CHARACTERIZATION OF SOIL HYDRAULIC PROPERTIES IN THE PAVANJE RIVER BASIN KARNATAKA, INDIA

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

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DECLARATION

by the Ph.D. Research Scholar

I hereby *declare* that the Research Thesis entitled **CHARACTERIZATION OF SOIL HYDRAULIC PROPERTIES IN THE PAVANJE RIVER BASIN, KARNATAKA, INDIA** which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in **CIVIL ENGINEERING DEPARTMENT** is a *bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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CERTIFICATE

This is to *certify* that the Research Thesis entitled **CHARACTERIZATION OF SOIL HYDRAULIC PROPERTIES IN THE PAVANJE RIVER BASIN, KARNATAKA, INDIA** submitted by SHWETHA (Register Number: AM09F05) as the record of the research work carried out by her, is *accepted as the Research Thesis submission* in partial fulfillment of the requirements for the award of degree of **Doctor of Philosophy**.

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ABSTRACT

Knowledge of the soil hydraulic properties is very important to solve many soil and water management problems related to agriculture, ecology, and environmental issues. The primary objective of this study was to characterize soil hydraulic properties for the Pavanje river basin soils that lie in the coastal region of Karnataka, India. This research work was mainly focused to develop and validate point and parametric PTF models based on nonlinear regression technique using the different set of predictors such as particle size distribution, bulk density, porosity and organic matter content. Soil samples were collected and subjected to laboratory measurements to get the basic soil properties such as particle size distribution, bulk density, and organic matter content and hydraulic properties like soil water characteristics curve and saturated hydraulic conductivity. The point PTF models estimated retention points at -33, -100, -300, -500, -1000, and -1500 kPa matric potentials and parametric PTF models estimated van Genuchten and Brooks-Corey water retention parameters.

The present study also developed and validated pedotransfer functions for the estimation of saturated hydraulic conductivity. In addition to this, an empirical relationship has been derived to approximate the soil moisture retention curve from saturated hydraulic conductivity for the sampled soils. The uncertainty analysis was done for all the measured and estimated soil physical and hydraulic properties. Runoff was also predicted for the forested hillslope soils from Green and Ampt infiltration method using measured values of saturated hydraulic conductivity, residual water content, porosity and water content at field capacity values. Finally spatial variability of all physical properties and hydraulic properties were studied for both agricultural and forested hillslope soils. The study of hydraulic properties done in this work could be very helpful for any hydrological modeling for this particular area.

Keywords: nonlinear regression, matric potential, pedotransfer functions, soil water retention curve, saturated hydraulic conductivity, runoff, spatial variability, correlation

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NOMENCLATURE

Symbol	Description
θ	Volumetric soil water content
h	Soil water pressure head
$\theta(h)$	Soil water retention curve
k	Unsaturated hydraulic conductivity
k_s	Saturated hydraulic conductivity
PTF	Pedotransfer function
SWRC	Soil water retention curve
FC	Field capacity
PWP	Permanent wilting point
MLR	Multiple linear regression
ENR	Extended non linear regression
ANN	Artificial neural networks
SVMs	Support vector machines
CFN	Cascade forward network
SUR	Seemingly unrelated regression
GMDH	Group method of data handling
d_g	Geometric mean
σ_g	Geometric standard deviation
R^2	Coefficient of determination
RMSE	Root mean square error
ME	Mean error
AIC	Akaike Information Criteria
GMER	Geometric mean error ratio
GSDER	Geometric standard deviation of the error ratio

SD	Standard deviation
S	Sand contents
Si	Silt contents
C	Clay contents
BD	Bulk density
P	Porosity
OM	Organic matter content
θ_s	Saturated water content
θ_r	Residual water contents
θ_{33}	Soil water content at 33 kPa potential head
θ_{100}	Soil water content at 100 kPa potential head
θ_{300}	Soil water content at 300 kPa potential head
θ_{500}	Soil water content at 500 kPa potential head
θ_{1000}	Soil water content at 1000 kPa potential head
θ_{1500}	Soil water content at 1500 kPa potential head
α	Inverse of air entry pressure
n	Curve fitting parameter
h_b	Bubbling pressure
λ	Pore size distribution index
RETC	Retention curve program for unsaturated soils
SCS	Soil conservation service curve number
USDA	United States Department of Agriculture
PRC	Phosphorous retention capacity

CHAPTER 1

INTRODUCTION

1.1 Introduction

Soil and water are the two fundamental natural resources on which the human beings depend most. Due to uncontrolled growth in population, development of agricultural technologies, rapid industrialization etc., it is essential to understand the relationship between soil and water so that, these resources can be used in a better way. These relationships are involved in water-solute transport through soil, drainage, water uptake by plants, evapotranspiration, cropping systems, tillage management and irrigation scheduling.

Soil surface plays an important role as a boundary between atmosphere and unsaturated zone; it separates hydrologic processes (e.g. rainfall and irrigation into runoff and infiltration). The unsaturated zone, sometimes called the vadose zone or zone of aeration, plays several critical hydrologic roles. As a storage medium, it is a zone in which water is immediately available to the biosphere. As a buffer zone between the land surface and aquifers below, the unsaturated zone is a controlling agent in the transmission of contaminants and aquifer recharging water. Thus, the flow processes that occur in the unsaturated zone substantially contribute to a wide variety of hydrologic processes. Scientifically, the unsaturated zone is highly complex and must be studied with an interdisciplinary approach.

In recent years, interest in the unsaturated zone has increased because of the growing concern for the quality of subsurface environment, which is being adversely affected by the release of variety of agricultural and industrial chemicals. Intensive or uncontrolled application of water and fertilizers in order to increase agricultural production has led to serious squander of water resources and environmental problems including surface water and groundwater contamination.

But countries like India are still looking at the scientific assessment of water resources at the micro level. The per capita availability of water in our country is more than the threshold figure of 1700 m^3/year. In view of the uneven distribution of this resource, many areas of our country face water shortage, including the coastal belt of Karnataka. Though the coastal region receives plentiful rainfall, most of the areas of this region become dry and the water table falls to a very low level. Many of the ponds and rivers will dry up during summer, making normal life difficult from the month of March to May. Since the streams get dried up and the aquifer in the region is of unconfined type, wells also would dry up by April/May. With the increasing population, water supply has become inadequate, so the region faces the acute water scarcity. The reason for the shortage is not the lack of water resources but the poor management of the water table. Primary reason for the poor management of water table is due to the insufficient knowledge about the hydraulic properties of the soil formations. So for the better planning and management of water resources, the knowledge of hydraulic properties of soil is essential. In this aspect, there is a need to understand the soil hydraulic properties represented by the relationships between the volumetric soil water content (θ), the soil water pressure head (h) and the hydraulic conductivity (k).

1.2 Soil hydraulic properties

In modern agricultural, environmental and engineering practices, varying degrees of quantitative aspects about soil hydraulic properties are needed for determining the soil water holding capacity, infiltration, percolation, and runoff rates, or for quantifying the transport of pollutants in soil (Dane & Topp, 2002). Water movement within the soil profile is an important agricultural and environmental component. It helps us to solve problems related to irrigation, subsurface drainage contributions to groundwater, growth of saline seeps, and water disposal. Adequate and effective management of soil and water therefore often necessitates characterization of soil hydraulic properties of the area concerned. Soil hydraulic properties depend mainly on soil structure, soil texture, organic matter content, and bulk density (Hillel, 1998). Therefore they vary both vertically and horizontally in each plot. Thus, knowledge of soil hydraulic properties with respect to horizons is a prerequisite to understand the overall hydrological behavior of a soil profile. The most frequently used hydraulic properties are the soil water retention curve and the unsaturated hydraulic conductivity function.

Soil water retention curve is a key parameter in soil and water management practices for sustainable and improved agricultural production. It describes the relationship between soil-water potential and its volumetric water content, θ(h). This relationship is a unique function for each soil because of variation in soil particle size distribution and structure. Both these factors influence this relationship by affecting the pore size distribution and the number of given size pore in each size class (Dexter, 2004). Soil water retention curve is used to predict the soil water storage, water supply to the plants and soil aggregate stability (Collis-George and Figueroa, 1984). Soil water retention curve is important for modeling the hydrology of segments of the landscape and also for evaluating field soil water regimes in relation to the potential of soil for various uses.

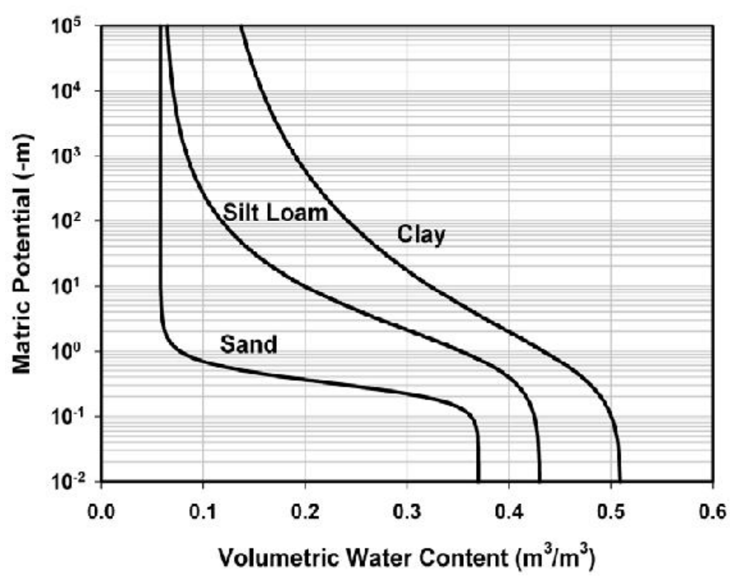


Figure 1.1: Soil water retention curves for three different types of soil textures

Hydraulic conductivity describes the ease of water flow in the soil. It is also an important soil property, especially for modeling water flow and solute transport in soil, irrigation and drainage design, groundwater modeling and other agricultural as well as engineering processes. In saturated conditions, the saturated hydraulic conductivity reflects the number of pores and their arrangement. Saturated hydraulic conductivity (k_s) represents the ease with which water flows through soil when pore spaces are completely filled with water. k_s is one of the most important parameters in controlling solute transport and hydrologic flow paths and it is a key variable in the terrestrial phase of the hydrological cycle through its partitioning of rainfall in the pedosphere, which is the interface between the atmosphere and the lithosphere. k_s is difficult to characterize because of its high variability even over short distances, and measurement methods, typically require considerable time and resources. However, accurate estimation of saturated hydraulic conductivity in soils is essential for various hydrological applications.

Knowledge of the hydraulic properties of soil is necessary in many science disciplines from agriculture to ecology. The water retention curve and hydraulic conductivity in saturated and unsaturated zones are fundamentals for irrigation and drainage modeling. Specification of the water retention curve is necessary for studying water availability for plants, plant water stress, infiltration, drainage, melioration as well as water and solutes movement in the soil (Kern, 1995). It governs the conditions of plant growth, development, yield, availability and uptake of nutrients, and toxic substances by plant root systems.

In a forested hillslope also, the water flow phenomenon is very important for water resource management and predicting slope failure caused by heavy rainfall. Forested hillslope is usually covered with forest soil, which has peculiar pore radius distribution and hydraulic properties. It has been frequently pointed out that the existence of large size pore increases the permeability of forest soil. This reduces the surface flow and increases the water infiltration into soil profiles (Kirkby, 1978; Tsukamoto, 1992).

The use of measurements from agricultural soils for the hydraulic modeling of forest soils is quite inappropriate because forest soils show distinctively different physical and hydraulic properties. They differ significantly from the arable land in their particle size distribution, bulk density, porosity, and organic matter content, and water retention parameters. Forest soils are less compacted, showing a greater aggregate stability and macro porosity and, therefore have greater saturated hydraulic conductivity and air capacity (Fisher and Binkley, 2000). There is higher field capacity in forest soils because of the higher portion of macropores and mesopores. There are only few datasets on the hydraulic properties of forest soils available in the literature. But relatively major portion of the research activities related to such measurements are restricted to agricultural land use (Mecke et al., 2000).

1.2.1 Measurement of soil hydraulic properties

Due to the importance of hydraulic properties in both agricultural and forested hillslopes, the process of measuring and estimating these properties gets prominence. Soil hydraulic properties are known to vary in space; hence to simulate realistic field conditions, a large number of samples are required. Many direct methods have been developed for its measurement in field and laboratory. However, the direct measurement of hydraulic properties in lab or field is difficult, time-consuming and expensive. Direct field measurements are associated with a high degree of uncertainty due to difficulties in calibrating monitoring equipment to heterogeneous geologic materials and due to uncertainty in the volume of the wetted region (van Genuchten et al., 1992). Although laboratory measurements typically have higher degree of measurement precision compared to in-situ analysis, direct laboratory measurement might be less pragmatic as it restricts the number of measurements.

In the wake of this, some indirect methods have been developed. Some of the popular indirect methods are pore size distribution models, inverse methods, and pedotransfer functions. Pore size distribution models are based on the distribution, connectivity, and tortuosity of pores within the porous medium and represented by the moisture retention curves. Inverse models combine a numerical solution of Richard's equation with an optimization algorithm to estimate pore size distribution model parameters from observed time series of infiltration, water content and/or pressure head. The results are non-unique although they are based on data collected from real flow conditions (van Genuchten et al., 1992). In general, indirect methods for estimating soil hydraulic properties are based on deriving the hydraulic properties from more easily, routinely, widely available, or cheaply measured properties. The cost effectiveness of obtaining soil hydraulic properties can be improved by indirect methods, which pertain to the prediction of hydraulic properties from more easily measured properties. One of such methods is pedotransfer function (PTF).

1.2.2 Estimation of soil hydraulic properties

Pedotransfer functions estimate hydraulic properties of soils based on textural and physical properties of porous medium (e.g., particle size distributions and bulk density or porosity). They translate existing surrogate data into soil hydraulic data. Bouma (1989) defined the concept with the term pedotransfer function, which he described as 'translating data we have into what we need', or predictive function of certain soil properties from other easily, routinely or cheaply measured soil properties. Pedotransfer functions allow basic information from soil surveys or geographic information systems into other more laborious and expensively determined soil properties. There are two different approaches in using pedotransfer functions for estimating soil quality indicators. The first approach is a static one, where pedotransfer functions are used to simulate soil quality indicators. The second approach, which is the dynamic one, predicts the soil properties which will be used as inputs into a process-simulation model. This model predicts effects of agricultural management scenarios on soil quality.

Pedotransfer functions can be divided into 3 types: (1) point PTFs, (2) parametric PTFs, and (3) semi physical models. Point PTFs are empirical functions that predict the water retention at a predefined potential. The most frequently estimated θ are at -10 kPa, -33 kPa (corresponding to field capacity) and at -1500 kPa (corresponding to permanent wilting point), which is commonly measured to predict available water content. The parametric

PTFs estimate the parameters of soil water retention models (Vereecken et al. 1992, Wösten et al. 1995, Schaap et al. 1998, Minasny and McBratney 2002). Two of the most commonly used water retention models are van Genuchten (1980) and Brooks and Corey (1964). Parametric PTFs are developed by estimating the parameters of a water retention model by fitting it to measured soil water retention data and then relating the parameters to basic soil properties. In a semi physical model approach, hydraulic properties are derived based on physical attributes. In water retention curve modeling, Arya and Paris (1981) translated the particle size distribution into a water retention curve by converting solid mass fractions to water content and pore size distribution into hydraulic potential by means of capillary equation.

Different methods are being used to derive the empirical relationship for PTFs. The most common method used in point PTF is multiple linear regressions. Multiple linear regressions are also used in parametric PTFs but not as widely as that of point PTFs. A drawback of parametric PTF is the inter dependency amongst the hydraulic model parameters. To overcome this problem, van den Berg et al. (1997) suggested the extended nonlinear regression approach. Another approach for fitting PTFs involves artificial neural networks (ANN) (Tamari et al., 1996).

1.3 Runoff

Soil hydraulic properties are important for understanding water balance, irrigation and transport processes. Hydraulic properties of surface soils influence the partition of rainfall and snowmelt into runoff and soil water storage, and their knowledge is essential for efficient soil and water management. Surface runoff, often used interchangeably with the term overland flow, resulting from the rainfall-runoff transformation process plays a significant part in the hydrological process.

Runoff occurs when parts of the landscape are saturated or impervious. Two runoff concepts include infiltration excess and saturation excess runoff. The infiltration excess runoff paradigm assumes that overland flow occurs when the rainfall intensity is greater than the infiltration rate at the surface soil. Infiltration excess runoff occurs less frequently (Freeze, 1972) except in disturbed or poorly vegetated areas that usually have a sub humid or semiarid climate (Wolock, 1993); clay dominated surface soils, watersheds where bedrock surfaces are exposed, and urban impervious surfaces. The second type of runoff generation occurs where the soil surface is saturated and any further rainfall, even at low intensities, contributes to stream flow. This process is termed as saturation excess runoff generation.

Runoff is a complex interaction between precipitation and landscape factors. While some of these factors (e.g., land use and cover, topography, soil characteristics, and hydrologic condition) have been defined for urban, rangeland, and agricultural drainages, runoff from mountainous, forested watersheds is poorly understood. In forests, soils typically have an enhanced infiltration capacity due to large leaf fall and decomposition rates that cover the ground in detritus and form a thick organic horizon. A thick, porous detritus and organic horizon protect the soil surface from compaction by raindrop impact and other processes, and the root biomass in the organic horizon maintains the large permeability and infiltration capacity of the surface soil (Mulungu et al., 2005). In many forests, overland flow is nonexistent, rare, or occurs infrequently.

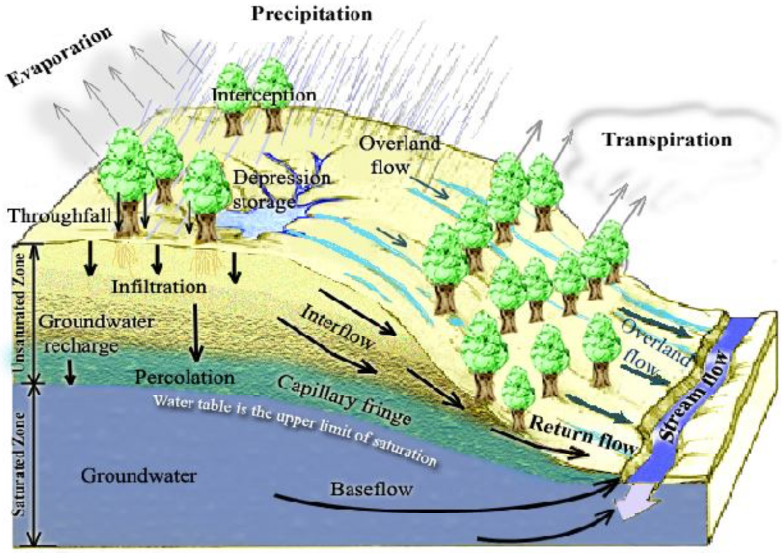


Figure 1.2: Physical processes involved in runoff generation

The prediction of both the volume and rate of runoff in a watershed from a rainfall event is vital for good design of hydraulic structures. Since the part of the rainfall that infiltrates into the soil is usually greater than the part that runs off, a good estimate of the runoff requires a good estimate of the infiltration. There are three most popular point infiltration models used in hydrology. Fundamentally, there are no advantages of one over the other. The Green-Ampt model provides a precise solution to a relatively crude approximation of infiltration in terms of a sharp wetting front. The Horton model can be justified as a solution to Richard's equation under specific (and practically limiting) assumptions. The Philip model has less limiting assumptions (than Horton) but deals a series approximation solution to Richard's equation. The Green-Ampt model is quite popular because Green-Ampt parameters based upon readily available soil texture information.

Green and Ampt (1911) developed their infiltration equation to describe how water entered the soil from a simple application of Darcy's law. During recent years, it has received wide attention as a method for predicting infiltration from rainfall events. The Green-Ampt equation is simple involving physically based parameters that can be related to other soil properties. Rawls and Brakensiek (1982, 1983, and 1985) developed the method of estimating the Green-Ampt parameters from the USDA soil survey data. This method allows the application of the Green-Ampt infiltration model to any watershed for which soil survey data exists.

1.4 Spatial variability of soil

Analysis and interpretation of spatial variability of soil properties is a keystone in site specific management. Spatial variability of soil physical properties within or across agricultural fields is inherent in nature due to geologic and pedologic soil forming factors, but some of the variability may be induced by tillage and other management practices. These factors interact with each other across spatial and temporal scales, and are further modified locally by erosion and deposition processes. Spatial variability of various soil properties are scale-dependent, especially the water transport properties of soils; therefore, it is a prerequisite to quantify the spatial variability of soils before designing site-specific applications like variable rate irrigation, seed rate, fertilizer rate, and strategies for future soil sampling.

The study of spatial variability of soil properties is a necessary and preliminary part for parametric soil, land survey (McKenzie & Austin, 1993), specific farm planning and management, hydrologic modeling, watershed management, and climate models. Soils are characterized by high degree of spatial variability due to the combined effect of physical, chemical or biological processes that operate with different intensities and at different scales. Knowledge of the spatial variability of soil properties is important in several disciplines, including agricultural field trial research and precision farming. An appropriate understanding of spatial variability of soil properties is essential for modeling at landscape scale. The most important way to gather knowledge is to prepare soil maps through spatial interpolation of point based measurements of soil properties. An effective representation of soil hydraulic properties and their spatial variability is of prime importance for hydrological studies.

1.5 Research objectives

- To characterize physical and hydraulic properties of different types of soils in Pavanje river basin located in coastal region of Karnataka, India, by laboratory methods.
- To develop and validate point and parametric PTFs for the estimation of soil water retention curves for both agricultural and forested hillslope soils in the Pavanje river basin.
- To estimate the water retention data from the saturated hydraulic conductivity for the same area.
- To characterize spatial variability of physical and hydraulic properties of soil of the same region.

1.6 Scope of the study

A very limited literature is available on an effective representation of soil water retention curve and saturated hydraulic conductivity and their spatial variability for the soils of Pavanje river basin, coastal region of Karnataka, India. Thus reliable measurements and predictions of those two hydraulic properties for these soils are essential for developing any hydrological model.

The broad scope of this study has been the characterization of soil hydraulic properties of Pavanje river basin that lies in the coastal region of Karnataka, India. The present study is the first one which characterized the soil hydraulic properties of different types of soils in agricultural and forested hillslopes of this region. Pedotransfer functions have been developed to estimate the soil water retention curve and saturated hydraulic conductivity. In addition to this, an attempt has been made to predict the soil moisture retention curve from the measured saturated hydraulic conductivity. Using soil water retention curve and saturated hydraulic conductivity, the surface runoffs in the forested hillslopes have been estimated based upon Green-Ampt infiltration method. Thesis also covers the spatial study of soil physical and hydraulic properties for both agricultural and forested hillslopes.

1.7 Structure of the thesis

The thesis comprises of seven chapters.

• **Chapter 1** gives the introduction to the topic and describes the theory relevant to soil hydraulic properties, runoff generation and spatial variability of soil. This chapter also presents the research objectives with the scope of study.

• **Chapter 2** provides a comprehensive review of relevant literature carried out on the study of hydraulic properties of soils, uncertainty, runoff and spatial variability.

• **Chapter 3** deals with the description on study area, and the experimental procedures of laboratory measurements of physical and hydraulic properties of soil.

- **Chapter 4** is concerned with the development and validation of point as well as parametric PTFs for the estimation of soil water retention curve for both agricultural and forest soils.
- **Chapter 5** focuses on the prediction of saturated hydraulic conductivity for agricultural and forest soils. The simple regression models for the development of pedotransfer functions for saturated hydraulic conductivity are described. It also includes the prediction and evaluation of soil moisture retention curve from saturated hydraulic conductivity using some evaluation criteria. This chapter also describes the surface runoff prediction using Green- Ampt infiltration model and uncertainty analysis.
- **Chapter 6** discusses the spatial variability of soil physical and hydraulic properties in two different land covers (agricultural and forest).
- **Chapter 7** of the thesis summarizes the research work with conclusions, and presents the limitations of the study and recommendations for future scope of work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Quantitative knowledge about soil hydraulic properties such as water retention and hydraulic conductivity has traditionally been an important factor for assessing the suitability of land for irrigation and rain fed agriculture, and also water balance calculations in forest soils. Furthermore, published information for soils around the world may have data on texture, bulk density and organic matter content, but the hydraulic properties data may be incomplete or missing. Adequate and effective management of soil and water therefore often necessitates characterization of water retention and hydraulic conductivity functions of the area concerned. Because of the time and expenses involved in making direct measurement of these hydraulic properties, several efforts have been made from easily and routinely measured soil physical, chemical and morphological properties. A review of literature about the research objectives are presented in this chapter.

2.2 Soil water retention curve

A soil water retention curve (SWRC) describes the amount of water retained in a soil (expressed as mass or volume water content, θ_m or θ_v) under equilibrium at a given matric potential. A SWRC is an important hydraulic property related to size and connectedness of pore spaces; hence strongly affected by soil texture and structure, and by other constituents including organic matter. At a zero pressure potential, the volumetric water content is defined as the saturated water content. The maximum pressure potential at which soil begins to desaturate (starting at saturation) is defined as the air entry value of the soil, and is determined by the largest pores in the soil. Modeling water distribution and flow in partially saturated soils requires knowledge of the SWRC, therefore plays a critical role in water management and in prediction of solute and contaminant transport in the environment. Typically, SWRC is highly nonlinear and is relatively difficult to obtain accurately. Because the matric potential extends over several orders of magnitude for the range of water contents commonly encountered in practical applications, the matric potential is often plotted on a logarithmic scale.

2.2.1 Methods of characterizing soil water retention curve

In recent decades many direct methods have been developed for measuring SWRC in the field and laboratory. However, the comparative studies of the different methods have shown that, their relative accuracy varies depending on the soil type and field conditions; no single method has been developed that performs very well in a wide range of circumstances and for all soil types. Most direct methods require restrictive initial and boundary conditions, which make measurements time consuming, range restrictive and expensive. Other investigators therefore have sought to derive soil water retention curve from the indirect methods.

Various indirect methods have been used; one of such methods is the prediction of SWRC from more easily measured soil properties, such as texture, bulk density and organic matter content, i.e. by using pedotransfer function (PTF). Wosten et al. (2001) have provided a good review of pedotransfer functions. Since PTF predicts missing characteristics from already available basic soil data, it is relatively inexpensive, easy to derive and convenient to use. The works carried out in this topic from the different parts of the world are described below.

2.2.1.1 Point regression models

Point PTFs are empirical functions that predict the water retention at a pre defined potential. The most frequently estimated θ are at -10 kPa, -33 kPa (field capacity), and at -1500 kPa (permanent wilting point) which is commonly measured to predict available water content.

Gupta and Larson (1979) developed regression equations based on percentage of sand, silt, clay, organic matter and bulk density for estimating soil moisture content at twelve soil matric potentials ranging from -4 kPa to -1500 kPa by considering laboratory measured water retention data for Eastern and Central American soils.

Rawls and Brakensiek (1982) considered data of five hundred American soils and developed three types of regression equations for predicting water retention from soil texture, organic matter, bulk density and water retention at -33 kPa and -1500 kPa for the range of -4 kPa to -1500 kPa. They found that the addition of -33 kPa and -1500 kPa soil water retention values significantly increased the accuracy of the equations.

Ahuja et al. (1989) concluded that the regression based method had too much error to characterize a spatially variable soil at a small watershed scale, when measured soil water content at two matric potentials was used with the regression method. This leads to the development of a scaling method that used a measured value of soil water content at one matric potential to generate an estimated soil water retention curve as an alternative to regression based functions.

Kern (1995) evaluated six well known PTFs for SWRC on data of twenty five thousand soil samples from United States, in which independent variables consisted of the particle size distribution, organic matter and bulk density. The results showed that values of matric potentials at -10 kPa, -33 kPa and -1500 kPa were often underestimated or overestimated.

Tamari et al. (1996) used Artificial Neural Network (ANN) to predict hydraulic conductivity at various potentials using horizon, textural class, organic matter content, bulk density and water content at a particular potential. They concluded that ANN is more efficient than multiple linear regressions. However, they also noted that ANN could only be useful if a large database with accurate measurements was available.

Koekkoek and Booltink (1999) estimated water retention at different potentials from Dutch and Scottish databases. They found that ANN technique performed somewhat better than PTFs of Gupta and Larson (1979), but the improvements were not significant either. Wösten et al. (2001) discussed the different techniques such as artificial neural networks, group methods of data handling, and classification and regression trees to develop the PTFs in addition to regression analysis. They demonstrated the actual development of PTFs by describing a practical case study. They concluded that, functional evaluation of pedotransfer functions proves to be a good tool to assess the desired accuracy of a PTF for a specific application.

Nemes et al. (2003) found that PTFs are more reliable if they include water retention data at one or more points in the water retention curve. These points should be measured at a near-saturated state to better include the impact of soil structure on the hydraulic properties. Givi et al. (2004) predicted soil water content at field capacity and permanent wilting point of some fine textured soils in the foot slope of the Zagros Mountains (Iran) using thirteen well known point PTFs. The point PTFs developed for the soils had better efficiency.

Shein and Arkhangel (2006) analyzed the potential, state of art, and outlooks of using the pedotransfer function concept in soil science. They considered the current methods of developing the pedotransfer functions and their statistical and functional testing methods. They discussed the problems related to the spatially distributed estimates of soil properties and parameters and their use in predictive modeling and soilscape assessment.

Stumpp et al. (2009) compared various PTFs in terms of their accuracy of the water retention prediction and found generally high deviations between PTF predictions and measurements for soils with high organic content. Alvaro et al. (2010) evaluated the applicability and the possibility of the transfer of eight point PTFs, in order to estimate the gravimetric soil water contents at matric potentials of -33 kPa and -1500 kPa, and their capability to describe the dependence structure of the response variable, using data from two lowland soils and geostatistical tools. They found a tendency to over-estimate at -33 kPa and under-estimate at -1500 kPa.

Jana Skalová et al. (2011) compared three regression models for determining water retention curves and evaluated the performances of the models. They used ANN and support vector machines (SVMs) for the development of PTFs for the point estimation of the soil water content for the seven pressure head values from the basic soil properties (particle size distribution, bulk density). They compared both ensemble data driven models to a multiple linear regression methodology. The MLR models perform somewhat better than the SVM models. Nevertheless, the results from both data driven models are quite close, and the results show that they provide a more precise outcome than traditional multiple linear regression.

Chakraborty et al. (2011) developed PTFs for predicting points on the moisture retention curve of Indian soils. They made an attempt to explore the possibility of developing PTFs from wide textural range of Indian soils for four points on the moisture retention curve, -33 kPa, -100 kPa, -500 kPa and -1500 kPa. Their results suggested the greater possibility of getting satisfactory prediction of hydraulic functions for various field levels by using a very limited number of easily and rapidly measurable properties. However, more number of data points need to be incorporated to tune into the functions for further improving the predictability and applicability of these PTFs in the field conditions.

Mohammad Reza Mosaddeghi & Ali Akbar Mahboubi (2011) derived point PTFs for prediction of water retention of selected soil series in a semi-arid region of western Iran. They derived the point PTFs through multiple linear regressions for the top soils and sub soils. They used particle size distribution, bulk density, organic matter, calcium carbonate and gravel contents as easily available inputs. They concluded that considering saturated water content as a predictor significantly increased the accuracy of point PTFs, especially at low matric suctions.

2.2.1.2 Parameter regression models

In parametric PTFs, $\theta(h)$ and $k(h)$ relationships are described by a closed form analytical equation, with a certain number of parameters. The most widely used equation is Brooks and Corey (1964), Campbell (1974) and van Genuchten (1980). In order to estimate such continuous functions, measured water retention and hydraulic conductivity data are fitted to these closed form analytical models and the model parameters are subsequently related to soil physical, chemical and morphological properties using regression analysis. A parametric PTFs are usually preferred as θ(h) is a continuous function here.

van Genuchten (1980) described a new and relatively simple equation for soil water retention curve which enables to derive closed form analytical expressions for the relative hydraulic conductivity when substituted in predictive conductivity models of Mualem (1976). He compared the results obtained from these closed form analytical expressions with observed hydraulic conductivity data for five soils and found that the unsaturated hydraulic conductivity was predicted well in four of five cases. Rawls et al. (1982) listed the average parameter values for the Brooks-Corey model and subsequently Rawls and Brakensiek (1985) derived the parameters as function of clay, sand and porosity for soils of United States using regression analysis.

Wösten and van Genuchten (1988) derived PTFs for the soil water retention and hydraulic conductivity equations of van Genuchten (1980) using regression analysis to relate estimated model parameters to more easily measured soil properties such as bulk density and percentages of silt, clay and organic matter. Vereecken et al. (1989) derived multiple linear regressions with sand, clay content, organic carbon content and bulk density data. They used an undisturbed sample of one eighty two horizons of forty two Belgian soil types to solve parameters of van Genuchten model for the soil water retention function and Gardner (1958) model for the hydraulic conductivity function.

Pachepsky et al. (1996) used ANN to estimate water content at eight water potentials and also van Genuchten parameters from particle size distribution and bulk density of two thirty soil data. They found that for point estimation PTFs, ANN was better than the regression method, but for parametric PTFs, the performance of both approaches was almost identical.

Lakshman Nandagiri and Prasad (1997) have tested six popular texture based regression models on three soils. They used neutron probe for measuring moisture content and tensiometers for matric potential in the field, and pressure plate apparatus for laboratory measurement of soil water retention curve. They compared the soil water retention curves generated from ex-situ and in-situ retention data statistically with moisture characteristics generated by the regression models. They concluded that regression models developed from ex-situ data were better estimators of the ex-situ soil water retention curve and the one developed from in-situ was the best estimator of the in-situ soil water retention curve.

Scheinost et al. (1997) developed a PTF that is particularly designed for a highly variable landscape. Their functions were based on eighty seven undisturbed soil samples collected in northern Germany and properties such as particle size distribution, organic carbon content and porosity. They predicted van Genuchten parameters by multiple linear regression equations, and related that parameters to the geometric mean particle diameter and its standard deviation, by making an attempt to include some physical meaning to the PTF.

Budiman Minasny et al. (1999) compared three different approaches such as multiple linear regression (MLR), extended non linear regression (ENR) and artificial neural networks (ANN) to develop point and parametric pedotransfer functions for water retention curves. They concluded that MLR performed better for point estimation compared to ANN, and ENR was most adequate for parametric PTFs.

Javier Tomasella et al. (2000) developed pedotransfer functions for estimation of soil water retention curve in Brazilian soils. They derived PTFs to predict the water retention parameters of the van Genuchten model parameters using multiple regressions. The water retention curves were better predicted by developed PTFs than by two temperate PTFs tested. The developed PTFs performed better even when the comparison was restricted to the range of textural validity of the temperate PTFs.

Tomasella et al. (2003) compared parametric and point based approaches to develop PTFs for water retention using a comprehensive database of Brazilian soils using the group method of data handling (GMDH). They concluded that regression based GMDH method of point method was superior to the parametric method of PTF development of Brazilian soils. They suggested that further comparisons were necessary to determine whether this conclusion holds for soil from regions with temperate climate.

Kalman Rajkai et al. (2004) estimated the water retention curve from soil properties and compared with linear, nonlinear and concomitant variable methods. They found that efficiency of the databases was increased by using the second nonlinear optimization approach. To increase the efficiency, they used a measured retention data point as an additional (concomitant) variable in the PTFs. They concluded that the nonlinear adjustment of the concomitant variable PTF, using a retention data point as concomitant variable produced the best PTF.

Børgesen and Schaap (2005) developed a point and a parametric model using neural networks and Bootsrap method for a large database of Danish soils. The point PTF models estimated retention points at -1, -10, -100 and -1500 kPa pressure heads and the parametric PTF models estimated the van Genuchten retention parameters. They evaluated the data with the root mean square residuals and the Akaike Information Criterion, both obtained from measured and predicted water contents at the four retention points. They concluded that adding organic matter and bulk density as the input parameters of neural networks could improve the estimation of soil water retention curve, and also they found that, the uncertainty in the prediction of water content using both the point and parametric PTFs increased with increasing clay content.

Carles Rubio (2008) aimed to evaluate the site-specific pedotransfer functions constructed for van Genuchten parameters, under two different vegetation covers (grassland and forest). He then compared the results with the results obtained for the same soils using Rosetta model software package. He found that the site-specific PTFs predicted the van Genuchten parameters better than Rosetta model.

Ghorbani Dashtaki et al. (2010) investigated the possibility of using geometric mean (d_g) and geometric standard deviation (σ_g) of particle diameters instead of soil particle size distribution to derive some PTFs. They concluded that d_g and σ_g can better predict the water contents at drier parts of the retention curve than the soil bulk density. This could be attributed to the fact that at near saturation the water content is mainly affected by total soil porosity, while at lower water contents the soil moisture is more influenced by geometric pore size distribution.

Merdun (2010) compared the performance of Cascade Forward Network (CFN), Multiple Linear Regression (MLR) and Seemingly Unrelated Regression (SUR) methods for the prediction capabilities of point and parametric PTFs. They found that the differences among three methods in prediction accuracies were not statistically significant, but overall MLR and SUR were somewhat better than CFN in prediction of the point PTFs, whereas CFN performed better than the other two methods in prediction of the parametric PTFs.

2.2.1.3 Semi physical models

These models are so called because although they use the shape similarities between pore size and particle size distributions, they also require empirical parameters. This approach is based on the similarity between cumulative particle size distribution and water retention curves. The water contents are derived from the soils predicted pore volume and the hydraulic potentials are derived from capillarity relationships. Semi physical models are usually complex, sometimes difficult to parameterize and may fail to predict an acceptable soil water retention characteristic to their inherent assumptions.

Arya and Paris (1981) translated the particle size distribution into a water retention curve by converting solid mass fractions to water content and pore size distribution into hydraulic potential by means of capillary equation. The main obstacle is the need to predict a parameter that characterizes the packing of the soil particles.

Wu et al. (1990) while analyzing laboratory retention data of American soils found that the soil aggregation had a significant effect on pore size distribution and water retention.

This effect was omitted in all previous models of estimating water retention from pore size distribution.

2.2.2. Statistical and functional validation

The main objective of developing PTFs is to predict soil properties that are difficult to measure. How well PTFs predict certain soil properties can be evaluated by comparing the observed or measured data with the predicted one. The predictability of the PTFs is usually evaluated on a set of data not used in generating the PTFs (usually called the validation set). There are several statistical measures that are used to assess the performance or predictability of the PTFs.

Tietje and Tapkenhinrichs (1993) proposed the use of mean deviations (MD) and root mean squared deviations (RMSD) as a measure of how well the PTFs fit to the retention curve. It is the sum of the area difference between the observed and predicted water retention curves. Imam et al. (1999) distinguished two main categories of goodness of fit measures i.e. the residual based and the statistical association based approaches. Residual based approaches provided quantitative estimates of the deviation of PTFs predictions from measured data. The indicators used were mean error (ME), mean absolute error (MAE), sum of squared error (SSE) and root mean squared error (RMSE).

Vereecken et al. (1990) termed functional validation, i.e. the evaluation of the performance of PTFs at the context of specific applications. Thus validation depends on the final application of interests. Statistical validation only assesses how well the PTFs describe the data. As the main or final objective of generating PTFs is to serve as input for simulation models, the validation should be evaluated in the final application.

Wösten et al. (1990) evaluated four different methods to generate soil hydraulic properties in characterizing soil water profile. The methods used in generating the soil hydraulic properties were direct on site measurement, hydraulic properties averaged on a regional scale, hydraulic properties averaged on a national scale and use of van Genuchten parameters correlated with soil texture and organic matter content on three sandy soils.

They concluded that direct on site measurement gave better results followed by continuous PTFs and averaged regional and national functions, but the cost involved was very high when compared to other three methods.

Vereecken et al. (1992) performed functional validation of hydraulic PTFs to evaluate land qualities in Belgium. Using soil plant water simulation, the parameters evaluated were moisture supply capacity (ratio of the actual to the potential rate of transpiration) and drain ability (cumulative amount of drainage from the soil profile). The effect of uncertainty of the input variables of the PTFs (e.g. bulk density or clay content) on the error of the estimated variables was evaluated by means of Monte Carlo simulation.

Espino et al. (1995) evaluated the performance of water retention and hydraulic conductivity PTFs to predict soil water contents, pressure heads and drainage fluxes for a layered profile. Simulations using PTFs as inputs over-predicted the actual moisture content throughout the soil profile, but predicted pressure heads near the soil surface were quite well. The drainage fluxes were four times higher when compared to the values calculated using measured hydraulic properties.

2.3 Saturated hydraulic conductivity

Accurate estimation of saturated hydraulic conductivity (k_s) in soils is required for various hydrological applications. Saturated hydraulic conductivity is difficult to characterize because of its high variability even over shorter distances, and measurement methods typically require considerable time and resources. Consequently, researchers often use a limited number of measurements for characterizing saturated hydraulic conductivity or use various soil properties for indirect estimation via pedotransfer functions.

Schaap et al. (1998) used neural network PTFs to predict soil water retention curve, saturated and unsaturated hydraulic properties from limited or more extended sets of soil properties. They distinguished four levels of input variables: (i) sand, silt and clay (SSC), (ii) SSC with the addition of bulk density (SSCBD), (iii) SSCBD with one measured retention point at 33 kPa (SSCBDθ_{33}) and (iv) SSCBD with retention points at 10 kPa and 33 kpa (SSCBD$\theta_{10}\theta_{33}$).

Binayak et al. (2000) measured saturated hydraulic conductivity (k_s) and soil water retention functions at 15 cm and 30 cm depths across a glacial till landscape in central Iowa that encompassed two soil types. Exploratory and geostatistical data analyses were performed to study the spatial variability of the measured (k_s, θ_{33} and θ_{1500}) or optimized (θ_s, θ_r, α, and n) hydraulic parameters. Results indicated that most of these parameters were significantly different across the soil-slope transition except θ_{33} and θ_{1500}. They suggested that a uniform texture (loam) and a pore size distribution developed by long term (no tillage) agricultural practices in the field are important controlling factors for the spatial variability of different hydraulic parameters.

van Alphen et al. (2001) combined pedotransfer functions with physical measurements to improve the estimation of soil hydraulic properties. They applied four methods like laboratory measurements, class PTFs, continuous PTFs and continuous PTFs combined with simple laboratory measurements to derive hydraulic properties by analyzing their effect on simulated soil moisture contents. They concluded that the combination of continuous PTFs and simple laboratory measurements method could clearly produce better results.

Zhuang et al. (2001) predicted unsaturated hydraulic conductivity of soil based on some basic soil properties. The authors combined the non similar media concept (NSMC) with the one- parameter model of Brooks and Corey, for estimating unsaturated hydraulic conductivity of soils. They used soil bulk density, particle size distribution, soil water retention characteristic and saturated hydraulic conductivity of soil as inputs to the new model. Their results indicated that the NSMC based model accurately predicted the unsaturated hydraulic conductivity better as compared to four one-parameter models and van Genuchten-Mualem model.

Ferrer Julia et al. (2004) constructed a saturated hydraulic conductivity map of Spain using PTFs and spatial prediction. They proposed an estimation of PTFs for a great variety of climatic and physiographic conditions, with a predominance of soils developed under semi-arid conditions. The results obtained, in spite of the variety of measuring methods of the variables used show that it is possible to estimate saturated hydraulic conductivity values for soils from sand content data. These are compared with results obtained by other researchers. Batjes, inverse distance weight and kriging interpolation methods were used to construct the saturated hydraulic conductivity map. The resulting map showed a good spatial fit after being compared with lithological distribution, which confirms the applicability of the method for future hydrological applications.

Do-Hun Lee (2005) evaluated the saturated and unsaturated hydraulic conductivity values by the inverse parameter estimation and PTF method. The inverse parameter estimation method combines numerical simulation of Richard’s equation with Levenberg-Marquardt nonlinear minimization method based on the in-situ measured tension infiltration data. This approach estimates soil hydraulic conductivity parameters indirectly based on the input variables such as soil textures, bulk density, and saturated water content. They used root mean squared error (RMSE) and mean absolute error (MAE) to compare soil hydraulic conductivity values between numerical inverse solution and PTF. The comparison of various PTFs indicated that PTF of Wösten et al. (1999) combined with the PTF of Cosby et al. (1984) was the best predictor for saturated hydraulic conductivity compared to the inverse solution. For unsaturated hydraulic conductivity, the PTF of Schaap (1999), showed the significant prediction.

Hasan Merdun et al. (2006) compared the ANN and regression PTFs, for prediction of soil water retention and saturated hydraulic conductivities using some evaluation criteria. They found that the differences among the two methods were not statistically significant, but regression predicted point and parametric variables of soil hydraulic properties better than ANN. Even though regression performs significantly better than ANN in their case, they concluded that ANN produces promising results and its advantages can be used by developing new algorithms in future studies. Pandey et al. (2006) compared the saturated hydraulic conductivity estimated by the four models namely multiple linear regression, Rosetta program, effective porosity model and relative effective porosity model with the laboratory measured saturated hydraulic conductivity for alluvial soils. They analyzed statistically and concluded that the relative effective porosity model gives reasonable estimate of saturated hydraulic conductivity.

Manyame et al. (2007) modeled hydraulic properties of sandy soils of Niger using pedotransfer functions. They tested the ability of three PTFs, (Campbell, van Genuchten and Vauclin) to determine soil water retention and unsaturated hydraulic conductivity (k) for sandy soils at two villages in Niger. Their results showed that the Campbell model was a cheaper alternative to direct measurement of moisture retention curve and the van Genuchten function was preferable to estimate k for Niger's sandy soils with modest accuracy. Li. Y et al. (2007) developed PTFs for soil water retention curve and saturated hydraulic conductivity of seven soil profiles in Fengqiu country in the north China. Then they compared the performance of the derived PTFs with that of several existing PTFs and concluded that the derived PTFs appear superior in predicting the soil hydraulic parameters compared to existing PTFs. This confirms the limitation of applying PTFs developed from one region to other regions.

Wahren et al. (2009) observed increased field capacities in forest soils than agricultural soils. They explained this by higher portion of macropores and mesopores in forest soils. They also found that the hydraulic conductivity at saturation and field capacity in forest sites were up to four times higher than those of the cropland site. Xi Chen et al. (2009) studied the impact of land use and land cover changes on soil moisture and hydraulic conductivity along the karst hillslopes of southwest China. They found a trend of decreasing hydraulic conductivity and increasing soil moisture with increasing soil depth. They claimed their study was very important for environmental protection and particularly for rehabilitation of vegetation in the mountainous areas.

Heike Puhlmann and Klaus von Wilpert (2012) developed PTFs for water retention and unsaturated hydraulic conductivity of forest soils. They concluded that the predictive accuracy of the established PTFs, both for the water retention curve and the hydraulic conductivity curve, was in the range of (and in some cases better than) other existing PTFs that were mostly derived for agricultural soils.

2.4 Uncertainty analysis

Direct measurements of hydraulic properties consist of both the true value and measurement error contributed by factors, which cannot be completely avoided. Imprecision and bias in the measuring device or human errors, such as misread values and transcription errors, may occur. In order to determine the relevance of laboratory data, the degree of measurement error should be identified and included in the data, typically in the form of the standard deviation from the mean value (Mandel, 1964).

Minasny et al (1999) analyzed the uncertainty in water retention predictions with Monte Carlo simulations and compared the effect that the input variables exerted on the uncertainty in the PTF model parameters. They showed that the uncertainty in the parameters was small when compared to the uncertainty due to error in the input variables and this error affects PTF predictions most significantly.

Christiaens and Feyen (2001) used a Latin hypercube sampling strategy to evaluate how the uncertainties in the predicted soil hydraulic properties propagate into the output of a distributed hydrological model applied to a one km^2 catchment area. Minasny and McBratney (2002) evaluated how measurement errors of the PTF input variables affect the uncertainty in PTF predictions and the soil water budget modeling. They concluded that small uncertainties in the input data could produce large uncertainty in the PTF predictions.

Hailin Denget al. (2009) quantified uncertainty in PTF based parameter estimation for unsaturated flow modeling. These results suggest that additional sample acquisition for the PTF input variables would have a more favorable impact on reduction of the parameter estimation uncertainty than collecting additional soil hydraulic parameter measurements for PTF development. Chirico et al. (2010) presented a methodology to assess uncertainties resulting from the use of PTFs when soil water budget is modeled at a hill slope scale. Two sources of uncertainty were examined. The examined PTFs showed worst level of performance with respect to the simulated evaporation. The simulated evaporation was much more affected by the PTF model error than by the input data error.

Venkatesh et al. (2011) analyzed the observed soil moisture patterns under different land covers in Western Ghats, India. They quantified the uncertainty in inferred volumetric soil moisture contents derived from matric potentials obtained from laboratory measurements. They calculated the mean moisture content and the standard deviations for ten samples for each pressure heads and found that the standard deviations were reasonably low and also consistent between the three land covers. Then optimal parameters of the fitted van Genucthen model were analyzed by R^2 and RMSE values. These error statistics were the indicative of the uncertainties introduced into inferred moisture contents on account of the model used. They found that values of RMSE in almost all cases were quite low thereby indicating that the uncertainties due to use of the model were small.

2.5 Runoff estimation

Understanding the basic relationships between rainfall, runoff and soil loss are vital for effective management and utilization of water resources and soil conservation planning. The surface runoff process is among the most extensively studied in the hydrological system, leading to great progress in the understanding of the processes governing the transformation of rainfall to runoff. Hydraulic properties of surface soils influence the partition of rainfall and snowmelt into runoff and soil water storage, and their knowledge is essential for efficient soil and water management. Substantial progress has been made in understanding the surface runoff process and its impact on the global water cycle in some parts of the world. There has been a great interest in the modeling of the infiltration process, because this process is the major factor in estimating the volume of direct runoff.

Green and Ampt (1911) developed the first physically based model. This model employed a simple equation for describing and calculating infiltration. Green and Ampt arrived at their simplified theory of infiltration by considering the wetting front as a precipitous border between wetted and nonwetted soils. They developed their infiltration equation to describe how water entered the soil from a simple application of Darcy's law.

Brakensiek et al. (1981) estimated and examined for normality the parameters of Green-Ampt and Brooks-Corey equations for ten soil classes scaling from sand to clay. The investigation proved the good fit of the Brooks-Corey equation to the soil characteristics data for capillary pressure less than bubbling pressure. Mean values and standard deviation of Green-Ampt parameters were obtained for each soil class. Rawls et al. (1983) also used the Brooks-Corey equation to calculate Green-Ampt parameters. They analyzed approximately one thousand two hundred soils covering thirty four states and employed all available soil survey information. The best result in the distinction of the Green-Ampt parameters was obtained for soil classification according to the soil texture classes.

Rawls and Brakensiek (1986) made a comparison between Green-Ampt and SCS curve number for runoff volume predictions. They used data from three thirty runoff events producing runoff more than 0.05 inches for watersheds of an area less than ten acres covering a range of soils from sandy loam to clay. The result of the investigation showed that Green-Ampt infiltration procedure provided the better predictions for higher volumes of runoff (more than one inch).

Stone et al. (1994) derived their approximation based on two first terms in Taylor-series expansion. They found that the approximation could be used for any event of constant rainfall and variable time to ponding. The investigation of approximation showed a good result (3.5%) in terms of maximum error, and a better fit to the Green-Ampt infiltration depth compared to the quadratic approximation. Euliss and Mushet (1996) revealed that surface runoff as a result of precipitation was larger from cultivated catchments than that from grasslands. He found that general climatic regime controls the total volume of runoff in any region through its effect on the water balance.

Lidén and Harlin (2000) concluded that surface runoff in the form of long-term water availability and extreme flows were also very important in designing hydraulic structures in civil engineering works. Swartzendruber (2000) investigated the effect of the initial ponding time, hydraulic conductivity coefficient, and interaction of the infiltration model (G-A) and binomial infiltration equation. He introduced the suitable resolving method for binomial infiltration equation using the (G-A) model.

Serrano (2001) presented another method for resolving infiltration equation (G-A) and estimated it using a series of mathematical equations and used it for calculation of the cumulative infiltration depth and the infiltration rate. He also made a comparison between this accurate solving method and the Lambert method. Hsu et al (2002) evaluated the three models of infiltration and their agreement with the Richard infiltration equation. They compared Philip, Green-Ampt, and Horton models with each other for several types of soil, and calculated the model parameters for these three models. Among three models, the (G-A) model parameters were in more consistency with the numerical results, which is due to considering the ponding state of the model when the rainfall intensity was greater than the hydraulic conductivity coefficient.

Chuan (2003) found that overland flow was lower in natural forests than in disturbed landscapes due to influence of agricultural practices. Hence, runoff was much higher in agricultural fields than under forests. This implies higher risk of erosion in the agricultural fields. Bruijnzeel (2004) assessed the influence of forest cover change on hydrological functions in Southeast Asia. Disturbance of forest had less effect on overland flows such as runoff than complete conversion of forests to other land uses like grasslands. He further found that surface runoff and erosion declines under well-developed forest cover but increases with clearing of forests. Overland flows and hence catchment sediment yield were found increasing with disturbance and conversion of forests to other land uses in Southeast Asia.

Chu and Marino (2005) proposed an algorithm for determining the ponding condition, simulating infiltration into a layered soil profile of arbitrary initial water distributions under unsteady rainfall, and partitioning the rainfall input into infiltration and surface runoff. Comparisons of the developed model with other infiltration models (both modified Green–Ampt infiltration model and fully numerical model) and field measurements were conducted, and good agreements were achieved.

Chen and Yang (2006) explained the direct physical effects of slope angle on infiltration and runoff generation by extending the Green-Ampt equation onto sloping surfaces. They concluded that occurrence of non vertical rainfall could increase runoff with increasing slope angle when rainfall deflects a large angle to upslope. Marc and Robinson (2007) stated that evaporation in forest lands was significantly different from that in grassland fields. This in turn showed differences in water balance between catchments dominated by forest and grasslands. Accordingly, stream flow and runoff were found higher in grasslands than under forest lands.

Cao et al. (2008) used, SWAT (Soil and Water Assessment Tool) to model impact of land use or land cover change on water resources. Total water yield, quick flow and base flow were found affected by changing land uses resulting in change of overall water balance. He concluded that the hydrological cycle of catchments changed due to the modifying effect of land use change on rainfall, evapotranspiration and runoff. Hong et al. (2009) found that ecological disturbance due to change in land use has a considerable effect on hydrological components such as base flow and surface runoff. According to them, runoff and base flow were sensitive to change in forest cover in such a way that decreasing area of forest cover in a certain watershed increases runoff while it decreases the amount of base flow.

2.6 Spatial variability of soil hydraulic properties

Spatial variability of soil hydraulic properties causes considerable variations in water and solute flow and transport processes. It remains a difficult task to determine and describe the spatial pattern of soil physical properties for modeling landscape-scale vadose zone processes. Strategies that involve measurements of relevant variables and appropriate spatial modeling tools need to be identified for this purpose. Simulation of soil-water systems is not limited to a single point; usually simulations over space are required. Modeling hydrological processes on a regional scale not only requires hydraulic properties characterization but also the description of spatial variability.

Shouse et al. (1995) studied the spatial variability of soil water retention functions in a silty loam soil. Using Akaike Information Criterion they found that scaling theory could adequately represent the spatial variation in water retention with only a limited number of parameters.

Nunzio Romano and Alessandro Santini (1997) studied the effectiveness of using PTFs to quantify the spatial variability of soil water retention characteristics. They evaluated some PTFs from the literature in the light of their ability to quantify the spatial structure and variability of soil water retention adequately. They tested four PTFs, two provided only values of water content at specific pressure potentials, whereas the remaining two estimated the parameters of closed-form relations describing the water retention function. Overall, the sample distributions of the PTF estimated retention characteristics at selected pressure potentials were close to those of the retention variables used as reference for comparisons.

Hendrayanto et al. (1999) studied spatial variability of soil hydraulic properties in a forested hillslope. They have taken the soil samples from six sites distributed from crest to the footslope. Soil hydraulic properties showed a considerable spatial variation at the forest hillslope in a headwater catchment of the Sumiyoshi river basin.

Wçsten et al. (2001) stated that landscape position may account for a substantial part of the variation in the soil hydraulic characteristics since soils and also the associated soil properties vary with landscape position. Pachepsky et al (2001) evaluated variability of texture and water retention of soils for a gently sloping 3.7 ha field. They studied the variability of water retention across the hillslope, and determined the correlations of soil water retention with soil texture and surface topography. They constructed a 30 m digital elevation model (DEM) from aerial photography data. Regressions with spatially correlated errors were used to relate water retention and texture to computed topographic variables. Sand, silt, and clay contents depended on slope and curvatures. The regression model relating water retention to the topographic variables explained more than 60% of variation in soil water content at -10 kPa and -33 kPa, and only 20% of variation at -100 kPa.

Yang Qiu et al. (2001) studied soil moisture variation in relation to topography and land use in a hillslope catchment of the Loess Plateau, China. They characterized the profile types as well as additional profile features of soil moisture content and the relationships between each of these profile features, to understand the relative importance of land use and topography on profile features of soil moisture. They used correlation analysis, to analyze soil moisture data and spatial variation of soil moisture content across landscape. They concluded that, spatial variability of soil moisture across landscape varies with both soil depths and temporal evolution.

Sobieraj et al. (2002) investigated the spatial variability of saturated hydraulic conductivity along a tropical rainforest catena. They measured k_s along transect at depths of 20 cm, 30 cm, 50 cm and 90 cm with a compact, constant head permeameter. Ordinary and robust linear regression models with distance from the interfluves as in the independent variable showed no significant change in k_s as a function of topography. Semivariograms showed no apparent spatial structure in k_s at distances greater than 25 m for all depths. They concluded that the strong topography dependence of soil types along this catena and hence primary soil attributes is not reflected in a similar dependence of k_s, and tentatively attribute this lack of dependence to the overriding influence of bioturbation-controlled macroporosity.

Javed Iqbal et al. (2005) analyzed spatial variability of physical properties of alluvial soils. Their research work was to determine the degree of spatial variability of soil physical properties and variance structure, and to model the sampling interval of alluvial floodplain soils. They used Autocorrelation and Moran's *I* statistics to investigate the adequate sampling interval for various soil physical properties. All the correlograms showed positive spatial autocorrelation without any cyclicity. The Moran's *I* values indicated that sampling at spacing closer than 400 m for soil texture and less than 100 m for soil hydraulic properties and bulk density, would be needed for designing soil sampling in the floodplain of Mississippi Delta.

Gupta et al. (2006) analyzed spatial variability of hydraulic conductivity at field scale. They determined hydraulic conductivity by double ring infiltrometer and Guelph permeameter along and across the slope of a field and analyzed using conventional statistical techniques and geostatistical techniques such as auto-correlation, variogram, and kriging. The results confirmed that geo-statistical techniques better describe spatial variability of hydraulic conductivity than conventional statistical techniques. The hydraulic conductivity showed more spatial variability along the field slope than across the field slope. The results indicated that, kriging method produced a convenient smooth hydraulic conductivity surface, which may be helpful in the quantification of dominant runoff generation mechanisms and identification of runoff generation areas.

Zuoxin Liu et al. (2007) applied PTFs to simulate spatial heterogeneity of cinnamon soil water retention characteristics in Western Liaoning Province. They measured soil water retention characteristics by pressure plate apparatus and fitted them to van Genuchten equation. Three types of PTFs were estimated using linear regression (MLR3) and nonlinear regression (ENR3) based on three textural classifications, and using linear regression (MLR7) based on seven textural classifications. Then they compared the fitted PTFs with that of estimated ones and concluded that, the parameters from MLR7 and ENR3 were closer to fitted values than ones from MLR3. Great autocorrelation range and proportion of structural variance showed linear regression (MLR3) could express suitably the spatial heterogeneity.

Priyabrata Santra and Bhabani Sankar Das (2008) derived pedotransfer functions for soil hydraulic properties of the hilly watershed of Eastern India. They found that PTFs may be developed from a limited number of soil samples, because there is sufficient variability in soil properties. They concluded that soils collected from hilly watersheds might possess variability and also a small area of a watershed was also convenient to collect large number of soil samples needed to develop PTFs. Priyabrata Santra et al. (2008) explored the possibility of fitting semivariogram models from irregularly sampled soil properties of an agricultural farm extending two forty three ha in area. They examined the difference in spatial variation of basic soil properties for two soil depths and prepared the spatial maps for those basic soil properties at two depths using ordinary kriging method. Finally, they concluded that, the respective maps of basic soil properties prepared could be used to generate maps of soil hydraulic parameters through linkage with suitable PTFs.

Aimrun and Amin (2009) developed PTFs for saturated hydraulic conductivity of lowland paddy soils. They attempted to seek a simplified method for determining k_s values based on common existing soil properties through PTF technique. They analyzed the samples for the properties of dry bulk density, soil particle percentage (Sand, Silt, and Clay), organic matter content and geometric mean diameter. The falling head method was used to measure k_s. Stepwise regression analysis was applied to determine the best fit model based on R^2 and significant level. The results of the study showed that there was a high spatial variability of the saturated hydraulic conductivity in the paddy area. They concluded that model inputs introduced by stepwise regression were commonly available; therefore this model was useful to replace the conventional method.

Venkatesh et al. (2011) analyzed the observed soil moisture patterns under different land covers in Western Ghats, India and also studied the spatio-temporal variability of soil water potential and soil moisture content under different land covers in the humid tropical Western Ghats region. They evaluated the relationships between soil moisture at different depths using correlation analysis.

One can find some more papers on this topic available in the literature, the descriptions of each and every one is not possible in the context of the relevance of the work involved in this thesis.

2.7. Gaps in the existing work

It is not always possible to present unique PTFs for all soils because these relationships depend on the region and mostly site-specific. The physical, chemical and m0rphological properties of soils from one region are significantly different from other region. In India also there is much variability in the properties of soil. Hence there is a need for carrying out studies, which are inter disciplinary in nature. In view of the above, the present study is to make use of the more easily measurable data on Indian soils and to relate these to the soil hydraulic properties by using pedotransfer functions. This information is needed for improving understanding of the effects of soil management or land use on soil profile hydrology.

A review of the literature cited in the previous sections reflects the importance of characterization of soil hydraulic properties. Most of the researchers have used PTFs as an indirect method to estimate the soil hydraulic properties. As mentioned earlier, very limited literature is available on the hydraulic properties of soils of coastal region of Karnataka. In particular, a critical study on hydraulic properties of soils of Pavanje river basin lying in the above region is not found in the literature. This is the gap where the thesis has been mainly focused on.

CHAPTER 3

LABORATORY CHARACTERIZATION OF SOIL PHYSICAL AND HYDRAULIC PROPERTIES

3.1 Introduction

As discussed in the chapter 1, the characterization of soil physical and hydraulic properties is important for all types of hydrological process. Particularly, the knowledge of soil hydraulic properties is essential for proper understanding and evaluation of the physical and chemical processes involved in flow of water and transport of dissolved salts and pollutants through soil systems (Al-Jabri et al., 2002), which may be related to many agronomic, engineering, and environmental fields of research. In the present study, laboratory investigations have been carried out to determine the basic soil properties, mainly the particle size distribution, bulk density, porosity and organic matter content. The key soil hydraulic properties are the soil moisture retention and saturated hydraulic conductivity of soils collected from various locations in Pavanje river basin in Karnataka, India.

3.2 Study area

The Pavanje river basin in the Dakshina Kannada district of coastal Karnataka, India was chosen for collecting soil samples. Dakshina Kannada district is situated in the south western part of the state and spreads between the Sahyadri mountain range (Western Ghats) and the Arabian Sea. It originates in the foothills of the Western Ghats and flows westwards to join the Arabian Sea. It lies between north latitudes 12°57’30’’ to 13°07’30’’ and east longitudes 74°45’00’’ to 75°02’30’’. The total geographical area of the district is 4843 sq.km. It is parallel to the coast. This stretch of coastal lowland is flat and covered with beach sand. The other side is the highland of the Western Ghats with its thick vegetation. This also runs almost parallel to the coast. Between these areas lies the midland, made up of laterite ridges and sporadic rounded hills surrounded by topographic lows with rivers, rivulets, creeks and fertile cultivable land. The important rivers of the district are Netravathi, Kumaradhara, Gurupura, Pavanje, Gowrihole, Gangolli, Kalluhole, Payaswini and Nandini. The catchment area is 202 km^2.

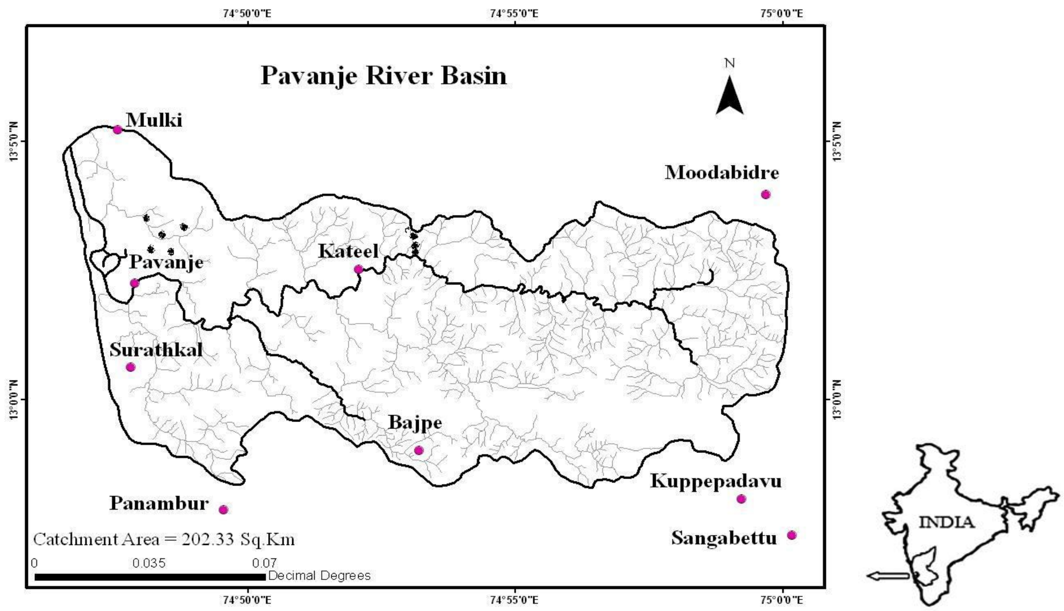


Figure 3.1 Location of study area of Pavanje river basin in coastal region of Karnataka, India

3.2.1 Geological perspective

The main rock types noticed in the basin are laterite, granite gneiss with occasional intrusions of dolerites. The basement rocks of Dakshina Kannada district are granitic gneisses of the Archaean age, one of the oldest rocks of peninsular India. These basement rocks are overlaid by ferruginous laterites. The ferruginous laterites cover vast areas of the district with 35-40%. These ferruginous laterites develop a hard crust of dark gray or black up to a depth of 15-20 cm. Below the hard crust, the laterites have red or brown mottled appearance and the cavities are filled with yellow or white clay. Ferruginous laterites occur mainly in the mid land region. Laterites cover a large area of Pavanje river basin. The thickness of laterites varies from 3 cm to 20 cm. Laterites are the cheapest building materials in this coast. Another type of laterite viz., aluminous laterites are found in the northern part of the district. They are not used for extraction of aluminium. Laterites are often associated with clay. It is normally found in valley regions. Fine clay is available in small quantities. The river basin under the present study is also found to consist of highly lateritic mounds under laid by a thin bed of clay, granites and gneisses. The basin also consists of coastal alluvium in the coastal belt.

3.2.2 Soil structural perspective

The soils of this basin mainly consist of coastal alluvium and lateritic soils. Coastal alluvium is relatively less and formed due to the marine and river activities. It consists of river sand, fine clay and silt. Lateritic soils are formed on the crust of the lateritic hills, and are yellowish red to dark red, or reddish brown to brown in color. In texture, they vary from clay loam to gravelly sandy loam in the surface horizon, and clay loam to gravelly sandy clay or clay in the subsurface horizon. The soils of the region can be grouped into the following categories. (i) Lateritic soil (ii) Sandy clay (iii) Sandy loam (iv) Sandy soil (v) Clay soil.

3.2.3 Climatological perspective

The study area has a hot humid climate. Differences in climate can be observed between the coastal and other regions. The coastal belt has almost the same weather throughout the year, whereas extremes are noticed towards the Ghats section. The climate of the region is marked by heavy rainfall (95%), high humidity and oppressive weather. The rainfall increases from the coastal region to the Western Ghats. The year may be divided into four seasons. (i) Pre-monsoon (March to May) (ii) South-west monsoon (June to September) (iii) Post-monsoon (October to December) (iv) Dry season (January to February). Rainfall is mainly due to cyclone and orographic effects. Annual rainfall in this region can reach 4000 mm. There are only two rain gauge stations located within the basin at Bajpe and at Surathkal. Four more are in the vicinity of the basin, at Mulki, Moodubidri, Panambur and Kuppepadavau.

The variations in daily temperature are low. The mean daily temperature during the months March to May is 35˚C and during December to February is 23˚C. The weather is highly humid all through the year and particularly so during the south-west monsoon when the humidity exceeds 85%.

The region experiences significant evaporation. It is found to be very high in the summer and moderate to low in monsoon and post-monsoon seasons. Evapotranspiration is very high in the summer and moderate to low in the monsoon and post-monsoon seasons; average values are about 5 mm/day during summer and 2.5 mm/day during winter. During the rest of the year, winds blow north-easterly during forenoons and westerly or north-westerly during afternoons. The sky is heavily clouded on most of days during south-west monsoon. The number of such heavily clouded days is less during the post-monsoon season. During the rest of the year, the sky is almost clear.

3.2.4 Vegetation perspective

The topography and climate of the Western Ghats in the highlands of the district have led to the growth of a variety of plants and grasses. All agricultural activities are confined to the topographic lows and the coastal tract. The torrential rains of the southwest monsoon are the chief source of water. Dakshina Kannada district provides favorable conditions for vegetation growth from seashore to the Western Ghats along the lowland, midland and forest regions of the highland. The mid region of the district has thick vegetation or cultivated coconut and areca nut palms on the shoulders of the valley. Evergreen forests occupy the steep Western Ghat slopes and narrow valleys. The higher elevated areas have mostly sparse vegetation with a cashew crop on a certain portion of the flat land surrounded by hillocks. Paddy is also irrigated on regular basis.

3.2.5 Crops and cropping pattern perspective

The cropping pattern of the study area is peculiar. In the low lying coastal belt mono-cropping sequence of rice crop, during the three seasons is practiced in some locations. While kharif rice crop is purely rainfed, rabi and summer crops are partially or fully irrigated with river water or well water. Sugarcane is another important crop cultivated in the alluvial soils of some places of the region. In the eastern part of the region, rice crop is raised in valley portions mainly during the khariff season. Plantation and horticultural crops, such as arecanut, coconut, banana, pepper and cocoa occupy the high lands. In the upper reaches cashew nut is also grown. Rice is the main crop extending over nine lakh hectares.

3.3 Methodology

3.3.1 Measurement of physical properties of soil by laboratory methods

Soil sample collection:

Soil samples were collected from the different locations at different depths in the agricultural and forested hillslope areas of the Pavanje river basin. At first, soil sampling was done in agricultural land. Fifty soil samples were collected from different locations at different soil profiles over a depth of 0-150 cm at 20 cm interval, during the first week of March 2011. The locations sampled were within 200-300 m of one another. Next fifty six samples were collected from the forested hillslopes at different elevations from crest (120 m) to footslope (30 m), during the last week of November 2011. The depth interval was 10 cm to 75 cm.

Laboratory measurements:

It is known that the physical properties of soil affect its hydraulic properties to a great extent. All the undisturbed and disturbed soil samples collected from the agriculture land and forested hillslopes were subjected to laboratory measurements to determine bulk density, porosity, organic matter content, particle-size distribution, saturated hydraulic conductivity and soil water retention characteristics.

1. Bulk density: Bulk density is an indicator of soil compaction. It is calculated as the weight of soil divided by its volume. This volume includes the volume of soil particles and the volume of pores among soil particles. Bulk density is typically expressed in g/cm^3 and is dependent on soil texture, densities of soil mineral (sand, silt, and clay) and organic matter particles, as well as their packing arrangement. Generally, loose, porous soils and those rich in organic matter content soils have lower bulk density. Sandy soils have relatively high bulk density than silt or clay, since total pore space in sandy soils is less than that of silt or clay soils. Fine textured soils, such as silt and clay loams have higher pore space and lower bulk density compared to sandy soils. Bulk density typically increases with soil depth since subsurface layers have reduced organic matter, aggregation, and root penetration compared to surface layers and therefore, contain less pore space.

<u>Procedural description</u>

- The core with a volume of 1020 cm^3 (10 cm diameter and 13 cm height) was used to collect the undisturbed soil samples of each selected location from both sites.
- A core sampler was mounted vertically on the soil surface and forced in using hydraulic jack to ensure sampling with minimum disturbance (Grossman & Reinsch, 2002).
- Immediately after taking the core samples, both ends were trimmed carefully to remove excess soil from the sample with a flat bladed knife. Care was taken such that the bottom of the sample was flat and even with the edges of the core.
- The core with soil sample was placed into a plastic sealable bag. Then sealed and labeled the bag, to prevent any soil disturbance during transportation.
- The undisturbed samples were used for the determination of bulk density and the disturbed soil samples were used for the determination of other soil properties.
- Immediately after the collection of soil samples from the field, core with the moist weight of the sample was taken. Then soils were removed from the core and weight of the empty core was noted down. Bulk density was calculated by using the formula,

$$Bulk\ density = \frac{Weight\ of\ dry\ soil}{Volume\ of\ soil} \tag{3.1}$$

- Some quantity of the moist soil samples were taken from the core and kept in the separate containers and weighed the containers with the moist soil. Oven dried the samples at 105° C. After 24 hours, the samples were taken out and the weight of the containers with the dry soil was noted down. Then water content was found by using the formula,

$$Water\ content = \frac{Weight\ of\ moist\ soil - Weight\ of\ oven\ dry\ soil}{Weight\ of\ oven\ dry\ soil} \times 100 \qquad (3.2)$$

From the obtained water content, dry density was determined by

$$Dry\ bulk\ density = \frac{Bulk\ density}{1+\frac{water\ content}{100}} \qquad (3.3)$$

Figure 3.2: A sampled location of agricultural land

2. Porosity: Porosity refers to the volume of soil voids that can be filled by water or air. The bulk density indirectly provides a measure of the soil porosity (amount of pore space). Soil porosity is the ratio of the volume of soil pores to the total soil volume. In general, clay soils have abundance of very small pores that give them higher total porosity compared to sands, which are dominated by larger, but fewer pores. There are more pore spaces between the clay than sand particles because clay particles are much smaller. Thus, clay soils tend to have higher total porosity than sandy soils, all else being equal. Bulk density is closely related to the soil porosity through the following relationship:

$$Porosity = 1 - \frac{Dry\ bulk\ density}{Particle\ density} \qquad (3.4)$$

Soil porosity values range from 0 to1. Soils with high bulk density have low total porosity because empty pores do not have any mass. When the bulk density is zero, porosity equals 1 meaning there are no particles. If the bulk density is equal to the particle density then there are no pores and porosity is zero.

The solid (mineral and organic) particles that make up soil have specific particle density (D_p), which is defined as the mass of solid particles in unit volume.

$$Particle\ density = \frac{mass\ of\ dry\ soil}{volume\ of\ solids} \tag{3.5}$$

The particle density of soil is not affected by particle size or arrangement; rather it depends on the type of solid particles present in the soils. Because mineral soil particles are heavier than organic matter, they have higher particle density on unit volume basis. The average particle density of mineral surface soil is about 2.65 g /cm^3.

3. Organic matter content: Organic matter in soils is widely distributed over the earth's surface occurring in almost all terrestrial and aquatic environments (Schnitzer, 1978). Soils contain a large variety of organic materials ranging from simple sugars and carbohydrates to the more complex proteins, fats, waxes, and organic acids. Important characteristics of the organic matter include their ability to form water-soluble and water insoluble complexes with metal ions and hydrous oxides; interact with clay minerals and bind particles together; absorb and release plant nutrients; and hold water in the soil environment. As a result of these characteristics, the determination of total organic carbon is an essential part of any site characterization since its presence or absence can markedly influence how chemicals will react in the soil. Total organic carbon contents may be used qualitatively to assess the nature of the sampling location (e.g., depositional area). Naturally occurring organic carbon forms are derived from the decomposition of plants and animals. In soils, wide variety of organic carbon forms are present and range from freshly deposited litter (e.g., leaves, twigs, branches) to highly decomposed forms such as humus. The spills or releases of contaminants into the environment increase the total carbon content present in the soil.

Walkley and Black, (1934) method for determining the soil organic matter (OM) content uses a specified volume of acidic dichromate solution reacting with a determined amount of soil in order to oxidize the OM. The oxidation step is then followed by titration of the excess dichromate solution with ferrous sulfate which gives volume of ferrous sulfate in milliliters (ml). OM is calculated using the difference between the total volumes of dichromate added and the volume titrated after reaction.

Reagents

1. Potassium Dichromate: $K_2Cr_2O_7$
2. Ferrous Ammonium Sulfate: Fe $(NH_4)_2(SO4)_26H_2O$
3. Sulfuric Acid: H_2SO_4
4. Phosphoric Acid: H_3PO_4
5. Sodium Fluoride: NaF
6. Diphenylamine: $C_6H_5NHC_6H_5$

Procedural description

Reagent Preparation

- *0.16M Potassium dichromate* - Dissolved 98.08 g of oven-dry/desiccated potassium dichromate in approximately 1500 ml of pure water and diluted to 2 liters (L). After preparation of the solution, transferred to a clean glass bottle for use with a repipetter.
- *1.0M Ferrous Sulfate* - Dissolved 556.04 g of ferrous sulfate in approximately 1500 ml of pure water. Carefully added 30 ml of concentrated sulfuric acid, mixed, cooled, and diluted to 2 L. After preparation, this solution was transferred to a clean 8 L plastic carboy. The tubing, stopcock, and attachments to the burette should be rinsed three times with new ferrous sulfate solution before titrating any blanks or samples.

Analysis

- 1.0 g of mineral soil was put into a 250 ml wide mouth graduated Erlenmeyer flask.
- Titrated two blank samples (no soil) before proceeding with any unknown samples in order to standardize the ferrous sulfate solution. If the difference between the two blanks was not within 0.2 ml of ferrous sulfate solution, cleaned the burette and

associated tubing and reanalyzed two more blank samples to determine if the problem has been eliminated.

- Pipetted 10 ml of the potassium dichromate solution into each flask containing unknown soil and mixed by carefully rotating the flask to wet all the soil.
- Under fume hood, carefully added 20 ml of concentrated sulfuric acid to each flask and mixed gently.
- Allowed flasks to stand for 5 min under the fume hood.

Figure 3.3: Laboratory set up for measuring organic matter content

- Pipetted 10 ml of the potassium dichromate solution into each flask containing unknown soil and mixed by carefully rotating the flask to wet all the soil.
- Under fume hood, carefully added 20 ml of concentrated sulfuric acid to each flask and mixed gently.
- Allowed flasks to stand for 5 min under the fume hood.
- Added pure water to each flask to raise the volume approximately to 125 ml. Mixed by swirling gently.
- Allowed the samples to cool and return to room temperature and rechecked volume after 30 minutes.
- Added 5 or 6 drops of phenanthroline complex and immediately titrated with the ferrous sulfate solution. Used mixing bar to properly mix the sample during titration. As the titration proceeded, the solution turned to green color and changed abruptly to reddish-brown when the endpoint of the titration was reached.
- Recorded each volumetric reading to the nearest ml.

<u>Calculation</u>

$$\text{Organic matter (\%) of sample} = (1 - S / B) * 10 * 0.68 \tag{3.6}$$

where,

S= Volume of ferrous sulfate solution required to titrate the sample, in ml.

B= Average volume of ferrous sulfate solution required to titrate the two blanks, in ml.

10 is the conversion factor for units and 0.68 is a factor derived from the conversion of percentage of organic carbon to that of organic matter content.

4. Particle-size distribution: The particle size distribution (also called grain size distribution) is one of the most important characteristics of the soil. It has an effect on many properties of the soil such as the ease of tillage, the capillary conductivity of soil, the available moisture, the permeability of soil, compaction, etc. Agricultural as well as soil scientific properties are greatly determined by the texture of a soil. Particle size analysis is the standard laboratory procedure for the determination of the particle size distribution of soil and it is required in classifying the soil. Soil consists of an assembly of ultimate soil particles of various shapes and sizes. The object of particle size analysis is to group these particles into separate ranges of sizes and so determine the relative proportion by weight of each size range. The complete procedure for particle size determination can be divided into three stages:

- Sieve analysis of soil fraction retained on 4.75 mm aperture sieve;
- Sieve analysis of soil passing 4.75 mm aperture sieve and retained on 75 μ (micron) aperture sieve;
- Sedimentation analysis (hydrometer) of soil passing 75 μ (micron) aperture sieves.

The mechanical or sieve analysis is performed to determine the particle sizes larger than 0.075 mm and the hydrometer method is used to determine the particle sizes smaller than 0.075 mm.

Mechanical analysis (Sieve analysis): This is mainly used to determine the particle size of coarse grained soils (gravel and sand). A sieve is an item containing squared openings of specified size, where only the particle smaller than that size can pass through the sieve with proper orientation. Sieves are constructed of wire mesh. The test was held by stacking number of standard sieves, ranging in sizes from the largest at top to the smallest at bottom. In the present study, the sieves were stacked in the following series; 4.75 mm, 2 mm, 1.18 mm, 0.6 mm, 0.3 mm, 0.15 mm, 0.075 mm and pan.

Procedural description

- Noted down the weight of each sieve as well as the bottom pan to be used in the analysis.
- Recorded the weight of the given dry soil sample.
- Carefully poured the soil sample into the top sieve and placed the cap over it.
- Placed the sieve stack in the mechanical shaker and allowed to shake for 10 minutes.
- Removed the stack from the shaker. Carefully weighed and recorded the weight of each sieve with its retained soil and also recorded the weight of the bottom pan with its retained fine soil.

Calculations

$$\text{Percentage retained on any sieve} = \frac{Weight\ of\ soil\ retained}{Total\ soil\ weight} \times 100$$

$$\text{Cumulative percentage retained on any sieve} = \sum Percentage\ retained$$

$$\text{Percentage finer than sieve size} = 100\,\% - \sum Percentage\ retained$$

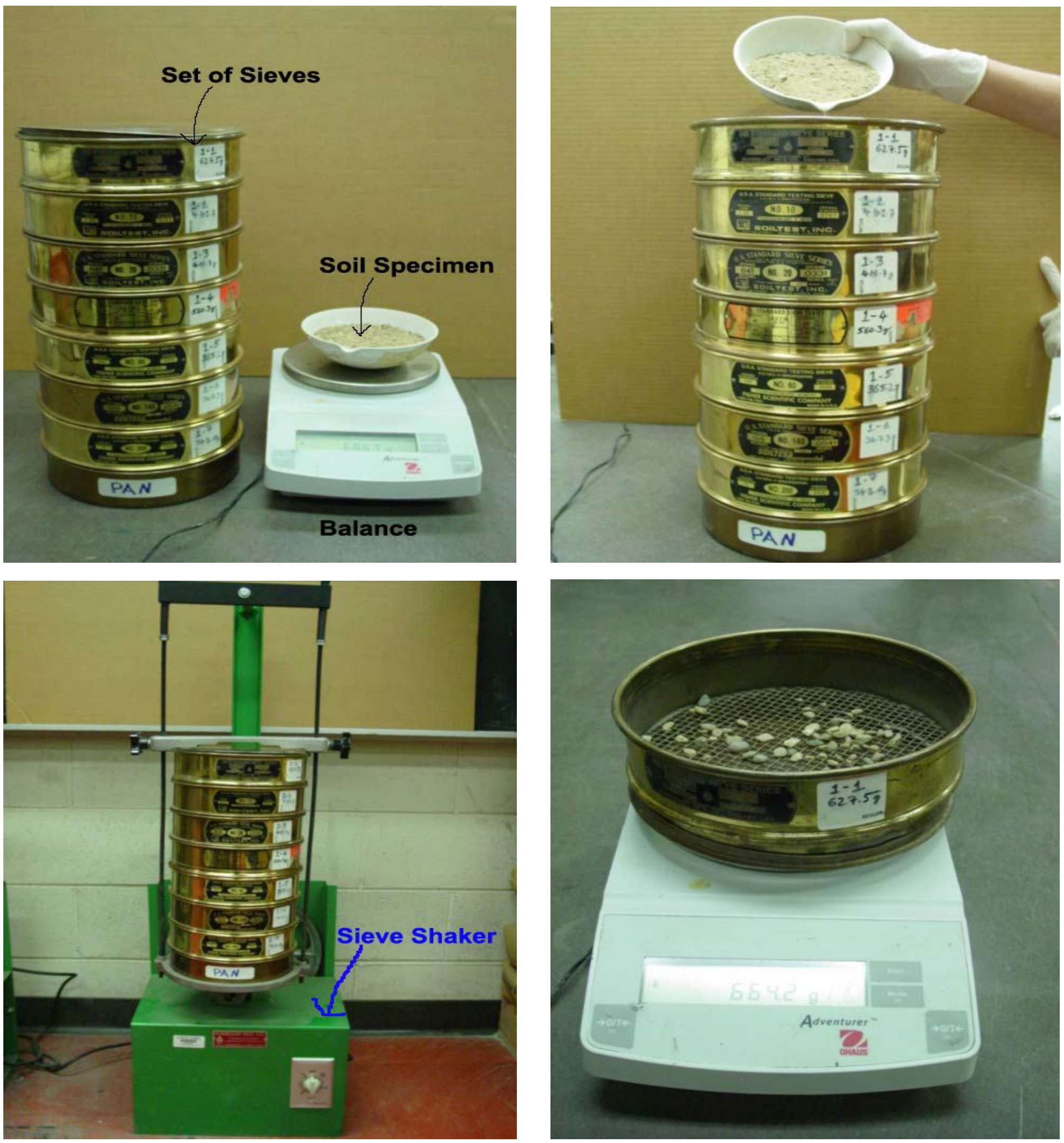


Figure 3.4: Experimental set up for sieve analysis

Classification of soils

Clay is defined as particles with diameter less than 0.002 mm. Silt has a particle diameter range from 0.002 mm to 0.075 mm and sand has particle diameter range from 0.075 mm to 2 mm. Larger particles with grain sizes greater than 2 mm and smaller than 4.75 mm are considered as gravels, are excluded from the proportioning in the determination of texture.

Sedimentation analysis (hydrometer): This is mainly used to measure the silt and clay particles. The screening process cannot be used for fine grained soils (silts and clays), because of their extremely small size. The hydrometer method is used to measure the density of the soil suspension. It is the common laboratory method to determine the size distribution of fine grained soils, which uses a principle based on Stoke's Law.

Procedural description:

- Fine soil from the bottom pan of the sieve set was taken, placed it into a beaker, and 125 ml of the dispersing agent (sodium hexametaphosphate (40 g/L)) solution was added. Stirred the mixture until the soil was thoroughly wet. Allowed the soil to soak for at least ten minutes.
- While the soil was soaking, 125 ml of dispersing agent was added into the control cylinder and filled it with distilled water to the mark. Reading was taken at the top of the meniscus formed by the hydrometer stem and the control solution. A reading less than zero was recorded as negative (-) correction and a reading between zero and sixty was recorded as a positive (+) correction. This reading is called the zero correction. The meniscus correction is the difference between the top of the meniscus and the level of the solution in the control jar (usually about +1). Control cylinder was shaken to make the contents mixed thoroughly. Inserted the hydrometer and thermometer into the control cylinder and noted the zero correction and temperature respectively.
- Transferred the soil slurry into a mixer by adding more distilled water, if necessary, until the mixing cup is at least half full. Then mixed the solution for a period of two minutes.

- Immediately transferred the soil slurry into the empty sedimentation cylinder. Added distilled water up to the mark.
- Covered the open end of the cylinder with a stopper and secured it with the palm. Then turned the cylinder upside down and back upright for a period of one minute.

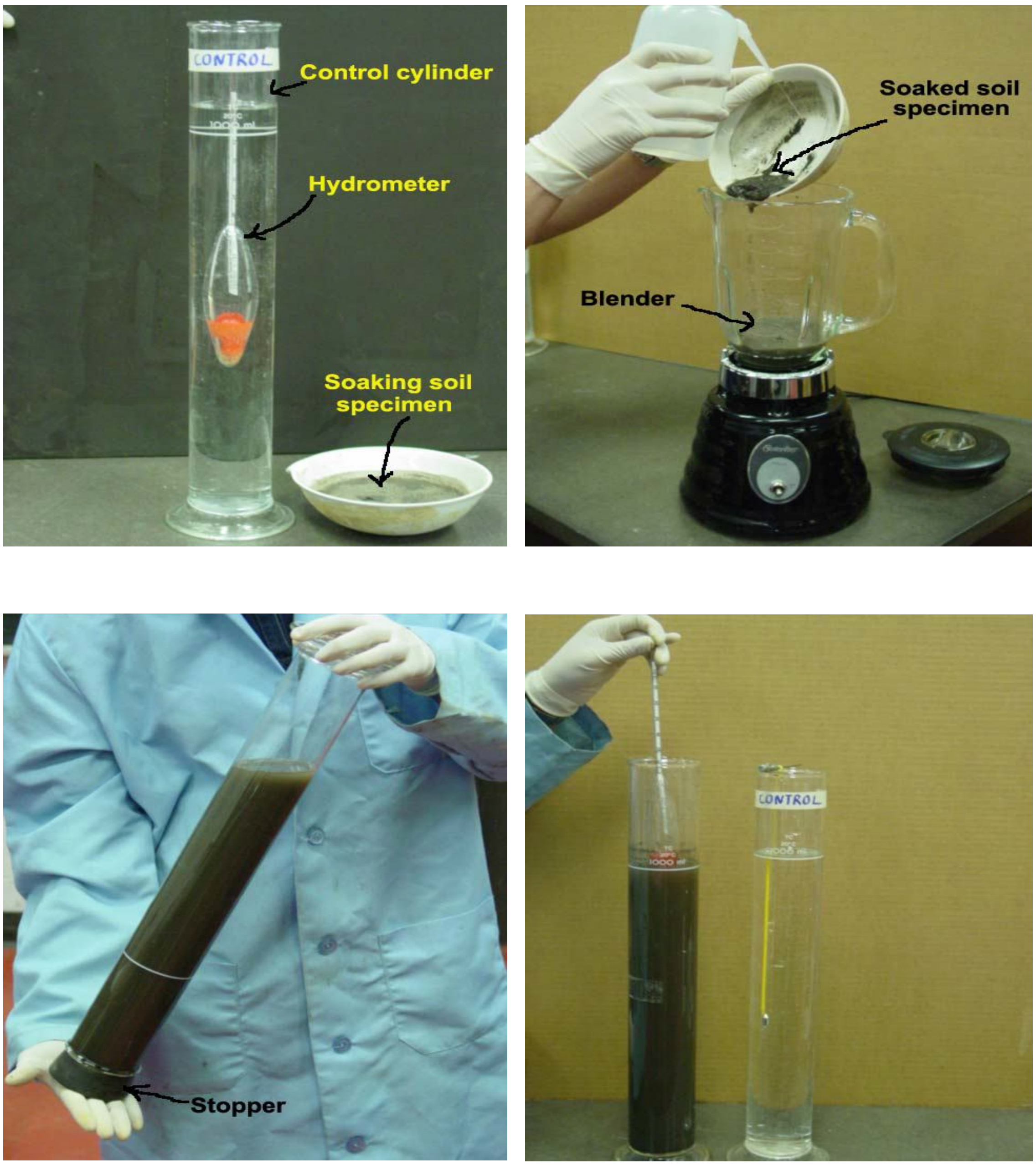


Figure 3.5: Experimental set up for hydrometer analysis

- Set the cylinder down and removed the stopper from the cylinder. Then hydrometer was slowly and carefully inserted into the cylinder for the first reading.
- The reading was taken by observing the top of the meniscus formed by the suspension and the hydrometer stem. The hydrometer was removed slowly and placed back into the control cylinder. Very gently spun it in control cylinder to remove any particles that might have adhered.
- Taken hydrometer readings after elapsed time of 15 and 30 seconds, 1, 2, 4, 8, 15, 30, 60 minutes and 2, 4, 8, 24 hours.

Calculations

The diameter D of the particle at time t_D was calculated from the formula:

$$D = \sqrt{\frac{18\,\mu\, z}{(G_S-1)\gamma_W\ t_D}} \tag{3.7}$$

where,

μ = viscosity of water, z = depth, γ_w = unit weight of water, and G_s = specific gravity.

The percentage finer (N) was calculated from the formula:

$$N = \frac{100 \times G \times R}{M_d(G-1)} \tag{3.8}$$

where

G = specific gravity, R = corrected hydrometer reading = Rh'+0.5, Rh'= (Rh-1)*1000; where Rh = actual hydrometer reading, M_d= weight of soil sample.

The results of sieve analysis are generally expressed in terms of the percentage of the total weight of soil that passed through different sieves and are presented by semi-logarithmic plots known as particle (grain) size distribution curves. From the obtained results of percentage passing, the grain size distribution curve was drawn on semi log paper, with the percentage passing representing the ordinate and the sieve size representing the abscissa. The graph of grain size curve D versus the adjusted percentage finer N on the semi logarithmic sheet is plotted as shown below;

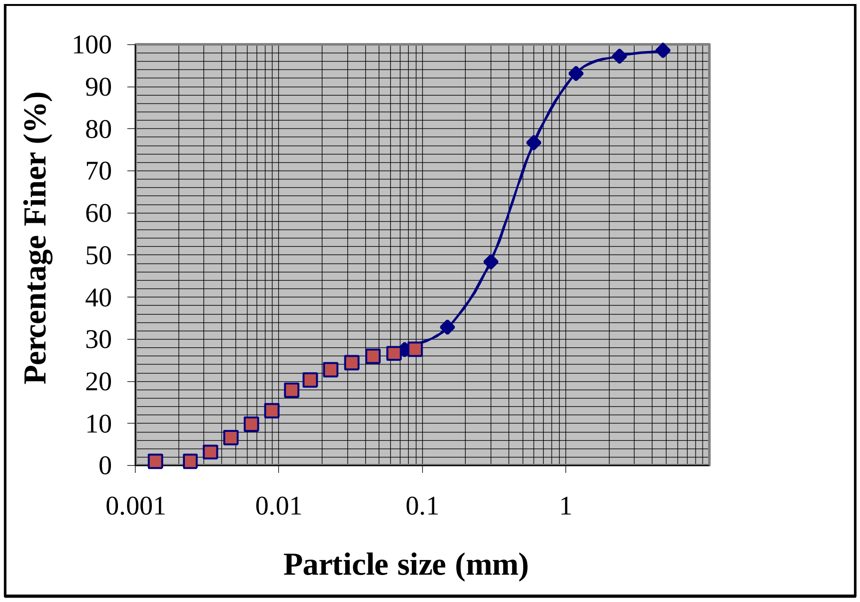


Figure 3.6: Particle size distribution curve obtained from sieve and hydrometer analysis

5. Soil texture: United States Department of Agriculture (USDA) system of soil classification was used to identify the texture of soil based on the percentages of sand, silt and clay contents. The following are the different types of textured identified in the present study.

If the percentage of sand;

> 85 % ------------- Sand

72% - 85% ------------- Loamy sand

49% - 72% ------------- Sandy loam

19 %- 49 % ------------ Silty sand

0 %- 19% -------------- Silt

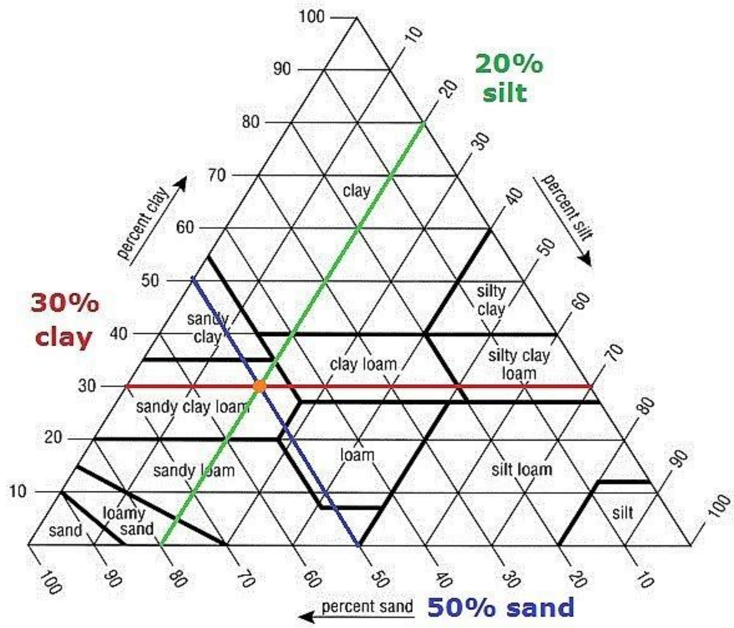


Figure 3.7: USDA system of soil classification

3.3.2 Measurement of hydraulic properties of soil by laboratory methods

1. Saturated hydraulic conductivity (k_s)

A comprehensive knowledge of soil hydraulic conductivity is essential when modeling the distribution of soil moisture within soil profiles and across catchments. Soil saturated hydraulic conductivity (k_s) is one of the most important soil hydraulic parameters as it characterizes the soil's ability to transmit water. It is an essential parameter for understanding soil movement and soil hydrology. Saturated hydraulic conductivity can be used to describe water movement under saturated conditions in the soils. It is a fundamental input for modeling runoff, drainage, and movement of solutes in soils (Mallants et.al, 1997). Soils with small values of hydraulic conductivity have low infiltration rates. During intense rains, water runoff will lead to consequent soil losses and surface transport of colloids, nutrients and microbes, which can then cause problems of eutrophication and pollution of downstream areas (Dexter A. R., 2004). Soil saturated hydraulic conductivity can be measured either in the field or from soil samples in the laboratory.

Many field methods have been developed for determining the saturated hydraulic conductivity of soils within a groundwater formation under unconfined and confined conditions. These methods include (1) the auger hole and piezometer methods, which are used in unconfined shallow water table conditions (Amoozegar and Warrick, 1986), and (2) well-pumping tests (Hantush et. al, 1964), which were primarily developed for the determination of aquifer properties used in the development of confined and unconfined groundwater systems.

In laboratory, the value of k_s can be determined by several different instruments and methods such as the permeameter, pressure chamber, and consolidometer. A common feature of all these methods is that a soil sample is placed in a small cylindrical receptacle, representing one dimensional soil configuration through which the circulating liquid is forced to flow. Depending on the flow pattern imposed through the soil sample, the laboratory methods for measuring hydraulic conductivity are classified as either a constant head test with a steady state flow regimen or a falling head test with an unsteady state flow regimen. Constant head methods are primarily used in samples of soil materials with estimated k_s above 1.0×10^2 m/yr, which corresponds to coarse grained soils such as clean sands and gravels. Falling head methods, on the other hand, are used in soil samples with estimated values of k_s below 1.0×10^2 m/yr (Freeze and Cherry, 1979).

Falling Head Test

The falling head test is used for fine grained soils because the flow of water through these soils is too slow to get reasonable measurements from the constant head test. A compacted soil sample or a sample extracted from the field is placed in a metal mould. The metallic mould is machined all over and has an inside diameter of 100 mm. The mould is 127.3 mm high and has a volume of 1000 ml.

<u>Specimen preparation</u>

Empty weight of the mould was taken and greased the inside of the mould. Then known quantity of soil was taken and mixed thoroughly with required amount of water to give a desired density for a given amount of compaction. Placed the extension collar and compacted the specimen in the mould in layers with the desired compaction effort simulating the field conditions. Once the compaction got over, removed the extension collar and trimmed the excess soil level with the top of the mould. Assembled the mould between the drainage bases and capped with the porous stones in the recesses. Porous stones were positioned at the top and bottom faces of the sample to prevent its disintegration and to allow water to percolate through it.

Procedural description:

- Connected the specimen through the top inlet to a selected standpipe for falling head arrangement.
- Filled the stand pipe with the desired water. Filled the cavity between the cap and the porous stone.
- Opened the bottom outlet and allowed the water to flow through the specimen.
- When the water was seen coming out of the outlet in the base, recorded the time interval required for the water level in the stand pipe to fall from the known initial head to a known final head.
- Filled the stand pipe again and repeat the test till three successive observations give the same time interval, the time interval being recorded for the drop in head from the same initial to final values.

Figure 3.8: Experimental set up for falling head test

Calculations

The saturated hydraulic conductivity has been calculated from the following formula:

$$k_s = \frac{2.303 \times a \times l}{A \times t} \log_{10}\left(\frac{h_1}{h_2}\right) \tag{3.9}$$

where

k_s = saturated hydraulic conductivity

a = inside cross sectional area of stand pipe in cm^2

A = area of cross section of the specimen

l= length of the specimen in cm

h_1 = initial head in cm

h_2 = final head in cm

t = time interval in seconds in which the head drops from h_1 to h_2 cm

2. Soil water retention curve θ(h)

The soil water retention curve describes the relationship between the series of the water contents of soil from very wet to very dry, and the matric suction (h) at which the water is held at each (θ) value. It is therefore sometimes described as a function θ(h). It is a physical soil property which describes the soil porous system. It depends basically on soil structure, texture, organic matter content, and bulk density. It will therefore vary both vertically (diagnostic horizons/layers in the profile) and horizontally in any field. Stratified sampling according to diagnostic horizons or specific layers is a prerequisite to determine the overall hydrological behavior of soil profile. Because of this and the importance of the hydrological behavior of soils to agriculture, forestry, hydrology, engineering and pollution, research concerning the soil water retention characteristics of soil horizons is important.

Information on soil water retention is needed for;

- To determine plant available water in the soil (the portion of water that can be readily absorbed by plants roots) (van Rensburg, 1988);
- To evaluate soils for irrigation purposes;

- To estimate the soil pore size distribution (Kutilek, 2004);
- To check changes in the structure of a soil, e.g. caused by tillage, mixing of soil layers (Kutilek, 2004);
- To predict other soil physical properties (e.g. hydraulic conductivity) (Mualem, 1976; van Genuchten, 1980);
- To provide inputs in most water balance and hydrological models (Bennie et al., 1994). Consequently, information about water retention characteristics can be useful for farmers and governments as a planning tool for development and investment strategies.

Owing to the relative importance of soil water retention curve $\theta(h)$, in many disciplines, including environmental engineering, soil physics (Hopmans et al., 2002) and agricultural issues, a wide variety of methods are being developed and improved to effectively determine soil water retention curves. Several field methods, laboratory methods and theoretical models for such determinations exist, each having their own limitations (Stephens, 1994). In-situ determinations are generally preferred owing to the large volume of soil tested and the preservation of soil structure during the experiments (Green et al., 1986). In situ measurements, though more representative of actual conditions, have the disadvantage of being costly and time consuming, whereas laboratory processes are perceived to be more convenient and offer many advantages compared to in-situ techniques.

In the laboratory, $\theta(h)$ relationship may be measured on replicated samples over range of water contents. Virtually the entire range from water saturated soil to very dry soil may be covered by using a hanging water column and pressure plate apparatus (Klute, 1986; Dirksen, 1999; Bohne, 2005). In the hanging water column technique, the water in the sample is subjected to a tension by the weight of hanging column of water below it. This is convenient for potentials 0 to -10 kPa (0 to -1 m of water). The pressure plate apparatus is normally used for the suction range of -30 kPa to -1500 kPa. According to, Reeve and

Carter (1991) the precision of pressure plate apparatus is very good, with a coefficient of variation of 1-2% attainable.

In the pressure plate technique (Soil moisture Equipment Corp., 2002) instead of applying suctions, pressures are exerted on the sample which is placed on a ceramic porous disc in a chamber to force water from the sample. This technique is relative rather than absolute values of pore air and pore water suction that govern water retention characteristics, and convenient for suctions from -10 kPa to -1500 kPa (-1 to -150 m of water). Equilibrium times may vary from days to weeks. The principle involved in this method is the amount of moisture a soil holds by matric tension, by placing the saturated soil on a porous plate and subjecting the two sides of the membrane to the desired difference in tension.

Pressure plate apparatus:

Pressure plate apparatus is commonly used to quantify the moisture retained in the soil. It has been used as a standard technique for determination of soil water retention at an imposed matric potential since the introduction of the method by Richards and Fireman (1943) and Richards (1948). The technique involves placing a saturated soil sample on a porous ceramic plate inside a pressure chamber. The underside of the ceramic plate is maintained at atmospheric pressure while the soil samples are pressurized, thus creating a hydraulic gradient and subsequent flow of water from the samples through the saturated ceramic plate. In theory, flow ceases once the soil samples reach equilibrium with the imposed pressure. If the water contained in the voids of a soil is subjected to no other force than gravity, the soil lying above the water table would be completely dry.

<u>Procedural description</u>

- Soil sample was powdered and sieved using 2 mm sieve. The sample passing through 2 mm sieve was placed on the retaining rings.
- The soil sample together with the ceramic plate was saturated with water. This was done by allowing excess water to stand on the surface for several hours.
- When the saturation was complete, the ceramic plate with soil sample was mounted in the pressure vessel.

- Air pressure was used to effect extraction of moisture from the soil samples under controlled condition.
- After reaching the equilibrium for the required pressure, the vessel was opened and the ceramic plate with soil sample was taken out.
- A pinch of soil sample was taken and recorded the sample weight. Oven dried for 24 hours at 105°C and reweighed.
- The same procedure was repeated for required pressures.




Figure 3.9: Experimental set up of Pressure plate apparatus

Thus soil water retention curve data at -33, -100, -300, -500, -1000 and -1500 kPa matric potentials were measured using pressure plate apparatus. Soil samples were pressurized adequately and weighed at every potential. The ceramic plates with their air entry pressures and corresponding equilibration times were as follows: for h =-33 kPa to -100 kPa, 100 kPa plates and 5 days; for h = -100 kPa to -300 kPa, 300 kPa plates and 7 days; for -500, -1000, and -1500 kPa, 1500 kPa plates and 10 days. After equilibration, the samples were weighed to determine the water content corresponding to the suction or pressure applied. The gravimetric water content was converted to volumetric water content by multiplying it by the relevant bulk density values.

3.4 Results and discussion

3.4.1. Profile description of agricultural land

Figure 3.10 shows location of the study area of the agricultural site. Five pits were dug out and samples were collected at different depths from surface layer down to 150 cm. The samples were taken out at every 20 cm depth interval up to 150 cm. At each depth all the physical and hydraulic properties were measured in the laboratory. The summary of the physical and hydraulic properties (minimum, maximum, mean and standard deviation) of the soil profiles are presented in Table 3.1.

Figure 3.10: A location of soil sampling in agricultural land

3.4.1.1 Physical properties of agricultural soils

Table 3.1 shows the particle size distribution, bulk density, porosity and organic matter content values of the soil profiles for agricultural site of Pavanje river basin. At the agricultural site, all soil layers had very high sand (S) contents, ranging from 41 to 89%, silt (Si) contents ranging from 10 to 52% and clay (C) contents of around 1 to 5%. Generally, bulk density (BD) increased with soil depth, ranging from 1.36 to 1.69 g/cm^3. The highest values were found in the middle of the profile, at 50-90 cm depth. Porosity (P) was in the range of 33% to 44%. Bulk density is one of the very important physical properties, which affects the soil water retention characteristics of the soil. These variations in bulk density and clay content influence the water retention properties, especially in the wet region. The amount of the organic matter (OM) was decreasing towards the bottom layer. It was varying from 0.24 to 2.52%. More the organic matter more was its water holding capacity. Laboratory measurements showed that the sampled soils were more or less homogeneous throughout their profiles and were assumed to be coarse textured based on the mean sand fraction, bulk density and organic matter content. Soils were classified as loamy sand, sandy loam, sand and silty loam based on the USDA system of soil texture triangle.

Table 3.1: Descriptive statistics of soil properties in agricultural land

Variables	Min	Max	Mean	SD
Physical properties				
S (%)	41	89	58.33	13.09
Si (%)	10	52	31.18	11.65
C (%)	1	5	1.80	1.09
BD (g /cm^3)	1.36	1.69	1.51	0.06
OM (%)	0.24	2.52	0.87	0.49
P (cm^3/cm^3)	0.33	0.44	0.39	0.03
Hydraulic properties				
θ_{33} (cm^3/cm^3)	0.05	0.29	0.21	0.08
θ_{100} (cm^3/cm^3)	0.05	0.27	0.19	0.07
θ_{300} (cm^3/cm^3)	0.03	0.25	0.17	0.07
θ_{500} (cm^3/cm^3)	0.03	0.25	0.17	0.06
θ_{1000} (cm^3/cm^3)	0.03	0.23	0.15	0.06
θ_{1500} (cm^3/cm^3)	0.02	0.19	0.13	0.05
k_s (cm /hr)	1.16	16.48	7.33	3.49

where S, Si, C are sand, silt, clay fractions (%), respectively, BD is bulk density (g/cm^3), OM is organic matter content (%), P is porosity (cm^3/cm^3), θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of -33, -100, -300, -500, -1000 and -1500 kPa, respectively, k_s is saturated hydraulic conductivity.

3.4.1.2. Hydraulic properties of agricultural soils

Table 3.1 also shows the summary of the water retention data obtained with Pressure plate apparatus and saturated hydraulic conductivity from the Permeameter. The experimental study considered six pressure heads (-33, -100, -300, -500, -1000, -1500 kPa) for each soil sample and obtained the moisture retention data for all the soil samples. It was observed that many soils were sandy loam textured. Only in the first and fourth pit, the soils were loamy sand. In rest of the pits, the soils were sandy loam textured; only at two depths in the second site it was silty loam textured.

For the loamy sands, water contents were varying from 0.05 to 0.08 (cm^3/cm^3) at -33 kPa and 0.03 to 0.05 (cm^3/cm^3) at -1500 kPa in site-1. But there was drastically increase in water contents of loamy sands from 0.24 to 0.27 at -33 kPa and 0.16 to 0.19 at -1500 kPa in the site-4. At different depths, not much variation was found. In sandy soils, water contents varied from 0.05 (cm^3/cm^3) at -33 kPa and 0.02 (cm^3/cm^3) at -1500 kPa. But in sandy loam soils, water content drastically increased from 0.21 to 0.29 (cm^3/cm^3) at -33 kPa and 0.11 to 0.19 (cm^3/cm^3) at -1500 kPa. In silty loam soils water content was 0.25 to 0.26 at -33 kPa and 0.16 to 0.17 at -1500 kPa. Some curves are shown in Figure 3.12

Figure 3.11 shows the detailed moisture retention data for the soils at different depths in agricultural sites. The data are averages of three replicates. It can be observed that, the shape of the curves for different horizons (for the Pavanje river basin soils) is fairly similar. This was expected in view of the textural, structural and mineralogical homogeneity of the profile. There were slight differences between the curves, particularly at high suctions. The reason for this is that, at these suctions soil texture is the dominant factor controlling water retention. As the matric potential increased, the water content decreased. This is mainly because the water retained at lower tensions is dependent on soil structure, whereas at higher tensions it is dependent on particle-size distribution and soil mineralogy. Saturated hydraulic conductivity was varying from 1.16 to 10.31 cm/hr for sandy loam textured soils, in loamy sand textured soils it ranges from 4.46 to 12.68 cm/hr and 13.92 to 6.48 cm/hr for sandy soils.

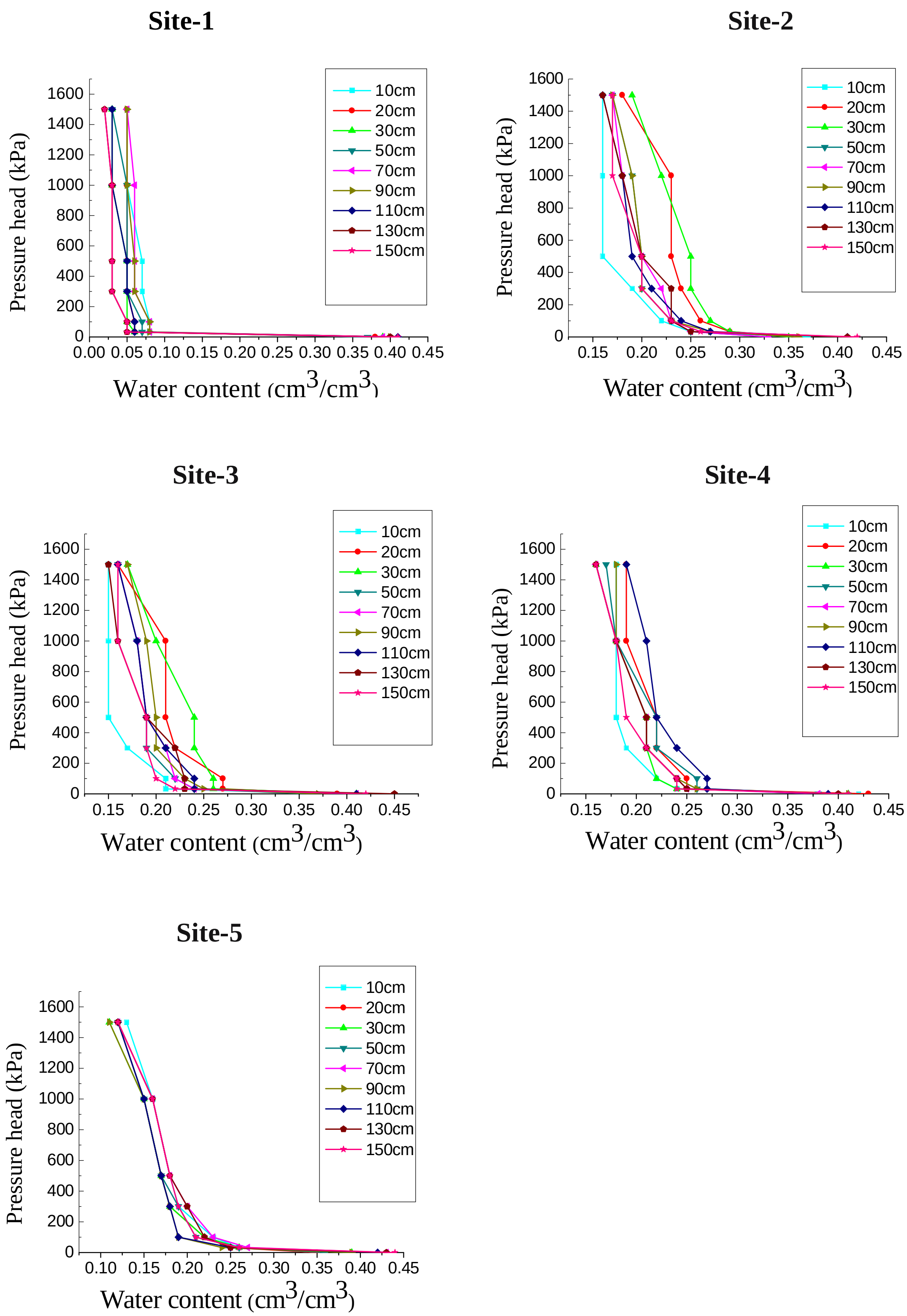
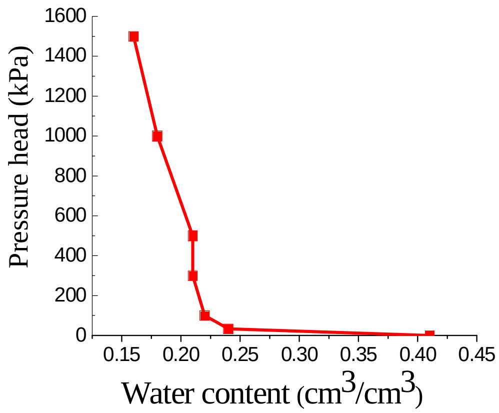
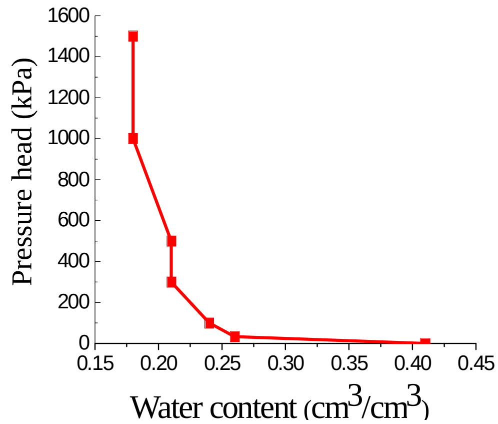
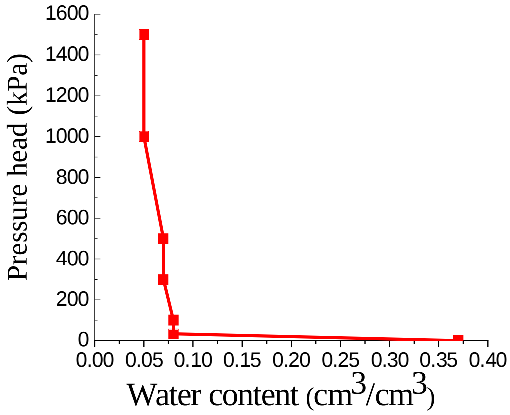


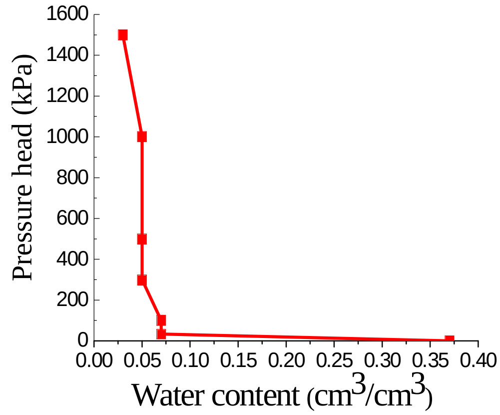
Figure 3.11: Soil water retention curves at different depths for agricultural soils

Loamy sand

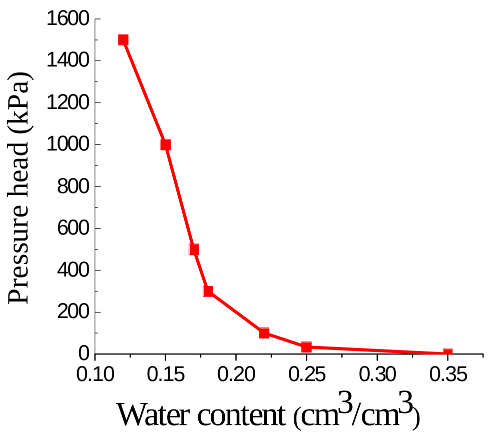


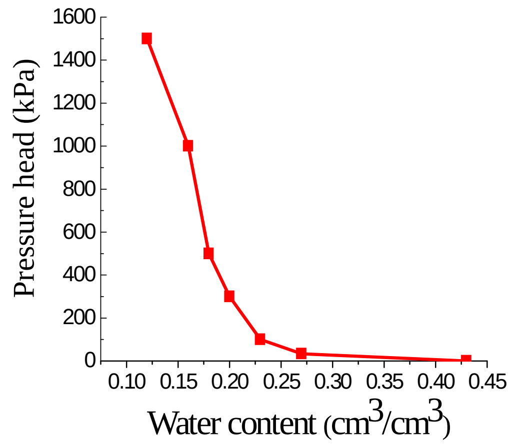


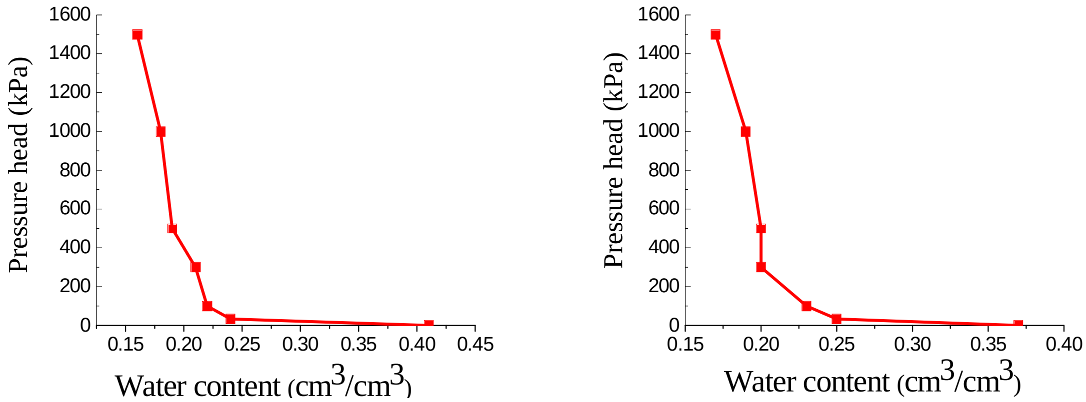




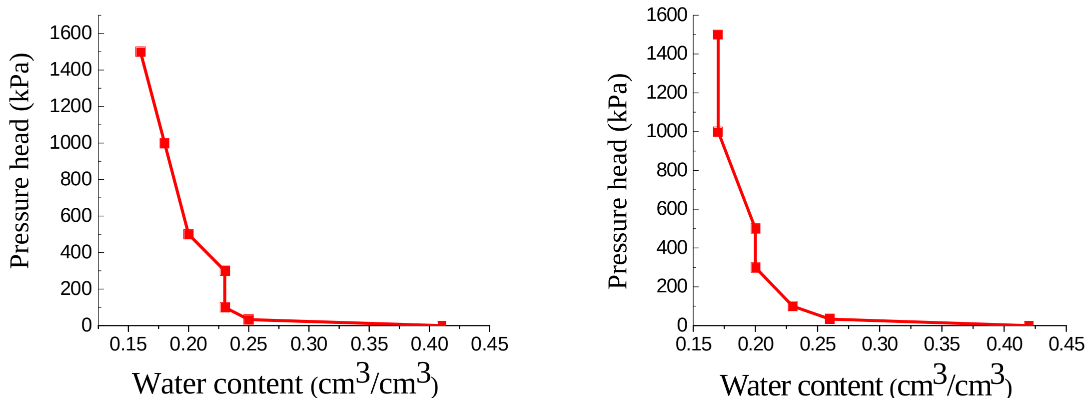
- **Sandy loam**







- **Silty sand**



- **Sand**

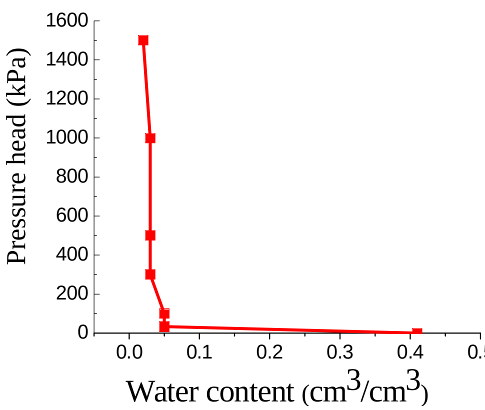


Figure 3.12: Soil water retention curves for different types of agricultural soils

3.4.2. Profile description of forested hillslope area

Figure 3.13 shows the study area of the forested hilllslope soils. Pits were dug out and soil samples were collected at different elevations distributed from the crest to the foot of the forested hillslopes. The sampling locations are referred to as 120 m to 30 m from the crest to the footslope. At each elevation, at seven different depths or soil layers with the thickness of 10 cm, 20 cm, 30 cm, 40 cm, 50 cm, 60 cm and 75 cm, physical and hydraulic properties were measured.

Figure 3.13: A location of soil sampling in forested hillslopes

3.4.2.1 Physical properties of forested hillslope soils

Compared to the soil at agricultural field, the soil at the forested hillslopes had less sand contents ranging from 30 to 57% and more gravel contents ranging from 11 to 51%, silt from 14 to 44% and clay content are very less from 0 to 5%. Porosity was ranging from 32% to 52%. Bulk density was ranging from 1.22 to 1.69 g/cm^3 and is one of the very important physical properties, which affects the soil water retention characteristics of the soil. Organic matter content is more for the forested hillslopes than the agricultural field. It was varying from 0.65 to 7.49%. Overall, the soils were quite homogeneous throughout their profiles with respect to particle size distribution, bulk density and organic matter content. Soils could be considered as coarse textured soils like loamy sand, sand and sandy loam soils based on USDA system of soil texture triangle. Table 3.2 shows some statistics of the particle size distribution, bulk density, porosity and organic matter content of the soil profiles for the forested hillslope soils from the surface layer down to 75 cm.

Table 3.2: Descriptive statistics of soil properties for forested hillslopes

Variables	Min	Max	Mean	SD
Physical properties				
S (%)	30	57	44.14	6.94
Si (%)	14	44	25.61	7.18
C (%)	0	5	1.23	1.22
BD (g /cm^3)	1.22	1.69	1.45	0.12
OM (%)	0.65	7.49	2.37	1.62
P (cm^3/cm^3)	0.32	0.52	0.39	0.05
Hydraulic properties				
θ_{33} (cm^3/cm^3)	0.17	0.28	0.22	0.03
θ_{100} (cm^3/cm^3)	0.12	0.23	0.17	0.03
θ_{300} (cm^3/cm^3)	0.11	0.20	0.15	0.02
θ_{500} (cm^3/cm^3)	0.10	0.17	0.13	0.02
θ_{1000} (cm^3/cm^3)	0.07	0.15	0.11	0.02
θ_{1500} (cm^3/cm^3)	0.06	0.13	0.09	0.02
k_s (cm /hr)	1.91	12.14	4.94	2.07

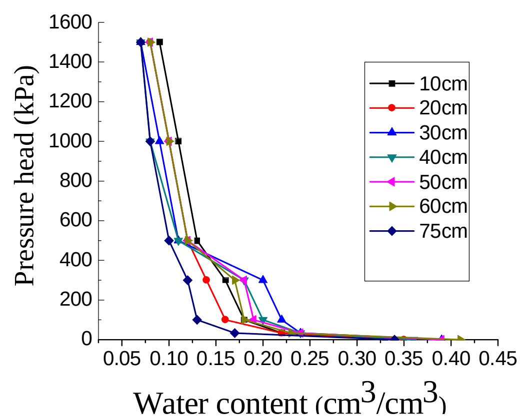
where S, Si, C are sand, silt, clay fractions (%), respectively, BD is bulk density (g/cm^3), OM is organic matter content (%), P is porosity (cm^3/cm^3), θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of -33, -100, -300, -500, -1000 and -1500 kPa, respectively, k_s is saturated hydraulic conductivity.

3.4.2.2 Hydraulic properties of forested hillslope soils

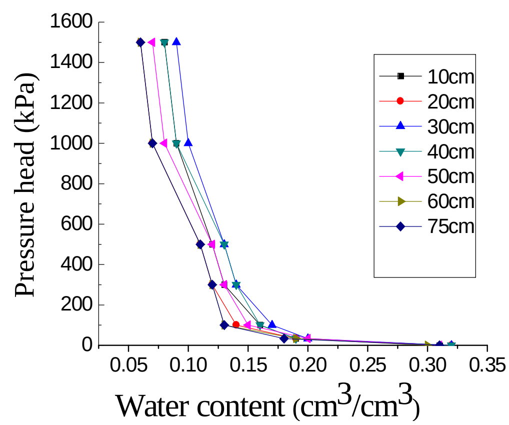
Table 3.2 also shows the statistics of the water retention data and saturated hydraulic conductivity from the laboratory experiments. Six pressure heads (-33, -100, -300, -500, -1000, -1500 kPa) were considered for each soil sample and obtained the moisture retention data for all the samples. For each location, hydraulic properties (SWRC and k_s) of seven soil layers with the same thickness were determined. Overall, fifty six sets of soil water retention and saturated hydraulic conductivity data were analyzed in this study. It was observed that, in most of the elevations, soils were sandy loam textured. Only at 40 m and 90 m elevations, the soils were loamy sand, and at 50 m elevations only two soil samples were sand and rest of all were loamy sand. It could be observed that not much difference in texture was found in soils of different depths in the same pits.

In sandy soils, water contents varied from 0.18 to 0.19 (cm^3/cm^3) at -33 kPa and 0.06 (cm^3/cm^3) at -1500 kPa. For the loamy sands, water contents were varying from 0.17 to 0.20 (cm^3/cm^3) at -33 kPa and 0.06 to 0.09 (cm^3/cm^3) at -1500 kPa. But in sandy loam textured soils, water content drastically increased from 0.18 to 0.28 (cm^3/cm^3) at -33 kPa and 0.07 to 0.13 (cm^3/cm^3) at -1500 kPa. Some soil water retention curves are plotted and shown in Figure 3.15. Saturated hydraulic conductivity was varying from 1.91 to 7.98 cm/hr for sandy loam textured soils, in loamy sand textured soils ranges from 2.57 to 6.49 cm/hr and 10.45 to 12.14 cm/hr for sandy soils. Figure 3.14 shows the detailed soil water retention curves for the forest soils at different depths and elevation.

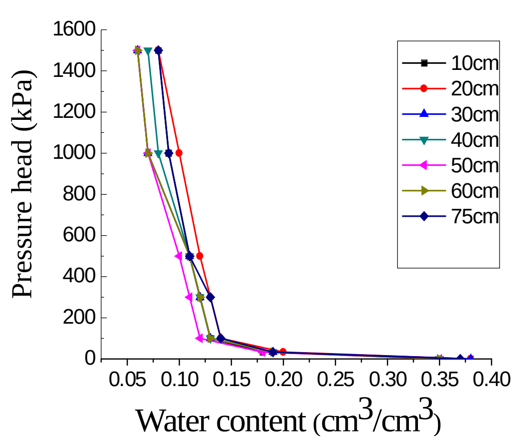
30m elevation



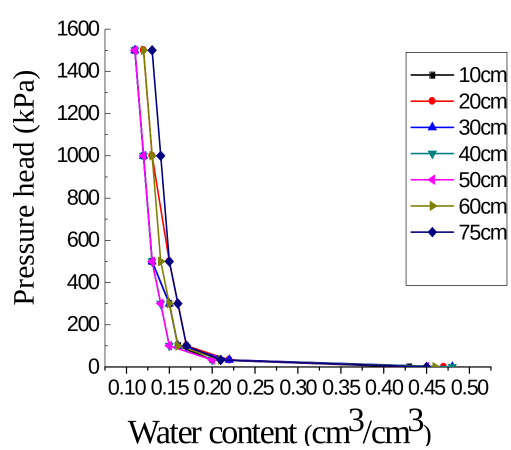
40m elevation



50m elevation



60m elevation



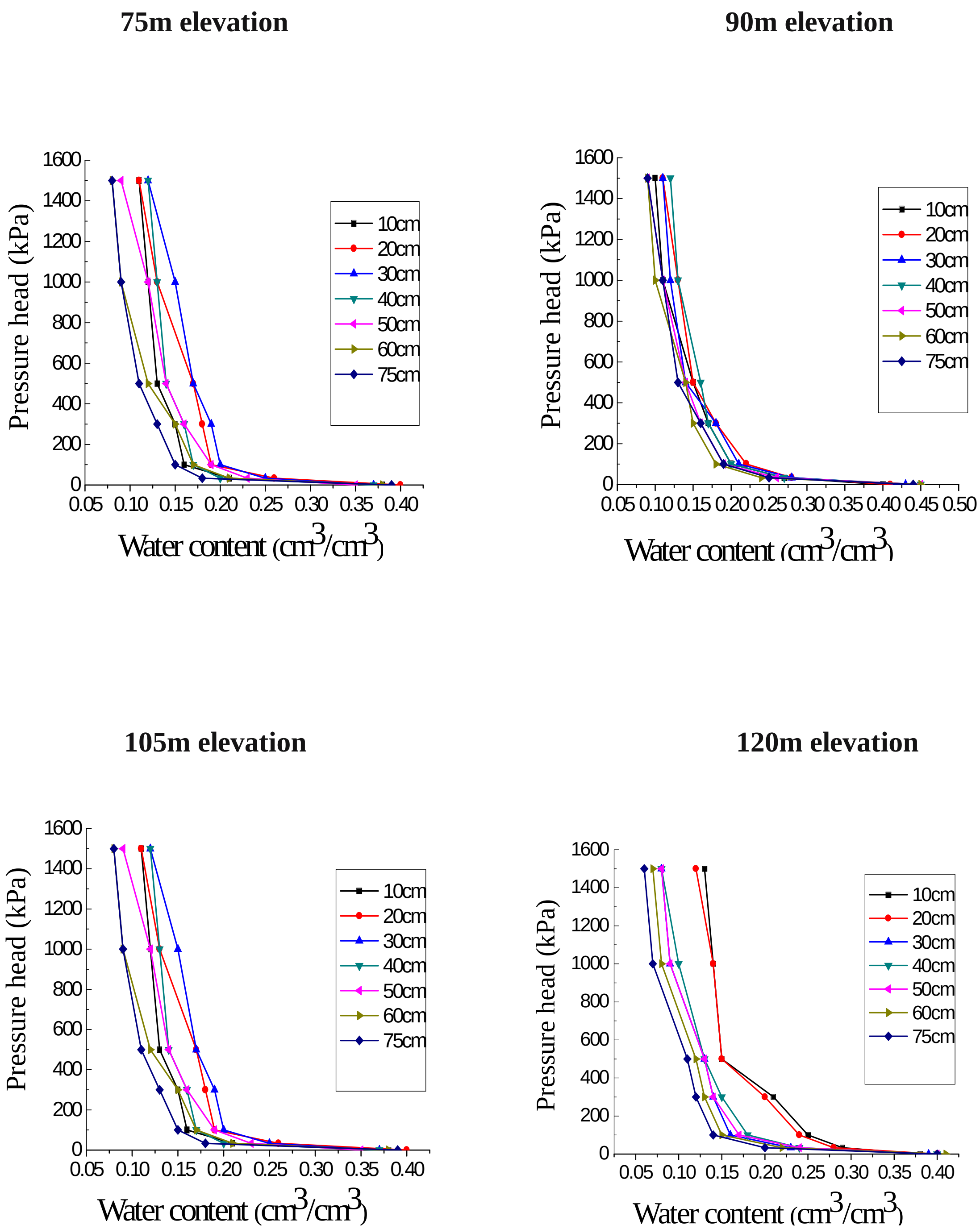
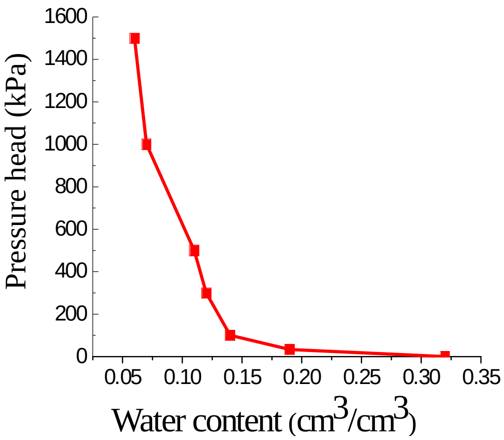
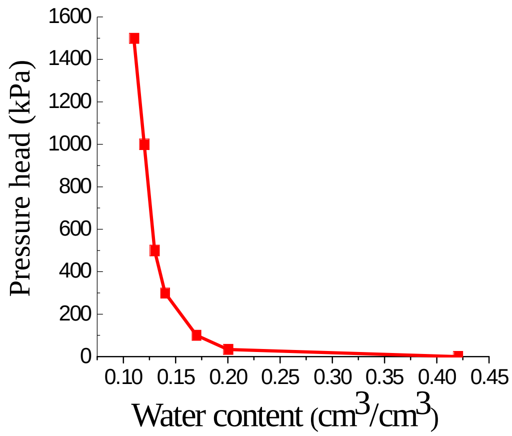
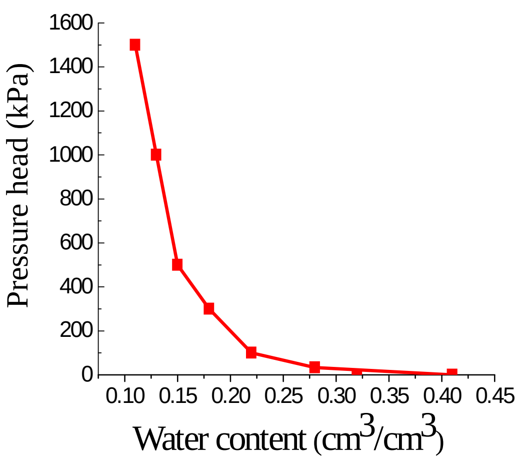


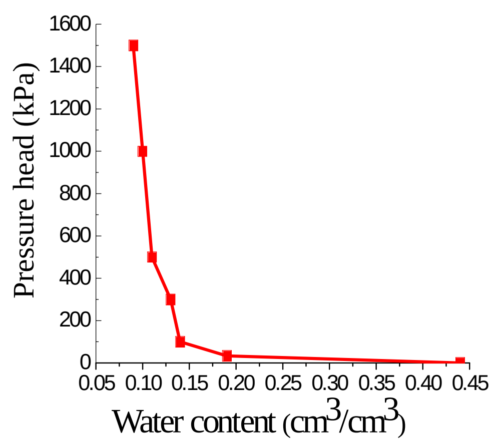
Figure 3.14: Soil water retention curves at different depths and elevations for forested hillslope soils

- **Loamy sand**

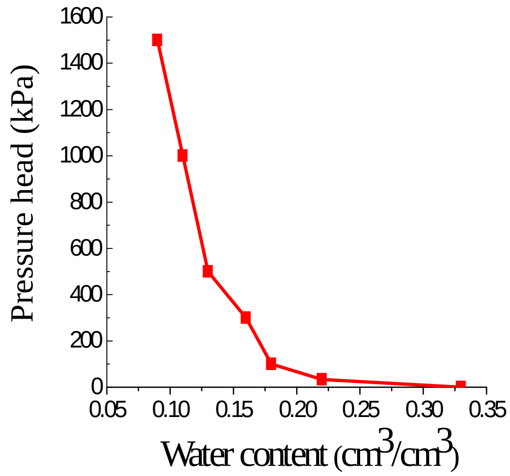

Pressure head (kPa)
Water content (cm3/cm3)

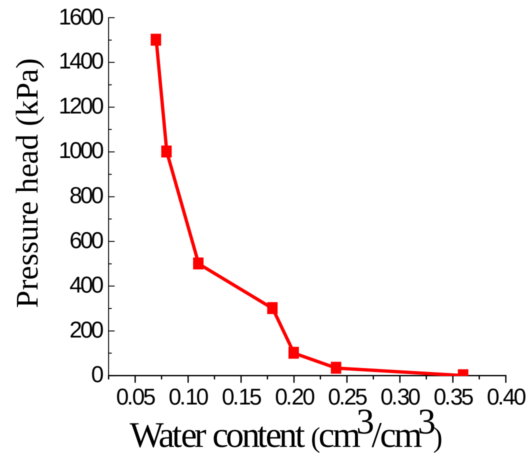

Pressure head (kPa)
Water content (cm3/cm3)

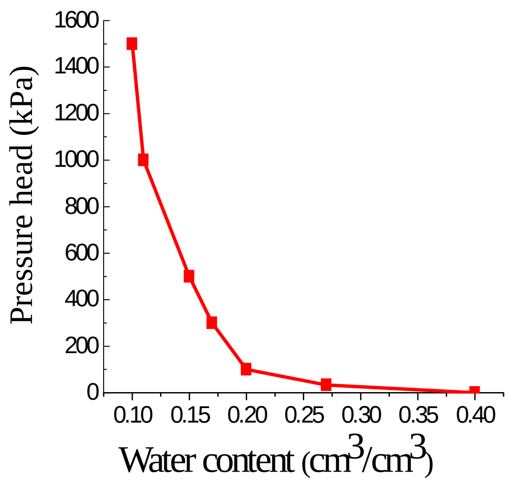

Pressure head (kPa)
Water content (cm3/cm3)

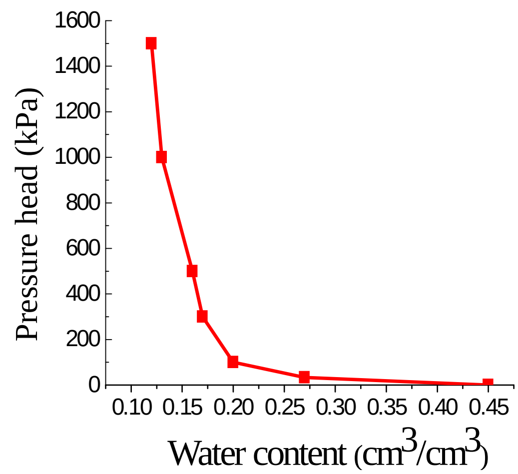

Pressure head (kPa)
Water content (cm3/cm3)

- **Sandy loam**


Pressure head (kPa)
Water content (cm3/cm3)


Pressure head (kPa)
Water content (cm3/cm3)


Pressure head (kPa)
Water content (cm3/cm3)


Pressure head (kPa)
Water content (cm3/cm3)

- **Sand**

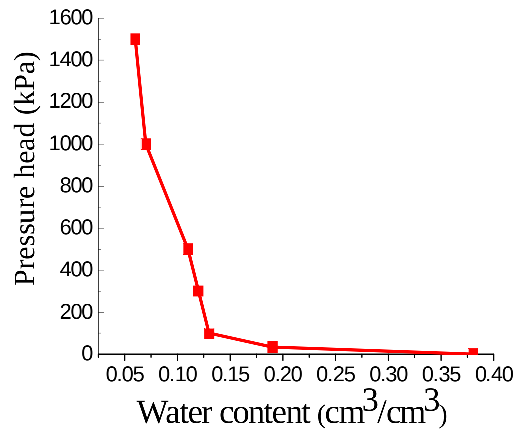


Figure 3.15: Soil water retention curves for different types of forested hillslope soils

CHAPTER 4

DEVELOPMENT OF PEDOTRANSFER FUNCTIONS FOR THE ESTIMATION OF SOIL WATER RETENTION CURVE

4.1 Introduction

As mentioned in chapter 1, knowledge of the soil hydraulic properties is indispensable to solve many soil and water management problems related to agriculture, ecology, and environmental issues. Soil hydraulic properties are key factors that regulate the movement of groundwater and transport of solutes. These properties are important inputs to hydrologic and water quality models. One of the most important hydraulic properties of soils is relationship between soil water content and soil matric potential, commonly referred to as soil water characteristic curve (SWCC) or soil water retention curve (SWRC) (van Genuchten, 1980).

Soil moisture retention curve describes relationship between soil water pressure (potential) and volumetric water content. As soil drains, the largest soil pores empty first, since the capillary forces are smallest in these pores. As the soil drains further, the maximum diameter of the water filled pores further decreases, corresponding with pores that have decreasing values for the pressure potential (water is held by larger capillary forces). The soil water potential is a soil variable controlling a large number of processes such as water infiltration, redistribution, evaporation, plant water uptake, and microbial activity. When the soil water potential measurement is combined with soil water content measurement, soil water retention curve is obtained.

Knowledge of soil water retention curve has main importance in agriculture since these properties have a significant effect on soil fertility, soil aeration, soil temperature, drainage, irrigation and cultivability (Puckett et al., 1985). When viewing soil as a water management system, soil water retention is a fundamental and important hydraulic property in modern agriculture. Soil water retention at field capacity (FC) and permanent wilting point (PWP) are used to estimate the water depth applied by irrigation (Hansen et al., 1980), and to calculate water availability, as a crucial factor to assess the land area suitability for crop producing. Upon conversion of natural lands to cultivated fields, water retention capacity is strongly influenced (Bormann and Klaassen, 2008; Zhou et al., 2008).

Forest soils differ significantly from the agricultural land in their distribution of the soil bulk density and humus content. Modeling the water circulation process in forest soils is important for the appropriate management of water resources for the prediction of slope failure caused by heavy rainfall, and for the analysis of the energy exchange process between forest and atmosphere. Forested hillslope is usually covered with forest soils, in which various types of water movement occur under the unsaturated condition. Water supplied by rainfall moves downward in the unsaturated soil profile to the ground water table. After rainfall ceases, some water moves upward to evaporate at the soil surface. Some water is extracted from the unsaturated soil by the root system of plants to be used for transpiration. The various studies have revealed that forest soil has peculiar pore radius distribution and hydraulic properties. It has been reported that the existence of macropores increases the permeability of forest soil and reduces the surface flow on forested hillslope (Kirkby, 1978).

The soil water retention capacity characterizes the water movement in the soil very well. However, soil water retention curve is not a readily available soil property primarily because of the cost and time of measurement especially with large scale (watershed and basin scale) applications. Instead of the direct measurement of soil water retention curve, PTFs (Bouma, 1989) have been developed to indirectly predict the soil water retention curve from more readily available soil properties such as, particle size distribution, organic matter content, porosity and bulk density. In most of the studies the water retention parameters are derived from the data of agricultural soils. Thus there is a need to relate physical parameters of forest soils with their water retention characteristics and compare them with those of agricultural soils. Therefore this study aimed to analyze the possibilities of soil water retention capacity estimations based on easily measurable soil properties for both agricultural and forested hillslope soils separately.

4.2 Estimation of soil water retention curve

4.2.1 Development of pedotransfer functions

PTFs are regression equations that relate readily available and easily measured soil physical and chemical properties to soil hydraulic properties. Many approaches such as regression analysis, artificial neural network and group method of data handling are used to develop PTFs. PTF is a tool for generating the soil water retention characteristics using a more or less complicated algorithm with combinations of the soil physical and chemical properties, primarily texture, bulk density and organic matter content. There are mainly three types of PTFs, used to predict the soil water characteristics from basic soil properties: i) point PTFs, ii) parametric PTFs, and iii) semi physical models. In this study, first two types of PTFs were developed to estimate soil water retention curve.

Type 1: Point pedotransfer functions

Point PTFs predict the soil water content at specific matric potentials as discrete points. There are no presuppositions about the shape of the soil water retention curve. Regression analysis that relates water contents at specific soil water pressure heads to soil texture, bulk density and organic matter content. In this study, point PTFs were developed to predict the water content at six matric potentials of -33, -100 ,-300, -500, -1000 and -1500 kPa, from the basic soil properties such as percentages of sand, silt and clay, bulk density, porosity and organic matter content using regression technique.

The general form of the multiple linear regression equations can be expressed as:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 \tag{4.1}$$

The general form of the extended non linear regression equations can be expressed as:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + b_5 X_5 + b_6 X_1^2 + b_7 X_2^2 + b_8 X_3^2 + b_9 X_4^2 + b_{10} X_5^2 + b_{11} X_1 X_2 + b_{12} X_2 X_3 + b_{13} X_3 X_4 + b_{14} X_4 X_5 + b_{15} X_5 X_1 \quad (4.2)$$

where Y represents the dependent variable such as water content at selected water potential or one of the parameters of the retention models, b_0 is the intercept, b_1, b_2, b_3, b_4, b_5 are the regression coefficients and X_1, X_2, X_3, X_4, X_5 are the independent variables representing the basic soil properties.

Type 2: Parametric pedotransfer functions

Parametric PTFs are more reliable to apply on hydrological models than point PTFs due to their continuous nature. Parametric PTFs for predicting soil water content are closed form equations to simulate the relationship between soil water retention and matric potential. The advantage of this is that the hydraulic characteristics are described as continuous curves, thus allowing the computation of hydraulic values at arbitrary pressures. In this method, point series of measured water retention data was fitted to an empirical closed form mathematical function.

The most often used functions are the Brooks and Corey function (1964), Campbell's function (1974), Mualem's function (1976a) and van Genuchten's function (1980). One weakness of the Brooks and Corey equation is the discontinuity in the derivative at air entry value. And also, approaches using the Brooks and Corey model fail to provide a realistic shape of the moisture characteristic curve in the wet range. This drawback has been removed in the van Genuchten's function, which is nowadays the most often used function in soil water balance models. Fuentes et al. (1992) concluded that van Genuchten's water retention function, θ(h), based on the Burdine (1953) theory together with the Brooks and Corey conductivity equation is valid for different types of soils without becoming inconsistent with the general water transfer theory. In this study the most popular and widely used closed form water retention relations, suggested by van Genuchten, (1980) (eqn. (4.3)) and Brooks and Corey, (1964) (eqn. (4.4)) were used.

$$\theta(h) = \frac{\theta_s - \theta_r}{\left(1 + |\alpha h|^n\right)^m} + \theta_r \qquad for \qquad h < 0 \tag{4.3}$$

$$\begin{aligned} \theta(h) &= \theta_r + (\theta_s - \theta_r)\left(\frac{h_b}{h}\right)^{\lambda} && for \quad 0 < h < h_b \\ &= \theta_s && for \quad h_b \le h \le 0 \end{aligned} \tag{4.4}$$

where θ, θ_s and θ_r are the volumetric water content, saturated water content and residual water content (cm^3/cm^3) respectively and h is the matric potential (kPa). In van Genuchten model, α is related to inverse of air entry pressure (kPa^{-1}), n is a curve fitting parameter that describes the slope of the pore-size distribution and m is empirical shape parameter, equal to 1-1/n. In Brooks and Corey model, the parameter h_b is the air entry value or bubbling pressure (kPa) and is assumed to be related to the maximum size of pores forming a continuous network of flow paths within the soil, λ is pore size distribution index (dimensionless).

The parameters were optimally estimated using a non linear least squares curve fitting procedure based on the Marquardt method as developed in the retention curve program for unsaturated soils (RETC), software package (van Genuchten et al., 1991). θ_r, θ_s, α, and n in van Genuchten, and θ_r, θ_s, h_b and λ in Brooks and Corey equation, were chosen as dependent variables to develop parametric PTFs using multiple linear and nonlinear regressions as follows:

1. Multiple linear regression equations relating the percent of sand (S), silt (Si), clay (C), bulk density (BD) and organic matter content (OM) as independent variables (eqn. (4.1)).
2. Nonlinear regression equations obtained from above variables with their combinations and various algorithmic transformations, such as lnC, BD^2, S^2, Si^2 etc (eqn. (4.2)).

4.2.2 Statistical performance criteria

In order to assess the performance of the developed PTFs, a statistical analysis has to be conducted. A common method to evaluate pedotransfer functions is to plot the measured values against the predicted values and the correlation between them is used for model evaluation (Givi et. al, 2004). In the present study, accuracy of the regression equations for PTFs was evaluated using coefficient of determination (R^2), root mean square error (RMSE), mean error (ME) and Akaike Information Criteria (AIC).

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2}{\sum_{i=1}^{n}\left(y_i - \overline{y}_i\right)^2} \tag{4.5}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2}{N}} \tag{4.6}$$

$$ME = \frac{\sum_{i=1}^{N}\left(y_i - \hat{y}_i\right)}{N} \tag{4.7}$$

$$AIC = N\,(\ln SSE) + 2\,Nv \tag{4.8}$$

where y_i denotes the measured value, $\hat{y}_i$ refers to the predicted value, $\overline{y}_i$ represents the average of the measured values of y, SSE is the sum of square of error between observed and predicted soil moisture contents, N_v is the number of independent variables included in the model, and N is the total number of observations.

Negative and positive values of ME indicate under-estimation and over-estimation of PTFs for given parameters, respectively. ME is a measure of prediction bias. RMSE is an absolute measure of the predictive accuracy of the model. It defines the expected magnitude of the prediction error. If the value of RMSE is smaller, then there will be smaller deviation or greater agreement between the predicted and measured values. The best condition yields the smallest RMSE and ME, and largest R^2. The regression models have different input requirements in terms of the number of soil properties to be specified a priori. A model may yield small errors at the cost of more parameters, and hence parameter parsimony is an important criterion in model selection. This factor may be accounted for in the AIC, which has been used in earlier model discrimination studies (Russo, 1988). A model with minimum AIC is considered best.

4.3 Results and discussions

4.3.1 Development of pedotransfer functions for agricultural soils

In the present study, soil sampling was carried out on agricultural land near the Pavanje river basin. The soil samples were collected from different locations at different soil profiles over a depth of 0-150 cm and at 20 cm intervals. The locations sampled were within 200-300 m of each other. Particle size distribution, bulk density, porosity, organic matter content and water retention characteristics of agricultural soils had been selected for developing point and parametric PTFs.

Laboratory measured soil water retention data were fitted to vG model (eqn. (4.3)) and B-C model (eqn. (4.4)). For each soil sample, the parameters θ_r (cm^3/cm^3), α (kPa^{-1}), h_b and λ were optimally estimated using a non linear least-squares curve fitting procedure based on the Marquardt method, as developed in the RETC software package (van Genuchten et al.,1991). For the initial estimate of the residual water content (θ_r), the value at permanent wilting point was taken. The saturated water content (θ_s) is often considered to be identical to the porosity, but in practice it could be smaller than the porosity because, in the field saturated condition, the pores are entrapped with air. Therefore θ_s was taken 0.93 times of soil porosity, for both the van Genuchten and Brooks -Corey model.

The Table 4.1 shows some statistics of fitted values of vG and B-C model parameter to measured soil water retention data. At first, all the parameters (θ_r, θ_s, α, n for vG model and θ_r, θ_s, h_b, λ for B-C model) were optimized using RETC software. Because of the poor results obtained, dropped out the idea of optimizing θ_s, n for vG model and θ_s, λ for B-C model and repeated the work on other parameters. The related descriptions are given in section 3.4.1. Figure 4.1 shows the soil water retention curve for four different types of soils for measured and fiited (vG model and B-C model) values.

Table 4.1: Descriptive statistics of fitted values of vG and B-C water retention model parameters for agricultural soils

Variables	van Genuchten model				Brooks-Corey model			
	θ_r (cm^3/cm^3)	θ_s (cm^3/cm^3)	α (cm^{-1})	n	θ_r (cm^3/cm^3)	θ_s (cm^3/cm^3)	h_b (cm)	λ
Min	0.02	0.35	0.02	1.274	0.02	0.35	3.6	0.274
Max	0.18	0.45	0.24	1.856	0.18	0.45	32.41	0.856
Mean	0.12	0.40	0.09	1.450	0.12	0.40	15.37	0.450
SD	0.06	0.03	0.08	0.130	0.06	0.03	9.42	0.120

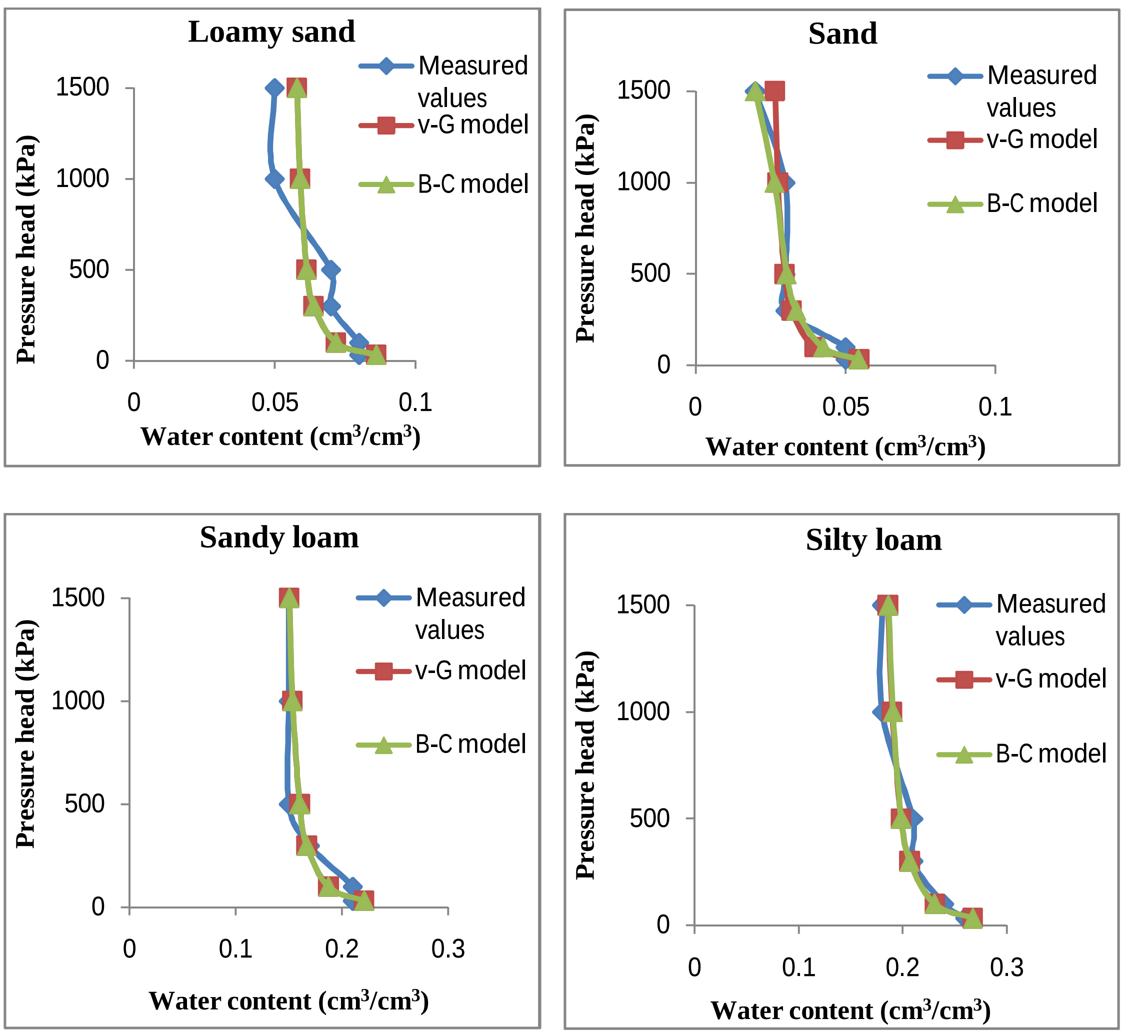


Figure 4.1: Soil water retention curves obtained from laboratory experiments, and fitted vG and B-C models for four different types of agricultural soils

The present study developed two types of PTFs (point and parametric). In both, multiple linear and non linear regression functions were used to relate specific soil water potential head values (-33, -100, -300, -500, -1000, and -1500 kPa) and vG and B-C model parameters (θ_r, θ_s, α, n for vG model and θ_r, θ_s, h_b, λ for B-C model) to basic soil properties (S, Si, C, BD, P and OM) in order to develop PTFs. The most significant input variables were determined and then linear, quadratic, and possible interaction terms of these basic soil properties were investigated. Descriptive statistics of physical and hydraulic properties used for the development of PTFs are summarized in Table 4.2.

Table 4.2: Descriptive statistics of agricultural soil properties to develop PTFs

Variables	**Calibration data set**				**Validation data set**			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Physical Properties								
S	41	89	62.93	14.64	41	80	51.94	12.77
Si	10	52	28.96	12.37	19	45	33.94	9.26
C	1	5	1.89	1.25	1	2	1.17	0.38
BD	1.36	1.69	1.51	0.08	1.43	1.61	1.53	0.07
OM	0.24	2.52	0.88	0.57	0.28	1.64	0.86	0.38
P	0.33	0.44	0.4	0.02	0.33	0.44	0.38	0.04
Soil water retention data								
θ_{33}	0.05	0.29	0.18	0.09	0.18	0.28	0.23	0.04
θ_{100}	0.05	0.27	0.18	0.09	0.13	0.23	0.19	0.03
θ_{300}	0.03	0.24	0.16	0.08	0.12	0.20	0.16	0.03
θ_{500}	0.03	0.24	0.15	0.07	0.11	0.18	0.15	0.03
θ_{1000}	0.03	0.21	0.13	0.07	0.10	0.17	0.14	0.03
θ_{1500}	0.02	0.19	0.12	0.06	0.08	0.16	0.13	0.03
van Genuchten model parameters								
θ_r	0.02	0.18	0.12	0.06	0.11	0.15	0.14	0.02
θ_s	0.35	0.41	0.39	0.02	0.32	0.41	0.37	0.03
α	0.02	0.24	0.09	0.08	0.01	0.05	0.02	0.05
n	1.27	1.86	1.45	0.13	1.19	1.36	1.29	0.08
Brooks-Corey model parameters								
θ_r	0.02	0.18	0.12	0.06	0.11	0.15	0.13	0.02
θ_s	0.31	0.41	0.39	0.02	0.32	0.41	0.37	0.03
h_b	3.60	32.41	15.37	9.42	4.57	35.68	14.78	8.97
λ	0.27	0.86	0.45	0.11	0.19	0.36	0.29	0.08

where S, Si, C are sand, silt, clay fractions (%), respectively, BD is bulk density (g/cm^3), OM is organic matter content (%), P is porosity (cm^3/cm^3), θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of -33, -100, -300, -500, -1000 and -1500 kPa, respectively, θ_r and θ_s are residual and saturated soil water contents (cm^3/cm^3) respectively, α is the inverse of air entry pressure head (cm^{-1}), h_b is air entry pressure head (cm), λ is pore size index and n is the empirical shape parameters, SD is standard deviation.

Approximately two third of the data was used for calibration and the remaining data was used for validation. At first, multiple linear regression equations have been developed by considering all the basic soil properties as the input to the equation and next tried with only particle size distribution factors such as percentages of sand, silt and clay, and finally with sand, BD and OM as the input. Vereecken et al. (1989) concluded that water retention characteristics can be estimated to a reasonable level of accuracy from such simple soil properties as particle size distribution, dry bulk density and carbon content. Williams et al. (1992) found that models which included even one known value of soil water content-matric potential relationship are much more valid than those based on soil texture and bulk density alone.

PTFs developed for the estimation of water contents at selected water potentials (point PTFs) and parameters of vG and B-C water retention models (parametric PTFs) by using multiple linear regressions are presented in Table 4.3. The general forms of the regression equations developed are as follows:

$$Y = b_0 + b_1 Sand + b_2 Silt + b_3 Clay + b_4 BD + b_5 OM \tag{4.9}$$

$$Y = b_0 + b_1 Sand + b_2 Silt + b_3 Clay \tag{4.10}$$

$$Y = b_0 + b_1 Sand + b_2 BD + b_3 OM \tag{4.11}$$

In terms of the coefficient of determination (R^2), multiple linear regressions predicted θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000}, θ_{1500} and parameters for θ_r and θ_s adequately, but the parameters α, n, h_b and λ were predicted very poorly. Measurement errors might also lead to poor prediction of the parameters (Tomasella et al. 2003). Minasny et al. (1999) inferred that linear regression could not be used to predict van Genuchten parameters because there is no linear relationship between the parameters and soil properties.

Table 4.3: Linear regression coefficients for predicting soil water retention curves for agricultural soils

Variables	b_0	b_1*% Sand	b_2*% Silt	b_3*% Clay	b_4* BD	b_5*% OM	R^2
	Water contents at specific matric potentials (Point PTFs)						
θ_{33}	0.326	-0.00456	0.00232	-0.00637	0.06951	-0.01028	0.98
	0.413	-0.00436	0.00210	-0.00549	-	-	0.98
	0.622	-0.00515	-	-	-0.07887	-0.00186	0.96
θ_{100}	0.337	-0.00437	0.00232	-0.00433	0.04631	-0.00788	0.97
	0.394	-0.00423	0.00218	-0.00370	-	-	0.97
	0.617	-0.00494	-	-	-0.08893	-0.00059	0.95
θ_{300}	0.412	-0.00386	0.00197	-0.00356	-0.03209	-0.01146	0.97
	0.345	-0.00380	0.00212	-0.00333	-	-	0.97
	0.648	-0.00434	-	-	-0.146	-0.00534	0.95
θ_{500}	0.321	-0.00395	0.00168	-0.00602	0.03932	-0.01719	0.96
	0.352	-0.00373	0.00158	-0.00507	-	-	0.95
	0.546	-0.00439	-	-	-0.07732	-0.01030	0.94
θ_{1000}	0.260	-0.00348	0.00167	-0.00581	0.04323	-0.00676	0.96
	0.314	-0.00335	0.00154	-0.00524	-	-	0.96
	0.483	-0.00392	-	-	-0.071775	0.000003	0.94
θ_{1500}	0.332	-0.00341	0.00089	-0.00496	-0.00728	-0.00139	0.98
	0.319	-0.00341	0.00093	-0.00496	-	-	0.98
	0.467	-0.00366	-	-	-0.08118	0.00328	0.97
	van Genuchten model Parameters (Parametric PTFs)						
θ_r	0.406	-0.00298	0.00041	-0.00433	-0.06976	-0.00225	0.97
	0.298	-0.00306	0.00067	-0.00472	-	-	0.96
	0.484	-0.00311	-	-	-0.117	0.00105	0.96
θ_s	0.925	-0.00003	-0.00008	-0.00215	-0.34176	-0.00124	0.99
	0.413	-0.000534	0.00114	-0.00446	-	-	0.6
	0.934	-0.00004	-	-	-0.35192	-0.00022	0.98
α	-0.051	0.00403	-0.00218	0.00243	-0.03573	-0.00402	0.9
	-0.111	0.00401	-0.00204	0.00234	-	-	0.9
	-0.300	0.00454	-	-	0.08058	-0.00995	0.89
n	2.061	0.00490	-0.00757	0.00816	-0.530	0.06288	0.66
	1.370	0.00349	-0.00585	0.00202	-	-	0.61
	1.197	0.00669	-	-	-0.128	0.04244	0.57
	Brooks-Corey model Parameters (Parametric PTFs)						
θ_r	0.399	-0.00301	0.00045	-0.00436	-0.06421	-0.00247	0.97
	0.299	-0.00308	0.00069	-0.00470	-	-	0.97
	0.482	-0.00316	-	-	-0.114	0.00092	0.96
h_b	-13.07	-0.604	-0.01713	-1.361	44.66	0.866	0.84
	55.03	-0.545	-0.179	-1.087	-	-	0.78
	-3.768	-0.615	-	-	36.55	1.594	0.82
λ	1.019	0.00490	-0.505	0.05770	-0.00717	0.00830	0.65
	0.358	0.00358	-0.00553	0.00254	-	-	0.61
	0.196	0.00660	-	-	-0.120	0.03802	0.58

This problem can be solved by using nonlinear regression equation (Minasny et al. 1999). Therefore, in order to improve R^2 values, nonlinear regression equations were considered. R^2 gives the proportion of variation in the parameters, i.e. the proportion of the difference on any of the response values that can be interpreted in terms of difference among the corresponding values of the prediction. In fact, it is the squared correlation between the predictor and the response and is a relative measure of what the model has accomplished. In a multiple regression, larger the value of the set of input variable collections, better the prediction of the dependent variable if the value of R^2 is larger.

In nonlinear regression equations, different combinations of input variables to improve the efficiency of the models have been tried. For the point PTFs, the same input variables, e.g. sand, silt and bulk density, were used at the indicated matric pressure heads, and it was observed that the point PTFs had a good relationship with the basic soil properties. In vG model both residual (θ_r) and saturated water contents (θ_s) showed the better efficiency than the shape factors α and n. For θ_r, the present study considered sand, silt and bulk density, and for θ_s, sand, bulk density and organic matter content as the input variables. For B-C model also, θ_r showed better results than the h_b and λ values. Here sand, BD and OM were used as the input variables for θ_r values. For α, h_b and λ values, sand silt and OM were considered. The developed nonlinear regression equations with different input combinations are shown in the Table 4.4.

Table 4.4: PTFs (non linear) developed for the estimation of soil water retention curves for agricultural soils

Pedotransfer functions developed	**R^2**	**AIC**
Water contents at specific matric potentials (Point PTFs)		
$\theta_{33} = -4.263 + 0.00194 * S + 0.02839 * Si + 5.568 * BD - 0.00005 * S^2 - 0.00011 * S * Si + 0.00106 * S * BD - 0.00005 * Si^2 - 0.01158 * Si * BD - 1.780 * BD^2$	0.98	-146.614
$\theta_{100} = -2.081 - 0.00776 * S + 0.00589 * Si + 3.452 * BD - 0.00007 * S^2 - 0.00018 * S * Si + 0.01047 * S * BD + 0.0000003 * Si^2 + 0.00402 * Si * BD - 1.400 * BD^2$	0.98	-140.580
$\theta_{300} = -2.029 - 0.00039 * S + 0.02393 * Si + 2.859 * BD - 0.00007 * S^2 - 0.000178 * S * Si + 0.00614 * S * BD - 0.000150 * Si^2 - 0.00352 * Si * BD - 1.092 * BD^2$	0.98	-144.951
$\theta_{500} = -1.079 + 0.01539 * S + 0.02272 * Si + 0.961 * BD - 0.00009 * S^2 - 0.00021 * S * Si - 0.00275 * S * BD - 0.000171 * Si^2 - 0.00146 * Si * BD - 0.287 * BD^2$	0.96	-133.080
$\theta_{1000} = -2.488 - 0.01215 * S + 0.00750 * Si + 4.051 * BD - 0.00007 * S^2 - 0.00016 * S * Si + 0.01333 * S * BD + 0.00002 * Si^2 + 0.00131 * Si * BD - 1.633 * BD^2$	0.97	-147.007
$\theta_{1500} = -1.076 - 0.00234 * S - 0.00334 * Si + 1.920 * BD - 0.00003 * S^2 + 0.00003 * S * Si + 0.00101 * S * BD + 0.00006 * Si^2 - 0.00077 * Si * BD - 0.666 * BD^2$	0.98	-154.596
van Genuchten model Parameters (Parametric PTFs)		
$\theta_r = 1.004 - 0.00286 * S - 0.01348 * Si - 0.572 * BD - 0.00004 * S^2 + 0.00001 * S * Si + 0.00306 * S * BD + 0.00001 * Si^2 + 0.00832 * Si * BD + 0.01413 * BD^2$	0.97	-152.485
$\theta_s = 0.760 + 0.00319 * S - 0.29801 * BD + 0.08499 * OM + 0.00001 * S^2 - 0.00294 * S * BD + 0.00007 * S * OM + 0.06126 * BD^2 - 0.06824 * BD * OM + 0.005 * OM^2$	0.99	-229.911
$\alpha = 0.923 - 0.03433 * S - 0.01367 * Si + 0.12629 * OM + 0.00027 * S^2 + 0.00045 * S * Si - 0.00171 * S * OM - 0.00016 * Si^2 + 0.00071 * Si * OM - 0.02398 * OM^2$	0.92	-109.566
$n = -33.82 + 0.171 * Si + 44.43 * BD - 1.611 * OM + 0.00108 * Si^2 - 0.139 * Si * BD - 0.02981 * Si * OM - 13.87 * BD^2 + 1.544 * BD * OM + 0.08174 * OM^2$	0.86	-71.312
Brooks-Corey model Parameters (Parametric PTFs)		
$\theta_r = 0.428 + 0.00345 * S - 0.463 * BD + 0.359 * OM - 0.00001 * S^2 - 0.00425 * S * BD + 0.00180 * S * OM + 0.273 * BD^2 - 0.317 * BD * OM + 0.00587 * OM^2$	0.97	-154.881
$h_b = -7.766 - 1.582 * S + 5.548 * Si + 28.38 * OM + 0.01667 * S^2 - 0.02579 * S * Si - 0.407 * S * OM - 0.06874 * Si^2 - 0.345 * Si * OM + 3.344 * OM^2$	0.84	165.379
$\lambda = -0.613 + 0.04239 * S - 0.01461 * Si + 0.295 * OM - 0.00029 * S^2 - 0.00052 * S * Si + 0.00425 * S * OM + 0.0010 * Si^2 - 0.02484 * Si * OM + 0.0970 * OM^2$	0.84	-67.707

where θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of -33, -100, --300, -500, -1000 and -1500 kPa, respectively, S, Si are sand and silt fractions (%), BD is bulk density (g/cm^3), OM is organic matter content (%), θ_r and θ_s are residual and saturated soil water contents (cm^3/cm^3), respectively, α and n are vG model parameters, h_b and λ are B-C model parameters. R^2 is coefficient of determination, AIC is Akaike Information Criteria.

Statistical evaluation

The performances of point and parametric PTFs (van Genuchten and Brooks–Corey) in predicting the measured or fitted data were evaluated using R^2, RMSE and ME. Calibration and validation accuracies of PTFs among measured or fitted and predicted water contents, together with model parameters are shown in Table 4.5. All three statistical measures were used to compare the water content at several suction points and van Genuchten and Brooks–Corey model parameters. Application of the two methods (point and parametric) to estimate soil water retention gave different results, even though the equation to fit water retention curves and soil properties as predictors is the same for both methods.

Table 4.5: Calibration and validation accuracies of developed PTFs for agricultural soils

Variables	Calibration			Validation		
	R^2	RMSE	ME	R^2	RMSE	ME
Soil water retention data						
θ_{33}	0.983	0.0114	0.0000	0.517	0.0100	0.0003
θ_{100}	0.977	0.0127	0.0000	0.835	0.0108	0.0004
θ_{300}	0.976	0.0118	0.0000	0.648	0.0074	0.0002
θ_{500}	0.960	0.0146	0.0000	0.558	0.0124	0.0005
θ_{1000}	0.971	0.0113	0.0000	0.626	0.0140	0.0006
θ_{1500}	0.976	0.0098	0.0000	0.633	0.0055	0.0001
vG model Parameters						
θ_r	0.967	0.0102	0.0000	0.823	0.0059	-0.0013
θ_s	0.991	0.0024	0.0000	0.985	0.0037	-0.0013
α	0.923	0.0226	0.0000	0.749	0.0815	-0.0062
n	0.861	0.0459	0.0000	0.524	0.2407	-0.1628
B-C model Parameters						
θ_r	0.970	0.0098	0.0000	0.617	0.0168	0.0029
h_b	0.841	0.3682	0.0000	0.578	0.3755	-0.0036
λ	0.838	0.0492	0.0000	0.595	0.1666	-0.1105

where θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of -33, -100, -300, -500, -1000 and -1500 kPa, respectively, θ_r and θ_s are residual and saturated soil water contents (cm^3/cm^3) respectively, α and n are vG model parameters, h_b and λ are B-C model parameters. R^2 is coefficient of determination, RMSE is root mean square error, ME is mean error.

The accuracy of each method was slightly better with the calibration data than with the validation data. The higher R^2 values indicated that water content held at different matric potentials was polynomially correlated to each other. The Table 4.5 also showed that water content at higher and lower matric potentials (degree of saturation) was strongly correlated with water content at field capacity and permanent wilting point, respectively, following a polynomial in higher variables.

Ahuja et al. (1985) applied the point based estimation to the Southern plain database and obtained the RMSE of accuracy 0.05 cm^3/cm^3. Schaap and Leij (1998) applied the parametric estimation method to three databases and obtained an overall RMSE 0.1 cm^3/cm^3. In this study, the RMSE value obtained for the point based estimation is 0.01 cm^3/cm^3 for both calibration and validation sets. Pachepsky et al. (1996) reported relatively higher prediction accuracies ($0.738 \leq R^2 \leq 0.984$) between measured and predicted water contents at eight selected water potentials. Similarly, Batjes (1996) developed PTFs for water contents at 10 different water potentials with equation accuracies of $0.880 \leq R^2 \leq 0.940$. Vereecken et al. (1992) found estimation accuracies of PTFs for van Genuchten parameters in the range $0.560 \leq R^2 \leq 0.848$. Wösten et al. (1995) derived PTFs for estimation of these parameters in sandy soils with the accuracy of R^2 = 0.71, 0.53 and 0.63 for θ_r, α and n, respectively. Tomasella et al. (2000) also developed regression PTFs for Brazilian soils with the R^2 values of 0.83, 0.84, 0.41 and 0.37 for θ_r, θ_s, α and n, respectively.

These results indicate that the prediction accuracies of parametric PTFs are generally lower, than that of the point predictions, possibly due to the collection of data from relatively large area where spatial variability exists in soil properties. In this study, relatively better prediction accuracies of $0.960 \leq R^2 \leq 0.983$ between measured and predicted water contents at six selected water potentials have been observed. The accuracies of van Genuchten model parameters were 0.967, 0.991, 0.923 and 0.861 for θ_r, θ_s, α and n, respectively and those for Brook sand Corey model, 0.970, 0.841 and 0.838 for θ_r, h_b and λ, respectively.

The accuracies of predicted soil water retention using three different models at selected water potentials on water retention curves are presented in Table 4.6 for both calibration and validation sets. The higher values of R^2 and lower values of RMSE and ME for point models as compared to those representing parametric models showed that the developed point PTFs estimated water content better than the other two models. Several factors might contribute to the superiority of the point method over the parametric method in this work. Differences in the data used did not contribute, because the same data set was used to calibrate and validate both methods. Also both point and parametric data were optimized using the sum of squared differences between measured and simulated water contents.

Table 4.6: Accuracies of soil water retention prediction obtained from developed PTFs for agricultural soils

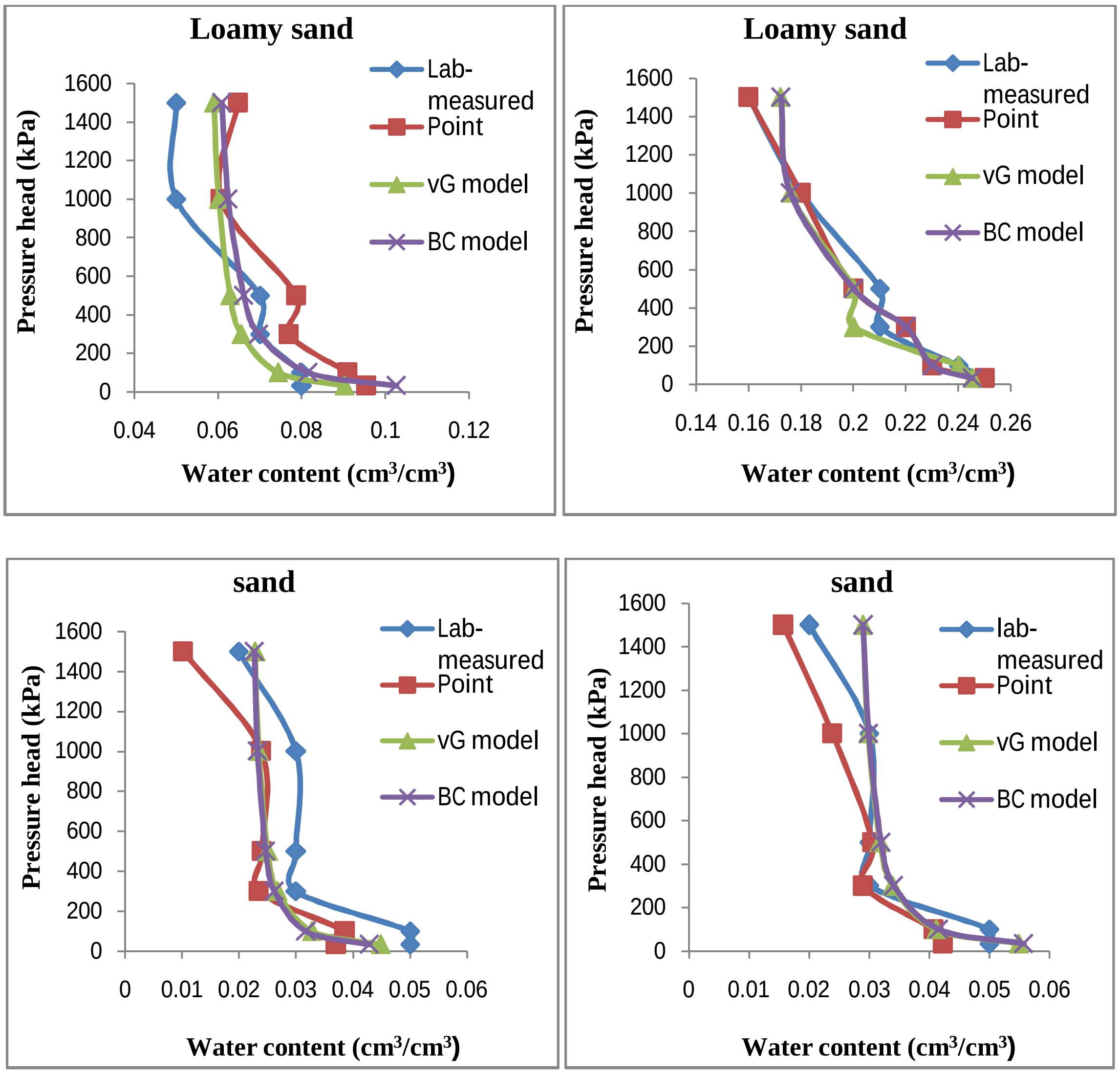
θ(h)	**R^2**			**RMSE**			**ME**		
	Point	vG	B-C	Point	vG	B-C	Point	vG	B-C
Calibration data set									
θ_{33}	0.983	0.958	0.974	0.0114	0.0176	0.0139	0.0000	0.0003	0.0002
θ_{100}	0.977	0.959	0.922	0.0127	0.0167	0.0232	0.0000	0.0003	0.0005
θ_{300}	0.976	0.970	0.947	0.0118	0.0132	0.0176	0.0000	0.0002	0.0003
θ_{500}	0.960	0.962	0.947	0.0146	0.0144	0.0169	0.0000	0.0002	0.0003
θ_{1000}	0.971	0.976	0.976	0.0113	0.0103	0.0104	0.0000	0.0001	0.0001
θ_{1500}	0.976	0.934	0.950	0.0098	0.0159	0.0138	0.0000	0.0003	0.0002
Validation data set									
θ_{33}	0.733	0.697	0.613	0.0152	0.0100	0.0258	-.0051	0.0003	0.0007
θ_{100}	0.787	0.835	0.737	0.0353	0.0108	0.0335	0.0084	0.0004	0.0011
θ_{300}	0.876	0.748	0.806	0.0431	0.0074	0.0253	0.0413	0.0002	0.0006
θ_{500}	0.784	0.758	0.659	0.0484	0.0124	0.0213	0.0452	0.0005	0.0005
θ_{1000}	0.724	0.726	0.677	0.0511	0.0140	0.0162	-0.0041	0.0006	0.0003
θ_{1500}	0.756	0.633	0.658	0.0192	0.0055	0.0095	0.0044	0.0001	0.0001

where θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of -33, -100, -300, -500, -1000 and -1500 kPa, respectively, point is point prediction, vG is van Genuchten model, B-C is Brooks-Corey model, R^2 is coefficient of determination, RMSE is root mean square error, ME is mean error.

It is therefore theoretically possible that a regression-based method would perform better on point data than on parametric data. It is well known that a group of basic soil properties is more important in the wet range of the water retention curve, whereas other properties control the variability in the dry range. Shape parameters for the analytical water retention curve; by contrast describe its behavior in both the dry and wet range. Therefore, the most acceptable explanation for the better performance of the point over the parametric method might be that the relationship between water-retention parameters and basic soil properties is too complex to be represented as a function.

Schaap and Bouten (1996) observed little difference between these two methods. However, their database consisted mostly of coarse soils. The present study found similar observations for the sandy soils. This study also observed a need to improve parameter estimates by refitting the van Genuchten equation to the actual data points. Of course, difficulties in measuring soil hydraulic properties might affect the estimation. The analysis performed here suggests that more input variables are needed to improve the prediction of the water retention curve and differences between the field and laboratory water retention data might be associated with sample quality, spatial variation, hysteresis, scale effects, etc. Prediction of the soil water retention curve using PTFs by the point estimation method for soils in the sampled region of India has considerable relative accuracy (best case R^2 = 0.983), whereas the parametric estimation method (van Genuchten and Brooks–Corey models) gives less accurate prediction of the parameters. Even though, the point estimation method needs fewer input variables to predict the water retention curve with relatively better accuracy (high R^2 and low RMSE), parametric estimation of the water retention curve using either of the water retention models with better accuracy is preferred, especially for producing continuous functions of water retention used in water and solute transport modeling.

The graphs (Figure 4.2) were plotted for the comparison of the soil water retention curve obtained from four different methods (laboratory, point estimation method, van Genuchten and Brooks–Corey water retention models) for the four different types of soils of the Pavanje river basin.



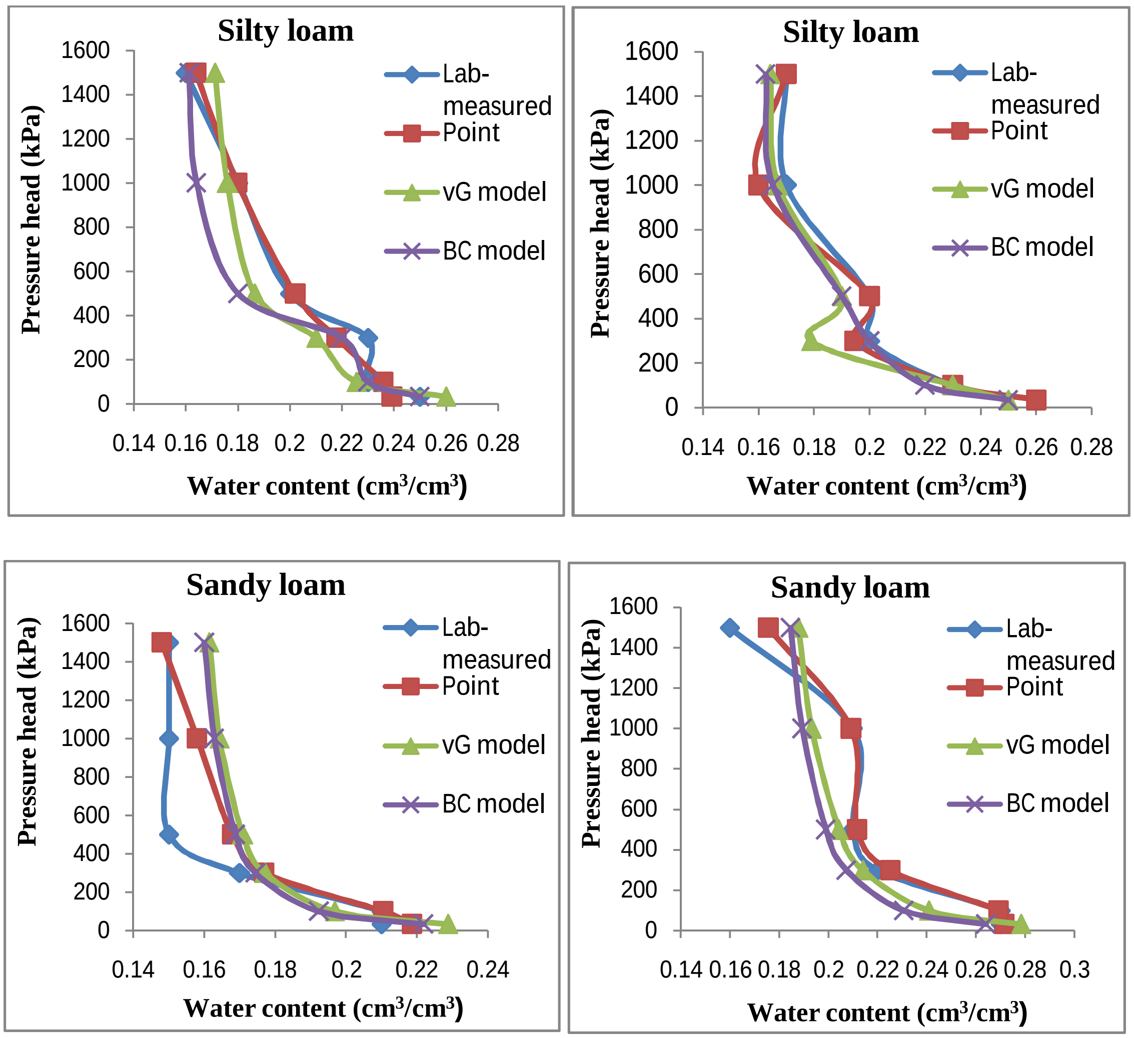


Figure 4.2: Soil water retention curves obtained from laboratory experiments, point PTFs, vG and BC models for four different types of agricultural soils

As explained earlier, there was no significant difference among the three methods in predicting water retention curves, but the point based method was found to be superior to the parametric method of PTF development for Pavanje river basin soils. In point estimation, limited discrete points on water retention curves are estimated; otherwise, the method is time consuming and requires intensive effort, especially for large and spatially variable land. However, parametric estimation methods yield continuous water retention functions with less time and effort.

4.3.1.1 Pedotransfer functions for agricultural soil: Comparison between existing and developed models

Existing PTFs for estimating soil water retention curve in the literature are not usually applicable in other regions with acceptable accuracy (Tietje and Tapkenhinrichs, 1993; Kern, 1995 and Nemes et al., 2003). But still a comparative study of the modeled PTFs with that of existing ones can be considered to gauge the improvement of degree of efficiency in the proposed model. In this context, the present study considered the following four models proposed by Gupta & Larson, (1979); Rawls et al., (1982); Masutti, (1997) and Oliveira et al., (2002) as shown in Table 4.7. These PTFs were taken from the different geographical regions but of same soil texture. The estimated soil water content for each model was correlated with the corresponding measured ones.

Table 4.7: Point pedotransfer functions taken from the literature for comparative analysis

Literature source	Tension (kPa)	Model
Gupta & Larson (1979)	33	$\theta = 0.00308 * \text{Sand} + 0.00589 * \text{Silt} + 0.00804 * \text{Clay} + 0.00221 * \text{OM} - 0.143 * \text{BD}$
	1500	$\theta = 0.000059 * \text{Sand} + 0.00114 * \text{Silt} + 0.00577 * \text{Clay} + 0.00223 * \text{OM} - .0267 * \text{BD}$
Rawls et al. (1982)	33	$\theta = 0.258 - 0.002 * \text{Sand} + 0.0036 * \text{Clay} + 0.0299$
	1500	$\theta = 0.026 - 0.005 * \text{Clay} + 0.016 * \text{OM}$
Masutti (1997)	33	$\theta = -1.569 + 0.429 * (\text{Silt} + \text{Clay})$
	1500	$\theta = -0.530 + 0.301 * \text{Silt} + 0.0928 * \text{Clay}$
Oliveira et al. (2002)	33	$\theta = 0.00333 * \text{Silt} + 0.00387 * \text{Clay}$
	1500	$\theta = -0.00038 * \text{Sand} + 0.00153 * \text{Silt} + 0.00341 * \text{Clay} - 0.0309 * \text{BD}$

where θ_{33} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of -33 kPa and -1500 kPa respectively, Sand, silt and clay are fractions of soil (%), OM is organic matter content(%), BD is bulk density in g /cm^3.

The PTFs can be generated when the particle size distribution, bulk density and organic matter content are known. Firstly, multiple linear regression equations were used for the development of PTFs by considering all the basic soil properties as input to the equation and next tried with only particle size distribution factors such as percentages of sand, silt and clay, and finally with sand, BD and OM as inputs. In terms of coefficient of determination (R^2), multiple linear regressions had highly representative for θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} for all three types of PTFs.

The present study deals with the set of multiple linear regression equations with percentages of sand, silt, clay, bulk density and organic matter content as inputs for the analysis because of its good accuracy. The independent variables included here were same as that of model presented by Gupta & Larson, (1979) and Rawls et al., (1982). The point PTFs developed by using multiple linear regression equations are shown in Table 4.8.

Table 4.8: Point pedotransfer functions developed using multiple linear regressions

Pedotransfer functions developed	$\mathbf{R^2}$
$\theta_{33} = .0.326 - 0.0046 * Sand + 0.0023 * Silt - 0.0064 * Clay + 0.0695 * BD - 0.0103 * OM$	0.98
$\theta_{100} = 0.337 - 0.0044 * Sand + 0.0023 * Silt - 0.0043 * Clay + 0.0463 * BD - 0.0079 * OM$	0.97
$\theta_{300} = 0.412 - 0.0039 * Sand + 0.0019 * Silt - 0.0036 * Clay - 0.0321 * BD - 0.0115 * OM$	0.97
$\theta_{500} = 0.321 - 0.0039 * Sand + .0.0017 * Silt - 0.0060 * Clay + 0.0393 * BD - 0.0172 * OM$	0.96
$\theta_{1000} = 0.260 - 0.0035 * Sand + 0.0017 * Silt - 0.0058 * Clay + 0.0432 * BD - 0.0068 * OM$	0.96
$\theta_{1500} = 0.332 - 0.0034 * Sand + 0.0009 * Silt - 0.0045 * Clay - 0.0073 * BD - 0.0014 * OM$	0.98

where θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of -33, -100, -300, -500, -1000 and -1500 kPa respectively, R^2 is coefficient of determination.

To evaluate the accuracy of the model developed, the estimated water contents were compared with those measured from the laboratory for the pressure heads of -33, -100, -300, -500, -1000 and -1500 kPa. The results were analyzed by the statistical tools like coefficient of determination R^2, the root mean square error RMSE and mean error ME. Calibration and validation accuracies of developed point PTFs between measured and predicted water contents are shown in Table 4.9.

Table 4.9: Calibration and validation accuracies of developed point PTFs between measured and predicted ones

Variables	Calibration			Validation		
	R^2	RMSE	ME	R^2	RMSE	ME
θ_{33}	0.983	0.0114	0.0000	0.517	0.0100	0.0003
θ_{100}	0.977	0.0127	0.0000	0.835	0.0108	0.0004
θ_{300}	0.976	0.0118	0.0000	0.648	0.0074	0.0002
θ_{500}	0.960	0.0146	0.0000	0.558	0.0124	0.0005
θ_{1000}	0.961	0.0113	0.0000	0.626	0.0140	0.0006
θ_{1500}	0.982	0.0098	0.0000	0.633	0.0055	0.0001

where θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of -33, -100, -300, -500, -1000 and -1500 kPa respectively, R^2 is coefficient of determination, RMSE is root mean square error, ME is mean error

Accuracy of point estimation method for calibration data set was slightly better than validation accuracies. The RMSE value for point based estimation was about 0.01(cm^3/cm^3) for both calibration and validation sets. The prediction accuracies of R^2 was relatively high i.e., (0.96-0.98) and (0.52-0.84) for calibration and validation sets respectively between measured and predicted water contents at six selected water potentials. ME value was zero for the calibration sets and very small error was there in validation sets. It is well known that a group of basic soil properties are more important in the wet range of the water retention curve, while other properties control the variability on the dry range.

Validation with pedotransfer functions from the literature

In this study, four different models from the literature were considered, shown in Table 4.7. The descriptive statistics of the soil properties used for developing the PTFs are presented in Table 4.2. The soil properties measured from the study area were substituted to these four models and the results obtained were compared with the soil water content measured in the laboratory for the pressure heads of -33 kPa and -1500 kPa (Table 4.10).

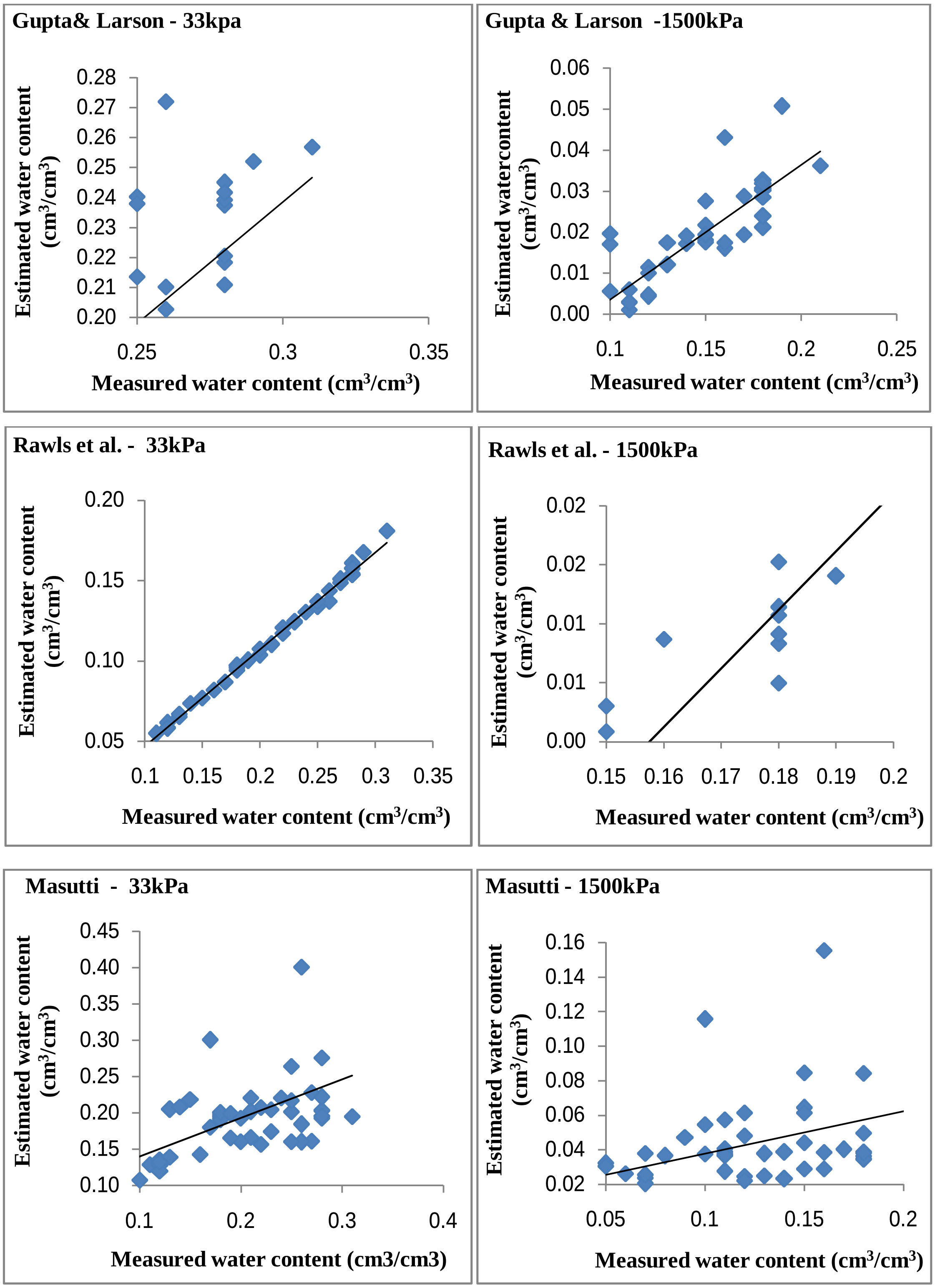
Of these four models, Rawls et al., (1982) at a pressure head of -33 kPa, Oliveira et al., (2002), at pressure head of -33 kPa and -1500 kPa estimated water retention best. With the exception of the model of Masutti, (1997) at a pressure head of -33 kPa and -1500 kPa, all the other models had better coefficients of determination. As compared to the results of the published PTFs at pressure heads of -33 kPa and -1500 kPa from the literature, the developed PTFs showed better coefficient of accuracy. The observations based on analysis of the models from the literature (Table 4.7 and Figure 4.3) and of the model proposed in this study (Table 4.8) clearly show the need for specific equations for soils with more homogeneous characteristics as described by Arruda et al., (1987); Vereecken et al., (1989); Wösten et al., (1995); Salchow et al., (1996) and Pachepsky & Rawls, (1999). The PTFs showed a tendency of overestimating θ_{33}, and underestimating θ_{1500}.

Table 4.10: Performance comparison of PTFs: Existing versus developed for the estimation of soil water retention at matric potentials of -33 kPa and -1500 kPa

PTF (author)	**θ_{33}**			**θ_{1500}**		
	R^2	RMSE	ME	R^2	RMSE	ME
Gupta & Larson (1979)	0.618	0.015	0.0007	0.789	0.019	0.0055
Rawls et al. (1982)	0.995	0.009	0.0002	0.934	0.026	0.0044
Masutti (1997)	0.253	0.038	0.004	0.104	0.069	0.0142
Oliveira et al. (2002)	0.995	0.036	0.0004	0.985	0.016	0.0023

where θ_{33} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of -33 kPa and -1500 kPa respectively, R^2 is coefficient of determination, RMSE is root mean square error, ME is mean error

For the estimation of θ_{33}, the PTF of Rawls et al. (1982) presented the best performance based on the lowest ME and RMSE values of 0.0002 and 0.009 respectively. For the estimate of θ_{1500}, the PTF of Oliveira et al. (2002) had the best performance with values of 0.0023 and 0.016 for ME and RMSE respectively, and also with the highest coefficient of determination R^2 (0.985). The soil water retention curves (Figure 4.3) were drawn for the better understanding of the performances of the developed PTFs compared to the PTFs taken from the literature.



Gupta& Larson - 33kpa
Estimated water content (cm³/cm³)
0.28 0.27 0.26 0.25 0.24 0.23 0.22 0.21 0.20
0.25 0.3 0.35
Measured water content (cm³/cm³)
Gupta & Larson -1500kPa
Estimated watercontent (cm³/cm³)
0.06 0.05 0.04 0.03 0.02 0.01 0.00
0.1 0.15 0.2 0.25
Measured water content (cm³/cm³)
Rawls et al. - 33kPa
Estimated water content (cm³/cm³)
0.20 0.15 0.10 0.05
0.1 0.15 0.2 0.25 0.3 0.35
Measured water content (cm³/cm³)
Rawls et al. - 1500kPa
Estimated water content (cm³/cm³)
0.02 0.02 0.01 0.01 0.00
0.15 0.16 0.17 0.18 0.19 0.2
Measured water content (cm³/cm³)
Masutti - 33kPa
Estimated water content (cm³/cm³)
0.45 0.40 0.35 0.30 0.25 0.20 0.15 0.10
0.1 0.2 0.3 0.4
Measured water content (cm3/cm3)
Masutti - 1500kPa
Estimated water content (cm³/cm³)
0.16 0.14 0.12 0.10 0.08 0.06 0.04 0.02
0.05 0.1 0.15 0.2
Measured water content (cm³/cm³)

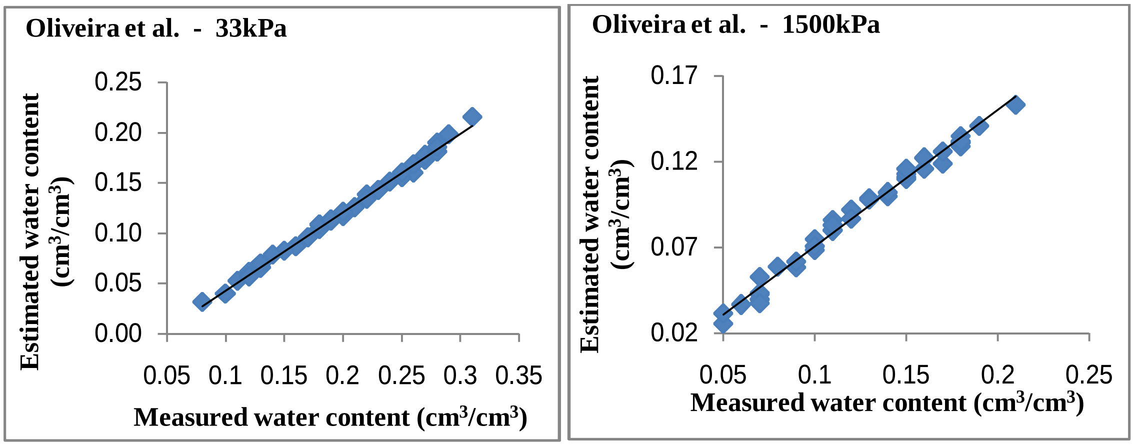


Figure 4.3: Prediction accuracy of the soil water retention curves from literature for the sampled agricultural soils

4.3.1.2 Point and parametric PTFs developed from geometric mean diameter and geometric standard deviation for agricultural soils

The possibility of using geometric mean (d_g) and geometric standard deviation (σ_g) of particle diameters instead of soil particle size distribution to derive some pedotransfer functions were investigated in this section.

Here

$$d_g = \exp(\alpha) \tag{4.12}$$

$$\sigma_g = \exp(\beta) \tag{4.13}$$

and

$$\alpha = 0.01 \sum_{i=1}^{n} f_i \, ln(d_i) \tag{4.14}$$

$$\beta = 0.01 \sum_{i=1}^{n} f_i \, ln^2(d_i) - \alpha^2 \tag{4.15}$$

where n is the number of soil separate groups, (clay, silt, sand) and f_i and d_i are the mass fraction and the arithmetic mean diameter of particle class i, respectively. The size fractions used in this study, (d_i) are 0.001, 0.026 and 1.025 mm for clay, silt, and sand respectively.

Point and two parametric PTFs were developed to predict six points on the water retention curve and the parameters of van Genuchten and Brooks-Corey models, using the stepwise regression method. The R^2 values obtained from the PTFs using the geometric mean diameter and geometric standard deviation as inputs were almost similar to the PTFs developed by considering particle size distribution as input. Therefore detailed statistical analysis has not done for this method. Only point and parametric PTFs were developed using linear and non linear regression equations for the prediction of soil water retention curve for the agricultural soils (Table 4.11 and Table 4.12).

The general form of the linear regression equations developed is as follows:

$$Y = b_0 + b_1 d_g + b_2 \sigma_g + b_3 BD + b_4 OM + b_5 P \qquad (4.16)$$

Table 4.11: Linear regression coefficients for predicting soil water retention curves for agricultural soils

Variables	b_0	$b_1{*}d_g$	$b_2{*}\ \sigma_g$	$b_3{*}BD$	$b_4{*}\ OM$	$b_5{*}P$	R^2
Water contents at specific matric potentials ((Point PTFs)							
θ_{33}	1.253	-0.861	-0.06034	-0.287	0.02007	0.07456	0.811
θ_{100}	1.161	-0.806	-0.05380	-0.283	0.02155	0.127	0.802
θ_{300}	1.034	-0.743	-0.04928	-0.271	0.01348	0.230	0.823
θ_{500}	1.104	-0.736	-0.05290	-0.259	0.00841	0.05626	0.794
θ_{1000}	1.105	-0.623	-0.04539	-0.288	0.01691	-0.114	0.799
θ_{1500}	0.955	-0.578	-0.04238	-0.263	0.02084	0.03832	0.806
van Genuchten model Parameters (Parametric PTFs)							
θ_r	0.893	-0.480	-0.03584	-0.278	0.01690	0.05614	0.802
θ_s	0.947	-0.0352	-0.00547	-0.339	-0.00082	0.02679	0.987
α	-0.765	0.744	0.04774	0.247	-0.03001	-0.135	0.760
n	0.578	1.375	0.08715	-0.083	0.02831	-0.156	0.546
Brooks-Corey model Parameters (Parametric PTFs)							
θ_r	0.894	-0.487	-0.03630	-0.275	0.01692	0.05782	0.802
h_b	78.42	-92.03	-7.803	2.009	5.153	24.80	0.559
λ	-0.509	1.314	0.08406	-0.023	0.02281	-0.0451	0.541

Table 4.12: PTFs (non linear) developed for estimation of soil water retention curves for agricultural soils

Pedotransfer functions developed	**R^2**
Water contents at specific matric potentials (Point PTFs)	
θ_{33}=(-12.48)+(17.64*d_g)+(1.489*σ_g)+(7.252*BD)-(8.269*d_g*d_g)-(1.012*d_g*σ_g)-(4.069*d_g*BD)–(0.023*σ_g*σ_g)–(0.592*σ_g*BD)-(0.814*BD*BD)	0.967
θ_{100}=(-12.26)+(18.08*d_g)+(1.531*σ_g)+(6.647*BD)-(7.815*d_g*d_g)-(1.001*d_g*σ_g)-(4.595*d_g*BD)-(0.025*σ_g*σ_g)–(0.603*σ_g*BD)-(0.530*BD*BD)	0.950
θ_{300}=(-9.618)+(14.40*d_g)+(1.207*σ_g)+(5.311*BD)+(6.720*d_g*d_g)-(0.777*d_g*σ_g)-(3.513*d_g*BD)-(0.016*σ_g*σ_g)-(0.511*σ_g*BD)-(0.422*BD*BD)	0.961
θ_{500}=(-9.137)+(15.20*d_g)+(1.218*σ_g)+(4.400*BD)-(6.733*d_g*d_g)-(0.825*d_g*σ_g)-(3.817*d_g*BD)-(0.022*σ_g*σ_g)-(0.461*σ_g*BD)-(0.174*BD*BD)	0.944
θ_{1000}=(-8.456)+(10.32*d_g)+(0.809*σg)+(6.193*BD)-(6.271*d_g*d_g)-(0.704*d_g*σ_g)-(1.368*d_g*BD)-(0.009*σ_g*σ_g)-(0.325*σ_g*BD)-(1.294*BD*BD)	0.944
θ_{1500}=(-5.488)+(11.47*d_g)+(0.776*σ_g)+(2.132*BD)-(4.167*d_g*d_g)-(0.320*d_g*σ_g)-(4.585*d_g*BD)+(0.003*σ_g*σ_g)-(0.496*σ_g*BD)+ (0.757*BD*BD)	0.963
v-G model parameters (Parametric PTFs)	
θ_r=(-3.055)+(9.186*d_g)+(0.518*σ_g)+(0.468*BD)-(3.209*d_g*d_g)-(0.154*d_g*σ_g)-(4.142*d_g*BD)+(0.011*σ_g*σ_g)-(0.420*σ_g*BD)+ (1.093*BD*BD)	0.964
θ_s=(-0.097)+(1.191*d_g)+(0.137*σ_g)+(0.193*BD)-(0.019*d_g*d_g)-(0.042*d_g*σ_g)-(0.616*d_g*BD)-(0.004*σ_g*σ_g)-(0.050*σ_g*BD)-0.007*BD*BD	0.992
α=(13.47)-(12.87*d_g)-(1.316*σ_g)-(10.01*BD)+(5.520*d_g*d_g)+(0.512*d_g*σ_g)+(4.171*d_g*BD)+(0.007*σ_g*σ_g)+(0.721*σ_g*BD)+ (1.458*BD*BD)	0.904
n=(19.82)-(47.07*d_g)-(3.191*σ_g)-(1.831*OM)+(28.42*d_g*d_g)+(4.146*d_g*σ_g)+(3.156*d_g*OM)+(0.136*σ_g*σ_g)+(0.114*σ_g*OM)+ (0.0762*OM*OM)	0.881
B-C Model parameters (Parametric PTFs)	
θ_r=(-3.310)+(9.443*d_g)+(0.549*σ_g)+(0.621*BD)-(3.323*d_g*d_g)-(0.177*d_g*σ_g)-(4.167*d_g*BD)+(0.009*σ_g*σ_g)-(0.425*σ_g*BD)+ (1.057*BD*BD)	0.964
h_b=(-500.14)+(1442.9*d_g)+(74.03*σ_g)+(168.90*OM)-(928.94*d_g*d_g)-(124.8*d_g*σ_g)-(123.28*d_g*OM)-(1.653*σ_g*σ_g)-(19.32*σ_g*OM)-4.126*OM*OM)	0.751
λ=(15.70)-(40.78*d_g)-(2.553*σ_g)-(1.740*OM)+(25.21*d_g*d_g)+(3.514*d_g*σ_g)+(3.041*d_g*OM)+(0.104*σ_g*σ_g)+(0.102*σ_g*OM)+ (0.082*OM*OM)	0.876

where θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of -33, -100, -300, -500, -1000 and -1500 kPa respectively, θ_r and θ_s are residual and saturated soil water contents (cm^3/cm^3) respectively, α and n are vG model parameters, h_b and λ are B-C model parameters, BD is bulk density (g/cm^3), P is porosity (cm^3/cm^3), OM is organic matter content (%), d_g is geometric mean and σ_g is geometric standard deviation of particle diameters, b_0, b_1, b_2, b_3, b_4 and b_5 are regression coefficients, R^2 is coefficient of determination.

4.3.2. Development of pedotransfer functions for forested hillslope soils

Soil sampling was carried out on a forested hillslopes of the Pavanje river basin. A total of fifty six soil samples were collected from eight different elevations distributed from the crest to footslope. For each elevation, physical properties and soil water retention data of seven soil layers with the thickness of 10, 20, 30, 40, 50, 60 and 75 cm were determined.

All the measured soil water retention data were fitted to vG model (eqn. (4.3)) and B-C model (eqn. (4.4)). For each soil sample the parameters θ_r (cm^3/cm^3), α (kPa^{-1}) and n, for vG model and θ_r (cm^3/cm^3), h_b (kPa) and λ for B-C model were optimally estimated. To get the optimized value of residual water content (θ_r), the value at permanent wilting point was considered. The saturated water content (θ_s) was taken as 0.93 times of soil porosity and it was considered same for both the vG and B-C model. Table 4.13 shows some statistics of fitted values of vG and B-C model parameter to measured soil water retention data and Figure 4.4 shows the soil water retention curve for different types of forest soils for measured and fiited (vG model and B-C model) values.

Table 4.13: Descriptive statistics of fitted values of vG and B-C water retention model parameters

	Van Genuchten model parameters				**Brooks-Corey model parameters**			
variables	**θ_r (cm^3/cm^3)**	**θ_s (cm3/ cm^3)**	**α (cm^{-1})**	**n**	**θ_r (cm^3/cm^3)**	**θ_s cm^3/cm^3)**	**h_b(cm)**	**λ**
Min	0.0001	0.3	0.0095	1.174	0	0.3	2.443	0.126
max	0.0844	0.48	0.2717	1.307	0.0687	0.48	79.365	0.297
Mean	0.0143	0.39	0.064	1.238	0.0054	0.3930	28.423	0.217
SD	0.0232	0.0464	0.0672	0.031	0.0135	0.0469	20.722	0.033

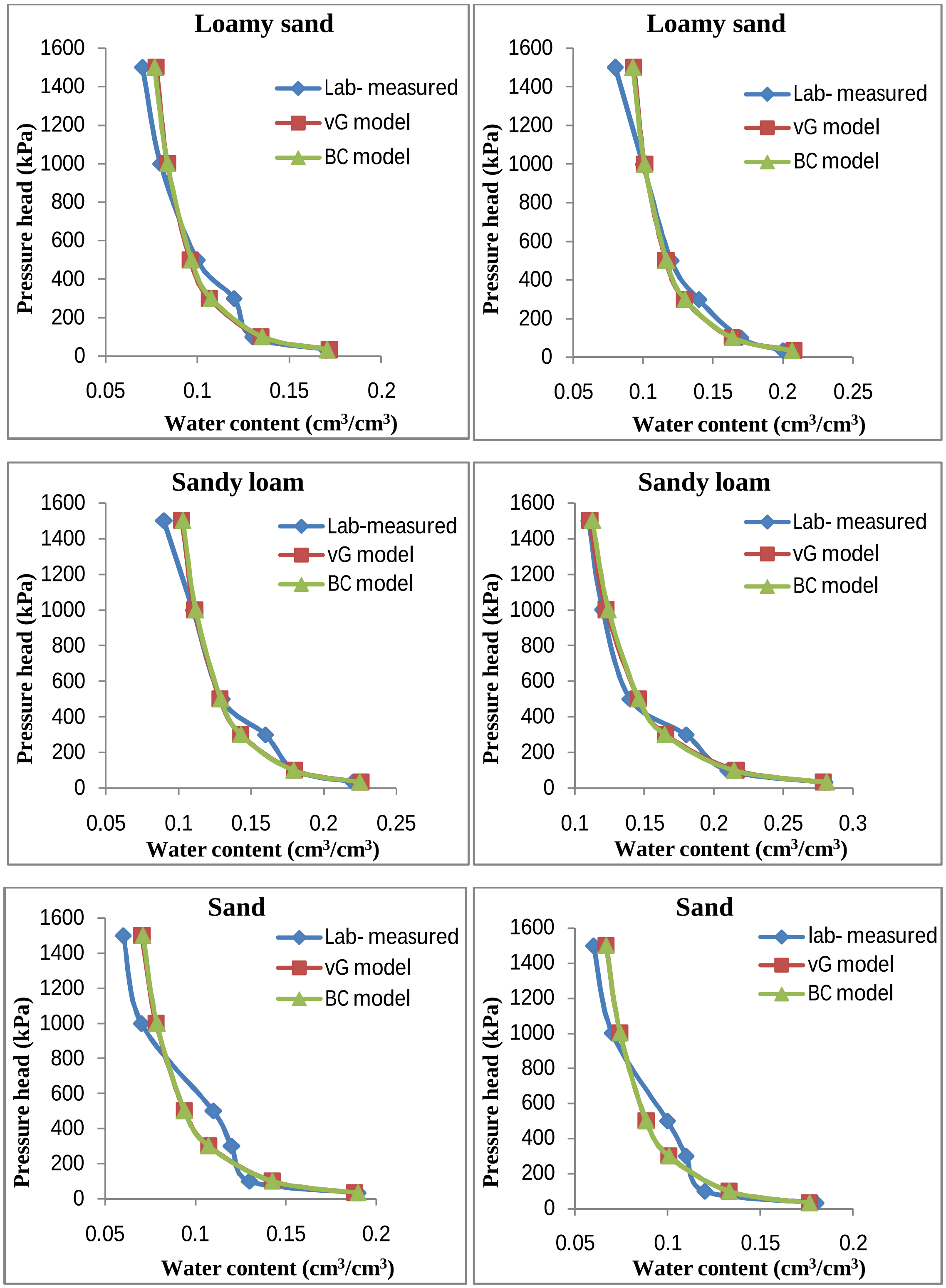


Figure 4.4: Soil water retention curves obtained from laboratory experiments and fitted vG and B-C models for three different textured forested hillslope soils

Each of the water contents at selected water potentials of -33, -100, -300, -500, -1000, and -1500 kPa and parameters of both models (vG and B-C) were related to basic soil properties (S, Si, C, BD, P and OM) using multiple linear regression techniques in order to develop PTFs. Approximately two third of the data were used in the calibration and the remaining data were used in the validation of PTFs. Descriptive statistics of physical and hydraulic properties used for the development of PTFs are summarized in Table 4.14.

Table 4.14: Descriptive statistics of forested hillslope soil properties to develop PTFs

Variables	**Calibration data set**				**Validation data set**			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Physical Properties								
S	43	74	62.08	7.32	58	73	64.34	4.65
Si	24	54	35.90	7.07	27	41	35.08	4.24
C	0	6	2.02	1.62	0	2	0.58	0.82
BD	1.22	1.69	1.47	0.13	1.31	1.49	1.39	0.06
OM	0.65	5.96	2.29	1.45	0.91	7.50	2.60	2.09
P	0.32	0.52	0.42	0.06	0.41	0.48	0.45	0.02
Soil water retention data								
θ_{33}	0.17	0.28	0.22	0.03	0.18	0.26	0.22	0.03
θ_{100}	0.12	0.22	0.17	0.03	0.15	0.23	0.18	0.02
θ_{300}	0.11	0.20	0.15	0.02	0.13	0.19	0.15	0.02
θ_{500}	0.10	0.17	0.13	0.02	0.11	0.16	0.13	0.01
θ_{1000}	0.07	0.15	0.10	0.02	0.10	0.13	0.11	0.01
θ_{1500}	0.06	0.13	0.09	0.02	0.08	0.11	0.09	0.01
van Genuchten parameters								
θ_r	0.00	0.08	0.02	0.03	0.00	0.05	0.01	0.01
θ_s	0.3	0.47	0.39	0.05	0.38	0.45	0.42	0.02
α	0.01	0.21	0.06	0.06	0.01	0.27	0.09	0.09
n	1.17	1.31	1.24	0.03	1.18	1.31	1.23	0.03
Brooks-Corey parameters								
θ_r	0	0.07	0.01	0.02	0.00	0.02	0.01	0.01
θ_s	0.3	0.47	0.39	0.05	0.38	0.45	0.42	0.02
h_b	2.44	79.37	30.17	20.78	3.48	71.43	23.18	20.40
λ	0.13	0.29	0.22	0.04	0.18	0.24	0.21	0.02

where S, Si, C are sand, silt, clay fractions (%), respectively, BD is bulk density (g /cm^3), OM is organic matter content (%), P is porosity (cm^3/cm^3), θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric pressures of -33, -100, -300, -500, -1000 and -1500 kPa, respectively, θ_r and θ_s are residual and saturated soil water contents (cm^3/cm^3) respectively, α is the inverse of air entry pressure head (cm^{-1}), h_b is air entry pressure head, λ is pore size index and n is the empirical shape parameters, SD is standard deviation.

Firstly, multiple linear regression equations have been developed by considering all the basic soil properties as inputs to the equation such as percentages of sand, silt, clay, bulk density, porosity and organic matter content. Then tried with different input combinations, like S, Si, C; Si, BD, P; BD, OM, P etc., and developed regression equations. R^2 values were also found out. Out of these equations, only the most efficient combination that had given higher R^2 values was considered. Linear regression equations developed for the estimation of soil water retention curve are presented in Table 4.15.

Table 4.15: Linear regression equations for predicting soil water retention curves for forested hillslope soils

Point PTFs	R^2
θ_{33} = 0.166-0.0013*S+0.0013*Si+0.0016*C-0.0198*BD+0.0095*OM+0.185*P	0.711
θ_{33} = 0.0896+0.0014*Si+0.154*P+0.0102*OM	0.634
θ_{100} = -0.371-0.0004*S+0.0019*Si+0.0019*C+0.168*BD+0.0078*OM+0.580*P	0.757
θ_{100}= 0.213+0.0019*Si-0.0769*BD+0.0087*OM	0.737
θ_{300} = 0.362-0.0003*S+0.0018*Si+0.0034*C-0.127*BD+0.0066*OM-0.195*P	0.832
θ_{300}= 0.144+0.0019*Si-0.0415*BD+0.0063*OM	0.803
θ_{500}= 0.2116+0.00002*S+0.0002*Si+0.0043*C-0.0671*BD+0.0079*OM-0.0380*P	0.735
θ_{500}= 0.200+0.0002*S-0.0659*BD+0.0079*OM	0.641
θ_{1000} = 0.222+0.0004*S+0.0007*Si+0.0044*C-0.102*BD+0.0074*OM-0.0689*P	0.792
θ_{1000}= 0.198+0.0009*Si-0.0916*BD+0.0068*OM	0.722
θ_{1500} = -0.338+0.0006*S+0.0005*Si+0.0032*C+0.124*BD+0.0059*OM+0.445*P	0.746
θ_{1500}= -0.0410+0.0007*S+0.207*BD+0.0064*OM	0.674
vG model parameters (Parametric PTFs)	**R^2**
θ_r = -0.337+0.0009*S+0.0001*Si+0.0026*C+0.108*BD-0.0017*OM+0.360*P	0.277
θ_r = -0.0807+0.0010*S+0.132*P-0.0015*OM	0.260
θ_s = -0.3934-0.000003*S+0.0001*Si-0.0003*C+0.1680*BD+0.0004*OM+1.2699*P	0.983
θ_s= 0.954-0.0002*Si-0.387*BD+0.0019*OM	0.972
α= -2.163+0.0037*S-0.0006*Si+0.0022*C+0.785*BD-0.0101*OM+2.255*P	0.653
α= -0.263+0.0036*S+0.430*P-0.0085*OM	0.621
n = 1.154-0.0011*S+0.0004*Si-0.0057*C+0.0588*BD-0.0095*OM+0.172*P	0.266
n= 1.341-0.0013*S-0.0131*BD-0.0090*OM	0.223
B-C model parameters (Parametric PTFs)	**R^2**
θ_r = 0.204+0.00036*S+0.0001*Si+0.0008*C-0.0973*BD-0.0015*OM-0.169*P	0.187
θ_r = -0.0387+0.0005*S+0.0001*Si+0.0498*P	0.149
h_b= -221.08-0.888*S+1.259*Si-1.679*C+134.55*BD+1.153*OM+144.25*P	0.462
h_b = 113.62-1.042*S+1.130*Si-160.93*P	0.439
λ= 1.467-0.0021*S-0.0002*Si-0.0070*C-0.462*BD-0.0078*OM-1.061*P	0.365
λ = 0.361-0.0023*S-0.0506*P-0.0087*OM	0.303

Table 4.16: PTFs (non linear) developed for the estimation of soil water retention curves for forested hillslope soils

Pedotransfer functions developed	**R^2**	**AIC**
Water contents at specific matric potentials (Point PTFs)		
$\theta_{33} = 0.394 - 0.0045 * Si - 0.705 * P - 0.0530 * OM + 0.00009 * Si^2 + 0.0047 * Si * P - 0.0004 * Si * OM + 0.438 * P^2 + 0.194 * P * OM - 0.0014 * OM^2$	0.82	-206.995
$\theta_{100} = 0.913 - 0.0045 * Si - 0.978 * BD + 0.0476 * OM + 0.0001 * Si + 0.0014 * Si * BD - 0.0008 * Si * OM + 0.300 * BD^2 - 0.0109 * BD * OM + 0.0001 * OM^2$	0.84	-213.110
$\theta_{300} = 0.456 - 0.0031 * Si - 0.42 * BD + 0.0382 * OM + 0.00008 * Si^2 + 0.0010 * Si * BD - 0.0004 * Si * OM + 0.128 * BD^2 - 0.0150 * BD * OM + 0.0004 * OM^2$	0.86	-237.264
$\theta_{500} = -0.0783 + 0.0049 * S + 0.264 * BD - 0.0477 * O + 0.000009 * S^2 - 0.0046 * S * BD + 0.0005 * S * OM - 0.0678 * BD^2 + 0.0328 * BD * OM - 0.00168 * OM^2$	0.80	-240.224
$\theta_{1000} = 0.044 + 0.0119 * Si + 0.0187 * BD - 0.0577 * OM - 0.00007 * Si^2 - 0.0057 * Si * BD + 0.0006 * Si * OM - 0.0199 * BD^2 + 0.0413 * BD * OM - 0.0016$	0.86	-240.074
$\theta_{1500} = -0.111 - 0.0027 * S + 0.637 * P + 0.0631 * OM - 0.000008 * S^2 + 0.0089 * S * P + 0.00004 * S * OM - 0.652 * P^2 - 0.132 * P * OM - 0.0003 * OM^2$	0.82	-236.316
van Genuchten model Parameters (Parametric PTFs)		
$\theta_r = -0.318 - 0.0040 * S + 1.501 * P + 0.0716 * OM - 0.00009 * S^2 + 0.0196 * S * P - 0.0008 * S * OM - 2.498 * P^2 - 0.0941 * P * OM + 0.000032 * OM^2$	0.68	-185.151
$\theta_s = 0.501 + 0.0074 * Si + 0.0675 * BD + 0.0249 * OM - 0.000004 * Si^2 - 0.0046 * S * BD - 0.0003 * Si * OM - 0.110 * BD^2 - 0.0082 * BD * OM - 0.0004 * OM^2$	0.98	-248.982
$\alpha = 0.662 - 0.0218 * S - 1.709 * P + 0.0957 * OM + 0.0001 * S^2 + 0.0355 * S * P - 0.0009 * S * OM + 1.011 * P^2 - 0.194 * P * OM + 0.0038 * OM^2$	0.91	-180.216
$n = 0.04352 + 0.0088 * S + 1.146 * BD + 0.192 * OM - 0.0001 * S^2 + 0.0030 * S * BD - 0.0012 * S * OM - 0.362 * BD^2 - 0.105 * BD * OM + 0.0004 * OM^2$	0.62	-175.198
Brooks-Corey model Parameters (Parametric PTFs)		
$\theta_r = -0.0105 - 0.0012 * S - 0.0017 * Si + 0.2276 * P - 0.00005 * S^2 - 0.00004 * S * Si + 0.0168 * S * P - 0.00004 * Si^2 + 0.0154 * Si * P - 1.6012 * P^2$	0.62	-217.779
$h_b = 117.57 + 12.64 * S - 3.291 * Si - 1461.8 * P - 0.0776 * S^2 + 0.120 * S * Si - 23.60 * S * P + 0.0755 * Si^2 - 11.39 * Si * P + 3251.2 * P^2$	0.74	373.852
$\lambda = 0.3235 + 0.0144 * S - 0.980 * P - 0.1545 * OM - 0.00009 * S^2 - 0.0191 * S * P + 0.000002 * S * OM + 1.2951 * P^2 + 0.3494 * P * OM - 0.0007 * OM^2$	0.70	-163.741

In terms of coefficient of determination (R^2), multiple linear regressions had adequately good values for θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000}, θ_{1500}, and but very low values for parameters of vG and B-C models. In vG model, the R^2 value for θ_r and n were very low and in B-C model, all parameters showed very poor results. In order to improve the R^2 values, non linear regression equations were considered. These equations increased the efficiency of the models effectively by increasing R^2 values. In non linear regression equations, different combinations of input variables have been tried to improve the efficiency of the models. For both PTFs (point and parametric), the different combinations of input variables such as sand, silt, bulk density, porosity and organic matter content were used and observed that water contents at selected pressure heads (point PTFs) have good relationship with the basic soil properties. And also the saturated water content (θ_s) showed the better efficiency when compared to other parameters. B-C model parameters show relatively less R^2 values when compared to vG model parameters. The developed non linear regression equations with different input combinations are shown in Table 4.16.

Statistical evaluation

The performances of point and parametric PTFs in predicting the measured (fitted) data were evaluated using R^2, RMSE and ME. The accuracies of PTFs between measured (fitted) and predicted water contents and model parameters for the calibration and validation sets are summarized in the Table 4.17. The calibration sets show the good agreement between measured and predicted values based on R^2 and RMSE values when compared to validation sets. All the three statistical measures were used to compare the water contents at several suction points and parameters of van Genuchten and Brooks-Corey model parameters.

Accuracy of each method with derivation data set was slightly better than validation accuracies. The present study reported relatively higher prediction accuracies of R^2= (0.804 to 0.862) and (0.613 to 0.718) for calibration and validation sets respectively between measured and predicted water contents at six selected matric potentials. The accuracy of vG model parameters was 0.681, 0.977, 0.913 and 0.623 for θ_r, θ_s, α and n respectively and for B-C model it was 0.621, 0.743 and 0.667 for θ_r, h_b and λ respectively for the calibration sets. For the validation sets, the obtained R^2 values for both vG and B-C model were slightly lower when compared to calibration sets.

Table 4.17: Calibration and validation accuracies of developed PTFs for forested hillslope soils

Variables	Calibration			Validation		
	R^2	RMSE	ME	R^2	RMSE	ME
Soil water retention data						
θ_{33}	0.812	0.0122	0.0000	0.631	0.0153	-0.0020
θ_{100}	0.844	0.0114	0.0000	0.652	0.0128	-0.0005
θ_{300}	0.862	0.0085	0.0000	0.617	0.0137	0.0053
θ_{500}	0.804	0.0082	0.0000	0.718	0.0094	-0.0062
θ_{1000}	0.861	0.0082	0.0000	0.613	0.0178	0.0015
θ_{1500}	0.819	0.0086	0.0000	0.672	0.0137	-0.0108
vG model parameters						
θ_r	0.681	0.0159	0.0008	0.632	0.0098	-0.0035
θ_s	0.977	0.0074	0.0000	0.747	0.0105	0.0022
α	0.913	0.0168	0.0000	0.855	0.0344	-0.0083
n	0.623	0.0178	-0.0005	0.587	0.0172	-0.0033
B-C model Parameters						
θ_r	0.621	0.0107	-0.0009	0.587	0.0039	-0.0011
h_b	0.743	0.0231	-0.0062	0.566	0.0336	-0.0036
λ	0.704	0.0205	0.0000	0.667	0.0124	0.0001

where θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at water pressures of -33, -100, -300, -500, -1000 and -1500 kPa respectively, θ_r and θ_s are residual and saturated soil water contents (cm^3/cm^3) respectively, α and n are vG model parameters, h_b and λ are B-C model parameters, R^2 is coefficient of determination, RMSE is root mean square error, ME is mean error.

RMSE value for point based estimation was about 0.01(cm^3/cm^3) for both calibration and validation sets, whereas for vG and B-C model, there were some errors in both calibration and validation sets (Table 4.17). ME for point estimation method was zero for calibration sets and there were errors in the validation sets. Even the vG and B-C models were also showed smaller mean errors. Under and over prediction of PTFs for given parameters are represented by positive and negative values of ME, respectively. For the validation data set, PTFs performed better in point prediction than in parameter prediction. PTFs over-predicted most of the water contents at specific pressure heads and model parameters.

These results indicate that the prediction accuracies of parametric PTFs are generally lower than that of the point PTFs.

Accuracies of point and parametric (by van Genuchten and Brooks-Corey models) predictions of water contents at selected water potentials on water retention curves are presented in Table 4.18 for both calibration and validation sets. The R^2 values did not change considerably for estimating the water content in three methods. This may be due to the fact that SWRC behaviour between saturation and inflection points depends more on the soil structure and macropores, whereas, beyond the inflection point it mostly depends on the soil textural properties and micropores. The corresponding graphs are plotted and given in the following Figures 4.5, 4.6, 4.7 for easier understanding of the comparative accuracies of the developed models.

Table 4.18: Accuracies of soil water retention prediction obtained from developed PTFs for forested hillslope soils

θ(h)	**R^2**			**RMSE**			**ME**		
	Poin	vG	B-C	Point	vG	B-C	Point	vG	B-C
Calibration data set									
θ_{33}	0.81	0.62	0.58	0.0122	0.0199	0.0221	0.0000	0.0023	-0.0077
θ_{100}	0.84	0.58	0.66	0.0114	0.0237	0.0177	0.0000	0.0028	-0.0058
θ_{300}	0.86	0.55	0.58	0.0085	0.0277	0.0186	0.0000	0.0175	0.0097
θ_{500}	0.80	0.62	0.59	0.0082	0.0149	0.0151	0.0000	0.0091	0.0018
θ_{1000}	0.86	0.65	0.77	0.0082	0.0129	0.0123	0.0000	0.0002	-0.0063
θ_{1500}	0.81	0.68	0.79	0.0086	0.0127	0.0150	0.0000	-0.0055	-0.0115
Validation data set									
θ_{33}	0.63	0.61	0.64	0.0153	0.0307	0.0373	-0.0020	0.0054	-0.0238
θ_{100}	0.65	0.56	0.68	0.0128	0.0309	0.0259	-0.0005	0.0152	-0.0091
θ_{300}	0.61	0.57	0.59	0.0137	0.0305	0.0228	0.0053	0.0206	0.0000
θ_{500}	0.71	0.64	0.65	0.0094	0.0240	0.0198	-0.0062	0.0110	-0.0077
θ_{1000}	0.61	0.63	0.64	0.0178	0.0186	0.0174	0.0015	0.0075	-0.0090
θ_{1500}	0.67	0.62	0.68	0.0137	0.0147	0.0240	-0.0108	-0.0064	-0.0217

where θ_{33}, θ_{100}, θ_{300}, $\theta_{500,}$ θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at water pressures of -33, -100, -300, -500, -1000 and -1500 kPa, respectively, point is point prediction, vG is van Genuchten model, B-C is Brooks-Corey model, R^2 is coefficient of determination, RMSE is root mean square error, ME is mean error.

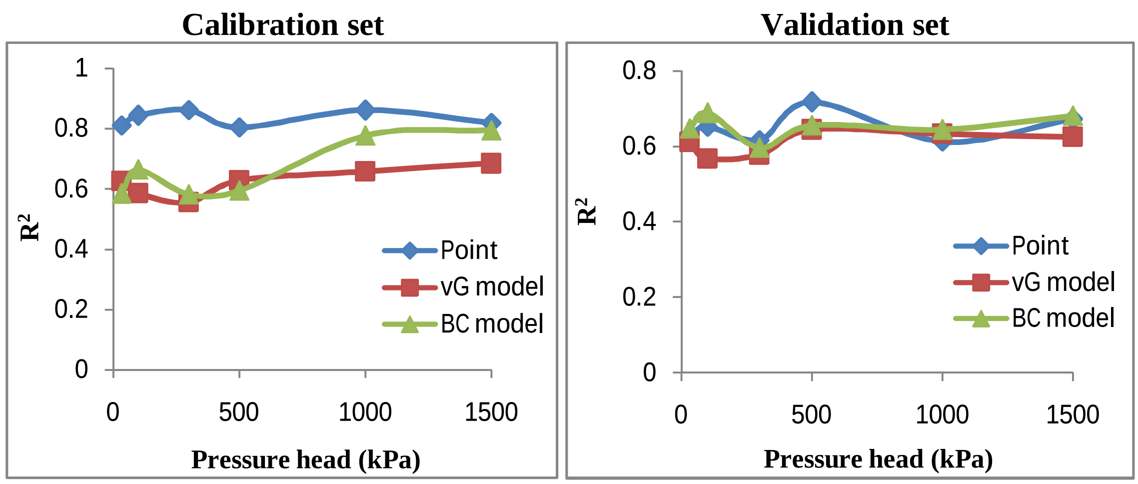


Figure 4.5: Comparison graphs of error analysis in terms of R^2 values

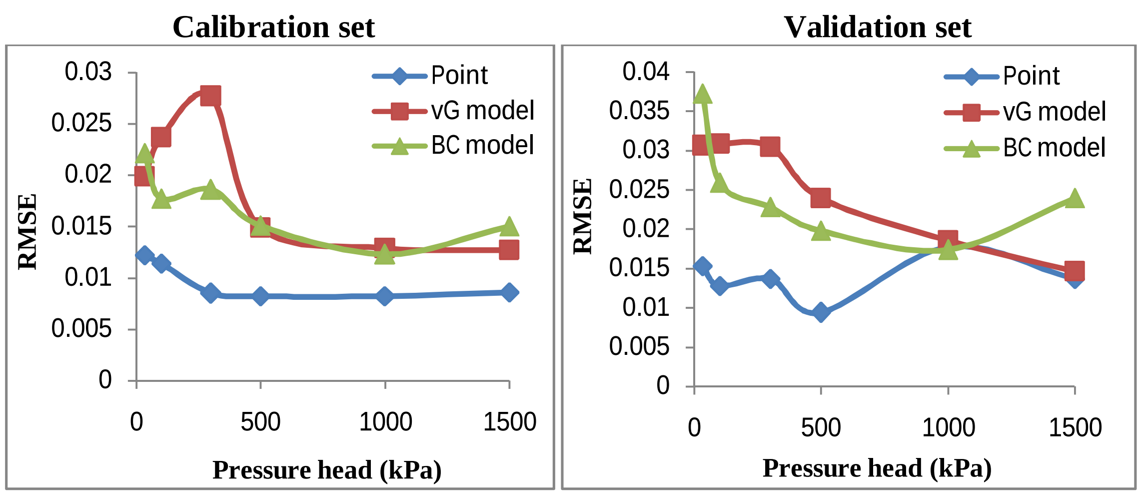


Figure 4.6: Comparison graphs of error analysis in terms of RMSE values

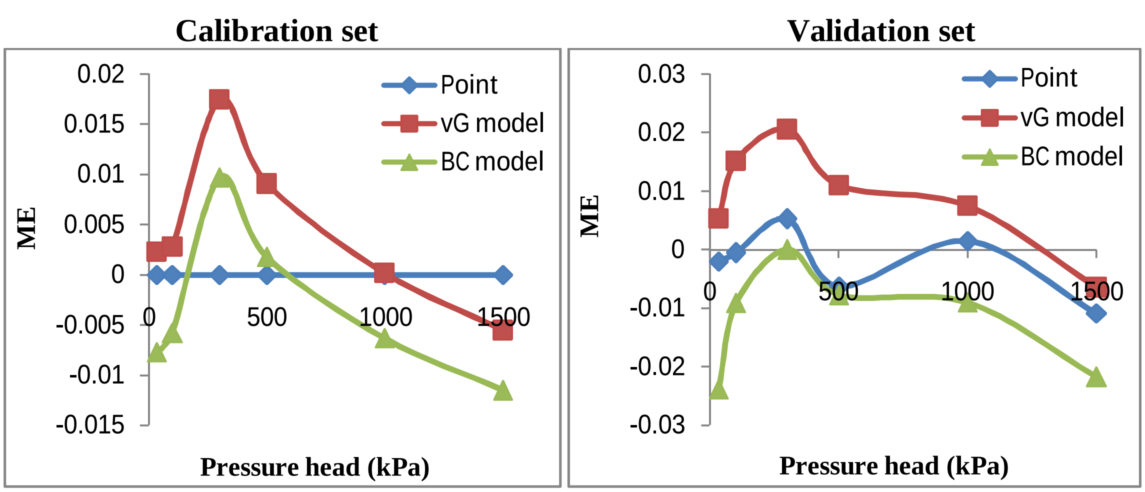
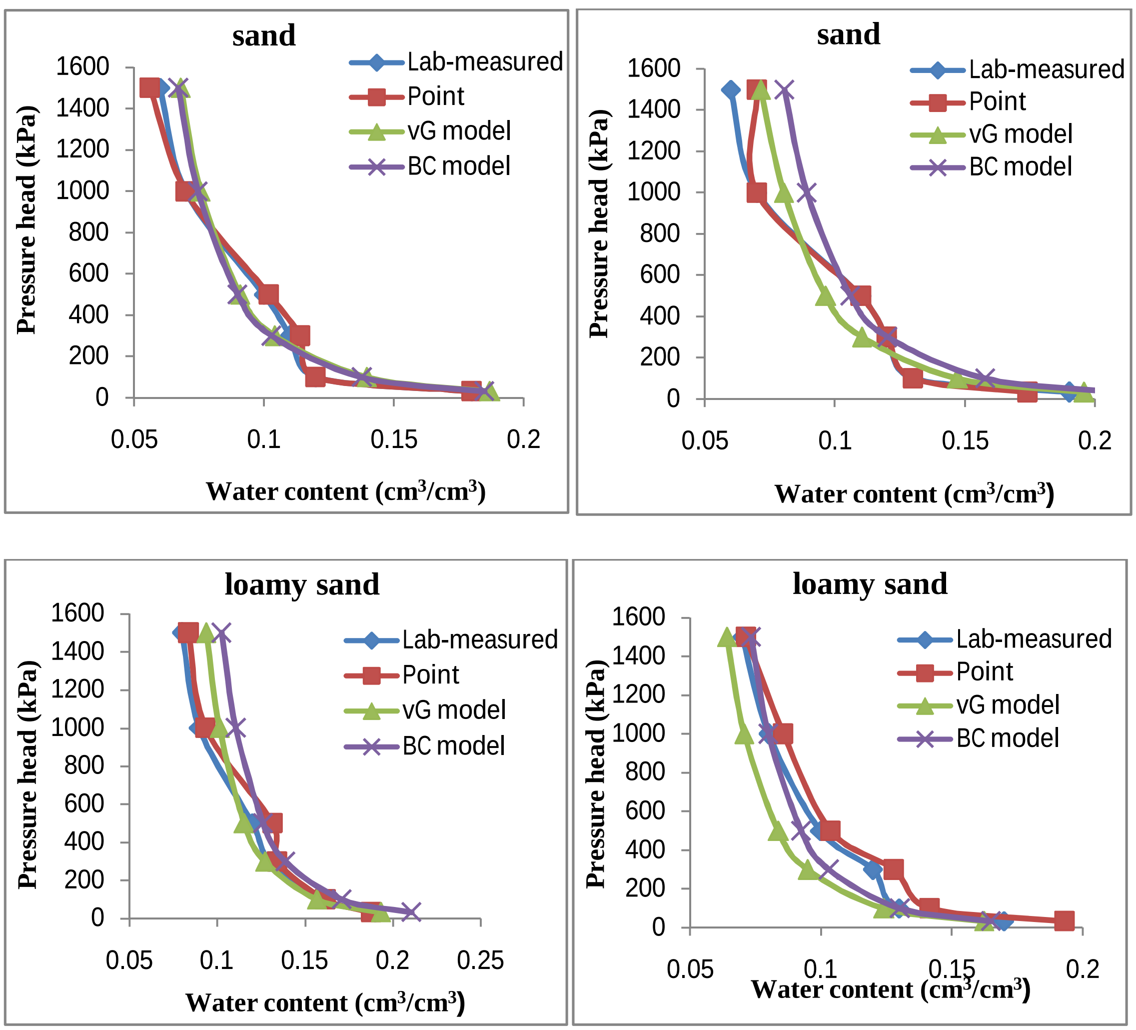


Figure 4.7: Comparison graphs of error analysis in terms of ME values

The prediction of soil water retention curve using PTFs by point estimation method for soils lying in the coastal region Karnataka in India is of relatively considerable accuracy (best case R^2=0.862), whereas parametric estimation method (van Genuchten and Brooks and Corey models) performs slightly lower in predicting the parameters. The graphs (Figure 4.8) are given for the better understanding of the performance comparison of the soil water retention curve obtained from four different methods (laboratory, point estimation method, van Genuchten and Brooks–Corey water retention models) for the three different types of forest soils in the Pavanje river basin.



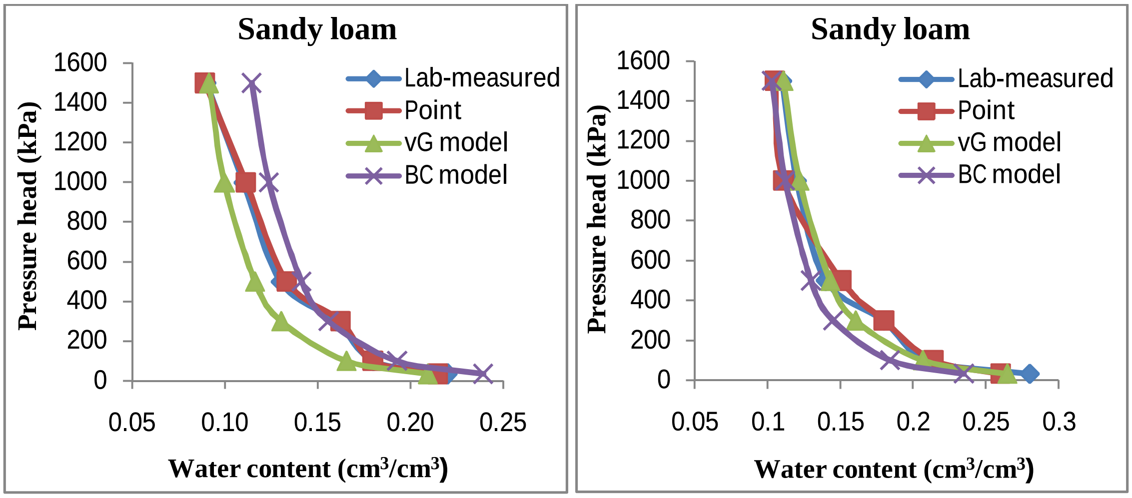


Figure 4.8: Soil water retention curves obtained from laboratory experiments, point PTFs, vG model and BC models for three different types of forest soils

The majority of PTFs available in the literature are established based on the measurements in samples taken from arable land. However, the PTFs established in this research work were based exclusively on samples from forest soils. There was a slight difference among the three methods (point, v-G and B-C model) in predicting water retention curves, but the point based method was superior to the parametric method of PTFs development for Pavanje river basin soils (Table 4.18). This might be explained by the fact that moisture content is controlled by different independent variables at different water potentials and PTFs developed for the point based method allow more appropriate combination of those independent variables.

4.3.2.1. Point and parametric PTFs developed from geometric mean diameter and geometric standard deviation for forested hillslope soils.

In this section geometric mean (d_g) and geometric standard deviation (σ_g) of particle diameters were used instead of soil particle size distribution to derive some pedotransfer functions. The procedure followed for the agricultural soil was once again adopted here also. Same soil samples were used as mentioned in chapter 3 and developed the PTFs. Point PTFs and two parametric PTFs were developed to predict six points on the retention curve and the parameters of vG and B-C models, using the stepwise regression method. R^2

values obtained from the PTFs by using the geometric mean diameter and geometric standard deviation as input were almost similar to PTFs developed by considering particle size distribution as input. Therefore detailed statistical analysis is not required. The PTFs derived are given in Table 4.19 and Table 4.20.

Table 4.19: Multiple linear regression equations developed for predicting soil water retention curves for forested hillslope soils

Pedotransfer functions developed	**R^2**
Water contents at specific matric potentials (Point PTFs)	
θ_{33} = 0.0477-0.156*d_g-0.00714*σ_g+0.074*BD+0.009*OM +0.323*P	0.614
θ_{100}= -0.177-0.202*d_g-0.0072*σ_g+0.156*BD+0.0075*OM +0.520*P	0.733
θ_{300}= 0.561-0.137*d_g-0.000583*σ_g-0.167*BD+0.00635*OM -0.307*P	0.791
θ_{500}= 0.160+0.0614*d_g+0.0109*σ_g-0.0753*BD+0.0079*OM-0.061*P	0.740
θ_{1000}= 0.330+0.0129*d_g+0.0098*σ_g-0.156*BD+0.0071*OM-0.182*P	0.792
θ_{1500}= -0.190+0.0224*d_g+0.0086*σ_g+0.0542*BD+0.0057*OM+0.311*P	0.729
vG model parameters (Parametric PTFs)	
θ_r= -0.169+0.0631*d_g+0.0101*σ_g+0.0179*BD-0.0019*OM+0.200*P	0.234
θ_s= -0.357-0.0215*d_g-0.0016*σ_g+0.161*BD+0.0003*OM+1.255*P	0.983
α= -1.406+0.226*d_g+0.0228*σ_g+0.413*BD-0.0109*OM+1.607*P	0.507
n= 1.058-0.187*d_g-0.0218*σ_g+0.169*BD-0.0094*OM+0.367*P	0.233
B-C Model parameters (Parametric PTFs)	
θ_r= 0.257+0.0142*d_g+0.0029*σ_g-0.123*BD-0.0017*OM-0.212*P	0.170
h_b= -177.55-199.88*d_g-14.54*σ_g+186.10*BD+1.131*OM+212.45*P	0.380
λ= 1.056-0.183*d_g-0.0265*σ_g-0.229*BD-0.0072*OM-0.638*P	0.264

where θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of -33, -100, -300, -500, -1000 and -1500 kPa respectively, θ_r and θ_s are residual and saturated soil water contents (cm^3/cm^3) respectively, α and n are vG model parameters, h_b and λ are B-C model parameters, BD is bulk density (g/cm^3), P is porosity (cm^3/cm^3), OM is organic matter content (%), d_g is geometric mean and σ_g is geometric standard deviation of particle diameters, R^2 is coefficient of determination.

Table 4.20: PTFs (non linear) developed for estimation of soil water retention curves for forested hillslope soils

Pedotransfer functions developed	**R^2**
Water contents at specific matric potentials (Point PTFs)	
θ_{33}=(0.737)-(1.102*d_g)-(0.089*OM)-(1.233*P)+(0.839*d_g*d_g)+(0.056*d_g*OM)+(0.577*d_g*P)-(0.001*OM*OM)+(0.204*OM*P)+ (0.878*P*P)	0.837
θ_{100}=0.880)-(0.252*d_g)+(-0.847*BD)+(0.003*OM)+(0.77*d_g*d_g)-(0.417*d_g*BD)+(0.079*d_g*OM)+(0.330*BD*BD)-(0.015*BD*OM)+ (0.0001*OM*OM)	0.840
θ_{300}=(0.441)-(0.450*d_g)-(0.271*BD)+(0.019*OM)+(0.673*d_g*d_g)-(0.20*d_g*BD)+(0.047*d_g*OM)+(0.124*BD*BD)-(0.023*BD*OM)+ (0.0006*OM*OM)	0.898
θ_{500}=(0.487)-(0.617*d_g)-(0.303*BD)+(0.02*OM)-(0.032*d_g*d_g)+(0.452*d_g*BD)-(0.035*d_g*OM)+(0.017*BD*BD)+(0.008*BD*OM)-(0.002*OM*OM)	0.814
θ_{1000}=(0.076)+(0.028*σ_g)-(0.058*OM)+(0.05*BD)+(0.0002*σ_g*σ_g)+(0.001*σ_g *OM)-(0.017*σ_g*BD)-(0.0003*OM*OM)+(0.042*OM*BD)-(0.044*BD*BD)	0.853
θ_{1500}=(0.406)-(0.405*d_g)-(0.054*OM)-(0.16*BD)-(0.327*d_g*d_g)-(0.029*d_g*OM)+(0.452*d_g*BD)+(0.00003*OM*OM)+(0.048*OM*BD)- (0.068*BD*BD)	0.837
v-G model parameters (Parametric PTFs)	
θ_r=(-0.174)-(0.364*d_g)-(0.110*OM)+(0.607*BD)-(0.780*d_g*d_g)-(0.056*d_g*OM)+(0.719*d_g*BD)+(0.001*OM*OM)+(0.083*OM*BD)-(0.384*BD*BD)	0.668
θ_s=(-0.061)+(0.013*d_g)+(1.310*P)-(0.013*OM)+(0.049*d_g*d_g)-(0.195*d_g*P) (0.195*d_g*P)+(0.014*d_g*OM)-(0.485*P*P)+(0.026*P*OM)-(0.0004*OM*OM)	0.984
α=(-0.335)+(1.630*d_g)-(1.160*P)+(0.191*OM)-(1.333*d_g*d_g)-(0.819*d_g*P)-(0.109*d_g*OM)+(3.697*P*P)-(0.468*P*OM)+ (0.006*OM*OM)	0.852
n=(1.164)-(0.366*d_g)+(1.558*P)-(0.134*OM)+(0.188*d_g*d_g)+(0.222*d_g *P)+(0.0663*d_g*OM)-(2.611*P*P)+(0.220*P*OM)+ (0.001*OM*OM)	0.675
B-C Model parameters (Parametric PTFs)	
θ_r=(173.98)-(3.102*d_g)-(138.65*BD)-(342.21*P)-(0.275*d_g*d_g)+(1.595* d_g*BD)+(2.327*d_g*P)+(27.55*BD*BD)+(136.52*BD*P)+(168.38*P*P)	0.585
h_b=(1132.4)-(1485.2*d_g)-(111.73*OM)-(3139.7*P)+(841.33*d_g*d_g)+(79.28*d_g*OM)+(1462.1*d_g*P)+(0.645*OM*OM)+(193.91*OM*P)+ (2310*P*P)	0.768
λ=(1.118)-(1.385*d_g)-(0.228*OM)-(1.712*P)+(0.937*d_g*d_g)+(0.106*d_g*OM)+(1.098*d_g*P)-(0.00099*OM*OM)+(0.445*OM*P)+ (0.215*P*P)	0.702

where θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of -33, -100, -300, -500, -1000 and -1500 kPa respectively, θ_r and θ_s are residual and saturated soil water contents (cm^3/cm^3) respectively, α and n are vG model parameters, h_b and λ are B-C model parameters, BD is bulk density (g/cm^3), P is porosity (cm^3/cm^3), OM is organic matter content (%), d_g is geometric mean and σ_g is geometric standard deviation of particle diameters, R^2 is coefficient of determination.

CHAPTER 5

DEVELOPMENT OF PEDOTRANSFER FUNCTIONS FOR THE ESTIMATION OF SATURATED HYDRAULIC CONDUCTIVITY

5.1 Introduction

Saturated hydraulic conductivity (k_s) is a challenging soil hydraulic property to describe because it can change many orders of magnitude over short distances; it represents the ease in which water flows through soil when pore spaces are completely filled with water. Determination of the saturated hydraulic conductivity is needed for many studies and applications related to irrigation, drainage, water movement and solute transport in the soil. It is a key variable in the terrestrial phase of the hydrological cycle; it controls the partitioning of rainfall in the pedosphere, the interface between the atmosphere and the lithosphere.

Heterogeneity of soil properties within and among soil horizons causes some regions to be more or less favorable to flow. The style of flow is highly variable with extremes represented by tortuous flow between individual particles and rapid flow through large, continuous macropores. Saturated hydraulic conductivity is also a key variable in all models that deal with the hydrological cycle or aspects of it, models that range from physically-based, fully-distributed small-catchment models to land surface parameterizing schemes of general circulation or global climate models. Due to spatial variability of soil hydraulic properties, large number of measurements is often required to properly characterize such properties even at the field scale.

Measurements of saturated hydraulic conductivity obtained by field or laboratory method are time consuming and labor-intensive. The importance and demand for saturated hydraulic conductivity data motivated researchers to develop indirect methods of obtaining it. In this regard, PTFs are becoming increasingly popular for estimating saturated hydraulic properties from soil physical properties such as particle size distribution, bulk density, porosity and organic matter content. The majority of PTFs are completely empirical, although physico-empirical models and fractal theory models have also been developed (Minasny and McBratney, 2000). Scientists have been aware that soil physical properties (e.g. soil texture, bulk density, organic matter content, etc.) influence soil hydraulic properties. This functional relationship motivated the development of PTFs, which use physical properties as input data to estimate soil hydraulic properties.

The primary motivation for conducting the study of saturated hydraulic conductivity stems from the lack of its detailed studies in this particular region in the literature. Most of the studies were carried out on agricultural soils or in other words a very few detailed study of saturated hydraulic conductivity has been conducted for forest soils. The present study was designed about saturated hydraulic conductivity of soils of both agricultural and forested hillslope areas in Pavanje river basin, Karnataka, India.

5.2 Estimation of saturated hydraulic conductivity

PTFs were developed using multiple linear regression technique to estimate the saturated hydraulic conductivity in terms of the more widely available basic soil properties such as the percentages of sand, silt and clay, bulk density, porosity and organic matter content. The following forms of PTFs were developed to estimate saturated hydraulic conductivity:

$$k_s = \sinh x \tag{5.1}$$

where

$$x = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_1^2 + b_5 x_1 x_2 + b_6 x_1 x_3 + b_7 x_2^2 + b_8 x_2 x_3 + b_9 x_3^2$$

where x represents the dependent variable, b_o is the intercept, b_1, b_2,……, b_9 are the regression coefficients and x_1, x_2, x_3 refer to the independent variables representing the basic soil properties.

Statistical evaluation for saturated hydraulic conductivity

In addition to R^2, RMSE and ME, the other two statistical criteria were used for the evaluation of PTFs to estimate saturated hydraulic conductivity based on the approach presented by Tietje and Hennings (1996). Geometric mean error ratio (GMER) and geometric standard deviation of the error ratio (GSDER) are those additional statistical criteria which were calculated from the error ratio (r_k) of measured saturated hydraulic conductivity $(k_s)_m$ versus predicted saturated hydraulic conductivity $(k_s)_p$ values:

$$r_k = \frac{(K_s)_p}{(K_s)_m} \tag{5.2}$$

$$GMER = exp\left[\frac{1}{n}\sum_{i=1}^{n} ln(r_k)\right] \tag{5.3}$$

$$GSDER = exp\left\{\left[\frac{1}{n-1}\sum_{i=1}^{n}[ln(r_k) - ln(GMER)]^2\right]^{\frac{1}{2}}\right\} \tag{5.4}$$

The GMER equals to 1 corresponds to an exact matching between measured and predicted saturated hydraulic conductivity; the GMER<1 indicates that predicted values are generally underestimated; GMER>1 points to over prediction. The GSDER equals to 1 corresponds to a perfect matching and it grows with deviation from measured data. The best PTF will, therefore, give a GMER close to 1 and a smaller GSDER.

5.3 Estimation of soil water retention curve from measured saturated hydraulic conductivity

Knowledge of the physics of soil water movement is crucial to the solution of many problems in watershed hydrology, for example, the prediction of runoff and infiltration following precipitation, the subsequent distribution of infiltrated water by drainage and evaporation, and estimation of the contribution of various parts of a watershed to the ground water storage. Soil water retention data is sparsely available when compared to other data. In order to have a quick derivation of soil water retention curve for typical regions without detailed laboratory investigations, an attempt has been made here to derive the same from saturated hydraulic conductivity. The following typical functional relation was derived for characterizing the soil water retention curve.

$$\theta = A + Be^{-(Ck_S + D|h|)} \tag{5.5}$$

where,

θ = Volumetric water content (cm^3/cm^3)

k_s = Saturated hydraulic conductivity (cm/hr)

h = Soil water pressure head (cm)

A, B, C, D = Constants

5.4 Results and discussion

5.4.1 Development of pedotransfer functions for saturated hydraulic conductivity

In the present study, the saturated hydraulic conductivity (k_s) was measured in the laboratory by variable falling head method using Permeameter for all the agricultural and forest soils. Totally there were forty five soil samples from the agricultural land and fifty six soil samples from the forested hillslopes. Most of the soils were sandy loam and loamy sand in both the agricultural and forest soils, only few were silty loam and sand. So the present study considered the sandy loam and loamy sand into two separate groups and developed the PTFs for the estimation of k_s by multiple non linear regression techniques for both agricultural and forest soils. Table 5.1 shows the statistics used for the development of PTFs for both the calibration and validation sets.

Table 5.1: Descriptive statistics of soil properties used for the development of PTFs for the estimation of saturated hydraulic conductivity

Variables	Calibration data set				Validation data set			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Physical and hydraulic properties of agricultural sandy loam textured soils								
S (%)	46	58	52.58	3.90	53	61	57.60	3.21
Si (%)	23	52	37.63	7.61	38	45	40.80	2.77
C (%)	1	5	1.75	1.03	1	2	1.20	0.45
BD (g/cm^3)	1.36	1.61	1.50	0.07	1.42	1.54	1.47	0.05
OM (%)	0.24	2.52	0.96	0.59	0.28	1.09	0.52	0.35
P (cm^3/cm^3)	0.33	0.45	0.38	0.03	0.39	0.44	0.42	0.02
k_s (cm/hr)	1.16	10.31	5.9	2.82	5.46	8.64	7.41	1.32
Physical and hydraulic properties of agricultural loamy sand textured soils								
S (%)	41	89	70.00	17.80	44	88	58.50	20.36
Si (%)	10	28	18.25	6.58	11	25	19.25	6.02
C (%)	1	4	2.42	1.31	1	1	1	0
BD (g/cm^3)	1.48	1.65	1.57	0.05	1.46	1.55	1.50	0.04
OM (%)	0.46	1.13	0.80	0.23	0.45	1.64	1.04	0.49
P (cm^3/cm^3)	0.37	0.41	0.39	0.01	0.41	0.43	0.42	0.01
k_s (cm/hr)	4.46	13.92	8.25	3.52	11.32	16.48	13.09	2.31
Physical and hydraulic properties of forested sandy loam textured soils								
S (%)	33	57	46.63	7.81	30	46	40.86	6.04
Si (%)	16	44	28.90	6.74	21	38	27.57	6.24
C (%)	0	5	1.57	1. 30	0	2	1.14	1.07
BD (g/cm^3)	1.22	1.59	1.42	1.10	1.32	1.46	1.37	0.05
OM (%)	0.66	7.50	2.36	1.78	1.62	5. 96	4.02	1.60
P (cm^3/cm^3)	0.36	0.52	0.43	0.04	0.43	0.48	0.46	0.02
k_s (cm/hr)	1.91	7.98	4.63	1.84	3.74	7.70	5.64	1.66
Physical and hydraulic properties of forested loamy sand textured soils								
S (%)	32	46	41.15	3.78	37	49	42.20	4.55
Si (%)	14	26	19.92	4.42	15	22	18.80	2.49
C (%)	0	3	0.46	0.88	1	3	1.60	0.89
BD (g/cm^3)	1.33	1.68	1.50	0.13	1.47	1.69	1.60	0.11
OM (%)	0.65	3.29	1.83	0.91	1.22	2.37	1.70	0.45
P (cm^3/cm^3)	0.33	0.47	0.40	0.06	0.32	0.41	0.36	0.05
k_s (cm/hr)	2.57	12.14	5.43	2.90	3.06	6.49	4. 40	1.47

where S, Si, C are the sand, silt and clay percentages, BD is bulk density (g/cm^3), OM is organic matter content (%), P is porosity (cm^3/cm^3), k_s is saturated hydraulic conductivity (cm/hr).

The PTFs were developed by multiple regressions between soil hydraulic parameter data and basic soil properties. Initially, the different input combinations of soil properties were tried (S, Si, BD; S, P, OM; BD, P, OM etc) to develop the PTFs, and finally selected the regression equation with higher R^2 and lower AIC values. The regression equations for loamy sand and sandy loam textured soils in the agricultural and forest area are in the following form as:

$$k_s = \sinh x$$

where, k_s is the saturated hydraulic conductivity, x is a non linear regression equation. So the hyperbolic sine of x will give the k_s. Initially saturated hydraulic conductivity values were related directly to regression equation (i.e., percentages of sand, silt and clay, bulk density, porosity and organic matter content) but in order to increase the efficiency of the PTFs, hyperbolic sine function was later considered. This gave relatively higher R^2 values. The developed PTFs are presented in Table 5.2.

Table 5.2: PTFs developed for the estimation of saturated hydraulic conductivity

Types of soil	**Pedotransfer functions developed**	**AIC**
Agricultural soil		
Sandy loam	$x = 80.16 + 0.810 * S - 143.57 * BD + 21.99 * OM + 0.0020 * S^2 - 0.687 * S * BD - 0.0022 * S * OM + 63.33 * BD^2 - 13.63 * BD * OM - 0.219 * OM^2$	16.5106
Loamy sand	$x = -238.90 - 3.248 * S - 5.468 * Si + 502.70 * BD + 0.0042 * S^2 + 0.0166 * S * Si + 1.589 * S * BD + 0.0362 * Si^2 + 2.057 * Si * BD - 206.43 * BD^2$	4.7876
Forest soil		
Sandy loam	$x = -1.272 - 0.0433 * Si + 0.693 * OM + 13.04 * P + 0.0009 * Si^2 - 0.0074 * Si * OM - 0.0910 * Si * P - 0.0036 * OM^2 - 1.128 * OM * P - 3.204 * P^2$	-34.9219
Loamy sand	$x = 271.11 - 9.116 * Si + 45.38 * OM - 289.13 * BD + 0.0809 * Si^2 - 0.695 * Si * OM + 4.681 * Si * BD + 1.991 * OM^2 - 25.74 * OM * BD + 80.04 * BD^2$	-40.87

where S, Si are the sand and silt percentages, BD is bulk density (g/cm^3), OM is organic matter content (%), P is porosity (cm^3/cm^3), AIC is Akaike Information Criteria.

Statistical evaluation

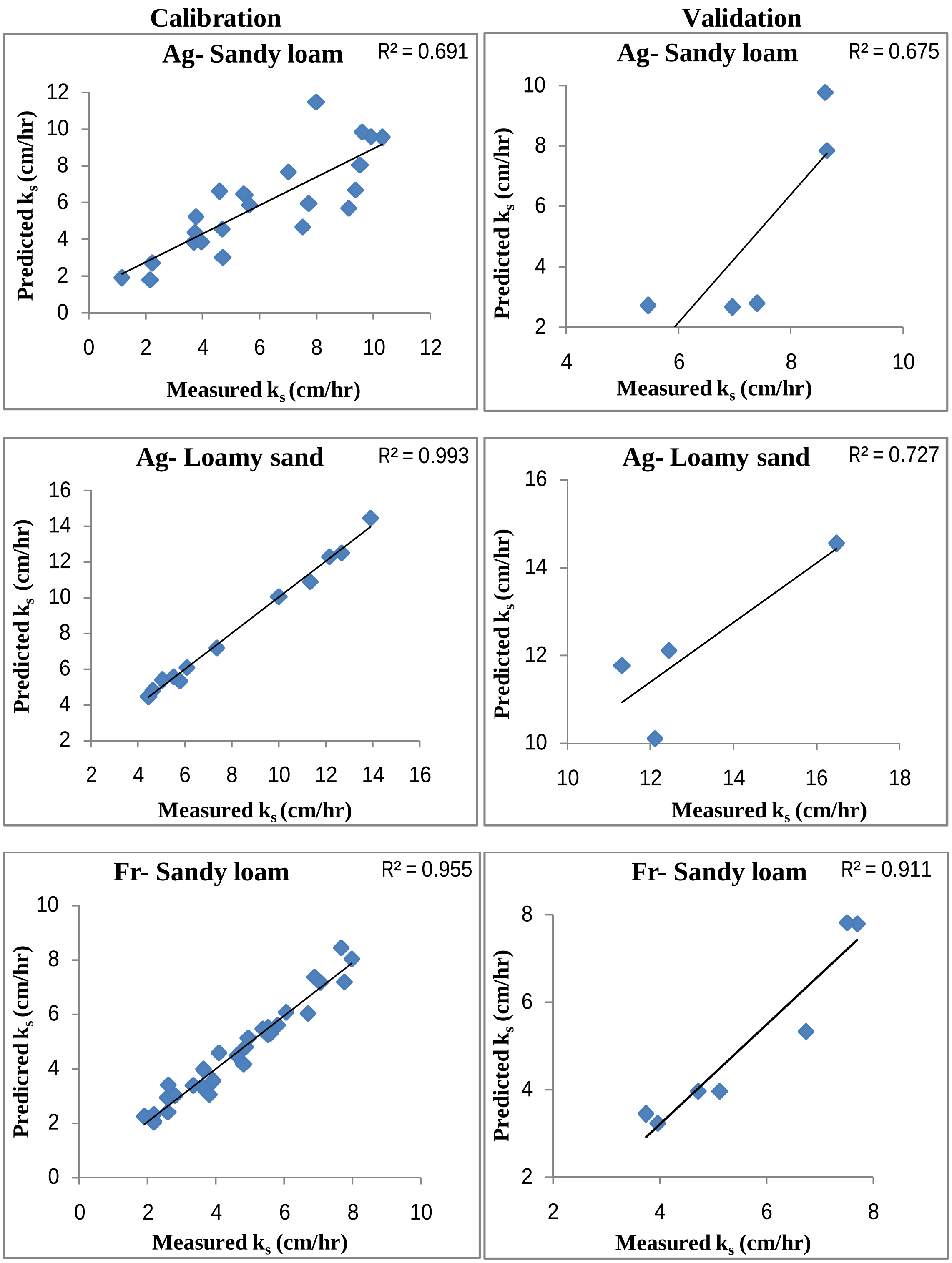
Using the developed PTFs, saturated hydraulic conductivity was estimated for sandy loam and loamy sand textured soils for both agricultural as well as forested hillslope soils. Then they were validated using the different sets of soil properties from the same region. As mentioned earlier, the present research work considered five statistical criteria for evaluating the performance accuracy of estimated saturated hydraulic conductivity, such as R^2, RMSE, ME, GMER and GSDER. The best PTF will give a higher R^2 values, lower RMSE and ME, and GMER close to 1 and a smaller GSDER. The results are shown in the Table 5.3.

Table 5.3: Statistical properties of measured values of k_s with that of estimated ones

Types of soil	R^2	RMSE	ME	GMER	GSDER
Calibration sets					
Sandy loam -Ag	0.691	0.0254	0.0000	1.0035	1.3109
Loamy sand-Ag	0.993	0.0264	-0.0007	1.0000	1.0385
Sandy loam -Fr	0.955	0.0923	-0.0077	1.0004	1.0811
Loamy sand -Fr	0.995	0.0457	0.0000	1.0003	1.0509
Validation sets					
Sandy loam -Ag	0.675	0.0672	0.0050	0.8592	1.3412
Loamy sand -Ag	0.727	0.0597	0.0048	0.9852	1.3908
Sandy loam -Fr	0.911	0.0165	0.0012	1.1367	1.1170
Loamy sand -Fr	0.862	0.0316	0.0016	0.9377	1.1838

where R^2 is coefficient of determination, RMSE is root mean square error, ME is mean error, GMER is geometric mean error ratio and GSDER is geometric standard deviation of the error ratio, Ag is agricultural soil, Fr is forest soil.

Relatively higher R^2 values were found for sandy loam and loamy sand textured soils of agricultural and forested hillslopes, for both calibration and validation sets. Even the RMSE and ME were less in all the cases. The geometric mean error ratios were also close to 1 in the calibration sets. So there was almost no difference between the measured and estimated saturated hydraulic conductivity values. But there was a small under prediction of saturated hydraulic conductivity in the validation sets. Figure 5.1 show the graph of measured saturated hydraulic conductivity versus the predicted ones for sandy loam and loamy sand textured soils.


Calibration
Validation
Ag- Sandy loam
R² = 0.691
Predicted k_s (cm/hr)
Measured k_s (cm/hr)
Ag- Sandy loam
R² = 0.675
Predicted k_s (cm/hr)
Measured k_s (cm/hr)
Ag- Loamy sand
R² = 0.993
Predicted k_s (cm/hr)
Measured k_s (cm/hr)
Ag- Loamy sand
R² = 0.727
Predicted k_s (cm/hr)
Measured k_s (cm/hr)
Fr- Sandy loam
R² = 0.955
Predicred k_s (cm/hr)
Measured k_s (cm/hr)
Fr- Sandy loam
R² = 0.911
Predicted k_s (cm/hr)
Measured k_s (cm/hr)

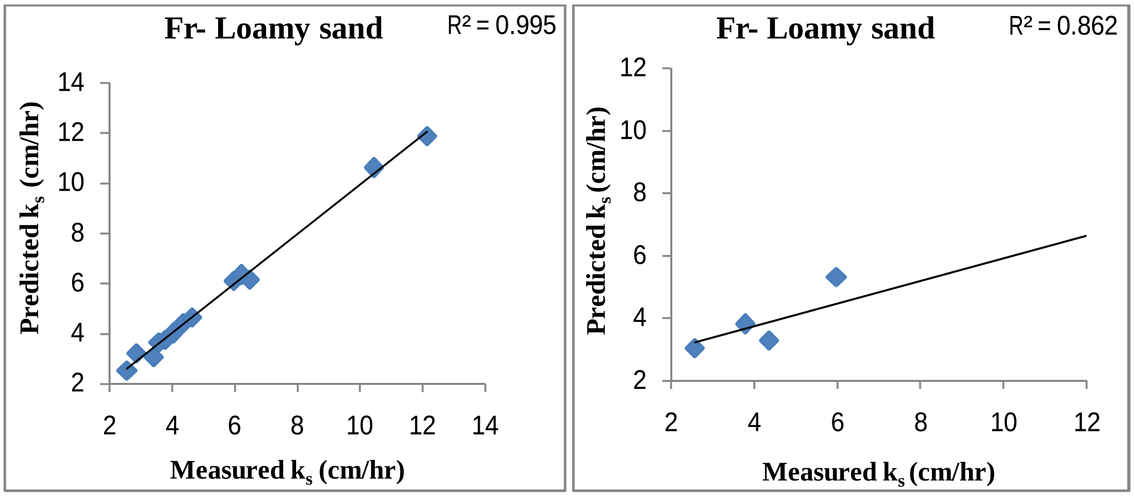


Figure 5.1: Measured versus estimated values of k_s for both calibration and validation sets

5.4.2 Development of empirical relationship between soil water retention curve and saturated hydraulic conductivity

In this study, the laboratory determination of soil moisture retention characteristics and saturated hydraulic conductivity were carried out for the soils of Pavanje river basin, located in coastal region of Karnataka, India. The texture of soils in this area is mainly sandy loam, loamy sand, sand and silty loam. A total of hundred and one soil samples were collected from both agricultural and forest soils in the above said area. Extensive laboratory measurements (physical and hydraulic properties) were done for each soil sample. Saturated hydraulic conductivity was measured through Permeameter in the laboratory. Soil water retention curve data was obtained through pressure plate apparatus. This has been used to develop an empirical relationship to derive the approximate soil moisture retention curve at the places in Pavnje river basin. Here both water retention curve and saturated hydraulic conductivity were measured in the laboratory and then developed an empirical relationship to approximate soil moisture retention curve from the saturated hydraulic conductivity data. The statistics of hydraulic properties used to develop these relationships are summarized in the Table 5.4.

Table 5.4: Descriptive statistics of soil properties used to derive the empirical relationship to estimate the soil water retention curves

variables	Calibration data set				Validation data set			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Hydraulic properties of agricultural sandy loam textured soils								
θ(h)	0.05	0.26	0.15	0.05	0.11	0.27	0.18	0.04
k_s (cm/hr)	1.16	10.31	5.89	2.82	5.46	8.64	7.41	1.32
Hydraulic properties of agricultural loamy sand textured soils								
θ(h)	0.03	0.26	0.13	0.08	0.02	0.27	0.10	0.09
k_s (cm/hr)	5.04	12.68	10.06	2.84	4.46	16.48	8.47	5.30
Hydraulic properties of forest sandy loam textured soils								
θ(h)	0.07	0.29	0.15	0.05	0.06	0.28	0.14	0.06
k_s (cm/hr)	1.91	7.7	4.43	1.69	5.61	7.98	6.97	0.99
Hydraulic properties of forest loamy textured soils								
θ(h)	0.06	0.20	0.12	0.04	0.08	0.20	0.14	0.03
k_s (cm/hr)	2.57	12.14	5.56	2.69	2.87	4.64	3.71	0.67

where θ(h) is soil water retention (cm^3/cm^3), k_s is saturated hydraulic conductivity (cm/hr), SD is standard deviation.

The present study considered the sandy loam and loamy sand textured soils separately for both agricultural and forested soils and developed the relationship. The developed formula is of this form;

$$\theta = A + Be^{-(Ck_S + D|h|)}$$

The developed empirical relationships between the soil water retention curve and saturated hydraulic conductivity are summarized in the Table 5.5.

Table 5.5: Formulae for soil water retention curves in terms of saturated hydraulic conductivity

Types of soil	Empirical equation
Agricultural-sandy loam	$\theta(h) = 0.15922 + 0.09708e^{-(0.01148k_S+0.0015\|h\|)}$
Agricultural- loamy sand	$\theta(h) = 0.04781 + 0.06611e^{-(0.0039k_S+0.0002\|h\|)}$
Forest-sandy loam	$\theta(h) = 0.10825 + 0.12881e^{-(0.0074k_S+0.0003\|h\|)}$
Forest-loamy sand	$\theta(h) = 0.06515 + 0.14066e^{-(0.0293k_S+0.0002\|h\|)}$

where θ(h) is soil water retention (cm^3/cm^3), k_s is saturated hydraulic conductivity (cm/hr), h is soil water pressure expressed in cm of water.

Statistical evaluation of predicted soil water retention curve

The developed equations have four constants for each type of soil textures and locations. The present study evaluated the performances of developed equations with R^2, RMSE, ME and AIC values. For all types of soils, calibration set as well as validation set, both have shown good results (Table 5.6.). R^2 values for validation set were quite good when compared to the calibration set. R^2 values vary between 0.687-0.862 for calibration set, and for validation set it was 0.713-0.895. RMSE values of the calibration set for agricultural sandy loam and loamy sand were 0.029 and 0.013 and that for forest sandy loam and loamy sand were 0.023 and 0.015 respectively. For validation set, the values were 0.022 and 0.021 for sandy loam and 0.033 and 0.019 for loamy sand of agricultural and forest soils respectively. The corresponding ME values show small errors in both calibration and validation sets.

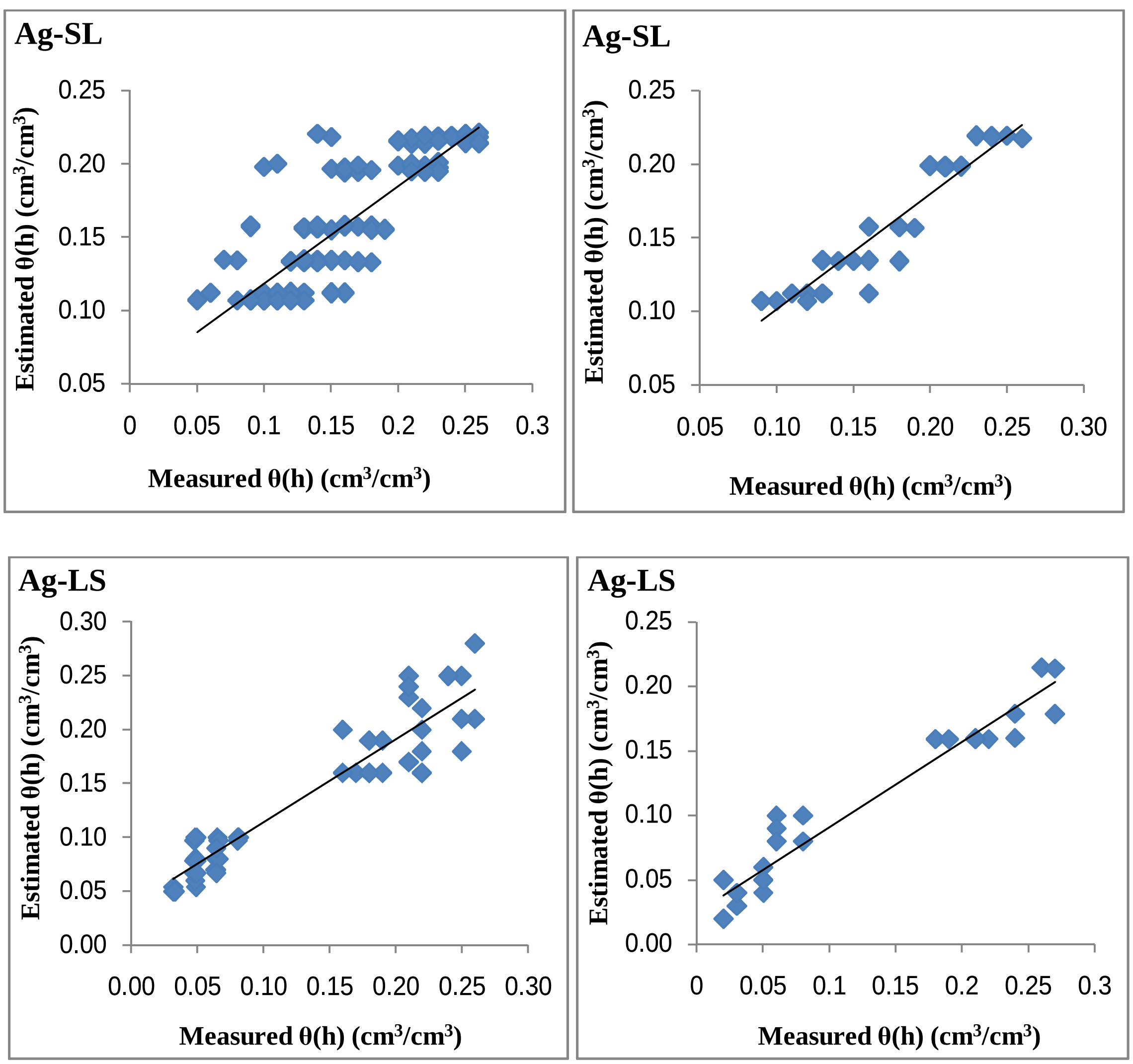
Table 5.6: Statistical properties of measured water retention curves with that of estimated ones

Types of soil	Calibration				Validation			
	R^2	RMSE	ME	AIC	R^2	RMSE	ME	AIC
Ag-SL	0.687	0.0288	-0.0007	-301.093	0.820	0.0216	0.0132	-124.145
Ag- LS	0.734	0.0133	0.0043	-309.557	0.844	0.0210	0.0183	-186.974
Fr-SL	0.780	0.0228	-0.0013	-422.096	0.713	0.0329	-0.0013	-102.412
Fr-LS	0.862	0.0149	-0.0014	-347.669	0.895	0.0190	0.0116	-131.694

where R^2 is coefficient of determination, RMSE is root mean square error, ME is mean error, AIC is Akaike Information Criteria, Ag is agricultural soil, Fr is forest soil, LS loamy sand, SL sandy loam.

The under prediction of water retention curve has been observed for all the soils except in agricultural loamy sand in the calibration set. In validation set, only the forested sandy loam soils show smaller under prediction of water retention curve. The model can be a good one, if it has low AIC values. Here AIC values were smaller. The results were plotted for both calibration and validation sets of different types of soil textures, which are shown in Figure 5.2.

Calibration set **Validation set**



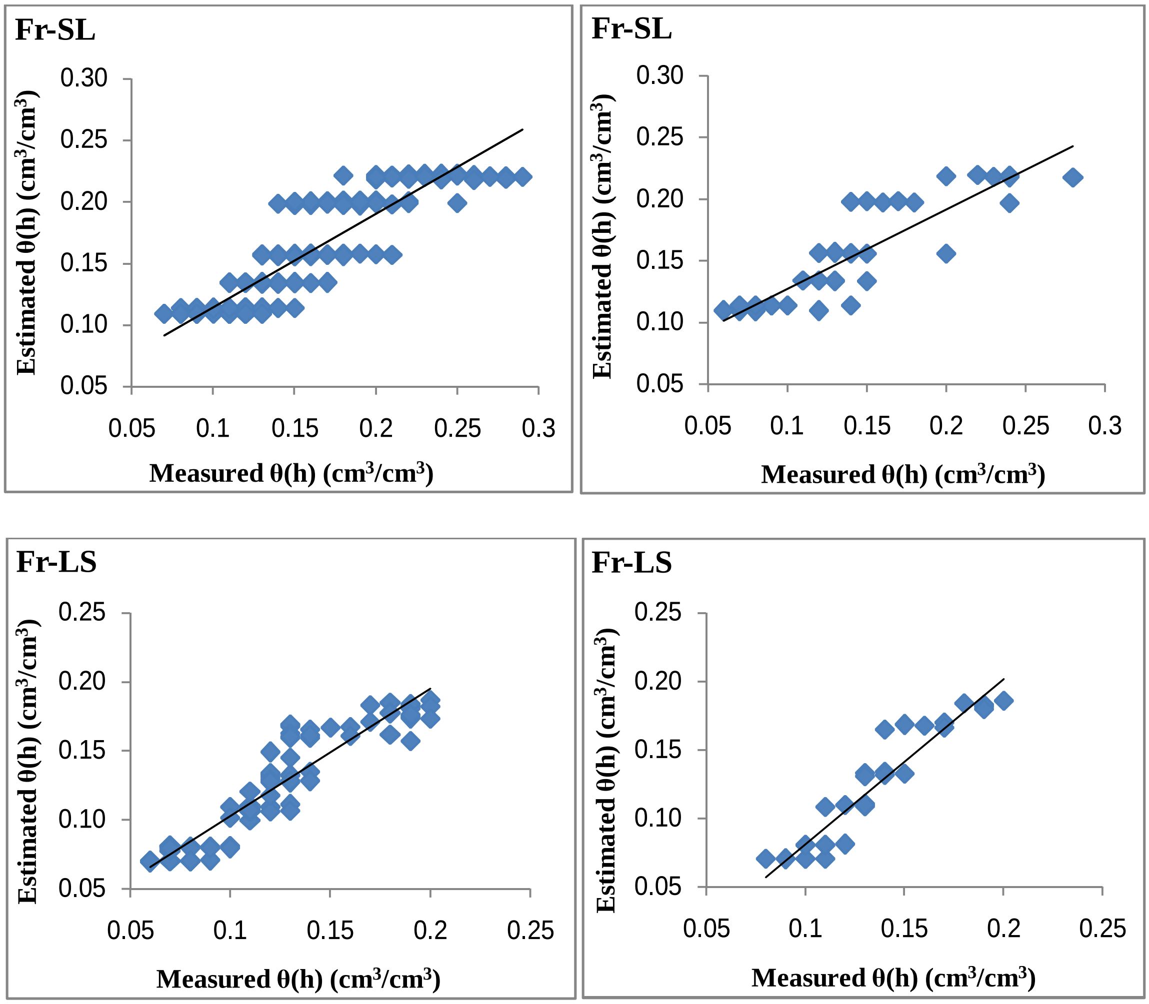


Figure 5.2: Estimated versus measured values of soil water retention curves

5.5 Uncertainty analysis

Pedotransfer functions have been developed particularly to translate readily available information into variables that are needed in simulation models (Bouma 1989). An important factor that needs consideration is the uncertainty in predictions. Uncertainty in pedotransfer functions can result from bias in the model, uncertainty in the parameters, and errors in the measurements of the input variables (Minasny and Mcbratney, 2002). Uncertainty analysis is required to gauge the reliability of the predictions.

Direct measurements of hydraulic and physical properties consist of both true value and measurement error contributed by factors which cannot be completely avoided. Imprecision and bias in the measuring device or researcher errors, such as misread values and transcription errors, may occur. In order to determine the relevance of laboratory data, the degree of measurement error should be identified and included in the data, typically in the form of the standard deviation from the mean value (Mandel, 1964). Measurement bias is the result of a constant deviation in the results. For example, measurements which are continually skewed in a particular direction from the true value due to improper instrument calibration are considered to be biased. Model estimates are considered biased if the estimated value does not equal the mean value (Isaaks and Srivastava, 1989).

Qualitatively speaking, measurement uncertainty refers to the fact that measured values are in some sense only a reasonable or useful guess at what the unknown value might be (Isaaks and Srivastava, 1989). In other words, no matter the measurement approach, there will always be a degree of error which may not be easily quantified. The uncertainty might be caused due to several reasons.

- Moisture retention uncertainty. This is mainly due to the hydraulic contact material used in the moisture retention experiments. The material stuck to the bottom of the cotton cloth attached to the sample rings and possibly permeated the samples to some degree creating lower permeability at the base of the samples. Removing the samples at equilibrium to obtain a sample weight may have resulted in a minor degree of evaporation, also contributing to measurement uncertainty.
- Uncertainty in saturated hydraulic conductivity measurements. The high flux rate applied to the samples during measurement of saturated hydraulic conductivity in the constant head permeameters may have contributed to sample disturbance during analysis, leading to overestimated conductivity values because of possible formation of preferential flow paths. Another possible contributor to measurement uncertainty may have been the small time period used to measure outflow and the small volumes measured to determine volumetric flux. It is also possible that not enough time was

allowed to reach steady state flow within the samples before measurements were made.

- Uncertainty in particle size distribution measurements. Although care was taken during analysis, uncertainty in particle-size distribution measurements using sieve methods may have resulted from sediment sticking to the sides of individual sieves (not passing through openings) and from particles sticking in the sieve openings instead of passing through. Soil hydrometer methods include measuring uncertainty primarily from sample loss while taking measurements (sediment sticking to the hydrometers) and from evaporation of the soil slurry during analysis (takes 24 hours to complete the measurements).
- Uncertainty in moisture retention curve fitting parameters. The van Genuchten and Brooks- Corey equations were used to fit to moisture retention data requiring the RETC curve fitting program to estimate unknown parameters (θ_r, θ_s, α, n, λ and h_b). The RETC program is limited to non unique results which contribute to model uncertainty (van Genuchten et al., 1991). The model uncertainty increases with the number of unknown parameters and fewer numbers of measured data points.

5.5.1 Results and discussion

Results of mean and standard deviations of physical and hydraulic properties obtained from different laboratory measurements are shown in Table 5.7 and Table 5.8 at each depth for both agricultural and forested hillslope soils respectively. In an effort to quantify the uncertainty in the measured physical and hydraulic properties, mean and standard deviations were calculated at different depths by considering the samples from the five sites of the agricultural land and eight of forested hillslopes. It could be seen that the standard deviations are reasonably low and also consistent between the two land covers (Agricultural and forest) for all physical and hydraulic properties.

Table 5.7: Descriptive statistics (mean and standard deviations) determined for agricultural soils at different depths

Physical properties							
Depth(cm)		S (%)	Si (%)	C (%)	BD (g/cm^3)	OM (%)	P (cm^3/cm^3)
10	Mean	56.20	31.81	2.40	1.54	1.72	0.38
	SD	11.54	10.91	1.51	0.06	0.61	0.03
20	Mean	57.20	29.10	2.00	1.54	1.22	0.38
	SD	15.80	12.86	1.00	0.06	0.28	0.03
30	Mean	58.80	30.20	1.60	1.51	1.03	0.39
	SD	13.59	11.65	0.89	0.07	0.17	0.02
50	Mean	58.20	31.60	1.60	1.56	1.07	0.36
	SD	13.99	12.12	0.89	0.06	0.20	0.01
70	Mean	57.60	33.00	1.80	1.51	0.93	0.39
	SD	12.70	13.23	0.84	0.06	0.17	0.04
90	Mean	57.40	29.80	1.80	1.55	0.65	0.39
	SD	14.09	11.65	1.30	0.02	0.23	0.02
110	Mean	58.40	28.60	2.40	1.50	0.56	0.41
	SD	14.74	11.33	1.95	0.04	0.27	0.01
130	Mean	60.60	33.40	1.60	1.46	0.37	0.42
	SD	16.63	15.42	0.54	0.07	0.09	0.02
150	Mean	60.40	33.20	1.00	1.45	0.32	0.42
	SD	15.77	14.75	0	0.07	0.09	0.01

Hydraulic properties (SWRC(cm^3/cm^3) and k_s (cm/hr))								
Depth (cm)		θ_{33}	θ_{100}	θ_{300}	θ_{500}	θ_{1000}	θ_{1500}	k_S
10	Mean	0.21	0.19	0.16	0.15	0.14	0.13	9.63
	SD	0.07	0.06	0.05	0.05	0.05	0.05	3.54
20	Mean	0.22	0.21	0.18	0.18	0.17	0.14	9.34
	SD	0.09	0.09	0.08	0.07	0.07	0.06	3.20
30	Mean	0.22	0.20	0.19	0.18	0.16	0.13	8.54
	SD	0.09	0.09	0.08	0.08	0.08	0.06	2.92
50	Mean	0.22	0.20	0.17	0.166	0.15	0.13	8.15
	SD	0.08	0.07	0.07	0.07	0.06	0.06	3.00
70	Mean	0.22	0.20	0.18	0.17	0.15	0.13	6.13
	SD	0.08	0.07	0.07	0.06	0.05	0.05	1.44
90	Mean	0.22	0.19	0.17	0.17	0.15	0.14	5.61
	SD	0.08	0.07	0.06	0.06	0.06	0.06	1.75
110	Mean	0.22	0.2	0.18	0.164	0.15	0.13	5.69
	SD	0.09	0.08	0.07	0.07	0.07	0.06	2.14
130	Mean	0.21	0.19	0.18	0.16	0.14	0.12	6.89
	SD	0.09	0.08	0.08	0.07	0.06	0.06	4.68
150	Mean	0.21	0.19	0.16	0.16	0.14	0.13	6.01
	SD	0.09	0.08	0.08	0.07	0.06	0.06	6.01

	Hydraulic properties (vG and B-C model parameters)							
Depth (cm)	vG model parameters					B-C model parameters		
		θ_r(cm^3/cm^3)	θ_s(cm^3/cm^3)	α (cm^{-1})	n	θ_r(cm^3/cm^3)	h_b (cm)	λ
10	Mean	0.12	0.38	0.07	1.46	0.12	19.24	0.46
	SD	0.05	0.03	0.09	0.11	0.05	14.35	0.11
20	Mean	0.12	0.39	0.05	1.44	0.12	16.91	0.44
	SD	0.06	0.03	0.06	0.29	0.06	9.62	0.29
30	Mean	0.12	0.39	0.09	1.36	0.12	10.24	0.36
	SD	0.06	0.03	0.10	0.15	0.06	5.72	0.15
50	Mean	0.12	0.38	0.08	1.38	0.12	18.35	0.38
	SD	0.06	0.02	0.10	0.07	0.06	14.36	0.07
70	Mean	0.13	0.39	0.07	1.41	0.13	13.68	0.41
	SD	0.05	0.02	0.07	0.11	0.05	7.73	0.11
90	Mean	0.13	0.39	0.05	1.42	0.13	19.99	0.42
	SD	0.05	0.01	0.05	0.12	0.05	12.25	0.12
110	Mean	0.12	0.40	0.08	1.40	0.12	16.07	0.40
	SD	0.06	0.02	0.10	0.10	0.06	11.49	0.10
130	Mean	0.12	0.42	0.09	1.41	0.12	12.75	0.42
	SD	0.06	0.02	0.10	0.11	0.06	8.31	0.10
150	Mean	0.12	0.42	0.09	1.44	0.12	11.06	0.44
	SD	0.06	0.02	0.10	0.10	0.06	7.23	0.10

Table 5.8: Descriptive statistics (mean and standard deviations) determined for forested hillslope soils at different depths

Physical properties							
Depth(cm)		S (%)	Si (%)	C (%)	BD (g/cm^3)	OM (%)	P (cm^3/cm^3)
10	Mean	45.38	27.13	0.75	1.49	3.33	0.41
	SD	6.30	5.51	1.16	0.10	2.05	0.04
20	Mean	47.63	24.25	0.88	1.44	3.47	0.43
	SD	6.19	4.83	1.13	0.12	2.03	0.05
30	Mean	44.13	25.75	1.75	1.44	2.81	0.43
	SD	5.22	10.05	1.98	0.13	1.52	0.05
40	Mean	42.13	25.00	1.13	1.45	2.38	0.43
	SD	7.62	7.89	0.99	0.14	1.70	0.06
50	Mean	42.00	24.88	1.63	1.45	1.78	0.42
	SD	6.99	8.94	1.06	0.13	1.02	0.05
60	Mean	42.75	25.00	1.38	1.43	1.51	0.43
	SD	5.80	6.16	1.06	0.13	0.83	0.06
75	Mean	45.00	27.25	1.13	1.45	1.31	0.42
	SD	10.18	7.81	0.99	0.13	0.30	0.05

Hydraulic properties (SWRC (cm^3/cm^3) and k_s (cm/hr))								
Depth(cm)		θ_{33}	θ_{100}	θ_{300}	θ_{500}	θ_{1000}	θ_{1500}	k_S
10	Mean	0.22	0.17	0.15	0.13	0.11	0.09	3.83
	SD	0.03	0.03	0.02	0.02	0.01	0.01	0.97
20	Mean	0.22	0.18	0.15	0.14	0.11	0.10	5.17
	SD	0.03	0.03	0.02	0.02	0.02	0.02	1.51
30	Mean	0.22	0.18	0.16	0.13	0.11	0.09	5.49
	SD	0.03	0.03	0.03	0.02	0.02	0.02	3.52
40	Mean	0.22	0.18	0.16	0.13	0.11	0.09	5.08
	SD	0.03	0.03	0.02	0.02	0.02	0.02	2.06
50	Mean	0.22	0.17	0.15	0.12	0.10	0.08	5.35
	SD	0.03	0.03	0.02	0.01	0.02	0.02	2.74
60	Mean	0.21	0.17	0.15	0.12	0.10	0.08	5.16
	SD	0.02	0.02	0.02	0.01	0.02	0.02	1.57
75	Mean	0.20	0.16	0.14	0.12	0.10	0.09	4.49
	SD	0.03	0.03	0.02	0.02	0.02	0.02	1.27

	Hydraulic properties (vG and B-C model parameters)							
Depth (cm)	vG model parameters					B-C model parameters		
		θ_r(cm^3/cm^3)	θ_s(cm^3/cm^3)	α (cm^{-1})	n	θ_r(cm^3/cm^3)	h_b (cm)	λ
10	Mean	0.02	0.38	0.04	1.25	0.01	32.80	0.22
	SD	0.03	0.04	0.03	0.04	0.02	25.27	0.04
20	Mean	0.01	0.40	0.08	1.22	0.01	25.84	0.21
	SD	0.02	0.05	0.09	0.03	0.02	18.87	0.03
30	Mean	0.01	0.40	0.06	1.23	0.00	32.67	0.21
	SD	0.01	0.04	0.07	0.04	0.00	24.09	0.04
40	Mean	0.02	0.40	0.09	1.23	0.00	26.55	0.20
	SD	0.03	0.05	0.10	0.04	0.00	25.83	0.05
50	Mean	0.01	0.39	0.05	1.25	0.00	35.07	0.23
	SD	0.02	0.05	0.06	0.03	0.01	21.74	0.03
60	Mean	0.01	0.40	0.06	1.24	0.00	27.88	0.23
	SD	0.02	0.06	0.06	0.02	0.01	17.32	0.03
75	Mean	0.02	0.39	0.06	1.24	0.00	18.15	0.21
	SD	0.03	0.05	0.05	0.01	0.01	11.57	0.02

Table 5.7 and Table 5.8 show the physical and hydraulic properties and also the optimal parameters of the fitted van Genuchten and Brooks-Corey model (eqn. (4.3) and eqn. (4.4)) by combining the pressure plate retention data of samples for each depth for agricultural and forested hillslope soils. The error statistics (R^2, RMSE and ME) are indicative of the uncertainties introduced on account of the model used. It can be seen from the Tables 4.5, 4.6, 4.17, 4.18, 5.3 and 5.4 that, the values of RMSE in almost all cases are quite low thereby indicating that the uncertainties due to use of the model are small. Reasonably high R^2 values support this conclusion. In any case, it must be reiterated that, since the major focus of this study was characterization of soil hydraulic properties in two types of soils (agricultural and forest) considered, relative differences and not absolute values of all these properties are important. It may be concluded that, the uncertainties due to measurements and modeling of retention data and saturated hydraulic conductivity were more or less similar for the two types of soils as indicated in the mean and standard deviation values. There is no much uncertainty even in the measured physical properties of both the soils.

5.6 Runoff analysis

Runoff is a complex interaction between precipitation and landscape factors. Understanding the basic relationships between rainfall, runoff and soil loss is vital for effective management and utilization of water resources and soil conservation planning. Gross runoff response as a result of complex interactions between climatologic and physiographic factors usually affects erosion in watersheds (Rai and Mathur, 2007). The rainfall-runoff processes on the mountainous hilly slopes are the source of the surface water. First, rainfall influences hydrological responses of a watershed, and this in turn influences soil erosion (Grunwald and Norton, 2000). Therefore, understanding the knowledge on hydrological processes of different parts of the watershed helps us in water and land resources management.

Runoff response depends on soil moisture in the watershed and soil moisture has influence on the hydrologic response of catchments (Brocca et al., 2008; Berthet et al., 2009). Soil moisture content can vary significantly from one soil type to another, both spatially and temporally, across watersheds or even within a single soil surface. Runoff generation mechanisms and processes depend not only on conditions during storms, but conditions in advance of storms and a complete understanding or representation of all the land surface hydrologic processes is required to quantify the generation of runoff.

Estimation of runoff distribution and volume is a critical point in engineering design of hydraulic structures, erosion estimations, and environmental impact evaluation. In the late forties and early fifties, the Soil Conservation Service (SCS) curve number method was developed for estimating direct runoff from ungaged small watersheds, and to determine the effects of changes in land treatment and use. However, the curve number method is not the most conceptually reliable model and has various shortcomings. Considering the great likelihood of the continued use of the model in the future, the SCS curve number method is in need of update and improvement. One possible way to improve the curve number method is to include some physically realistic infiltration model. National Resources Conservation Service (NRCS), formally SCS espouses the infiltration model as one such possibility (Miller and Cronshey, 1989). There are three infiltration models namely Green and Ampt Model, Horton Model and Philip Model, out of which the Green and Ampt model is popular because parameters involved in this model are based upon readily available soil texture information.

Green and Ampt (1911) developed their infiltration equation to describe how water enters the soil from a simple application of Darcy's law to unsaturated flow in a homogeneous soil profile. During recent years, it received increased attention as a method for predicting infiltration from rainfall events. Though there are no extensive data available for evaluating the equation parameters, they are physically based and can be related to soil properties. Rawls and Brakensiek (1982, 1983, and 1986) developed the method of estimating the Green and Ampt parameters from the USDA soil survey data. This method allows the application of the Green and Ampt infiltration model to any watershed for which soil survey data exists. The Green and Ampt method is a proven method for describing soil parameters within a hydrologic model. A great deal of research into the use of the Green and Ampt (G-A) method has been done (Bouwer, 1969; Chen and Young, 2006). The Green and Ampt method considers a rainfall event under two separate conditions. First one is when rainfall intensity is less than the saturated hydraulic conductivity of the soil, in this case, the precipitation infiltrates into the ground. The second condition considers the case when precipitation intensity is greater than or equal to the saturated hydraulic conductivity of the soil. In this case, the infiltration rate into the soil is described by the Green and Ampt equation (Mein and Larson, 1973; Dingman, 2002):

$$f(t) = k_s\left[1 + \frac{\psi_s(\Delta\theta)}{F(t)}\right] \tag{5.6}$$

where f(t) is the infiltration rate, F(t) is the total infiltration for that time step, k_s is the saturated hydraulic conductivity, $\Delta\theta$ is the soil water deficit, described as the difference between the initial soil moisture content and the porosity, and ψ_s is the wetting front soil suction parameter.

Green and Ampt (G-A) method

The Green and Ampt (1911) model is an approximation to the infiltration excess process. The Green and Ampt model approximates the curved soil moisture profiles, that result in practice, and from solution to Richard's equation, as a sharp interface with saturation conditions, $\theta = n$, above the wetting front and initial moisture content, $\theta = \theta_o$, below the wetting front. The initial moisture content is assumed to be uniform over depth. Let L denote the depth to the wetting front and the difference between initial and saturation moisture contents be $\Delta\theta = n - \theta_o$. Then the depth of infiltrated water following initiation of infiltration is,

$$F = L\Delta\theta \tag{5.7}$$

The datum for the definition of hydraulic head is taken as the surface and an unlimited supply of surface water input is assumed, but with small ponding depth, so the contribution to hydraulic gradient from the depth of ponding at the surface is neglected.

Immediately below the wetting front, at depth just greater than L, the soil is at its initial unsaturated condition, with corresponding suction head $|\psi_f|$. The hydraulic head difference driving infiltration, measured from the surface to just below the wetting front is therefore,

$$h = -(L + |\psi_f|) \tag{5.8}$$

The hydraulic gradient is obtained by dividing this head difference by the distance L between the surface and the wetting front to obtain,

$$\frac{dh}{dz} = -\frac{L+|\psi_f|}{L} \tag{5.9}$$

Using this in Darcy's equation (q= -k dh/dL), the infiltration capacity can be obtained as,

$$f_c = k_s \frac{L + |\psi_f|}{L} = k_s \left[1 + \frac{|\psi_f|}{L}\right]$$

$$= k_s \left[1 + \frac{|\psi_f|\,\Delta\theta}{F}\right]$$

$$= k_s \left[1 + \frac{P}{F}\right] \tag{5.10}$$

Hence, expression (5.7) has been used to express $L=F/\Delta\theta$. This provides an expression for the reduction in infiltration capacity as a function of infiltrated depth $f_c(F)$. The parameters involved are k_s and the product $P=|\psi|\Delta\theta$. Using the soil moisture characteristic ψ_f may be estimated as

$$\psi_f = \psi(\theta_o) \tag{5.11}$$

Values for θ_o may be estimated from field capacity θ_{fc}, or wilting point θ_{pwp}, depending on the antecedent conditions. Rawls et al. (1993) recommended evaluating $|\psi_f|$ from the air entry pressure by the formula,

$$\left|\psi_f\right| = \frac{2b+3}{2b+6}\left|\psi_a\right| \tag{5.12}$$

where $\left|\psi_a\right|$ and b are taken from Clapp and Hornberger (1978) parameters.

Given a surface water input rate of w, the cumulative infiltration prior to ponding is F = wt. Ponding occurs when infiltration capacity decreases to the point where it equals the water input rate, f_c = w. Setting f_c = w in (5.10) and solving for F, one obtains the cumulative infiltration at ponding.

Green and Ampt cumulative infiltration at ponding;

$$F_p = \frac{k_s\left|\psi_f\right|\Delta\theta}{(w-k_s)} \tag{5.13}$$

Green and Ampt time to ponding;

$$t_p = \frac{F_p}{w} = \frac{k_s\left|\psi_f\right|\Delta\theta}{w(w-k_s)} \tag{5.14}$$

To solve for the infiltration that occurs after ponding with the Green and Ampt model, recognize that infiltration rate as the derivative of cumulative infiltration;

$$f(t) = \frac{dF}{dt} = f_c(t) \tag{5.15}$$

Here the functional dependence on time is explicitly shown. Now using (5.10), the following differential equation is obtained,

$$\frac{dF}{dt} = k_s\left[1 + \frac{P}{F}\right] \tag{5.16}$$

Using separation of variables, this can be integrated from any initial cumulative infiltration depth F_s at time t_s to a final cumulative infiltration depth F at time t.

Green-Ampt infiltration under ponded conditions;

$$t - t_s = \frac{F-F_s}{k_s} + \frac{P}{k_s}\ ln\left(\frac{F_s+P}{F+P}\right) \tag{5.17}$$

There is no explicit expression for F from this equation. However by setting $t_s = t_p$, and $F_s = F_p$, this equation can be solved numerically for F given any arbitrary t (greater than t_p) to give the cumulative infiltration as a function of time.

Steps carried out to estimate the runoff by Green and Ampt method

The present study considered surface water input hyetograph and the parameters of infiltration equation and then determined the ponding time, the infiltration after ponding occurs, and the runoff generated. The output is the runoff generated from excess surface water input over the infiltration capacity integrated over each time interval. Infiltration capacity decreases with time due to its dependence on the cumulative infiltrated depth F, which serves as a state variable through the calculations. Figure 5.3 presents a flow chart for determining infiltration and runoff generated under variable surface water input intensity. The steps followed are as follows:

- Considered a series of time intervals of length Δt. Interval 1 was designated as the interval from $t=0$ to $t=\Delta t$, interval 2 from $t=\Delta t$ to $t=2\Delta t$ and so on. In general interval i is from $t= (i-1)\,\Delta t$ to $t= i\Delta t$.
- The surface water input intensity during the interval was denoted by w_t and taken as constant throughout the interval.
- The cumulative infiltration depth at the beginning of the interval, representing the initial state, was designated as F_t. The infiltration capacity at the beginning of the interval was then obtained from the equation (5.10) corresponding to the Green-Ampt model as $f_c\,(F_t)$.

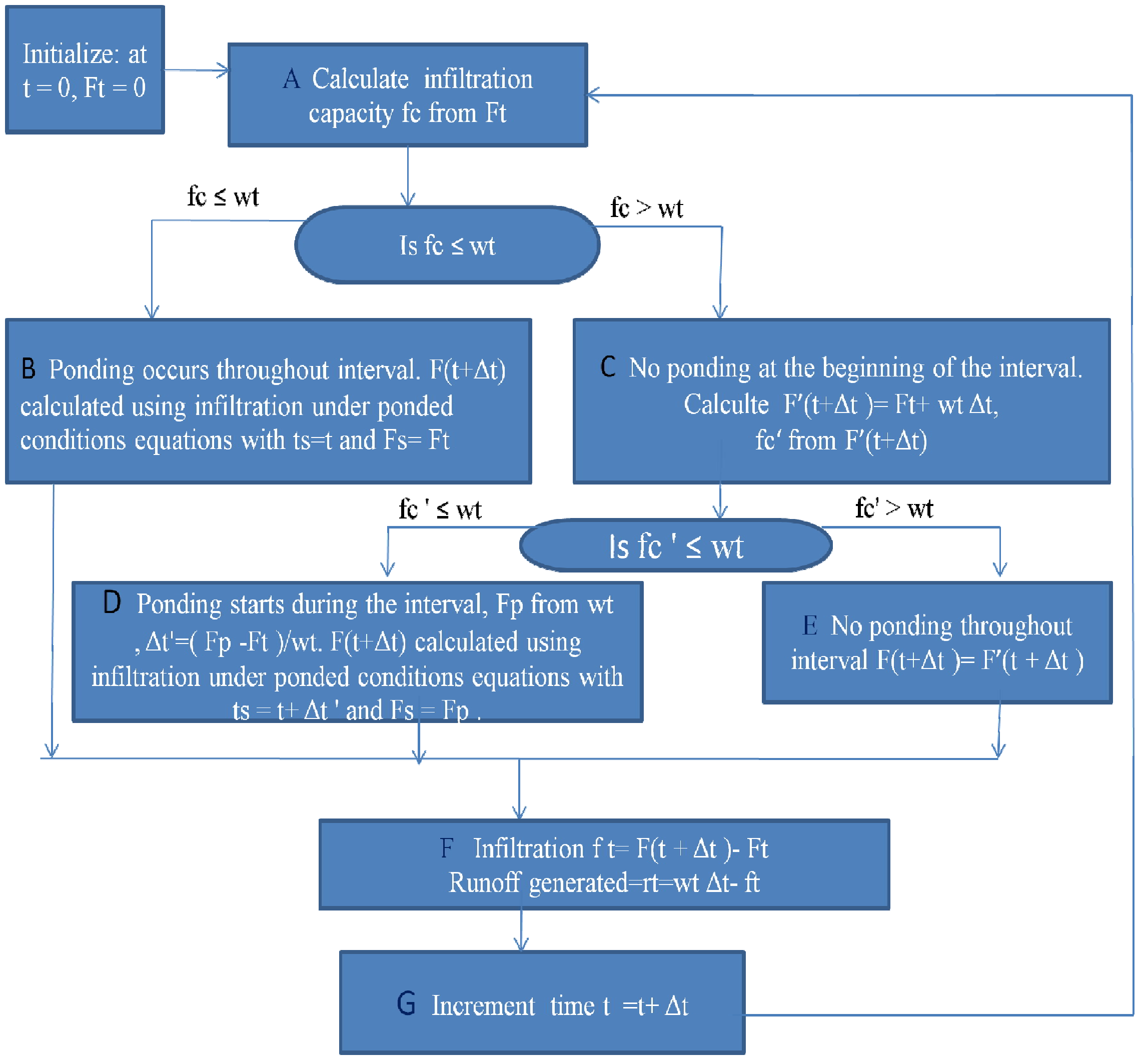


Figure 5.3: Flow chart for determining infiltration and runoff generated under variable surface water input intensity

- The goal was to, calculate infiltration f_t during the interval and hence $F_{t+\Delta t}$ at the end of the interval, together with any runoff r_t generated during the time interval for the given infiltrated depth F_t at the beginning of the time interval and water input w_t during the interval.
- The calculation was initialized with F_0 at the beginning of a storm and proceeds step wise for the full duration of the surface water input hyetograph. There are three cases to be considered: (1) ponding occurs throughout the interval; (2) no ponding

throughout the interval; and (3) ponding begins part-way through the interval. The infiltration capacity is always decreasing or constant with time. So once the ponding is established under a given surface water input intensity, it will continue. Ponding cannot cease in the middle of an interval. However ponding may cease at the end of an interval when the surface water input intensity changes.

5.6.1 Results and discussion

The present study considered the Pavanje river basin as the study area, and runoff was estimated for the forested hillslope areas. The samples were collected at different elevations form the crest to the footslope (120 m to 30 m); in each elevation there were seven depths (10, 20, 30, 40, 50, 60, 75 cm). The study considered the soil properties at different elevations at 10 cm depth like, 120 m elevation at 10 cm depth, 105 m elevation at 10 cm depth and so on up to 30 m elevations at 10 cm depth. For the particular elevation, the corresponding measured soil properties were considered and for some unavailable data, the values from the literature were considered. Here the runoff was measured for one day in hourly basis, means every one hour runoff was estimated. The rainfall data for this particular region was taken from the irrigation department, located in Mangalore. Because of the unavailability of measured runoff data, the validation has not done for the estimated runoff. The present study followed the Green and Ampt model for the runoff estimation.

The runoff estimation calculation is shown in the Table 5.9. The rainfall data used for this was of the previously said sampled location for one day i.e., July 17th 2011. One sample example for finding the parameters involved is shown below; similar procedure was followed for other elevations, and corresponding properties were taken from the literature as mentioned above.

At 90m elevation, the texture of the soil is loamy sand.

The parameters used at 10 cm depth are,

Porosity, n=0.42

Field capacity θ_{fc}=0.20

Residual water content θ_r=0.11

Wetting front soil suction head, h_f = 7.17 cm

where $h_f = (2b+3/2b+6)* h_a$

h_a= air entry pressure =9, b=4.38 for loamy sand (Clapp and Hornberger,1978 based on analysis of 1845 soils)

k_s= 2.87 cm/hr

$P= h_f (n-\theta_{fc})$ =1.57.

A rainfall intensity is given in column 2 of Table 5.9. The rain falls on a forested hillslope soils with initial moisture content equal to the field capacity and the runoff was determined using the Green-Ampt approach. The detailed steps carried out to calculate the runoff generation is presented below.

The parameter P was calculated by,

$P = |\psi_f| (n-\theta_{fc})$

The time interval taken as one hour, i.e., Δt =1h. The work has been carried out as per procedure followed through the flowchart (Figure 5.3). Initially F = 0, so fc = ∞ (from eq. 5.10) and hence ponding did not occur at time 0. The time between the start of the rainfall and the initiation of runoff is known as the time to ponding. The next step was to move from box A to box C.

$F'_{(t+\Delta t)} = F_t + w_t \Delta_t$

This is the preliminary cumulative infiltration under the assumption of no ponding. The corresponding value of $f'_{t+\Delta t}$ is (from eq. 5.10)

$$f'_{t+\Delta t} = k_s \left[1 + \frac{P}{F}\right]$$

as shown in column 8 of the table. This value is greater than w_t, therefore no ponding occured during this interval and moving on to box E, the cumulative infiltration was set to the preliminary value, as shown in column 12.

$F_{(t+\Delta t)} = F'_{(t+\Delta t)}$

Box F gives the infiltration (column 14) and runoff (column 15). The calculation then proceeded to box G where time is incremented and back to box A for the next time step. The same sequence was followed for the other time steps where it was found no ponding.

No ponding was observed in the 120 m elevation in different time intervals i.e., one day (24 hours). Same method was followed for other different elevations also. Only at 90 m and 30 m elevations some amount of runoff was observed. In 90 m elevation, during the ninth time interval, the $f'_{t+\Delta t}$ value was less than w_t (3.32885<3.4), so ponding starts during this interval. Following the preliminary infiltration rate calculation in box C, the calculation proceeded to box D. The cumulative infiltration at ponding is given by

$$F_p = \frac{k_s P}{(w - k_s)}$$

The partial time interval required for ponding is

$\Delta t' = (F_p - F_t)/w_t$

The cumulative infiltration at the end of this interval was obtained by using equation (5.17) for F. The formula was solved numerically for g(F) = 0.

$$g(F) = t - t_s - \frac{F - F_s}{k_s} - \frac{P}{k_s}\, ln\left(\frac{F_s + P}{F + P}\right)$$

This was accomplished easily using the solver function in excel. This result in,

$F_{t+\Delta t} = 6.8$ cm

The infiltration in this time interval was therefore,

$f_t = F_{t+\Delta t} - F_t = 6.8 - 6.42 = 0.38$ cm. The rainfall was 3.4 cm and the runoff generated was 3.4-0.38 = 3.02 cm.

At the start of the tenth time interval (time =10 h), the cumulative infiltration was 6.8 cm. This led to an infiltration capacity,

$$f_c = k_s \left[1 + \frac{P}{F}\right]$$

This was more than the rainfall rate (0.3 cm/h). So the calculation proceeded through box B on the flowchart. The procedure is exactly the same as for box D, except that the starting values F_s and t_s were taken as the beginning of the time step values. There is no need to solve for the time when ponding starts during the interval. Numerical solution of g(F) = 0 was used to obtain $F_{t+\Delta t}$. Similar procedure was also followed for other time intervals also (Table 5.9).

The rate of infiltration might be more due to the soil characteristics including ease of entry, storage capacity, and transmission rate through the soil, soil texture and structure, vegetation types and cover, water content of the soil, soil temperature, and rainfall intensity etc. Coarse-grained sandy soils have large spaces between each grain and allow water to infiltrate quickly. Vegetation creates more porous soils by both protecting the soil from ponding rainfall, which can close natural gaps between soil particles, and loosening soil through root action. Soils with higher hydraulic conductivities tend to have more infiltration and less runoff. In addition, the pore size distribution influences the rate of change of infiltrability. Generally speaking, the wider the range of pore sizes the more gradual the change in the infiltration rate. This is why forested areas have the highest infiltration rates of any vegetative types. Almost same results have been observed in this study also. A small amount of runoff was observed only in 90 m and 30 m elevations at 10 cm depth. In the remaining elevations, infiltration was more and hence runoff was not observed. The detailed runoff observations are tabulated in Table 5.9.

Table 5.9: Runoff generation calculation in forested hillslope soils

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Time	**Rainfall intensity**	**F_t**	**f_c**	**F' or ($F'_{t+\Delta t}$)**	**k_s**	**P**	**f_c' or $f'_{t+\Delta t}$**	**F_p or F_s**	**$\Delta t'$**	**t_s**	**$F_{t+\Delta t}$**	**g(F)**	**Infiltration**	**Run off**
	w_t			**$F_t+w_t\Delta t$**			**$k_s(1+P/F)$**	**k_s*P/(w-k_s)**	**(F_p-F_t)/w_t**				**$f_t=F_{t+\Delta t}-F_t$**	
(h)	(cm/hr)	cm	(cm/hr)	cm	cm/hr		cm/hr	cm	h	h	cm		cm	cm
One day (17-7-11)							**120 m Elevation**							
0	0.30	0	∞	0.3	4.63	2.11	37.1943	-	-	-	0.3	0	0.3	0
1	0.10	0.3	37.194	0.4	4.63	2.11	29.0533	-	-	-	0.4	0	0.1	0
2	0.00	0.4	29.053	0.4	4.63	2.11	29.0533	-	-	-	0.4	0	0	0
3	0.40	0.4	29.053	0.8	4.63	2.11	16.8416	-	-	-	0.8	0	0.4	0
4	0.00	0.8	16.841	0.8	4.63	2.11	16.8416	-	-	-	0.8	0	0	0
5	0.30	0.8	16.841	1.1	4.63	2.11	13.5112	-	-	-	1.1	0	0.3	0
6	2.72	1.1	13.511	3.82	4.63	2.11	7.18741	-	-	-	3.82	0	2.72	0
7	1.40	3.82	7.1874	5.22	4.63	2.11	6.50151	-	-	-	5.22	0	1.4	0
8	1.20	5.22	6.5015	6.42	4.63	2.11	6.1517	-	-	-	6.42	0	1.2	0
9	3.40	6.42	6.1517	9.82	4.63	2.11	5.62484	-	-	-	9.82	0	3.4	0
10	0.30	9.82	5.6248	10.12	4.63	2.11	5.59535	-	-	-	10.12	0	0.3	0
11	3.50	10.12	5.5953	13.62	4.63	2.11	5.34728	-	-	-	13.62	0	3.5	0
12	0.40	13.62	5.3472	14.02	4.63	2.11	5.32681	-	-	-	14.02	0	0.4	0
13	0.00	14.02	5.3268	14.02	4.63	2.11	5.32681	-	-	-	14.02	0	0	0
14	0.00	14.02	5.3268	14.02	4.63	2.11	5.32681	-	-	-	14.02	0	0	0
15	3.28	14.02	5.3268	17.3	4.63	2.11	5.1947	-	-	-	17.3	0	3.28	0
16	0.00	17.3	5.1947	17.3	4.63	2.11	5.1947	-	-	-	17.3	0	0	0
17	0.03	17.3	5.1947	17.33	4.63	2.11	5.19372	-	-	-	17.33	0	0.03	0
18	0.20	17.33	5.1937	17.53	4.63	2.11	5.18729	-	-	-	17.53	0	0.2	0
19	0.00	17.53	5.1872	17.53	4.63	2.11	5.18729	-	-	-	17.53	0	0	0
20	0.10	17.53	5.1872	17.63	4.63	2.11	5.18413	-	-	-	17.63	0	0.1	0
21	0.00	17.63	5.1841	17.63	4.63	2.11	5.18413	-	-	-	17.63	0	0	0
22	0.00	17.63	5.1841	17.63	4.63	2.11	5.18413	-	-	-	17.63	0	0	0

23	0.00	17.63	5.1841	17.63	4.63	2.11	5.18413	-	-	-	17.63	0	0	0
24	0.00	17.63	5.1841	17.63	4.63	2.11	5.18413				17.63	0	0	0
105 m Elevation														
0	0.30	0	∞	0.3	3.96	2.47	36.564	-	-	-	0.3	0	0.3	0
1	0.10	0.3	36.564	0.4	3.96	2.47	28.413	-	-	-	0.4	0	0.1	0
2	0.00	0.4	28.413	0.4	3.96	2.47	28.413	-	-	-	0.4	0	0	0
3	0.40	0.4	28.413	0.8	3.96	2.47	16.1865	-	-	-	0.8	0	0.4	0
4	0.00	0.8	16.186	0.8	3.96	2.47	16.1865	-	-	-	0.8	0	0	0
5	0.30	0.8	16.186	1.1	3.96	2.47	12.852	-	-	-	1.1	0	0.3	0
6	2.72	1.1	12.852	3.82	3.96	2.47	6.52052	-	-	-	3.82	0	2.72	0
7	1.40	3.82	6.5205	5.22	3.96	2.47	5.83379	-	-	-	5.22	0	1.4	0
8	1.20	5.22	5.8337	6.42	3.96	2.47	5.48355	-	-	-	6.42	0	1.2	0
9	3.40	6.42	5.4835	9.82	3.96	2.47	4.95605	-	-	-	9.82	0	3.4	0
10	0.30	9.82	4.9560	10.12	3.96	2.47	4.92652	-	-	-	10.12	0	0.3	0
11	3.50	10.12	4.9265	13.62	3.96	2.47	4.67815	-	-	-	13.62	0	3.5	0
12	0.40	13.62	4.6781	14.02	3.96	2.47	4.65766	-	-	-	14.02	0	0.4	0
13	0.00	14.02	4.6576	14.02	3.96	2.47	4.65766	-	-	-	14.02	0	0	0
14	0.00	14.02	4.6576	14.02	3.96	2.47	4.65766	-	-	-	14.02	0	0	0
15	3.28	14.02	4.6576	17.3	3.96	2.47	4.52539	-	-	-	17.3	0	3.28	0
16	0.00	17.3	4.5253	17.3	3.96	2.47	4.52539	-	-	-	17.3	0	0	0
17	0.03	17.3	4.5253	17.33	3.96	2.47	4.52441	-	-	-	17.33	0	0.03	0
18	0.20	17.33	4.5244	17.53	3.96	2.47	4.51797	-	-	-	17.53	0	0.2	0
19	0.00	17.53	4.5179	17.53	3.96	2.47	4.51797	-	-	-	17.53	0	0	0
20	0.10	17.53	4.5179	17.63	3.96	2.47	4.5148	-	-	-	17.63	0	0.1	0
21	0.00	17.63	4.5148	17.63	3.96	2.47	4.5148	-	-	-	17.63	0	0	0
22	0.00	17.63	4.5148	17.63	3.96	2.47	4.5148	-	-	-	17.63	0	0	0
23	0.00	17.63	4.5148	17.63	3.96	2.47	4.5148	-	-	-	17.63	0	0	0
24	0.00	17.63	4.5148	17.63	3.96	2.47	4.5148	-	-	-	17.63	0	0	0
90 m Elevation														
0	0.30	0	∞	0.3	2.87	1.57	17.8897	-	-	-	0.3	0	0.3	0
1	0.10	0.3	17.889	0.4	2.87	1.57	14.1348	-	-	-	0.4	0	0.1	0

2	0.00	0.4	14.134	0.4	2.87	1.57	14.1348	-	-	-	0.4	0	0	0
3	0.40	0.4	14.134	0.8	2.87	1.57	8.50238	-	-	-	0.8	0	0.4	0
4	0.00	0.8	8.5023	0.8	2.87	1.57	8.50238	-	-	-	0.8	0	0	0
5	0.30	0.8	8.5023	1.1	2.87	1.57	6.96627	-	-	-	1.1	0	0.3	0
6	2.72	1.1	6.9662	3.82	2.87	1.57	4.04955	-	-	-	3.82	0	2.72	0
7	1.40	3.82	4.0495	5.22	2.87	1.57	3.7332	-	-	-	5.22	0	1.4	0
8	1.20	5.22	3.7332	6.42	2.87	1.57	3.57185	-	-	-	6.42	0	1.2	0
9	3.40	6.42	3.5718	9.82	2.87	1.57	3.32885	8.5017	0.61226	9.6123	6.8	0	0.38	3.02
10	0.30	6.8	3.5326	7.1	2.87	1.57	3.50463				7.1	0	0.3	0
11	3.50	7.1	3.5046	10.6	2.87	1.57	3.29508	7.15222	0.01492	11.015	8.1	0	1	2.5
12	0.40	8.1	3.4262	8.5	2.87	1.57	3.40011	-	-	-	8.5	0	0.4	0
13	0.00	8.5	3.4001	8.5	2.87	1.57	3.40011	-	-	-	8.5	0	0	0
14	0.00	8.5	3.4001	8.5	2.87	1.57	3.40011	-	-	-	8.5	0	0	0
15	3.28	8.5	3.4001	11.78	2.87	1.57	3.2525	10.99	0.75915	15.759	9.1	0	0.6	2.68
16	0.00	9.1	3.3651	9.1	2.87	1.57	3.36515	-	-	-	9.1	0	0	0
17	0.03	9.1	3.3651	9.13	2.87	1.57	3.36353	-	-	-	9.13	0	0.03	0
18	0.20	9.13	3.3635	9.33	2.87	1.57	3.35295	-	-	-	9.33	0	0.2	0
19	0.00	9.33	3.3529	9.33	2.87	1.57	3.35295	-	-	-	9.33	0	0	0
20	0.10	9.33	3.3529	9.43	2.87	1.57	3.34783	-	-	-	9.43	0	0.1	0
21	0.00	9.43	3.3478	9.43	2.87	1.57	3.34783	-	-	-	9.43	0	0	0
22	0.00	9.43	3.3478	9.43	2.87	1.57	3.34783	-	-	-	9.43	0	0	0
23	0.00	9.43	3.3478	9.43	2.87	1.57	3.34783	-	-	-	9.43	0	0	0
24	0.00	9.43	3.3478	9.43	2.87	1.57	3.34783	-	-	-	9.43	0	0	0
75 m Elevation														
0	0.30	0	∞	0.3	3.81	3	41.91	-	-	-	0.3	0	0.3	0
1	0.10	0.3	41.91	0.4	3.81	3	32.385	-	-	-	0.4	0	0.1	0
2	0.00	0.4	32.385	0.4	3.81	3	32.385	-	-	-	0.4	0	0	0
3	0.40	0.4	32.385	0.8	3.81	3	18.0975	-	-	-	0.8	0	0.4	0
4	0.00	0.8	18.097	0.8	3.81	3	18.0975	-	-	-	0.8	0	0	0
5	0.30	0.8	18.097	1.1	3.81	3	14.2009	-	-	-	1.1	0	0.3	0
6	2.72	1.1	14.200	3.82	3.81	3	6.80215	-	-	-	3.82	0	2.72	0

7	1.40	3.82	6.8021	5.22	3.81	3	5.99966	-	-	-	5.22	0	1.4	0
8	1.20	5.22	5.9996	6.42	3.81	3	5.59037	-	-	-	6.42	0	1.2	0
9	3.40	6.42	5.5903	9.82	3.81	3	4.97395	-	-	-	9.82	0	3.4	0
10	0.30	9.82	4.9739	10.12	3.81	3	4.93945	-	-	-	10.12	0	0.3	0
11	3.50	10.12	4.9394	13.62	3.81	3	4.64921	-	-	-	13.62	0	3.5	0
12	0.40	13.62	4.6492	14.02	3.81	3	4.62526	-	-	-	14.02	0	0.4	0
13	0.00	14.02	4.6252	14.02	3.81	3	4.62526	-	-	-	14.02	0	0	0
14	0.00	14.02	4.6252	14.02	3.81	3	4.62526	-	-	-	14.02	0	0	0
15	3.28	14.02	4.6252	17.3	3.81	3	4.47069	-	-	-	17.3	0	3.28	0
16	0.00	17.3	4.4706	17.3	3.81	3	4.47069	-	-	-	17.3	0	0	0
17	0.03	17.3	4.4706	17.33	3.81	3	4.46955	-	-	-	17.33	0	0.03	0
18	0.20	17.33	4.4695	17.53	3.81	3	4.46203	-	-	-	17.53	0	0.2	0
19	0.00	17.53	4.4620	17.53	3.81	3	4.46203	-	-	-	17.53	0	0	0
20	0.10	17.53	4.4620	17.63	3.81	3	4.45833	-	-	-	17.63	0	0.1	0
21	0.00	17.63	4.4583	17.63	3.81	3	4.45833	-	-	-	17.63	0	0	0
22	0.00	17.63	4.4583	17.63	3.81	3	4.45833	-	-	-	17.63	0	0	0
23	0.00	17.63	4.4583	17.63	3.81	3	4.45833	-	-	-	17.63	0	0	0
24	0.00	17.63	4.4583	17.63	3.81	3	4.45833	-	-	-	17.63	0	0	0
60 m Elevation														
0	0.30	0	∞	0.3	4.09	4.06	59.4413	-	-	-	0.3	0	0.3	0
1	0.10	0.3	59.441	0.4	4.09	4.06	45.6035	-	-	-	0.4	0	0.1	0
2	0.00	0.4	45.603	0.4	4.09	4.06	45.6035	-	-	-	0.4	0	0	0
3	0.40	0.4	45.603	0.8	4.09	4.06	24.8468	-	-	-	0.8	0	0.4	0
4	0.00	0.8	24.846	0.8	4.09	4.06	24.8468	-	-	-	0.8	0	0	0
5	0.30	0.8	24.846	1.1	4.09	4.06	19.1858	-	-	-	1.1	0	0.3	0
6	2.72	1.1	19.185	3.82	4.09	4.06	8.43696	-	-	-	3.82	0	2.72	0
7	1.40	3.82	8.4369	5.22	4.09	4.06	7.27111	-	-	-	5.22	0	1.4	0
8	1.20	5.22	7.2711	6.42	4.09	4.06	6.67651	-	-	-	6.42	0	1.2	0
9	3.40	6.42	6.6765	9.82	4.09	4.06	5.78098	-	-	-	9.82	0	3.4	0
10	0.30	9.82	5.7809	10.12	4.09	4.06	5.73085	-	-	-	10.12	0	0.3	0
11	3.50	10.12	5.7308	13.62	4.09	4.06	5.30919	-	-	-	13.62	0	3.5	0

12	0.40	13.62	5.3091	14.02	4.09	4.06	5.27441	-	-	-	14.02	0	0.4	0
13	0.00	14.02	5.2744	14.02	4.09	4.06	5.27441	-	-	-	14.02	0	0	0
14	0.00	14.02	5.2744	14.02	4.09	4.06	5.27441	-	-	-	14.02	0	0	0
15	3.28	14.02	5.2744	17.3	4.09	4.06	5.04985	-	-	-	17.3	0	3.28	0
16	0.00	17.3	5.0498	17.3	4.09	4.06	5.04985	-	-	-	17.3	0	0	0
17	0.03	17.3	5.0498	17.33	4.09	4.06	5.04819	-	-	-	17.33	0	0.03	0
18	0.20	17.33	5.0481	17.53	4.09	4.06	5.03726	-	-	-	17.53	0	0.2	0
19	0.00	17.53	5.0372	17.53	4.09	4.06	5.03726	-	-	-	17.53	0	0	0
20	0.10	17.53	5.0372	17.63	4.09	4.06	5.03188	-	-	-	17.63	0	0.1	0
21	0.00	17.63	5.0318	17.63	4.09	4.06	5.03188	-	-	-	17.63	0	0	0
22	0.00	17.63	5.0318	17.63	4.09	4.06	5.03188	-	-	-	17.63	0	0	0
23	0.00	17.63	5.0318	17.63	4.09	4.06	5.03188	-	-	-	17.63	0	0	0
24	0.00	17.63	5.0318	17.63	4.09	4.06	5.03188	-	-	-	17.63	0	0	0
50 m Elevation														
0	0.30	0	∞	0.3	5.33	1.43	30.8074	-	-	-	0.3	0	0.3	0
1	0.10	0.3	30.807	0.4	5.33	1.43	24.4381	-	-	-	0.4	0	0.1	0
2	0.00	0.4	24.438	0.4	5.33	1.43	24.4381	-	-	-	0.4	0	0	0
3	0.40	0.4	24.438	0.8	5.33	1.43	14.884	-	-	-	0.8	0	0.4	0
4	0.00	0.8	14.884	0.8	5.33	1.43	14.884	-	-	-	0.8	0	0	0
5	0.30	0.8	14.884	1.1	5.33	1.43	12.2784	-	-	-	1.1	0	0.3	0
6	2.72	1.1	12.278	3.82	5.33	1.43	7.33084	-	-	-	3.82	0	2.72	0
7	1.40	3.82	7.3308	5.22	5.33	1.43	6.79422	-	-	-	5.22	0	1.4	0
8	1.20	5.22	6.7942	6.42	5.33	1.43	6.52053	-	-	-	6.42	0	1.2	0
9	3.40	6.42	6.5205	9.82	5.33	1.43	6.10833	-	-	-	9.82	0	3.4	0
10	0.30	9.82	6.1083	10.12	5.33	1.43	6.08526	-	-	-	10.12	0	0.3	0
11	3.50	10.12	6.0852	13.62	5.33	1.43	5.89118	-	-	-	13.62	0	3.5	0
12	0.40	13.62	5.8911	14.02	5.33	1.43	5.87517	-	-	-	14.02	0	0.4	0
13	0.00	14.02	5.8751	14.02	5.33	1.43	5.87517	-	-	-	14.02	0	0	0
14	0.00	14.02	5.8751	14.02	5.33	1.43	5.87517	-	-	-	14.02	0	0	0
15	3.28	14.02	5.8751	17.3	5.33	1.43	5.7718	-	-	-	17.3	0	3.28	0
16	0.00	17.3	5.7718	17.3	5.33	1.43	5.7718	-	-	-	17.3	0	0	0

17	0.03	17.3	5.7718	17.33	5.33	1.43	5.77104	-	-	-	17.33	0	0.03	0
18	0.20	17.33	5.7710	17.53	5.33	1.43	5.76601	-	-	-	17.53	0	0.2	0
19	0.00	17.53	5.7660	17.53	5.33	1.43	5.76601	-	-	-	17.53	0	0	0
20	0.10	17.53	5.7660	17.63	5.33	1.43	5.76353	-	-	-	17.63	0	0.1	0
21	0.00	17.63	5.7635	17.63	5.33	1.43	5.76353	-	-	-	17.63	0	0	0
22	0.00	17.63	5.7635	17.63	5.33	1.43	5.76353	-	-	-	17.63	0	0	0
23	0.00	17.63	5.7635	17.63	5.33	1.43	5.76353	-	-	-	17.63	0	0	0
24	0.00	17.63	5.7635	17.63	5.33	1.43	5.76353	-	-	-	17.63	0	0	0
40 m Elevation														
0	0.30	0	∞	0.3	3.78	0.86	14.616	-	-	-	0.3	0	0.3	0
1	0.10	0.3	14.616	0.4	3.78	0.86	11.907	-	-	-	0.4	0	0.1	0
2	0.00	0.4	11.907	0.4	3.78	0.86	11.907	-	-	-	0.4	0	0	0
3	0.40	0.4	11.907	0.8	3.78	0.86	7.8435	-	-	-	0.8	0	0.4	0
4	0.00	0.8	7.8435	0.8	3.78	0.86	7.8435	-	-	-	0.8	0	0	0
5	0.30	0.8	7.8435	1.1	3.78	0.86	6.73527	-	-	-	1.1	0	0.3	0
6	2.72	1.1	6.7352	3.82	3.78	0.86	4.63099	-	-	-	3.82	0	2.72	0
7	1.40	3.82	4.6309	5.22	3.78	0.86	4.40276	-	-	-	5.22	0	1.4	0
8	1.20	5.22	4.4027	6.42	3.78	0.86	4.28636	-	-	-	6.42	0	1.2	0
9	3.40	6.42	4.2863	9.82	3.78	0.86	4.11104	-	-	-	9.82	0	3.4	0
10	0.30	9.82	4.1110	10.12	3.78	0.86	4.10123	-	-	-	10.12	0	0.3	0
11	3.50	10.12	4.1012	13.62	3.78	0.86	4.01868	-	-	-	13.62	0	3.5	0
12	0.40	13.62	4.0186	14.02	3.78	0.86	4.01187	-	-	-	14.02	0	0.4	0
13	0.00	14.02	4.0118	14.02	3.78	0.86	4.01187	-	-	-	14.02	0	0	0
14	0.00	14.02	4.0118	14.02	3.78	0.86	4.01187	-	-	-	14.02	0	0	0
15	3.28	14.02	4.0118	17.3	3.78	0.86	3.96791	-	-	-	17.3	0	3.28	0
16	0.00	17.3	3.9679	17.3	3.78	0.86	3.96791	-	-	-	17.3	0	0	0
17	0.03	17.3	3.9679	17.33	3.78	0.86	3.96758	-	-	-	17.33	0	0.03	0
18	0.20	17.33	3.9675	17.53	3.78	0.86	3.96544	-	-	-	17.53	0	0.2	0
19	0.00	17.53	3.9654	17.53	3.78	0.86	3.96544	-	-	-	17.53	0	0	0
20	0.10	17.53	3.9654	17.63	3.78	0.86	3.96439	-	-	-	17.63	0	0.1	0
21	0.00	17.63	3.9643	17.63	3.78	0.86	3.96439	-	-	-	17.63	0	0	0

22	0.00	17.63	3.9643	17.63	3.78	0.86	3.96439	-	-	-	17.63	0	0	0
23	0.00	17.63	3.9643	17.63	3.78	0.86	3.96439	-	-	-	17.63	0	0	0
24	0.00	17.63	3.9643	17.63	3.78	0.86	3.96439	-	-	-	17.63	0	0	0
30 m Elevation														
0	0.30	0	∞	0.3	2.18	1.94	16.2773	-	-	-	0.3	0	0.3	0
1	0.10	0.3	16.277	0.4	2.18	1.94	12.753	-	-	-	0.4	0	0.1	0
2	0.00	0.4	12.753	0.4	2.18	1.94	12.753	-	-	-	0.4	0	0	0
3	0.40	0.4	12.753	0.8	2.18	1.94	7.4665	-	-	-	0.8	0	0.4	0
4	0.00	0.8	7.4665	0.8	2.18	1.94	7.4665	-	-	-	0.8	0	0	0
5	0.30	0.8	7.4665	1.1	2.18	1.94	6.02473	-	-	-	1.1	0	0.3	0
6	2.72	1.1	6.0247	3.82	2.18	1.94	3.28712	-	-	-	3.82	0	2.72	0
7	1.40	3.82	3.2871	5.22	2.18	1.94	2.99019	-	-	-	5.22	0	1.4	0
8	1.20	5.22	2.9901	6.42	2.18	1.94	2.83875	-	-	-	6.42	0	1.2	0
9	3.40	6.42	2.8387	9.82	2.18	1.94	2.61067	3.46656	-0.8687	8.1313	6.51	0	0.09	3.31
10	0.30	6.51	2.8296	6.81	2.18	1.94	2.80103	-	-	-	6.81	0	0.3	0
11	3.50	6.81	2.8010	10.31	2.18	1.94	2.5902	3.20394	-1.0303	9.9697	8.8	0	1.99	1.51
12	0.40	8.8	2.6605	9.2	2.18	1.94	2.6397	-	-	-	9.2	0	0.4	0
13	0.00	9.2	2.6397	9.2	2.18	1.94	2.6397	-	-	-	9.2	0	0	0
14	0.00	9.2	2.6397	9.2	2.18	1.94	2.6397	-	-	-	9.2	0	0	0
15	3.28	9.2	2.6397	12.48	2.18	1.94	2.51888	3.84473	-1.6327	13.367	10.1	0	0.9	2.38
16	0.00	10.1	2.5987	10.1	2.18	1.94	2.59873	-	-	-	10.1	0	0	0
17	0.03	10.1	2.5987	10.13	2.18	1.94	2.59749	-	-	-	10.13	0	0.03	0.0
18	0.20	10.13	2.5974	10.33	2.18	1.94	2.58941	-	-	-	10.33	0	0.2	0.0
19	0.00	10.33	2.5894	10.33	2.18	1.94	2.58941	-	-	-	10.33	0	0	0.0
20	0.10	10.33	2.5894	10.43	2.18	1.94	2.58548	-	-	-	10.43	0	0.1	0.0
21	0.00	10.43	2.5854	10.43	2.18	1.94	2.58548	-	-	-	10.43	0	0	0.0
22	0.00	10.43	2.5854	10.43	2.18	1.94	2.58548	-	-	-	10.43	0	0	0.0
23	0.00	10.43	2.5854	10.43	2.18	1.94	2.58548	-	-	-	10.43	0	0	0.0
24	0.00	10.43	2.5854	10.43	2.18	1.94	2.58548	-	-	-	10.43	0	0	0.0

CHAPTER 6

SPATIAL VARIABILITY OF PHYSICAL AND HYDRAULIC PROPERTIES OF SOIL

6.1 Introduction

Soils are spatially variable natural bodies. Variations of parent material and vegetation across the landscape from which soils are derived, affect the variability of soils even at relatively short distances (Kutilek and Nielsen, 1994). Soils are a product of the factors of formation and continuously change over the earth's surface. The analysis of the spatial variability of soil properties is important for land management and construction of an ecological environment. Soils are characterized by high degree of spatial variability due to the combined effect of physical, chemical or biological processes that operate with different intensities and at different scales. An understanding of the spatial distribution of soil properties at the field or watershed scale is important for refining agricultural management practices and assessing the effects of agriculture on environmental quality (Cambardella et al., 1994).

The spatial variability of soil physical properties is inherent in nature because of geological and pedological factors. Land use and management practices may contribute to the spatial variability of soil physical properties (Iqbal et al., 2005). Soil physical properties such as soil particle size distribution, bulk density, porosity and organic matter content are interrelated and have important effects on watershed hydrology. These properties influence runoff, infiltration, percolation, subsurface storage and the transmission rate of water into stream networks (Price et al., 2010). The variation of the textural characteristics of soil occur in response to the deposition of sediment, vegetation, and relief that governs the time of exposure of materials to the action of weathering (Young and Hammer, 2000) and mainly of original material (Cunha et al. 2005).

Understanding the behaviour of soil particle size is important to understand the distribution of sediments, the formation dynamics of a case and make inferences about the behaviour of the soil.

The spatial variability of soil hydraulic properties helps us to find the subsurface flux of water. In order to simulate water flow and solute transport process under field scale or to assess the hydrological response of an agricultural area using models, not only determination of soil hydraulic properties in a large number of points but detailed features of spatial variability exhibited from these properties are also required (Sharma and Luxmoore 1979; Farajalla and Vieux 1995). The most frequently used hydraulic properties are soil water retention curve and saturated hydraulic conductivity. Both these hydraulic properties exhibit a high degree of spatial and temporal variability (Owe et al., 1982; Grayson et al., 1997).

Soil moisture retention curve is important for understanding and predicting a range of hydrological processes including flooding, erosion and solute transport, and land atmosphere interactions. Both surface soil moisture and subsoil moisture have profound effects on the above processes (Western and Grayson, 1998). Water retention characteristics exhibit heterogeneous distribution in both horizontal and vertical space. Spatial distribution of water content at field capacity and permanent wilting point at different zones of a farm governs the available water for plant growth. The field capacity and permanent wilting point play key roles in crop selection for different blocks of a farm, and in scheduling irrigation of crops in a field.

Saturated hydraulic conductivity (k_s) is the other important soil hydraulic property having the highest statistical spatial variability (Biggar and Nielsen, 1976). Bouma (1973) stressed the need for more studies on field variability of k_s and soil water retention curves. k_s is difficult to characterize because of its high variability even over short distances, and measurement methods typically require considerable time and resources. The results indicate that soil water dynamics is strongly affected by the variability of saturated soil hydraulic conductivity, even in homogenous anthropogenic soils. This information may have a strong impact in irrigation management and subsurface drainage efficiency as well as other water conservation issues.

While, many researchers have studied the horizontal variation and temporal changes of soil moisture (Hawley et al., 1983; Famiglietti et al., 1998; Western et al., 1998), little attention has been paid to the profile features of soil moisture retention and saturated hydraulic conductivity (Loague, 1992). The primary motivation for conducting this study was the lack of spatial study on soil physical and hydraulic properties of Pavanje river basin soils. Correlation analysis technique has been used to analyze various soil properties. This study characterized the profile types as well as additional profile features of various soil properties (particle size distribution, bulk density, organic matter content, soil water retention data and saturated hydraulic conductivity), and also quantified the spatial variation of soil properties at layers under the study area.

6.2. Calculations of variables

The overall methodology adopted in this study focused on analyzing spatial characteristics of measured soil physical and hydraulic properties. Qiu et al. (2001) proposed computation of several variables to characterize temporal and spatial variability in a quantitative manner. Calculations of several variables used in this study are demonstrated as follows: Let the soil properties of site i and the layer j be expressed as $M_{i,j}$, N_p is the number of sites and N_l is number of sampling layers or depths. The following variables may be defined as:

1. Mean of soil variable of site i, (M_i)

$$M_i = \frac{1}{N_l}\sum_{j=1}^{N_l} M_{i,j} \tag{6.1}$$

2. Mean of soil variable at soil layer j, (M_j)

$$M_j = \frac{1}{N_p}\sum_{i=1}^{N_p} M_{i,j} \tag{6.2}$$

3. Profile variability of soil variable on plot, i, (VP_i)

$$VP_i = \sqrt{\frac{N_l \sum_{j=1}^{N_l} (M_{i,j})^2 - \left(\sum_{j=1}^{N_l} M_{i,j}\right)^2}{N_l(N_l - 1)}} \quad (6.3)$$

4. Spatial variability of layered averaged soil variable at soil layer j, (VS_j)

$$VS_j = \sqrt{\frac{N_p \sum_{i=1}^{N_p} (M_{i,j})^2 - \left(\sum_{i=1}^{N_p} M_{i,j}\right)^2}{N_p(N_p - 1)}} \quad (6.4)$$

The four variables defined by eqns. (6.1)-(6.4) were computed for five sites (N_p) in agricultural land and eight elevations in forested hillslopes of the Pavanje river basin at different depths (N_l) for both physical and hydraulic properties.

6.3. Results and discussions

In this study, four different variables such as mean of soil property of sites, mean of soil property at soil layers, profile variability of soil property on sites and spatial variability of layered averaged soil property at soil layers have been studied. The bar charts are drawn for all variables of each soil physical and hydraulic properties. Considerable differences were found in all the variables for each soil property across the agricultural and forest lands. Also, every variable of each soil property of individual sites within each land cover recorded different values.

6.3.1 Analysis of different variables of physical properties of agricultural soils

Now let us discuss about the analysis done for the calculations of four variables mentioned above. Here physical properties include the sand, silt, clay, bulk density (BD) and organic matter content (OM). To understand how the percentage of sand varies across the different sites and depths, different variables of sand using the eqns. (6.1)-(6.4) have been computed. To find the mean sand of site, the percentage of sand from all the depths (layers) from 10 to 150 cm of one particular site was considered and then calculated the mean sand for that particular site using the eqn. (6.1). The same procedure was repeated for other remaining sites also. Table 6.1 shows the calculated values of the mean sand at each site.

Table 6.1: Mean sand at five different sites of agricultural land

Depth (cm)	Site-1	Site-2	Site-3	Site-4	Site-5
10	75	54	58	46	48
20	84	58	49	44	51
30	82	58	49	56	49
50	83	52	51	50	55
70	80	50	55	50	53
90	79	55	51	41	61
110	82	58	47	45	60
130	89	46	52	58	58
150	88	48	56	54	56
Total	742	479	468	444	491
Mean (%)	82.44	53.22	52	49.33	54.56

In Figure 6.1, the bar chart entitled mean sand of site shows the results of mean sand of five sites. From this, one can easily observe that, in the first site there is a maximum sand content compared to other sites and is about 82%. In all the other four sites, the sand content was almost same. The minimum sand content in the fourth site was about 52%. The higher mean sand observed in the first site might be the consequence of more agricultural practices such as soil tillage, fertilization, vertical eluviations of finer materials, and the changes of soil water balance etc.

The study was then carried out to determine the mean sand at each soil layer (depths) from 10 to 150 cm using the eqn. (6.2). Here the percentage of sand was taken from one particular depth (layer) of each site and mean sand at that depth (layer) was determined.

Table 6.2: Mean sand at different soil layers of agricultural land

Depth (cm)	Layers	Site-1	Site-2	Site-3	Site-4	Site-5	Total	Mean (%)
10	1	75	54	58	46	48	281	56.2
20	2	84	58	49	44	51	286	57.2
30	3	82	58	49	56	49	294	58.8
50	4	83	52	51	50	55	291	58.2
70	5	80	50	55	50	53	288	57.6
90	6	79	55	51	41	61	287	57.4
110	7	82	58	47	45	60	292	58.4
130	8	89	46	52	58	58	303	60.6
150	9	88	48	56	54	56	302	60.4

The same procedure was followed for other soil depths also. The computed values are listed in Table 6.2. The sand content was almost same in all the layers of five sites and not much difference was found between the layers ranging from 56.2% to 58.4%. It was about 60% in the last two layers. Mean sand is lowest in the first layer as expected and increased with the depth with exceptions in fifth and sixth layers. This observation leads us to conclude that these two layers are almost similar to first layer in sand perspective.

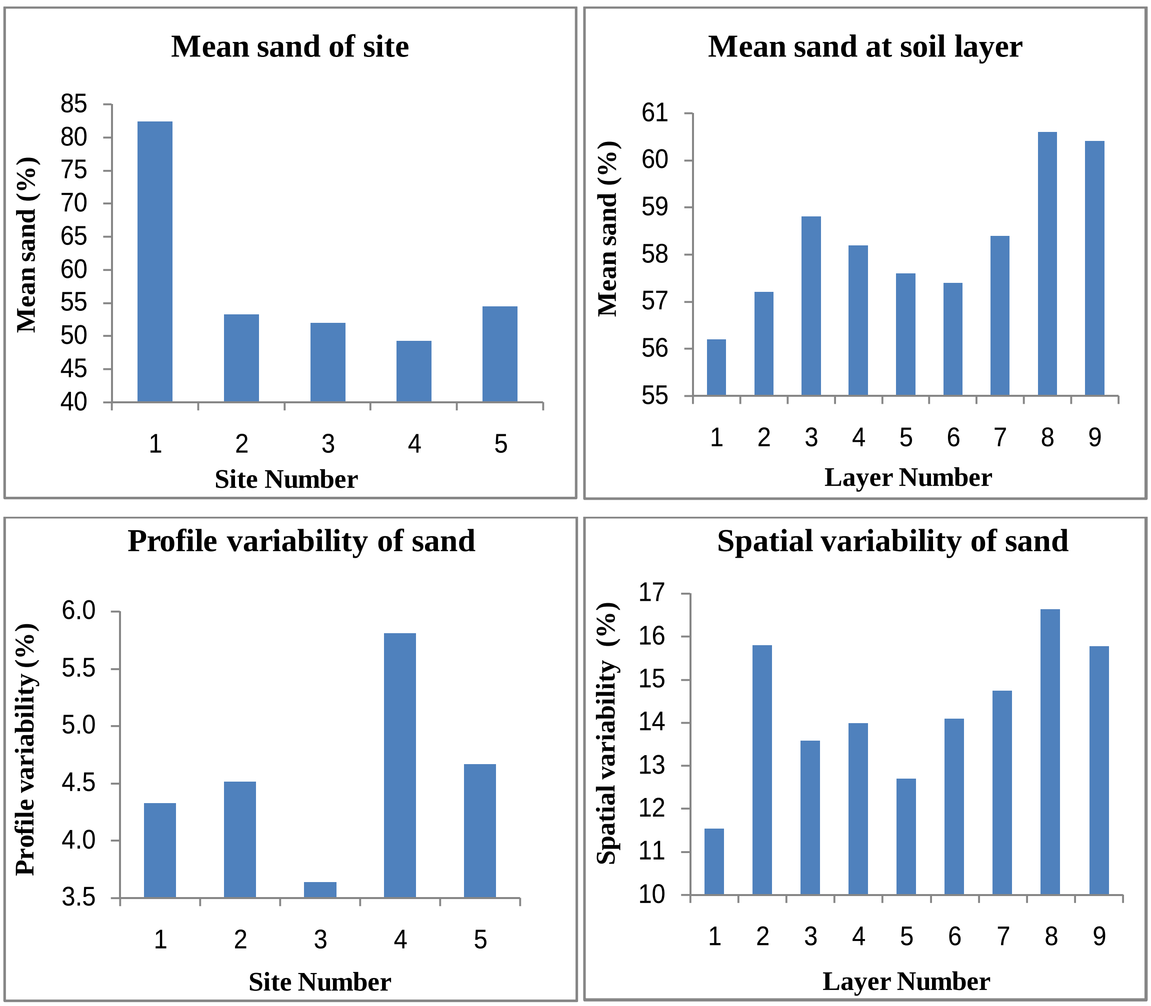


Figure 6.1: Different variables of sand

The profile variability of sand for different site was computed using the eqn. (6.3). The variation within the profile is defined by the profile variability. The profile variability is higher when the profile gradient is high, (Venkatesh et al. 2011and Qiu et al. 2001). The profile gradient is defined as the difference in soil property from the bottom most layer to the uppermost layer and divided by the profile thickness. The percentage of sand from all depths of one particular site was considered and determined the profile variability of that site. The same procedure was followed for other sites also and calculations are shown in the Table 6.3. The analysis of the observed results revealed that, the profile variability was more in the fourth site (5.81%) and less in the third site (3.64%), when compared to other sites. In other three sites (site 1, 2 and 5) not much variation was found. Profile variability is also an important realistic representation of soil property in different regions. Average layered profile variability is lowest in the little humid east and highest in the vegetated north portion of the study area. Different vegetation types in vegetated, texturally variable soils might be attributing this kind of variations among the sites.

Table 6.3: Profile variability of sand in different sites of agricultural land

Depth (cm)	Site-1	Site-2	Site-3	Site-4	Site-5
10	75	54	58	46	48
20	84	58	49	44	51
30	82	58	49	56	49
50	83	52	51	50	55
70	80	50	55	50	53
90	79	55	51	41	61
110	82	58	47	45	60
130	89	46	52	58	58
150	88	48	56	54	56
Profile variability (%)	4.33	4.52	3.64	5.81	4.67

To analyze the spatial variability of sand at different depths (layers), the percentage of sand at one particular depth from different sites was considered and computed the spatial variability using the eqn. (6.4). The same procedure was followed for the other depths also. Not much spatial variability was observed between the five sites at different depths in agricultural land. The bar chart (Figure 6.1) shows the spatial variability of sand at different soil depths. There was more spatial variation at 130 cm depth (16.64%) and less at 10 cm depth (11.54%). In other depths, small variations were observed ranging from 12.71% to 15.81%. Table 6.4 shows the spatial variation of sand content at different depths. Spatial variability in the five sites was unpredictably high in order of magnitude and reflects variability due to differences in soil texture.

Table 6.4: Spatial variability of sand at different depths of agricultural land

Depth (cm)	Layers	Site-1	Site-2	Site-3	Site-4	Site-5	Total	Spatial Variability (%)
10	1	75	54	58	46	48	281	11.54
20	2	84	58	49	44	51	286	15.81
30	3	82	58	49	56	49	294	13.59
50	4	83	52	51	50	55	291	13.99
70	5	80	50	55	50	53	288	12.71
90	6	79	55	51	41	61	287	14.09
110	7	82	58	47	45	60	292	14.74
130	8	89	46	52	58	58	303	16.64
150	9	88	48	56	54	56	302	15.77

Next physical property considered was the percentage of silt in the soil. Four different variables of silt were computed using eqns. (6.1)-(6.4) and the results are presented in the Figure 6.2. The mean silt of the site was found out by considering the percentage of silt from all the depths of one particular site. The same method was followed for other sites also. Mean silt content was more in the second and fifth site and less in first site (13.89%). Not much variation was found between the third and fourth site. By taking mean silt at soil layer as the next variable, it was found that, in the seventh layer, there was mean silt content about 28.6% and increased in last two layers (33%). Some amount of variation was found between the other depths or layers, (29% to 31.8%). The mean silt of soil properties was large towards bottom layers, which shows that the silt is not homogeneous in spatial distribution because of the effect of geology, topography and difference of land use and land management measures in this area. Coming to the profile variability of silt, there was a higher profile variation in the second site about 5.74%, and was less in the first and fifth sites, (2.83% to 2.85%). In other two layers it was almost same. Lastly, the spatial variability of the silt at layers was determined. Almost the same spatial variation between the different depths among the five sites have been observed and was quite more in 130 cm depth (15.42%) and less in the first layer (10.92%).

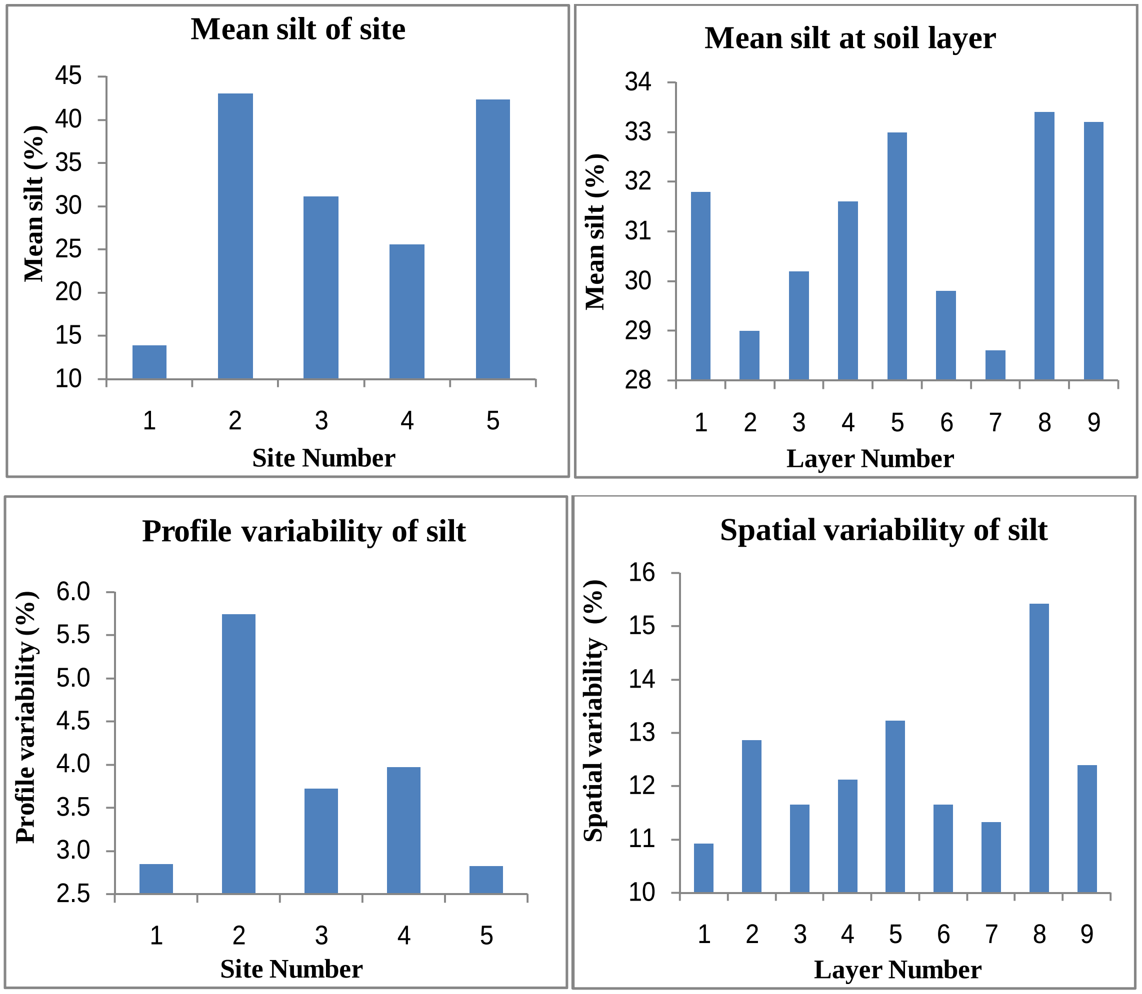


Figure 6.2: Different variables of silt

The present work was then continued with the next soil property, that is the percentage of clay in the soil and analyzed the each variable for clay. Clay content was very less in all the sites of the agricultural land under consideration. It might be due to the location of the area considered, which was near the river side. Figure 6.3 shows the different variables of the clay. While studying the mean clay of the site, it was found that there was a very less amount of clay in the fourth and fifth site (1%). Only in the first site, the clay content was quite more about 2.89%, in other sites it was 2.11% to 1.22%. Mean clay at each layer was then calculated. There was not much variation in the mean clay in the layers (depths). Only at 150 cm depth i.e., in the ninth layer, the mean clay content was less about 1%, and in the remaining depths it was 1.6 to 2.4%.

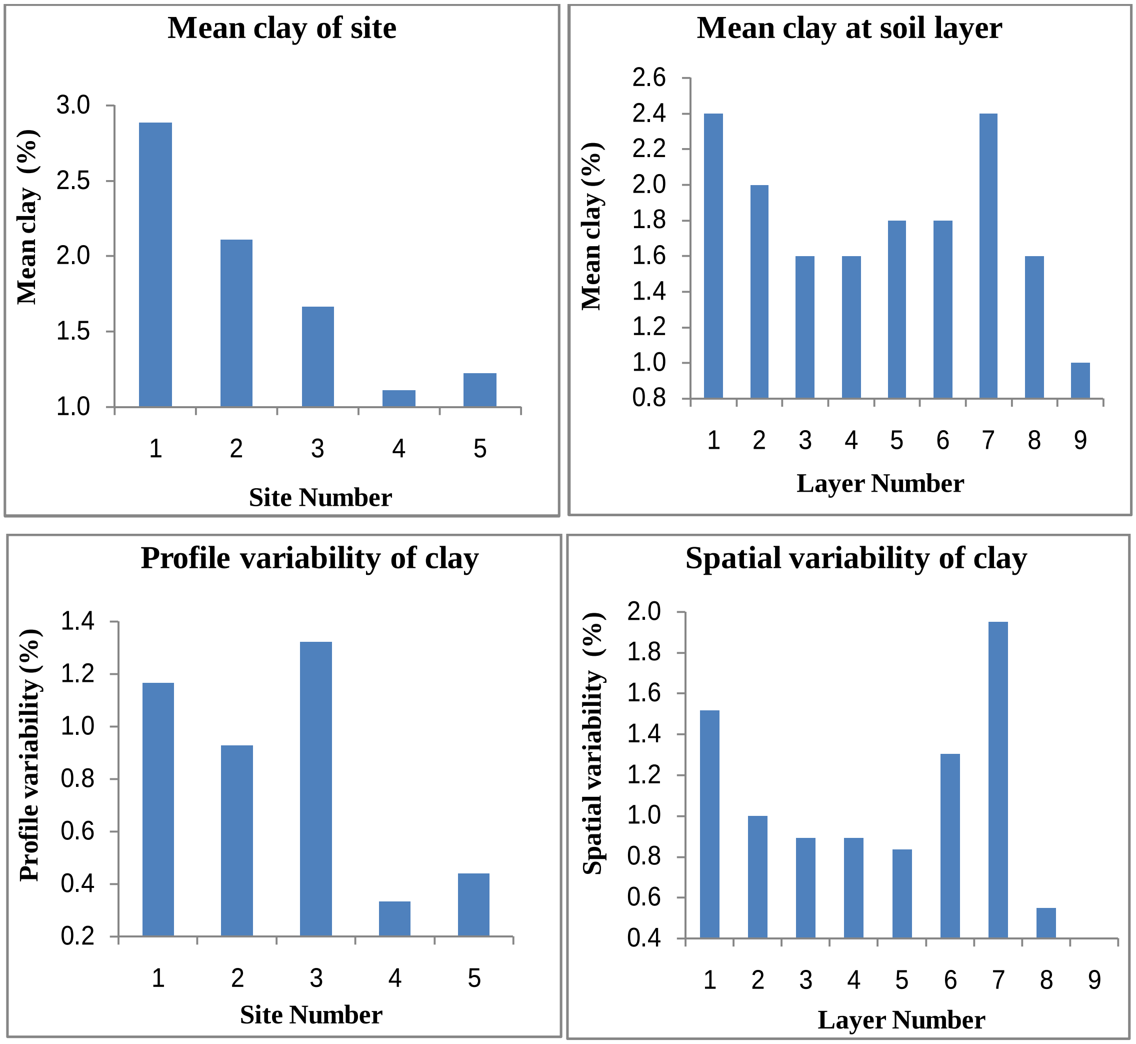


Figure 6.3: Different variables of clay

A very less profile variability was observed in the fourth and fifth site ranging from 0.33% to 0.44% and more profile variability in the third site about 1.32%. In other two sites, it was almost same ranging from 0.93% to 1.17%. The spatial variability of clay was then analyzed at layers; it was observed that more spatial variation in the seventh layer about 1.95%. There was no spatial variability in the ninth layer i.e., at 150 cm depth. In other layers small amount of spatial variation was observed. Clay seems to be the most discriminating factor for describing variability of a soil property than the other properties. A significant positive correlation was found between soil salinity and depth in a field with high clay content, having low infiltration capacity.

Bulk density is one of the important soil physical properties. In general, the variation of bulk density is higher in surface than in subsurface soil layers, whereas the trend is reverse for silt content and clay content. This study also observed the same results. This might be due to variety of crops grown at different times and different blocks of the land. In the present study, the mean bulk density was very less in the third site, more in the first site and almost same in the fourth and fifth site. Mean bulk density was very less in eighth and ninth layer and in other layers slight variation was found. Profile variability was less in the fourth site when compared to other sites and quite more in the third site. In other layers, it was almost same. The spatial variation was less in sixth layer and was almost same in other layers. Figure 6.4 shows the different variables of bulk density.

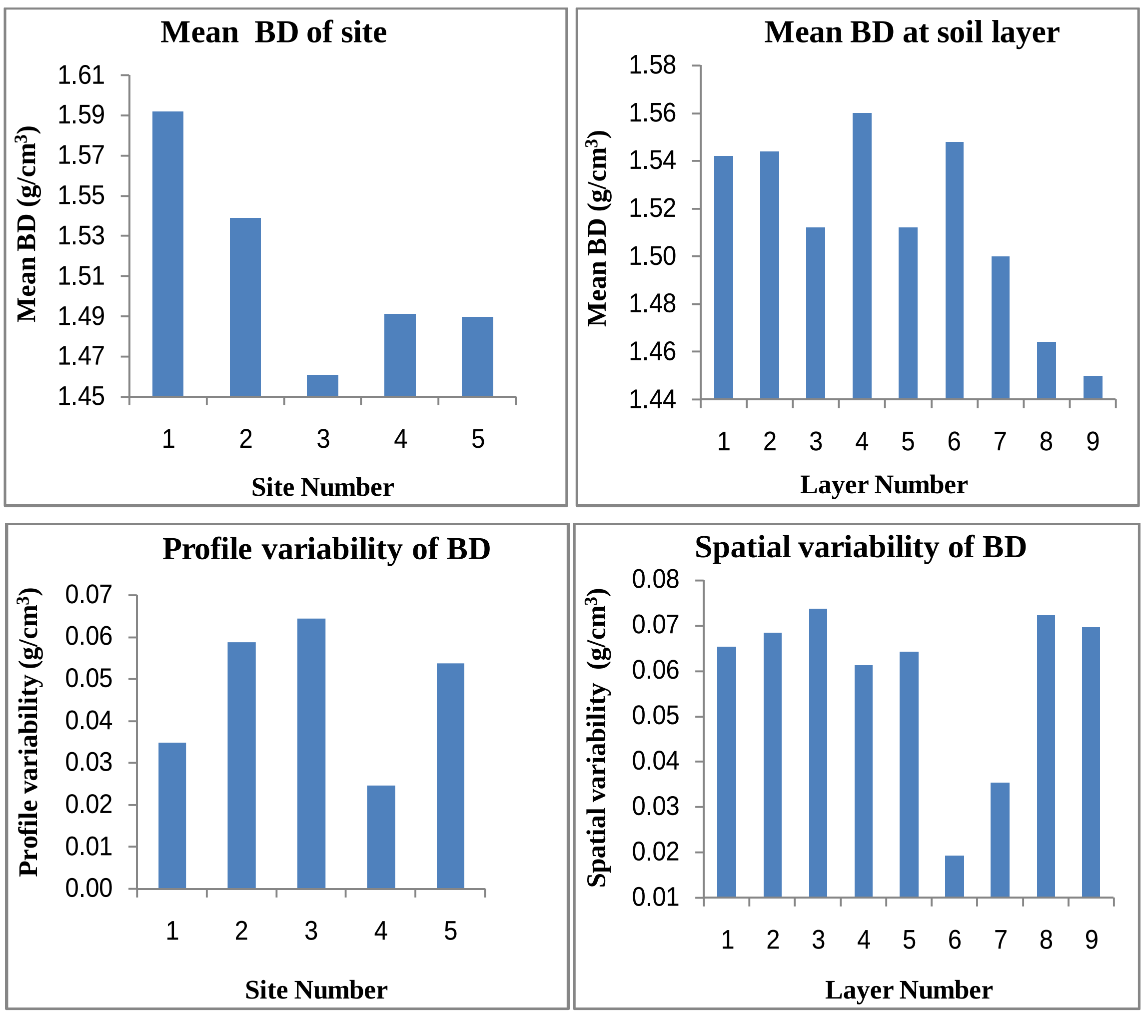


Figure 6.4: Different variables of bulk density (BD)

Drainage has often been found to cause an increase in bulk density (Minkkinen and Laine 1998). Drainage also changes the patterns of total nutrient uptake by the vegetation (Laiho et al. 2003) and element leaching (Sallantaus 1992). This impact was detected in present work also. Of all the elements studied, BD showed the considerable within-site variation, and its variability was even higher on the drained than on the undrained sites.

Organic matter content is another soil property. Here also the computations of four different variables were done. First variable was the mean organic matter content of the site. It was observed that mean organic matter content was less in the first site (0.68%) and more in the third site (1.04%). In other sites, not much difference was found. Mean organic matter content at soil layer was in decreasing mode; means the organic matter content was more at the topmost layer and less in the bottommost layer. It was ranging from 0.32% to1.72%. So the organic matter content at the surface was more than that of the subsurface, which might be due to continuous addition of crop residues on the surface of cropped fields. Profile variability of organic matter content was very less in the first site (0.24%). In second and third site it was quite more ranging from 0.66 to 0.68% and again in the fourth and fifth site, it decreased to 0.4%.

The spatial variability was more in the top layer (0.61%) and in other layers it was less ranging from 0.09% to 0.28%. This might be mainly because the differential growth behavior of each crop results in different quantities of shoot and root biomass. The spatial variation of organic carbon content is higher in surface layer than in subsurface layer. The Figure 6.5 shows the different variables of organic matter content. Organic matter concentrations of soils were high in landward sites and decreased gradually towards the sea in both transects, with an average content of 0.3 to 1.7%. When compared with other ecosystems in Asia-Pacific regions, organic matter concentrations (both average values and ranges) recorded in this was somewhat comparable i.e., PRC (0.4-4.5%). Exceptionally low values of organic matter (<.3%) were found in landward sites. On the contrary, soils collected from the bottom 50 cm depths had low organic matter content; probably due to some amount of possible tidal flushing.

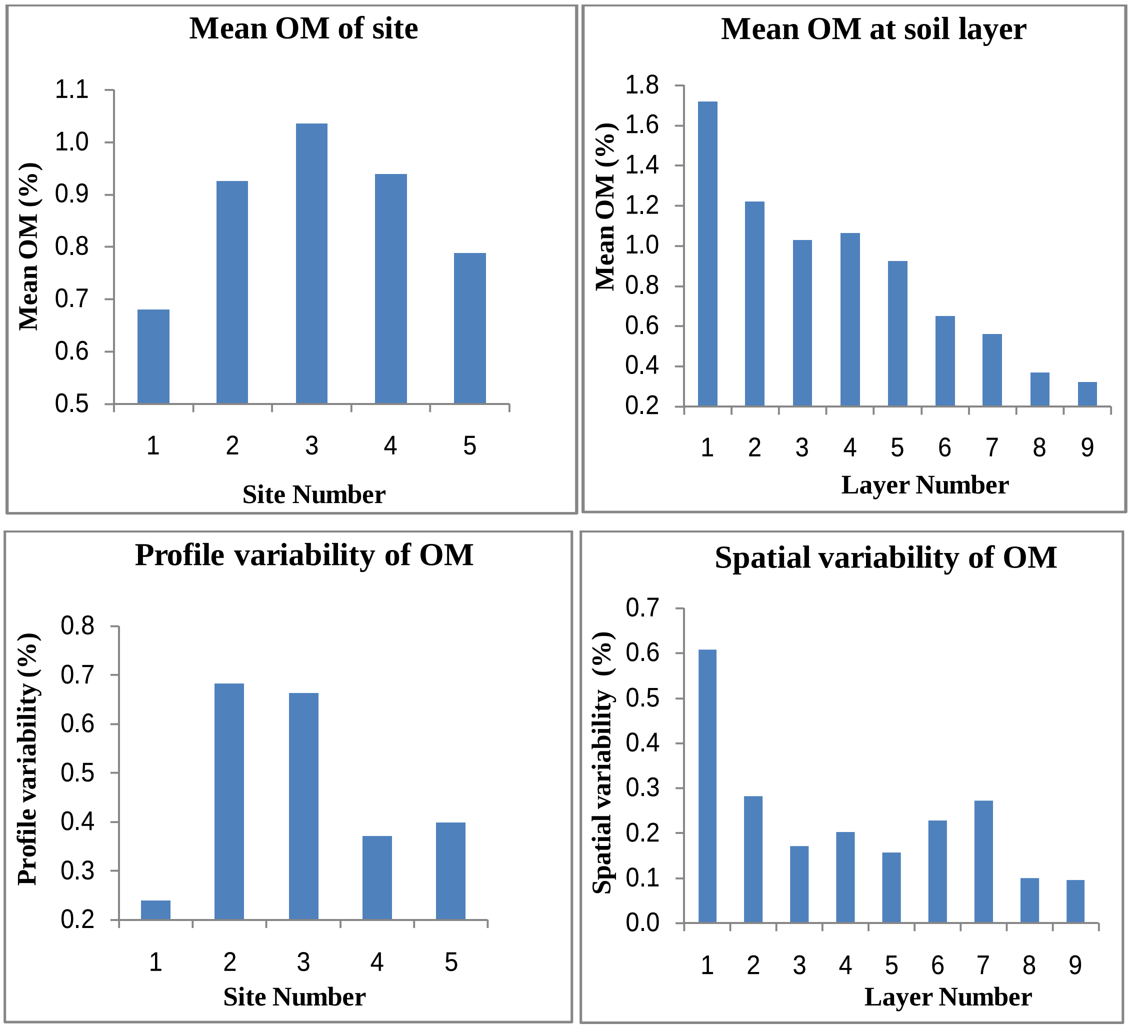


Figure 6.5: Different variables of organic matter content (OM)

Table 6.5 shows the spatial variation of the physical properties of agricultural soils at different depths. The spatial variation was quite more in the subsurface layers than in surface layers for sand and silt. But for the clay, spatial variation was less in the subsurface layer. Bulk density was almost identical in all the layers; it did not show much spatial variation between the layers. Spatial variation of organic matter content was more in the top layer and then it decreased towards the bottom soil layers. The fine-scale distributions of various soil physical properties across the layers have been noticed. The spatial distribution of water retention properties closely followed the distribution pattern of sand, silt and clay content. This indicates a differential water holding capacity of different textured soils across the sampled field.

Table 6.5: Spatial variability of physical properties of agricultural soils at various depths

Depth (cm)	Physical properties				
	Sand (%)	Silt (%)	Clay (%)	Bulk density (g/cm^3)	Organic matter content (%)
10	11.541	10.918	1.517	0.065	0.607
20	15.802	12.865	1.000	0.068	0.282
30	13.590	11.649	0.894	0.074	0.170
50	13.989	12.116	0.894	0.061	0.202
70	12.700	13.229	0.837	0.064	0.156
90	14.100	11.649	1.304	0.019	0.227
110	14.741	11.327	1.949	0.035	0.271
130	16.637	15.421	0.548	0.072	0.099
150	15.773	12.398	0.000	0.070	0.095

6.3.2 Analysis of different variables of hydraulic properties for agricultural soils

This study investigates the four different variables of the soil water retention and the saturated hydraulic conductivity of the agricultural soils. The four different variables include mean of site, mean at soil layer, profile variability and spatial variability of the layered soil. The same procedure was followed here also as explained for the physical properties.

Next water retention at -33 kPa pressure head, (θ_{33}) was considered to study its different variables. Mean water retention at -33 kPa of the site was computed using the eqn. (6.1) and bar charts are given for the different variables of θ_{33} (Figure 6.6). In the first site, the mean θ_{33} of the site was lowest, about 6.48%. In other four sites, mean θ_{33} was more and change in water retention at 33kPa was ranging from 23.86% to 26.32%. Mean of the water retention at -33 kPa for different layers was then computed. In the last two layers i.e. at 130 cm and 150 cm depth it was still lesser about 0.20% compared to other layers. In other remaining layers, not much difference was found. It was in the negligible range of

0.21% to 0.22%. Profile variations were quite more in the third site (1.92%) and low in the fifth site (0.88%). In first and second site, it was almost same ranging from 1.36% to1.6% and in fourth site it was about 1.05%. The spatial variability was low at the top layer (7.4%) and increased towards the bottom three layers (9%). In other layers, minor variations were found ranging from 7.7% to 9.12%.

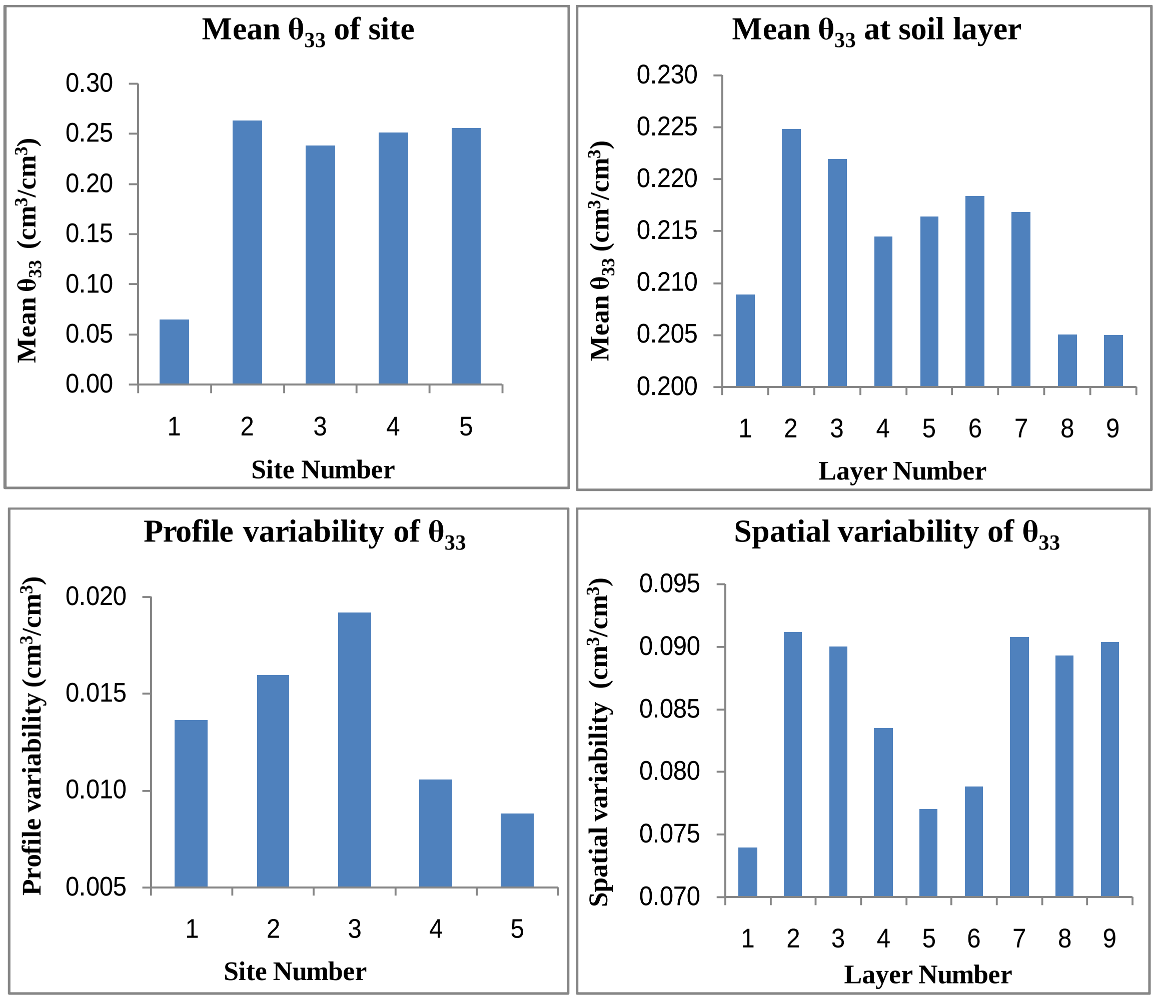


Figure 6.6: Different variables of θ_{33}

Next, this study focused on the different variables for water retention at -100 kPa pressure head, (θ_{100}). It was observed that in the first site, the mean of water retention at -100 kPa was lowest (6.3%) and it was higher in other four sites (21.33% to 24.22%). Then mean θ_{100} at different layers were studied. At 150 cm depth, mean θ_{100} was low (18.65%) and increased in second layer (21.24%). In the remaining sites, small differences were found ranging from 19.25% to 20.36%. Very low profile variations were observed in all the sites except in third site. In the third site, it was about 2.2% and in other sites, 1.48% to 1.64%. The spatial variability was low at the top layer (6.25%) and in other layers some variations were observed ranging from 6.74% to 9.01%. The bar charts are given for different variables of θ_{100} as shown in Figure 6.7.

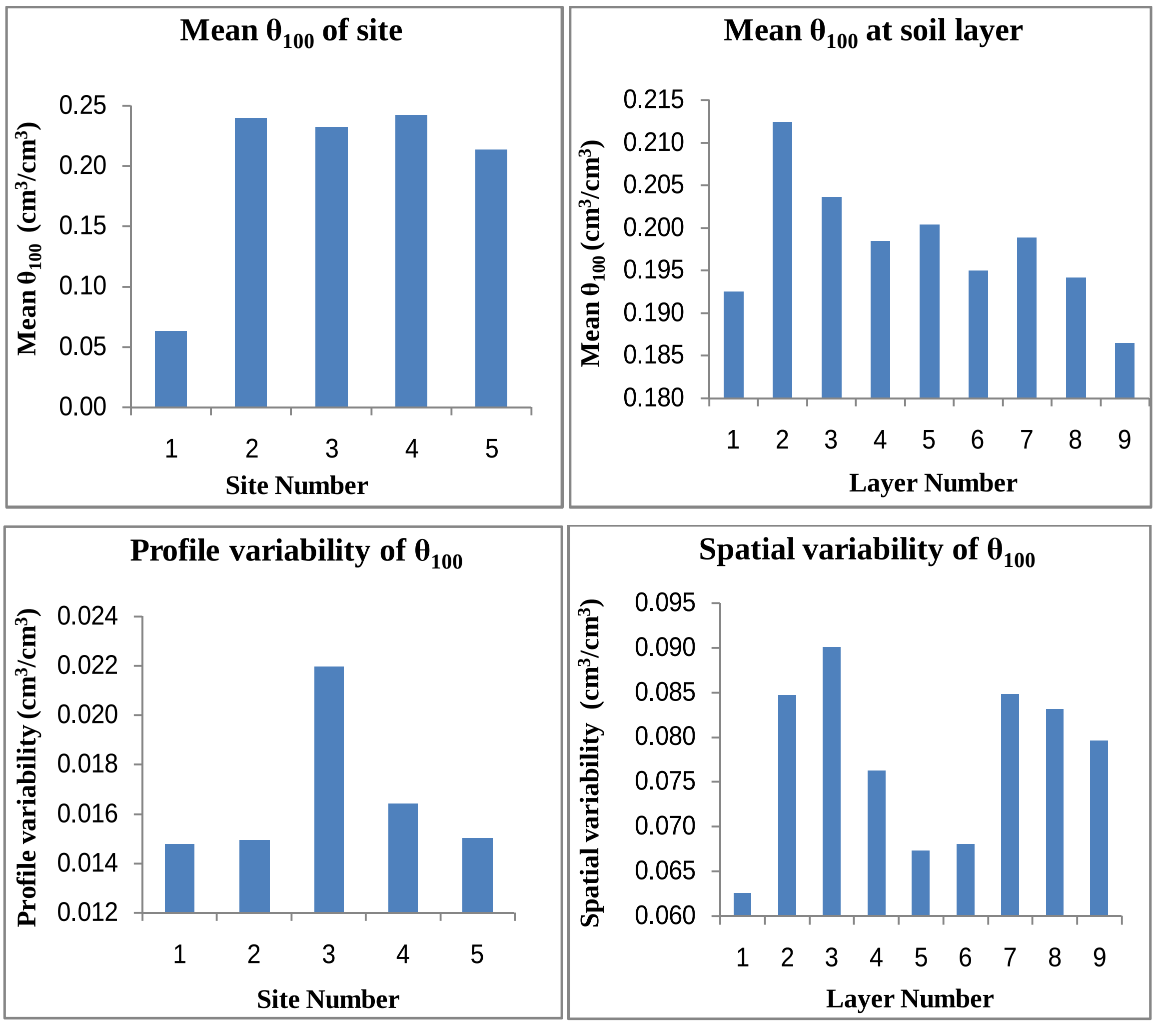


Figure 6.7: Different variables of θ_{100}

Water retention at -300 kPa pressure head, (θ_{300}) was considered next. Almost same results were found as in the case of θ_{100} for all the variables. Mean θ_{300} of the sites was first found out, was low for first site about 4.98% and higher in other sites. Some amount of differences was found in the other four remaining sites (18.78% to 21.7%). For water retention at -300 kPa at different layers, mean θ_{300} in first layer was less (16.12%), in intermediate layers some variations were found ranging from 17.09% to 18.64%. In the last layer, it recorded 16.47%. Profile variability was less in the fifth site (0.83%) and high in the second and third site about 2% and in first and fourth sites it was almost same (1.32%). Spatial variability of water retention at -300 kPa was less in first layer about 5.44% and some variations were found in between the other layers about 6.17% to 8.35%. The bar charts (Figure 6.8) are drawn for the different variables of water retention at -300 kPa.

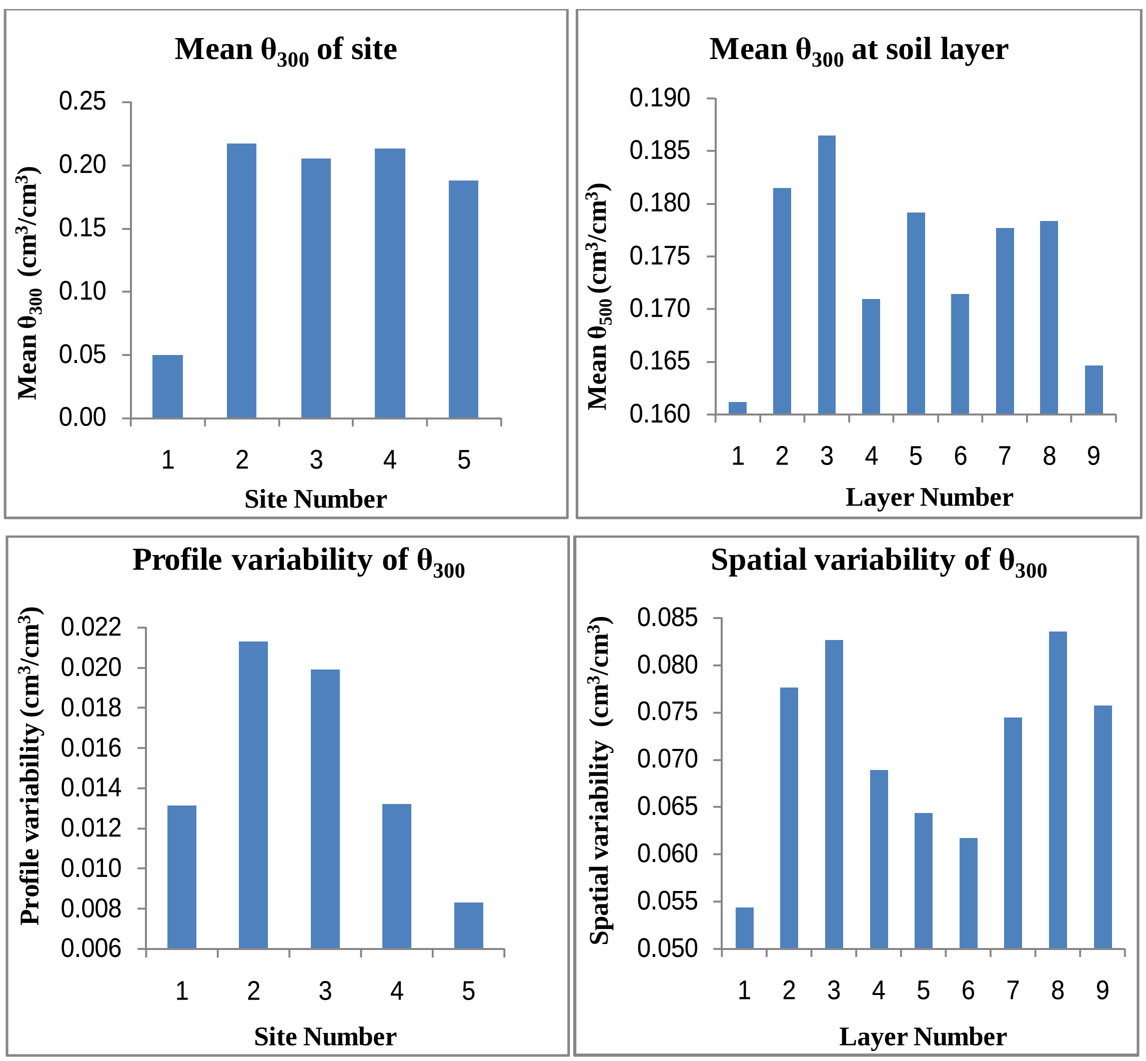


Figure 6.8: Different variables of θ_{300}

Next analysis was done for water retention at -500 kPa pressure head, (θ_{500}). Mean water retention at -500 kPa of the site was computed and it was low in first site about 4.99% and in other four sites variations were found ranging from 17.44% to 20.78%. When mean θ_{500} at different layers were studied, it was observed that, in top layer it was low about 14.66% and was quite high in third layer about 18.44%, and in other remaining layers, it was ranging from 15.88% to 17.47%. More profile variability was observed in second and third site (2.4%), quite low in the first and fourth sites (1.4%) and lowest in the fifth site (0.53%). Spatial variability was low at the top layer (4.75%), quite high in the third layer (8.3%) and in other layers, some variations were observed ranging from 5.96% to 7.5%. The following bar charts (Figure 6.9) are drawn for the each variable of water retention at -500 kPa.

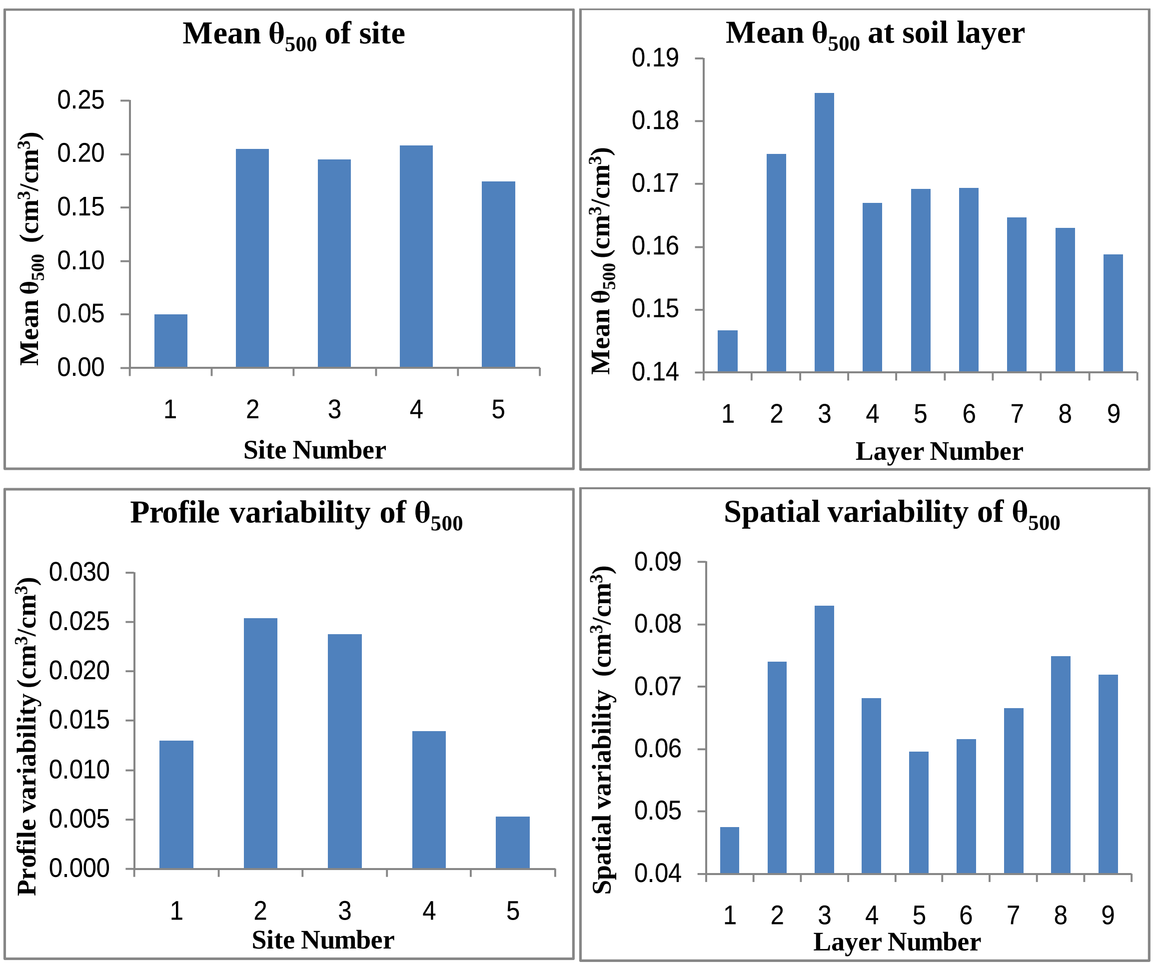


Figure 6.9: Different variables of θ_{500}

The present study then focused on the analysis of different variables of water retention at -1000 kPa pressure head, (θ_{1000}). Mean water retention at -1000 kPa of the site was first computed using the eqn. (6.1). Low mean θ_{1000} was observed in first site (4.22%) and in other remaining four sites; it was ranging from 15.44% to 18.82%. Mean water retention at -1000 kPa was quite low in top layer (13.94%) and increased in second layer (16.47%). In other intermediate layers, it was almost in decreasing mode from top to bottom layers except in eighth and ninth layer. Low profile variability was observed in fifth site about 0.53% and relatively more in second and third site ranging from 1.92% to 2.21%. Spatial variability was less in first and fifth layer and not much variation was observed in other layers except in second, third and seventh layers. The different variables of water retention at -1000 kPa are shown in Figure 6.10.

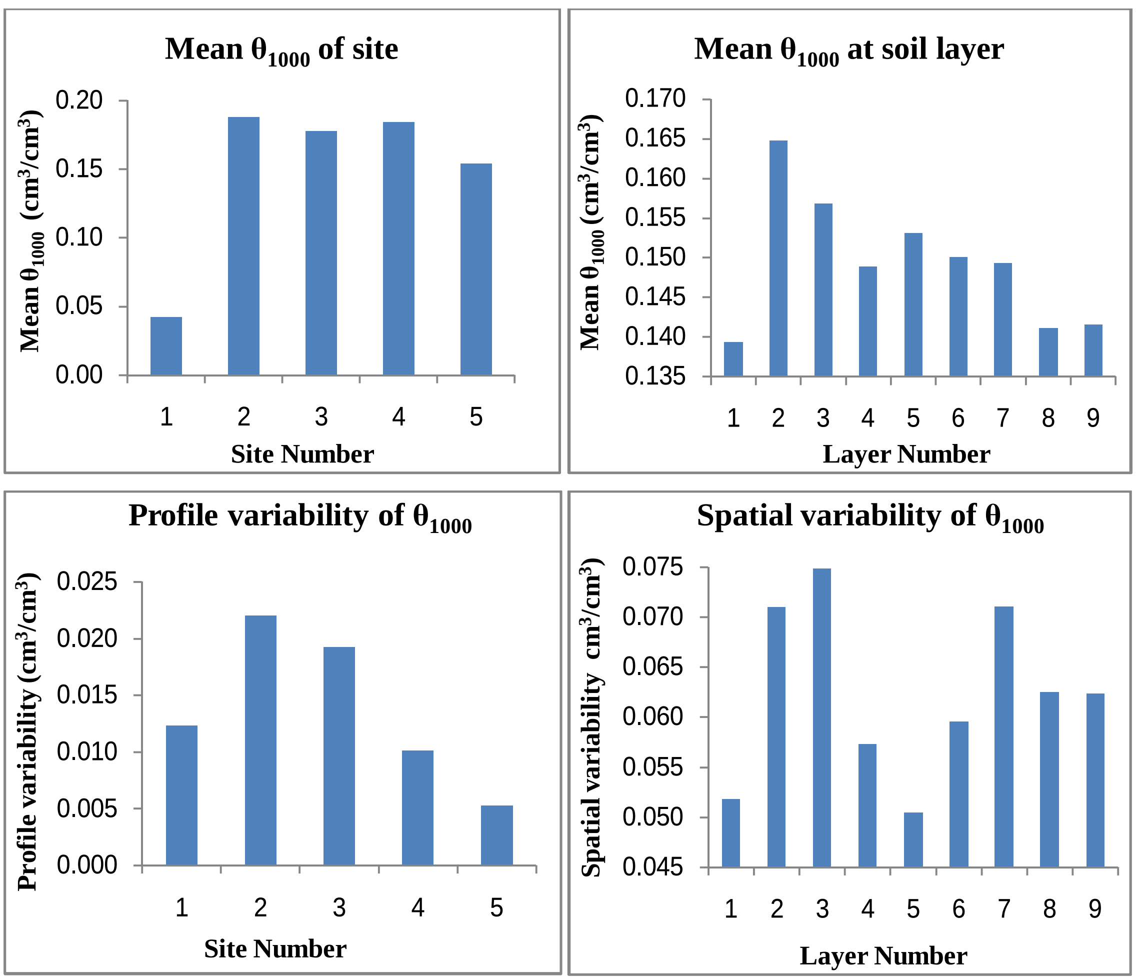


Figure 6.10 Different variables of θ_{1000}

The study was then continued with the analysis of water retention at -1500 kPa pressure head (θ_{1500}). At first, mean water retention at -1500 kPa of the site was studied. Mean θ_{1500} was low in first site (3.51%) and in the remaining sites some differences were found ranging from 11.89% to 17.22%. Mean θ_{1500} at soil layer was low in the eighth layer (12.12%), quite increased in the second layer (13.91%) and in the remaining sites considerable variations were not found. Low profile variability was observed in fifth site about 0.6%. It was almost equal in first and fourth layer about 1.3% and in second and third sites low variations were found ranging from 0.74% to 0.96%. Low spatial variability was observed in the first and fifth layers (5.1%). It relatively increased in the bottom most layers (6.54%) and in the other layers some variations were observed ranging from 5.69% to 6.36%. The following bar charts (Figure 6.11) are drawn for the different variables of water retention at -1500 kPa.

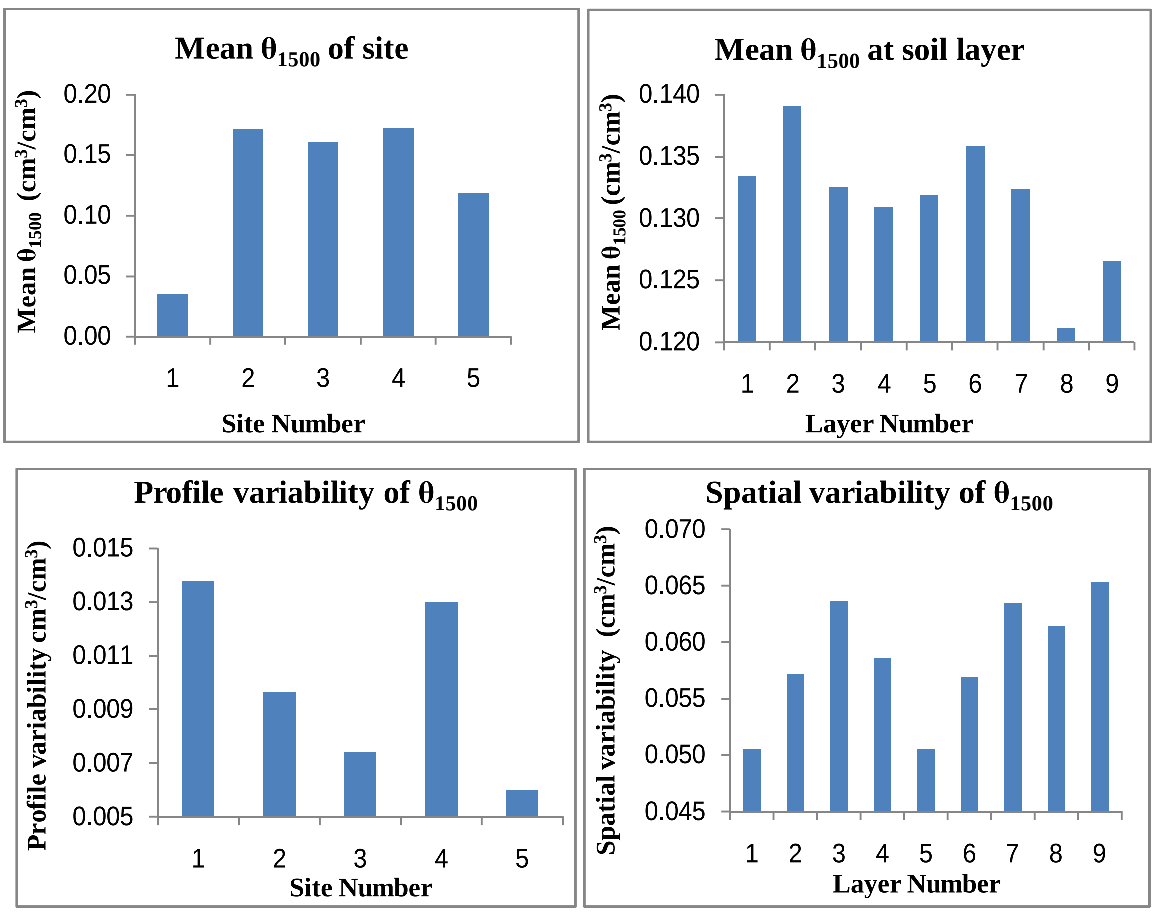


Figure 6.11: Different variables of θ_{1500}

The following discussion aims to describe the hydrological processes that influence the water content in a given soil volume. The water stored in an elementary soil volume is one part of a water balance for the volume. Water gets added to the soil volume by infiltration from the ground surface. Upslope areas may act as input the soil volume, and also as output from the soil volume as downslope flow. The lateral flow can be either saturated or unsaturated and the spatial distribution of the lateral flow is to a large extent determined by different topographical factors (e.g. Anderson and Burt, 1978). Although unsaturated flow is commonly thought to be directed vertically, published examples were found where unsaturated flow vectors had both vertical and lateral components (e.g. Haan, 1977; Johansson, 1985). Usually the role of topography in the spatial variability of water retention is seen from the measurements of water content at different pressure heads. In the wake of this the correlations between water content and matric potential here indicated that micro-topography was a major contributor to the variability in water retention, since the sampled area is smaller.

The different variables of the saturated hydraulic conductivity (k_s) were then comprehensively analyzed. Mean k_s were high in the first site and low in the second site. In third, fourth and fifth sites smaller differences were observed. When calculating the mean k_s at different soil layers, remarkable variations were found. In the first layer, mean k_s were higher, then it started decreasing, and in sixth and seventh layers it attained lowest. Different sites showed different profile variations. It was low in the second and fifth sites. First and fourth sites showed almost same profile variations.

There was not much spatial variability observed up to fourth layer. In fifth layer, it was low and then it increased from fifth to ninth layer. In the ninth layer, the spatial variability was more. The Figure 6.12 shows the different variables of the saturated hydraulic conductivity. The considerably larger k_s, values were observed in almost all the layers. One possible reason for this finding may be the variable amount of preferential flow caused by the variable amount of macroporosity present in the soil sample (Everts and Kanwar, 1989). A sample size of this kind has a moderate probability for the presence of large macropores, resulting in little higher k_s values. There is also a possibility that the vertical macropores may be functioning well under laboratory conditions because most of the entrapped air is removed gradually by saturating the core from the bottom. Moreover, profile variability was high at shallow depths of 10 cm because of the presence of macropores in different sample soil cores.

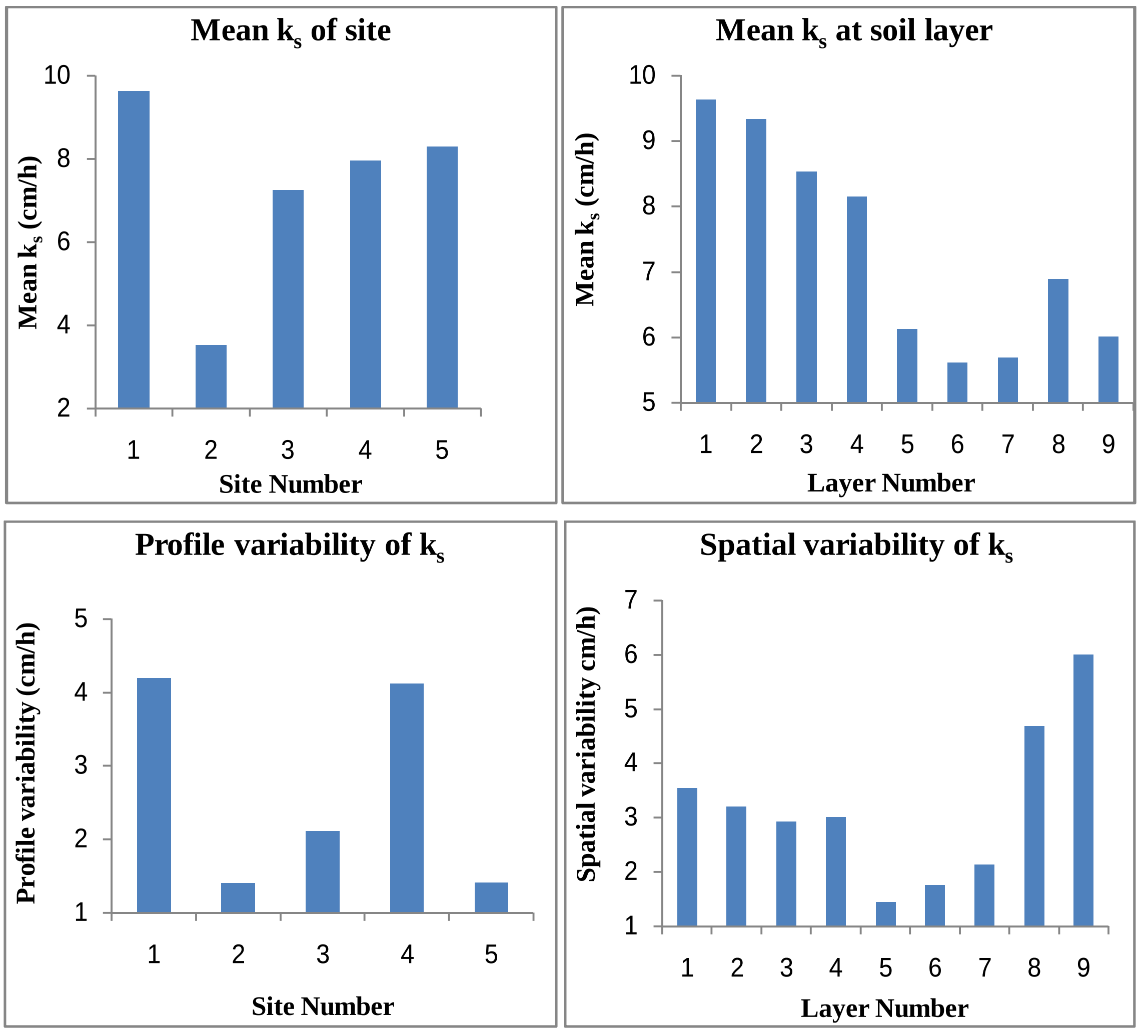


Figure 6.12: Different variables of saturated hydraulic conductivity (k_s)

The comparison of spatial variability of soil hydraulic properties in the agricultural site across all depths and sites are presented in Table 6.6 to compare the variables for individual depths and sites. Here the spatial variability of water retention at different pressure heads and saturated hydraulic conductivity at different depths are given.

Table 6.6: Spatial variability of hydraulic properties of agricultural soils at various depths

Depth (cm)	Hydraulic properties						
	θ_{33} (cm^3/cm^3)	θ_{100} (cm^3/cm^3)	θ_{300} (cm^3/cm^3)	θ_{500} (cm^3/cm^3)	θ_{1000} (cm^3/cm^3)	θ_{1500} (cm^3/cm^3)	k_s(cm /hr)
10	0.074	0.063	0.054	0.047	0.052	0.051	3.54
20	0.091	0.085	0.078	0.074	0.071	0.057	3.20
30	0.090	0.090	0.083	0.083	0.075	0.064	2.92
50	0.084	0.076	0.069	0.068	0.057	0.059	3.00
70	0.077	0.067	0.064	0.060	0.050	0.051	1.44
90	0.079	0.068	0.062	0.062	0.061	0.057	1.75
110	0.091	0.085	0.074	0.067	0.071	0.063	2.14
130	0.089	0.083	0.084	0.075	0.062	0.061	4.68
150	0.091	0.082	0.076	0.072	0.062	0.065	6.01

In Table 6.6, water retention at different pressure heads is shown together according to the depth. Spatial variability of water retention increased from 10 cm to 150 cm depth for all the pressure heads. It was relatively high at the first four pressure heads i.e., at θ_{33}, $\theta_{100,}$ θ_{300} and θ_{500}. In θ_{33}, spatial variation was 7.4% - 9%; in θ_{100}, 6.3% -8%; in θ_{300}, 5.4% - 7.6%; in θ_{500}, 4.7% -7.2%; in θ_{1000}, 5.2% -6.2%; and in θ_{1500}, 5.1% -6.5%. Saturated hydraulic conductivity was varying from 3.54 to 6.01 cm/hr. It was almost same in the top layers, i.e., up to 110 cm depth, but it was higher in the bottom two layers. Furthermore, the results for an individual depth showed some differences when analyzed across all depths. A possible reason for this is that all these methods are subjected to different amounts of variability at different depths. Variability can be caused by factors like pore-size distribution, horizontal/vertical pore ratio, soil texture, and soil water content. In addition to all these factors, number of measurements at different depths for the laboratory method caused some differences in variability.

6.3.3 Analysis of different variables of physical properties of forested hillslope soils

The present study then focused on the analysis of different properties of forested hillslope soils. The different variables were computed for both physical (sand, silt, clay, bulk density and organic matter content) and hydraulic properties (θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000}, θ_{1500} and k_s) at different elevations. The elevations were from crest to foot of the hillslope i.e., at 30, 40, 50, 60, 75, 90, 105 and 120 m elevations. The same procedure was followed as that of agricultural soils explained in the section 6.3.1. At first, different variables were computed for physical properties of forested hillslope soils. i.e., mean of the elevations, mean at soil layers, profile variability of the elevations and spatial variability at layers were computed for sand, silt, clay, bulk density and organic matter content using the eqns. (6.1)-(6.4). In bar charts, number of elevations 1 to 8 represents 30 m to 120 m elevations and layers 1, 2, 3, 4, 5, 6 and 7 represent 10, 20, 30, 40, 50, 60 and 75 cm respectively.

At first, the study was carried out to analyze the different variables of sand, from forested hillslopes. The bar charts are drawn for the four different variables of sand as shown in Figure 6.13. To find the mean sand of the elevation, the percentage of sand from all the depths (layers) from 10 to 75 cm at one elevation was considered and computed the mean sand of that elevation using the eqn. (6.1).

Table 6.7: Mean sand at different elevations of forested hillslope soils

Depth (cm)	Elevations							
	30 m	40 m	50 m	60 m	75 m	90 m	105 m	120 m
10	45	40	49	53	42	46	35	53
20	41	43	44	56	57	44	45	51
30	42	45	39	54	48	39	46	40
40	48	32	40	57	36	41	43	40
50	42	37	40	57	36	46	42	36
60	39	40	40	52	41	50	45	35
75	57	41	41	54	53	51	30	33
Total	314	278	293	383	313	317	286	288
Mean (%)	44.85	39.71	41.86	54.71	44.71	45.29	40.86	41.14

The same procedure was repeated for the other remaining elevations also. Table 6.7 shows the computed values of the mean sand at each elevation. It could be observed from Figure 6.13 that, mean sand was maximum in the fourth elevation i.e. at 60 m, (54.71%). In other elevations, it was ranging from 39.71 to 45.28%.

Then mean sand at each soil layers (depths) from 10 to 75 cm was computed using the eqn. (6.2). Here the percentage of sand was taken from one particular depth (layer) of each elevation and mean sand at that depth (layer) was determined. The same procedure was followed for other soil depths also and calculated values are shown in Table 6.8. It could be seen from Figure 6.13 that, the mean sand content was quite more in second layer i.e., at 20 cm depth (47.63%) and minimum in fourth and fifth layers (42%), at 40 and 50 cm depths. In other layers, small variations were found ranging from 42.75% to 45.38%.

Table 6.8: Mean sand at different soil layer of forested hillslope soils

Depth (cm)	Layers	Elevations (m)								Total	Mean (%)
		30 (1)	40 (2)	50 (3)	60 (4)	75 (5)	90 (6)	105 (7)	120 (8)		
10	1	45	40	49	53	42	46	35	53	363	45.38
20	2	41	43	44	56	57	44	45	51	381	47.63
30	3	42	45	39	54	48	39	46	40	353	44.13
40	4	48	32	40	57	36	41	43	40	337	42.13
50	5	42	37	40	57	36	46	42	36	336	42.00
60	6	39	40	40	52	41	50	45	35	342	42.75
75	7	57	41	41	54	53	51	30	33	360	45.00

The profile variability of sand was computed using the eqn. (6.3). At one elevation, by considering percentage of sand from all depths, the profile variability was determined. The same procedure was followed for other elevations also. The profile variability in fifth and eighth elevations i.e. at 75 m and 120 m elevations was ranging from 7.86% to 8.2% and reported less in the fourth elevation i.e., at 60 m (1.98%). In other elevations, some variations were found ranging from 3.53% to 6.09%. Table 6.9 shows the profile variability of sand at different layers.

Table 6.9: Profile variability of sand at different elevations of forested hillslopes

Depth (cm)	Layers	Elevations (m)							
		30 (1)	40 (2)	50 (3)	60 (4)	75 (5)	90 (6)	105 (7)	120 (8)
10	1	45	40	49	53	42	46	35	53
20	2	41	43	44	56	57	44	45	51
30	3	42	45	39	54	48	39	46	40
40	4	48	32	40	57	36	41	43	40
50	5	42	37	40	57	36	46	42	36
60	6	39	40	40	52	41	50	45	35
75	7	57	41	41	54	53	51	30	33
Profile variability (%)		6.09	4.23	3.53	1.98	8.19	4.39	6.04	7.86

The spatial variability of sand at different depths (layers) was then calculated. The percentage of sand from one particular depth at different elevations was considered and calculated the spatial variability using eqn. (6.4). The same procedure was followed for the other depths also. Spatial variability was maximum in the seventh layer i.e., at 75 cm depth (10.18%). In other layers, spatial variability was from 5.22% to 7.62%. Figure 6.13 shows the spatial variability of sand in different soil depths. The results are shown in Table 6.10.

Table 6.10: Spatial variability of sand at different depths of forested hillslopes

Depth (cm)	Layers	Elevations (m)								Spatial variability (%)
		30 (1)	40 (2)	50 (3)	60 (4)	75 (5)	90 (6)	105 (7)	120 (8)	
10	1	45	40	49	53	42	46	35	53	6.30
20	2	41	43	44	56	57	44	45	51	6.19
30	3	42	45	39	54	48	39	46	40	5.22
40	4	48	32	40	57	36	41	43	40	7.62
50	5	42	37	40	57	36	46	42	36	6.99
60	6	39	40	40	52	41	50	45	35	5.80
75	7	57	41	41	54	53	51	30	33	10.18

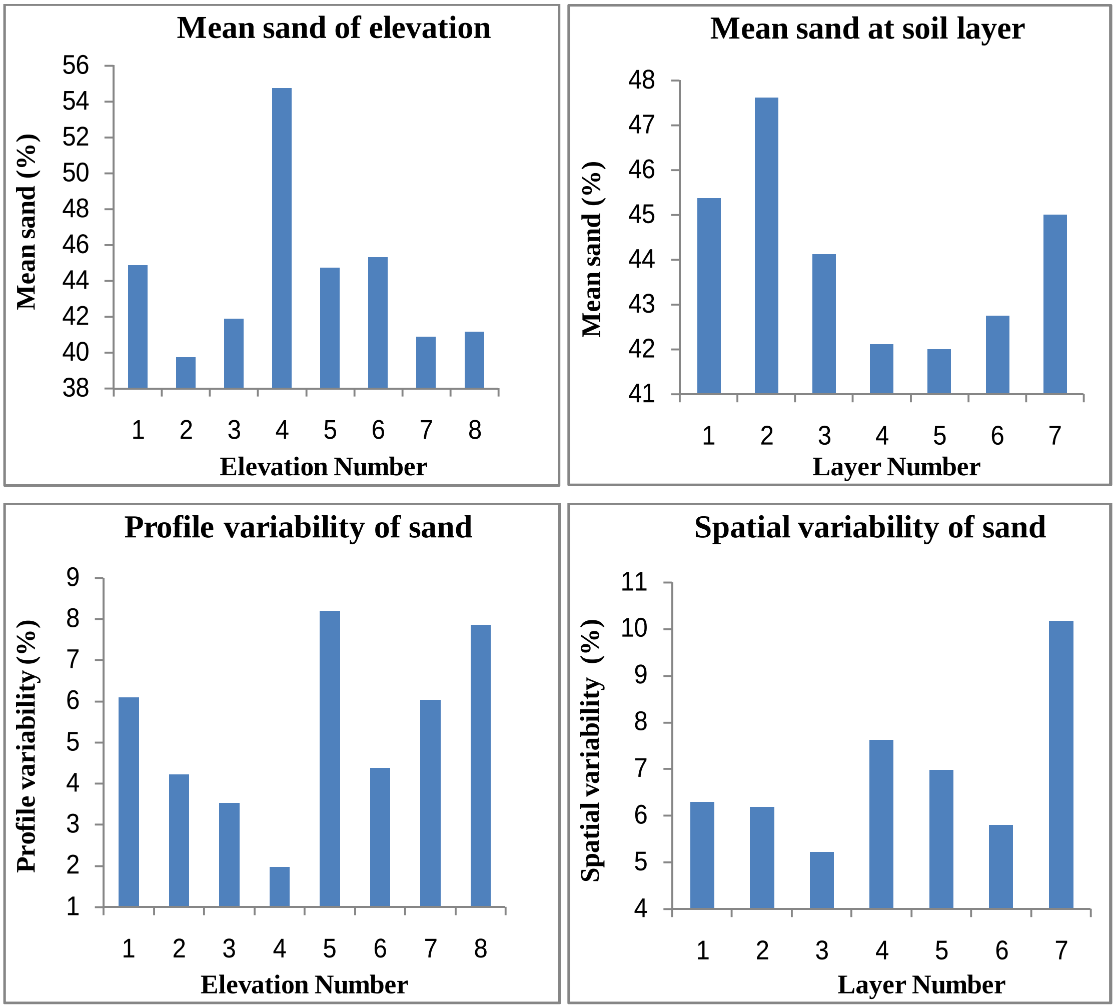


Figure 6.13: Different variables of sand

The present study was then continued with the computation of different variables of silt. Mean silt of the elevation was analyzed; it was observed that mean silt was more in first elevation (33.43%), and it decreased in second and third elevations (18%) and again increased in the fourth elevation (29.43%). It was almost same in all other elevations. Mean silt at layer was also determined; it was less in second layer (24.25%) and attained maximum in the first and seventh layer (27%). In other layers, small differences were found. Higher profile variability was observed in the first elevation (7.59%) and was quite moderate in second and fourth elevations ranging from 1.77% to 1.9%. Small variations were observed in other elevations ranging from 3.1% to 6.24%. Low spatial variability was found in the first and second layers ranging from 4.83% to 5.51%, attained maximum in the third layer (10.05%) and in other layers it was 6.16% to 8.93%. The bar charts are drawn for the different variables of silt property (Figure 6.14).

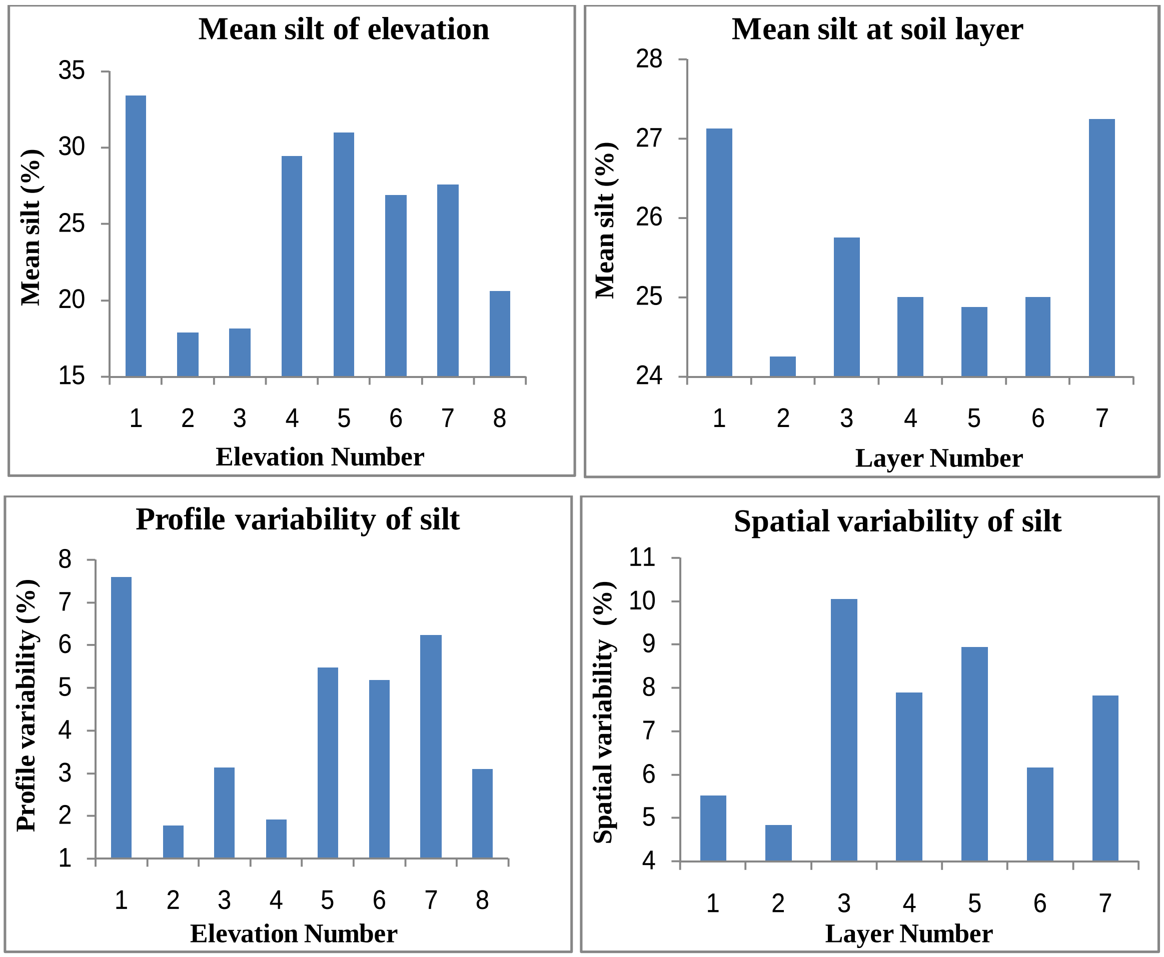


Figure 6.14: Different variables of silt

The different variables of clay were then calculated using eqns. (6.1)-(6.4). Mean clay of the elevation was 2.57% in fourth elevation and decreased in third, sixth and eighth elevations, ranging from 0.29% to 0.43%; in other elevations not much variation was observed. The mean clay at different layers was then analyzed. It was observed that, mean clay was less in first and second layers (0.75% to 0.88%), and in other layers small variations were observed ranging from 1.13% to 1.75%. Profile variability was quite low in the third, sixth and eighth elevations (0.5%) and increased in fifth elevation (1.53%).

Some minor profile variations were observed in other elevations. The spatial variability was maximum in third layer (1.98%) and in other layers, it was ranging from 0.99% to 1.17%. The different variables of clay are shown in Figure 6.15.

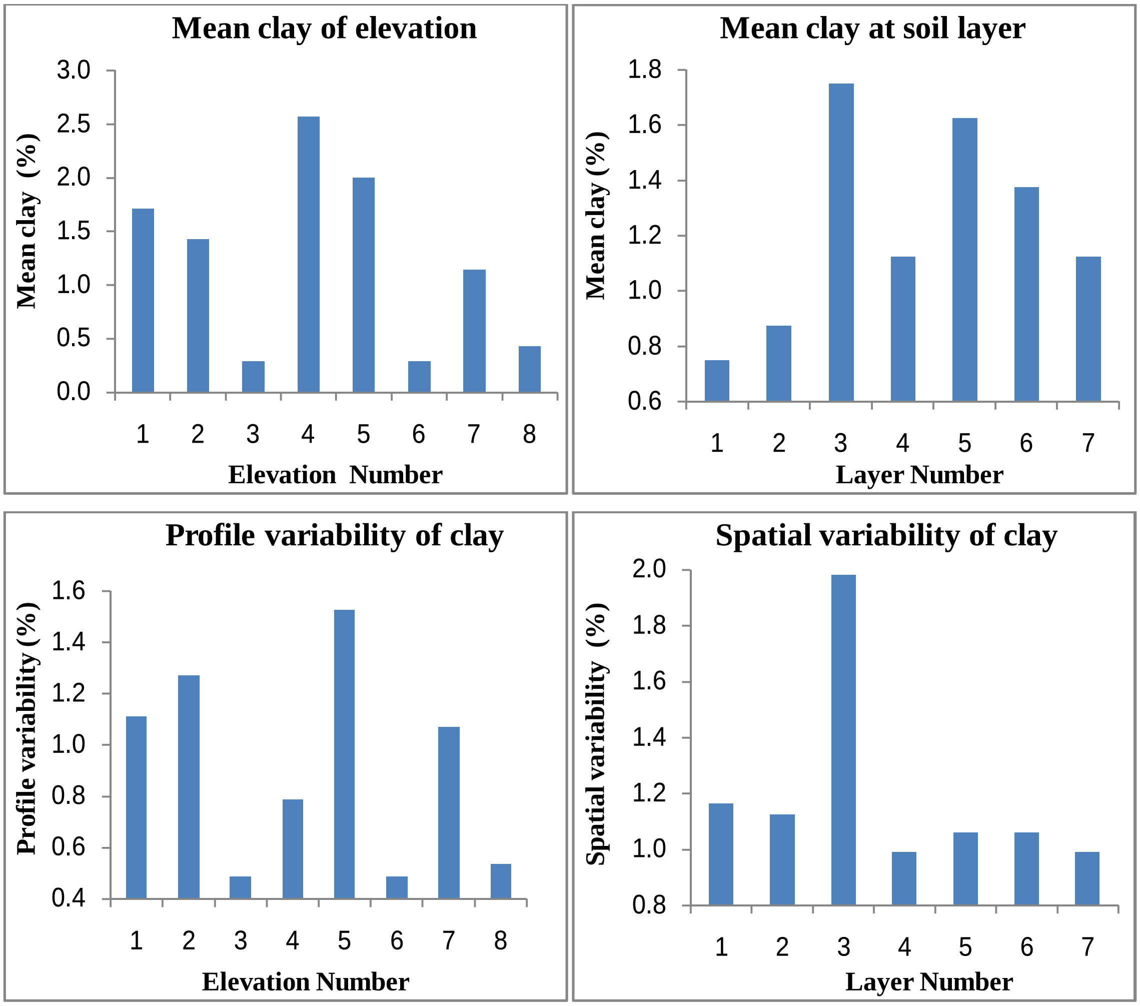


Figure 6.15: Different variables of clay

The bulk density was then taken into consideration for the calculation of different variables. Mean bulk density of the elevation was high in the second elevation and low in the fourth elevation and in other remaining elevations, not much variation was found. Mean bulk density at the layer was maximum in first layer and minimum in sixth layer when compared to other layers. More profile variability was observed in first layer, minimum in second layer and in other remaining layers small variations were found. The spatial variability was in the increasing mode from first to fourth layer, but it decreased in the fifth layer, again increased in the sixth layer and decreased in seventh layer. The different variables of bulk density are shown in the Figure 6.16.

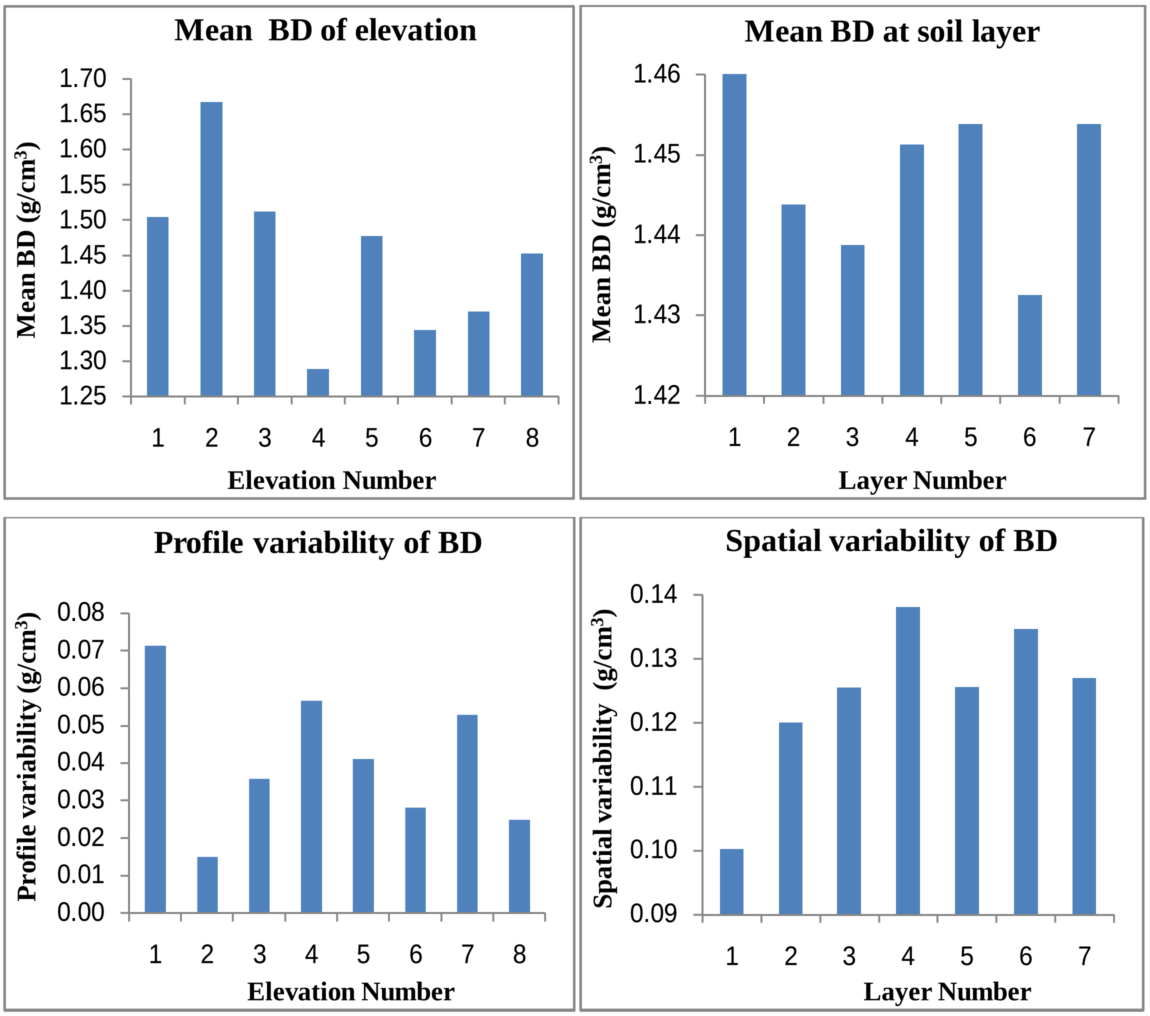


Figure 6.16: Different variables of bulk density

The present study was then taken up the analysis of different variables of organic matter content. Mean organic matter content of the elevation was computed and observed some variations in each elevation. It was maximum in the seventh elevation (4.02%) and minimum at the third and fourth elevations (1.3%). In other elevations, it was from 1.57% to 3.64%. In first and second layers, mean organic matter content was almost same, and then it decreased from third layer to seventh layer in the range of 2.82 to 1.31%. Higher profile variability was observed at the top elevations i.e. at 75 m, 105 m and 120 m elevations ranging from 1.59% to 2.55%. In other elevations profile variability was observed in the range of 0.54% to 0.79%. Spatial variability at layers was almost in the decreasing mode from fourth layer to last layer ranging from 1.69% to 0.3%. In first two layers, it was same about 2% and in the third layer 1.52%. The bar charts (Figure 6.17) are drawn for the different variables of the organic matter content.

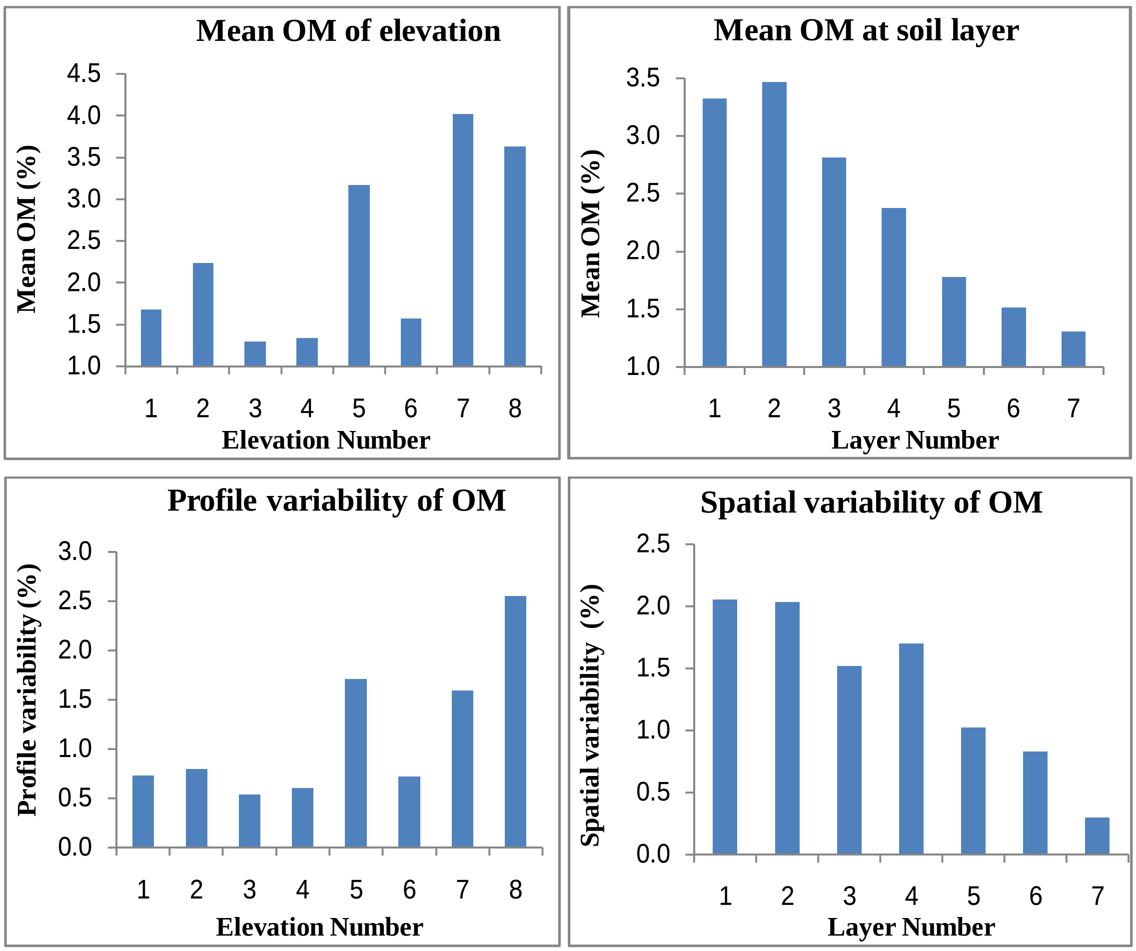


Figure 6.17: Different variables of organic matter content

Table 6.11 shows the spatial variability of physical properties of the forested hillslope soils at different depths. It was observed that, the spatial variability of sand increased from top to bottom depths about 6.3% to 10.18%. In silts also, same trend was observed. Spatial variation was from 5.52% to 7.82%, but in clay, spatial variation decreased from top depths to bottom depths i.e., 1.17% to 0.99%. In bulk density, spatial variation increased from top layer to bottom layer in the range of 0.1 to 0.13g/cm^3.

Spatial variation of organic matter content was relatively more in the top layer and it decreased in the bottom layers ranging from 2.05% to 0.3%. Spatial variability of soil properties is inherent in nature because of variations in soil parent materials and microclimate. However, geological, pedological and land use factors interact with each other on spatial and temporal scales. Duffera et al. (2007) and Iqbal et al. (2005), found that soil physical properties had moderate to strong spatial dependence, especially in topsoil. The range values varied considerably among the soil physical properties. The above findings indicate that environmental factors may lead to differences in spatial variability among soil physical properties.

Table 6.11: Spatial variability of physical properties of forested hillslope soils at various depths

Depth (cm)	Physical properties				
	Sand (%)	Silt (%)	Clay (%)	Bulk density (g/cm^3)	Organic matter content (%)
10	6.301	5.515	1.165	0.100	2.053
20	6.186	4.833	1.126	0.120	2.034
30	5.222	10.053	1.982	0.126	1.519
40	7.624	7.892	0.991	0.138	1.696
50	6.989	8.935	1.061	0.126	1.023
60	5.800	6.164	1.061	0.135	0.829
75	10.184	7.815	0.991	0.127	0.297

6.3.4 Analysis of different variables of hydraulic properties of forested hillslope soils

An analysis was carried out to understand how soil moisture retention data and saturated hydraulic conductivity vary across the different elevations within the forested hillslope area. In order to collect the more information on hydraulic properties of the forested hillslopes, this study investigated the different variables of the soil water retention curve and the saturated hydraulic conductivity properties of forest soils of the Pavanje river basin. The present study computed four different variables i.e., mean of the elevations, mean at soil layers, profile variability of the elevations and spatial variability at layers for soil water retention curve and saturated hydraulic conductivity. The bar charts are also drawn for all these variables of the soil water retention curve and saturated hydraulic conductivity.

At first, the present study considered the water retention at -33 kPa pressure head, (θ_{33}). Mean of the different elevations was found out using the eqn. (6.1). Only at the top two elevations, mean water retention was relatively high when compared to other elevations i.e. at 105 m elevation (26%) and 120 m elevation (23.57%). Some variations were observed in the other elevations ranging from 18.71% to 22.29%. Mean water retention at -33 kPa, was computed using eqn. (6.2) at different layers. It could be noticed that, from first layer to third layer, mean θ_{33} increased in the range of 21.5% to 22.38% and then it was almost same in other bottom layers, but in seventh layer i.e. at 75 cm depth, it was quite low about 20.13%.

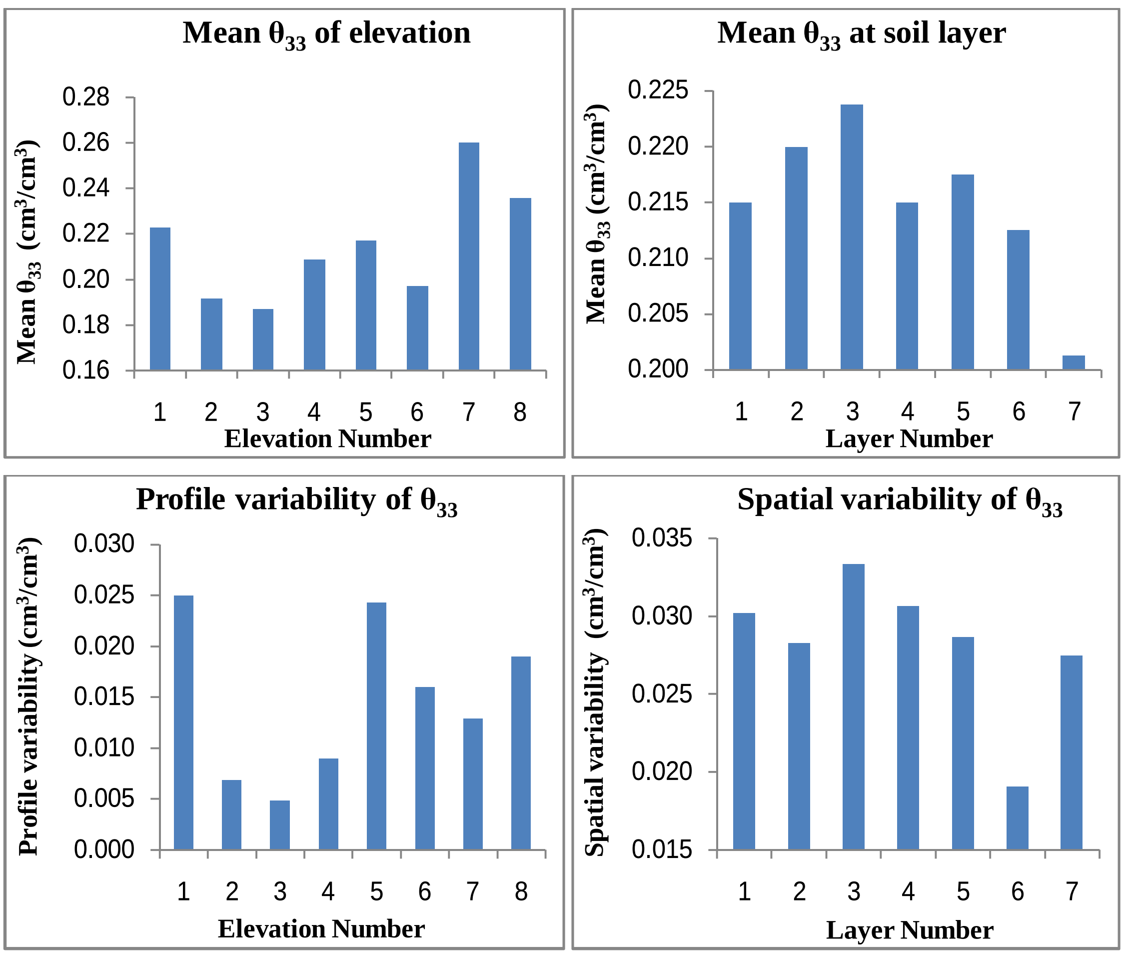


Figure 6.18: Different variables of θ_{33}

Higher profile variability was observed at the top, middle and bottom most elevations (30 m, 75 m and 120 m) in range of 1.9% to 2.5% and lowest in third elevation (0.49%). In the remaining elevations, minor differences were found. Spatial variability was less in sixth layer (1.91%) and increased in third elevation (3.34%). In other elevations, variations were found ranging from 2.74% to 3.07%. Figure 6.18 shows the different variables of water retention at -33 kPa.

This study was then taken up to determine the different variables of water retention at -100 kPa pressure head, (θ_{100}). Mean water retention at -100 kPa was computed for different elevations. It was more at the top two elevations i.e. at 105 m and 120 m about 20.43% and 19.86% respectively, minimum in the third elevation (13.14%) and some differences were found in other elevations ranging from 14.86% to 18.14%.

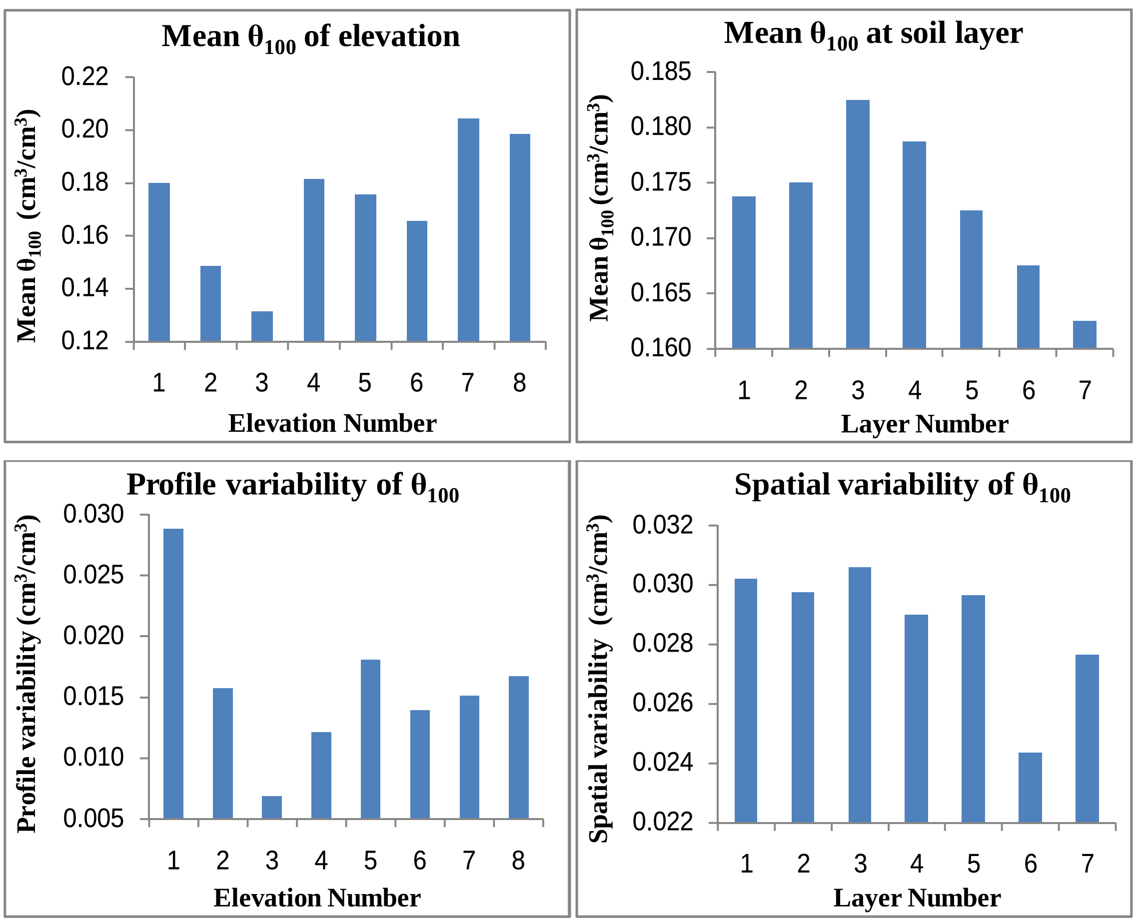


Figure 6.19: Different variables of θ_{100}

Mean θ_{100} at layers was then computed; it increased from first layer to third layer (17% to 18%) and then it decreased from 18% to16% in the bottom layers. Profile variability of 2.88% was observed in first elevation (at 30 m) and attained minimum (0.69%) in the third elevation. In other elevations, small differences were found ranging from 1.21% to 1.81%. Spatial variation was almost same in all the layers (3%), quite low in the sixth layer (2.43%) and more in the third layer (3.06%). Figure 6.19 shows the different variables of water retention at -100 kPa.

Water retention at -300 kPa pressure head, (θ_{300}) was then taken into consideration and calculated the different variables; bar charts are drawn for the different variables as shown in Figure 6.20. Mean water retention was higher at the top two elevations i.e., at seventh and eighth elevations (16.71 and 16.57%) respectively.

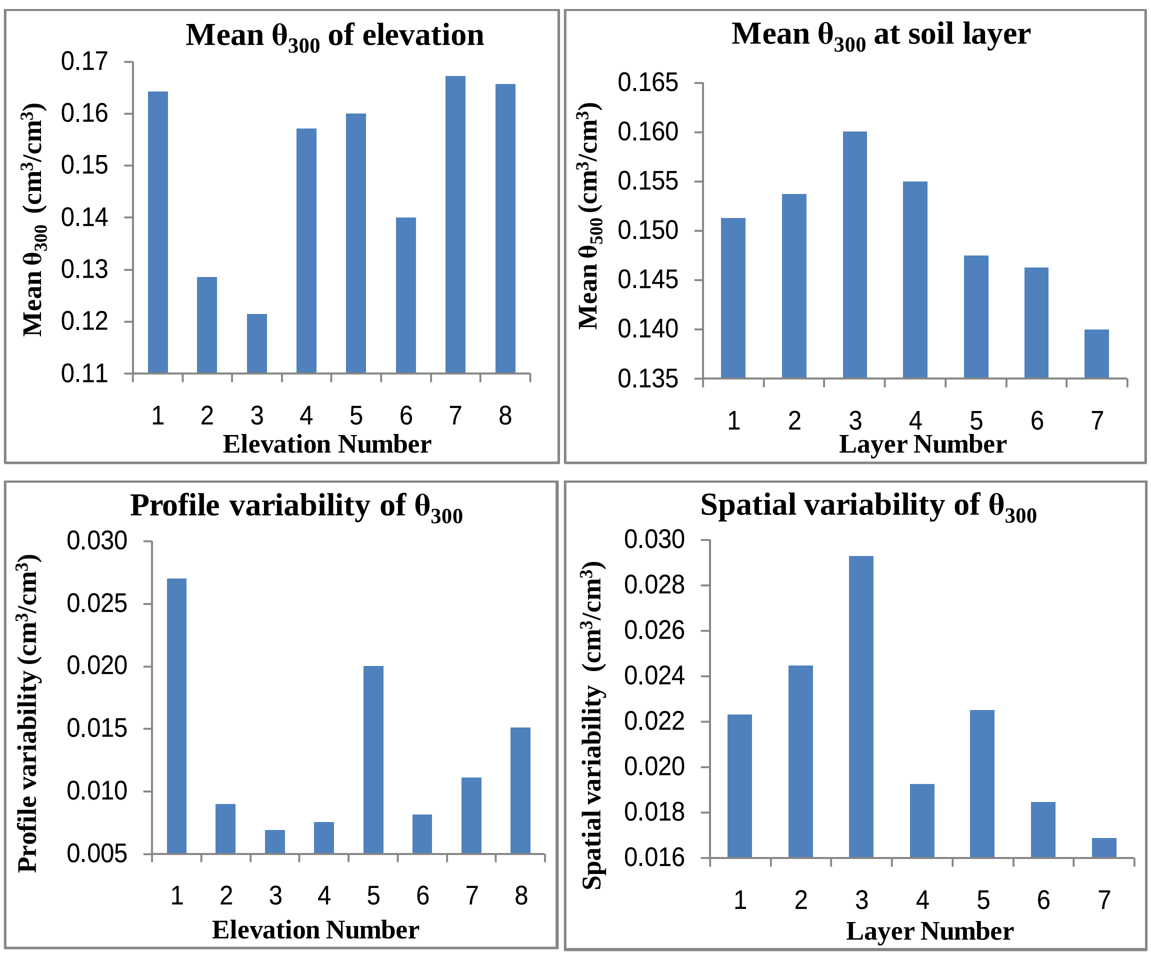


Figure 6.20: Different variables of θ_{300}

Even in the first elevation i.e. at bottom most elevation, mean water retention was quite more (16.43%). In second and third elevations, it decreased and again increased in other elevations (15.71% to 16. 71%) except in sixth elevation, where it decreased to 14%. Mean θ_{300} at layers were found; it increased in the top layers i.e. from first layer to third layer in the range of 15.13% to 16% and then decreased from fourth layer to seventh layer in the range of 15.5% to 14%. High profile variation was observed in the first elevation (2.7%), and then it decreased in the other three elevations to 0.76%. Again in fifth elevation, it increased to 2% and then suddenly decreased to 0.82% in sixth elevation. From sixth elevation, mean water retention was once again increased from 0.82% to 1.51%. Some spatial variations were observed accross the layers. It was about 2.23% to 2.93% in the top layers and in the bottom layers, 1.69% to 2.25%.

The analysis was then carried out for the different variables of water retention at -500 kPa pressure head, (θ_{500}). Mean water retention at -500 kPa was comparatively less in the bottom elevations about 11% to 11.86% and increased in the top elevations (12.29% to 14.43%). Mean θ_{500} at different layers was then calculated; it was almost same in the top layers i.e., up to fourth layer (13%) and then decreased to 12% in the bottom layers. Profile variability was more in fifth elevation about 2.31%, in other elevations it was ranging from 0.58% to 1.38%. More spatial variability was observed in second layer, about 2.05% and then it decreased to 1.19% in the sixth layer. In first and last layers, spatial variability was almost same (1.6%). The bar charts are drawn for the different variables of water retention at -500 kPa as shown in Figure 6.21.

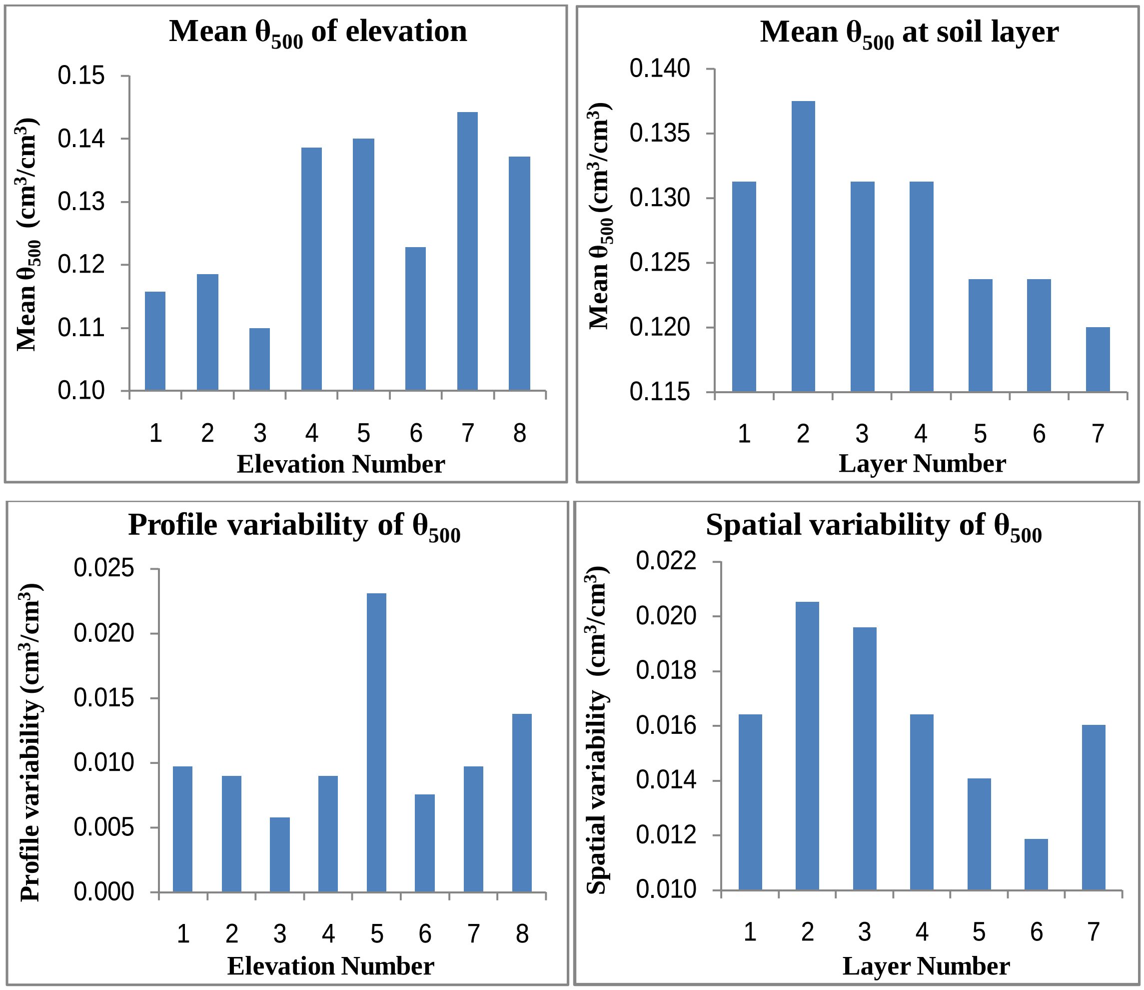


Figure 6.21: Different variables of θ_{500}

The analysis was then done for the different variables of water retention at -1000 kPa pressure head, (θ_{1000}). At first, mean water retention at -1000 kPa was determined for different elevations. It was noticed that, mean water retention at -1000 kPa was less at the bottom elevations i.e. at 30, 40 and 50 m ranging from 9.42% to 8.14%. It increased in the fourth elevation (12.71%) and in remaining elevations it was ranging from 10.57% to 11.86 %. Mean θ_{1000} at different layers was computed and observed that it was quite high in second layer about 11.25% compared to other layers. Then it was in the decreasing order from second layer to sixth layer (11.25% to 9.63%). More profile variability was observed in fifth elevation (2.2%) and less in fourth and sixth elevations ranging from 0.76% to 0.79%. In the remaining layers, it was almost same about 1.1 to 1.2%. 1.46%

spatial variability was observed in first layer and increased in third layer (2.47%). In other layers it was almost same. Figure 6.22 shows the different variables of water retention at -1000 kPa.

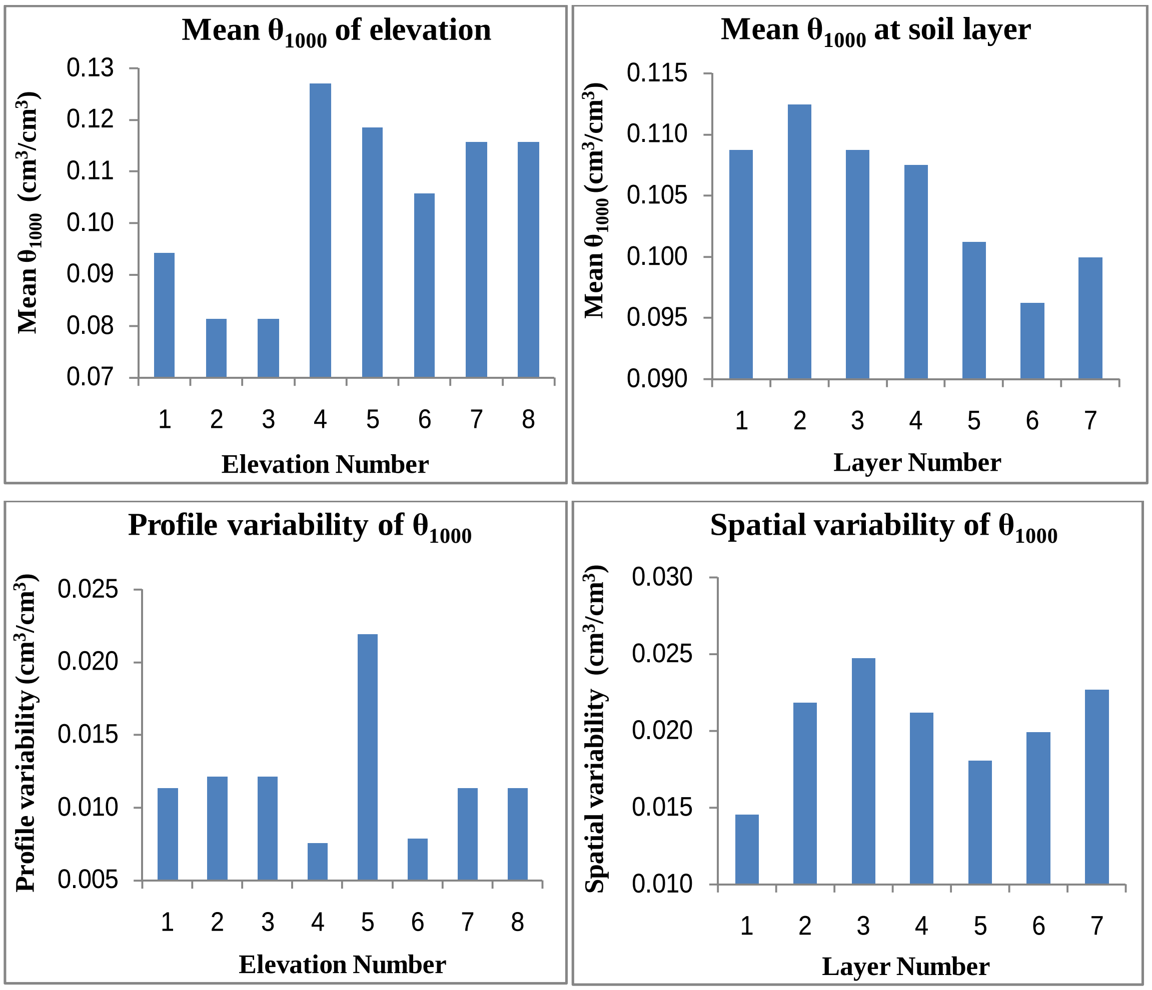


Figure 6.22: Different variables of θ_{1000}

The analysis was then continued with the study of different variables of water retention at -1500 kPa pressure head, (θ_{1500}). Mean water retention at -1500 kPa was lower in the bottom three elevations (7%), and then it drastically increased to 11.57% in the fourth elevation. In other top elevations, it was relatively less ranging from 8.71% to 10.14%. Then mean θ_{1500} at different layers were computed; it was almost same in the top four layers about 9.13% to 9.5%, and then it decreased to 8% in the other three bottom layers. More profile variability was observed in the fifth elevation about 1.77% and in other elevations small variations were found. Spatial variability was lower in the first layer (1.3%), and in other layers it was almost same about 1.91% to 2.13% except in the fifth layer. Figure 6.23 shows the different variables of water retention at -1500 kPa.

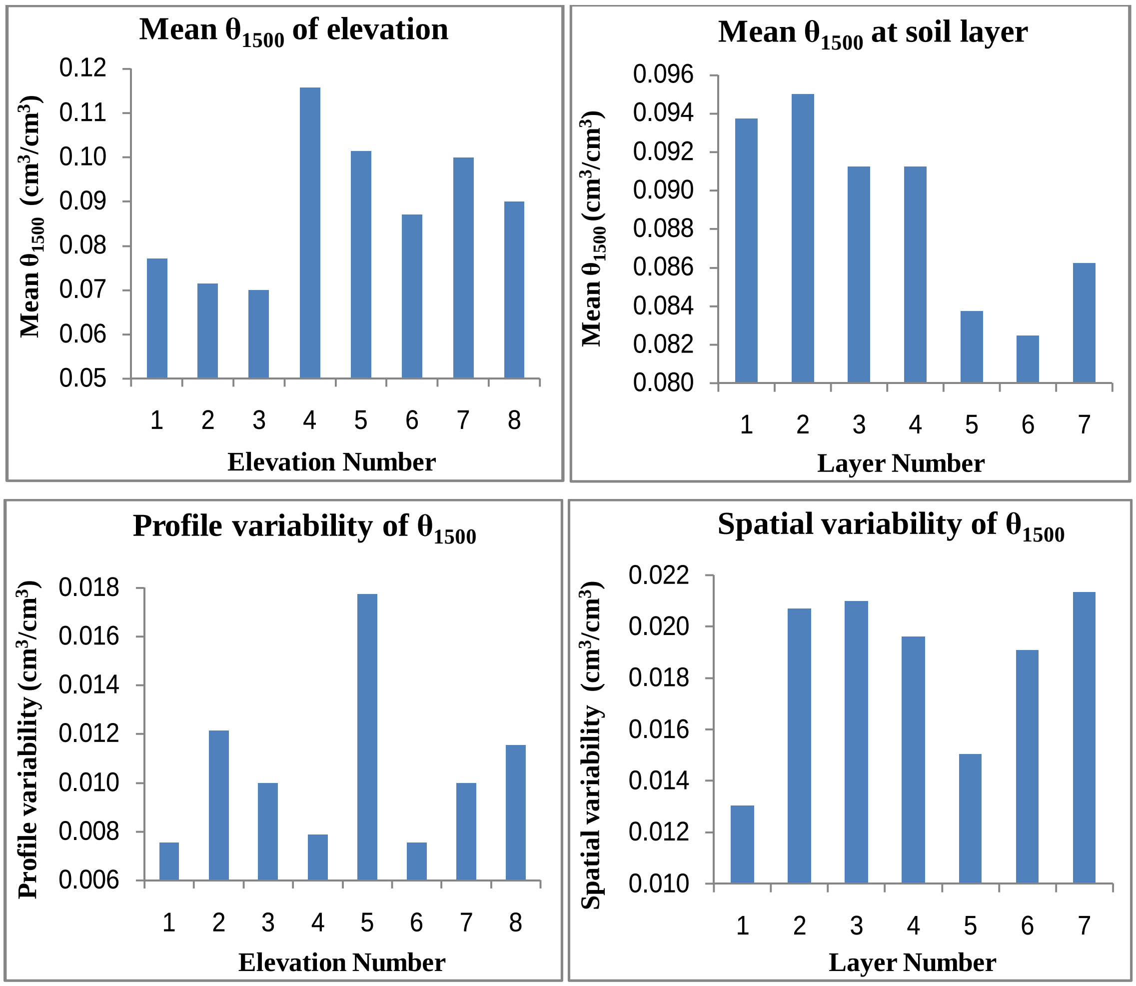


Figure 6.23: Different variables of θ_{1500}

The different variables of saturated hydraulic conductivity (k_s) were then computed and analyzed. Mean k_s at different elevation was found out and it was more in third elevation. In lower elevations i.e., from first elevation to third elevation, mean k_s was in increasing order, but then it decreased in fourth and fifth elevations, and again from fifth elevation it increased up to top most elevation. Mean k_s at different layers was then studied; it was less in first layer. In the remaining layers not considerable variations were found. Profile variability was quite more in third elevation and less in first elevation; in the other elevations it was almost same. Spatial variability was more in third layer, less in first layer and in other layers small variations were observed. The bar charts (Figure 6.24) are drawn for each variable in this case also.

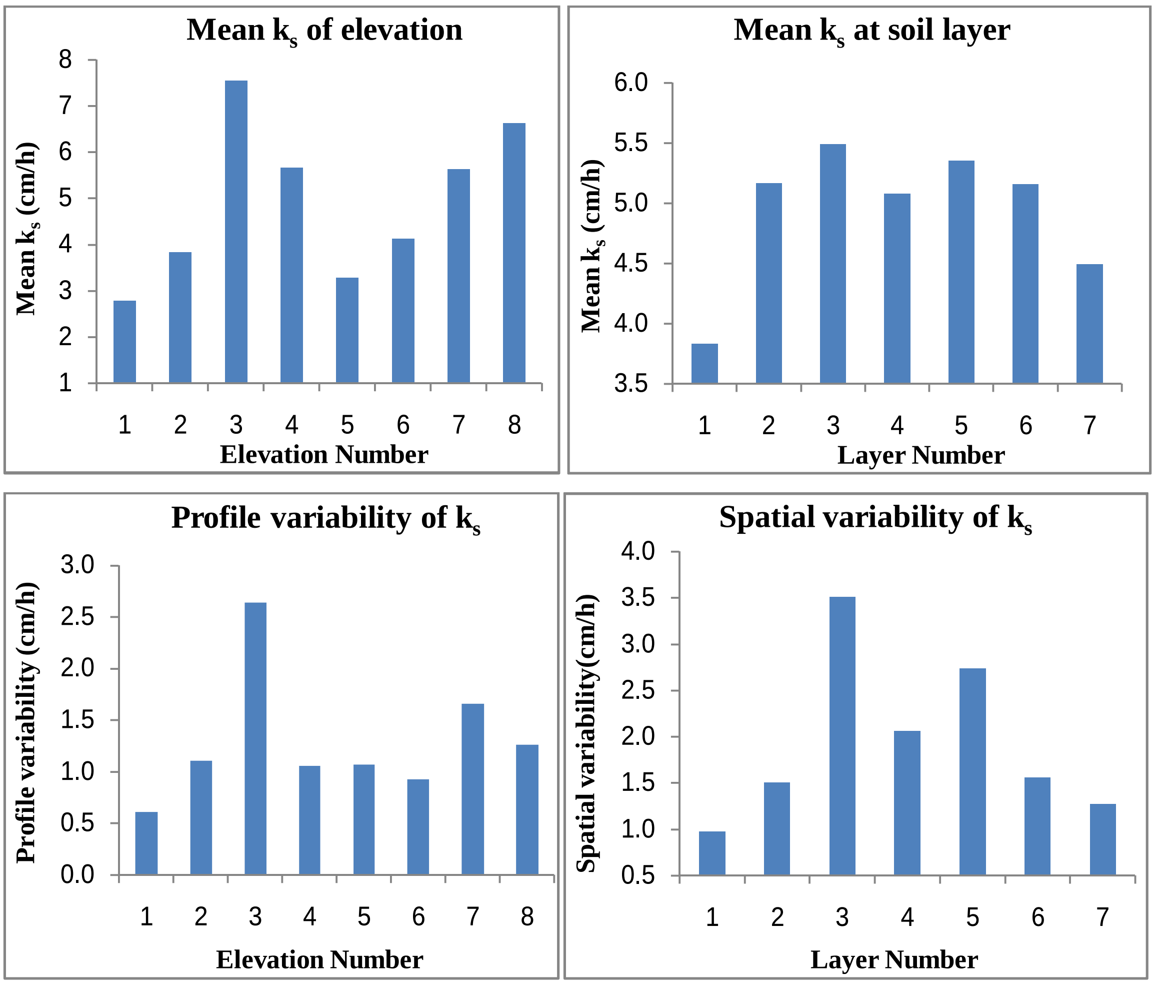


Figure 6.24: Different variables of saturated hydraulic conductivity (k_s)

It can be observed from Table 6.12 that, in the present case, forested hillslope soils show highest soil water retention of 3% at the top layer and 2.8% at the bottom most layer at -33 and -100 kPa pressure heads. Even at -300 kPa, water retention was higher at the top layers and was lower at the bottom layers varying from 2.2% to1.7%. The changes observed across the different layers may be due to continuous inflow of water from the upper zone to the lower zone after every rainfall events. This may be the possible explanation for higher soil moisture retention in the top layers than that of other bottom layers. At -500 kPa pressure head, soil water retention was almost same in all the depths. At -1000 and -1500 kPa, water retention was higher in the bottom layers than that of the top layers. As it has been reported by many researchers (Asano et al., 2002; Freer et al., 2002), the contribution of flow from bedrock to the soil may be another possible explanation for the persistence of soil water retention in the bottom layers of these hillslopes. Saturated hydraulic conductivity was more in the top layers around 3.54 cm/hr and then it decreased towards the bottom layers. The least saturated hydraulic conductivity was 1.44 cm/hr.

Table 6.12: Spatial variability of hydraulic properties of forested hillslope soils at various depths

	Hydraulic properties						
Depth (cm)	θ_{33} cm^3/cm^3	θ_{100} cm^3/cm^3	θ_{300} cm^3/cm^3	θ_{500} cm^3/cm^3	θ_{1000} cm^3/cm^3	θ_{1500} cm^3/cm^3	k_s cm/hr
10	0.030	0.030	0.022	0.016	0.015	0.013	3.54
20	0.028	0.029	0.025	0.021	0.022	0.021	3.20
30	0.033	0.031	0.029	0.019	0.025	0.021	2.92
40	0.031	0.029	0.019	0.016	0.021	0.019	3.00
50	0.029	0.029	0.023	0.014	0.018	0.015	1.44
60	0.019	0.024	0.019	0.012	0.02	0.019	1.75
75	0.028	0.028	0.017	0.016	0.023	0.021	2.14

Almost all the topsoils were found to belong to the sandy loam soil class. No significant differences in hydraulic properties were found in terms of pedologic units. The lowest dry bulk density value was obtained in forested soils with the highest organic matter content. Marshall et al. (2009) reported higher saturated hydraulic conductivity of soil beneath tree hedges than in agricultural fields, with a ratio of the both of about three. More stable soil structure and increased biological activity might explain the larger hydraulic conductivity in forest, permanent pasture or minimum tillage systems (Bodhinayake and Si, 2004). Stolte et al. (2003) reported that the permanent land use (forest, orchard, wasteland, and shrub) showed a greater heterogeneity of saturated hydraulic conductivity than the arable areas and the values were significantly higher in permanent land use than in cultivated areas, as in our study. This was probably due to more macropores, associated with the activity of fauna and roots in the permanent system than in arable land. Such changes in topsoil hydraulic properties are very important for hydrological processes such as surface runoff groundwater, and water quality. They modify the hydrological response in terms of water balance components and their annual temporal variability (Fohrer et al., 2005; Bormann et al., 2007).

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Introduction

This dissertation investigated soil hydraulic properties in the Pavanje river basin located in coastal region of Dakshina Kannada District, Karnataka State, India. The study involves laboratory measurement of soil hydraulic properties (soil water retention curve and saturated hydraulic conductivity) and their estimation by indirect methods. Major focus was given for the measurement and estimation of soil water retention curve for both agricultural and forest soils. This study also included the measurement of some physical properties, like particle size distribution, bulk density, porosity, and organic matter content. The runoff estimation, uncertainty analysis and spatial variability of physical and hydraulic properties of soils were also presented in the thesis.

Major conclusions drawn from results obtained are presented herein. Also, limitations of the study and scope for future research work are briefed.

7.2 Summary of work

An understanding of hydrological processes is essential for assessing water resources as well as the changes to the resource caused by changes in the land use or climate. There is a relative abundance of literature dealing with the theory and application of soil hydraulic properties in different places of the world, but there are no systematic studies that give detailed description of soil hydraulic properties on Pavanje river basin soils. Research carried out on an effective representation of water retention curves for soils from the coastal region of Karnataka, India is not available in the literature. This article is the first study in the region under consideration. This information is needed for improving and understanding of the effects of soil management or land use on soil profile hydrology.

This study was intended to help fill this gap by measuring soil hydraulic properties of these soils and utilize the results and compare the results to validate their applicability. The soils from two different land covers were successfully characterized thereby providing the basic information needed to fulfill the requirements for developing pedotransfer functions.

7.2.1 Measurement of soil water retention curve

Samples collected from the field were subjected to the laboratory measurements for physical properties like particle size distributions, bulk density, organic matter content and hydraulic properties like moisture retention curves and saturated hydraulic conductivity. In agricultural site, five pits were dug out and samples were collected at different depths, i.e., at 10, 20, 30, 50, 70, 90, 110, 130 and 150 cm. For forested hilllslope soils, pits were dug out at different elevations distributed from the crest to the footslope. At each elevation, seven different depths with the same thickness were considered i.e., at 10, 20, 30, 40, 50, 60 and 75 cm. Six pressure heads (-33, -100, -300, -500, -1000 and -1500 kPa) were considered for each soil sample and obtained the moisture retention data for all these soil samples. Totally hundred and six samples of soil water retention data were analyzed in this study. The soil water retention characteristics were successfully determined using the pressure plate apparatus for both agricultural and forest soils. It was observed that most of the soils in the agricultural land were sandy loam textured. Only in the first and fourth pit, it was loamy sand. In rest of the pits, the soils were sandy loam textured; only at two depths in second site, it was silty loam textured. The shapes of the curves for the different depths were fairly similar.

In forested hillslope soils, in most of the elevations, the soils were sandy loam textured. Only at 40 m and 90 m elevations, the soils were loamy sands, and at 50 m elevations only two soil samples were sand and rest of all were loamy sand. There was not much difference found in soils of different depths in the same pits. The water retention characteristics for both soils were generally well defined with little variability between the two land covers. The main variations were due to texture differences between the horizons.

7.2.2 Estimation of soil water retention curve

Direct measurement is the best and accurate way to obtain soil parameters that are needed for hydrologic models. However, direct measurements are feasible for field scale and small scale applications that need limited number of measurements. With large scale (watershed or basin scale) applications, direct measurements are time consuming and expensive. The focus of the research described in this document was to characterize the hydraulic properties using laboratory and indirect estimation techniques. The soil water retention curve was determined by Pressure plate apparatus and then van Genuchten and Brooks-Corey models were fitted to these measured water retention data using RETC curve fitting program. The RETC program is limited to non-unique results which contribute to model uncertainty. Model uncertainty increases with the number of unknown parameters and less number of measured data points. For this reason, careful interpretation should be used in curve fitting process. The measured water retention data corresponded well with fitted curve by the van Genuchten and Brooks-Corey model.

PTFs are useful tools for assessing the static and dynamic soil quality indicators. Point and parametric PTFs have been developed for Pavanje river basin soils to predict the soil water retention curve from particle size distribution, bulk density, porosity and organic matter content using multiple linear regression techniques. Different types of input combinations were considered and found the coefficient of determination. The PTFs predicted water content at different potentials with reasonable accuracy. But difficulty has been encountered when relating the shape parameters of the van Genuchten and Brooks-Corey models to basic soil properties, because of over-parameterization. Moderate to weak correlations were identified in the parameters of the van Genuchten and Brooks-Corey models, which may be due to measurement error and uncertainty. This can be countered by using non linear regression equations as discussed in the previous chapters. Point and parametric PTFs using multiple non linear regressions predicted water content at particular pressure heads and parameters of van Genuchten and Brooks-Corey models respectively better than multiple linear regressions. Comparison of point and parametric PTFs has been done for both calibration and validation data set using some statistical evaluation criteria. These statistical criteria included the coefficient of determination (R^2), root mean square error (RMSE), mean error (ME) and Akaike Information Criteria (AIC). The performance of point PTFs was relatively better than the performance of the parametric PTFs for both agricultural and forest soils. The developed PTFs were then evaluated with some published PTFs from the literature. The possibility of using geometric mean and geometric standard deviation of particle diameters instead of soil particle size distribution to derive pedotransfer functions were also investigated.

7.2.3 Pedotransfer functions for saturated hydraulic conductivity

PTFs have been developed to estimate the saturated hydraulic conductivity for both agricultural and forest soils. The saturated hydraulic conductivity was measured in the laboratory by the variable falling head method using Permeameter. Most of the soils in the agricultural and forested areas of the Pavanje river basin were sandy loam and loamy sand textured. This study had taken up to develop the separate PTFs for sandy loam and loamy sand textured soils for both agricultural and forest soils. Five statistical criteria were used to evaluate the performance of estimated saturated hydraulic conductivity, i.e., R^2, RMSE, ME, GMER and GSDER. The developed PTFs showed quantitative results for the estimation of saturated hydraulic conductivity, for both agricultural and forested hillslope soils.

In addition to this, an empirical relationship was developed to predict soil water retention curve from saturated hydraulic conductivity for sandy loam and loamy sand textured soils of both agricultural and forested hillslopes. Model predictions were compared to results obtained using direct methods and finally an uncertainty analysis was conducted to determine model requirements for achieving optimum results and to examine the impact of measurement error on the predictions. The runoff was also predicted for the forested hillslope soils from Green and Ampt infiltration method using measured values of saturated hydraulic conductivity, residual water content, porosity and water content at field capacity values.

7.2.4 Spatial variability of physical and hydraulic properties of soils

An understanding of soil variability is necessary to characterize the linkages between a region's hydrology, ecology and physiography. Spatial variability of physical and hydraulic properties of the soil is quite significant for heterogeneous unsaturated zone environments. Spatial variability was examined for different physical (particle size distribution, bulk density and organic matter content) and hydraulic properties (soil water retention data and saturated hydraulic conductivity) at different depths for agricultural and forested hillslope soil profiles. In order to gain a better understanding of soil variations in relation to land use and topography, the present study used correlation analysis to analyze the soil properties obtained from two different land covers. The aim was to characterize the different variables of soil properties i.e., mean of each soil property of the site, mean of each soil property at layers, profile variability of each soil property and spatial variability of each soil property at layers across agricultural and forested hillslope soils.

7.3 Conclusion

Based on the results obtained, conclusions can be summarized as follows:

- Majority of the soil deposits in the agricultural land of Pavanje river basin are sandy loam textured, with high sand contents. Bulk density increases and the organic matter content decreases with soil depth. The sampled soils are more or less homogeneous throughout their profiles.
- The soils of the forested hillslopes of Pavanje river basin has less sand content and more organic matter content than the agricultural soils of the same region. Porosity is marginally higher in forested soils than that of agricultural soils. Water retention capacity is more in the forest soils.
- There is no large difference among the three methods (point, vG model and B-C model) in predicting water retention curves, but the point based method is slightly

superior to the parametric method of PTF development for both agricultural and forested hillslopes of this region.

- From the experimentation and validation of this study, it is once again proved that the PTFs are useful tools for estimating the soil water retention curve. When comparing the results of the developed PTFs with the published PTFs taken from literature, the present study concludes that, the PTFs generated from soils of other geographical regions are not adequate for estimating the water retention curve for the soils of this region located in India. The developed PTFs could be used in predicting soil water retention curves for loamy sand and sandy loam textured soils of this region.
- From the results of statistical evaluation criteria carried out in this work, it is observed that the values of estimated saturated hydraulic conductivity are in excellent agreement with the measured saturated hydraulic conductivity for both calibration and validation sets. So it could be concluded that, PTFs are powerful tools to estimate saturated hydraulic conductivity.
- PTFs estimated both water retention curve and saturated hydraulic conductivity from easily measurable soil properties such as particle size distribution, bulk density, porosity and organic matter content. So they have the clear advantage of being relatively inexpensive and easy to use. The results obtained from the prediction of soil moisture retention curve from saturated hydraulic conductivity, shows that the developed relationship are reasonably useful to get the soil moisture retention curve for the soils of agricultural and forested hillslopes of the surrounding region also.
- In agricultural soil, the spatial variability of sand and silt are quite high in the subsurface layers than surface layers, but in clay, spatial variation is low in the subsurface layer. Bulk density is not much varied between the layers. Spatial variation of organic matter content is high in the top layers and it decreases towards the bottom layers. Spatial variability of water retention at all the different pressure head is low at the top layers, and increases towards the bottom layers. Spatial variability of saturated hydraulic conductivity is almost same in the top layers, but more in the bottom layers of agricultural soil.

- In forested hillslope soils, the spatial variability of sand and silt increases from top to bottom depths, but for clay, spatial variation decreases from top to bottom depths. The spatial variation of bulk density increases from top layer to bottom layer and spatial variation of organic matter content is more in the top layer and it decreases towards the bottom layers. The spatial variation of soil water retention at -33, -100 and -300 kPa pressure head in the forested hillslope soils is relatively high in the top layer and lowers at the bottom most layers. Spatial variation of saturated hydraulic conductivity is also similar to that of soil water retention.

7.4 Limitations

Some of the limitations of the study are presented as follows:

- Determining the water retention curve in the laboratory has certain weaknesses. Laboratory method for determining the water retention curve which was used, do not take the macropores of the soil sample into consideration.
- It may be suggested that hydraulic properties estimated through PTFs are useful for simulating large areas, but may not be accurate enough to predict the properties for site-specific purposes. On a coarse scale, the PTFs can provide useful information. When using the function for site-specific prediction, the results may have some uncertainties.
- The developed PTFs could be used for the prediction of soil water retention curve for the Pavanje river basin soils of same texture, while for using other soil textures, PTFs may be questionable.

7.5 Future scope of work

The scope for future research work and recommendations are presented below:

- Currently there are no large data sets with standard measurements on soil water retention curves for the Pavanje river basin soils, thus further investigation using standardized measurements over a region with additional information will be valuable.

The present work was limited to smaller area, so this could be continued for the entire basin or entire coastal belt lying in this region.

- In the present study, multiple regression technique was used to develop the pedotransfer functions. The same analysis could be done with the other alternative methods like, artificial neural network, genetic algorithm and regression trees.
- Future work could be done to test the application of developed pedotransfer functions in predicting soil-water balance, crop production, and spatial variability of soil hydraulic properties in the field. Traditionally, soil-water-plant models have been used to predict an average soil-water balance or crop yield. With the recognition of spatial variability and the innovation of precision farming, simulation models can be used to predict site-specific soil-water status and crop yield.
- Future work can focus on tackling issues such as (a) better mathematical expressions for PTF equations, (b) the most influential soil basic parameters to be used as PTF inputs, (c) finding alternative methods to derive or fit the PTFs. An optimum pedotransfer system is envisaged to provide the best estimates of soil properties from the available information as well as to report the associated uncertainties.
- It is suggested that, extensive measurements of water retention curves in the laboratory and field are necessary for detailed analysis, comparison and evaluation. Field and laboratory studies should continually be carried out, in order to quantitatively assess the field description of soil structure and improve on understanding soil water retention curve. Although similar hydraulic properties are observed between undisturbed and disturbed soil samples, it is unlikely that natural structures are captured or preserved during sample collection.

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