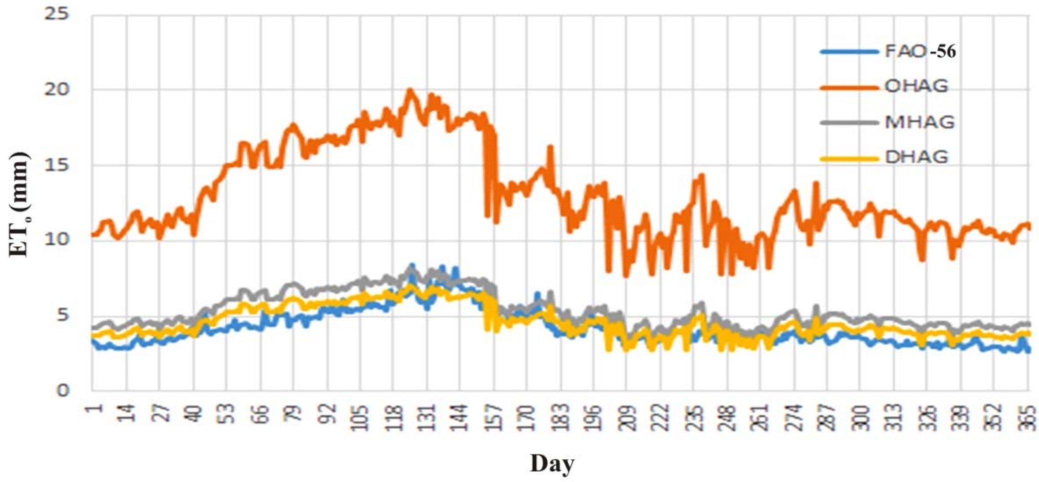


Figure 6.29: Mean Daily ET₀ Variation in a year for Ahmednagar

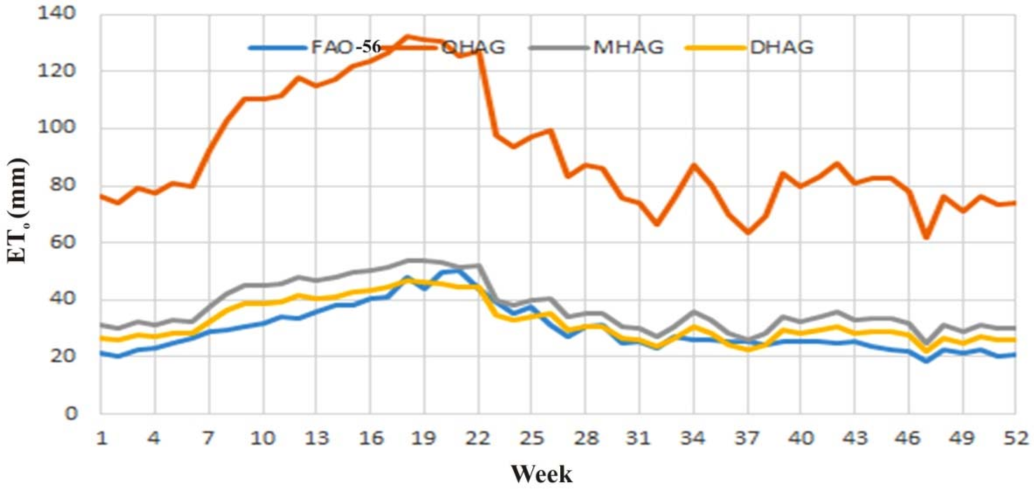


Figure 6.30: Weekly ET₀ for Ahmednagar

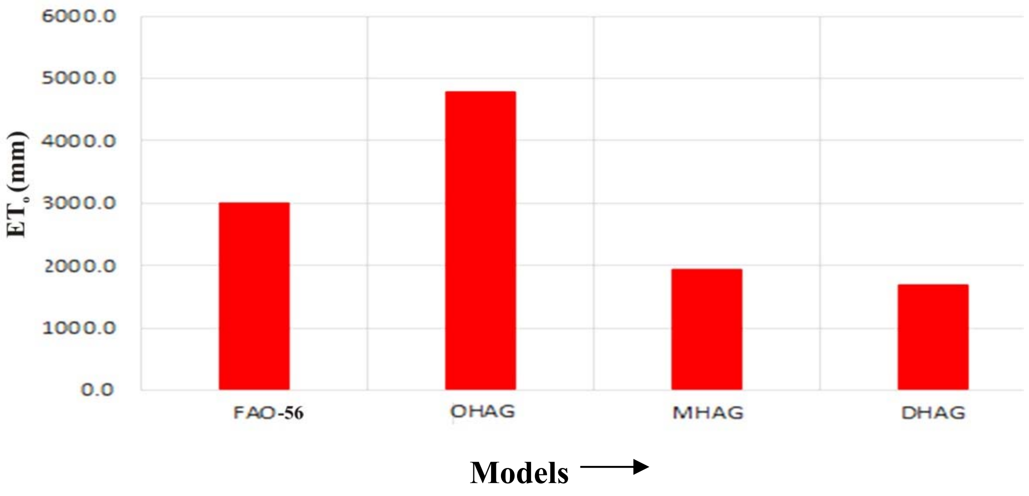


Figure 6.31: Yearly Total ET_o Estimated by Different Models for Ahmednagar

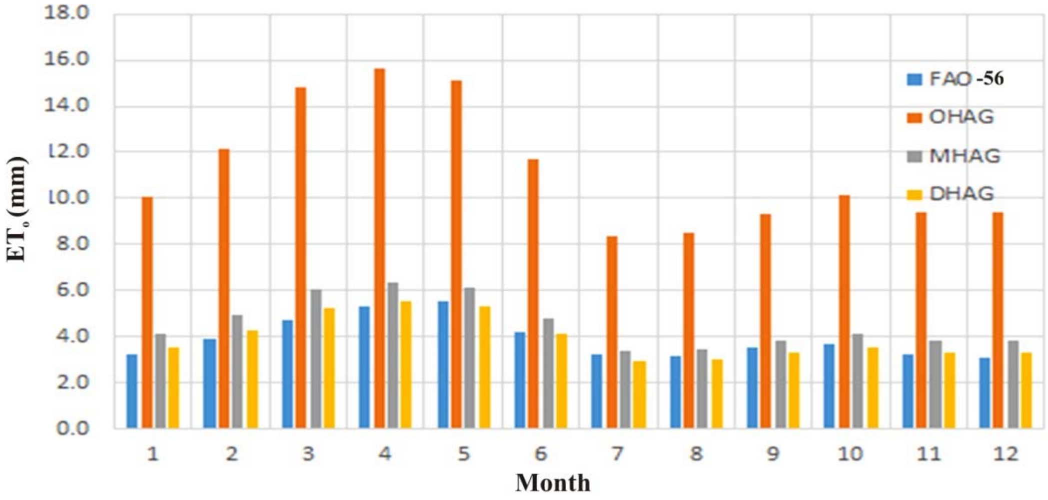


Figure 6.32: Monthly Mean ET_o for Kolhapur

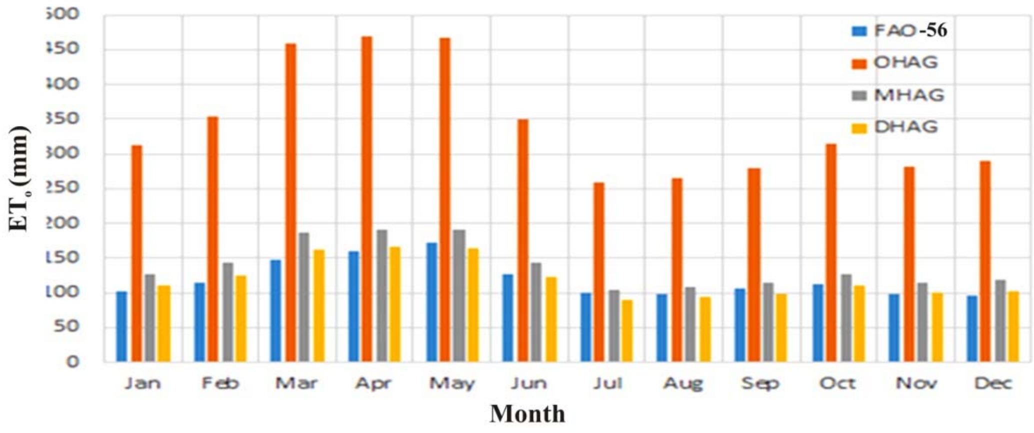


Figure 6.33: Monthly Total ET_o for Kolhapur

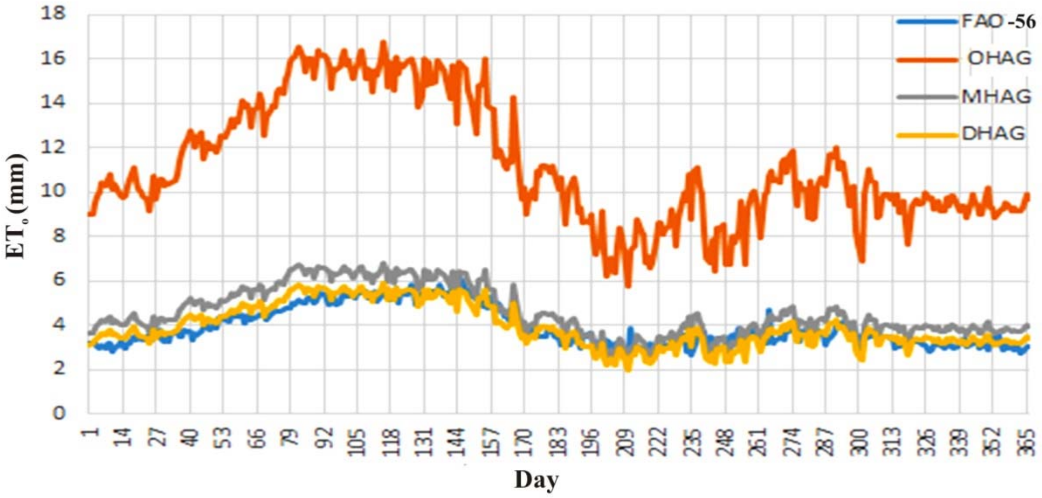


Figure 6.34: Mean Daily ET$_o$ Variation in a year for Kolhapur

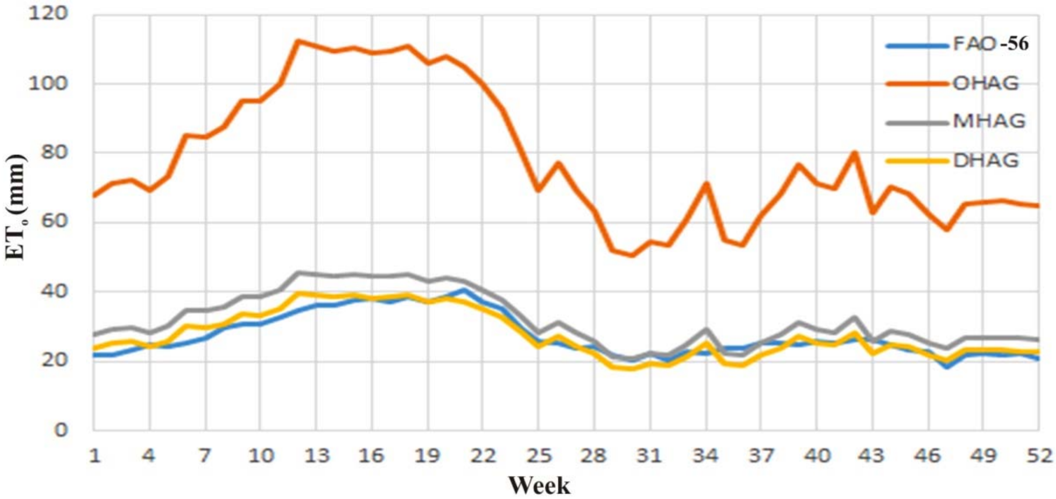
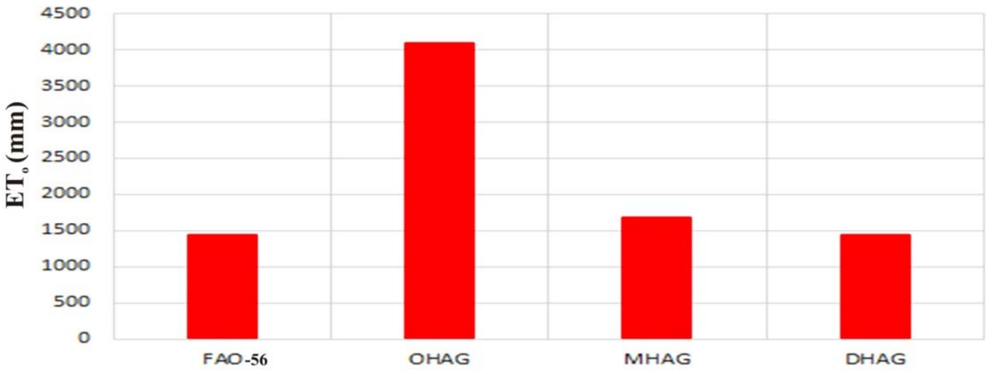


Figure 6.35: Weekly ET$_o$ for Kolhapur



Models →

Figure 6.36: Yearly Total ET$_o$ Estimated by Different Models for Kolhapur

6.4 MODEL RESULT EVALUATION

The procedures of model evaluation consist of using the statistical analysis to calculate the Average Error (AE), the Mean Absolute Error (MAE), the Relative Root Mean Square error (RRMSE), the Efficiency of Model (EM), and the Coefficient of Residual Mass (CRM) between the standard consider for evaluation and simulated values by model.

$$AE = \frac{\sum_{i=1}^{n}(E_i - S_i)}{n} \tag{6.26}$$

$$MAE = \frac{\sum_{i=1}^{n}|(E_i - S_i)|}{n} \tag{6.27}$$

$$RRMSE = 100 * \frac{\sqrt{\frac{\sum_{i=1}^{n}(E_i - S_i)^2}{n}}}{\overline{S_i}} \tag{6.28}$$

$$EM = \frac{\sum_{i=1}^{n}(S_i - \overline{S_i})^2 - \sum_{i=1}^{n}(E_i - S_i)^2}{\sum_{i=1}^{n}(S_i - \overline{S_i})^2} \tag{6.29}$$

$$CRM = \frac{\sum_{i=1}^{n} S_i - \sum_{i=1}^{n} E_i}{\sum_{i=1}^{n} S_i} \tag{6.30}$$

Where E_i and S_i are the simulated/estimated values of ET_o and ET_o estimated by FAO respectively, $\overline{S_i}$ is the mean of the Standard ET_o values, and n is the number of ET_o values. The optimum values of the AE, MAE, RRMSE, EM and CRM criteria are 0, 0, 0, 1, and 0 respectively. Positive values of CRM indicate that the model underestimates the measurements, and negative values of CRM indicate a tendency to overestimate. The EM value compares the predicted values to the average value of the measurements. If EM is less than zero, the model predicted values are worse than the observed mean values.

Table 6.7: Sensitivity Analysis of different Models for ET_o Estimation for Sholapur Research station

Statistical Parameter	**OHAG**	**MHAG**	**DHAG**
AE	8.6191	0.6956	-0.0526
MAE	8.6191	0.9089	0.6539
RRMSE	184.6844	27.7081	18.2750
EM	-31.4624	0.5092	0.6821
CRM	-1.8088	-0.1460	0.0110

Table 6.8: Sensitivity Analysis of different Models for ET_o Estimation for Pune Research station

Statistic Parameter	**OHAG**	**MHAG**	**DHAG**
AE	7.6761	0.6258	-0.0399
MAE	7.6761	0.8723	0.6151
RRMSE	187.5334	23.7255	18.9955
EM	-27.1849	0.5489	0.7108
CRM	-1.8133	-0.1478	0.0094

Table 6.9: Sensitivity Analysis of different Models for ET_o Estimation for Kolhapur Research station

Statistic Parameter	**OHAG**	**MHAG**	**DHAG**
AE	7.2105	0.6235	-0.0016
MAE	7.2178	0.7822	0.4649
RRMSE	192.7052	23.5584	15.0761
EM	-64.841	0.0159	0.5971
CRM	-1.84125	-0.1592	-0.0004

Table 6.10: Sensitivity Analysis of different Models for ET_o Estimation for Ahmednagar Research station

Statistic Parameter	**OHAG**	**MHAG**	**DHAG**
AE	8.8443	1.1819	0.4584
MAE	8.8505	1.2622	0.6985
RRMSE	222.7633	34.4558	20.8413
EM	-57.5533	-0.4008	0.4875
CRM	-2.1577	-0.2884	-0.1118

The model DHAG Efficiency for Sholapur, Pune, Kolhapur and Ahmednagar research station shows better than those two other available model OHAG and MHAG. The average error is much less than other models considered for study area. The CRM values show less than other model. This all parameters of sensitivity analysis indicate that the DHAG gives better results. The principle objective 2 (To develop a forecasting model for reference evapotranspiration) stated in Chapter 1 has been explored in this Chapter.

6.5 SUMMARY

To simplify the process of determining ET_o, DHAG model has been developed and used to estimate ET_o. This model is useful in environments that lack direct ET_o measurements. Successful irrigation scheduling, however, is dependent on an accurate assessment of ET_o. Thus, there is a definite need for simple model available for satisfying the purposes. A major complication in modeling ET_o is the requirement for meteorological data that may not be easily available everywhere. The FAO-56 model is used as the International Standard model for calculating ET_o. It has the serious drawback of requiring meteorological data that are found only at a few IMD stations. This restriction at times prohibits use of more accurate FAO-56 model, and necessitates use of models that have less demanding data requirements. The models discussed in this present Chapter DHAG generally require data that is more readily available such as temperature. Now day's farmers can measure daily temperature at their field. The multiplying coefficient 0.3521 is established from available data and results were validated with FAO-56. The results found satisfactory. The available other two methods OHAG and MHAG were also analyzed with available data but not show much good result as one DHAG. These two models are not found suitable here to this study area. The trends and analysis shows that there is little variation in sensitive analysis of all 4 research station. This model can be used in Semi-arid climatic zone of western Maharashtra. The obtained ET_o by the FAO-56 and DHAG method were used in Chapter 7 for obtaining water requirement for crop.

CHAPTER -7
CROP WATER MANAGEMENT

7.1 INTRODUCTION

Hydrological models for water transfer in the crop-soil system are either too approximate like water budget models or employ complex numerical schemes like dynamic or physical models. In this study a sufficiently accurate algorithm which can be easily adopted in agro-hydrological models for the simulation of water dynamics is proposed for study area. Information from Tripathi et al. (2008a and b) is considered in practical application. We used a single crop coefficient approach proposed by the FAO for estimating evapotranspiration. The Borg and Grimes (1986) model for calculating relative root length distribution on a daily basis is considered. The Richards equation describing soil water movement was solved using a finite element method with frontal solution technique. Measuring the existing soil moisture is difficult. It is therefore easier to start the water budget or dynamic model after a thorough irrigation or rainfall that fills the entire root zone. The model would then start with a full storage value equal to the Soil Water Storage.

In Chapter 5 the soil parameters required for running Dynamic Model were dealt in detail, and estimated for study area. In Chapter 6 Reference Evapotranspiration (ET_o) is discussed in detail. The simple model DHAG for finding out ET_o is validated with FAO 56. Finite Element Method (FEM) is discussed in detail in Chapter 5 and analysis software is developed for running dynamic model and validated with Celia et al. (1990) model. Pearl millet crop is considered for running water budget model and dynamic model. When soil and ET_o data is available the dynamic model can be used for finding water requirement. But if data is insufficient water budget model is to be used.

7.2 PEARL MILLET (i.e. BAJRA)

Pearl millet is selected for study as it is the main staple crop for the arid and semi-arid regions in India. India's two-thirds of its pearl millet production, is grown in the drier areas of the country. In semi-arid area, the cropping choice is restricted due to moisture stress and lack of assured sources of irrigation. Pearl Millet is hardy crop that thrive in adverse agro-ecological situations, making less risky for producers. Pearl millet is widely cultivated during the rainy and post-rainy seasons in central western Maharashtra. Besides grain, pearl millet is an important feed for livestock, especially in the dry months when other feed resources are in short supply. Irrigation intervals and the amount of water is determined by: rainfall, soil's water-holding characteristics, plant root depth and other climatic conditions like air temperature etc.

7.2.1 Sowing Period for Pearl Millet

Traditional farmers have developed their own sowing method by their ancestral experience. Generally the onset date of monsoon season in that area and accumulated rainfall totals and rainfall evapotranspiration relation is considered criteria for deciding the sowing date. The poor soil moisture at sowing time reduces seedling emergence and it leads to poor crop development and its production. The probability of dry spells of ten days or more is dangerous for this crop and water supply gets exhausted. It is then necessary to sow after the next sufficiently large rain event. The delayed sowing is generally associated with declined yield.

7.3 Rainfall and Reference Evapotranspiration (ET_o) Analysis for Study Area

Rainfall and reference evapotranspiration (ET_o) analysis has been carried out for the four research stations namely Sholapur, Pune, Ahmednagar and Kolhapur and presented in Graph Figure: 7.1 to 7.16.

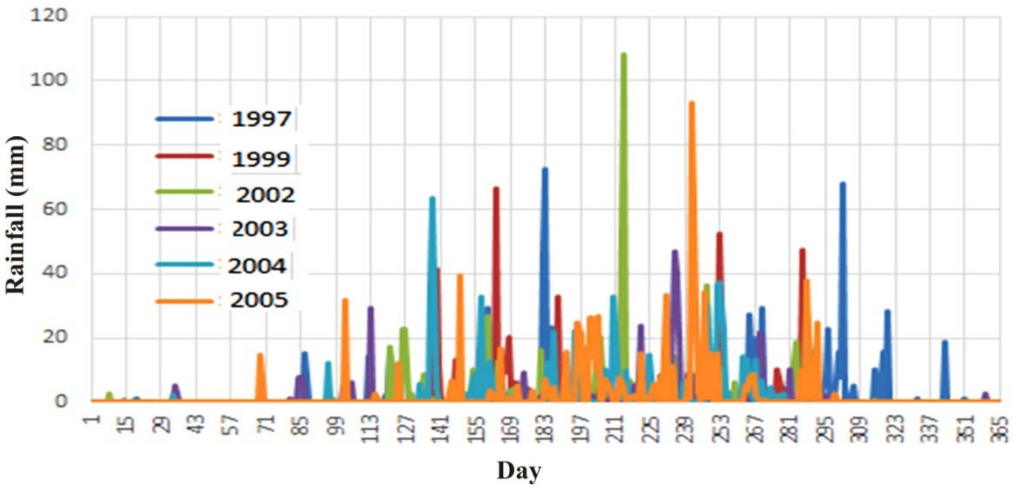


Figure 7.1: Rainfall for Sholapur (Various years)

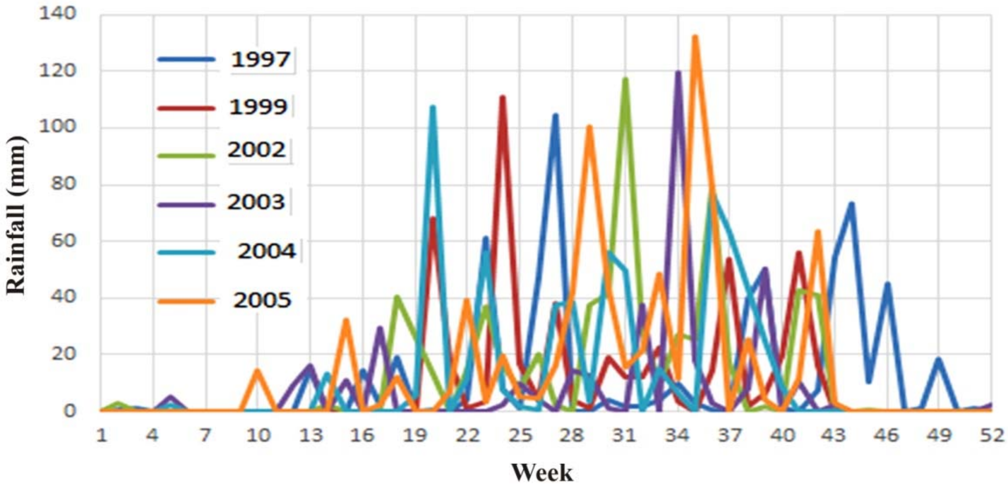


Figure 7.2: Weekly Rainfall for Sholapur

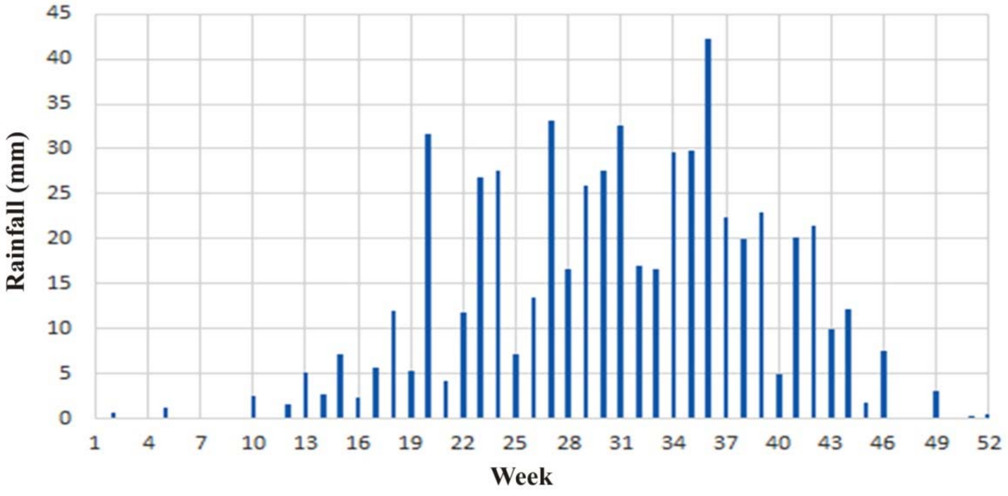


Figure 7.3: Weekly Rainfall for Sholapur

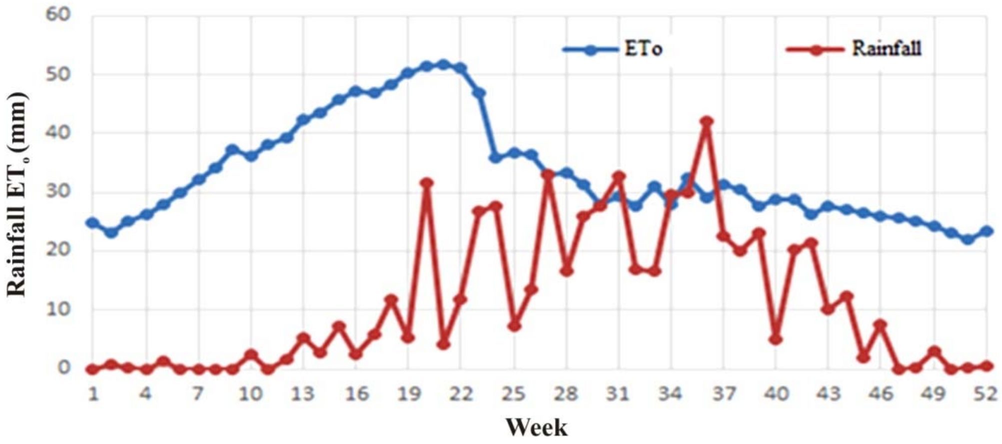


Figure 7.4: Graphical Presentation of Weekly ET$_0$ and Rainfall for Sholapur

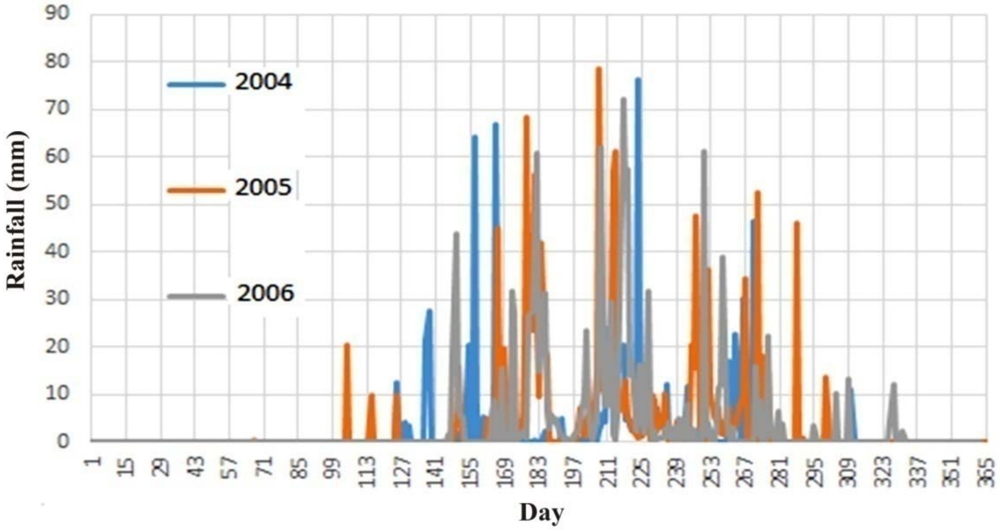


Figure 7.5: Rainfall for Pune

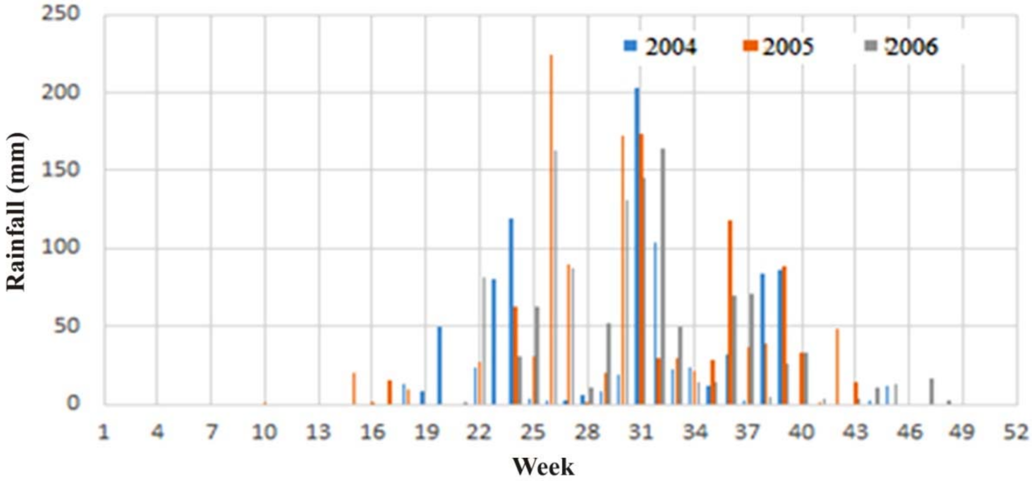


Figure 7.6: Weekly Total Rainfall for Pune

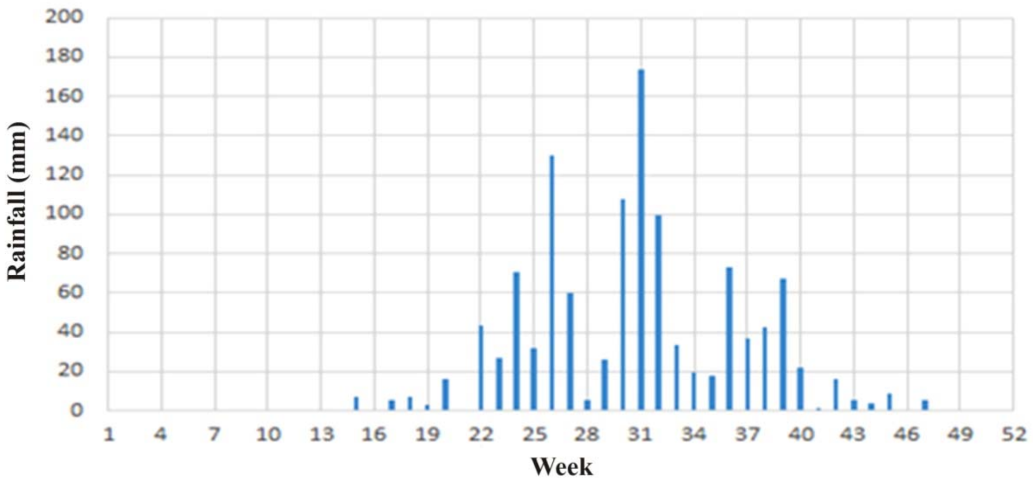


Figure 7.7: Weekly Rainfall for Pune

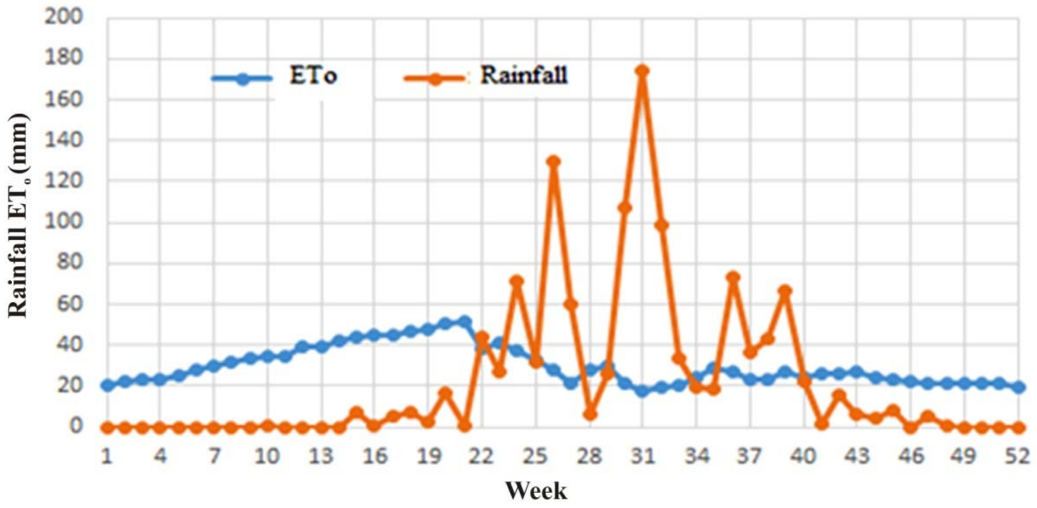


Figure 7.8: Weekly Rainfall and ET_o for Pune

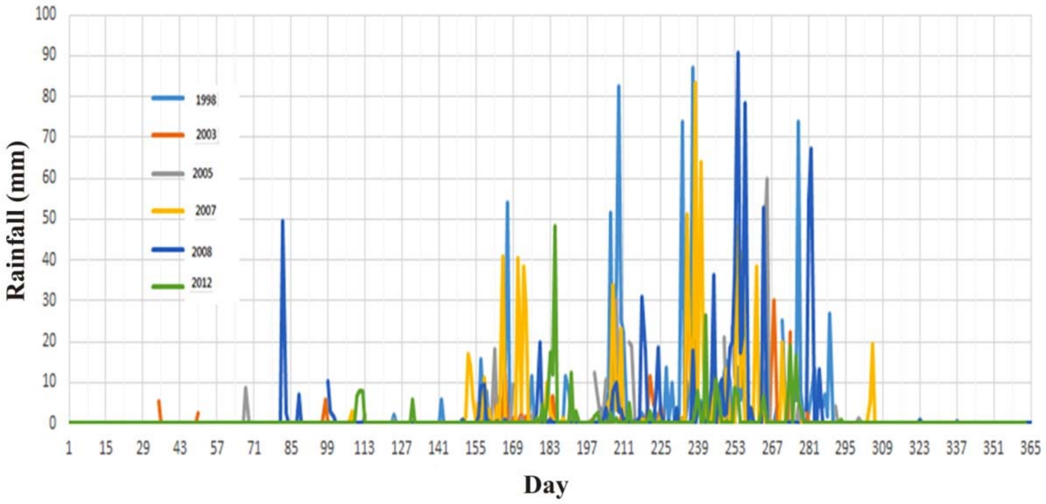


Figure 7.9: Rainfall for Ahmednagar

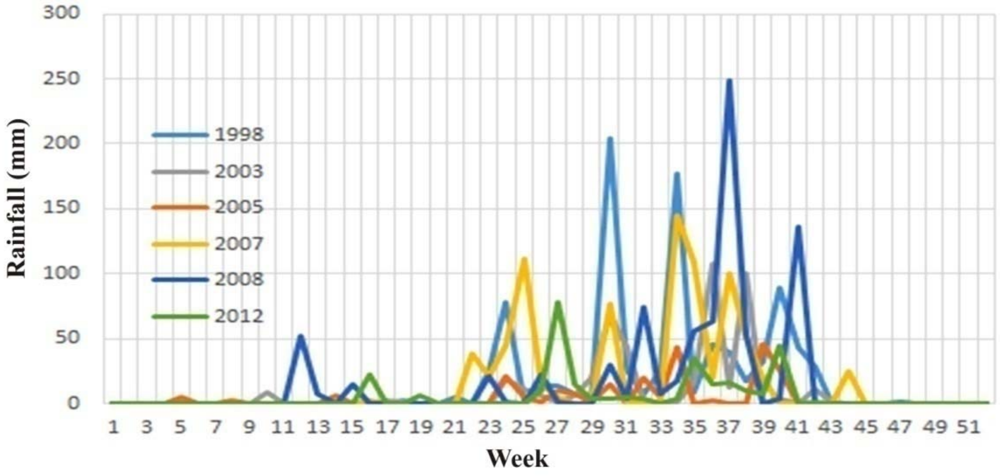


Figure 7.10: Weekly Rainfall for Ahmednagar

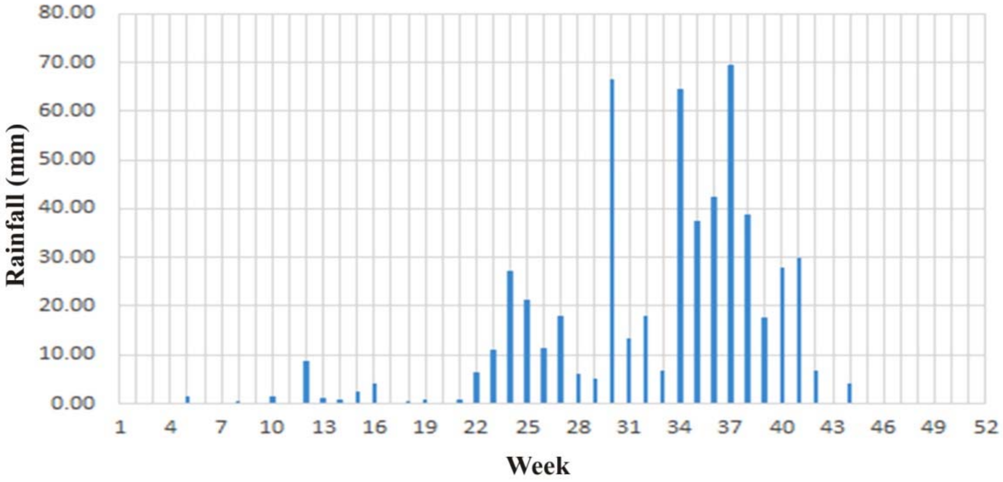


Figure 7.11: Weekly Mean Rainfall for Ahmednagar

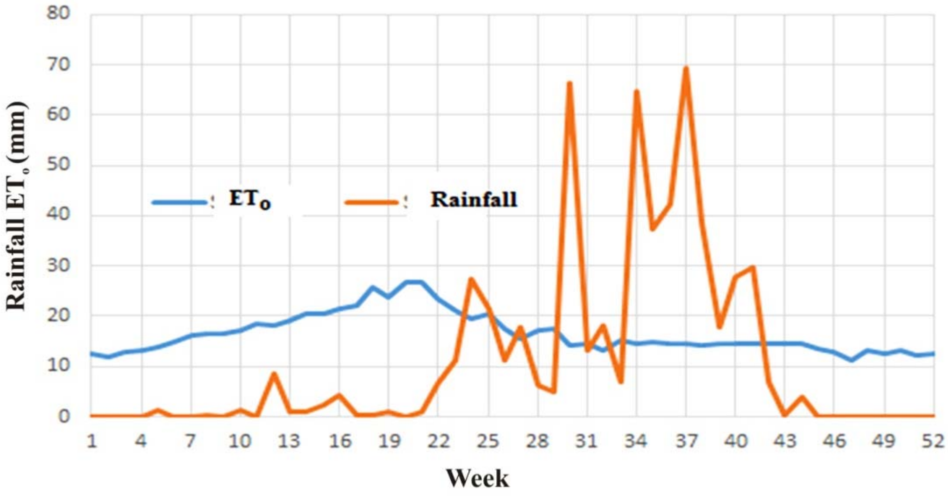


Figure 7.12: Weekly rainfall and ET$_o$ for Ahmednagar

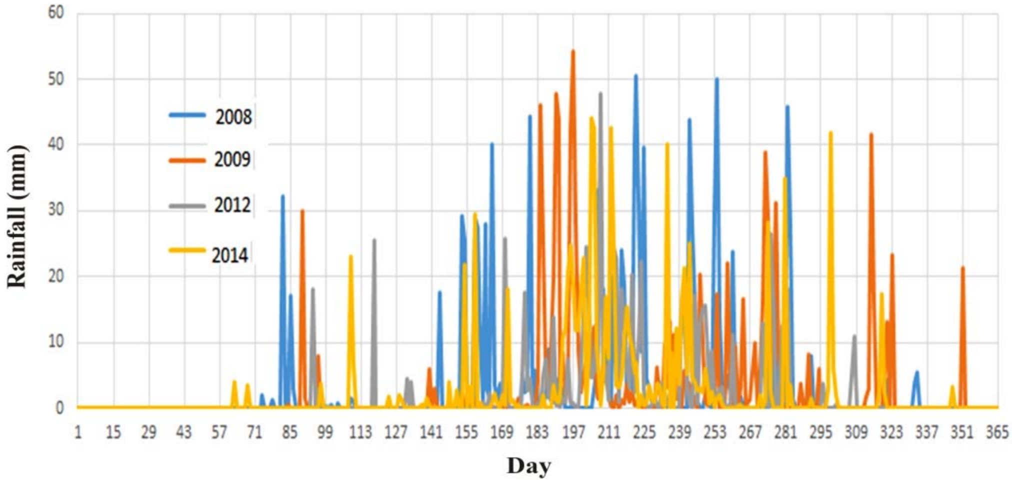


Figure 7.13: Rainfall for Kolhapur

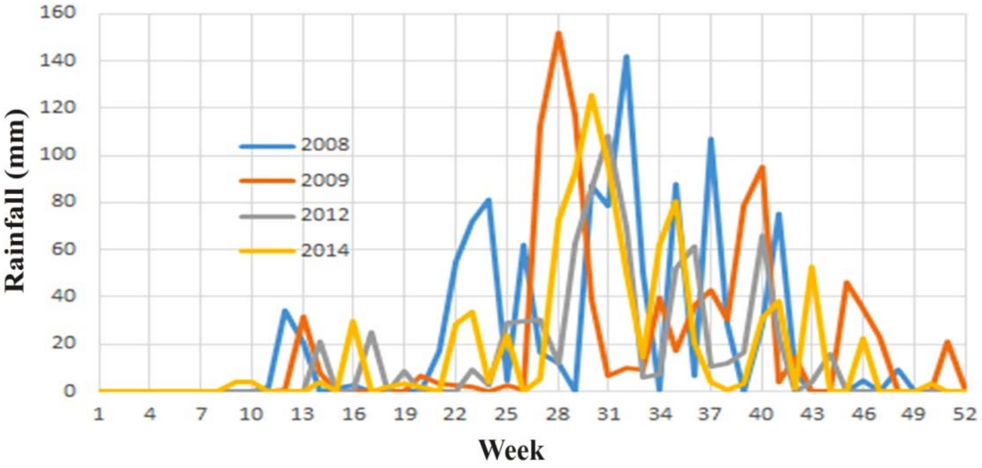


Figure 7.14: Weekly Rainfall for Kolhapur

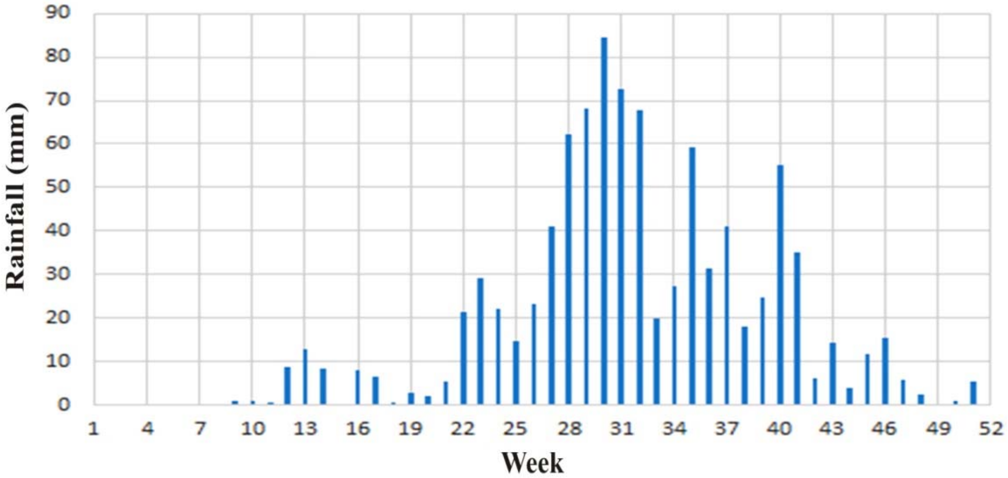


Figure 7.15: Weekly Rainfall for Kolhapur

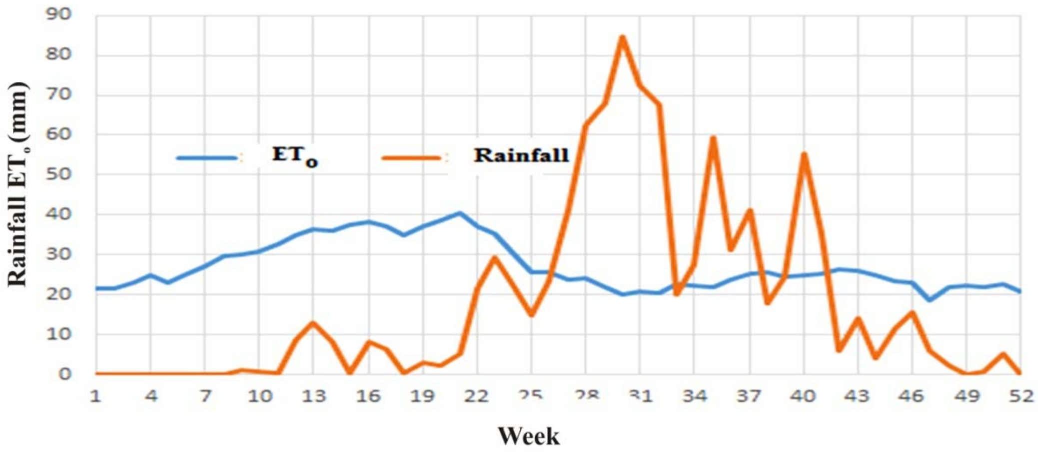


Figure 7.16: Weekly rainfall and ET$_0$ for Kolhapur

On observing the above Graph Figures: 7.1 to 7.16, it is quite clear that the normal sowing of pearl millet should be in 27th week of calendar year for study area. The monsoon rainfall would help in providing sufficient moisture to the crop growth.

The water holding capacity is different for different types of soil. Following Table gives the water holding capacity for different soils.

Table 7.1: Water holding capacity of various soil (Clark, 1970)

Sr. No.	Soil	Water holding capacity (mm / cm depth of soil)
01	Very coarse sand	0.4
02	Sands	0.7
03	Sandy loams	1.05
04	Medium loams	1.6
05	Clayey loams	1.75
06	Clayey	1.70

7.4 WATER BUDGET MODEL

In arid and semi-arid region, the amount of water applied to fields is strongly influenced by seasonal rainfall. Determination of irrigation timing is crucial in irrigation planning and management. During the period when no rainfall occurs, about 2.0 cm of irrigation water may be required. During the crop period, if rainfall occurs, frequently with uniform spaced, irrigation may not be required. Most of the water budget models for arid and semi-arid is simple book keeping procedure of computation. Various parameters of water budget model are given in the Table 7.2.

The detailed water budget calculation sheets for all four research stations as per FAO-56 method and DHAG method for week numbers 27 to 39 for available years has been presented below.

Table 7.2: Water Budget Sheet

Year	WEEK No.	PPT (mm)	PET (mm)	K_c	WR = K_c x PET (mm)	PPT-WR (mm)	SMR (mm)	AET (mm)	AET/WR (MAI)

PPT = Weekly Precipitation,
PET = Normal Potential Evapotranspiration,
Kc = Crop coefficient,
WR = Water Requirement,
SMR = Soil Moisture Reserve [cumulative (PPT-WR) subject to minimum of 0.00, and maximum of 150.00 mm],
AET = Actual Evapotranspiration,

$$\frac{\text{AET}}{\text{WR}} = \text{MAI} = \text{Moisture Adequacy Ratio.}$$

The application and results of this water budget model are presented in following Tables. The data which is entered in bold indicates the irrigation requirement. If the irrigation demand is not met, it effect on crop growth as well as on crop yield. Drought evaluation is simple and irrigation managers can make decision of irrigation scheduling.

Table 7.3: Drought Evaluation Criteria for Water Budget Model

Sr. No.	Week No	Drought Occur
1	27	If AE/ PET < 0.18
2	28	If AE/ PET < 0.275
3	29	If AE/ PET < 0.42
4	30	If AE/ PET < 0.575
5	31	If AE/ PET < 0.74
6	32	If AE/ PET < 0.88
7	33	If AE/ PET < 1.00
8	34	If AE/ PET < 1.075
9	35	If AE/ PET < 1.10
10	36	If AE/ PET < 1.05
11	37	If AE/ PET < 0.90
12	38	If AE/ PET < 0.65
13	39	If AE/ PET < 0.25

7.5 WATER BUDGET MODEL FOR SHOLAPUR

Table 7.4: Water Budget Model calculation sheet (ET_o taken from FAO-56) for Sholapur Research station

Year	Week No.	PPT (mm)	PET (mm)	K_c	WR = K_c x PET (mm)	PPT-WR (mm)	SMR (mm)	AET (mm)	AET/WR	AET/PET
1997	27	150.80	21.72	0.18	3.91	146.89	146.89	3.91	1.000	0.1800
	28	1.00	32.94	0.28	9.06	-8.06	138.83	9.06	1.000	0.2750
	29	0.00	34.36	0.42	14.43	-14.43	124.40	14.43	1.000	0.4200
	30	4.30	37.05	0.58	21.30	-17.00	107.40	21.30	1.000	0.5750
	31	1.50	34.75	0.74	25.71	-24.21	83.19	25.71	1.000	0.7400
	32	1.80	40.52	0.88	35.66	-33.86	49.33	35.66	1.000	0.8800
	33	4.20	36.57	1.00	36.57	-32.37	16.95	36.57	1.000	1.0000
	34	9.60	29.42	1.08	31.63	**-22.03**	**0.00**	**0.00**	**0.000**	**0.0000**
	35	3.10	31.05	1.10	34.16	**-31.06**	**0.00**	**0.00**	**0.000**	**0.0000**
	36	0.90	35.75	1.05	37.53	**-36.63**	**0.00**	**0.00**	**0.000**	**0.0000**
	37	0.00	35.59	0.90	32.03	**-32.03**	**0.00**	**0.00**	**0.000**	**0.0000**
	38	32.90	33.75	0.65	21.94	**10.96**	**0.00**	**0.00**	**0.000**	**0.0000**
	39	57.60	27.73	0.25	6.93	**50.67**	**0.00**	**0.00**	**0.000**	**0.0000**
1999	27	33.00	35.89	0.18	6.46	26.54	26.54	6.46	1.000	0.18
	28	9.40	21.76	0.28	5.98	3.42	29.96	5.98	1.000	0.28
	29	1.20	27.77	0.42	11.66	-10.46	19.50	11.66	1.000	0.42
	30	17.80	26.64	0.58	15.32	2.48	21.98	15.32	1.000	0.58
	31	12.40	24.28	0.74	17.97	-5.57	16.41	17.97	1.000	0.74
	32	12.70	22.37	0.88	19.68	-6.98	9.43	19.68	1.000	0.88
	33	8.20	24.83	1.00	24.83	**-16.63**	**0.00**	**0.00**	**0.000**	**0.00**
	34	17.70	25.57	1.08	27.49	**-9.79**	**0.00**	**0.00**	**0.000**	**0.00**
	35	0.00	27.06	1.10	29.77	**-29.77**	**0.00**	**0.00**	**0.000**	**0.00**
	36	0.00	31.12	1.05	32.67	**-32.67**	**0.00**	**0.00**	**0.000**	**0.00**
	37	68.40	18.16	0.90	16.34	**52.06**	**0.00**	**0.00**	**0.000**	**0.00**
	38	2.00	30.13	0.65	19.58	**-17.58**	**0.00**	**0.00**	**0.000**	**0.00**
	39	6.40	22.81	0.25	5.70	**0.70**	**0.00**	**0.00**	**0.000**	**0.00**

Table 7.4 (Continued)

Year	Week No.	PPT (mm)	PET (mm)	K_c	WR = K_c x PET (mm)	PPT-WR (mm)	SMR (mm)	AET (mm)	AET/WR	AET/PET
2002	27	16.30	41.47	0.18	7.46	8.84	8.84	7.46	1.000	0.18
	28	2.40	48.73	0.28	13.40	**-11.00**	**0.00**	**0.00**	**0.000**	**0.00**
	29	26.50	37.25	0.42	15.64	10.86	8.69	15.64	1.000	0.42
	30	52.70	30.79	0.58	17.71	34.99	43.68	17.71	1.000	0.58
	31	110.20	37.50	0.74	27.75	82.45	126.13	27.75	1.000	0.74
	32	33.10	23.47	0.88	20.65	12.45	138.58	20.65	1.000	0.88
	33	8.00	28.21	1.00	28.21	-20.21	118.37	28.21	1.000	1.00
	34	31.50	27.20	1.08	29.24	2.26	120.63	29.24	1.000	1.08
	35	0.00	34.35	1.10	37.79	-37.79	82.84	37.79	1.000	1.10
	36	105.00	22.44	1.05	23.56	81.44	150.00	23.56	1.000	1.05
	37	10.80	34.07	0.90	30.66	-19.86	144.42	30.66	1.000	0.90
	38	6.40	31.52	0.65	20.49	-14.09	130.33	20.49	1.000	0.65
	39	2.00	31.84	0.25	7.96	-5.96	124.37	7.96	1.000	0.25
2003	27	2.20	33.79	0.18	6.08	**-3.88**	**0.00**	**0.00**	**0.000**	**0.00**
	28	14.30	32.51	0.28	8.94	5.36	1.48	8.94	1.000	0.28
	29	12.60	27.00	0.42	11.34	1.26	2.74	11.34	1.000	0.42
	30	1.40	29.29	0.58	16.84	**-15.44**	**0.00**	**0.00**	**0.000**	**0.00**
	31	0.00	38.33	0.74	28.36	**-28.36**	**0.00**	**0.00**	**0.000**	**0.00**
	32	37.40	28.37	0.88	24.97	**12.43**	**0.00**	**0.00**	**0.000**	**0.00**
	33	0.00	36.75	1.00	36.75	**-36.75**	**0.00**	**0.00**	**0.000**	**0.00**
	34	119.60	28.88	1.08	31.05	88.55	23.17	31.05	1.000	1.08
	35	17.90	31.80	1.10	34.98	**-17.08**	**6.09**	**34.98**	**1.000**	**1.10**
	36	2.80	36.51	1.05	38.34	**-35.54**	**0.00**	**0.00**	**0.000**	**0.00**
	37	0.00	39.29	0.90	35.36	**-35.36**	**0.00**	**0.00**	**0.000**	**0.00**
	38	0.00	37.74	0.65	24.53	**-24.53**	**0.00**	**0.00**	**0.000**	**0.00**
	39	58.70	26.50	0.25	6.62	**52.08**	**0.00**	**0.00**	**0.000**	**0.00**

Table 7.4 (Continued)

Year	Week No.	PPT (mm)	PET (mm)	K_c	WR = K_c x PET (mm)	PPT-WR (mm)	SMR (mm)	AET (mm)	AET/WR	AET/PET
2004	27	37.50	35.00	0.18	6.30	31.20	31.20	6.30	1.000	0.18
	28	34.90	34.10	0.28	9.38	25.52	56.72	9.38	1.000	0.28
	29	7.30	33.57	0.42	14.10	-6.80	49.92	14.10	1.000	0.42
	30	23.10	27.36	0.58	15.73	7.37	57.29	15.73	1.000	0.58
	31	82.60	18.66	0.74	13.81	68.79	126.08	13.81	1.000	0.74
	32	0.60	27.98	0.88	24.62	-24.02	102.06	24.62	1.000	0.88
	33	15.00	29.62	1.00	29.62	-14.62	87.44	29.62	1.000	1.00
	34	0.00	31.35	1.08	33.70	-33.70	53.74	33.70	1.000	1.08
	35	6.20	39.02	1.10	42.93	-36.73	17.01	42.93	1.000	1.10
	36	40.60	26.98	1.05	28.33	12.27	29.28	28.33	1.000	1.05
	37	100.10	27.78	0.90	25.00	75.10	104.38	25.00	1.000	0.90
	38	38.10	28.69	0.65	18.65	19.45	123.84	18.65	1.000	0.65
	39	25.30	29.38	0.25	7.34	17.96	141.79	7.34	1.000	0.25
2005	27	16.10	32.18	0.18	5.79	10.31	10.31	5.79	1.000	0.18
	28	17.00	29.53	0.28	8.12	8.88	19.19	8.12	1.000	0.28
	29	115.50	28.02	0.42	11.77	103.73	122.92	11.77	1.000	0.42
	30	53.70	19.40	0.58	11.16	42.54	150.00	11.16	1.000	0.58
	31	13.80	22.58	0.74	16.71	-2.91	150.00	16.71	1.000	0.74
	32	23.00	23.55	0.88	20.73	2.27	150.00	20.73	1.000	0.88
	33	15.20	25.86	1.00	25.86	-10.66	150.00	25.86	1.000	1.00
	34	45.00	27.04	1.08	29.07	15.93	150.00	29.07	1.000	1.08
	35	132.40	31.00	1.10	34.10	98.30	150.00	34.10	1.000	1.10
	36	63.00	26.96	1.05	28.31	34.69	150.00	28.31	1.000	1.05
	37	15.40	26.03	0.90	23.42	-8.02	150.00	23.42	1.000	0.90
	38	16.80	24.94	0.65	16.21	0.59	150.00	16.21	1.000	0.65
	39	12.80	26.69	0.25	6.67	6.13	150.00	6.67	1.000	0.25

Table 7.4 (Continued)

Year	Week No.	PPT (mm)	PET (mm)	K_c	WR = K_c x PET (mm)	PPT-WR (mm)	SMR (mm)	AET (mm)	AET/WR	AET/PET
Avg.	27	42.65	33.34	0.18	6.00	36.65	36.65	6.00	1.000	0.18
	28	13.17	33.26	0.28	9.15	4.02	40.67	9.15	1.000	0.28
	29	27.18	31.33	0.42	13.16	14.03	54.69	13.16	1.000	0.42
	30	25.50	28.42	0.58	16.34	9.16	63.85	16.34	1.000	0.58
	31	36.75	29.35	0.74	21.72	15.03	78.88	21.72	1.000	0.74
	32	18.10	27.71	0.88	24.39	-6.29	72.60	24.39	1.000	0.88
	33	8.43	30.31	1.00	30.31	-21.87	50.72	30.31	1.000	1.00
	34	37.23	28.25	1.08	30.36	6.87	57.59	30.36	1.000	1.08
	35	26.60	32.38	1.10	35.62	-9.02	48.58	35.62	1.000	1.10
	36	35.38	29.96	1.05	31.46	3.93	52.50	31.46	1.000	1.05
	37	32.45	30.15	0.90	27.14	5.31	57.82	27.14	1.000	0.90
	38	16.03	31.13	0.65	20.23	-4.20	53.62	20.23	1.000	0.65
	39	27.13	27.49	0.25	6.87	20.26	73.88	6.87	1.000	0.25

Table 7.5: Water Budget Model calculation sheet (ET_o taken from DHAG) for Sholapur Research station

Year	Week No.	PPT (mm)	PET (mm)	K_c	WR = K_c x PET (mm)	PPT-WR (mm)	SMR (mm)	AET (mm)	AET/WR	AET/PET
1997	27	150.80	29.49	0.18	5.31	145.49	145.49	5.31	1.000	0.1800
	28	1.00	30.90	0.28	8.50	-7.50	137.99	8.50	1.000	0.2750
	29	0.00	33.11	0.42	13.91	-13.91	124.09	13.91	1.000	0.4200
	30	4.30	33.39	0.58	19.20	-14.90	109.19	19.20	1.000	0.5750
	31	1.50	30.33	0.74	22.44	-20.94	88.25	22.44	1.000	0.7400
	32	1.80	34.83	0.88	30.65	-28.85	59.40	30.65	1.000	0.8800
	33	4.20	33.80	1.00	33.80	-29.60	29.80	33.80	1.000	1.0000
	34	9.60	29.35	1.08	31.55	-21.95	7.85	31.55	1.000	1.0750
	35	3.10	32.68	1.10	35.95	**-32.85**	**0.00**	**0.00**	**0.000**	**0.0000**
	36	0.90	35.05	1.05	36.80	**-35.90**	**0.00**	**0.00**	**0.000**	**0.0000**
	37	0.00	32.82	0.90	29.54	**-29.54**	**0.00**	**0.00**	**0.000**	**0.0000**
	38	32.90	32.02	0.65	20.81	**12.09**	**0.00**	**0.00**	**0.000**	**0.0000**
	39	57.60	27.41	0.25	6.85	**50.75**	**0.00**	**0.00**	**0.000**	**0.0000**
1999	27	33.00	35.45	0.18	6.38	26.62	26.62	6.38	1.000	0.18
	28	9.40	31.78	0.28	8.74	0.66	27.25	8.74	1.000	0.28
	29	1.20	33.94	0.42	14.26	-13.06	14.00	14.26	1.000	0.42
	30	17.80	31.64	0.58	18.19	-0.39	13.83	18.19	1.000	0.58
	31	12.40	32.76	0.74	24.24	-11.84	1.99	24.24	1.000	0.74
	32	12.70	29.74	0.88	26.17	**-13.47**	**0.00**	**0.00**	**0.000**	**0.00**
	33	8.20	31.92	1.00	31.92	**-23.72**	**0.00**	**0.00**	**0.000**	**0.00**
	34	17.70	29.18	1.08	31.37	**-13.67**	**0.00**	**0.00**	**0.000**	**0.00**
	35	0.00	32.04	1.10	35.24	**-35.24**	**0.00**	**0.00**	**0.000**	**0.00**
	36	0.00	34.38	1.05	36.10	**-36.10**	**0.00**	**0.00**	**0.000**	**0.00**
	37	68.40	26.88	0.90	24.19	**44.21**	**0.00**	**0.00**	**0.000**	**0.00**
	38	2.00	32.78	0.65	21.31	**-19.31**	**0.00**	**0.00**	**0.000**	**0.00**
	39	6.40	30.69	0.25	7.67	**-1.27**	**0.00**	**0.00**	**0.000**	**0.00**

Table 7.5 (Continued)

Year	Week No.	PPT (mm)	PET (mm)	K_c	WR = K_c x PET (mm)	PPT-WR (mm)	SMR (mm)	AET (mm)	AET/WR	AET/PET
2002	27	16.30	34.15	0.18	6.15	10.15	10.15	6.15	1.000	0.18
	28	2.40	36.64	0.28	10.08	-7.68	2.48	10.08	1.000	0.28
	29	26.50	32.62	0.42	13.70	12.80	15.28	13.70	1.000	0.42
	30	52.70	30.77	0.58	17.69	35.01	50.28	17.69	1.000	0.58
	31	110.20	32.75	0.74	24.24	85.96	136.25	24.24	1.000	0.74
	32	33.10	26.71	0.88	23.50	9.60	145.84	23.50	1.000	0.88
	33	8.00	28.07	1.00	28.07	-20.07	125.78	28.07	1.000	1.00
	34	31.50	28.65	1.08	30.79	0.71	126.48	30.79	1.000	1.08
	35	0.00	31.92	1.10	35.11	-35.11	91.37	35.11	1.000	1.10
	36	105.00	26.89	1.05	28.24	76.76	150.00	28.24	1.000	1.05
	37	10.80	31.39	0.90	28.25	-17.45	150.00	28.25	1.000	0.90
	38	6.40	31.89	0.65	20.73	-14.33	136.35	20.73	1.000	0.65
	39	2.00	32.51	0.25	8.13	-6.13	130.23	8.13	1.000	0.25
2003	27	2.20	33.21	0.18	5.98	**-3.78**	**0.00**	**0.00**	**0.000**	**0.00**
	28	14.30	33.53	0.28	9.22	5.08	1.30	9.22	1.000	0.28
	29	12.60	31.44	0.42	13.21	-0.61	0.70	13.21	1.000	0.42
	30	1.40	29.78	0.58	17.12	**-15.72**	**0.00**	**0.00**	**0.000**	**0.00**
	31	0.00	33.54	0.74	24.82	**-24.82**	**0.00**	**0.00**	**0.000**	**0.00**
	32	37.40	29.67	0.88	26.11	**11.29**	**0.00**	**0.00**	**0.000**	**0.00**
	33	0.00	33.46	1.00	33.46	**-33.46**	**0.00**	**0.00**	**0.000**	**0.00**
	34	119.60	28.59	1.08	30.74	88.86	26.84	30.74	1.000	1.08
	35	17.90	30.27	1.10	33.30	-15.40	11.44	33.30	1.000	1.10
	36	2.80	31.46	1.05	33.04	**-30.24**	**0.00**	**0.00**	**0.000**	**0.00**
	37	0.00	32.68	0.90	29.41	**-29.41**	**0.00**	**0.00**	**0.000**	**0.00**
	38	0.00	32.45	0.65	21.09	**-21.09**	**0.00**	**0.00**	**0.000**	**0.00**
	39	58.70	27.34	0.25	6.84	**51.86**	**0.00**	**0.00**	**0.000**	**0.00**

Table 7.5 (Continued)

Year	Week No.	PPT (mm)	PET (mm)	K_c	WR = K_c x PET (mm)	PPT-WR (mm)	SMR (mm)	AET (mm)	AET/WR	AET/PET
2004	27	37.50	33.25	0.18	5.98	31.52	31.52	5.98	1.000	0.18
	28	34.90	34.27	0.28	9.43	25.47	56.99	9.43	1.000	0.28
	29	7.30	33.21	0.42	13.95	-6.65	50.34	13.95	1.000	0.42
	30	23.10	30.05	0.58	17.28	5.82	56.17	17.28	1.000	0.58
	31	82.60	22.08	0.74	16.34	66.26	122.43	16.34	1.000	0.74
	32	0.60	29.38	0.88	25.86	-25.26	97.17	25.86	1.000	0.88
	33	15.00	29.01	1.00	29.01	-14.01	83.16	29.01	1.000	1.00
	34	0.00	31.06	1.08	33.39	-33.39	49.77	33.39	1.000	1.08
	35	6.20	34.33	1.10	37.76	-31.56	18.21	37.76	1.000	1.10
	36	40.60	29.01	1.05	30.46	10.14	28.35	30.46	1.000	1.05
	37	100.10	25.89	0.90	23.30	76.80	105.15	23.30	1.000	0.90
	38	38.10	29.51	0.65	19.18	18.92	124.07	19.18	1.000	0.65
	39	25.30	28.02	0.25	7.01	18.29	142.36	7.01	1.000	0.25
2005	27	16.10	26.50	0.18	4.77	11.33	11.33	4.77	1.000	0.18
	28	17.00	28.75	0.28	7.91	9.09	20.43	7.91	1.000	0.28
	29	115.50	31.55	0.42	13.25	102.25	122.68	13.25	1.000	0.42
	30	53.70	23.69	0.58	13.62	40.08	150.00	13.62	1.000	0.58
	31	13.80	26.99	0.74	19.97	-6.17	150.00	19.97	1.000	0.74
	32	23.00	25.46	0.88	22.40	0.60	150.00	22.40	1.000	0.88
	33	15.20	28.11	1.00	28.11	-12.91	144.27	28.11	1.000	1.00
	34	45.00	27.99	1.08	30.09	14.91	150.00	30.09	1.000	1.08
	35	132.40	31.60	1.10	34.76	97.64	150.00	34.76	1.000	1.10
	36	63.00	28.60	1.05	30.03	32.97	150.00	30.03	1.000	1.05
	37	15.40	26.03	0.90	23.43	-8.03	150.00	23.43	1.000	0.90
	38	16.80	26.20	0.65	17.03	-0.23	150.00	17.03	1.000	0.65
	39	12.80	27.03	0.25	6.76	6.04	150.00	6.76	1.000	0.25

Table 7.5 (Continued)

Year	Week No.	PPT (mm)	PET (mm)	K_c	WR = K_c x PET (mm)	PPT-WR (mm)	SMR (mm)	AET (mm)	AET/WR	AET/PET
Avg.	27	42.65	32.01	0.18	5.76	36.89	36.89	5.76	1.000	0.19
	28	13.17	32.64	0.28	8.98	4.19	41.08	8.98	1.000	0.28
	29	27.18	32.65	0.42	13.71	13.47	54.55	13.71	1.000	0.40
	30	25.50	29.89	0.58	17.18	8.32	62.87	17.18	1.000	0.55
	31	36.75	29.74	0.74	22.01	14.74	77.61	22.01	1.000	0.73
	32	18.10	29.30	0.88	25.78	-7.68	69.92	25.78	1.000	0.83
	33	8.43	30.73	1.00	30.73	-22.29	47.63	30.73	1.000	0.99
	34	37.23	29.14	1.08	31.32	5.91	53.54	31.32	1.000	1.04
	35	26.60	32.14	1.10	35.35	-8.75	44.79	35.35	1.000	1.11
	36	35.38	30.90	1.05	32.44	2.94	47.73	32.44	1.000	1.02
	37	32.45	29.28	0.90	26.35	6.10	53.82	26.35	1.000	0.93
	38	16.03	30.81	0.65	20.03	-3.99	49.83	20.03	1.000	0.66
	39	27.13	28.83	0.25	7.21	19.93	69.76	7.21	1.000	0.24

Table 7.6: Drought Evaluation for Sholapur Research station

Week No.	FAO	DHAG
27	1	1
28	1	0
29	0	0
30	1	1
31	1	1
32	1	2
33	2	2
34	6	6
35	6	6
36	6	6
37	3	3
38	3	3
39	3	3

The weekwise drought frequency is given in Table 7.6 for Sholapur research station. It is observed that the frequency of drought evaluated by using FAO-56 and DHAG methods is nearly the same.

7.6 WATER BUDGET MODEL FOR PUNE

Table 7.7: Water Budget Model calculation sheet (ET$_o$ taken from FAO-56) for Pune Research station

Year	Week No.	PPT (mm)	PET (mm)	K_c	WR = K_c x PET (mm)	PPT-WR (mm)	SMR (mm)	AET (mm)	AET/WR	AET/PET
2004	27	2.70	27.54	0.18	4.96	**-2.26**	**0.00**	**0.00**	**0.000**	**0.0000**
	28	5.60	29.43	0.28	8.09	**-2.49**	**0.00**	**0.00**	**0.000**	**0.0000**
	29	7.80	31.85	0.42	13.38	**-5.58**	**0.00**	**0.00**	**0.000**	**0.0000**
	30	18.60	24.36	0.58	14.01	**4.59**	**0.00**	**0.00**	**0.000**	**0.0000**
	31	203.40	16.56	0.74	12.25	191.15	150.00	12.25	1.000	0.7400
	32	104.40	20.73	0.88	18.24	86.16	150.00	18.24	1.000	0.8800
	33	22.80	20.85	1.00	20.85	1.95	150.00	20.85	1.000	1.0000
	34	23.80	21.76	1.08	23.39	0.41	150.00	23.39	1.000	1.0750
	35	11.70	32.17	1.10	35.39	-23.69	150.00	35.39	1.000	1.1000
	36	32.10	26.84	1.05	28.18	3.92	150.00	28.18	1.000	1.0500
	37	2.40	26.20	0.90	23.58	-21.18	150.00	23.58	1.000	0.9000
	38	84.30	30.27	0.65	19.68	64.62	150.00	19.68	1.000	0.6500
	39	86.30	26.80	0.25	6.70	79.60	150.00	6.70	1.000	0.2500
2005	27	90.00	22.13	0.18	3.98	86.02	86.02	3.98	1.000	0.18
	28	1.20	29.05	0.28	7.99	-6.79	79.23	7.99	1.000	0.28
	29	19.80	28.73	0.42	12.07	7.73	86.96	12.07	1.000	0.42
	30	172.60	19.05	0.58	10.95	161.65	150.00	10.95	1.000	0.58
	31	173.30	18.53	0.74	13.71	159.59	150.00	13.71	1.000	0.74
	32	29.40	21.69	0.88	19.08	10.32	150.00	19.08	1.000	0.88
	33	29.30	21.85	1.00	21.85	7.45	150.00	21.85	1.000	1.00
	34	21.10	26.14	1.08	28.10	-7.00	150.00	28.10	1.000	1.08
	35	28.00	29.43	1.10	32.37	-4.37	150.00	32.37	1.000	1.10
	36	117.90	22.54	1.05	23.67	94.23	150.00	23.67	1.000	1.05
	37	36.20	16.49	0.90	14.84	21.36	150.00	14.84	1.000	0.90
	38	39.00	21.14	0.65	13.74	25.26	150.00	13.74	1.000	0.65
	39	88.10	25.21	0.25	6.30	81.80	150.00	6.30	1.000	0.25

Table 7.7 (Continued)

Year	Week No.	PPT (mm)	PET (mm)	K_c	WR = K_c x PET (mm)	PPT-WR (mm)	SMR (mm)	AET (mm)	AET/WR	AET/PET
2006	27	87.30	17.03	0.18	3.06	84.24	84.24	3.06	1.000	0.18
	28	10.60	24.94	0.28	6.86	3.74	87.98	6.86	1.000	0.28
	29	51.60	25.17	0.42	10.57	41.03	129.01	10.57	1.000	0.42
	30	131.30	20.32	0.58	11.69	119.61	150.00	11.69	1.000	0.58
	31	145.50	18.63	0.74	13.78	131.72	150.00	13.78	1.000	0.74
	32	163.60	15.11	0.88	13.30	150.30	150.00	13.30	1.000	0.88
	33	49.20	18.55	1.00	18.55	30.65	150.00	18.55	1.000	1.00
	34	14.10	24.26	1.08	26.08	-11.98	150.00	26.08	1.000	1.08
	35	14.30	25.17	1.10	27.69	-13.39	150.00	27.69	1.000	1.10
	36	70.10	30.49	1.05	32.01	38.09	150.00	32.01	1.000	1.05
	37	70.70	26.11	0.90	23.50	47.20	150.00	23.50	1.000	0.90
	38	5.20	18.59	0.65	12.08	-6.88	150.00	12.08	1.000	0.65
	39	26.50	29.24	0.25	7.31	19.19	150.00	7.31	1.000	0.25
Avg.	27	60.00	21.01	0.18	3.78	56.22	56.22	6.00	1.000	0.29
	28	5.80	27.70	0.28	7.62	-1.82	54.40	9.15	1.000	0.33
	29	26.40	29.96	0.42	12.58	13.82	68.22	13.16	1.000	0.44
	30	107.50	21.21	0.58	12.19	95.31	150.00	16.34	1.000	0.77
	31	174.07	17.57	0.74	13.00	161.07	150.00	21.72	1.000	1.24
	32	99.13	19.10	0.88	16.81	82.33	150.00	24.39	1.000	1.28
	33	33.77	20.21	1.00	20.21	13.56	150.00	30.31	1.000	1.50
	34	19.67	23.92	1.08	25.71	-6.04	150.00	30.36	1.000	1.27
	35	18.00	28.92	1.10	31.81	-13.81	150.00	35.62	1.000	1.23
	36	73.37	26.72	1.05	28.06	45.31	150.00	31.46	1.000	1.18
	37	36.43	23.51	0.90	21.16	15.27	150.00	27.14	1.000	1.15
	38	42.83	23.45	0.65	15.24	27.59	150.00	20.23	1.000	0.86
	39	66.97	26.64	0.25	6.66	60.31	150.00	6.87	1.000	0.26

Table 7.8: Water Budget model calculation sheet (ET_o taken from DHAG) for Pune Research station

Year	Week No.	PPT (mm)	PET (mm)	K_c	WR = K_c x PET (mm)	PPT-WR (mm)	SMR (mm)	AET (mm)	AET/WR	AET/PET
2004	27	2.70	23.30	0.18	4.19	**-1.49**	**0.00**	**0.00**	**0.000**	**0.0000**
	28	5.60	25.42	0.28	6.99	**-1.39**	**0.00**	**0.00**	**0.000**	**0.0000**
	29	7.80	27.12	0.42	11.39	**-3.59**	**0.00**	**0.00**	**0.000**	**0.0000**
	30	18.60	23.32	0.58	13.41	5.19	0.00	0.00	1.000	0.5750
	31	203.40	18.53	0.74	13.71	189.69	150.00	13.71	1.000	0.7400
	32	104.40	19.61	0.88	17.25	87.15	150.00	17.25	1.000	0.8800
	33	22.80	19.94	1.00	19.94	2.86	150.00	19.94	1.000	1.0000
	34	23.80	21.03	1.08	22.60	1.20	150.00	22.60	1.000	1.0750
	35	11.70	24.93	1.10	27.42	-15.72	150.00	27.42	1.000	1.1000
	36	32.10	26.29	1.05	27.61	4.49	150.00	27.61	1.000	1.0500
	37	2.40	24.33	0.90	21.90	-19.50	150.00	21.90	1.000	0.9000
	38	84.30	25.97	0.65	16.88	67.42	150.00	16.88	1.000	0.6500
	39	86.30	27.09	0.25	6.77	79.53	150.00	6.77	1.000	0.2500
2005	27	90.00	20.32	0.18	3.66	86.34	86.34	3.66	1.000	0.18
	28	1.20	24.27	0.28	6.67	-5.47	80.87	6.67	1.000	0.28
	29	19.80	27.61	0.42	11.60	8.20	89.07	11.60	1.000	0.42
	30	172.60	19.48	0.58	11.20	161.40	150.00	11.20	1.000	0.58
	31	173.30	16.55	0.74	12.25	161.05	150.00	12.25	1.000	0.74
	32	29.40	20.72	0.88	18.23	11.17	150.00	18.23	1.000	0.88
	33	29.30	22.01	1.00	22.01	7.29	150.00	22.01	1.000	1.00
	34	21.10	23.92	1.08	25.72	-4.62	150.00	25.72	1.000	1.08
	35	28.00	26.96	1.10	29.65	-1.65	150.00	29.65	1.000	1.10
	36	117.90	27.59	1.05	28.97	88.93	150.00	28.97	1.000	1.05
	37	36.20	19.62	0.90	17.66	18.54	150.00	17.66	1.000	0.90
	38	39.00	20.35	0.65	13.23	25.77	150.00	13.23	1.000	0.65
	39	88.10	23.13	0.25	5.78	82.32	150.00	5.78	1.000	0.25

Table 7.8 (Continued)

Year	Week No.	PPT (mm)	PET (mm)	K_c	WR = K_c x PET (mm)	PPT-WR (mm)	SMR (mm)	AET (mm)	AET/WR	AET/PET
2006	27	87.30	16.37	0.18	2.95	84.35	84.35	2.95	1.000	0.18
	28	10.60	21.62	0.28	5.94	4.66	89.01	5.94	1.000	0.28
	29	51.60	23.03	0.42	9.67	41.93	130.94	9.67	1.000	0.42
	30	131.30	19.09	0.58	10.98	120.32	150.00	10.98	1.000	0.58
	31	145.50	18.87	0.74	13.96	131.54	150.00	13.96	1.000	0.74
	32	163.60	13.85	0.88	12.19	151.41	150.00	12.19	1.000	0.88
	33	49.20	18.57	1.00	18.57	30.63	150.00	18.57	1.000	1.00
	34	14.10	22.84	1.08	24.56	-10.46	150.00	24.56	1.000	1.08
	35	14.30	22.52	1.10	24.77	-10.47	150.00	24.77	1.000	1.10
	36	70.10	26.67	1.05	28.01	42.09	150.00	28.01	1.000	1.05
	37	70.70	27.40	0.90	24.66	46.04	150.00	24.66	1.000	0.90
	38	5.20	21.80	0.65	14.17	-8.97	150.00	14.17	1.000	0.65
	39	26.50	26.43	0.25	6.61	19.89	150.00	6.61	1.000	0.25
Avg.	27	60.00	19.79	0.18	3.56	56.44	56.44	3.56	1.000	0.30
	28	5.80	23.66	0.28	6.51	-0.71	55.73	6.51	1.000	0.39
	29	26.40	26.25	0.42	11.03	15.37	71.10	11.03	1.000	0.50
	30	107.50	20.73	0.58	11.92	95.58	150.00	11.92	1.000	0.79
	31	174.07	17.89	0.74	13.24	160.83	150.00	13.24	1.000	1.21
	32	99.13	18.04	0.88	15.88	83.26	150.00	15.88	1.000	1.35
	33	33.77	20.00	1.00	20.00	13.77	150.00	20.00	1.000	1.52
	34	19.67	22.28	1.08	23.95	-4.28	150.00	23.95	1.000	1.36
	35	18.00	24.68	1.10	27.15	-9.15	150.00	27.15	1.000	1.44
	36	73.37	26.89	1.05	28.24	45.13	150.00	28.24	1.000	1.17
	37	36.43	24.35	0.90	21.91	14.52	150.00	21.91	1.000	1.11
	38	42.83	22.79	0.65	14.81	28.02	150.00	14.81	1.000	0.89
	39	66.97	25.44	0.25	6.36	60.61	150.00	6.36	1.000	0.27

Table 7.9: Drought Evaluation for Pune Research station

Week No.	From FAO	From DHAG
27	1	1
28	1	1
29	1	1
30	1	0
31	0	0
32	0	0
33	0	0
34	3	3
35	3	3
36	3	3
37	0	0
38	0	0
39	0	0

The weekwise drought frequency is given in Table 7.9 for Pune research station. It is observed that the frequency of drought evaluated by using FAO-56 and DHAG methods is nearly the same.

Table 7.10: Water Budget Model calculation sheet (ET_o taken from FAO-56) for Kolhapur Research station

YEAR	WEEK No.	PPT	PET	K_c	WR = K_c x PET	PPT-WR	SMR	AE	AE/WR	AE/PET
2012	27	30.40	22.78	0.18	4.10	26.30	26.30	4.10	1.000	0.1800
	28	12.10	25.29	0.28	6.96	5.14	31.44	6.96	1.000	0.2750
	29	62.70	22.36	0.42	9.39	53.31	84.75	9.39	1.000	0.4200
	30	86.10	20.41	0.58	11.74	74.36	150.00	11.74	1.000	0.5750
	31	108.30	20.00	0.74	14.80	93.50	150.00	14.80	1.000	0.7400
	32	69.20	20.58	0.88	18.11	51.09	150.00	18.11	1.000	0.8800
	33	6.10	23.12	1.00	23.12	-17.02	150.00	23.12	1.000	1.0000
	34	7.20	22.33	1.08	24.01	-16.81	150.00	24.01	1.000	1.0750
	35	52.20	27.90	1.10	30.69	21.51	150.00	30.69	1.000	1.1000
	36	61.70	23.54	1.05	24.71	36.99	150.00	24.71	1.000	1.0500
	37	10.40	25.30	0.90	22.77	-12.37	150.00	22.77	1.000	0.9000
	38	12.00	26.38	0.65	17.15	-5.15	150.00	17.15	1.000	0.6500
	39	16.80	23.89	0.25	5.97	10.83	150.00	5.97	1.000	0.2500
2014	27	5.50	28.54	0.18	5.14	0.36	0.36	5.14	1.000	0.18
	28	72.70	24.39	0.28	6.71	65.99	66.36	6.71	1.000	0.28
	29	92.40	25.63	0.42	10.77	81.63	147.99	10.77	1.000	0.42
	30	125.70	26.78	0.58	15.40	110.30	150.00	15.40	1.000	0.58
	31	96.20	28.80	0.74	21.32	74.88	150.00	21.32	1.000	0.74
	32	50.20	23.46	0.88	20.64	29.56	150.00	20.64	1.000	0.88
	33	14.40	22.71	1.00	22.71	-8.31	150.00	22.71	1.000	1.00
	34	61.90	17.61	1.08	18.93	42.97	150.00	18.93	1.000	1.08
	35	80.40	22.04	1.10	24.24	56.16	150.00	24.24	1.000	1.10
	36	20.50	22.70	1.05	23.83	-3.33	150.00	23.83	1.000	1.05
	37	4.30	22.33	0.90	20.10	-15.80	150.00	20.10	1.000	0.90
	38	0.80	23.49	0.65	15.27	-14.47	150.00	15.27	1.000	0.65
	39	3.20	21.13	0.25	5.28	-2.08	150.00	5.28	1.000	0.25

Table 7.10 (Continued)

YEAR	WEEK No.	PPT	PET	K_c	WR = K_c x PET	PPT-WR	SMR	AE	AE/WR	AE/PET
Avg.	27	41.20	23.87	0.18	4.30	36.90	36.90	4.30	1.000	0.18
	28	62.25	24.22	0.28	6.66	55.59	92.49	6.66	1.000	0.28
	29	68.08	21.85	0.42	9.18	58.90	150.00	9.18	1.000	0.42
	30	84.63	20.20	0.58	11.61	73.01	150.00	11.61	1.000	0.58
	31	72.50	20.00	0.74	14.80	57.70	150.00	14.80	1.000	0.74
	32	67.75	20.42	0.88	17.97	49.78	150.00	17.97	1.000	0.88
	33	19.98	22.76	1.00	22.76	-2.79	150.00	22.76	1.000	1.00
	34	27.33	22.34	1.08	24.02	3.31	150.00	24.02	1.000	1.08
	35	59.38	24.00	1.10	26.40	32.98	150.00	26.40	1.000	1.10
	36	31.35	23.80	1.05	24.99	6.36	150.00	24.99	1.000	1.05
	37	41.20	25.39	0.90	22.85	18.35	150.00	22.85	1.000	0.90
	38	17.95	25.51	0.65	16.58	1.37	150.00	16.58	1.000	0.65
	39	24.58	24.58	0.25	6.15	18.43	150.00	6.15	1.000	0.25

Table 7.11: Water Budget Model calculation sheet (ET_o taken from DHAG) for Kolhapur Research station

YEAR	WEEK No.	PPT	PET	K_c	WR = K_c x PET	PPT-WR	SMR	AE	AE/WR	AE/PET
2012	30	2.70	21.85	0.18	3.93	**-1.23**	**0.00**	**0.00**	**0.000**	**0.0000**
	12	5.60	23.78	0.28	6.54	**-0.94**	**0.00**	**0.00**	**0.000**	**0.0000**
	63	7.80	18.76	0.42	7.88	-0.08	6.09	7.88	1.000	0.4200
	86	18.60	17.85	0.58	10.26	8.34	150.00	10.26	1.000	0.5750
	108	203.40	24.42	0.74	18.07	185.33	150.00	18.07	1.000	0.7400
	69	104.40	18.59	0.88	16.36	88.04	150.00	16.36	1.000	0.8800
	6	22.80	22.22	1.00	22.22	0.58	150.00	22.22	1.000	1.0000
	7	23.80	24.29	1.08	26.12	-2.32	150.00	26.12	1.000	1.0750
	52	11.70	24.23	1.10	26.66	-14.96	150.00	26.66	1.000	1.1000
	62	32.10	17.50	1.05	18.37	13.73	150.00	18.37	1.000	1.0500
	10	2.40	20.95	0.90	18.86	-16.46	150.00	18.86	1.000	0.9000
	12	84.30	23.93	0.65	15.55	68.75	150.00	15.55	1.000	0.6500
	17	86.30	26.80	0.25	6.70	79.60	85.12	6.70	1.000	0.2500
2014	0	90.00	27.10	0.18	4.88	85.12	80.57	4.88	1.000	0.18
	6	1.20	20.93	0.28	5.75	-4.55	92.86	5.75	1.000	0.28
	73	19.80	17.88	0.42	7.51	12.29	150.00	7.51	1.000	0.42
	92	172.60	17.84	0.58	10.26	162.34	150.00	10.26	1.000	0.58
	126	173.30	20.02	0.74	14.81	158.49	150.00	14.81	1.000	0.74
	96	29.40	19.23	0.88	16.92	12.48	150.00	16.92	1.000	0.88
	50	29.30	20.60	1.00	20.60	8.70	150.00	20.60	1.000	1.00
	14	21.10	25.95	1.08	27.89	-6.79	150.00	27.89	1.000	1.08
	62	28.00	20.31	1.10	22.34	5.66	150.00	22.34	1.000	1.10
	80	117.90	20.12	1.05	21.12	96.78	150.00	21.12	1.000	1.05
	21	36.20	22.57	0.90	20.31	15.89	150.00	20.31	1.000	0.90
	4	39.00	24.04	0.65	15.63	23.37	150.00	15.63	1.000	0.65
	1	88.10	27.26	0.25	6.81	81.29	82.89	6.81	1.000	0.25

Table 7.11 (Continued)

YEAR	WEEK No.	PPT	PET	Kc	WR = Kc x PET	PPT-WR	SMR	AE	AE/WR	AE/PET
Avg	3	87.30	24.47	0.18	4.41	82.89	87.35	4.41	1.000	0.18
	0	10.60	22.35	0.28	6.15	4.45	131.25	6.15	1.000	0.28
	41	51.60	18.32	0.42	7.69	43.91	150.00	7.69	1.000	0.42
	62	131.30	17.85	0.58	10.26	121.04	150.00	10.26	1.000	0.58
	68	145.50	22.22	0.74	16.44	129.06	150.00	16.44	1.000	0.74
	85	163.60	18.91	0.88	16.64	146.96	150.00	16.64	1.000	0.88
	73	49.20	21.41	1.00	21.41	27.79	150.00	21.41	1.000	1.00
	68	14.10	25.12	1.08	27.00	-12.90	150.00	27.00	1.000	1.08
	20	14.30	22.27	1.10	24.50	-10.20	150.00	24.50	1.000	1.10
	27	70.10	18.81	1.05	19.75	50.35	150.00	19.75	1.000	1.05
	59	70.70	21.76	0.90	19.58	51.12	150.00	19.58	1.000	0.90
	31	5.20	23.99	0.65	15.59	-10.39	150.00	15.59	1.000	0.65
	41	26.50	27.03	0.25	6.76	19.74	0.00	0.00	0.000	0.00

Table 7.12: Drought Evaluation for Kolhapur Research Station

Week No.	From FAO Model	From DHAG
27	1	1
28	1	1
29	1	0
30	1	0
31	0	0
32	0	0
33	0	0
34	3	3
35	3	3
36	3	3
37	0	0
38	0	0
39	0	1

The weekwise drought frequency is given in Table 7.12 for Kolhapur research station. It is observed that the frequency of drought evaluated by using FAO-56 and DHAG methods is nearly the same.

Table 7.13: Water Budget Model calculation sheet (ET_o taken from FAO-56) for Ahmednagar Research station

YEAR	WEEK No.	PPT	PET	K_c	WR = K_c x PET	PPT-WR	SMR	AE	AE/WR	AE/PET
2003	27	9.60	31.00	0.18	5.58	4.02	4.02	5.58	1.000	0.1800
	28	7.60	33.84	0.28	9.31	-1.71	2.31	9.31	1.000	0.2750
	29	1.20	33.00	0.42	13.86	**-12.66**	**0.00**	**0.00**	**0.000**	**0.0000**
	30	15.20	23.23	0.58	13.36	**1.84**	**0.00**	**0.00**	**0.000**	**0.0000**
	31	0.00	25.75	0.74	19.05	**-19.05**	**0.00**	**0.00**	**0.000**	**0.0000**
	32	20.00	20.64	0.88	18.16	**1.84**	**0.00**	**0.00**	**0.000**	**0.0000**
	33	4.60	24.94	1.00	24.94	**-20.34**	**0.00**	**0.00**	**0.000**	**0.0000**
	34	43.60	24.03	1.08	25.83	**17.77**	**0.00**	**0.00**	**0.000**	**0.0000**
	35	0.00	25.88	1.10	28.47	**-28.47**	**0.00**	**0.00**	**0.000**	**0.0000**
	36	2.20	25.25	1.05	26.51	**-24.31**	**0.00**	**0.00**	**0.000**	**0.0000**
	37	0.00	24.67	0.90	22.20	**-22.20**	**0.00**	**0.00**	**0.000**	**0.0000**
	38	0.00	24.27	0.65	15.78	**-15.78**	**0.00**	**0.00**	**0.000**	**0.0000**
	39	46.00	24.37	0.25	6.09	**39.91**	**0.00**	**0.00**	**0.000**	**0.0000**
2008	27	1.10	23.93	0.18	4.31	**-3.21**	**0.00**	**0.00**	**0.000**	**0.00**
	28	0.20	28.02	0.28	7.71	**-7.51**	**0.00**	**0.00**	**0.000**	**0.00**
	29	0.00	29.96	0.42	12.58	**-12.58**	**0.00**	**0.00**	**0.000**	**0.00**
	30	30.00	26.12	0.58	15.02	**14.98**	**0.00**	**0.00**	**0.000**	**0.00**
	31	3.70	25.48	0.74	18.86	**-15.16**	**0.00**	**0.00**	**0.000**	**0.00**
	32	74.40	25.92	0.88	22.81	51.59	28.12	22.81	1.000	0.88
	33	7.30	28.95	1.00	28.95	-21.65	6.47	28.95	1.000	1.00
	34	17.70	27.51	1.08	29.57	**-11.87**	**0.00**	**0.00**	**0.000**	**0.00**
	35	55.30	25.90	1.10	28.49	26.81	21.41	28.49	1.000	1.10
	36	63.10	25.36	1.05	26.63	36.47	57.89	26.63	1.000	1.05
	37	249.00	26.52	0.90	23.87	225.13	150.00	23.87	1.000	0.90
	38	53.70	24.77	0.65	16.10	37.60	150.00	16.10	1.000	0.65
	39	0.00	25.99	0.25	6.50	-6.50	150.00	6.50	1.000	0.25

Table 7.13 (Continued)

YEAR	WEEK No.	PPT	PET	Kc	WR = Kc x PET	PPT-WR	SMR	AE	AE/WR	AE/PET
Avg.	27	17.95	27.47	0.18	4.94	13.01	13.01	4.94	1.000	0.18
	28	6.18	30.93	0.28	8.51	-2.32	10.68	8.51	1.000	0.28
	29	5.02	31.48	0.42	13.22	-8.20	2.48	13.22	1.000	0.42
	30	66.42	24.68	0.58	14.19	52.23	54.71	14.19	1.000	0.58
	31	13.28	25.61	0.74	18.95	-5.67	49.04	18.95	1.000	0.74
	32	18.05	23.28	0.88	20.48	-2.43	46.60	20.48	1.000	0.88
	33	6.87	26.94	1.00	26.94	-20.08	26.52	26.94	1.000	1.00
	34	64.65	25.77	1.08	27.70	36.95	63.47	27.70	1.000	1.08
	35	37.35	25.89	1.10	28.48	8.87	72.35	28.48	1.000	1.10
	36	42.32	25.31	1.05	26.57	15.75	88.09	26.57	1.000	1.05
	37	69.43	25.60	0.90	23.04	46.40	134.49	23.04	1.000	0.90
	38	38.78	24.52	0.65	15.94	22.84	150.00	15.94	1.000	0.65
	39	17.73	25.18	0.25	6.29	11.44	150.00	6.29	1.000	0.25

Table 7.14: Water Budget Model calculation sheet (ET_o taken from DHAG) for Ahmednagar Research station

YEAR	WEEK No.	PPT	PET	K_c	WR = K_c x PET	PPT-WR	SMR	AE	AE/WR	AE/PET
2003	27	9.60	28.72	0.18	5.17	4.43	3.77	5.17	1.000	0.1800
	28	7.60	30.05	0.28	8.26	**-0.66**	**0.00**	**0.00**	**0.000**	**0.0000**
	29	1.20	34.42	0.42	14.46	**-13.26**	**0.00**	**0.00**	**0.000**	**0.0000**
	30	15.20	27.34	0.58	15.72	**-0.52**	**0.00**	**0.00**	**0.000**	**0.0000**
	31	0.00	25.36	0.74	18.76	**-18.76**	**0.00**	**0.00**	**0.000**	**0.0000**
	32	20.00	19.41	0.88	17.08	**2.92**	**0.00**	**0.00**	**0.000**	**0.0000**
	33	4.60	22.49	1.00	22.49	**-17.89**	**0.00**	**0.00**	**0.000**	**0.0000**
	34	43.60	29.17	1.08	31.35	**12.25**	**0.00**	**0.00**	**0.000**	**0.0000**
	35	0.00	29.33	1.10	32.27	**-32.27**	**0.00**	**0.00**	**0.000**	**0.0000**
	36	2.20	27.68	1.05	29.06	**-26.86**	**0.00**	**0.00**	**0.000**	**0.0000**
	37	0.00	21.03	0.90	18.93	**-18.93**	**0.00**	**0.00**	**0.000**	**0.0000**
	38	0.00	22.16	0.65	14.40	**-14.40**	**0.00**	**0.00**	**0.000**	**0.0000**
	39	46.00	29.84	0.25	7.46	**38.54**	**0.00**	**0.00**	**0.000**	**0.0000**
2008	27	1.10	29.81	0.18	5.37	**-4.27**	**0.00**	**0.00**	**0.000**	**0.00**
	28	0.20	31.25	0.28	8.59	**-8.39**	**0.00**	**0.00**	**0.000**	**0.00**
	29	0.00	26.38	0.42	11.08	**-11.08**	**0.00**	**0.00**	**0.000**	**0.00**
	30	30.00	25.80	0.58	14.84	**15.16**	**0.00**	**0.00**	**0.000**	**0.00**
	31	3.70	26.61	0.74	19.69	-15.99	25.65	19.69	1.000	0.74
	32	74.40	27.49	0.88	24.19	50.21	2.28	24.19	1.000	0.88
	33	7.30	30.66	1.00	30.66	**-23.36**	**0.00**	**0.00**	**0.000**	**0.00**
	34	17.70	32.29	1.08	34.71	-17.01	10.65	34.71	1.000	1.08
	35	55.30	27.20	1.10	29.92	25.38	51.19	29.92	1.000	1.10
	36	63.10	21.48	1.05	22.56	40.54	150.00	22.56	1.000	1.05
	37	249.00	23.87	0.90	21.49	227.51	150.00	21.49	1.000	0.90
	38	53.70	26.84	0.65	17.44	36.26	150.00	17.44	1.000	0.65
	39	0.00	29.45	0.25	7.36	-7.36	12.68	7.36	1.000	0.25

Table 7.14 (Continued)

YEAR	WEEK No.	PPT	PET	Kc	WR = Kc x PET	PPT-WR	SMR	AE	AE/WR	AE/PET
Avg.	27	17.95	29.26	0.18	5.27	12.68	10.44	5.27	1.000	0.18
	28	6.18	30.65	0.28	8.43	-2.25	2.69	8.43	1.000	0.28
	29	5.02	30.40	0.42	12.77	-7.75	53.82	12.77	1.000	0.42
	30	66.42	26.57	0.58	15.28	51.14	47.88	15.28	1.000	0.58
	31	13.28	25.98	0.74	19.23	-5.94	45.30	19.23	1.000	0.74
	32	18.05	23.45	0.88	20.63	-2.58	25.59	20.63	1.000	0.88
	33	6.87	26.58	1.00	26.58	-19.71	57.20	26.58	1.000	1.00
	34	64.65	30.73	1.08	33.03	31.62	63.46	33.03	1.000	1.08
	35	37.35	28.27	1.10	31.09	6.26	79.97	31.09	1.000	1.10
	36	42.32	24.58	1.05	25.81	16.51	129.19	25.81	1.000	1.05
	37	69.43	22.45	0.90	20.21	49.23	150.00	20.21	1.000	0.90
	38	38.78	24.50	0.65	15.92	22.86	150.00	15.92	1.000	0.65
	39	17.73	29.64	0.25	7.41	10.32	**0.00**	**0.00**	**0.000**	**0.00**

Table 7.15: Drought Evaluation for Ahmednagar Research station

Week No.	From FAO Model	Total Drought Weeks
27	1	1
28	1	2
29	2	2
30	2	2
31	2	1
32	1	1
33	1	2
34	3	3
35	3	3
36	3	3
37	1	1
38	1	1
39	1	2

The weekwise drought frequency is given in Table 7.15 for Ahmednagar research station. It is observed that the frequency of drought evaluated by using FAO-56 and DHAG methods is nearly the same.

7.7 USING DYNAMIC MODEL

Water budget models are the simplest types of soil moisture flow models used in irrigation water application and discussed in previous section 7.5 and 7.6. The amount of irrigation water for a crop field is dependent on the rooting pattern of that crop and the layer-wise distribution of soil moisture in the root zone profile. The flow to individual roots is ignored and the overall root system is considered to uptake moisture from each layer of the root zone at some rate. This rate depends on position of depth point in a coordinate system, existing moisture content, and time from initial condition. The Dynamic model used for study purpose here consist two major components. One is main governing model and the second one is the sink.

$$\frac{\partial}{\partial z}\left(K(\psi)\frac{\partial\psi}{\partial z}+1\right)+\text{ Sink}= C(\psi)\frac{\partial\psi}{\partial t} \tag{7.1}$$

$$\text{Sink}=S_r(\Psi, z, \theta, t)= \phi(\psi)\, S_{max}(0\le\phi(\psi)\le 1) \tag{7.2}$$

The soil parameters established by Van Genuchten Model (VG) needed for running governing model. The soil parameters used for study area Sholapur are listed in following Table 7.16. The detail discussion is made in Chapter 3 and 5. The relation between suction and moisture content established is shown in Chapter 5. For sake of presentation one graph figure is produced again in following Figure 7.17.

Table 7.16: Soil Parameters Used In The Model For Sholapur Station

Depth	Moisture at saturation θ_s	Residual Moisture θ_r	Parameters established			Hydraulic Conductivity Ks (cm/ hr)
			n	m	α	
0 to 15 cm	0.6264	0.2172	1.66	0.40	0.009	0.175
15 to 30 cm	0.615	0.209	1.63	0.39	.0096	0.114
30 to 60 cm	0.613	0.2018	1.61	0.38	.0118	0.171

(Note: - Above soil parameters are established by modified Van Genuchten (VG)Model.)

As per Miller and Donahue (1997) irrigation is recommended when 50% of available water or available moisture has been utilised in the zone of maximum root activity, except in ripening seed crop or sugar crops. The moisture content in soil should never approach the permanent wilting point unless rapid maturing is needed. In most of the plants available water is held in high matric suction from -1/3 to -1 bar. This relation shows that up to 100 to 140 cm of suction moisture content is reduced rapidly and suction pressure change slowly. This reveals that this moisture content at this point is at field capacity. The irrigation water is needed when suction pressure changes rapidly and moisture content release is very slow. The soil moisture release start decreasing when suction increasing beyond 1000 cm.

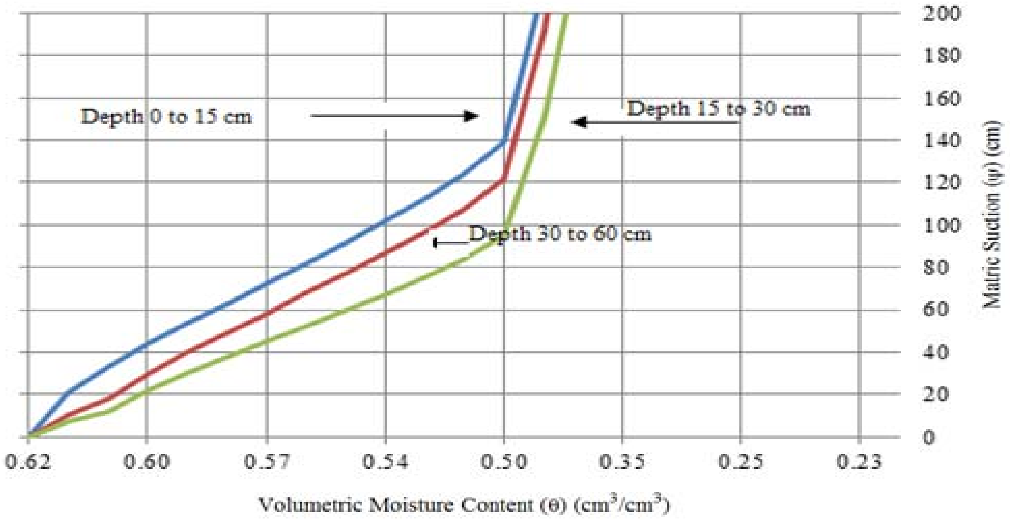


Figure 7.17: Matric Suction vs Moisture Content Plot for Study Area (Sholapur)

Levin et al. (2007) stated that under water stress conditions the plant roots may not supply the maximum moisture required for potential transpiration. This lack of available moisture condition in the soil root zone causes most plants to biologically react by closing stomata, reducing transpiration, and reducing metabolic reactions. Levin et al. (2007) and Homae et al. (2002a and b) modelled this reducing in transpiration rate by a limiting function. This determines the percentage decrease in the plants' ability to draw moisture as the soil moisture matric suction increases in the root zone. To account for such conditions, it is necessary to relate the actual transpiration to the potential transpiration in the model. This is discussed in detail in the model formulation and in one dimensional analysis concept. The S_{max} term used in the study is given by the Ojha and Rai (1996) model as follows:

$$S_{max} = \left\{ \left[\frac{T_p}{L_r}\right] [\beta + 1] \left[1 - \left(\frac{z}{L_r}\right)\right]^{\beta} \right\} \tag{7.3}$$

Where,
S_{max} = Maximum root water uptake rat,
T_p= Transpiration on j th day,
L_r = Root depth on j th day,
Z = Depth below ground (cm).

Ojha and Rai gave different values of β for some crops. Here the crop considered for study is pearl millet. Perrochet (1987); Babajimopoulos et al. (1995); Wu et al. (1999) and Babajimopoulos and Panoras (2005) gave transpiration model as follows:

$$T_p = ET_o - E_P \tag{7.4}$$

Where,
WR = Requirement = K_c ET_o,
E_p = Potential Evaporation.

Babajmopoulos et al. 1995 and Babajmopoulos and Panoras (2005) gave a simple equation for E_p.

$$E_P = \text{WR} \exp(-0.623 \text{ LAI}) \tag{7.5}$$

Where LAI = Leaf area index.

Huda et al. (1982) stated that the leaf area growth is slow early in the season. As their size of the embryonic leaves is small and it increases approximately 15 to 20 days after their emergence, as the size of the individual leaves increases and tillers start noticing the expansion of leaves. The LAI values are taken from Boken and Chandra (2012) and they are presented in Table 7.17.

Table 7.17: LAI values for study area considered

S. No.	Days after Sowing	LAI
1	19	0.6
2	23	0.9
3	32	1.97
4	40	2.51
5	51	0.79
6	59	0.35
7	72	0.07

Using above LAI and estimated ET_o of study area Transpiration for study area is evaluated. The results represented for Sholapur research station are in following Table 7.18. This type of exercise can be carried out for other research stations also.

Table 7.18: Transpiration (T_p) Evaluation for Sholapur (1997)

Sr. No.	Week	Day from sowing	Day in the Year	Leaf Area Index	ET_o	K_c	Water Requirement (mm)	Potential Evaporation (mm)	Transpiration (mm)
1	27	1	182	0.00	4.85	0.18	0.87	0.87	0.00
2	27	2	183	0.00	4.12	0.18	0.74	0.74	0.00
3	27	3	184	0.00	4.13	0.18	0.74	0.74	0.00
4	27	4	185	0.00	3.89	0.18	0.70	0.70	0.00
5	27	5	186	0.00	3.74	0.18	0.67	0.67	0.00
6	27	6	187	0.04	4.26	0.18	0.77	0.75	0.02
7	27	7	188	0.09	4.50	0.18	0.81	0.77	0.04
8	28	8	189	0.13	4.14	0.28	1.14	1.05	0.09
9	28	9	190	0.17	4.62	0.28	1.27	1.14	0.13
10	28	10	191	0.21	4.57	0.28	1.26	1.10	0.16
11	28	11	192	0.26	4.57	0.28	1.26	1.07	0.19
12	28	12	193	0.30	4.09	0.28	1.12	0.93	0.19
13	28	13	194	0.34	4.53	0.28	1.25	1.01	0.24
14	28	14	195	0.39	4.39	0.28	1.21	0.95	0.26
15	29	15	196	0.43	4.52	0.28	1.27	0.97	0.30
16	29	16	197	0.47	4.66	0.42	1.96	1.46	0.50
17	29	17	198	0.51	4.27	0.42	1.80	1.30	0.49
18	29	18	199	0.56	3.93	0.42	1.65	1.17	0.48
19	29	19	200	0.60	5.10	0.42	2.14	1.47	0.67
20	29	20	201	0.68	5.24	0.42	2.20	1.44	0.76
21	29	21	202	0.75	5.33	0.42	2.24	1.40	0.84
22	30	22	203	0.83	5.21	0.58	3.00	1.79	1.20
23	30	23	204	0.90	5.06	0.58	2.91	1.66	1.25
24	30	24	205	1.02	5.37	0.58	3.09	1.64	1.45
25	30	25	206	1.14	5.30	0.58	3.05	1.50	1.55
26	30	26	207	1.26	4.21	0.58	2.42	1.11	1.31
27	30	27	208	1.38	3.98	0.58	2.29	0.97	1.32
28	30	28	209	1.49	4.25	0.58	2.45	0.96	1.48
29	31	29	210	1.61	4.77	0.74	3.53	1.29	2.24
30	31	30	211	1.73	4.36	0.74	3.22	1.10	2.13
31	31	31	212	1.85	3.96	0.74	2.93	0.93	2.01
32	31	32	213	1.97	3.35	0.74	2.48	0.73	1.75
33	31	33	214	2.04	4.43	0.74	3.28	0.92	2.36
34	31	34	215	2.11	4.52	0.74	3.34	0.90	2.44
35	31	35	216	2.17	4.93	0.74	3.65	0.94	2.71
36	32	36	217	2.24	4.95	0.88	4.35	1.08	3.28
37	32	37	218	2.31	4.58	0.88	4.03	0.96	3.07

Table 7.18 (Continued)

Sr. No.	Week	Day from sowing	Day in the Year	Leaf Area Index	ET_o	K_c	Water Requirement (mm)	Potential Evaporation (mm)	Transpiration (mm)
38	32	38	219	2.38	4.74	0.88	4.18	0.95	3.22
39	32	39	220	2.44	4.95	0.88	4.36	0.95	3.40
40	32	40	221	2.51	5.21	0.88	4.58	0.96	3.62
41	32	41	222	2.35	5.31	0.88	4.67	1.08	3.59
42	32	42	223	2.20	5.09	0.88	4.48	1.14	3.34
43	33	43	224	2.04	4.89	1.00	4.89	1.37	3.52
44	33	44	225	1.88	4.57	1.00	4.57	1.41	3.16
45	33	45	226	1.73	4.96	1.00	4.96	1.69	3.27
46	33	46	227	1.57	4.61	1.00	4.61	1.73	2.88
47	33	47	228	1.42	4.82	1.00	4.82	1.99	2.82
48	33	48	229	1.26	4.83	1.00	4.83	2.21	2.63
49	33	49	230	1.10	5.11	1.00	5.11	2.57	2.54
50	34	50	231	0.95	5.14	1.08	5.52	3.06	2.46
51	34	51	232	0.79	5.01	1.08	5.38	3.29	2.09
52	34	52	233	0.73	4.22	1.08	4.53	2.87	1.67
53	34	53	234	0.68	3.89	1.08	4.18	2.73	1.44
54	34	54	235	0.62	4.27	1.08	4.59	3.11	1.48
55	34	55	236	0.57	2.91	1.08	3.12	2.19	0.93
56	34	56	237	0.51	3.92	1.08	4.22	3.06	1.16
57	35	57	238	0.46	4.51	1.10	4.96	3.73	1.24
58	35	58	239	0.40	4.25	1.10	4.68	3.63	1.04
59	35	59	240	0.35	4.73	1.10	5.20	4.18	1.02
60	35	60	241	0.34	4.49	1.10	4.93	3.99	0.95
61	35	61	242	0.33	4.68	1.10	5.14	4.18	0.96
62	35	62	243	0.32	4.97	1.10	5.47	4.47	1.00
63	35	63	244	0.31	5.06	1.10	5.56	4.57	0.99
64	36	64	245	0.31	5.24	1.05	5.50	4.54	0.96
65	36	65	246	0.30	5.13	1.05	5.39	4.48	0.91
66	36	66	247	0.29	4.61	1.05	4.84	4.05	0.80
67	36	67	248	0.28	5.03	1.05	5.28	4.43	0.85
68	36	68	249	0.27	5.17	1.05	5.43	4.59	0.84
69	36	69	250	0.26	5.15	1.05	5.40	4.59	0.82
70	36	70	251	0.25	4.71	1.05	4.95	4.23	0.72
71	37	71	252	0.24	3.55	0.90	3.20	2.74	0.45
72	37	72	253	0.24	4.78	0.90	4.31	3.72	0.59
73	37	73	254	0.23	4.24	0.90	3.81	3.31	0.50
74	37	74	255	0.22	4.96	0.90	4.46	3.89	0.57
75	37	75	256	0.21	5.32	0.90	4.78	4.20	0.59

Table 7.18 (Continued)

Sr. No.	Week	Day from sowing	Day in the Year	Leaf Area Index	ET_o	K_c	Water Requirement (mm)	Potential Evaporation (mm)	Transpiration (mm)
76	37	76	257	0.20	4.93	0.90	4.44	3.92	0.52
77	37	77	258	0.19	5.04	0.90	4.54	4.02	0.51
78	38	78	259	0.18	4.66	0.65	3.03	2.70	0.33
79	38	79	260	0.17	4.84	0.65	3.15	2.82	0.32
80	38	80	261	0.17	4.51	0.65	2.93	2.64	0.29
81	38	81	262	0.16	4.15	0.65	2.70	2.45	0.25
82	38	82	263	0.15	4.44	0.65	2.89	2.63	0.26
83	38	83	264	0.14	5.02	0.65	3.26	2.99	0.27
84	38	84	265	0.13	4.39	0.65	2.86	2.63	0.22
85	39	85	266	0.12	3.39	0.25	0.85	0.79	0.06
86	39	86	267	0.11	3.86	0.25	0.96	0.90	0.07
87	39	87	268	0.10	3.91	0.25	0.98	0.91	0.06
88	39	88	269	0.10	3.88	0.25	0.97	0.91	0.06
89	39	89	270	0.09	4.06	0.25	1.02	0.96	0.05
90	39	90	271	0.08	3.71	0.25	0.93	0.88	0.04
91	39	91	272	0.07	4.60	0.25	1.15	1.10	0.05

The root depth model used here is the Borg and Grimes (1986) sinusoidal simple root growth model.

$$L_r(\mathrm{t}) = L_m\left(0.5 + \left(0.5\sin\left(3.303\left(\frac{\mathrm{DAP}}{\mathrm{DTM}}\right) - 1.47\right)\right)\right) \tag{7.6}$$

Where,

DAP = Days after planting,

DTM = Days required to maturity of the plant,

L_m = Maximum root depth.

Table 7.19: Effective Depths for Plant Roots in cm (Clark 1970)

Sr. No.	Name of the plant	Effective depth (cm)
01	Onion and lettuce.	30
02	Pasture, potato, bean, cabbage, spinach, strawberry.	60
03	Sweet corn, table beet, peas, squash, carrot, eggplant and peppers.	90
04	Sugar beet, sweet potato, cotton, citrus, lima bean and artichoke.	120
05	Melon, flax, maize and small grains.	150
06	Alfalfa, asparagus, non-citrus orchard, grapes, hops, grains other than maize, Sudan grass, sorghum and tomato.	180

The maximum root depth (L_m) is generally considered as 1.80 m. The depth of soil for Sholapur is varying. The root growth model is used to simulate the root growth for pearl millet. The result is graphically presented as in the following Figure 7.18.

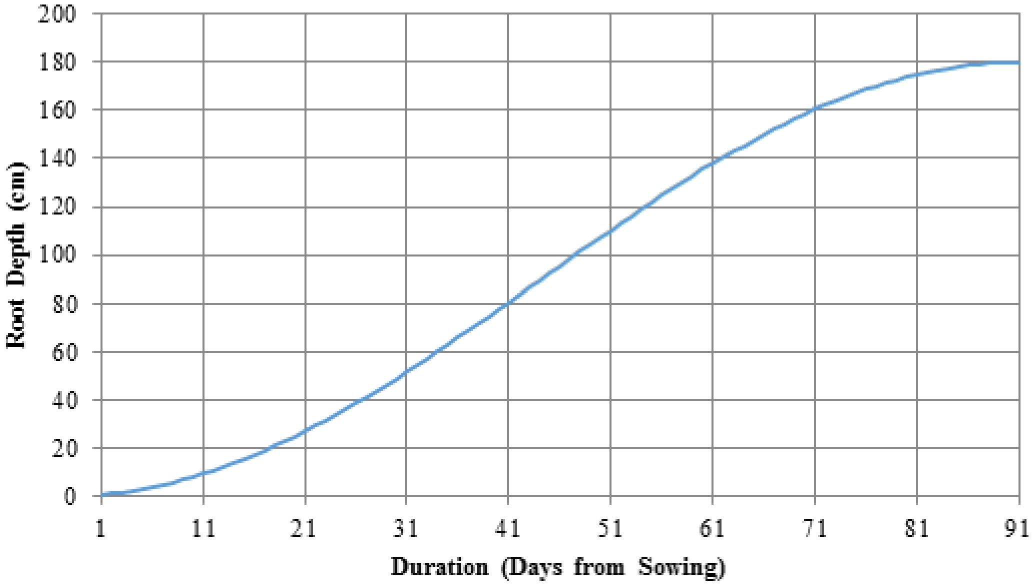


Figure 7.18: Simulated Root Growth over the Crop Period for Sholapur

β value is estimated from the available root growth and crop evapotranspiration is taken as 0.88 while the S_{max} value obtained from the model represented in Equation 7.3 is overestimated, Hence we need to multiply by a multiplying factor $\gamma = 0 .88$ to estimate a realistic value of S_{max}.

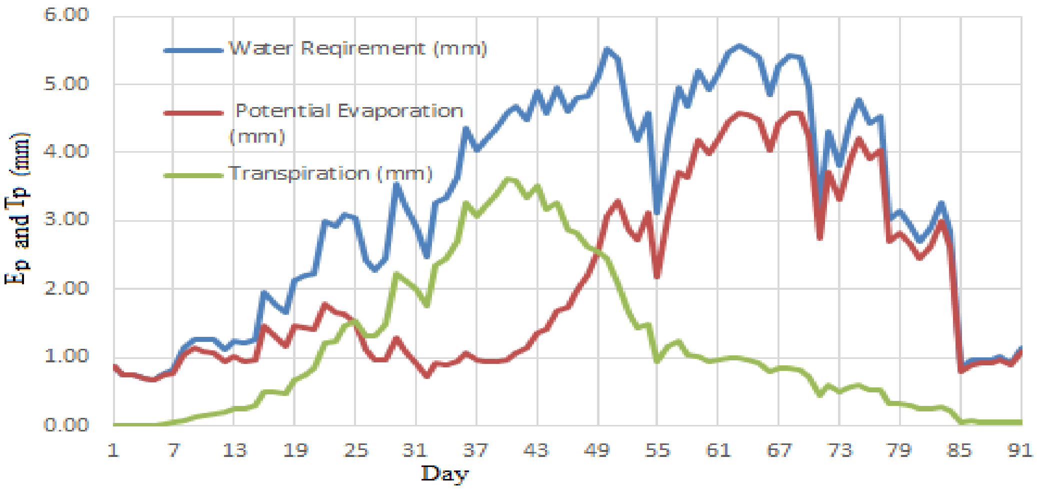


Figure 7.19: Variation of WR, E_p and T_p during crop period for Sholapur (1997)

Table 7.20: Statistical Analysis for Sholapur (1997)

Days	Root growth (cm)	S_{max} (mm) X	S_{max} estimated By model (mm) X_1	$(X_1-X)^2$	$(Xa-X)^2$
1	0.8977	0.8725	1.6080	0.5409	1.4118
2	1.3976	0.7413	1.1678	0.1819	2.6516
3	2.0070	0.7429	0.9504	0.0430	3.4069
4	2.7249	0.7009	0.8428	0.0201	3.8157
5	3.5507	0.6731	0.7602	0.007	4.1453
6	4.4834	0.7676	0.8254	0.0033	3.8840
7	5.5219	0.8097	0.8396	0.0008	3.8282
8	6.6653	0.8097	0.8396	0.0008	3.8282
9	7.9120	0.8097	0.8396	0.0008	3.8282
10	9.2609	0.8097	0.8396	0.0008	3.8282
11	10.7104	0.8097	0.8396	0.0008	3.8282
12	12.2588	0.8097	0.8396	0.0008	3.8282
13	13.9045	0.8097	0.8396	0.0008	3.8282
14	15.6457	0.8097	0.8396	0.0008	3.8282
15	17.4803	0.8097	0.8396	0.0008	3.8282
16	19.4065	0.8097	0.8396	0.0008	3.8282
17	21.4220	0.8097	0.8396	0.0008	3.8282
18	23.5246	0.8097	0.8396	0.0008	3.8282
19	25.7119	0.8097	0.8396	0.0008	3.8282
20	27.9817	0.8097	0.8396	0.0008	3.8282
21	30.3312	0.8097	0.8396	0.0008	3.8282
22	32.7580	0.8097	0.8396	0.0008	3.8282
23	35.2594	2.9122	2.6315	0.0788	0.0271
24	37.8325	3.0861	2.7834	0.0916	0.0001
25	40.4745	3.0459	2.7431	0.0916	0.0028
26	43.1825	2.4214	2.1774	0.0595	0.3829
27	45.9535	2.2881	2.0546	0.0545	0.5499

Table 7.20 (Continued)

Days	Root growth (cm)	S_{max} (mm) X	S_{max} estimated By model (mm) X_1	$(X_1\text{-}X)^2$	$(Xa\text{-}X)^2$
28	48.7844	2.4462	2.1943	0.0634	0.3623
29	51.6721	3.5301	3.1633	0.1345	0.1347
30	54.6134	3.2238	2.8860	0.1141	0.0080
31	57.6050	2.9314	2.6219	0.0957	0.0303
32	60.6435	2.4817	2.2178	0.0696	0.3344
33	63.7257	3.2811	2.9301	0.1232	0.0179
34	66.8482	3.3433	2.9835	0.1294	0.0350
35	70.0073	3.6506	3.2556	0.1560	0.2110
36	73.1997	4.3534	3.8803	0.2238	1.1752
37	76.4219	4.0295	3.5897	0.193	0.6296
38	79.6701	4.1751	3.7176	0.2093	0.8489
39	82.9409	4.3559	3.8766	0.2297	1.1672
40	86.2306	4.5820	4.0762	0.2558	1.6384
41	89.5356	4.6709	4.1537	0.2675	1.8427
42	92.8522	4.4807	3.9754	0.2553	1.3905
43	96.1767	4.8912	4.3464	0.2968	2.4031
44	99.5054	4.5726	4.0620	0.2607	1.6023
45	102.8347	4.9611	4.4057	0.3084	2.5903
46	106.1609	4.6113	4.094	0.2676	1.6841
47	109.4802	4.8159	4.2745	0.2931	2.1854
48	112.7890	4.8321	4.2877	0.2963	2.2247
49	116.0836	5.1147	4.5374	0.3333	3.0317
50	119.3604	5.5231	4.8987	0.3898	4.4206
51	122.6158	5.3806	4.7713	0.3712	3.9009
52	125.8460	4.5325	4.0184	0.2643	1.4937
53	129.0476	4.1775	3.7030	0.2251	0.8222
54	132.2171	4.5922	4.0699	0.2727	1.6223
55	135.3508	3.1249	2.7691	0.1266	0.0007
56	138.4453	4.2172	3.7364	0.2311	0.8840
57	141.4972	4.9621	4.3957	0.3207	2.5584
58	144.5030	4.6753	4.1411	0.2853	1.8087
59	147.4596	5.2008	4.6059	0.3538	3.2750
60	150.3635	4.9347	4.3697	0.3191	2.4760
61	153.2116	5.1432	4.5539	0.3473	3.0893
62	156.0008	5.4670	4.8399	0.3932	4.1765
63	158.7278	5.5619	4.9235	0.4075	4.5253
64	161.3897	5.4993	4.8674	0.3993	4.2897
65	163.9836	5.3894	4.7698	0.3838	3.8951
66	166.5066	4.8444	4.2872	0.3104	2.2230
67	168.9558	5.2789	4.6712	0.3692	3.5156
68	171.3286	5.4306	4.8052	0.3911	4.0362
69	173.6223	5.4044	4.7804	0.3893	3.9371
70	175.8344	4.9504	4.3796	0.3257	2.5072
71	177.9624	3.1963	2.8276	0.1359	0.0009

Table 7.20 (Continued)

Days	**Root growth (cm)**	**S_{max} (mm) X**	**S_{max} estimated By model (mm) X_1**	**$(X_1\text{-}X)^2$**	**$(Xa\text{-}X)^2$**
72	180.0040	4.305	3.8089	0.2469	1.0255
73	181.9569	3.8142	3.3738	0.1939	0.3336
74	183.8190	4.4626	3.9472	0.2656	1.3248
75	185.5881	4.7849	4.2321	0.3056	2.0617
76	187.2623	4.4394	3.9263	0.2632	1.2770
77	188.8399	4.5376	4.0130	0.2752	1.4805
78	190.3189	3.0299	2.6795	0.1227	0.0136
79	191.6978	3.1450	2.7811	0.1323	0.0002
80	192.9751	2.9298	2.5907	0.1149	0.0422
81	194.1492	2.6987	2.3864	0.0975	0.1679
82	195.2191	2.8870	2.5528	0.1116	0.0592
83	196.1833	3.2647	2.8867	0.1428	0.0081
84	197.0410	2.8550	2.5244	0.1093	0.0738
85	197.7910	0.8477	0.7495	0.0096	4.1888
86	198.4327	0.9647	0.8530	0.0124	3.7761
87	198.9652	0.9767	0.8636	0.0128	3.7349
88	199.3880	0.9689	0.8566	0.0125	3.7619
89	199.7006	1.0152	0.8976	0.0138	3.6046
90	199.9028	0.9275	0.8201	0.0115	3.9051
91	199.9941	1.1510	1.0176	0.0177	3.1632
Total		282.0402	254.4579	15.2520	200.5428
Average		3.0993	2.7962	0.1676	2.2037
Stand deviation		1.74877	1.4927		
Average Error			27.582		
Relative Error			0.0977		
Root Mean Square Error				0.4093	
	Coefficient of Variation			0.1464	
	Coefficient of Efficiency			0.9239	
	(Correlation Coefficient)			0.9612	

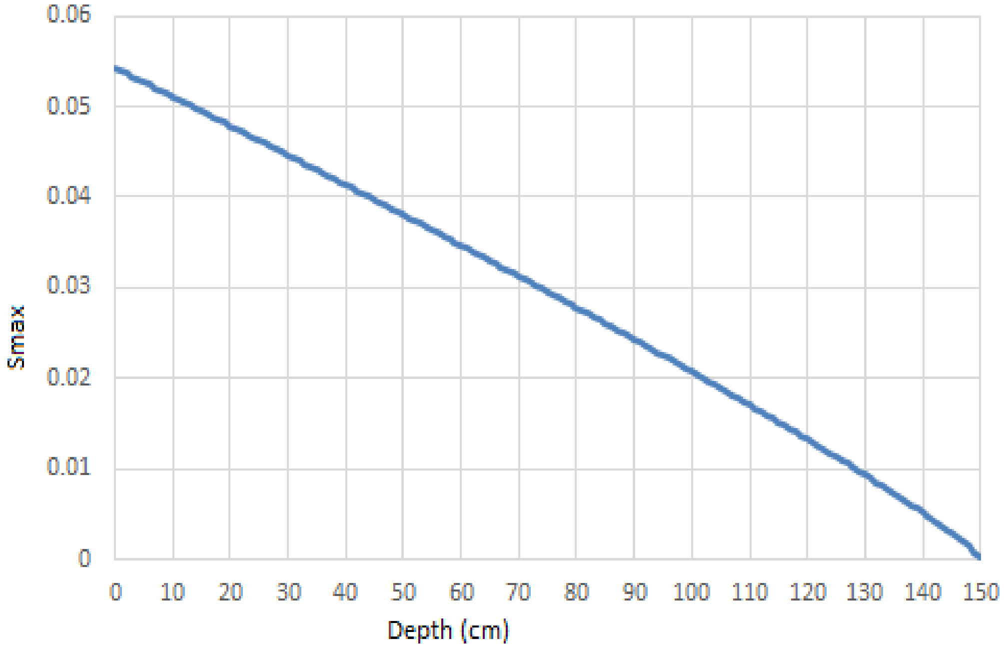


Figure 7.20: Variation of S_{max} with Depth on Crop Duration 61 Days After Sowing for Sholapur

The above Fig. no. 7.20 shows the depthwise distribution of water requirement at day 61 from sowing. The S_{max} is maximum at the top and goes on reducing to as depth increases. It means the mature root part take maximum moisture and newly grown root part take less water.

The governing model is run for 21 days. The results are graphically represented in Figure: 7.21, 7.22, 7.23 and 7.24. The figures are drawn for 8th, 9th days. The figure for suction pressure variation can be drawn for each day. The Figures represented here only for two days (i.e. for 8th and 9th day). The Figure 7.21 is representing suction pressure variation with day for first week and the Figure 7.22 for second week.

Table 7.21: Input file written in FORTAN 77 for Sholapur (first day) (1997)

1	1.000	24	1			
61	60	2	3	0		
1	0.6264	0.2172	1.6600	0.3975	0.0090	0.1750
2	0.6150	0.2090	1.6300	0.3865	0.0096	0.1140
3	0.6130	0.2018	1.6200	0.3827	0.0120	0.1710
1	0.000	0.000				
2	1.000	0.000				
3	2.000	0.000				
4	3.000	0.000				
5	4.000	0.000				
6	5.000	0.000				
7	6.000	0.000				
8	7.000	0.000				
9	8.000	0.000				
10	9.000	0.000				
11	10.000	0.000				
12	11.000	0.000				
13	12.000	0.000				
14	13.000	0.000				
15	14.000	0.000				
16	15.000	0.000				
17	16.000	0.000				
18	17.000	0.000				
19	18.000	0.000				
20	19.000	0.000				
21	20.000	0.000				
22	21.000	0.000				
23	22.000	0.000				
24	23.000	0.000				
25	24.000	0.000				
26	25.000	0.000				
27	26.000	0.000				
28	27.000	0.000				
29	28.000	0.000				
30	29.000	0.000				
31	30.000	0.000				
32	31.000	0.000				
33	32.000	0.000				
34	33.000	0.000				
35	34.000	0.000				
36	35.000	0.000				
37	36.000	0.000				

38	37.000	0.000				
39	38.000	0.000				
40	39.000	0.000				
41	40.000	0.000				
42	41.000	0.000				
43	42.000	0.000				
44	43.000	0.000				
45	44.000	0.000				
46	45.000	0.000				
47	46.000	0.000				
48	47.000	0.000				
49	48.000	0.000				
50	49.000	0.000				
51	50.000	0.000				
52	51.000	0.000				
53	52.000	0.000				
54	53.000	0.335				
55	54.000	-10.543				
56	55.000	-17.684				
57	56.000	-23.177				
58	57.000	-27.933				
59	58.000	-32.255				
60	59.000	-36.290				
61	60.000	-40.748				
1	1	2	0	2	3	
2	2	3	0	2	3	
3	3	4	0	2	3	
4	4	5	0	2	3	
5	5	6	0	2	3	
6	6	7	0	2	3	
7	7	8	0	2	3	
8	8	9	0	2	3	
9	9	10	0	2	3	
10	10	11	0	2	3	
11	11	12	0	2	3	
12	12	13	0	2	3	
13	13	14	0	2	3	
14	14	15	0	2	3	
15	15	16	0	2	3	
16	16	17	0	2	3	
17	17	18	0	2	3	
18	18	19	0	2	3	
19	19	20	0	2	3	

20	20	21	0	2	3	
21	21	22	0	2	3	
22	22	23	0	2	3	
23	23	24	0	2	3	
24	24	25	0	2	3	
25	25	26	0	2	3	
26	26	27	0	2	3	
27	27	28	0	2	3	
28	28	29	0	2	3	
29	29	30	0	2	3	
30	30	31	0	2	2	
31	31	32	0	2	2	
32	32	33	0	2	2	
33	33	34	0	2	2	
34	34	35	0	2	2	
35	35	36	0	2	2	
36	36	37	0	2	2	
37	37	38	0	2	2	
38	38	39	0	2	2	
39	39	40	0	2	2	
40	40	41	0	2	2	
41	41	42	0	2	2	
42	42	43	0	2	2	
43	43	44	0	2	2	
44	44	45	0	2	2	
45	45	46	0	2	1	
46	46	47	0	2	1	
47	47	48	0	2	1	
48	48	49	0	2	1	
49	49	50	0	2	1	
50	50	51	0	2	1	
51	51	52	0	2	1	
52	52	53	0	2	1	
53	53	54	0	2	1	
54	54	55	0	2	1	
55	55	56	0	2	1	
56	56	57	0	2	1	
57	57	58	0	2	1	
58	58	59	0	2	1	
59	59	60	0	2	1	
60	60	61	0	2	1	
1	1	0.000				
61	1	-40.121				

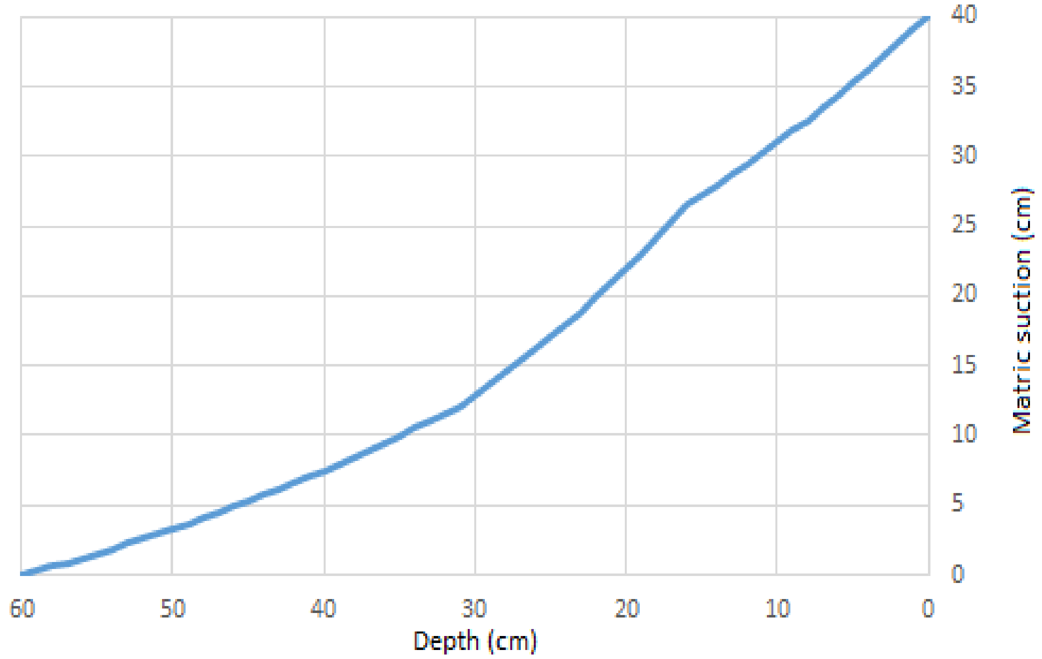


Figure 7.21: Variation of Suction Pressure with Depth on 8th Day for Season 1997

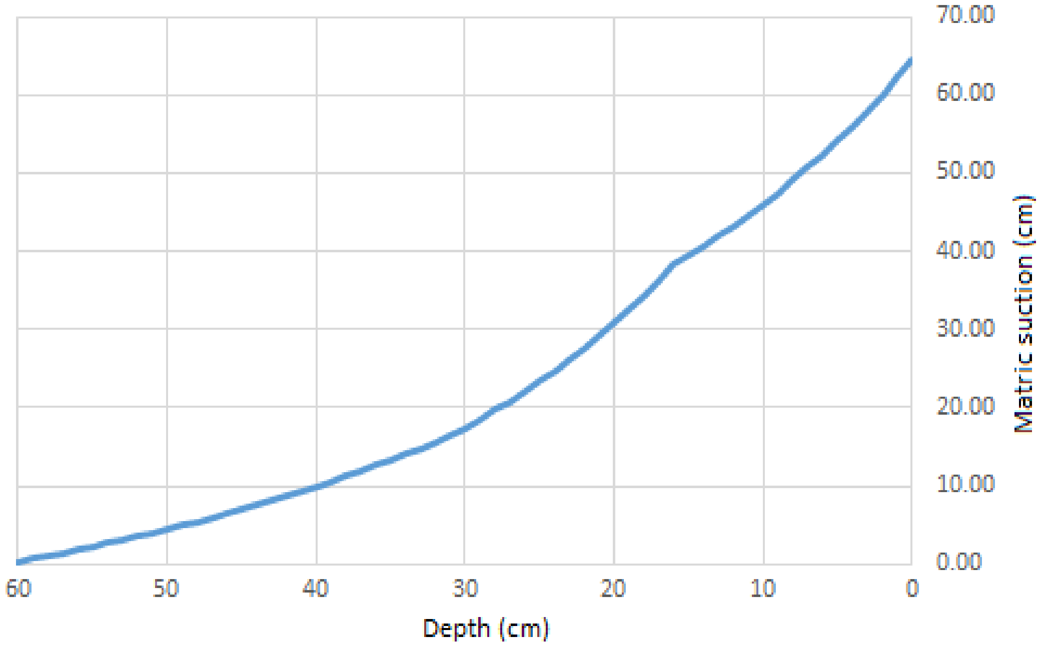


Figure 7.22: Variation of Suction Pressure with Depth on 9th Day for Season (1997)

Table 7.22: Matric Suction variation with Day for Sholapur (1997)

Depth (cm)	Days from sowing running the model													
	8	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
0	40.1	64.4	85	104	121	140	159	179	211	245	280	330	391	467
1	39.1	62.1	81.1	98.5	113	128	143	158	179	198	215	232	244	247
2	38.1	60	77.6	93.3	106	119	131	143	158	171	182	193	199	202
3	37.1	57.9	74.3	88.6	100	111	121	131	143	153	161	168	173	175
4	36.2	56	71.2	84.4	94.8	105	113	121	131	139	145	151	155	157
5	35.3	54.2	68.4	80.5	90	98.7	106	113	121	128	133	138	141	143
6	34.4	52.4	65.7	77	85.7	93.5	100	106	113	119	123	127	130	132
7	33.5	50.7	63.2	73.7	81.8	88.8	94.6	100	106	111	115	119	121	122
8	32.6	49.1	60.9	70.7	78.2	84.5	89.7	94.7	100	105	108	111	113	115
9	31.8	47.5	58.7	67.8	74.9	80.7	85.4	89.9	94.9	98.8	102	105	107	108
10	31	46.1	56.6	65.2	71.8	77.1	81.4	85.5	90.1	93.6	96.5	99	101	102
11	30.2	44.6	54.6	62.7	69	73.8	77.8	81.6	85.7	89	91.6	93.9	95.7	96.9
12	29.4	43.2	52.7	60.4	66.3	70.8	74.4	77.9	81.8	84.8	87.3	89.4	91.1	92.2
13	28.7	41.9	50.9	58.2	63.8	68	71.3	74.6	78.1	81	83.3	85.3	86.8	87.9
14	27.9	40.6	49.1	56.1	61.4	65.3	68.4	71.5	74.8	77.4	79.6	81.5	83	84.1
15	27.2	39.4	47.5	54.1	59.2	62.8	65.7	68.6	71.7	74.2	76.2	78	79.5	80.5
16	26.5	38.2	45.9	52.2	57	60.5	63.2	65.9	68.8	71.2	73.1	74.8	76.2	77.2
17	25.3	36.2	43.3	49	53.5	56.6	59	61.5	64.1	66.2	68	69.5	70.8	71.8
18	24.1	34.3	40.8	46.1	50.3	53.1	55.2	57.5	59.8	61.8	63.4	64.8	66	67
19	23	32.5	38.5	43.5	47.3	49.9	51.8	53.8	56	57.8	59.3	60.6	61.8	62.7
20	21.9	30.8	36.3	41	44.6	46.9	48.6	50.6	52.5	54.2	55.6	56.9	58	58.9
21	20.9	29.2	34.3	38.6	42	44.2	45.7	47.5	49.4	50.9	52.3	53.4	54.5	55.4
22	19.9	27.6	32.4	36.5	39.7	41.6	43.1	44.7	46.5	47.9	49.2	50.3	51.3	52.2
23	18.9	26.1	30.6	34.4	37.4	39.3	40.6	42.2	43.8	45.1	46.4	47.4	48.4	49.3
24	18	24.7	28.9	32.5	35.3	37.1	38.3	39.7	41.3	42.6	43.7	44.8	45.7	46.5
25	17.1	23.4	27.2	30.6	33.4	35	36.1	37.5	38.9	40.2	41.3	42.3	43.2	44
26	16.2	22.1	25.7	28.9	31.5	33	34	35.4	36.7	37.9	39	39.9	40.8	41.7
27	15.3	20.8	24.2	27.3	29.7	31.2	32.1	33.4	34.7	35.8	36.8	37.8	38.6	39.4
28	14.5	19.7	22.8	25.7	28.1	29.4	30.3	31.5	32.7	33.8	34.8	35.7	36.6	37.4
29	13.7	18.5	21.4	24.2	26.5	27.7	28.5	29.7	30.9	32	32.9	33.8	34.6	35.4
30	12.9	17.4	20.1	22.8	25	26.2	26.9	28	29.2	30.2	31.1	32	32.8	33.5
31	12.1	15.5	18.9	21.4	23.5	24.6	25.3	26.4	27.5	28.5	29.4	30.2	31	31.8
32	11.6	14.7	17.9	20.4	22.4	23.5	24.1	25.1	26.2	27.1	28	28.8	29.6	30.4

Table 7.22 (Continued)

Depth (cm)	Days from sowing running the model													
	8	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
33	11	14	17	19.4	21.3	22.3	22.9	23.9	24.9	25.9	26.7	27.5	28.3	29
34	10.5	13.3	16.1	18.4	20.3	21.2	21.8	22.8	23.7	24.6	25.5	26.2	27	27.7
35	9.95	12.6	15.3	17.4	19.3	20.2	20.7	21.7	22.6	23.5	24.3	25	25.8	26.5
36	9.43	11.9	14.5	16.5	18.3	19.2	19.7	20.6	21.5	22.3	23.1	23.9	24.6	25.3
37	8.93	11.2	13.7	15.7	17.4	18.2	18.7	19.6	20.5	21.3	22	22.7	23.5	24.1
38	8.44	10.5	12.9	14.8	16.5	17.3	17.8	18.6	19.4	20.2	21	21.7	22.4	23.1
39	7.96	9.92	12.2	14	15.6	16.4	16.8	17.7	18.5	19.2	20	20.7	21.3	22
40	7.49	9.31	11.4	13.2	14.8	15.6	15.9	16.7	17.5	18.3	19	19.7	20.3	21
41	7.03	8.71	10.7	12.5	14	14.7	15.1	15.9	16.6	17.4	18.1	18.7	19.4	20
42	6.58	8.13	10.1	11.7	13.2	13.9	14.3	15	15.8	16.5	17.2	17.8	18.5	19.1
43	6.14	7.56	9.41	11	12.4	13.1	13.5	14.2	14.9	15.6	16.3	16.9	17.6	18.2
44	5.71	7.01	8.77	10.3	11.7	12.4	12.7	13.4	14.1	14.8	15.5	16.1	16.7	17.3
45	5.29	6.48	8.14	9.67	11	11.6	11.9	12.6	13.3	14	14.7	15.3	15.9	16.5
46	4.88	5.96	7.54	9.02	10.3	10.9	11.2	11.9	12.6	13.2	13.9	14.5	15.1	15.7
47	4.48	5.45	6.95	8.39	9.65	10.2	10.5	11.2	11.8	12.5	13.1	13.7	14.3	14.9
48	4.08	4.95	6.38	7.77	9	9.58	9.82	10.5	11.1	11.7	12.4	12.9	13.6	14.2
49	3.7	4.47	5.83	7.17	8.37	8.93	9.16	9.8	10.4	11	11.7	12.2	12.8	13.4
50	3.32	4	5.29	6.59	7.76	8.31	8.52	9.14	9.75	10.4	11	11.5	12.1	12.7
51	2.95	3.54	4.76	6.03	7.16	7.69	7.89	8.5	9.1	9.7	10.3	10.8	11.4	12
52	2.59	3.09	4.25	5.48	6.59	7.1	7.28	7.88	8.46	9.05	9.64	10.2	10.8	11.3
53	2.24	2.65	3.76	4.95	6.02	6.52	6.69	7.28	7.85	8.42	9	9.53	10.1	10.7
54	1.89	2.23	3.27	4.43	5.48	5.96	6.12	6.69	7.25	7.82	8.38	8.91	9.47	10
55	1.55	1.82	2.8	3.92	4.95	5.41	5.56	6.12	6.67	7.22	7.78	8.3	8.86	9.42
56	1.22	1.42	2.35	3.43	4.43	4.88	5.02	5.57	6.1	6.65	7.2	7.71	8.26	8.82
57	0.904	1.03	1.9	2.95	3.93	4.37	4.49	5.03	5.55	6.09	6.63	7.13	7.68	8.24
58	0.592	0.653	1.47	2.49	3.44	3.86	3.98	4.5	5.02	5.55	6.08	6.57	7.12	7.67
59	0.29	0.29	1.06	2.04	2.96	3.38	3.48	4	4.5	5.02	5.54	6.03	6.57	7.11
60	0	0.2	0.653	1.6	2.5	2.9	3	3.5	3.99	4.5	5.02	5.5	6.03	6.57

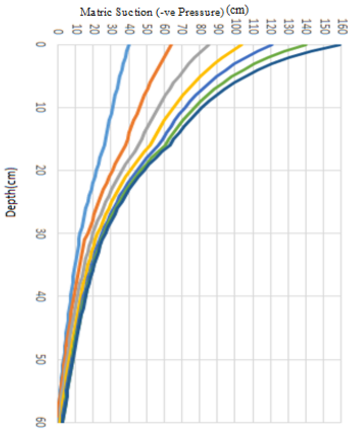


Figure 7.23: Pressure Variation with Depth for First Week

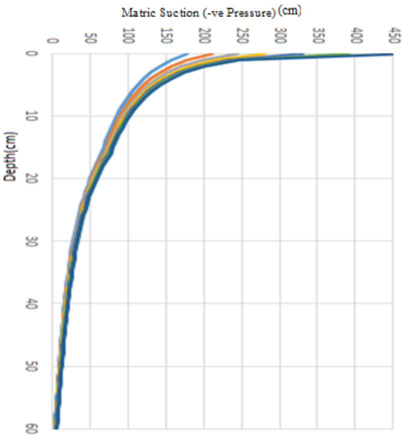


Figure 7.24: Pressure Variation with Depth for Second Week

The typical graph figure 7.21and 7.22, shows variation of suction pressure with depth for 8th days and 9th days. The graphs can be drawn for all the days of season but here only for two days shown (Figure 7.21 and 7.22). These graphs are for initial days when suction changes slowly and moisture content fast whereas, in Figure 7.23 and 7.24 indicates there is little amount of moisture changes corresponding suction pressure changes rapidly. It indicates that soils do not release water easily after some days/ it is indication of water requirement for plant or crop. Depending upon crop stages application of irrigation water is decided. The data obtained for soil parameters (Chapter 5) and the estimated ET_o (Chapter 6) used in running the Dynamic model and estimating the water requirement for crop. All the three objectives stated in Chapter 7 have been explored.

Table 7.23: Soil parameters to be used in model (Pune)

Depth	Moisture at saturation θ_s	Residual Moisture θ_r	Parameters established (Modified VG)		
			n	m	α
0 to 15 cm	0.5632	0.2189	1.70	0.41	0.0060
15 to 30 cm	0.5627	0.218	1.70	0.41	0.0060
30 to 60 cm	0.5513	0.2143	1.74	0.43	0.0054
60 to 90 cm	0.5471	0.1973	1.69	0.41	0.0060
90 to 120 cm	0.541	0.1921	1.60	0.37	0.0175

Table 7.24: Soil parameters to be used in model (Ahmednagar)

Depth	Moisture at saturation θ_s	Residual Moisture θ_r	Parameters established (Modified VG)		
			n	m	α
0 to 15 cm	0.5938	0.2247	1.68	0.40	0.0089
15 to 30 cm	0.6091	0.2126	1.65	0.39	0.0093
30 to 60 cm	0.5924	0.2213	1.86	0.46	0.0029
60 to 90 cm	0.5924	0.2192	1.80	0.44	0.0028
90 to 120 cm	0.5858	0.2095	1.82	0.45	0.0033
120 to 150 cm	0.5860	0.2058	1.67	0.40	0.0104

Table 7.25: Soil parameters to be used in model (Kolhapur)

Depth	Moisture at saturation θ_s	Residual Moisture θ_r	Parameters established (Modified VG)		
			n	m	α
0 to 15 cm	0.5261	0.2165	1.56	0.34	0.0216
15 to 30 cm	0.5278	0.2142	1.50	0.33	0.0313
30 to 60 cm	0.5427	0.2192	1.50	0.33	0.0364
60 to 90 cm	0.5234	0.1871	1.45	0.31	0.0484

Note: Above soil parameters are established by Modified Van Genuchten (VG) Model. The input file for Pune Research station is given in Appendix D. The methodology and procedure applied for other research station is the same as that for Sholapur study area.

CHAPTER-8

CONCLUSIONS AND RECOMMENDATIONS

The main challenge for irrigation engineers and water management department in semi-arid region is to improve water use and application efficiency. An accurate quantification of moisture uptake by plants under different environmental conditions is essential for deciding efficient irrigation scheduling. There are several approaches and methods are available for deciding irrigation water application scheduling. They can be classified into two categories. First one Plant/ crop based method which is very accurate but at the same time it is finding difficult in measuring or determining plant/ crop water stress. Therefore second method of soil moisture based irrigation scheduling is most popular and is used. There are several irrigation scheduling means based on second approach are available now a days to assist in irrigation scheduling. Some of the few techniques are: soil probes, soil moisture sensors in the field, crop water use estimators, computerized daily soil water balance, and physically based models for estimating soil moisture status. In Chapter 2 these means are discussed in detail. The soil moisture reserve status (SMR) and its spatial and temporal coverage can be made available by using models (water budget and physical) which estimate soil moisture changes from readily available meteorological and soil analysed data.

Water budget models are the simplest types of soil moisture flow models used in irrigation water application. In this method soil medium profile is treated as bucket. As the measurement of soil moisture at regular intervals is not economical and time consuming, there has been continuing interest in developing physical parameter based mathematical models. The living root system is a dynamic system. The detailed geometry of the root system is practically impossible to measure. The permeability of the root varies with position along the root. These Microscopic, bottom up approach dynamic models, deal with the radial flow of water to an individual (single) root are difficulty and tedious, the limitation of this model are presented in Section 2.3.3.2.1. Macroscopic (Root System) Dynamic Models are top-down approach models which eliminate the need for to obtaining soil and plant parameters. The flow to individual roots is ignored and the overall root system is considered to uptake moisture from each layer of the root zone at some rate. This rate depends on position of depth point in a coordinate system, existing moisture content, and time from initial condition. These models divided into two categories. In first category the water potential and hydraulic parameters inside the plant roots which were difficult to quantify, were considered. In the second category water uptake by plants was simulated using the potential transpiration rate, soil moisture availability, and the plant root density distribution. The parameters required were relatively easy to obtain hence considered for study.

In this study a simple water budget model and sufficiently accurate algorithm is developed for Richards Equation. The Richards Equation describing soil water movement was solved using a finite element method with frontal solution technique. This is discussed in Chapter 4 in detail. Measuring the existing soil moisture can be difficult. It is therefore easier to start the water budget or dynamic model after a thorough irrigation or rainfall that fills the entire root zone. The model would then start with a full storage value equal to the Soil Water Storage. The parameters required for water budget model and dynamic model were estimated. The work is summarized as follows.

1. For soil moisture analysis four research stations namely Sholapur, Pune, Kolhapur and Ahmednagar have been selected. These area fall in the semi-arid climatic zone of western Maharashtra, India. The Van Genuchten model is used for soil analysis with some modification in the obtained results. The result of these parameters are presented in Table: 5.46.
2. For curve fitting, three methods have been used, i.e., $y = a\ e^{bx}$, $y = a\ x^b$ and $y = a\ b^x$. Two methods ($y = a\ e^{b\ x}$ and $y = a\ b^{\ x}$) yield the same result and the equation $y = a\ x^b$ is found to be more suitable. The abstract of sensitivity analysis is presented in the Tables: 5.46, 5.48, 5.50 and 5.52
3. The computer program for Van Genuchten Model is developed and its listing is given in Appendix A. The estimated parameters by Curve Fitting Method 2 are used to evaluate soil parameters m, n and α. By these evaluated parameters soil moisture content (θ) is simulated. The parameter m evaluated is increased

by 10 %, 20 %, 30 % and 40 % with corresponding other parameters (Figures: 5.10, 5.11, 5.16, 5.21, 5.26, 5.31, 5.36, 5.40, 5.44, 5.49, 5.53, 5.57, 5.61, 5.64, 5.65, 5.66, 5.67, 5.68 and 5.69). The simulated soil moisture content (θ) is compared with observed moisture content of the soil moisture characteristic curve (SMCC). A 40 % increase in m shows better agreement. The sensitivity analysis is presented in Tables: 5.47, 5.49, 5.51 and 5.53 and procedure adopted is presented in Section 5.3.

4. After evaluation of soil parameters needed to run the main governing model, the second most important parameter is reference evapotranspiration. This is used in sink term in both the models viz water budget model and dynamic model. Daily outputs from three evapotranspiration models (OHAG, MHAG and DHAG) have been tested against reference evapotranspiration data computed by the FAO-56 Penman-Monteith Model. The Original Hargreaves (OHAG) model has a tendency to predict much higher values of reference evapotranspiration. The modified form of Hargreaves method (MHAG) is also not suitable here which can be used alternatively where the accurate data collection is difficult. A new approach viz new version of Developed Hargreaves Method (DHAG) is proposed for Sholapur, Pune, Kolhapur, and Ahmednagar research station. The model was verified and found most suitable for this region.

   The main advantage of this models that it requires only daily maximum and minimum temperature. Where the data is not available this model can be used for estimation of reference evapotranspiration. The model efficiency and sensitivity analysis is presented in Chapter 6.

5. In the study area Drought is evaluated by water budget model with using ET_o estimated by FAO-56 method and DHAG method. Both methods yield nearly same result. The procedure for drought evaluation is discussed in Chapter 7.
6. Pearl millet is considered for study as it is the main staple crop of the arid and semi-arid regions of Maharashtra.

7. Generally onset date of monsoon in that area, accumulated rainfall totals and rainfall-evapotranspiration relation criteria is used for deciding sowing date. Analysis reveals that the 27th week of the calendar year is excellent for sowing pearl millet in the study area.
8. Single crop coefficient (K_c) approach is used which is proposed by the FAO-56 for estimating actual crop evapotranspiration.
9. Borg and Grimes dynamic model is used for generating relative root length distribution on a daily basis.
10. The irrigation is recommended when about 50 % of available water has been used in the zone of maximum root activity, probably within the 15-60 cm depth. Except in ripening seed crop or sugar crops, the moisture content in soil should never be allowed to approach the permanent wilting point unless rapid maturing is needed.
11. For most of the plants available water is held in high matric suction from -1/3 to -1 bar. The soil parameters established by VG are used in dynamic model for developing relation between suction pressure and moisture content as well as its movement in soil medium.
12. The finite element approach for one dimensional flow is developed. Computer software is prepared and listing is given in Appendix-B. The software is validated with Celia et al. (1990). The analysis reveals that after 100 to 140 cm suction, moisture content release is reduced very slowly and suction pressure is changing relatively fast . This reveals that the field capacity is at suction 100 to 300 cm. The moisture from saturation to field capacity is not useful. The software prepared is useful for monotonic drying case only. The water budget models are weekly or daily but dynamic model can be used for 1 hr time step or even small as needed.
13. The results presented in Chapter 5 and 6 show very little variation in sensitivity analysis. Hence, developed models can be used for other Districts of study area too.

Recommendations:

1) It is recommended that the model used in the present study should be utilized for analyzing drought situations, as it is capable of determining the stage and time of the crop when plant suffer from soil moisture stress conditions and it can operate on daily/ weekly basis. Hence model will be extremely helpful in determining the irrigation water requirement of the crop on daily/ weekly basis and to know before hand as whether the crop needs irrigation or not.
2) Irrigation planning and management depends upon reliability of data of sufficient length with respect to climate and crop. Since the model is quite sensitive to variations in the climatological, crop and soil data, it is recommended to ensure the quality of data, collected before using them in the model.
3) The research presented in this thesis provides basic guidance to the agricultural community in south west Maharashtra as to which model will give a better estimate of ET_o. These results may help the agricultural industry in reducing stress on the water supply system thereby potentially increasing productivity.
4) The week wise drought analysis suggests that proper water harvesting structures be constructed so that runoff from the rainfall is stored and utilized during the dry periods. During a bad year the demand may be met with the ground water resources with a single pearl millet crop in order to satisfy the subsistence requirement of the marginal farmer.

Future Scope of Work:

In the light of conclusions drawn from the study and recommendations the work can be extended for the development of model based on:

1. The model for evapotranspiration is tested for four district of semi-arid region of western Maharashtra. This model can be tested for other parts of Maharashtra.
2. The dynamic model can be used and it can be validated further with experimental plot/ data with measuring soil moisture status.

3. Regional modeling study for irrigation planning in the arid and semi-arid regions of Maharashtra and in other parts of the country can be undertaken as there is a very wide space variability in rainfall, evapotranspiration and soils.
4. Management information system (MIS) and simulated based approach can be further developed so that real time irrigation management can be done.
5. Further, there is a scope to integrate the scientific knowledge presented by mathematical models with the practical and heuristic knowledge acquired by the irrigation managers and field scientists.

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APPENDIX-A

LISTING OF VAN GENUCHTEN MODEL

```
%=========================================================================
%This script file is developed for graphical representation of SMCC Curve of unsaturated soil (psi versus theta) and curve fitting for finding Van Genuchten parameters and hydraulic conductivity.
%Programme written by S T DHOTRE. (Research Scholar MNIT Jaipur)
%Guided by prof. Gunwant Sharma (Civil Engg. Department, MNIT Jaipur)
%=========================================================================
%Start
%=========================================================================
%Turn on 15 digit display.
format long
%remove old variable definition
clear all
%remove old graphics window
close all
%=========================================================================
%define the vector of values of the variable
% first input is name of the Station%
name=input ('Enter the name of soil moisture measuring station:\n','s');
%input is Depth of profile at which soil water is measured
depth=input ('Enter the depth of soil profile to plot:\n','s');
%Input commands is used for taking the values of soil moisture at various values of matric suction
x1=input('Enter moisture content at matric suction 1/10 bar:\n ');
x2=input('Enter moisture content at matric suction 1/3 bar:\n ');
x3=input('Enter moisture content at matric suction 1/2 bar:\n ');
x4=input('Enter moisture content at matric suction 1 bar:\n ');
x5=input('Enter moisture content at matric suction 5 bar: \n ');
x6=input('Enter moisture content at matric suction 10 bar:\n ');
```

```
x7=input('Enter moisture content at matric suction 15 bar:\n ');

y1=100; y2=330; y3=500; y4=1000; y5=5000; y6=10000; y7=15000;

xs=x1;xr=x7;

x=[x1 x2 x3 x4 x5 x6 x7];

y=[y1 y2 y3 y4 y5 y6 y7];

%==================================================================

%Creating plot (Linear plot) Figure No. (1)

%==================================================================

figure(1)

Plot(x,y,'MarkerFaceColor',[1 1 0],'MarkerEdgeColor',[0 1 1],...

'MarkerSize',4,'Marker','diamond','LineWidth',4,'Color',[1 0 1]);

hold on

axis on

grid on

box on

%background color of the plot itself

set(gca,'color',[0 .5 1]);

hold off

%create label

xlabel(' moisture content (\theta) (cm^3/cm^3) (Linear Scale)',...

'fontsize',12);

ylabel('Matric suction (\psi) (cm)(Linear Scale) ','fontsize',12);

%Create a title

title([' Soil Moisture Characteristic Curve of observation station '...

,num2str(name),' at depth ',num2str(depth)],'FontSize',16,...

'FontName','Times New Roman');

%Create legend

legend('SMCC Curve');

ylim([-100 15000]);
```

```
xlim([xr-.01 xs+.01]);
set(gca,'yTick',[-100,y1,y4,y5,y6,y7]);
set(gca,'xTick',[x7 x6 x5 x4 x3 x2 x1]);
hold off
%================================================================================
% Create a plot on semilog scale figure No 2
%================================================================================
figure(2)
%y axis log and x axis linear%
semilogy(x,y,'MarkerFaceColor',[1 1 0],'MarkerEdgeColor',[0 1 1],...
'MarkerSize',4,'Marker','diamond','LineWidth',4,'Color',[1 0 1]);
hold on
axis on
grid on
box on
%background color of the plot itself
set(gca,'color',[0 .5 1]);
%create x label
xlabel(' moisture content (\theta) (cm^3/cm^3) (Linear Scale) ',...
'fontsize',12);
%Create y label
ylabel('Matric suction (\psi) (cm) (Log Scale)','FontSize',12);
%Create a title
title([' Soil Moisture Characteristic Curve of observation station '...
,num2str(name),' at depth ',num2str(depth)],'FontSize',16,...
'FontName','Times New Roman');
%Create legend
legend('SMCC Curve');
set(gca,'xTick',[x7 x6 x5 x4 x3 x2 x1]);
```

```
ylim([10 15000]);
xlim([xr-.01 xs+.01]);
hold off
%==============================================================
%Curve Fitting calculation of parameters (constant a and b)
%for method 1) y=a*e^(b*x) figure no 3
%==============================================================
figure(3)
%method one y=a*e^(b*)x
%the curve fitting type using the principle of least square
%logy=loga+(bxloge)
%let logy=Y,loga=A,bloge=B
%then the above equation become
%Y=Bx+A
%thus it is equivalent to fitting straight
%the least square normal equation are
%B(xi)^2+A(xi)=xiYi-----------------1
%B(xi)+nA=Yi------------------------2
%solving above two equation we get values of constant
%data for this is taken from field observation as for curve plot
n=7;
%here toal points on Graph are seven
A=log(y);
A1=sum(x);
A2=sum(A);
A3=x.^2;
A4=sum(A3);
A5=x.*A;
A6=sum(A5);
```

```
a1=(A2-(A6*A1/A4))*(A4/((A4*n)-A1^2));
b1=(A6-(A1*a1))/A4;
a1=exp(a1);
xfit1=x;
yfit1=a1.*exp(b1.*xfit1);
plot(x,y,'-k*','linewidth',.5,'markersize',8,'markeredgecolor',...
'b', 'markerfacecolor','g');
hold on
plot(xfit1,yfit1,'-r*','linewidth',.5,'markersize',8,...
'markeredgecolor','m', 'markerfacecolor','r')
axis on
grid on
box on
% Createxlabel
xlabel('Volumetric Moisture Content (\theta)',...
'FontSize',16,'FontName','Times New Roman');
 % Createylabel
ylabel('Matric Suction (\psi)','FontSize',16,'FontName',...
'Times New Roman');
%Create a title%
title([' Curve Fitting of station ' ,...
num2str(name),' at depth ',num2str(depth)],...
 'FontSize',16,'FontName','Times New Roman');
%----------------------------------------------------------------------
% Curve Fitting calculation of parameters (constant a and b)
%for method y=a*x^b (figure three is coniued)
%----------------------------------------------------------------------
B=sum(log(x));
B1=sum(log(y));
```

```
B2=sum(log(x).*log(y));
B3=(log(x)).^2;
B4=sum(B3);
%B1=n*ao+bo*B-----------------------------(1)
%B2=ao*B+bo*B4-----------------------------(2)
%ao=(B1-bo*B)/na
B5=B1/n;B6=B/n;
%ao=B5-bo*B6;--------------------------------(3)
%B2=(B5-bo*B6)*B+(bo*B4);
%B2=(B5*B)-(bo*B6*B)+(bo*B4);
B7=B5*B;B8=B6*B;
%B2=B7-(b0*B8)+(b0*B4);
B9=B2-B7;
%B9=b0*(B4-B8);
b2=B9/(B4-B8);
a2=(B1-b2*B)/n;
a2=exp(a2);
xfit2=x;
yfit2=a2*(xfit2.^b2);
plot(xfit2,yfit2,'-b*','linewidth',.5,'markersize',8,...
'markeredgecolor','m', 'markerfacecolor','r')
ylim([0 15000]);xlim([xr-.01 xs+.01]);
%---------------------------------------------------------------------------
% Curve Fitting calculation of parameters (constant a and b)
%for method y=a*b^x
%---------------------------------------------------------------------------
C1=sum(x);
C2=sum(log(y));
C3=sum((x.*log(y)));
```

```
C4=x.^2;
C5=sum(C4);
%n*a+C1*b=C2--------------------------(1)
%C1*a+C5*b=C3----------------------------(2)
%a=(C2-C1*b)/n
C6=C2/n;C7=C1/n;
%a=(C6-C7*b)
%C1*(C6-C7*b)+C5*b=C3
C8=C1*C6;C9=C7*C1;
%C8-C9*b+C5*b=C3
%b(C5-C9)=C3-C8
b3=(C3-C8)/(C5-C9);
a3=(C6-C7*b3);
a3=exp(a3);
b3=exp(b3);
xfit3=x;
yfit3=a3.*(b3.^xfit3);
plot(xfit3,yfit3,'-m*','linewidth',.5,'markersize',8,...
'markeredgecolor','m', 'markerfacecolor','r')
%--------------------------------------------------------------------------
% data calculation for text box
%--------------------------------------------------------------------------
yfit11=a1*exp(b1*x1);
yfit12=a1*exp(b1*x2);
yfit13=a1*exp(b1*x3);
yfit14=a1*exp(b1*x4);
yfit15=a1*exp(b1*x5);
yfit16=a1*exp(b1*x6);
yfit17=a1*exp(b1*x7);
```

```
%----------------------------------------------------------------------
yfit21=a2*(x1.^b2);
yfit22=a2*(x2.^b2);
yfit23=a2*(x3.^b2);
yfit24=a2*(x4.^b2);
yfit25=a2*(x5.^b2);
yfit26=a2*(x6.^b2);
yfit27=a2*(x7.^b2);
%----------------------------------------------------------------------
yfit31=a3.*(b3.^x1);
yfit32=a3.*(b3.^x2);
yfit33=a3.*(b3.^x3);
yfit34=a3.*(b3.^x4);
yfit35=a3.*(b3.^x5);
yfit36=a3.*(b3.^x6);
yfit37=a3.*(b3.^x7);
%-----------------------------------------------------------------------
% Create textbox
annotation('textbox',[0.3118 0.7514 0.1695 0.1631],...
'String',{[' y7 = ',num2str(y7)],[' y7 fit2 = ',...
num2str(yfit27)],...
[' y7 fit1 = ',num2str(yfit17)],['y7fit3 = ',num2str(yfit37)]},...
'FontWeight','bold','FontSize',...
14, 'FontName','Times New Roman','FitBoxToText','off');
annotation('textbox',[0.5146 0.7514 0.1695 0.1589],...
'String',{[' y6 = ',num2str(y6)],[' y 6fit2 = ',...
num2str(yfit26)],...
[' y6 fit1 = ',num2str(yfit16)],['y6fit3 = ',num2str(yfit36)]},...
'FontWeight','bold','FontSize',14,'FontName','Times New Roman',...
```

```
'FitBoxToText','off');
annotation('textbox',[0.3403 0.5402 0.1695 0.1488],...
'String',{[' y5 = ',num2str(y5)],[' y5 fit2 = ',...
num2str(yfit25)],...
[' y5 fit1 = ',num2str(yfit15)],['y5fit3 = ',num2str(yfit35)]},...
'FontWeight','bold',...
'FontSize',14,'FontName','Times New Roman','FitBoxToText','off');
annotation('textbox',[0.606 0.5402 0.1695 0.1574],...
'String',{[' y4 = ',num2str(y4)],[' y4 fit2 = ',...
num2str(yfit24)],...
[' y4 fit1 = ',num2str(yfit14)],['y4fit3 = ',num2str(yfit34)]},...,
'FontWeight','bold',...
'FontSize',14,'FontName','Times New Roman','FitBoxToText','off');
annotation('textbox',[0.3551 0.3592 0.1695 0.1517],...
'String',{[' y3 = ',num2str(y3)],[' y3 fit2 = ',...
num2str(yfit23)],...
[' y3 fit1 = ',num2str(yfit13)],['y3fit3 = ',num2str(yfit33)]},...
'FontWeight','bold',...
'FontSize',14,'FontName','Times New Roman','FitBoxToText','off');
annotation('textbox',[0.6619 0.3534 0.1695 0.1546],...
'String',{[' y2 = ',num2str(y2)],[' y2 fit2 = ',...
num2str(yfit22)],...
[' y2 fit1 = ',num2str(yfit12)],['y2fit3 = ',num2str(yfit32)]},...
'FontWeight','bold',...
'FontSize',14,'FontName','Times New Roman','FitBoxToText','off');
annotation('textbox',[0.6489 0.1609 0.1695 0.1459],...
'String',{[' y1 = ',num2str(y1)],[' y1 fit2 = ',...
num2str(yfit21)],...
[' y1 fit1 = ',num2str(yfit11)],['y1fit3 = ',num2str(yfit31)]},...
```

```
'FontWeight','bold',...

'FontSize',14,'FontName','Times New Roman','FitBoxToText','off');

%-----------------------------------------------------------------------

set(gca,'yTick',[100 500 1000 3000 5000 7000 9000 11000 13000 15000]);

set(gca,'xTick',[x7 x6 x5 x4 x3 x2 x1 ]);

%background color of the border of the window

set(gcf,'color',[1 1 0]);

%background color of the plot itself

set(gca,'color',[.11 1 1]);

% Create legend

legend('SMCC','Fitted curve type y=a*e^b^x',...

'Fitted curve type y=a*x^b','Fitted curve type y=a*b^x');

hold off

%=========================================================================

% Creating plot on seilogscale figure No .4

%=========================================================================

figure(4)

semilogy(x,y,'-k*','linewidth',2,'markersize',8,'markeredgecolor',...

'b', 'markerfacecolor','g');

hold on

semilogy(xfit1,yfit1,'-r*','linewidth',2,'markersize',8,...

'markeredgecolor','m', 'markerfacecolor','r')

axis on

grid on

box on

semilogy(xfit2,yfit2,'-b*','linewidth',2,'markersize',8,'markeredgecolor',...

'm', 'markerfacecolor','r')

semilogy(xfit3,yfit3,'-k*','linewidth',2,'markersize',8,'markeredgecolor',...

'm', 'markerfacecolor','r')
```

```
% Createxlabel
xlabel('Volumetric Moisture Content (\theta) (Linear Scale)',...
'FontSize',16,'FontName','Times New Roman');
 % Createylabel
ylabel('Matric Suction (\psi) (log scale)','FontSize',16,'FontName',...
'Times New Roman');
%Create a title%
title([' Curve Fitting of station ' ,...
num2str(name),' at depth ',num2str(depth)],...
 'FontSize',16,'FontName','Times New Roman');
xlim([xr-.01 xs+.01]);
ylim([10 15000]);
set(gca,'xTick',[x7 x6 x5 x4 x3 x2 x1]);
%background color of the border of the window
set(gcf,'color',[1 1 0]);
%background color of the plot itself
set(gca,'color',[.11 1 1]);
% Create legend
legend('SMCC','Fitted curve type y=a*e^b^x',...
 'Fitted curve type y=a*x^b','Fitted curve type y=a*b^x');
hold off
%=================================================================
%calculating van Genuchten parameter by curve fit y=a*e^(bx)
%=================================================================
% finding the value of m from curve fit y=ae^(bx)
%xs=saturation moisture content
%xr=resudial moisture content
xp=(xs+xr)/2;
%xp=Moisture content at point p
```

```
%for findinding parameter the point p on the smcc is taken at
%average value
%of two extreme moisture cotentie (xs+xr)/2
xe=(xp-xr)/(xs-xr);
%xe=effective saturation at moisture content xp
yp=a1*exp(b1*xp);
%yp and is matric suction at point p and moisture content xp
%psi*dtheta/dpsi=1/b=yp/b;
xd=xs-xr;xk=xd*xe;yc=1/(xk*b1);
%-----------------------------------------------------------------------
% calling the function from my fun programme
%-----------------------------------------------------------------------
% write following program in separate m file save it as myfun.m
%function F=myfun(m,xe,yc)
%F=(((-m)/(1-m))*(1-(xe^(1/m))))-yc;
%-----------------------------------------------------------------------
% Make a starting guess at the solution (here 0<m<1)
m0 = [0];
%above initially m value is given zero
options=optimset('Display','iter');
% Option to display output
[m,fzero] = fsolve(@myfun,m0,options,xe,yc);
% Call optimizer
%here end of calculating m
%-----------------------------------------------------------------------
%calculation of n
%-----------------------------------------------------------------------
n=(1/(1-m));
%as we know m=1-1/n
```

```
%----------------------------------------------------------------------
% calculation of alfa
%----------------------------------------------------------------------
alfa=(1/yp)*((xe^(-1/m))-1)^(1/n);
al1=(b1*yp);
al3=(-m)/(1-m);al4=(xs-xr);al5=al3*al4;al6=xe;
al7=al6^(1/m);
al8=(1-al7)^m;al9=al5*al7*al8;
al2=1/(al9*al1);
alfaa=al2;
%creating a table with five rows for values of ycypxe a1 b1
constant1=[alfa;m;n;a1;b1];
constant3=[name];
constant4=[depth];
%opening text file named curvefit1.text for writing a format
%writing a format
fid1=fopen('curve1.txt','w');
fprintf(fid1,'Curve fitting parameters of equation y=ae^(bx)');
fprintf(fid1,'Name of the soil moisture mesuring station: \n');
fprintf(fid1,' %s \n',constant3);
fprintf(fid1,'Depth of soil profile : \n');
fprintf(fid1,' %s \n',constant4);
%writing a format
fprintf(fid1,'======================================================\n');
fprintf(fid1,' alfa m n a1 b1\n');
fprintf(fid1,' %5.6f %5.6f %5.6f %5.6f %5.6f \n',constant1);
fprintf(fid1,'=======================================================\n');
%closing the files fid1
fclose(fid1);
```

```
%-----------------------------------------------------------------------
%calculating van genuchtenparameter by curve fit y=a*x^b 10
%-----------------------------------------------------------------------
% finding the value of m from curve fit y=a1x^b1
%xe=effective saturation at moisture content xp
yp1=a2*xp^b2;
%yp1 is matric suction at point p
ya2=(yp1)/((b2*a2)*(xp^(b2-1)));
%psi*dtheta/dpsi;
xk=(xd*xe);yc1=ya2/xk;
%-----------------------------------------------------------------------
% calling the function from my fun programme
% write following program in separate m file save it as %myfun1.m
%function F=myfun(m1,yc1,xe)
 %F=(((-m1)/(1-m1))*(1-(xe^(1/m1))))-yc;
%-----------------------------------------------------------------------
% Make a starting guess at the solution(here 0<m<1)
m10 = [0];
%above initialy m value is given zero
options=optimset('Display','iter');
% Option to display output
[m1,fzero] = fsolve(@myfun,m10,options,xe,yc1);
% Call optimizer
%here end of calculating m
%-----------------------------------------------------------------------
%calculation of n1
%-----------------------------------------------------------------------
n1=(1/(1-m1));
%as we know m=1-1/n
```

```
%------------------------------------------------------------

% calculation of alfa

%------------------------------------------------------------

alfa1=(1/yp1)*((xe^(-1/m1))-1)^(1/n1);

al1=b2*a1*xp^(b2-1);

al3=(-m1)/(1-m1);

al4=(xs-xr);

al5=al3*al4;

al7=al6^(1/m1);

al8=(1-al7)^m;

al9=al5*al7*al8;

al2=1/(al9*al1);

alfaA=al2;

%creating a table with five rows for values of yc1 yp1 xe a2 b2

constant2=[alfa1;m1;n1;a2;b2];

constant3=[name];

constant4=[depth];

%opening text file curvefit2.text for writing a format for table value

%writing a format

fid2=fopen('curve2.txt','w');

fprintf(fid2,'Curve fitting parameters of equation y=ax^(b)');

fprintf(fid2,'Name of the soil moisture mesuring station: \n');

fprintf(fid2,' %s \n',constant3);

fprintf(fid2,'Depth of soil profile : \n');

fprintf(fid2,' %s \n',constant4);

%writing a format

fprintf(fid2,'==========================================\n');

fprintf(fid2,' alfa1 m1 n1 a2 b2\n');

fprintf(fid2,' %5.6f %5.6f %5.6f %5.6f %5.6f\n',constant2);
```

```
fprintf(fid2,'=======================================================\n');
%closing the files fid2
fclose(fid2);
%=========================================================================
%plot psi vs theta of genrated data of moisture content (y=ax^b)
%against assumed matric Suction with values m1,n1 and alfa1 (11) fig(5)
%=========================================================================
figure(5)
%using m ,n and alfa of curve fitting y=ae^(bx)
%xg=xr+(xs-xr)/[1+(alfa*y)^n]^m;
%where xg=generated moisture content,
x1g=((alfa*y).^n);
x2g=((1+x1g).^m);
x3g=(1./(x2g));
x4g=(xd.*x3g);
xg=xr+x4g;
semilogy(x,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...
'MarkerSize',7,'Marker','*','LineWidth',4,'Color',[0.07059 0.2118 0.1412]);
hold on
semilogy(xg,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...
'MarkerSize',4,'Marker','*','LineWidth',4,'Color',[1 0.6941 0.3922]);
axis on
grid on
%background color of the border of the window or outside color
set(gcf,'color',[.1 1 0.9876]);
title(['SMCC Curve and generated curve' ],'FontSize',16,...
'FontName','Times New Roman');
xlabel('Volumetric Moisture Content (\theta)','FontSize',16,...
 'FontName','Times New Roman');
```

```
% Createylabel
ylabel('Suction (\psi)','FontSize',16,'FontName','Times New Roman');
%-----------------------------------------------------------------------
%using m1 ,n1 and alfa1 of curve Fitting y=ax^b
%-----------------------------------------------------------------------
%xg1=xr+(xs-xr)/[1+(alfa1*y)^n1]^m1;
%where xg=generated moisture content,
x1g1=((alfa1*y).^n1);
x2g1=((1+x1g1).^m1);
x3g1=(1./(x2g1));
x4g1=(xd.*x3g1);
xg1=xr+x4g1;
semilogy(xg1,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...
'MarkerSize',4,'Marker','*','LineWidth',4,'Color',[0.3922 0.4745 0.6353]);
%-----------------------------------------------------------------------
%using 1.05 of average value of m1 of curve fitting y=a x^b
%-----------------------------------------------------------------------
m2=1.05*m1;
n2=(1/(1-m2));
alfa2=(1/yp1)*((xe^(-1/m2))-1)^(1/n2);
x1g2=((alfa2*y).^n2);
x2g2=((1+x1g2).^m2);
x3g2=(1./(x2g2));
x4g2=(xd.*x3g2);
xg2=xr+x4g2;
semilogy(xg2,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...
'MarkerSize',4,'Marker','*','LineWidth',2,'LineStyle','--','Color',[1 0 0]);
%-----------------------------------------------------------------------
%using 1.10 of average value of m1 of fitting y=a x^b
```

```
%----------------------------------------------------------------------
m3=1.10*m1;
n3=(1/(1-m3));
alfa3=(1/yp1)*((xe^(-1/m3))-1)^(1/n3);
x1g3=((alfa3*y).^n3);
x2g3=((1+x1g3).^m3);
x3g3=(1./(x2g3));
x4g3=(xd.*x3g3);
xg3=xr+x4g3;
semilogy(xg3,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...
'MarkerSize',4,'Marker','*','LineWidth',2,'Color',[0 0 1]);
%----------------------------------------------------------------------
%using 1.13 of average value of m1 of fitting y=a x^b
%----------------------------------------------------------------------
m4=1.13*m1;n4=(1/(1-m4));alfa4=(1/yp1)*((xe^(-1/m4))-1)^(1/n4);
x1g4=((alfa4*y).^n4);
x2g4=((1+x1g4).^m4);
x3g4=(1./(x2g4));
x4g4=(xd.*x3g4);
xg4=xr+x4g4;
semilogy(xg4,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...
'MarkerSize',4,'Marker','*','LineWidth',2,'LineStyle','--','Color',[0 0 0]);
%----------------------------------------------------------------------
%using 1.15 of average value of m1 of fitting y=a x^b
%----------------------------------------------------------------------
m5=1.15*m1;
n5=(1/(1-m5));
alfa5=(1/yp1)*((xe^(-1/m5))-1)^(1/n5);
x1g5=((alfa5*y).^n5);
```

```
x2g5=((1+x1g5).^m5);

x3g5=(1./(x2g5));

x4g5=(xd.*x3g5);

xg5=xr+x4g5;

semilogy(xg5,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...

'MarkerSize',2,'Marker','*','LineWidth',2,'LineStyle','--','Color',[1 0 1]);

%-----------------------------------------------------------------------

%using 1.20 of average value of m1 of fitting y=a x^b

%-----------------------------------------------------------------------

m6=1.20*m1;

n6=(1/(1-m6));

alfa6=(1/yp1)*((xe^(-1/m6))-1)^(1/n6);

x1g6=((alfa6*y).^n6);

x2g6=((1+x1g6).^m6);

x3g6=(1./(x2g6));

x4g6=(xd.*x3g6);

xg6=xr+x4g6;

semilogy(xg6,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...

'MarkerSize',4,'Marker','*','LineWidth',2,'LineStyle','--','Color',[0 0 0]);

%-----------------------------------------------------------------------

%using 1.25 of average value of m1 of fitting y=a x^b

%-----------------------------------------------------------------------

m7=1.25*m1;

n7=(1/(1-m7));

alfa7=(1/yp1)*((xe^(-1/m7))-1)^(1/n7);

x1g7=((alfa7*y).^n7);x2g7=((1+x1g7).^m7);x3g7=(1./(x2g7));

x4g7=(xd.*x3g7);

xg7=xr+x4g7;

semilogy(xg7,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...
```

```
'MarkerSize',4,'Marker','*','LineWidth',2,'LineStyle','--','Color',[1 .5 1]);
%-------------------------------------------------------------------------
%using 1.30 of average value of m1 of fitting y=a x^b
%-------------------------------------------------------------------------
m8=1.30*m1;
n8=(1/(1-m8));
alfa8=(1/yp1)*((xe^(-1/m8))-1)^(1/n8);
x1g8=((alfa8*y).^n8);
x2g8=((1+x1g8).^m8);
x3g8=(1./(x2g8));
x4g8=(xd.*x3g8);
xg8=xr+x4g8;
semilogy(xg8,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...
'MarkerSize',4,'Marker','*','LineWidth',2,'LineStyle','--','Color',[1 .5 1]);
%-------------------------------------------------------------------------
%using 1.35 of average value of m1 of fitting y=a x^b
%-------------------------------------------------------------------------
m9=1.35*m1;n9=(1/(1-m9));
alfa9=(1/yp1)*((xe^(-1/m9))-1)^(1/n9);
x1g9=((alfa9*y).^n9);
x2g9=((1+x1g9).^m9);x3g9=(1./(x2g9));
x4g9=(xd.*x3g9);
xg9=xr+x4g9;
semilogy(xg9,y,'MarkerFaceColor',[1 1 0],'MarkerEdgeColor',[1 1 0],...
'MarkerSize',4,'Marker','*','LineWidth',2,'LineStyle','--','Color',[1 .5 0]);
%-------------------------------------------------------------------------
%using 1.40of average value of m1 of fitting y=a x^b
%-------------------------------------------------------------------------
m10=1.40*m1;
```

```
n10=(1/(1-m10));
alfa10=(1/yp1)*((xe^(-1/m10))-1)^(1/n10);
x1g10=((alfa10*y).^n10);
x2g10=((1+x1g10).^m10);
x3g10=(1./(x2g10));
x4g10=(xd.*x3g10);
xg10=xr+x4g10;
semilogy(xg10,y,'MarkerFaceColor',[1 1 0],'MarkerEdgeColor',[1 1 0],...
'MarkerSize',4,'Marker','*','LineWidth',2,'LineStyle','--','Color',[1 .5 1]);
legend('SMCC curve','generated curve with m,n',...
'generated curve with m1,n1,','developed curve of m2, n2',...
'developed curve of m3, n3','developed curve of m4, n4',...
'developed curve of m5, n5','developed curve of m6, n6',...
'developed curve of m7, n7','developed curve of m8, n8',...
'developed curve of m9, n9','developed curve of m10, n10');
set(gca,'xTick',[.21 .22 .23 .24 .25 .26 .27 .28 .29 .30 .31 .32 .33...
 .34 .35 .36 .37 .38 .39 .40 .41 .42 .43 .44 .45 .46 .47 .48 .49 .5]);
% Create textbox
annotation('textbox',[0.5672 0.3564 0.325 0.3023],...
'String',{['m = ',num2str(m),' n = ',num2str(n),' \alpha=',num2str(alfa)],...
[' m1= ',num2str(m1),' n1= ',num2str(n1),' \alpha 1=',num2str(alfa1)],...
[' m2= ',num2str(m2),' n2= ',num2str(n2),' \alpha 2=',num2str(alfa2)],...
[' m3= ',num2str(m3),' n3= ',num2str(n3),' \alpha 3=',num2str(alfa3)],...
[' m4= ',num2str(m4),' n4= ',num2str(n4),' \alpha 4= ',num2str(alfa4)],...
[' m5= ',num2str(m5),' n5= ',num2str(n5),' \alpha 5= ',num2str(alfa5)],...
[' m6= ',num2str(m6),' n6= ',num2str(n6),' \alpha 6= ',num2str(alfa6)],...
[' m7= ',num2str(m7),' n7= ',num2str(n7),' \alpha 7= ',num2str(alfa7)],...
[' m8= ',num2str(m8),' n8= ',num2str(n8),' \alpha 8= ',num2str(alfa8)],...
[' m9= ',num2str(m9),' n9= ',num2str(n9),' \alpha 9= ',num2str(alfa9)],...
```

```
[' m10= ',num2str(m10),' n9= ',num2str(n10),' \alpha 9= ',num2str(alfa10)]},...
'FontWeight','bold','FontSize',14,'FontName','Times New Roman',...
 'FitBoxToText','off');
ylim([0 20000]);xlim([xr-.01 xs+.01]);
hold off
%=====================================================================
%plot psi vs theta of genrated data of moisture content (y=ae^(bx))
%against assumed matric Suction with values m1,n1 and alfa1 (11) fig(6)
%=====================================================================
figure(6)
%using m ,n and alfa of curve fitting y=ae^(bx)
%x11g11=xr+(xs-xr)/[1+(alfa*y)^n]^m;
%where x11g11=generated moisture content,
x11g=((alfa*y).^n);
x12g=((1+x11g).^m);
x13g=(1./(x12g));
x14g=(xd.*x13g);
x11g11=xr+x14g;
semilogy(x,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...
'MarkerSize',7,'Marker','*','LineWidth',4,'Color',[0.07059 0.2118 0.1412]);
hold on
semilogy(x11g11,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...
'MarkerSize',4,'Marker','*','LineWidth',4,'Color',[1 0.6941 0.3922]);
axis on
grid on
%background color of the border of the window or out side color
set(gcf,'color',[.1 1 0.9876]);
title(['SMCC Curve and generated curve' ],'FontSize',16,...
 'FontName','Times New Roman');
```

```
xlabel('Volumetric Moisture Content (\theta)','FontSize',16,...
 'FontName','Times New Roman');
% Createylabel
ylabel('Suction (\psi)','FontSize',16,'FontName','Times New Roman');
%-----------------------------------------------------------------------
%using m1 ,n1 and alfa1 of curve Fitting y=ax^b
%-----------------------------------------------------------------------
%xg1=xr+(xs-xr)/[1+(alfa1*y)^n1]^m1;
%where xg=generated moisture content,
x11g1=((alfa1*y).^n1);
x12g1=((1+x11g1).^m1);
x13g1=(1./(x12g1));
x14g1=(xd.*x13g1);
x11g12=xr+x14g1;
semilogy(x11g12,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...
'MarkerSize',4,'Marker','*','LineWidth',4,'Color',[0.3922 0.4745 0.6353]);
%-----------------------------------------------------------------------
%using 1.05 of average value of m1 of curve fitting y=a e^(x*b)
%-----------------------------------------------------------------------
m12=1.05*m;
n12=(1/(1-m12));
alfa12=(1/yp)*((xe^(-1/m12))-1)^(1/n12);
x11g2=((alfa12*y).^n12);
x12g2=((1+x11g2).^m12);
x13g2=(1./(x12g2));
x14g2=(xd.*x13g2);
x11g13=xr+x14g2;
semilogy(x11g13,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...
'MarkerSize',4,'Marker','*','LineWidth',2,'LineStyle','--','Color',[1 0 0]);
```

```
%----------------------------------------------------------------------
%using 1.10 of average value of m of fitting y=a e^(x*b)
%----------------------------------------------------------------------
m13=1.10*m;
n13=(1/(1-m13));
alfa13=(1/yp)*((xe^(-1/m13))-1)^(1/n13);
x11g3=((alfa13*y).^n13);
x12g3=((1+x1g3).^m13);
x13g3=(1./(x2g3));
x14g3=(xd.*x3g3);
x11g14=xr+x4g3;
semilogy(x11g14,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...
'MarkerSize',4,'Marker','*','LineWidth',2,'Color',[0 0 1]);
%----------------------------------------------------------------------
%using 1.13 of average value of m of fitting y=a e^(x*b)
%----------------------------------------------------------------------
m14=1.13*m;
n14=(1/(1-m14));
alfa14=(1/yp)*((xe^(-1/m14))-1)^(1/n14);
x11g4=((alfa14*y).^n14);
x12g4=((1+x11g4).^m14);
x13g4=(1./(x12g4));
x14g4=(xd.*x13g4);
x11g15=xr+x14g4;
semilogy(x11g15,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...
'MarkerSize',4,'Marker','*','LineWidth',2,'LineStyle','--','Color',[0 0 0]);
%----------------------------------------------------------------------
%using 1.15 of average value of m of fitting y=a e^(x*b)
%----------------------------------------------------------------------
```

```
m15=1.15*m;

n15=(1/(1-m15));

alfa15=(1/yp)*((xe^(-1/m15))-1)^(1/n15);

x11g5=((alfa15*y).^n15);

x12g5=((1+x11g1).^m15);

x13g5=(1./(x12g5));

x14g5=(xd.*x13g5);

x11g16=xr+x14g5;

semilogy(x11g16,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...

'MarkerSize',2,'Marker','*','LineWidth',2,'LineStyle','--','Color',[1 0 1]);

%--------------------------------------------------------------------

%using 1.20 of average value of m of fitting y=a e^(x*b)

%--------------------------------------------------------------------

m16=1.20*m;

n16=(1/(1-m16));

alfa16=(1/yp)*((xe^(-1/m16))-1)^(1/n16);

x11g6=((alfa16*y).^n16);

x12g6=((1+x11g6).^m16);

x13g6=(1./(x12g6));

x14g6=(xd.*x13g6);

x11g17=xr+x14g6;

semilogy(x11g17,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...

'MarkerSize',4,'Marker','*','LineWidth',2,'LineStyle','--','Color',[0 0 0]);

%--------------------------------------------------------------------

%using 1.25 of average value of m of fitting y=a e^(x*b)

%--------------------------------------------------------------------

m17=1.25*m;n17=(1/(1-m17));alfa17=(1/yp)*((xe^(-1/m17))-1)^(1/n17);

x11g7=((alfa17*y).^n17);x12g7=((1+x11g7).^m17);x13g7=(1./(x12g7));

x14g7=(xd.*x13g7);x11g18=xr+x14g7;
```

```
semilogy(x11g18,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...
'MarkerSize',4,'Marker','*','LineWidth',2,'LineStyle','--','Color',[1 .5 1]);
%-----------------------------------------------------------------------
%using 1.30 of average value of m1 of fitting y=a x^b
%-----------------------------------------------------------------------
m18=1.30*m;
n18=(1/(1-m18));
alfa18=(1/yp)*((xe^(-1/m18))-1)^(1/n18);
x11g8=((alfa18*y).^n18);
x12g8=((1+x11g8).^m18);
x13g8=(1./(x12g8));
x14g8=(xd.*x13g8);
x11g19=xr+x14g8;
semilogy(x11g19,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 1],...
'MarkerSize',4,'Marker','*','LineWidth',2,'LineStyle','--','Color',[1 .5 1]);
legend('SMCC curve','generated curve with m,n',...
'generated curve with m1,n1,','developed curve of m2, n2',...
'developed curve of m3, n3','developed curve of m4, n4',...
'developed curve of m5, n5','developed curve of m6, n6',...
'developed curve of m7, n7','developed curve of m8, n8');
set(gca,'xTick',[.21 .22 .23 .24 .25 .26 .27 .28 .29 .30 .31 .32 .33...
 .34 .35 .36 .37 .38 .39 .40 .41 .42 .43 .44 .45 .46 .47 .48 .49 .5]);
% Create textbox
annotation('textbox',[0.5672 0.3564 0.325 0.3023],...
'String',{['m = ',num2str(m),' n = ',num2str(n),' \alpha=',num2str(alfa)],...
[' m1= ',num2str(m1),' n1= ',num2str(n1),' \alpha 1=',num2str(alfa1)],...
[' m2= ',num2str(m12),' n2= ',num2str(n12),' \alpha 2=',num2str(alfa12)],...
[' m3= ',num2str(m13),' n3= ',num2str(n13),' \alpha 3=',num2str(alfa13)],...
[' m4= ',num2str(m14),' n4= ',num2str(n14),' \alpha 4= ',num2str(alfa14)],...
```

```
[' m5= ',num2str(m15),' n5= ',num2str(n15),' \alpha 5= ',num2str(alfa15)],...
[' m6= ',num2str(m16),' n6= ',num2str(n16),' \alpha 6= ',num2str(alfa16)],...
[' m7= ',num2str(m17),' n7= ',num2str(n17),' \alpha 7= ',num2str(alfa17)],...
[' m8= ',num2str(m18),' n8= ',num2str(n18),' \alpha 8= ',num2str(alfa18)]},...
'FontWeight','bold','FontSize',14,'FontName','Times New Roman','FitBoxToText','off');
ylim([0 20000]);xlim([xr-.01 xs+.01]);
hold off
%==============================================================================
%plot no 7 SMCC curve and selected curve figure no(7)
%==============================================================================
figure(7)
semilogy(x,y,'MarkerFaceColor',[1 0 0],'MarkerEdgeColor',[1 0 0],...
'Marker','diamond','LineWidth',4,'Color',[0.07059 0.2118 0.1412]);
hold on
semilogy(xg10,y,'MarkerFaceColor',[0 0 1], 'MarkerEdgeColor',[0 0 1],...
'MarkerSize',8,'Marker','hexagram','LineWidth',2,'LineStyle',':',...
'Color',[1 0 0]);
axison;gridon;box on;
%background color of the border of the window or out side color
set(gcf,'color',[.1 1 0.9876]);
%background color of the plot itself or in side color
set(gca,'color',[0.9451 0.9686 0.949]);
% Createxlabel
xlabel(' Generated (\theta)',...
'FontSize',16,'FontName','Times New Roman');
 % Createylabel
ylabel('Matric Suction (\psi)','FontSize',16,'FontName',...
'Times New Roman');
%Create a title%
```

```
title([' SMCC Curve and selected curve '],...
'FontSize',16,'FontName','Times New Roman');
legend('SMCC curve',' developed curve one');
set(gca,'xTick',[.21 .22 .23 .24 .25 .26 .27 .28 .29 .30 .31 .32 .33...
 .34 .35 .36 .37 .38 .39 .40 .41 .42 .43 .44 .45 .46 .47 .48 .49 .5]);
% Create textbox
annotation('textbox',[0.2773 0.181 0.3039 0.2851],...
 'String',{'\theta=\thetar+(\thetas-\thetar)/[1+(\alpha*\psi)^n]^m',...
 '','where \theta=generated moisture','content at assumed \psi'},...
 'FontWeight','bold','FontSize',20,'FontName','Times New Roman',...
 'FitBoxToText','off','BackgroundColor',[1 1 0],...
 'Color',[0.07059 0.2118 0.1412]);
ylim([10 15000]);
hold off
%======================================================================
%calculation of relative hydraulic conductivity by Van Genuchten model
% based on theory of Mualem(1977)and Curve fitting figure(8)
%======================================================================
figure(8)
%method one y=ae^bx
%the curve fitting type using the principle of least square
%logy=loga+(bxloge)
%let logy=Y,loga=A,bloge=B
%then the above equation become
%Y=Bx+A
%thus it is equivalent to fitting straight
%the least square normal equation are
%B(xi)^2+A(xi)=xiYi-----------------1
%B(xi)+nA=Yi------------------------2
```

```
%solving above two equation we get values of constant
%data for this is taken from field observation and calculated as folow
xxk=linspace (xr+.001,xs,100);
k11=((xxk-xr)./(xs-xr));
k12=k11.^(1/2);
k13=k12.^(1/m);
k14=(1-k13).^m;
k15=(1-k14).^2;
kr1=k12.*k15;
N=100;
x=xxk;
y=kr1;
Y=log(y);
C=sum(x);
E=sum(Y);
x2=x.^2;
F=sum(x2);
xiYi=x.*Y;
G=sum(xiYi);
A=(E-(G*C/F))*(F/((F*N)-C^2));
B=(G-(C*A))/F;bk=B;
ak=exp(A);
xnew1=x;
ynew1=ak*exp(bk*xnew1);
plot(x,y,'MarkerEdgeColor',[0 0 1],'MarkerSize',5,...
 'Marker','*',...
 'LineWidth',3,...
 'LineStyle','--',...
 'Color',[0 1 0]);
```

```
hold on
plot(xnew1,ynew1,'MarkerFaceColor',[0 0 1],...
 'MarkerEdgeColor',[0 0 1],...
 'MarkerSize',5,...
 'Marker','hexagram',...
 'LineWidth',3,...
 'LineStyle','-.');
axis on
grid on
box on
%background color of the border of the window or out side color
set(gcf,'color',[0.1 1 0.9876]);
%background color of the plot itself or in side color
set(gca,'color',[0.9608 0.9216 0.9216]);
%Createylabel
ylabel(' Predicted Hydraulic Conductivity',...
'FontSize',16,'FontName','Times New Roman');
 % Createxlabel
xlabel(' Generated Moisture Content(\theta)','FontSize',16,'FontName',...
'Times New Roman');
% Create textbox
annotation('textbox',[0.3102 0.4138 0.3593 0.3478],...
 'String',{'Kr (\Phi)=\Phi^1^/^2*[1-(1-\Phi^1^/^m)^m]^2',...
 '','\Phi=(\theta-\thetar)/(\thetas-\thetar )','','K=Ks*Kr',...
 '','m=1-1/n and 0<m<1'},...
 'FontWeight','bold',...
 'FontSize',20,...
 'FontName','Times New Roman',...
 'FitBoxToText','off',...
```

```
 'BackgroundColor',[0.7569 0.8667 0.7765]);
%Create a title
title([' Curve Fitting on linear plot '],...
'FontSize',16,'FontName','Times New Roman');
%--------------------------------------------------------------------
%we use here curve fitting method y=ax^b
%--------------------------------------------------------------------
na=100;
xa=sum(log(x));
ya=sum(log(y));
xb=sum(log(x).*log(y));
xsqure=(log(x)).^2;
xc=sum(xsqure);
%ao=(ya-bo*xa)/na
xd=ya/na;xk=xa/na;
%ao=xd-bo*xk;--------------------------------(3)
%xb=(xd-bo*xk)*xa+(bo*xc);
%xb=(xd*xa)-(bo*xk*xa)+(bo*xc);
xf=xd*xa;xg=xk*xa;
%xb=xf-(b0*xg)+(b0*xc);
xh=xb-xf;
%xh=b0*(xc-xg)
bo=xh/(xc-xg);
ao=xd-(bo*xk);
ak1=exp(ao);
bk1=bo;
xfit1=x;
yfit1=ak1*(xfit1.^bk1);
plot(xfit1,yfit1,'MarkerFaceColor',[1 0 0],...
```

```
 'MarkerEdgeColor',[1 0 1],...
 'MarkerSize',5,...
 'Marker','diamond',...
 'LineWidth',3,...
 'Color',[1 0 0]');
legend({'Van Genuchten Curve','fitted curve y=a*e^(^b^x^)',...
'fitted curve y=a*x^b'},...
'FontSize',14,'FontName','Times New Roman','Color',[1 1 0]);
set(gca,'yTick',[-.01 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 1.1 1.2 1.3...
 1.4 1.5 1.6]);
ylim([-.01 1.6]);
hold off
%============================================================================
%The relative hydraulic Conductivity can be expressed in terms of the pressure head figure(9)
%============================================================================
figure(9)
%the van genuchten model is as follow
%kr(h)={1-(alfa*h)^n-1[1+(alfa*h)^n]^-m}^2/[1+alfa*h)^n]^m/2
m=m10;
n=n10;
alfa=alfa10;
p1=0:20000;
p2=(alfa.*p1);
p3=p2.^n;p4=(1+p3);
p5=p4.^(-m);p6=p2.^(n-1);
p7=p5.*p6;
p8=(1-p7);
p9=p8.^2;
p10=(1+p3);
```

```
p11=p10.^(m/2);
p12=1./p11;
kr2=p9.*p12;
loglog(p1,kr2,'MarkerSize',2,'Marker','*','LineWidth',2,...
 'Color',[0.1059 0.3098 0.2078]);
hold on
% Createxlabel
xlabel('Matric Suction (generated) \psi','FontSize',16,'FontName',...
 'Times New Roman');
% Createylabel
%Createylabel
ylabel('Predicted Hydraulic Conductivity','FontSize',16,'FontName',...
'Times New Roman');
% Create title
title('Hydraulic Conductivity vs Matric Suction Plot','FontWeight',...
 'bold','FontSize',16,'FontName','Times New Roman');
xlim([1 1.5e+004]); ylim([1e-005 10]);
box('on');grid on;
%background color of the border of the window or out side color
set(gcf,'color',[0.1 1 0.9876]);
%background color of the plot itself or in side color
set(gca,'color',[0.9608 0.9216 0.9216]);
legend({'K vs \psi curve'});
% Create textbox
annotation('textbox',[0.1735 0.1508 0.4617 0.2241],'String',{'',...
'kr(\psi)=[1-(\alpha*\psi)^n^-^1(1+(\alpha*\psi)^n)^-^m]^2 /[1+(\alpha*\psi)^n]^m^/^2'},...
'FontWeight','bold','FontSize',20,'FontName','Times New Roman',...
'FitBoxToText','off','BackgroundColor',[0.7569 0.8667 0.7765]);
hold off
%===============================================================
% END OF APENDIX A
%===============================================================
```

APPENDIX-B

LISTING OF ONE DIMENSIONAL FINITE ELEMENT MODEL

```
C*****FINITE ELEMENT ANALYSIS OF ONE DIMENSIONAL SOIL MEDIUM*****
 COMMON/A/NP,NE,NB,NMAT,NDF,NEQ,NCN,NSIZE,NCL,DELT
 COMMON/B/ES(4,4),SM(4,4),R(4),JOP(4),FACT(1500)
 COMMON/C/CORD(1500,2),R1(1500),IFFIX(1500),FIXED(1500)
 COMMON/D/NOP(1500,3),IMAT(1500),ICN(1500),ORT(16,8),HD
 COMMON/E/NBC(50),NFIX(50,2),FIX(50,2),REACT(50,2),NSEG
 COMMON/F/LOCEL(4),NDEST(4),LCASE,MFRON,GSTIF(3500)
 COMMON/G/ALOAD(80),NACVA(80),VECRV(80),EQUAT(80),NITER
 COMMON/H/R2(1500),AK(1500),NPROB
C*****INPUT/OUTPUT FILES*****
 OPEN(1,FILE='VC.INP',ACCESS='SEQUENTIAL')
 OPEN(2,FILE='VC.OUT',ACCESS='SEQUENTIAL',STATUS='NEW')
 OPEN(3,FILE='VCR.OUT',ACCESS='SEQUENTIAL',STATUS='NEW')
C*****CONTROL*****
 LCASE=1
 WRITE(2,1)
 1 FORMAT(5X,'NPROB',6X,'DELT',6X,'ISEG',6X,'ITER')
 READ(1,2)NPROB,DELT,ISEG,ITER
 WRITE(2,2)NPROB,DELT,ISEG,ITER
 2 FORMAT(I10,F10.3,2I10 )
C*****DATA DEVELOPEMENT*****
 CALL GDATA
 WRITE(*,*)NPROB
 CALL BEGIN
 DO 50 N=1,NE
 50 WRITE(2,51)N,AK(N),FACT(N)
 51 FORMAT(I10,2E10.3)
C WRITE(*,*)NPROB
 IF(NCL.GT.0)CALL LOAD
 CALL WIDTH
C*****TERMINATE FOR ONLY DATA*****
 IF(NPROB.EQ.0)GO TO 30
C*****PERFORM ANALYSIS*****
 DO 20 NSEG=1,ISEG
C*****PRINT RESPONSE*****
```

```
 DO 10 NITER=1,ITER
 CALL FRONT
 CALL MODIFY
 10 CONTINUE
 DO 15 N=1,NE
 15 WRITE(2,16)N,AK(N),FACT(N)
 16 FORMAT(I10,2E10.3)
 CALL DISPLY(ISEG)
 20 CONTINUE
 30 CONTINUE
 STOP
 END
 SUBROUTINE GDATA
 COMMON/A/NP,NE,NB,NMAT,NDF,NEQ,NCN,NSIZE,NCL,DELT
 COMMON/B/ES(4,4),SM(4,4),R(4),JOP(4),FACT(1500)
 COMMON/C/CORD(1500,2),R1(1500),IFFIX(1500),FIXED(1500)
 COMMON/D/NOP(1500,3),IMAT(1500),ICN(1500),ORT(16,8),HD
 COMMON/E/NBC(50),NFIX(50,2),FIX(50,2),REACT(50,2),NSEG
 COMMON/F/LOCEL(4),NDEST(4),LCASE,MFRON,GSTIF(3500)
 COMMON/G/ALOAD(80),NACVA(80),VECRV(80),EQUAT(80),NITER
 COMMON/H/R2(1500),AK(1500),NPROB
 NDF=1
C*****PRINT TITLE*****
 WRITE(2,401)
C*****PRINT BOUNDARIES*****
 WRITE(2,301)
 WRITE(2,302)
 WRITE(2,301)
C*****READ AND WRITE CONTROL PARAMETERS*****
 WRITE(2,201)
 WRITE(2,101)
 READ(1,1)NP,NE,NB,NMAT,NCL
 WRITE(2,1)NP,NE,NB,NMAT,NCL
 1 FORMAT(5I10)
C MATERIAL DATA
 READ(1,2)(I,(ORT(I,J),J=1,6),I=1,NMAT)
 WRITE(2,2)(I,(ORT(I,J),J=1,6),I=1,NMAT)
 2 FORMAT(I10,6F10.4)
C*****READ AND WRITE NODAL COORDINATES*****
```

```
 WRITE(2,203)
 WRITE(2,103)
 READ(1,3)(N,(CORD(N,M),M=1,2),N=1,NP)
 WRITE(2,3)(N,(CORD(N,M),M=1,2),N=1,NP)
 3 FORMAT(I10,2F10.3)
C*****READ AND WRITE ELEMENT DETAILS*****
 WRITE(2,204)
 WRITE(2,104)
 READ(1,4)(N,(NOP(N,M),M=1,3),ICN(N),IMAT(N),N=1,NE)
 WRITE(2,4)(N,(NOP(N,M),M=1,3),ICN(N),IMAT(N),N=1,NE)
 4 FORMAT(6I10)
C*****BOUNDARY CONDITIONS*****
 WRITE(2,205)
 WRITE(2,105)
 READ(1,5)(NBC(I),(NFIX(I,J),J=1,NDF),(FIX(I,J),J=1,NDF),I=1,NB)
 WRITE(2,5)(NBC(I),(NFIX(I,J),J=1,NDF),(FIX(I,J),J=1,NDF),I=1,NB)
 5 FORMAT(2I10,F10.3)
C*****NODAL HEADS AT TIME T-0*****
 DO 20 I=1,NP
 20 R2(I)=CORD(I,2)
C*****ADDITIONAL SPECIFICATIONS*****
 101 FORMAT(8X,'NP',8X,'NE',8X,'NB',7X,'NCL')
 102 FORMAT(8X,'NO',6X,'KSAT',8X,'TS',8X,'TR',9X,'N',9X,'M',
 15X,'ALPHA')
 103 FORMAT(6X,'NODE',9X,'X',9X,'Y')
 104 FORMAT(4X,'ELE NO',9X,'I',9X,'J',9X,'K',
 17X,'NCN',4X,'MAT NO')
 105 FORMAT(3X,'NODE NO',6X,'CODE',7X,'PHI')
 201 FORMAT('CONTROL PARAMETERS')
 203 FORMAT('NODAL COORDINATES')
 204 FORMAT('ELEMENT DETAILS')
 205 FORMAT('BOUNDARY CONDITIONS')
 301 FORMAT(40(2H**))
 302 FORMAT(40(2HXX))
 401 FORMAT('ANALYSIS OF ONE DIMENSIONAL SOIL MEDIUM')
 RETURN
 END
 SUBROUTINE LOAD
 COMMON/A/NP,NE,NB,NMAT,NDF,NEQ,NCN,NSIZE,NCL,DELT
```

```
 COMMON/B/ES(4,4),SM(4,4),R(4),JOP(4),FACT(1500)
 COMMON/C/CORD(1500,2),R1(1500),IFFIX(1500),FIXED(1500)
 COMMON/D/NOP(1500,3),IMAT(1500),ICN(1500),ORT(16,8),HD
 COMMON/E/NBC(50),NFIX(50,2),FIX(50,2),REACT(50,2),NSEG
 COMMON/F/LOCEL(4),NDEST(4),LCASE,MFRON,GSTIF(3500)
 COMMON/G/ALOAD(80),NACVA(80),VECRV(80),EQUAT(80),NITER
 COMMON/H/R2(1500),AK(1500),NPROB
 DO 10 I=1,NCL
 READ(1,1)N,Q
 R1(N)=Q
 WRITE(2,1)N,Q
 1 FORMAT(I10,F10.3)
 10 CONTINUE
 RETURN
 END
 SUBROUTINE STIFTG(N)
 COMMON/A/NP,NE,NB,NMAT,NDF,NEQ,NCN,NSIZE,NCL,DELT
 COMMON/B/ES(4,4),SM(4,4),R(4),JOP(4),FACT(1500)
 COMMON/C/CORD(1500,2),R1(1500),IFFIX(1500),FIXED(1500)
 COMMON/D/NOP(1500,3),IMAT(1500),ICN(1500),ORT(16,8),HD
 COMMON/E/NBC(50),NFIX(50,2),FIX(50,2),REACT(50,2),NSEG
 COMMON/F/LOCEL(4),NDEST(4),LCASE,MFRON,GSTIF(3500)
 COMMON/G/ALOAD(80),NACVA(80),VECRV(80),EQUAT(80),NITER
 COMMON/H/R2(1500),AK(1500),NPROB
C WRITE(2,1)N
 1 FORMAT('ELEMENT NO-',I10)
C*****CONTROL PARAMETERS*****
 L=IMAT(N)
C AK(N)=ORT(L,1)
 NCN=ICN(N)
 NSIZE=NCN*NDF
 DO 5 I=1,NCN
 JOP(I)=IABS(NOP(N,I))
 5 CONTINUE
 IF(NCN.EQ.2)CALL STIF1(N)
 IF(NCN.EQ.3)CALL STIF2(N)
 RETURN
 END
 SUBROUTINE STIF1(N)
```

```
 COMMON/A/NP,NE,NB,NMAT,NDF,NEQ,NCN,NSIZE,NCL,DELT
 COMMON/B/ES(4,4),SM(4,4),R(4),JOP(4),FACT(1500)
 COMMON/C/CORD(1500,2),R1(1500),IFFIX(1500),FIXED(1500)
 COMMON/D/NOP(1500,3),IMAT(1500),ICN(1500),ORT(16,8),HD
 COMMON/E/NBC(50),NFIX(50,2),FIX(50,2),REACT(50,2),NSEG
 COMMON/F/LOCEL(4),NDEST(4),LCASE,MFRON,GSTIF(3500)
 COMMON/G/ALOAD(80),NACVA(80),VECRV(80),EQUAT(80),NITER
 COMMON/H/R2(1500),AK(1500),NPROB
 J1=JOP(1)
 Z1=CORD(J1,1)
 J2=JOP(2)
 Z2=CORD(J2,1)
 EL=Z2-Z1
C*****SEEPAGE STIFFNESS MATRIX*****
 ES(1,1)=AK(N)/EL
 ES(1,2)=-AK(N)/EL
 ES(2,1)=ES(1,2)
 ES(2,2)=ES(1,1)
C*****MASS MATRIX*****
 SM(1,1)=EL/3.0
 SM(1,2)=EL/6.0
 SM(2,1)=SM(1,2)
 SM(2,2)=SM(1,1)
C*****LEFT SIDE COMPONENTS*****
 DO 10 I=1,2
 DO 10 J=1,2
 ES(I,J)=ES(I,J)-FACT(N)*SM(I,J)/DELT
 10 CONTINUE
C*****RESIDUAL LOAD VECTOR*****
 PHI1=R2(J1)
 PHI2=R2(J2)
 R(1)=EL*PHI1/2.0
C R(1)=-(EL*PHI1/3.0+EL*PHI2/6.0)
 R(2)=EL*PHI2/2.0
C R(2)=-(EL*PHI1/6.0+EL*PHI1/3.0)
 R(1)=-FACT(N)*R(1)/DELT
 R(2)=-FACT(N)*R(2)/DELT
 RETURN
 END
```

```
 SUBROUTINE STIF2(N)
 COMMON/A/NP,NE,NB,NMAT,NDF,NEQ,NCN,NSIZE,NCL,DELT
 COMMON/B/ES(4,4),SM(4,4),R(4),JOP(4),FACT(1500)
 COMMON/C/CORD(1500,2),R1(1500),IFFIX(1500),FIXED(1500)
 COMMON/D/NOP(1500,3),IMAT(1500),ICN(1500),ORT(16,8),HD
 COMMON/E/NBC(50),NFIX(50,2),FIX(50,2),REACT(50,2),NSEG
 COMMON/F/LOCEL(4),NDEST(4),LCASE,MFRON,GSTIF(3500)
 COMMON/G/ALOAD(80),NACVA(80),VECRV(80),EQUAT(80),NITER
 COMMON/H/R2(1500),AK(1500),NPROB
 J1=JOP(1)
 Z1=CORD(J1,1)
 J2=CORD(J2,1)
 EL=Z2-Z1
 J3=JOP(3)
C*****SEEPAGE STIFFNESS MATRIX*****
 AMT=1.0/6.0
 ES(1,1)=14.0*AMT*AK(N)/EL
 ES(1,2)=2.0*AMT*AK(N)/EL
 ES(1,3)=-16.0*AMT*AK(N)/EL
 ES(2,1)=ES(1,2)
 ES(2,2)=14.0*AMT*AK(N)/EL
 ES(2,3)=-16.0*AMT*AK(N)/EL
 ES(3,1)=ES(1,3)
 ES(3,2)=ES(2,3)
 ES(3,3)=32.0*AMT*AK(N)/EL
C*****MASS MATRIX*****
 SM(1,1)=4.0*EL/30.0
 SM(1,2)=-EL/30.0
 SM(1,3)=2.0*EL/30.0
 SM(2,1)=SM(1,2)
 SM(2,2)=4.0*EL/30.0
 SM(2,3)=2.0*EL/30.0
 SM(3,1)=SM(1,3)
 SM(3,2)=SM(2,3)
 SM(3,3)=16.0*EL/30.0
C*****LEFT SIDE COMPONENTS*****
 DO 10 I=1,3
 DO 10 J=1,3
 ES(I,J)=ES(I,J)+FACT(N)*SM(I,J)/DELT
```

```
 10 CONTINUE
C*****RESIDUAL LOAD VECTOR*****
 PHI1=R2(J1)
 PHI2=R2(J2)
 PHI3=R2(J3)
 R(1)=PHI1*SM(1,1)+PHI2*SM(1,2)+PHI3*SM(1,3)
 R(2)=PHI1*SM(2,1)+PHI2*SM(2,2)+PHI3*SM(2,3)
 R(3)=PHI1*SM(3,1)+PHI2*SM(3,2)+PHI3*SM(3,3)
 R(1)=FACT(N)*R(1)/DELT
 R(2)=FACT(N)*R(2)/DELT
 R(3)=FACT(N)*R(3)/DELT
 RETURN
 END
 SUBROUTINE WIDTH
 COMMON/A/NP,NE,NB,NMAT,NDF,NEQ,NCN,NSIZE,NCL,DELT
 COMMON/B/ES(4,4),SM(4,4),R(4),JOP(4),FACT(1500)
 COMMON/C/CORD(1500,2),R1(1500),IFFIX(1500),FIXED(1500)
 COMMON/D/NOP(1500,3),IMAT(1500),ICN(1500),ORT(16,8),HD
 COMMON/E/NBC(50),NFIX(50,2),FIX(50,2),REACT(50,2),NSEG
 COMMON/F/LOCEL(4),NDEST(4),LCASE,MFRON,GSTIF(3500)
 COMMON/G/ALOAD(80),NACVA(80),VECRV(80),EQUAT(80),NITER
 COMMON/H/R2(1500),AK(1500),NPROB
C*****INITIALIZATION*****
 MFRON=80
 LFRON=0
 JFRON=0
 NFRON=0
 DO 10 I=1,MFRON
 10 NACVA(I)=0
C*****DETERMINE ELEMENT NODES*****
C*****CHANGE THE SIGN OF LAST APPERANCE OF EACH NODE*****
 DO 50 I=1,NP
 KLAST=0
 DO 40 J=1,NE
 NCN=ICN(J)
 DO 30 K=1,NCN
 IF(NOP(J,K).NE.I) GO TO 30
 KLAST=J
 NLAST=K
```

```
 30 CONTINUE
 40 CONTINUE
 IF(KLAST.NE.0)NOP(KLAST,NLAST)=-I
 50 CONTINUE
C*****LOOP OVER THE ELEMENTS*****
 DO 130 N=1,NE
 NCN=ICN(N)
 DO 90 I=1,NCN
 NIKNO=NOP(N,I)
 IF(NIKNO.LT.0)NIKNO=-NIKNO
 KEXIS=0
 DO 60 J=1,NFRON
 IF(NIKNO.NE.NACVA(J))GO TO 60
 KEXIS=1
 LFRON=J
 60 CONTINUE
 IF(KEXIS.NE.0) GO TO 90
 DO 70 J=1,MFRON
 IF(NACVA(J).NE.0) GO TO 70
 NACVA(J)=NIKNO
 LFRON=J
 GO TO 80
 70 CONTINUE
 80 IF(LFRON.GT.NFRON)NFRON=LFRON
 90 CONTINUE
 IF(NFRON.GT.JFRON)JFRON=NFRON
 DO 120 I=1,NCN
 NIKNO=-NOP(N,I)
 IF(NIKNO.LT.0) GO TO 120
 DO 100 II=1,NFRON
 IF(NACVA(II).NE.NIKNO) GO TO 100
 NACVA(II)=0
 GO TO 110
 100 CONTINUE
 110 IF(NACVA(NFRON).NE.0) GO TO 120
 NFRON=NFRON-1
 IF(NFRON.GT.0) GO TO 110
 120 CONTINUE
 130 CONTINUE
```

```
C*****CALCULATE REQUIRED POINT WIDTH*****
 MFRON=JFRON*NDF
C*****RESET ELEMENT CONNECTION ARRAY*****
 DO 140 N=1,NE
 NCN=ICN(N)
 DO 140 M=1,NCN
 I=NOP(N,M)
 IF(I.LT.0)NOP(N,M)=-I
 140 CONTINUE
 WRITE(2,141)MFRON
 141 FORMAT(/,'FRONT WIDTH=',I10)
 RETURN
 END
 SUBROUTINE FRONT
 COMMON/A/NP,NE,NB,NMAT,NDF,NEQ,NCN,NSIZE,NCL,DELT
 COMMON/B/ES(4,4),SM(4,4),R(4),JOP(4),FACT(1500)
 COMMON/C/CORD(1500,2),R1(1500),IFFIX(1500),FIXED(1500)
 COMMON/D/NOP(1500,3),IMAT(1500),ICN(1500),ORT(16,8),HD
 COMMON/E/NBC(50),NFIX(50,2),FIX(50,2),REACT(50,2),NSEG
 COMMON/F/LOCEL(4),NDEST(4),LCASE,MFRON,GSTIF(3500)
 COMMON/G/ALOAD(80),NACVA(80),VECRV(80),EQUAT(80),NITER
 COMMON/H/R2(1500),AK(1500),NPROB
 OPEN(11,FILE='ROUGH1.DAT',ACCESS='DIRECT',RECL=5)
 OPEN(12,FILE='ROUGH2.DAT',ACCESS='DIRECT',RECL=5)
C*****CONTROLS*****
 INDICT=0
 NTAPE=11
 MTAPE=12
 MSTIF=MFRON*(MFRON+1)/2
C*****INITIALIZATION*****
 DO 10 I=1,MSTIF
 10 GSTIF(I)=0.0
 DO 30 I=1,MFRON
 ALOAD(I)=0.0
 VECRV(I)=0.0
 30 NACVA(I)=0
 DO 50 I=1,NEQ
 FIXED(I)=0.0
 50 IFFIX(I)=0
```

```
C*****INSERT BOUNDARY CONDITIONS*****
 DO 80 I=1,NB
 II=(NBC(I)-1)*NDF
 DO 70 J=1,NDF
 II=II+1
 REACT(I,J)=0.0
 FIXED(II)=FIX(I,J)
 70 IFFIX(II)=NFIX(I,J)
 80 CONTINUE
C*****ELEMENT CONNECTION ARRAY*****
 DO 110 I=1,NP
 JLAST=0
 DO 100 J=1,NE
 NCN = ICN(J)
 DO 90 K=1,NCN
 IF(NOP(J,K).NE.I) GO TO 90
 JLAST=J
 KLAST=K
 90 CONTINUE
 100 CONTINUE
 IF(JLAST.NE.0)NOP(JLAST,KLAST)=-I
 110 CONTINUE
C*****FRONTAL OPERATIONS*****
 NFRON=0
 KELVA=0
C*****LOOP OVER ELEMENTS*****
 DO 360 N=1,NE
C*****ELEMENT CHARACTERISTICS*****
 CALL STIFTG(N)
 WRITE(*,*)LCASE,N
C*****ELEMENT LOCATION ARRAY*****
 KEVAB=0
 II=0
 DO 120 I=1,NCN
 DO 120 J=1,NDF
 II=II+1
 LOCNO=NOP(N,I)
 IF(LOCNO.GT.0)LOCEL(II)=(LOCNO-1)*NDF+J
 IF(LOCNO.LT.0)LOCEL(II)=(LOCNO+1)*NDF-J
```

```
 120 CONTINUE
C*****DESTINATION ARRAYS*****
C*****START BY LCOKING FOR EXISTING DESTINATION*****
 DO 160 I=1,NSIZE
 NIKNO=LOCEL(I)
 IF(NIKNO.LT.0) NIKNO=-NIKNO
 KEXIS=0
 DO 130 J=1,NFRON
 IF(NIKNO.NE.NACVA(J))GO TO 130
 KEVAB=KEVAB+1
 KEXIS=1
 NDEST(KEVAB)=J
 130 CONTINUE
 IF(KEXIS.NE.0)GO TO 160
 DO 140 J=1,MFRON
 IF(NACVA(J).NE.0) GO TO 140
 NACVA(J)=NIKNO
 KEVAB=KEVAB+1
 NDEST(KEVAB)=J
 GO TO 150
 140 CONTINUE
C*****INCREASE CURRENT FRONT WIDTH IF REQUIRED*****
 150 IF(NDEST(KEVAB).GT.NFRON)NFRON=NDEST(KEVAB)
 160 CONTINUE
C*****SUPER POSTIONING*****
 DO 190 I=1,NSIZE
 IDEST=NDEST(I)
 NIKNO=LOCEL(I)
 IF(NIKNO.LT.0)NIKNO=-NIKNO
C*****FIRST LOAD VECTOR*****
 ALOAD(IDEST)=ALOAD(IDEST)+R(I)+R1(NIKNO)
 R1(NIKNO)=0.0
C*****NEXT STIFFNESS COEFFICIENTS*****
 IF(LCASE.GT.1)GO TO 190
 DO 180 J=1,I
 JDEST = NDEST(J)
 IF(JDEST.GE.IDEST)NGST=(JDEST*JDEST-JDEST)/2+IDEST
 IF(JDEST.LT.IDEST)NGST=(IDEST*IDEST-IDEST)/2+JDEST
 180 GSTIF(NGST)=GSTIF(NGST)+ES(I,J)
```

```
 190 CONTINUE
C*****ELIMINATION PROCESS*****
 DO 300 I=1,NSIZE
 NIKNO=-LOCEL(I)
 IF(NIKNO.LE.0)GO TO 300
C*****FIND POSTIONS OF VARIABLE READY FOR ELIMINATION*****
 DO 280 II=1,NFRON
 IF(NACVA(II).NE.NIKNO)GO TO 280
 KELVA=KELVA+1
 JCON=(KELVA-1)*(MFRON+3)
C*****EXTRACT THE LOAD TERM*****
 GLOAD=ALOAD(II)
 ALOAD(II)=0.0
C*****AND ALSO STIFFNESS COEFFICIENTS*****
 IF(LCASE.GT.1)GO TO 225
 DO 210 JJ=1,MFRON
 IF(JJ.LE.II) NLOCA=(II*II-II)/2+JJ
 IF(JJ.GT.II)NLOCA= (JJ*JJ-JJ)/2+II
 EQUAT(JJ)=GSTIF(NLOCA)
 210 GSTIF(NLOCA)=0.0
C*****RECORD THE EXTRACTED INFORMATION*****
 DO 215 IN=1,MFRON
 JCON=JCON+1
 WRITE(NTAPE,REC=JCON)EQUAT(IN)
 215 CONTINUE
 JCON=JCON+1
 WRITE(NTAPE,REC=JCON)II
 JCON=JCON+1
 WRITE(NTAPE,REC=JCON)NIKNO
 JCON=JCON+1
 WRITE(NTAPE,REC=JCON)GLOAD
 GO TO 230
 225 CONTINUE
 DO 226 IN=1,MFRON
 JCON=JCON+1
 READ(NTAPE,REC=JCON)EQUAT(IN)
 226 CONTINUE
 WRITE(MTAPE,REC=KELVA)GLOAD
 230 PIVOT=EQUAT(II)
 EQUAT(II)=0.0
C*****MODIFY LOAD TERMS*****
 DO 240 JJ=1,NFRON
 IF(IFFIX(NIKNO).EQ.0)AMT=GLOAD/PIVOT
```

```
 IF(IFFIX(NIKNO).EQ.1)AMT=FIXED(NIKNO)
 240 ALOAD(JJ)=ALOAD(JJ)-AMT*EQUAT(JJ)
 IF(IFFIX(NIKNO).EQ.1) GO TO 270
C*****ALSO STIFFNESS COEFFICIENTS IF REQUIRED*****
 IF(LCASE.GT.1)GO TO 270
 DO 260 JJ=1,NFRON
 NLOCA=(JJ*JJ-JJ)/2
 DO 250 KK=1,JJ
 NGST=NLOCA+KK
 250 GSTIF(NGST)=GSTIF(NGST)-EQUAT(JJ)*EQUAT(KK)/PIVOT
 260 CONTINUE
 270 EQUAT(II)=PIVOT
 IF(ICASE.EQ.1)GO TO 275
 IF(PIVOT.LT.0.0)INDICT=INDICT+1
 275 CONTINUE
C*****REDUCE FRONT WIDTH IF POSSIBLE*****
 NACVA(II)=0
 GO TO 290
 280 CONTINUE
 290 IF(NACVA(NFRON).NE.0) GO TO 300
 NFRON=NFRON-1
 IF(NFRON.GT.0) GO TO 290
 300 CONTINUE
C*****END LOOP OVER ELEMENTS*****
 360 CONTINUE
C*****BACK SUBSTITUTION*****
 370 CONTINUE
 DO 460 I=1,KELVA
 JCON=(KELVA-I)*(MFRON+3)
 DO 375 IN=1,MFRON
 JCON=JCON+1
 READ(NTAPE,REC=JCON)EQUAT(IN)
 375 CONTINUE
 JCON=JCON+1
 READ(NTAPE,REC=JCON)II
 JCON=JCON+1
 READ(NTAPE,REC=JCON)NIKNO
 JCON=JCON+1
 READ(NTAPE,REC=JCON)GLOAD
 IF(LCASE.EQ.1)GO TO 390
 LCON=KELVA-I+1
 READ(MTAPE,REC=LCON)GLOAD
 390 PIVOT=EQUAT(II)
 IF(IFFIX(NIKNO).EQ.0)GO TO 410
```

```
C*****ENTER PRESCRIBED VALUE OF VARIABLES IF ANY*****
 400 VECRV(II)=FIXED(NIKNO)
 GO TO 420
 410 EQUAT(II)=0.0
 420 CONTINUE
 DO 430 JJ=1,MFRON
 430 GLOAD=GLOAD-VECRV(JJ)*EQUAT(JJ)
 IF(IFFIX(NIKNO).EQ.1)GO TO 440
 VECRV(II)=GLOAD/PIVOT
 R1(NIKNO)=VECRV(II)
 GO TO 450
 440 R1(NIKNO)=-GLOAD
 450 CONTINUE
 460 CONTINUE
C*****STRUCTURAL REACTIONS*****
 DO 480 I=1,NB
 II=(NBC(I)-1)*NDF
 DO 480 J=1,NDF
 II=II+1
 IF(IFFIX(II).NE.1) GO TO 480
 REACT(I,J)=R1(II)
 R1(II)=FIXED(II)
 480 CONTINUE
C*****RESET ELEMENT CONNECTIONS*****
 DO 490 N=1,NE
 NCN=ICN(N)
 DO 490 M=1,NCN
 I=NOP(N,M)
 IF(I.LT.0)NOP(N,M)=-I
 490 CONTINUE
 500 CONTINUE
 RETURN
 END
 SUBROUTINE DISPLY(ISEG)
 COMMON/A/NP,NE,NB,NMAT,NDF,NEQ,NCN,NSIZE,NCL,DELT
 COMMON/B/ES(4,4),SM(4,4),R(4),JOP(4),FACT(1500)
 COMMON/C/CORD(1500,2),R1(1500),IFFIX(1500),FIXED(1500)
 COMMON/D/NOP(1500,3),IMAT(1500),ICN(1500),ORT(16,8),HD
 COMMON/E/NBC(50),NFIX(50,2),FIX(50,2),REACT(50,2),NSEG
 COMMON/F/LOCEL(4),NDEST(4),LCASE,MFRON,GSTIF(3500)
 COMMON/G/ALOAD(80),NACVA(80),VECRV(80),EQUAT(80),NITER
 COMMON/H/R2(1500),AK(1500),NPROB
 DIMENSION GRADEX(200,4),GRADEY(200,4),VELX(200,4),VELY(200,4)
C*****MARK THE INITIAL BOUNDARIES*****
```

```
 IF(NSEG.EQ.ISEG)WRITE(3,1)
 IF(NSEG.EQ.ISEG)WRITE(3,1)
 IF(NSEG.EQ.ISEG)WRITE(3,1)
 1 FORMAT(40(2H**))
 2 FORMAT(40(2HXX))
C*****WRITE NODAL RESPONSE*****
 IF(NSEG.EQ.ISEG)WRITE(3,3)
 3 FORMAT('NODAL POTENTIALS')
 IF(NSEG.EQ.ISEG)WRITE(3,4)
 4 FORMAT(6X,'NODE',8X'PR')
 DO 5 I=1,NP
 PHI=R1(I)
 PR=PHI-CORD(I,2)
 IF(NSEG.EQ.ISEG)WRITE(3,6)PHI
 R2(I)=R1(I)
 R1(I)=0.0
 5 CONTINUE
 6 FORMAT(E10.3)
C*****LOOP OVER THE NODES*****
 IF(NSEG.EQ.ISEG)WRITE(3,13)
 13 FORMAT(6X,'NODE',9X,'Q')
 IF(NSEG.EQ.ISEG)WRITE(3,11)(NBC(I),(REACT(I,J),J=1,NDF),I=1,NB)
 11 FORMAT(I10,E10.3)
 QQ=0.0
 DO 120 I=1,NB
 120 QQ=QQ+REACT(I,1)
 IF(NSEG.EQ.ISEG)WRITE(3,21)QQ
 21 FORMAT(E10.3)
 80 CONTINUE
 RETURN
 END
 SUBROUTINE MODIFY
 COMMON/A/NP,NE,NB,NMAT,NDF,NEQ,NCN,NSIZE,NCL,DELT
 COMMON/B/ES(4,4),SM(4,4),R(4),JOP(4),FACT(1500)
 COMMON/C/CORD(1500,2),R1(1500),IFFIX(1500),FIXED(1500)
 COMMON/D/NOP(1500,3),IMAT(1500),ICN(1500),ORT(16,8),HD
 COMMON/E/NBC(50),NFIX(50,2),FIX(50,2),REACT(50,2),NSEG
 COMMON/F/LOCEL(4),NDEST(4),LCASE,MFRON,GSTIF(3500)
 COMMON/G/ALOAD(80),NACVA(80),VECRV(80),EQUAT(80),NITER
 COMMON/H/R2(1500),AK(1500),NPROB
 DO 10 N=1,NE
 L=IMAT(N)
 THETAS=ORT(L,1)
 THETAR=ORT(L,2)
```

```
 AN=ORT(L,3)
 AM=ORT(L,4)
 ALPHA=ORT(L,5)
 PS=ORT(L,6)
 N1=NOP(N,1)
 N2=NOP(N,2)
 S1=R1(N1)
 S2=R1(N2)
 SIE=0.5*(S1+S2)
 SIE=ABS(SIE)
C*****CALCULATION OF THETA*****
C*****INPUT REQUIRED HERE ARA THETAS THETAR ALPHA KS N AND M*****
 SATUD=THETAS-THETAR
 THETAA=ALPHA*SIE
 THETAB=THETAA**AN
 THETAC=1+THETAB
 THETAD=THETAC**AM
 THETAE=1/THETAD
 THETA=THETAR+(SATUD*THETAE)
C*****CALCULATION OF C(SI)*****
 SATUE=THETA-THETAR
 SATUP=SATUE/SATUD
 CSIA=-ALPHA*AM*SATUD
 CSIB=1-AM
 RAISE=1/AM
 CSIC=SATUP**RAISE
 CSIO=(1-CSIC)
 CSID=CSIO**AM
 CSIDEN=CSIA*CSIC*CSID
 CSINU=1/CSIB
 CSI=CSINU*CSIDEN
C*****CALCULATION K(SI)*****
 PSIA=ALPHA*SIE
 PSIB=AN-1
 PSIC=PSIA**PSIB
 PSID=PSIA**AN
 PSIE=(1+PSID)**(-AM)
 PSIF=PSIC*PSIE
 PSIN=(1-PSIF)**2
 PSIG=(1+PSID)
 RAISEK=AM/2
 PSID=PSIG**RAISEK
 PSI=PSIN/PSID
 PSI=PS*PSI
```

```
C*****END OF CALCULATION THETA C(SAI) AND K(SAI)*****
 AK(N)=PSI
 FACT(N)=CSI
 10 CONTINUE
 RETURN
 END
 SUBROUTINE BEGIN
 COMMON/A/NP,NE,NB,NMAT,NDF,NEQ,NCN,NSIZE,NCL,DELT
 COMMON/B/ES(4,4),SM(4,4),R(4),JOP(4),FACT(1500)
 COMMON/C/CORD(1500,2),R1(1500),IFFIX(1500),FIXED(1500)
 COMMON/D/NOP(1500,3),IMAT(1500),ICN(1500),ORT(16,8),HD
 COMMON/E/NBC(50),NFIX(50,2),FIX(50,2),REACT(50,2),NSEG
 COMMON/F/LOCEL(4),NDEST(4),LCASE,MFRON,GSTIF(3500)
 COMMON/G/ALOAD(80),NACVA(80),VECRV(80),EQUAT(80),NITER
 COMMON/H/R2(1500),AK(1500),NPROB
 DO 10 N=1,NE
 WRITE(*,*)N
 L=IMAT(N)
 THETAS=ORT(L,1)
 THETAR=ORT(L,2)
 AN=ORT(L,3)
 AM=ORT(L,4)
 ALPHA=ORT(L,5)
 PS=ORT(L,6)
C THETAS=.5410
C THETAR=.1921
C AN=1.6
C AM=.38
C ALPHA=.0175
C PS=.3650/100.0
 N1=NOP(N,1)
 N2=NOP(N,2)
 S1=CORD(N1,2)
 S2=CORD(N2,2)
 SIE=0.5*(S1+S2)
 SIE=ABS(SIE)
C SIE=.144
C WRITE(*,*)NPROB
C*****CALCULATION OF THETA*****
C*****INPUT REQUIRED HERE ARA THETAS THETAR ALPHA KS N AND M*****
 SATUD=THETAS-THETAR
 THETAA=ALPHA*SIE
 THETAB=THETAA**AN
 THETAC=1+THETAB
```

```
 THETAD=THETAC**AM
 THETAE=1/THETAD
 THETA=THETAR+(SATUD*THETAE)
C WRITE(*,*)NPROB
C*****CALCULATION OF C(SI)*****
 SATUE=THETA-THETAR
 SATUP=SATUE/SATUD
 CSIA=-ALPHA*AM*SATUD
 CSIB=1-AM
 RAISE=1/AM
 CSIC=SATUP**RAISE
 CSIO=(1-CSIC)
 CSID=CSIO**AM
 CSIDEN=CSIA*CSIC*CSID
 CSINU=1/CSIB
 CSI=CSINU*CSIDEN
C WRITE(*,*)NPROB
C*****CALCULATION K(SI)*****
 PSIA=ALPHA*SIE
 PSIB=AN-1
 PSIC=PSIA**PSIB
 PSID=PSIA**AN
C WRITE(2,*)PSAID
 PSIE=(1+PSID)**(-AM)
C WRITE(2,*)PSATE
 PSIF=PSIC*PSIE
 PSIN=(1-PSIF)**2
 PSIG=(1+PSID)
 RAISEK=AM/2
 PSID=PSIG**RAISEK
 PSI=PSIN/PSID
 PSI=PS*PSI
C WRITE(*,*)NPROB
C*****END OF CALCULATION THETA C(SAI) AND K(SAI)*****
 AK(N)=PSI
 FACT(N)=CSI
 10 CONTINUE
 RETURN
 END
```

APPENDIX-C

INPUT FILE FOR MODEL VALIDATION OF ONE DIMENSIONAL MODEL

```
    1        1.00          24        1
  101         100           2        1        0
    1       .3680       .1020  2 .0000    .5000     .0335     33.1920
    1       0.000   -1000.000
    2       1.000   -1000.000
    3       2.000   -1000.000
    4       3.000   -1000.000
    5       4.000   -1000.000
    6       5.000   -1000.000
    7       6.000   -1000.000
    8       7.000   -1000.000
    9       8.000   -1000.000
   10       9.000   -1000.000
   11      10.000   -1000.000
   12      11.000   -1000.000
   13      12.000   -1000.000
   14      13.000   -1000.000
   15      14.000   -1000.000
   16      15.000   -1000.000
   17      16.000   -1000.000
   18      17.000   -1000.000
   19      18.000   -1000.000
   20      19.000   -1000.000
   21      20.000   -1000.000
   22      21.000   -1000.000
   23      22.000   -1000.000
   24      23.000   -1000.000
   25      24.000   -1000.000
   26      25.000   -1000.000
   27      26.000   -1000.000
   28      27.000   -1000.000
   29      28.000   -1000.000
   30      29.000   -1000.000
   31      30.000   -1000.000
   32      31.000   -1000.000
   33      32.000   -1000.000
   34      33.000   -1000.000
   35      34.000   -1000.000
   36      35.000   -1000.000
   37      36.000   -1000.000
   38      37.000   -1000.000
   39      38.000   -1000.000
   40      39.000   -1000.000
   41      40.000   -1000.000
   42      41.000   -1000.000
   43      42.000   -1000.000
   44      43.000   -1000.000
   45      44.000   -1000.000
   46      45.000   -1000.000
   47      46.000   -1000.000
   48      47.000   -1000.000
```

```
    49        48.000     -1000.000
    50        49.000     -1000.000
    51        50.000     -1000.000
    52        51.000     -1000.000
    53        52.000     -1000.000
    54        53.000     -1000.000
    55        54.000     -1000.000
    56        55.000     -1000.000
    57        56.000     -1000.000
    58        57.000     -1000.000
    59        58.000     -1000.000
    60        59.000     -1000.000
    61        60.000     -1000.000
    62        61.000     -1000.000
    63        62.000     -1000.000
    64        63.000     -1000.000
    65        64.000     -1000.000
    66        65.000     -1000.000
    67        66.000     -1000.000
    68        67.000     -1000.000
    69        68.000     -1000.000
    70        69.000     -1000.000
    71        70.000     -1000.000
    72        71.000     -1000.000
    73        72.000     -1000.000
    74        73.000     -1000.000
    75        74.000     -1000.000
    76        75.000     -1000.000
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    94        93.000     -1000.000
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    99        98.000     -1000.000
   100        99.000     -1000.000
   101       100.000     -1000.000
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     2             2             3       0         2         1
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     4             4             5       0         2         1
     5             5             9       0         2         1
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101	1	-1000.000			

APPENDIX-E

CHART AND TABLES

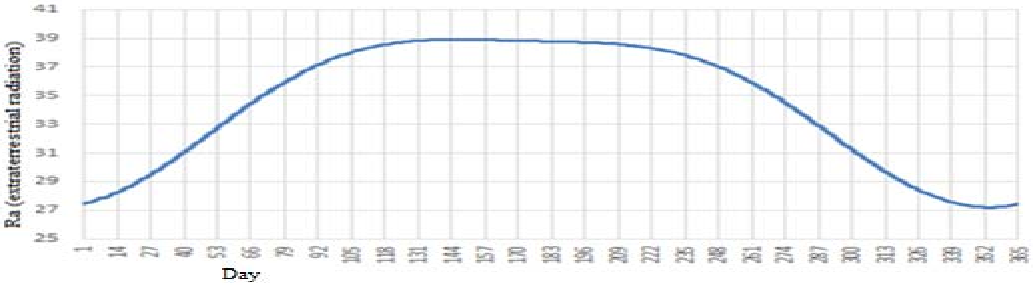

Figure E1: R_a variation with Day in the Year for Sholapur

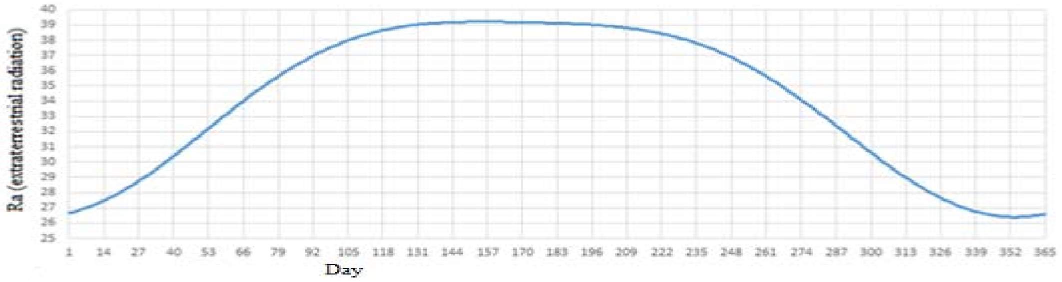

Figure E2: R_a variation with Day in the Year for Pune

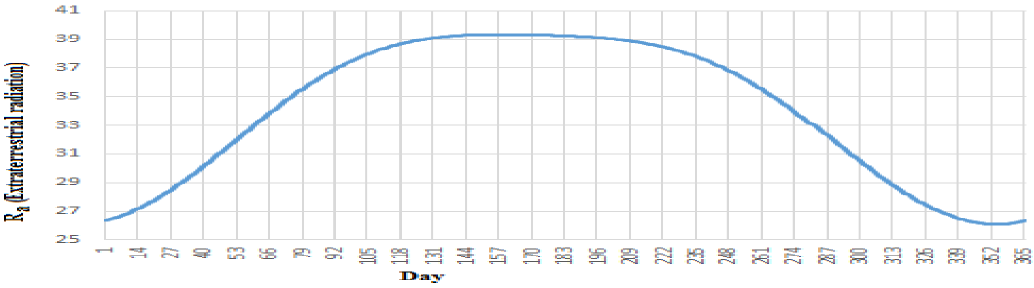

Figure E3: R_a variation with Day in the Year for Ahmednagar

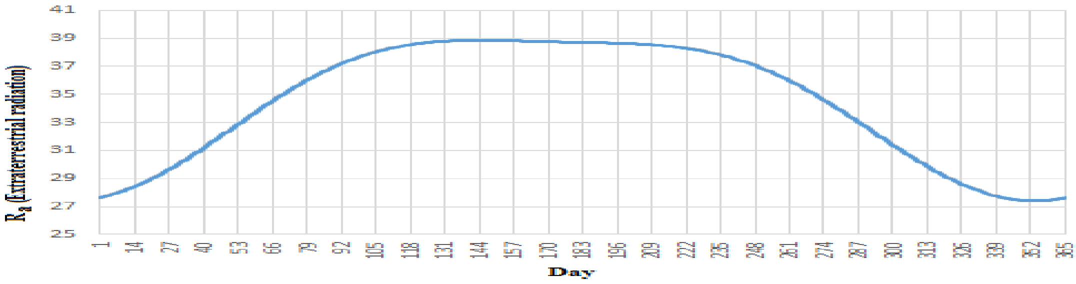

Figure E4: R_a variation with Day in the Year for Kolhapur

Table E1: Abstract of Average (Mean) and Total ET$_o$ Estimation for Sholapur by various Models

		Jan.	**Feb.**	**Mar.**	**April**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**	**TOTAL**
FAO	Total (mm)	110.3	128.2	171	196.7	224.2	172.3	139.4	130.5	125.8	123	111.1	102.6	1735.1
	Daily Average (mm)	3.6	4.5	5.5	6.6	7.2	5.8	4.5	4.2	4.2	4	3.7	3.3	
OHAG	Total (mm)	332.5	372.3	502.7	530.4	543.4	437	397.3	379.6	361.7	367.4	329.4	317.3	4871
	Daily Average (mm)	10.7	13.2	16.3	17.7	17.5	14.6	12.8	12.2	12.2	11.9	11	10.3	
MHAG	Total (mm)	135.6	151.9	205.1	216.4	221.7	178.3	162.1	154.9	147.6	149.9	134.4	129.5	1987.4
	Daily Average (mm)	4.4	5.4	6.7	7.2	7.2	6	5.2	5	5	4.8	4.5	4.2	
DHAG	Total (mm)	117	131.1	177	186.8	191.3	153.9	139.9	133.7	127.4	129.3	116.6	111.7	1715.7
	Daily Average (mm)	3.8	4.7	5.7	6.2	6.2	5.2	4.5	4.3	4.3	4.2	3.9	3.6	

Table E2: Abstract of Average (Mean) and Total ET_o Estimation for Pune by various Models

	Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
FAO	Total (mm)	102.3	117.6	161.2	189	210.8	147	108.5	99.2	108	114.7	96	93	1547.3
	Daily Average (mm)	3.3	4.2	5.2	6.3	6.8	4.9	3.5	3.2	3.6	3.7	3.2	3	
OHAG	Total (mm)	331.7	367.92	486.7	513	496	357	279	260.4	303	341	309	313.1	4357.82
	Daily Average (mm)	10.7	13.14	15.7	17.1	16	11.9	9	8.4	10.1	11	10.3	10.1	
MHAG	Total (mm)	136.4	151.2	198.4	210	201.5	144	114.7	105.4	123	139.5	126	127.1	1777.2
	Daily Average (mm)	4.4	5.4	6.4	7	6.5	4.8	3.7	3.4	4.1	4.5	4.2	4.1	
DHAG	Total (mm)	111.6	128.8	170.5	180	173.6	126	99.2	93	105	120.9	108	108.5	1525.1
	Daily Average (mm)	3.6	4.6	5.5	6	5.6	4.2	3.2	3	3.5	3.9	3.6	3.5	

Table E3: Weekly ET$_o$ for Sholapur and Pune by various Models

Week	Sholapur				Pune			
	FAO	OHAG	MHAG	DHAG	FAO	OHAG	MHAG	DHAG
1	24.8000	70.2000	28.3000	24.8000	20.5403	70.5668	28.7913	24.8466
2	23.2000	72.4000	29.5000	25.5000	21.8764	73.6881	30.0647	25.9456
3	25.1000	76.9000	31.3000	27.1000	23.3531	79.1216	32.2816	27.8587
4	26.1000	80.6000	32.8000	28.5000	23.4548	71.9067	29.3379	25.3183
5	27.9000	80.2000	32.7000	28.3000	24.6323	74.5605	30.4207	26.2527
6	29.8000	85.7000	35.0000	30.2000	28.2326	87.5660	35.7269	30.8320
7	32.2000	93.9000	38.2000	32.9000	29.6925	93.7281	38.2411	33.0017
8	34.0000	100.3000	40.8000	35.3000	31.8436	98.6080	40.2321	34.7199
9	37.2000	104.2000	42.5000	36.6000	33.5204	102.9209	41.9917	36.2385
10	36.0000	108.4000	44.1000	38.1000	34.7238	104.6719	42.7062	36.8550
11	38.1000	113.4000	46.3000	39.8000	34.6041	106.4139	43.4169	37.4684
12	39.3000	118.7000	48.4000	41.8000	39.0541	115.5507	47.1447	40.6854
13	42.3000	122.8000	50.1000	43.3000	39.5806	116.5747	47.5625	41.0460
14	43.6000	119.7000	48.8000	42.4000	42.3625	119.3100	48.6785	42.0091
15	45.7000	123.7000	50.5000	43.5000	44.0912	120.5661	49.1910	42.4513
16	47.2000	124.8000	50.8000	43.9000	45.2791	118.9180	48.5186	41.8710
17	47.0000	126.4000	51.5000	44.5000	44.5646	118.9966	48.5506	41.8987
18	48.2000	124.9000	50.9000	44.1000	47.0145	120.6054	49.2070	42.4652
19	50.3000	121.8000	49.6000	42.9000	47.6678	112.1832	45.7707	39.4997

Table E3 (Continued)

Week	Sholapur				Pune			
	FAO	**OHAG**	**MHAG**	**DHAG**	**FAO**	**OHAG**	**MHAG**	**DHAG**
20	51.3000	123.8000	50.6000	43.4000	50.4551	113.4375	46.2825	39.9413
21	51.6000	121.5000	49.5000	42.9000	51.5100	106.7966	43.5730	37.6031
22	51.2000	120.8000	49.4000	42.5000	38.5152	97.4398	39.7555	34.3086
23	47.0000	111.9000	45.7000	39.4000	40.7850	93.8020	38.2712	33.0277
24	35.8000	100.0000	40.7000	35.4000	36.9854	87.8478	35.8419	30.9312
25	36.8000	93.4000	38.1000	33.0000	32.3988	80.8140	32.9721	28.4546
26	36.5000	94.2000	38.4000	33.3000	27.6061	71.7507	29.2743	25.2634
27	33.1000	90.8000	37.1000	32.0000	21.0137	56.2019	22.9304	19.7887
28	33.2000	93.0000	37.9000	32.7000	27.6993	67.1977	27.4166	23.6603
29	31.2000	92.5000	37.8000	32.6000	29.9601	74.5666	30.4232	26.2549
30	28.0000	83.7000	34.2000	29.6000	21.2080	58.8834	24.0244	20.7328
31	29.4000	84.2000	34.3000	29.7000	17.5664	50.8087	20.7300	17.8897
32	27.5000	83.1000	33.9000	29.4000	19.1003	51.2353	20.9040	18.0399
33	31.1000	88.2000	36.1000	31.0000	20.2110	56.8030	23.1756	20.0003
34	27.9000	82.3000	33.6000	29.0000	23.9159	63.2691	25.8138	22.2771
35	32.3000	91.7000	37.4000	32.4000	28.9227	70.0961	28.5992	24.6809
36	29.0000	85.2000	34.8000	30.1000	26.7243	76.3805	31.1633	26.8936
37	31.4000	85.1000	34.7000	30.0000	23.5093	69.1558	28.2156	24.3498
38	30.4000	86.8000	35.5000	30.8000	23.4529	64.7228	26.4069	22.7889

Table E3 (Continued)

Week	Sholapur				Pune			
	FAO	**OHAG**	**MHAG**	**DHAG**	**FAO**	**OHAG**	**MHAG**	**DHAG**
39	27.5000	82.0000	33.5000	28.9000	26.6357	72.2506	29.4782	25.4394
40	28.8000	87.3000	35.5000	30.7000	24.2657	70.2052	28.6437	24.7192
41	28.8000	85.4000	34.9000	30.1000	26.2125	78.1295	31.8768	27.5094
42	26.2000	79.1000	32.4000	27.8000	25.6074	77.0662	31.4430	27.1350
43	27.6000	81.6000	33.4000	28.7000	27.0207	80.9093	33.0110	28.4882
44	27.0000	80.0000	32.6000	28.0000	24.2191	74.5619	30.4213	26.2533
45	26.4000	77.4000	31.7000	27.2000	23.0165	71.7513	29.2745	25.2636
46	25.8000	77.0000	31.3000	27.1000	21.9741	72.8789	29.7346	25.6606
47	25.6000	76.9000	31.3000	27.0000	21.3037	73.4485	29.9670	25.8612
48	25.1000	75.1000	30.6000	26.3000	21.6572	68.3306	27.8789	24.0592
49	24.1000	72.9000	29.7000	25.8000	20.9640	70.0682	28.5878	24.6710
50	23.1000	72.2000	29.3000	25.5000	21.2945	71.2106	29.0539	25.0733
51	22.0000	73.0000	29.7000	25.6000	20.9447	71.8566	29.3175	25.3007
52	23.5000	71.2000	29.1000	25.0000	19.8837	68.5282	27.9595	24.1288

Table E4: Weekly ET_o for Ahmednagar by various Models

Week	Ahmednagar			
	FAO	**OHAG**	**MHAG**	**DHAG**
1	21.47861	76.16906	31.07698	26.81913
2	20.446	73.84408	30.12839	26.0005
3	22.73248	79.22733	32.32475	27.89594
4	23.35536	77.22034	31.5059	27.18928
5	24.69419	80.88755	33.00212	28.48051
6	26.81479	79.98746	32.63488	28.16358
7	29.17376	92.6492	37.80087	32.62178
8	29.75565	103.0495	42.04418	36.28371
9	30.4157	110.3744	45.03276	38.86283
10	31.77878	110.124	44.93058	38.77465
11	34.15835	111.2947	45.40824	39.18686
12	33.35547	117.7308	48.03415	41.453
13	35.65704	114.9618	46.90441	40.47805
14	38.24619	117.2329	47.83102	41.2777
15	37.90483	121.8168	49.70127	42.89171
16	40.18916	123.5364	50.40286	43.49717
17	41.17303	126.4106	51.57552	44.50917
18	48.00162	132.4473	54.03848	46.63468
19	43.86643	131.2333	53.5432	46.20726

Table E4 (Continued)

Week	Ahmednagar			
	FAO	OHAG	MHAG	DHAG
20	49.99707	130.4732	53.23305	45.9396
21	50.23664	125.6344	51.25882	44.23586
22	43.72419	126.995	51.81395	44.71493
23	39.16828	97.79573	39.90066	34.43388
24	35.486	93.68869	38.22498	32.98779
25	37.67774	97.06494	39.6025	34.17657
26	31.41702	99.53238	40.60921	35.04535
27	27.46834	83.11109	33.90932	29.26341
28	30.93069	87.04532	35.51449	30.64866
29	31.47879	86.34075	35.22703	30.40058
30	24.67565	75.47253	30.79279	26.57388
31	25.61442	73.79126	30.10683	25.9819
32	23.27726	66.59145	27.16931	23.44685
33	26.94386	75.47961	30.79568	26.57637
34	25.76691	87.27096	35.60655	30.7281
35	25.88929	80.2825	32.75526	28.26747
36	25.30566	69.81431	28.48424	24.58162
37	25.59594	63.76923	26.01784	22.45314
38	24.52103	69.57307	28.38581	24.49668

Table E4 (Continued)

Week	Ahmednagar			
	FAO	**OHAG**	**MHAG**	**DHAG**
39	25.17899	84.19335	34.35089	29.64448
40	25.26046	79.8077	32.56154	28.10029
41	25.38647	83.3254	33.99676	29.33887
42	25.01722	87.75698	35.80485	30.89923
43	25.51386	80.83361	32.98011	28.46151
44	23.47322	82.39656	33.6178	29.01183
45	22.81203	82.86281	33.80803	29.176
46	22.15733	78.17144	31.89395	27.52416
47	18.70196	61.67462	25.16324	21.71563
48	22.29008	76.36118	31.15536	26.88677
49	21.17795	71.03436	28.98202	25.0112
50	22.44302	76.4512	31.19209	26.91847
51	20.11684	73.33362	29.92012	25.82077
52	20.86137	73.83891	30.12628	25.99868

Table E5: Weekly ET_o for Kolhapur by various Models

Week	FAO	HAG	MHAG	DHAG	WEEK	FAO	HAG	MHAG	DHAG
1	21.7200	68.0026	27.7451	23.9437	27	23.8702	69.5073	28.3590	24.4735
2	21.6813	71.5345	29.1861	25.1873	28	24.2242	63.4792	25.8995	22.3510
3	23.1645	72.5157	29.5864	25.5328	29	21.8514	52.0300	21.2282	18.3197
4	24.7229	69.4245	28.3252	24.4444	30	20.1972	50.6850	20.6795	17.8462
5	24.3387	73.4951	29.9860	25.8776	31	22.1823	54.3455	22.1730	19.1350
6	25.2995	85.1812	34.7539	29.9923	32	20.4181	53.7042	21.9113	18.9092
7	27.0037	84.7252	34.5679	29.8317	33	22.7623	60.8059	24.8088	21.4098
8	29.7961	87.6225	35.7500	30.8519	34	22.3424	71.3422	29.1076	25.1196
9	30.5558	95.0976	38.7998	33.4839	35	23.8439	54.8259	22.3690	19.3042
10	30.6674	94.8594	38.7026	33.4000	36	23.7965	53.4171	21.7942	18.8082
11	32.5193	100.1196	40.8488	35.2521	37	25.3870	61.7995	25.2142	21.7596
12	34.7837	112.2999	45.8184	39.5408	38	25.5126	68.1211	27.7934	23.9854
13	36.2424	110.9653	45.2739	39.0709	39	24.5803	76.7702	31.3222	27.0308
14	36.2181	109.3067	44.5971	38.4869	40	25.5805	71.1017	29.0095	25.0349
15	37.4854	110.4735	45.0732	38.8977	41	25.1129	69.8045	28.4802	24.5782
16	38.1196	108.7264	44.3604	38.2826	42	26.3388	80.0164	32.6467	28.1738
17	37.2710	109.4107	44.6396	38.5235	43	26.1707	62.7534	25.6034	22.0955
18	38.4054	110.7410	45.1823	38.9919	44	24.7043	70.1482	28.6205	24.6992
19	37.3101	105.7958	43.1647	37.2507	45	23.3650	68.5388	27.9638	24.1325
20	38.7873	107.7225	43.9508	37.9291	46	22.8744	62.4983	25.4993	22.0057
21	40.6095	105.1407	42.8974	37.0200	47	18.4502	57.8220	23.5914	20.3591
22	37.0535	99.9689	40.7873	35.1990	48	21.8027	65.5914	26.7613	23.0947
23	35.3654	92.8256	37.8728	32.6839	49	22.1351	65.7761	26.8367	23.1598
24	29.9156	81.3001	33.1705	28.6258	50	21.8909	66.1782	27.0007	23.3014
25	25.5950	69.3735	28.3044	24.4264	51	22.5524	65.1895	26.5973	22.9532
26	25.5162	77.0930	31.4539	27.1444	52	20.9405	64.8995	26.4790	22.8511

Table E6: Abstract of average (Mean) and Total ET_o Estimation for Ahmednagar by various Models

		Jan.	**Feb.**	**Mar.**	**April**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**	**TOTAL**
FAO	Total (mm)	98.5	117.3	147.9	170.7	210.7	155.7	125.8	112.5	108.3	113.8	95.8	90.5	1547.6
	Daily Average (mm)	3.2	4.0	4.8	5.7	6.8	5.2	4.1	3.6	3.6	3.7	3.2	2.9	
OHAG	Total (mm)	340.6	385.6	501.2	524.7	574.6	424.5	361.3	342.3	312.5	378.9	329.8	318.8	4794.9
	Daily Average (mm)	11.0	13.3	16.2	17.5	18.5	14.2	11.7	11.0	10.4	12.2	11.0	10.3	
MHAG	Total (mm)	139.0	157.3	204.5	214.1	234.4	173.2	147.4	139.7	127.5	154.6	134.6	130.1	1956.3
	Daily Average (mm)	4.5	5.4	6.6	7.1	7.6	5.8	4.8	4.5	4.2	5.0	4.5	4.2	
DHAG	Total (mm)	119.9	135.8	176.5	184.8	202.3	149.5	127.2	120.5	110.0	133.4	116.1	112.3	1688.3
	Daily Average (mm)	3.9	4.7	5.7	6.2	6.5	5.0	4.1	3.9	3.7	4.3	3.9	3.6	

Table E7: Abstract of average (Mean) and Total ET_o Estimation for Kolhapur by various Models

		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	TOTAL
FAO	Total (mm)	101.3	114.1	147.1	159.8	171.4	126.5	100.5	97.8	106.7	113.3	97.1	96.5	1432.0
	Daily Average (mm)	3.3	3.9	4.7	5.3	5.5	4.2	3.2	3.2	3.6	3.7	3.2	3.1	
OHAG	Total (mm)	312.8	353.2	459.8	469.4	468.2	350.3	258.1	264.2	280.4	313.7	282.7	291.0	4103.8
	Daily Average (mm)	10.1	12.2	14.8	15.6	15.1	11.7	8.3	8.5	9.3	10.1	9.4	9.4	
MHAG	Total (mm)	127.6	144.1	187.6	191.5	191.0	142.9	105.3	107.8	114.4	128.0	115.3	118.7	1674.3
	Daily Average (mm)	4.1	5.0	6.1	6.4	6.2	4.8	3.4	3.5	3.8	4.1	3.8	3.8	
DHAG	Total (mm)	110.1	124.4	161.9	165.3	164.8	123.3	90.9	93.0	98.7	110.5	99.5	102.4	1444.9
	Daily Average (mm)	3.6	4.3	5.2	5.5	5.3	4.1	2.9	3.0	3.3	3.6	3.3	3.3	

BRIEF BIO-DATA

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5. Laboratory manual Author for MSBTE Mumbai (1 manual).
6. Laboratory manual Coordinator of Hydraulic (1 manual).

LIST OF PUBLICATIONS

Publications made from the work done for the thesis:

International Journals:

1. Finite Element Analysis for Seepage through Saturated and Unsaturated Soil-masses With Special Reference to the Details of Formulation of Equations Governing the Phenomenon
2. Soil Moisture Estimating Governing Models- A Review
3. Soil Moisture Estimating Governing Models Parameter Estimation- A Review

International Conferences:

1. Finite Element Analysis for seepage through Soil media

National Conferences:

1. Finite Element Analysis of seepage through Soils-Aspect of Water Management.