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VARIATION OF SOIL MOISTURE CHARACTERISTICS IN A PART OF HINDON RIVER CATCHMENT

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PREFACE

Knowledge of the physics of soil water movement is crucial to the solution of 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. Convenient and reliable techniques for estimating the soil hydraulic properties are required for prediction of soil water flow.

This report entitled "*Variation of Soil Moisture Characteristics in a part of Hindon River Catchment*" is a part of the research activities of 'Ground Water Assessment' division of the Institute. The purpose of this study is to determine the soil moisture characteristics (particle size distribution, hydraulic conductivity, and soil moisture retention curve) in a part of Hindon river catchment and to study their variation along the Hindon river in its upstream reach. The study has been carried out by Mr. C. P. Kumar, Scientist 'E' in collaboration with the staff of Ground Water Assessment division and Drainage division.

(S. M. Seth)
Director

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ABSTRACT

Mathematical models of hydrologic and agricultural systems require knowledge of the relationships between soil moisture content (θ), soil water pressure (h) and unsaturated hydraulic conductivity (K). Hence, a sustained research effort towards the parameterisation of K(h) and h(θ) has resulted in the development of several laboratory, field and theoretical methods.

This study aims at field and laboratory determination of soil moisture characteristics in a part of Hindon river catchment and to study their variation along the Hindon river in its upstream reach. A total of 38 soil samples were collected from 14 sites in Aurangabad, Kamalpur, Budhakhera, Gagalheri and Dudhil Bukhara comprising around 24 km reach, upstream of Hindon river. Field determination of saturated hydraulic conductivity was made at 8 locations through Guelph Permeameter. Extensive laboratory measurements were made for each soil sample collected. Soil texture was determined through sieve analysis and laser diffraction technique. Porosity was obtained for each soil sample. Saturated hydraulic conductivity was measured through ICW Permeameter in the laboratory. Retention curve was obtained through pressure plate apparatus. Unsaturated hydraulic conductivity function was indirectly derived through van Genuchten retention parameters. The report presents a thorough soil investigation results for the uppermost part of Hindon river.

1.0 INTRODUCTION

The water movements in the unsaturated zone, together with the water holding capacity of this zone, are very important for the water demand of the vegetation, as well as for the recharge of the ground water storage. A fair description of the flow in the unsaturated zone is crucial for predictions of the movement of pollutants into ground water aquifers.

For analytical studies on soil moisture regime, critical review and accurate assessment of the different controlling factors is necessary. The controlling factors of soil moisture may be classified under two main groups viz. climatic factors and soil factors. Climatic factors include precipitation data containing rainfall intensity, storm duration, interstorm period, temperature of soil surface, relative humidity, radiation, evaporation, and evapotranspiration. The soil factors include soil matric potential and water content relationship, hydraulic conductivity and water content relationship of the soil, saturated hydraulic conductivity, and effective medium porosity. Besides these factors, the information about depth to water table is also required.

Quantitative measurements of soil physical properties are required for many purposes. In the area of land management, one may wish to know whether a particular management scheme will increase or decrease infiltration, runoff, erosion, leaching, salinization etc. We may need to predict material transport, such as the depth to a wetting front, position of a seepage face, time of arrival of a tracer plume, cumulative evaporation etc.

The soil water movement may be modelled mathematically from bases provided by:

(a) the soil moisture characteristic,

(b) equations describing the volume flux of water and water vapour in response to potential gradients, and

(c) the law of continuity of matter and additionally, in the case of evaporation, the law of continuity of heat energy.

The water in soil is dynamic. It is constantly moving from one place to another in response to forces that are created by percolation, evaporation, irrigation, rainfall, plant use, and temperature. Water applied to the surface of the land may move into a soil at one rate in one place and a greatly different rate in an adjacent location. This differential infiltration rate may be attributed to differences in permeability and openness of the surface, undulations in the surface that are caused by uneven levelling or by tillage operations, chemical or mineralogical differences that might occur in localized areas, or differences in compaction and plant cover. As a result of the constant movement of water, there are likely to be differences in the amount and energy condition of water in contiguous volumes of soil. In addition, plants remove water at different rates from adjacent soil areas because of differences in intensity of crop cover and differences in the rates with which water can adjust in the soil.

Any measurement of soil water in the field depends upon sampling at a given location, both in area and depth of soil profile, at a given time or times. These samples are then used to estimate the water condition of the entire area. Many methods are sufficiently accurate to measure the water condition in a given sample at a given time. Difficulty comes when one tries to apply these conditions to a large area or at a different time. In reality, the water condition measured is a transient one in a system that is continuously changing in three-dimensional space and time and the situation would likely be different at any other location at the same time, or at the same location at a different time.

In order to evaluate completely the condition of water in soil, one must know the energy of the water, the amount of water in the soil, and how these conditions change in space and time. This requires a complete understanding of water movement and flow in soils. Such complete evaluations of soil water conditions are not easily made, and are available only under controlled laboratory conditions.

There are two general reasons for measuring soil water. One is to determine the moisture content of a soil, that is, the amount of water contained in a unit mass or volume of soil. This information is necessary to calculate the water needed to restore the soil water in the root zone of the crop. The second reason is to determine the magnitude of the soil water potential, which is the negative of the work that must be done to remove a unit amount of the most loosely held water.

Plant response to water appears to be more closely related to the water potential than any other single factor, although the velocity of movement of water to the absorbing root is an important consideration. This movement rate is strongly related to the potential. Because of this relation, one desires to know the potential of the soil water whenever he is concerned about plant response. Knowledge of the soil water potential is also desired by irrigators since it indicates directly when water should be applied.

Prediction of infiltration is important in the design of irrigation areas and for the estimation of runoff in catchment management studies. Many predictive models exist and various methods have been employed in measuring infiltration behaviour. The proper evaluation of infiltration behaviour depends on knowledge of the hydrological soil properties.

Saturated hydraulic conductivity and unsaturated hydraulic conductivity are related to the degree of resistance from soil particles when water flows in pores. These resistances are affected by the forms, sizes, branchings, jointings, and tortuosities of pores as well as viscosity of water. In addition, unsaturated hydraulic conductivity is affected markedly by the volumetric water content of soil.

The relation between matric potential and volumetric water content in a soil is termed as the soil moisture characteristic curve because the curve is characteristic of each soil. The differences among soil moisture characteristic curves are attributed primarily to the differences in pore size distribution among soils. These curves are sensitive to the changes in bulk densities and disturbances of soil structures. In addition, the curves generally show hysteresis according to the wetting or drying of soils.

In the present study, field and laboratory investigations have been carried out to determine the soil characteristics (particle size distribution, hydraulic conductivity, and soil moisture retention curve) at various locations along the uppermost part of Hindon river.

2.0 STUDY AREA

The study area is a part of the Gangetic plain, which has been divided into three belts: Bhabhar belt, Terai belt and Alluvial plain. In the foothill region of the Himalaya, the hills are fringed towards the south by talus fans. The upper portion of talus fans is composed of rock fragments, gravel and soil which support thick forests. This zone, known as the Bhabhar, has a thickness of about 200 m. The Bhabhar formation is chiefly made up of unconsolidated boulders. The zone is characterized by steep ground slope and deep water table lying between 5 to 37 m depths below the ground surface. The southern limit of the Bhabhar generally forms a spring line that also defines the northern limit of the Terai tract.

The Terai tract lies immediately south of the Bhabhar zone. It is a transition zone between the Bhabhar and the Alluvial plain. It is composed of alternate layers of clay and sand often having marshy conditions covered with grass and thick forest. In the Terai, ground slope varies from mild to steep and the water table is at very shallow depth. The width of the belt varies from 5.5 to 8 km. The study area lies in the Alluvial plain, which is almost a level country with gentle slope from NW to SE. Lithologically, the Gangetic plain has thick alluvial deposits consisting of unconsolidated sands, clay and kankar.

The study area lies in the upper part of Hindon basin, bounded between latitude $29^{o}55'$ and $30^{o}6'$ N and longitude $77^{o}35'$ and $77^{o}46'$ E (figure 1). The area is located within Saharanpur district of Uttar Pradesh (India) and included in the Survey of India topographic sheets 53 F/12, 53 F/16, 53 G/9 and 53 G/13 in the scale of 1:50,000. The investigated area covers a reach of around 24 km along the Hindon river in its upstream reach. The study is confined to a stretch of Hindon river in between Aurangabad and Dudhil Bukhara villages.

The climate in the Hindon basin is moderate to subtropical monsoon type. Thus, there exists a well-marked seasonal variation in precipitation, temperature, and relative humidity. The average annual monsoon rainfall in Saharanpur town is 886 mm and the temperature variation is from $8^{o}C$ in winter to $40^{o}C$ in summer. The drainage of the area comprises of the Hindon river, which is an ephemeral river flowing towards south. The river finally meets the Yamuna river (a tributary to the river Ganges) near Ghaziabad (latitude $28^{o}28'$N) outside the study area.

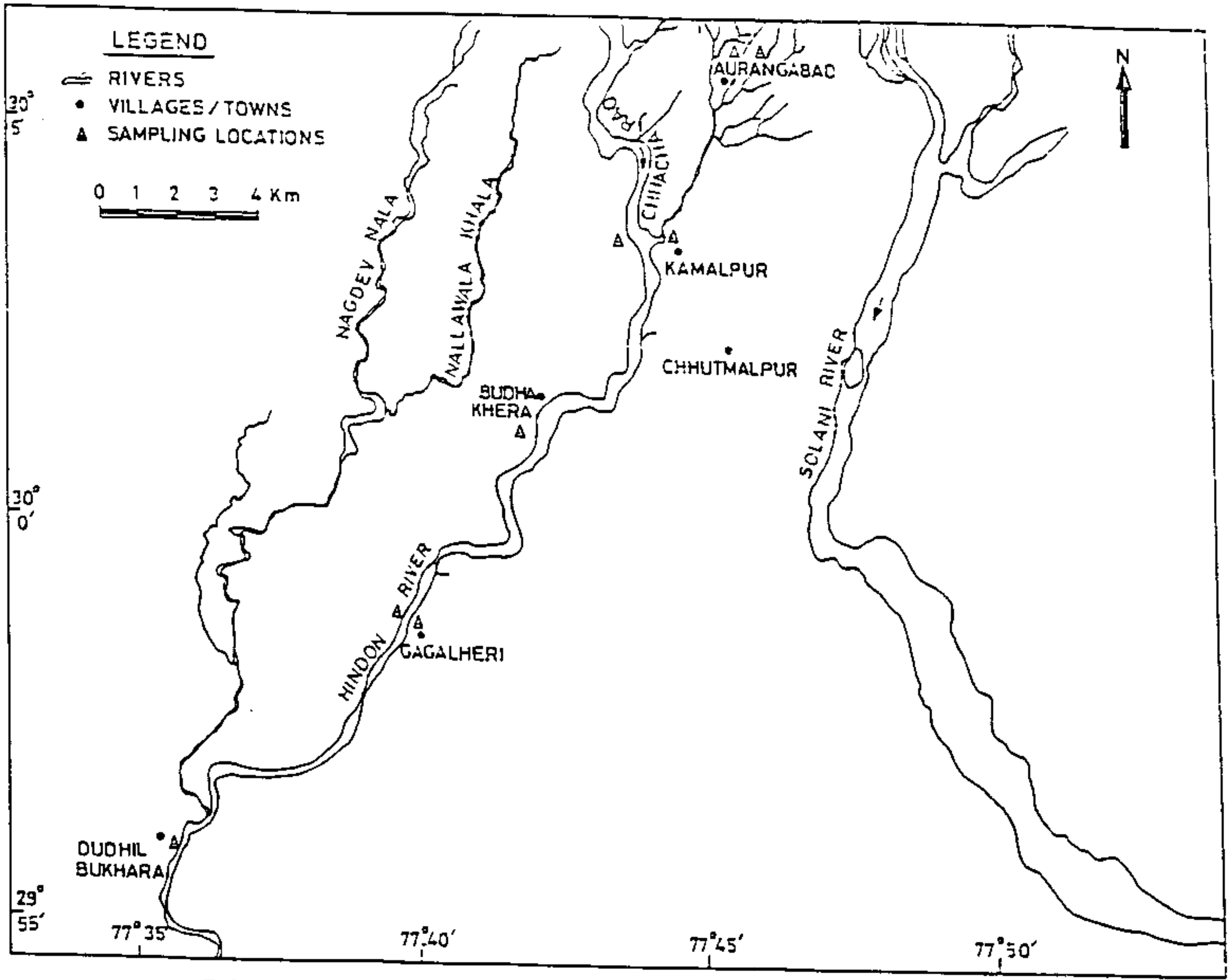

FIG.1: LOCATION MAP OF THE STUDY AREA

The soil is alluvial type deposited by Hindon river system. Lithologically, it mainly consists of clay, silt and fine to coarse sand. The soils are very fertile for growing wheat, sugarcane and vegetables. However, along the sandy river course, fruit orchards are also common.

3.0 METHODOLOGY

3.1 General

The general soil physical properties are those which govern the transport and storage of energy, momentum and mass. In many cases, soil water properties govern gas, solute and heat transport in the soil. Fundamental soil water properties include volumetric water content, soil water flux density, soil water potential and hydraulic conductivity while derived properties are the soil water diffusivity, sorptivity and macroscopic capillary length.

It is now recognised that laboratory tests can not fully duplicate the field conditions. However, routine use of field methods is often inhibited by cost considerations, especially when large areas are to be characterised for their hydraulic properties. This has led to the development of theoretical methods for estimation of hydraulic conductivity from basic soil properties which may be either physical and chemical properties (e.g. percentages of clay, silt, sand, organic matter etc.) or the soil moisture characteristic, $h(\theta)$.

3.2 Particle Size Distribution

Particle size distribution of soils and sediments is important to many of their properties. Whether soils consist of sand, clay, or some mixture of those and silt, the size distribution affects the movement and retention of water, consistency and tilth, and capacity to shrink and swell etc. Moreover, particle size distribution is influenced little by tillage or other manipulation unless it is drastic. Most soil classification systems therefore use particle size distribution as one criterion.

Particle size distribution of soil samples is determined partly by sieving and partly by sedimentation. The sand fractions are separated from the silt and clay by sieving, which is also used to determine proportions of the size fractions of sand. The silt and clay fractions are determined by sedimentation, measurements being made with either a pipette or hydrometer.

One or more pretreatments are normally used for particle size analysis, also known as mechanical analysis. For samples containing organic matter, some treatment to destroy it is usually a first step. Samples must also be treated with compounds such as sodium metaphosphate to effect dispersion. Dry sieving of sand to determine the proportions of the different size fractions is done with a nest of sieves having the proper openings. Difficulties due to shapes of sieve openings and soil particles and time of shaking can not be eliminated. Consequently, a standard procedure must be followed to obtain comparable results.

Porosity and pore-size distribution are important soil properties in the disposition of water falling on the earth and the growth of plants. Soils with large and stable pores absorb rainfall and permit it to percolate downward rather than flow away over the surface. Maximum plant growth depends on suitable distribution of large, intermediate and small pores. Predominance of small pores favours waterlogged conditions and poor aeration whereas too many large pores make soils droughty.

3.2.1 Sieve Analysis

The grain size analysis is an attempt to determine the relative proportions of the different grain sizes that make up a given soil mass. Obviously, to have significance, the sample must be statistically representative of the soil mass. Actually it is not possible to determine the individual soil particle sizes; the test can only bracket the various ranges of sizes. This is accomplished by obtaining the quantity of material passing through a given sieve openings but retained on a sieve of smaller sized openings and then relating this retained quantity to the total sample. It is evident that the material retained on any sieve in this manner consists of particles of many sizes, all of which are smaller than the openings of the sieve through which the material passed but larger than the openings of the sieve on which the soil is retained.

The sieves are made of woven wire with rectangular openings. The No. 200 sieve (0.075 mm) is the smallest practical sieve size. This mesh is considered the finest size that will permit relatively free passage of water. Soil, of course, provides considerably more resistance to sieving than water, thus sieve sizes smaller than No. 200 are more academic than practical.

All the soil classification systems use the No. 200 sieve as a dividing point, i.e. classifications are in terms of the amount retained or passing the No. 200 sieve. Occasionally, it is desired to know the approximate range of grain sizes smaller than the No. 200 sieve, for which the hydrometer method is normally used.

The sieving process does not provide information on the shape of the soil grains, i.e., whether they are angular or rounded. It only yields information on grains that can pass, or with proper orientation do pass, through rectangular sieve openings of a certain size. Obviously, not all grains in larger samples that can pass a given opening do pass, since they may not ever become properly oriented with the square opening. The smaller particles may not be broken down to the elemental particle size in the pulverizing process; or the finer particles, especially the No. 200 sieve size (i.e., material that will pass the No. 200 sieve), may adhere to the larger particles as dust and not pass the proper sieve openings.

A sieve stack generally consists of a series (usually 5 to 7) of sieves with the sizes approximately doubling in opening from the bottom to top sieve. For convenience and practical reasons such as sieve availability, size of stack, introducing control sieves of other sizes, some sizes may be omitted. This is acceptable since strict adherence to the doubling ratio does not greatly improve the distribution curve and only enough sieves need be used to produce the reasonable curve with statistical reliability. The doubling ratio should be used as a guide in developing the sieve stack.

Information obtained from the grain size analysis is presented in the form of a curve. Standard procedure uses the percent passing (also termed percent finer) as the ordinate plotted to a natural scale against grain sizes on a logarithmic scale. It should be evident that a grain size distribution curve can only be approximate. This is due to several reasons, including physical limitations on obtaining a statistically representative sample, presence of soil lumps, practical limitations of using sieve mesh openings for irregularly shaped soil particles, and the limit on the number of sieves used in a "stack" for the analysis. Due to the statistical distribution of particle sizes, even the most representative soil samples do not yield reproducible distribution curves.

3.2.2 Laser Particle Size Analyser

When a beam of light is passed through an aperture and is allowed to fall on a screen, rings of light and dark bands (with monochromatic light i.e. a laser) or coloured bands (with a white light source) are observed on the screen. This phenomenon, which is a particular case of interference, is due to the wave nature of light and is known as diffraction. The smaller the aperture, the greater the radial separation of the rings and vice-versa. In the laser particle size analyser, the screen is represented by a high precision light sensitive silicon wafer on which concentric rings of increasing radius are etched, each one corresponding to pre-determined angle of diffracted light.

A parallel laser beam of 12 mm diameter is formed by spatially filtering and collimating a low power Helium Neon Laser of 6328 Angstroms wavelength. The particles of interest are made to pass through this beam within an appropriate area, either as a spray (for aerosols or blown dry powders) or dispersed in a fluid suspension. Laser light is then diffracted off these particles where the angles of diffraction are, in the simplest case, inversely related to the particle size. The scattered light is collected by a Fourier optical system and regardless of the precise position of the particles or their movement, it is brought to a focus on the diode array detector. The signal from each detector element, proportional to the intensity of light falling on it, is amplified and digitised and transferred to the controlling computer where it is analysed. The choice of liquid medium is virtually limitless. There is no need to know viscosity or density values and no need for calibration. In the 0.1-600 μm size range, the laser particle size analyser is the ideal choice for all suspensions, emulsions and any powder that is to be dispersed in liquid for analysis.

Software using Fraunhofer and Mie light scattering theories derives a complete and detailed particle size distribution that can be presented in a variety of graphical and tabular formats. The results can also be tabulated against users own computerised sieve (mesh) sizes. The required sieve sizes are prestored in the system or the user can input his own choice of reporting points. The multi-lens configuration allows high-resolution particle size for each range selected. For samples with exceptionally wide size ranges, it is possible to blend measurements from two ranges to give single results or it is also possible to extend a laser particle size analyser result with data obtained by a completely different technique e.g. sieving.

3.3 Soil Moisture Retention Curves

The graph giving the relation between soil moisture tension and soil moisture content is called moisture retention curve or soil moisture characteristic. If the tension is expressed as the logarithmic value of cm water, the graph is referred to as a pF-curve. Moisture retention curves are used:

- to determine an index of the available moisture in soil (the portion of water that can be readily absorbed by plant roots) and to classify soils accordingly, e.g. for irrigation purposes,
- to determine the drainable pore space (effective pore space, effective porosity, specific yield) for drainage design,
- to check changes in the structure of a soil, e.g. caused by tillage, mixing of soil layers etc.,
- to ascertain the relation between soil moisture tension and other physical properties of a soil (e.g. capillary conductivity, thermal conductivity, clay and organic matter content).

Clay soils show a slow and regular decrease in water content with increasing pF tension. Sandy soils may show only a slight decrease in moisture content in the lower pF range till the point where only a small rise in pF causes a considerable discharge of water due to a relatively large number of pores in a particular diameter range. The intersection point of the curve with the volumetric water content axis (tension: 1 cm water, pF = 0) gives the water content of the soil under nearly saturated conditions, which means that this point almost indicates the total pore space percentage (if no air entrapment has taken place). The zero moisture content is based on the oven-dry condition (105 °C), corresponding to a pF of approximately 7.

To construct the moisture retention curve of a soil sample, the moisture content of that sample must be measured. This is done by equilibrating the moist soil sample at a succession of known pF values and each time determining the amount of moisture that is retained. If the equilibrium moisture content (expressed preferably as volume percentage) is plotted against the corresponding tension (pF), the moisture retention curve (pF-curve) can be drawn. There is no single method of inducing the whole range of tensions from $pF = -\infty$ (total saturation) to $pF = 7$ (oven dry).

The ceramic plates equipment is suitable for determination of pF-curves in the pF range of 2.0-4.2 (0.1-15 bar of suction). Soil moisture is removed from the soil samples by raising air pressure in an extractor. A porous ceramic plate serves as a hydraulic link for water to move from the soil to the exterior of the extractor. The high-pressure air will not flow through the pores in the plate since the pores are filled with water. The smaller the pore size, the higher the pressure that can be exerted before air will pass through. During an experimental run, at any set pressure in the extractor, soil moisture will flow around each of the soil particles and out through the ceramic plate and outflow tube.

Equilibrium is reached when water flow from the outflow tube ceases. At equilibrium, there is an exact relationship between the air pressure in the extractor and the soil suction (and hence the moisture content) in the samples. Accuracy of equilibrium values will be no more accurate than the regulation of air supply; therefore the pressure control panel has independent double regulators.

For each soil type, the characteristic pF-curve may be developed. These curves relate the soil suction to its moisture content. This relationship is important in studies of soil moisture movement and quantity and availability of soil moisture for plant growth.

Pressure Plate Apparatus

It consists of a ceramic pressure plate cell mounted in a pressure vessel, with the outflow tube running through the vessel wall to the atmosphere and soil sample held in place on the porous ceramic surface of the cell. Each ceramic pressure plate cell consists of a porous ceramic plate covered on one side by a thin neoprene diaphragm sealed to the edges of the ceramic plate. An internal screen between the plate and diaphragm provides a passage for flow of water, An outlet stem running through the plate connects this passage to an outflow tube fitting which connects to the atmosphere outside of the extractor.

To use the ceramic pressure plate cell, one or more soil samples are placed on the porous ceramic surface and held in place by retaining rings of appropriate height. The soil samples, together with the porous ceramic plate, are then saturated with water. This is usually done by allowing excess water to stand on the surface of the cell for several hours. When the saturation is complete, the cell can be mounted in the pressure vessel. Air pressure is used to effect extraction of moisture from the soil samples under controlled conditions.

As soon as air pressure inside the chamber is raised above the atmospheric pressure, higher pressure inside the chamber forces excess water through the microscopic pores in the ceramic plate and out through the outlet stem. The high pressure air, however, will not flow through the pores in the ceramic plate since the pores are filled with water and the surface tension of water, at the gas-liquid interface at each of the pores, supports the pressure similar to a flexible rubber diaphragm.

The maximum air pressure that any given wetted porous ceramic plate can stand before letting air pass through the pores, is determined by the diameter of pore. The smaller the pore sizes, the higher the pressure needed for air to pass through. The pressure value that finally breaks down the water meniscus, is called the "bubbling pressure" or the "air entry value" for the porous plate. Pressure plate cells must always be used at air pressure extraction values below the "bubbling pressure" or "air entry value" for the cell.

During an experimental run, for any set air pressure in the extractor, soil moisture will flow from around each of the soil particles and out through the ceramic plate until the effective curvature of water films throughout the soil are same as at the pores in the plate. When this occurs, an equilibrium is reached and the flow of moisture ceases. When air pressure in the extractor is increased, flow of soil moisture from the samples starts again and continues until a new equilibrium is reached. At equilibrium, there is an exact relationship between the air pressure in the extractor and the soil suction (and hence the moisture content) in the samples. For example, if air pressure in the extractor is maintained at 1/3 bar, the soil suction in the samples at equilibrium will be 1/3 bar. If air pressure is maintained at 1 bar, the soil suction at equilibrium will be 1 bar.

The 1 bar ceramic plate cells are ideal for the routine determination of the 1/10 bar and 1/3 bar percentages in the cataloging of soils as well as all other soil moisture equilibrium studies in the 0-1 bar range of soil suction. The bubbling pressure of these cells is in excess of 1 bar. These cells also have the highest permeability amongst the pressure plate cells and hence time to reach the equilibrium will be the shortest possible. The 3 bar ceramic plate cells can also be used for determination of the 1/10 bar and 1/3 bar percentages as well as soil moisture equilibrium studies in the extended range of 0-3 bars of soil suction. Bubbling pressure of these cells is in excess of 3 bars. The 15 bar ceramic plate cells are not suitable for work in the 0-1 bar range of soil suction due to their small pore size. They can, however, be used effectively for soil moisture equilibrium studies in the 1-5 bar range of soil suction. Bubbling pressure of these cells is in excess of 15 bars. To use full range, these cells must be used in the 15 bar ceramic plate extractor.

The various pressure plate cells are not suitable for extracting solution from soils for chemical analysis. The immense surface area within the porous ceramic plate can cause disturbance and contamination of the soil solution. Where experiments for moisture equilibrium studies are being run, it is desirable to keep the sample heights small in order to reach equilibrium in reasonable time. The time required to reach equilibrium varies as the square of sample height. For example, a soil sample 2 cm high will require four times as long to reach equilibrium as a sample of 1 cm high. Whenever possible, soil sample heights should be limited to 1 cm.

Moisture retention studies can be made with prepared soil samples or undisturbed soil cores. Frequently, soil structure is quite an important determining factor in the value of 1/10 bar and 1/3 bar percentages and this aspect should be considered before electing to use undisturbed soil cores or prepared samples.

A source of regulated gas pressure is required for all extraction work. If the extractor is to be used extensively, compressed air from a compressor is the most satisfactory source of supply. Accuracy of equilibrium values will be no more accurate than the regulation of air supply. For working in the low soil suction range and particularly determination of the 1/10 bar and 1/3 bar percentages, it is essential to have excellent pressure regulation. If a laboratory compressed air supply line is available, the pressure control panel can be conveniently attached to the laboratory wall adjacent to the extractor and connected directly to the supply line.

The moisture retention curves can be developed for different soil types with this type of equipment. These "moisture characteristic" curves for each soil are extremely important in soils research and development of practical, effective irrigation practices.

3.4 Saturated Hydraulic Conductivity

The hydraulic conductivity is not an exclusive property of the soil alone, since it depends upon the attributes of the soil and the fluid together. The soil characteristics, which affect the hydraulic conductivity, are the total porosity, the distribution of pore sizes and the tortuosity – in short, the pore geometry of the soil. The fluid attributes, which affect the hydraulic conductivity, are fluid density and viscosity.

The simplest technique to measure the saturated hydraulic conductivity (K_s) is to take an 'undisturbed' cylindrical sample of the soil, saturate it, and let water flow through it in the laboratory. From the velocity and the hydraulic gradient observed on the sample, K_s can be calculated with Darcy's equation. Because truly undisturbed samples are difficult to obtain and the sample size is relatively small, laboratory methods have limited usefulness and direct measurement of K_s in the field is usually preferred.

3.4.1 Guelph Permeameter

The Guelph Permeameter is a constant-head device that operates on the Mariotte siphon principle and provides a quick and simple method for simultaneously determining field saturated hydraulic conductivity, matrix flux potential and soil sorptivity in the field.

Theory

Some of the most important factors governing liquid transmission in unsaturated soils are field-saturated hydraulic conductivity K_{fs}, matric flux potential ϕ_m, and sorptivity S. Hydraulic conductivity is a measure of the ability of a soil to conduct water under a unit hydraulic potential gradient. K_{fs} or field-saturated hydraulic conductivity refers to the saturated hydraulic conductivity of soil containing entrapped air. K_{fs} is more appropriate than the truly saturated hydraulic conductivity for vadose (unsaturated) zone investigations because positive pressure heads do not persist in unsaturated conditions long enough for entrapped air to dissolve.

Matric flux potential, ϕ_m is a measure of the soil's ability to pull water by capillary force through a unit cross-sectional area in a unit time. Sorptivity, S is a measure of the ability of a soil to absorb a wetting liquid. In general, the greater the volume of a wetting liquid that can be absorbed, the more rapidly the liquid is absorbed. Since sorptivity is defined in part by matric flux potential, they are essentially two different ways of describing the same phenomenon. The Guelph Permeameter is used to determine K_{fs} and ϕ_m for a particular soil.

Mode of Operation

The Guelph Permeameter is an in-hole constant-head permeameter, employing the Mariotte principle. The method involves measuring the steady state rate of water recharge into unsaturated soil from a cylindrical well hole, in which a constant depth (head) of water is maintained.

Constant head level in the well hole is established and maintained by regulating the level of the bottom of the air tube, which is located in the centre of the permeameter. As the water level in the reservoir falls, a vacuum is created in the air space above the water. The vacuum can only be relieved when air, which enters at the top of the air tube, bubbles out of the air inlet tip and rises to the top of the reservoir. Whenever the water level in the well begins to drop below the air inlet tip, air bubbles emerge from the tip and rise into reservoir air space. The vacuum is then partially relieved and water from the reservoir replenishes water in the well. The size of opening and geometry of the air inlet tip is designed to control the size of air bubbles in order to prevent the well water level from fluctuating.

When the permeameter is operating, an equilibrium is established. The reduced pressure (vacuum) in the air above the water in the reservoir together with the pressure of the water column extending from the surface of well to the surface of water in the reservoir always equals the atmospheric pressure.

When a constant well height of water is established in a cored hole in the soil, a "bulb" of saturated soil with specific dimensions is rather quickly established. This "bulb" is very stable and its shape depends on the type of soil, the radius of the well and the head of water in the well. The shape of the "bulb" is numerically described by the C- factor (Reynolds et al., Groundwater Monitoring Review, 6:1:84-95, 1985) used in the calculations. Once the unique "bulb" shape is established, the outflow of water from the well reaches a steady state flow rate that can be measured. The rate of this constant outflow of water together with the diameter of the well and height of water in the well can be used to accurately determine the field saturated conductivity, matrix flux potential and sorptivity of the soil.

Governing Analytic Equations

The Richards' analysis of steady-state discharge from a cylindrical well in unsaturated soil, as measured by the Guelph Permeameter technique, accounts for all the forces that contribute to three dimensional flow of water into soils viz. the hydraulic push of water into soil, the gravitational pull of liquid out through the bottom of the well, and the capillary pull of water out of the well into the surrounding soil. The Richards' analysis is the basis for the calculations used to determine hydraulic conductivity and matric flux potential.

The following formulae are used to determine hydraulic conductivity, K_{fs} and matric flux potential, ϕ_m when following the standardized procedure.

When using both reservoirs:

$$K_{fs} = (0.0041)(X)(\bar{R}_2) - (0.0054)(X)(\bar{R}_1) \quad \ldots (3.1)$$

$$\phi_m = (0.0572)(X)(\bar{R}_1) - (0.0237)(X)(\bar{R}_2) \quad \ldots (3.2)$$

When using the inner reservoir:

$$K_{fs} = (0.0041)(Y)(\bar{R}_2) - (0.0054)(Y)(\bar{R}_1) \quad \ldots (3.3)$$

$$\phi_m = (0.0572)(Y)(\bar{R}_1) - (0.0237)(Y)(\bar{R}_2) \quad \ldots (3.4)$$

where,

X = Reservoir constant used when the reservoir combination is selected;

Y = Reservoir constant used when only the inner reservoir is selected;

$\bar{R}_1$ = Steady state rate of fall of water in the reservoir at first well height (always 5 cm in the standardized procedure); and

$\bar{R}_2$ = Steady state rate of fall of water in the reservoir at second well height (always 10 cm in the standardized procedure).

Sorptivity

When the volumetric water content of the soil can be measured or estimated with reasonable accuracy, soil sorptivity S can be calculated as follows:

$$S = \sqrt{\{2(\Delta\theta)\phi_m\}} \quad \ldots (3.5)$$

where,

$\Delta\theta = \theta_{fs} - \theta_i$;

θ_i = initial volumetric water content; and

θ_{fs} = field-saturated volumetric water content.

Alpha Constant and the Conductivity – Pressure Head Relationship

Alpha is a constant that is dependent on the porous properties of soil. It is calculated as follows:

$$\alpha = K_{fs} / \phi_m \quad \ldots (3.6)$$

The hydraulic conductivity and pressure head relationship, K(φ) describes the change in K with soil suction. Generally, as soil suction increases, hydraulic conductivity decreases exponentially. For any soil suction (as measured in cm of water), the hydraulic conductivity can be predicted by the following equation.

$$K = K_{fs}\,[e^{(\alpha)(\varphi)}] \quad \ldots (3.7)$$

where,

φ = soil water suction (in cm of water); and

e = 2.71828 (base of natural logarithm).

The results of measurements with the Guelph Permeameter can indicate soil heterogeneity. When a negative K_{fs} or ϕ_m value is calculated, it is indicative of the presence of a hydrologic discontinuity, typically caused by soil stratification or the presence of rodent and/or root holes. This underlines the value of a profile description.

When a negative value for K_{fs} or ϕ_m is obtained, it indicates that further measurements are needed to account for the degree and kind of soil heterogeneity.

Soils typically have three-dimensional heterogeneity. The Guelph Permeameter method yields essentially a "point" measurement. The size of land under investigation, degree of soil heterogeneity, soil type and kind of application will dictate the number of measurements needed to adequately characterise a given area and depth of soil. A soil profile description and soil survey report will greatly enhance the value and understanding of data obtained with the Guelph Permeameter. Because of the ease and simplicity of Guelph Permeameter and its depth profiling capability, it is a very useful method for understanding the three dimensional distribution of the water transmission properties of soils.

3.4.2 I C W Laboratory Permeameter

The water permeability of the soil, to a large extent, determines how efficient an irrigation or drainage system function. The saturated water permeability (horizontal as well as vertical) can be determined in the field or laboratory with a laboratory permeameter. The I C W laboratory permeameter is used for measuring the saturated permeability of. undisturbed soil samples stored in soil sample rings. Determination of the permeability of undisturbed soil samples is a simple matter. By creating a difference in water pressure on both sides of a well-saturated soil sample, water flow passes through the sample. This flow is measured and forms the essential data together with pressure difference and sample dimensions for permeability calculations.

In principle, it is possible to design the permeameters in any required size. The size is determined by the number of soil samples for which the saturated water permeability is to be determined simultaneously. These permeameters are suitable for soil sample rings with an external diameter of 53, 60 or 84 mm. A closed system or an open system can be applied. In case of a closed system, a storage cistern, a circulation pump and a filter are provided. These attributes are not needed for an open system because the setup allows for a connection to the main water supply and drainage can take place in a washing basin. A closed system offers the facility to measure other fluids from the main supply. For instance, in case of samples from a salty environment, salt needs to be added to the water. The advantages of a closed system compared to an open system are (a) location independence as no drainage is needed, (b) constant water temperature guarantees constant viscosity, (c) always the same water quality, and (d) saves water.

3.5 Unsaturated Hydraulic Conductivity

Hydraulic conductivity decreases as the soil water suction increases. This relationship is called the conductivity - pressure head relationship. Once the soil water suction is measured, the hydraulic conductivity for that soil at that soil water suction can be readily calculated. In the present study, hydraulic conductivity function has been indirectly derived through van Genuchten retention parameters. The method involves initially fitting the van Genuchten model (1980) to the experimental retention data and then conversion of the van Genuchten model parameters to the equivalent desired function parameters. Estimation of parameters of the van Genuchten soil moisture characteristic equation involves the use of non-linear regression technique.

4.0 ANALYSIS AND RESULTS

4.1 General

The genesis and evolution of soils guarantee an inherent spatial and temporal heterogeneity. Three types of heterogeneity have been identified: stochastic, in which soil properties vary in an imperfectly known fashion in space and time; deterministic, where the variations are known everywhere; and flawed heterogeneity, in which a material with known properties is flawed by the presence of cracks or holes. These distinctions are artificial and contain implicit assumptions about the scale of observation.

The nature of field soils and use of the techniques principally evolved from the laboratory, indicate that almost all field measurements involve a degree of soil disturbance. The very act of measurement may influence both the observed magnitude and variability of the property under study. One method of sidestepping the problem of measurement disturbance is to avoid the measurement. Instead, one property is inferred from another simple-to-measure parameter or property using either an exact relationship or an empirical correlation. The most studied relation is that between soil particle size distribution or texture and hydraulic conductivity. While this approach works well for very simple materials such as graded sands, it is generally inappropriate for field soils. This failure is hardly surprising since flow is governed by the geometry of pore space, which may have little dependence on soil texture in structured field soils.

Table 1 presents the location and depth of soil samples collected from uppermost part of the Hindon river catchment. Results of field and laboratory investigations are given below.

4.2 Particle Size Distribution

Soil is composed of inorganic solid particles of various sizes and irregular shapes. The origins of these particles are weathered rocks, erupted materials, and sediment in ocean, lakes, marshes and rivers. Soil hydraulic properties are macroscopic properties i.e. properties defined at a scale much larger than the pore scale. However, the properties

Table 1 : Location of Soil Sampling Sites

S. No.	Soil Sample Code	Village	Normal Distance from Centre of River (m)	Bank	Depth Range (cm)
1	A11	Aurangabad	200	Left	90 – 110
2	A12	Aurangabad	200	Left	150 – 180
3	A21	Aurangabad	100	Left	0 – 40
4	A22	Aurangabad	100	Left	100 – 120
5	A23	Aurangabad	100	Left	160 – 180
6	A31	Aurangabad	100	Right	0 – 30
7	A32	Aurangabad	100	Right	90 – 110
8	A33	Aurangabad	100	Right	160 – 180
9	A41	Aurangabad	200	Right	0 – 30
10	A42	Aurangabad	200	Right	90 - 110
11	A43	Aurangabad	200	Right	170 - 190
12	K11	Kamalpur	100	Left	0 - 100
13	K12	Kamalpur	100	Left	100 – 150
14	K13	Kamalpur	100	Left	150 - 200
15	K21	Kamalpur	200	Left	0 – 70
16	K22	Kamalpur	200	Left	70 – 110
17	K23	Kamalpur	200	Left	110 – 180
18	K31	Kamalpur	400	Left	0 - 100
19	K32	Kamalpur	400	Left	100 – 180
20	K33	Kamalpur	400	Left	180 – 220
21	K41	Kamalpur	100	Right	40 – 60
22	K42	Kamalpur	100	Right	105 – 125
23	K51	Kamalpur	200	Right	40 – 60
24	K52	Kamalpur	200	Right	100 – 120
25	K53	Kamalpur	200	Right	160 – 180
26	K61	Kamalpur	400	Right	45 – 65
27	K62	Kamalpur	400	Right	100 – 120
28	B11	Budhakhera	100	Right	35 – 55
29	B12	Budhakhera	100	Right	70 – 90
30	B13	Budhakhera	100	Right	120 – 140
31	G11	Gagalheri	100	Right	35 – 55
32	G12	Gagalheri	100	Right	70 – 90
33	G13	Gagalheri	100	Right	130 - 150
34	G21	Gagalheri	100	Left	70 – 90
35	D11	Dudhil Bukhara	100	Right	5 - 15
36	D12	Dudhil Bukhara	100	Right	30 – 50
37	D13	Dudhil Bukhara	100	Right	85 – 95
38	D14	Dudhil Bukhara	100	Right	110 - 120

depend very much on the characteristics of the soil at the pore scale and in particular on the pore size distribution. Since the pore size distribution is controlled to a large extent by the size distribution of the soil particles, hydraulic properties will vary with the particle size distribution of the soil.

Sand, silt and clay of respective sizes 2 to 0.05 mm, 0.05 to 0.002 mm and less than 0.002 mm (as per U.S. Department of Agriculture Classification) are the primary particles of soil which form its texture. Particles larger than 2.0 mm may be graded as gravel. The results of sieve analysis (particle sizes > 0.075 mm) and laser particle size analyser (particle sizes 1.2 µm – 600 µm) were blended to determine the percentages of clay, silt, sand and gravel in each soil sample. Table 2 presents the particle size distribution for all soil samples. The major soil types found in the study area include sand, loamy sand, sandy loam and silt loam. The following soil types were found at each site.

Aurangabad	:	Silt Loam, Sandy Loam
Kamalpur	:	Sand, Loamy Sand
Budhakhera	:	Sand
Gagalheri	:	Silt Loam, Loamy Sand, Sand
Dudhil Bukhara	:	Sand, Silt Loam

4.3 Saturated Hydraulic Conductivity

Saturated hydraulic conductivity, K_s, is one of the most important field hydraulic properties. It was measured through Guelph Permeameter in the field at 8 locations in the study area. The results are presented in table 3.

Saturated hydraulic conductivity was also measured in the laboratory through I C W Permeameter for all the soil samples collected. Wide variations in saturated hydraulic conductivity were observed at different locations and depths. The values obtained through Guelph Permeameter were not found in confirmity with the corresponding laboratory results for I C W Permeameter (presented later). Therefore, K_s values obtained through I C W Permeameter were utilised for determining the parameters of hydraulic conductivity function.

Table 2 : Particle Size Distribution

S. No.	Site	Sample No.	Soil Texture (%)			
			Clay	Silt	Sand	Gravel
1	Aurangabad	A11	9.40	60.08	30.51	0.01
2	Aurangabad	A12	9.17	58.14	32.58	0.11
3	Aurangabad	A21	8.90	57.75	33.35	0.00
4	Aurangabad	A22	9.09	58.61	32.28	0.02
5	Aurangabad	A23	8.33	54.57	36.94	0.16
6	Aurangabad	A31	8.53	51.48	39.99	0.00
7	Aurangabad	A32	8.70	58.83	32.47	0.00
8	Aurangabad	A33	6.56	47.96	45.48	0.00
9	Aurangabad	A41	4.19	35.75	60.06	0.00
10	Aurangabad	A42	11.28	68.83	19.89	0.00
11	Aurangabad	A43	5.42	52.50	42.04	0.04
12	Kamalpur	K11	0.06	1.38	98.23	0.33
13	Kamalpur	K12	0.12	2.66	97.16	0.06
14	Kamalpur	K13	0.07	1.55	96.69	1.69
15	Kamalpur	K21	0.53	10.77	88.70	0.00
16	Kamalpur	K22	ERROR			
17	Kamalpur	K23	0.10	2.52	97.01	0.37
18	Kamalpur	K31	0.88	23.10	75.60	0.42
19	Kamalpur	K32	ERROR			
20	Kamalpur	K33	0.37	7.00	92.63	0.00
21	Kamalpur	K41	0.08	1.12	98.76	0.04
22	Kamalpur	K42	0.08	1.24	98.17	0.51
23	Kamalpur	K51	0.17	3.15	96.68	0.00
24	Kamalpur	K52	0.29	5.84	93.87	0.00
25	Kamalpur	K53	0.65	17.41	81.94	0.00
26	Kamalpur	K61	0.71	13.29	86.00	0.00
27	Kamalpur	K62	0.54	8.41	91.05	0.00
28	Budhakhera	B11	ERROR			
29	Budhakhera	B12	0.30	5.16	94.54	0.00
30	Budhakhera	B13	0.34	7.11	92.55	0.00
31	Gagalheri	G11	5.84	75.89	16.36	1.91
32	Gagalheri	G12	5.14	70.59	22.27	2.00
33	Gagalheri	G13	1.10	17.17	81.73	0.00
34	Gagalheri	G21	0.10	1.49	98.31	0.10
35	Dudhil Bukhara	D11	2.62	50.03	47.35	0.00
36	Dudhil Bukhara	D12	0.74	13.96	85.30	0.00
37	Dudhil Bukhara	D13	ERROR			
38	Dudhil Bukhara	D14	0.22	3.96	95.82	0.00

Table 3 : Field - Saturated Hydraulic Conductivity measured through Guelph Permeameter

Site	Location	Depth (cm)	Field - Saturated Hydraulic Conductivity (cm / hour)
Aurangabad	A1	45	0.00779
		46	0.26089
		50	0.11899
	A2	44	2.95884
		46	0.02007
	A3	30	0.13766
	A4	44	6.01200
		45	5.48280
		46	0.64548
Kamalpur	K1	50	0.26780
		80	0.11765
Budhakhera	B1	45	143.748
		80	48.0240
		130	1.74816
Gagalheri	G1	45	0.59288
		80	0.17460
Dudhil Bukhara	D1	20	0.54936
		45	37.1520
		85	70.0128

The following empirical relationship was derived by fitting the experimental data of soil texture (percentages of clay, silt and sand) and the corresponding values of saturated hydraulic conductivity obtained through I C W Permeameter.

$$K_s = 1.640 (S_a / S_i) - 0.052 (S_a / C_l) \qquad \dots (4.1)$$

where,

K_s = saturated hydraulic conductivity (cm/h) ;

S_a = percentage of sand ;

S_i = percentage of silt ; and

C_l = percentage of clay.

The "proportion of variance explained" was found to be 44.93% for the above empirical relationship. The "proportion of variance explained" indicates how much better the function predicts the dependent variable than just using the mean value of the dependent variable. This is also known as the "coefficient of multiple determination". It is computed as follows : Suppose that we did not fit an equation to the data and ignored all information about the independent variables in each observation. Then, the best prediction for the dependent variable value for any observation would be the mean value of the dependent variable over all observations. The "variance" is the sum of the squared differences between the mean value and the value of the dependent variable for each observation. Now, if we use our fitted function to predict the value of the dependent variable, rather than using the mean value, a second kind of variance can be computed by taking the sum of the squared differences between the value of the dependent variable predicted by the function and the actual value. Hopefully, the variance computed by using the values prediction by the function is better (i.e., a smaller value) than the variance computed using the mean value. The "Proportion of variance explained" is computed as [1 – (variance using predicted value / variance using mean)]. If the function perfectly predicts the observed data, the value of this statistic will be 1.00 (100%). If the function does no better a job of predicting the dependent variable than using the mean, the value will be 0.00.

Equation (4.1) can be used to obtain approximate estimate of saturated hydraulic conductivity from the measured percentages of clay, silt and sand in the study area. It is to be emphasized that the above relationship has been derived for basically sandy soils and therefore may not be applicable for general use.

4.4 Soil Moisture Characteristics

To model the retention and movement of water and chemicals in the unsaturated zone, it is necessary to know the relationships between soil water pressure, water content and hydraulic conductivity. It is often convenient to represent these functions by means of relatively simple parametric expressions. The problem of characterizing the soil hydraulic properties then reduces to estimating parameters of the appropriate constitutive model. The following typical functional relations, as reported by Haverkamp et al. (1977), were used for characterising the hydraulic properties (unsaturated hydraulic conductivity and moisture retention curve) of soil.

$$K = K_S \frac{A}{A+|h|^{\beta_1}} \quad \ldots (4.2)$$

and

$$\theta = \frac{\alpha(\theta_s - \theta_r)}{\alpha + |h|^{\beta_2}} + \theta_r \quad \ldots (4.3)$$

where K is the hydraulic conductivity of the soil (cm/h); h the soil water pressure (relative to the atmosphere) expressed in cm of water; θ the volumetric water content (cm^3/cm^3); and A, α, β_1 and β_2 the parameters for the soil. Subscript s refers to saturation, i.e. the value of θ for which h = 0, and the subscript r to residual water content.

The measurements of θ(h) from soil cores (obtained through pressure plate apparatus) can be fitted to the desired soil water retention model. Once the retention function (e.g. equation 4.3) is estimated, the hydraulic conductivity relation, K(h), can be evaluated if the saturated hydraulic conductivity, K_s, is known. In the present study, parameters of hydraulic conductivity function (A and β_1 in equation 4.2) were indirectly derived through the van Genuchten retention parameters. For the van Genuchten model, the water retention function is given by

$$\begin{aligned} S_e = (\theta - \theta_r)/(\theta_s - \theta_r) &= [\,1 + (\alpha_v |h|)^n\,]^{-m} && \text{for } h < 0 \\ &= 1 && \text{for } h \geq 0 \end{aligned} \quad \ldots (4.4)$$

and the hydraulic conductivity function is described by

$$K = K_s S_e^{1/2} [\,1 - (1 - S_e^{1/m})^m\,]^2 \quad \ldots (4.5)$$

where, α_v and n are van Genuchten model parameters, $m = 1 - 1/n$.

The parameters of soil moisture retention function (including θ_r) and hydraulic conductivity function were obtained through non-linear regression analysis. The saturated moisture content (θ_s) was assumed to be equal to (0.93*soil porosity). The porosity for each soil sample was measured in the laboratory.

Table 4 presents the parameters of Haverkamp h-θ function (equation 4.3) and "proportion of variance explained" for all the soil samples. The depth-averaged soil moisture retention curves at each site, generated with the parameter sets given in table 4, are graphically presented in figures 2 to 14.

Table 5 presents the saturated hydraulic conductivity obtained through I C W Permeameter, van Genuchten retention parameters, Haverkamp K-h function (equation 4.2) parameters, and "proportion of variance explained" for all the soil samples. The depth-averaged variations of hydraulic conductivity (K) with soil water suction (-h) at each site, generated with the parameter sets given in table 5, are graphically presented in figures 15 to 27.

By observing tables 4 and 5, it may be concluded that soil moisture characteristics vary widely along the Hindon river in its upstream reach.

Table 4 : Parameters of Haverkamp h - θ Function

Sample No.	Porosity	θ_s	α	β_2	θ_r	Proportion of Variance Explained (%)
A11	0.4466	0.415	28.980	0.565	0.072	94.23
A12	0.4722	0.439	46.762	0.681	0.088	96.85
A1 (Average)	0.4594	0.427	18.689	0.486	0.050	95.41
A21	0.4687	0.436	171.510	0.952	0.077	99.36
A22	0.4388	0.408	452.927	1.054	0.101	98.24
A23	0.4652	0.433	28.143	0.552	0.037	94.19
A2 (Average)	0.4576	0.426	156.978	0.897	0.086	91.38
A31	0.4051	0.377	1997.722	1.360	0.095	99.43
A32	0.4520	0.420	430.479	1.060	0.117	98.26
A33	0.4520	0.420	60.843	0.800	0.076	99.39
A3 (Average)	0.4364	0.406	340.197	1.062	0.098	82.98
A41	0.5040	0.469	38.176	0.834	0.039	99.45
A42	0.4476	0.416	13.688	0.473	0.055	99.68
A43	0.4846	0.451	47.788	0.750	0.045	99.23
A4 (Average)	0.4787	0.445	24.264	0.680	0.058	59.14
K11	0.4082	0.380	4.176	0.608	0.008	98.77
K12	0.4020*	0.374	22.611	0.848	0.015	99.68
K13	0.3959	0.368	6.747	0.628	0.014	99.04
K1 (Average)	0.4020	0.374	15.771	0.807	0.015	94.02
K21	0.4163	0.387	119.900	1.033	0.026	99.48
K22	0.3551	0.330	1.534	0.493	0.002	98.89
K23	0.3673	0.342	8.945	0.675	0.006	98.62
K2 (Average)	0.3796	0.353	17.220	0.753	0.009	57.86
K31	0.5061	0.471	135.006	0.921	0.042	99.69
K32	0.5102	0.474	122.687	0.916	0.034	99.63
K33	0.5082*	0.473	24.258	0.903	0.011	99.82
K3 (Average)	0.5082	0.473	27.306	0.686	0.013	70.07
K41	0.3747*	0.348	2.123	0.594	0.006	99.79
K42	0.3747	0.348	1.835	0.513	0.006	98.63
K4 (Average)	0.3747	0.348	1.491	0.489	0.005	95.40
K51	0.5061*	0.471	9.928	0.802	0.018	99.01
K52	0.5061*	0.471	59.769	0.937	0.048	98.60
K53	0.5061	0.471	34.853	0.673	0.075	98.55
K5 (Average)	0.5061	0.471	17.438	0.704	0.048	43.32
K61	0.4082	0.380	190.938	1.043	0.059	99.96
K62	0.4204	0.391	39.309	0.704	0.076	99.63
K6 (Average)	0.4143	0.385	88.275	0.872	0.064	93.73
B11	0.4400	0.409	690.350	1.600	0.010	99.66
B12	0.4700	0.437	20.166	1.068	0.007	97.22
B13	0.4300	0.400	3.701	0.626	0.004	96.88
B1 (Average)	0.4467	0.415	34.558	1.076	0.008	83.31
G11	0.4200	0.391	499.356	1.085	0.127	99.53
G12	0.4450	0.414	686.994	1.184	0.109	98.81
G13	0.4200	0.391	49.309	0.986	0.023	97.29
G1 (Average)	0.4283	0.398	115.747	0.944	0.083	50.17
G21	0.4450	0.414	12.314	0.991	0.004	97.42
D11	0.5800	0.539	10.324	0.522	0.016	97.38
D12	0.5450	0.507	15.953	0.805	0.007	97.91
D13	0.4500	0.418	10084.52	1.698	0.036	99.39
D14	0.5000	0.465	1.986	0.588	0.003	96.04
D1 (Average)	0.5188	0.482	24.504	0.780	0.018	56.39

* Assumed

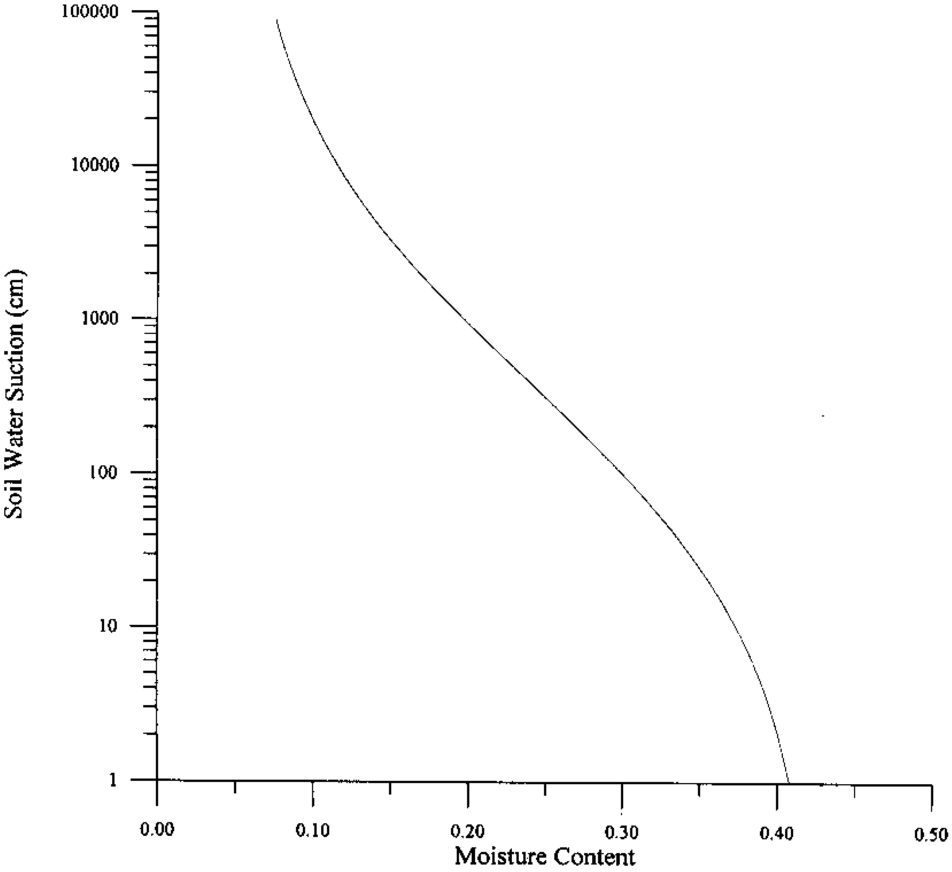

Figure 2 : Soil Moisture Retention Curve at Aurangabad (A1)

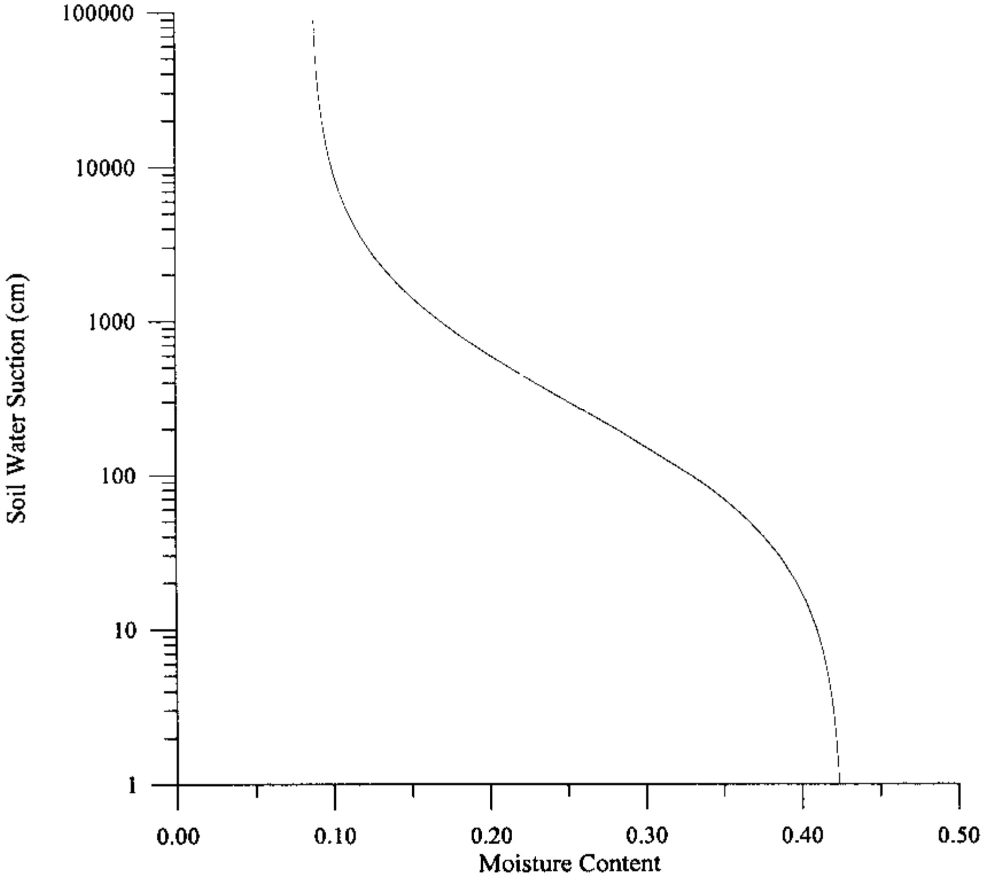

Figure. 3 : Soil Moisture Retention Curve at Aurangabad (A2)

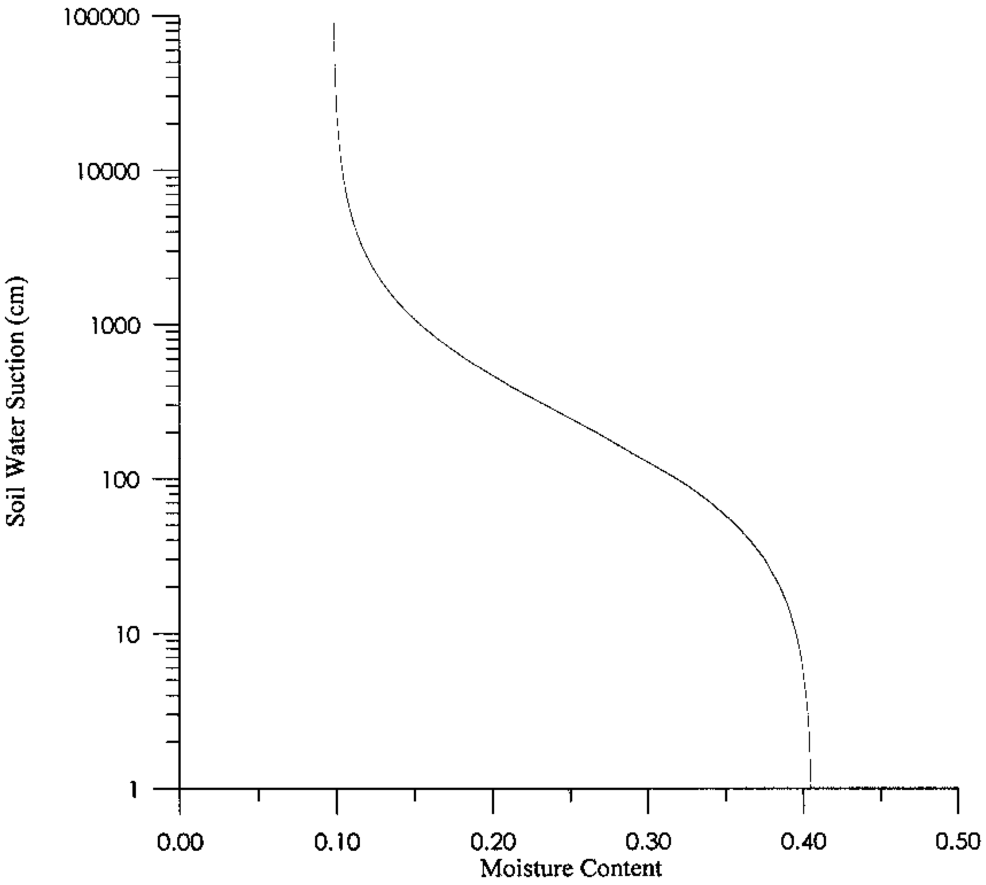

Figure 4 : Soil Moisture Retention Curve at Aurangabad (A3)

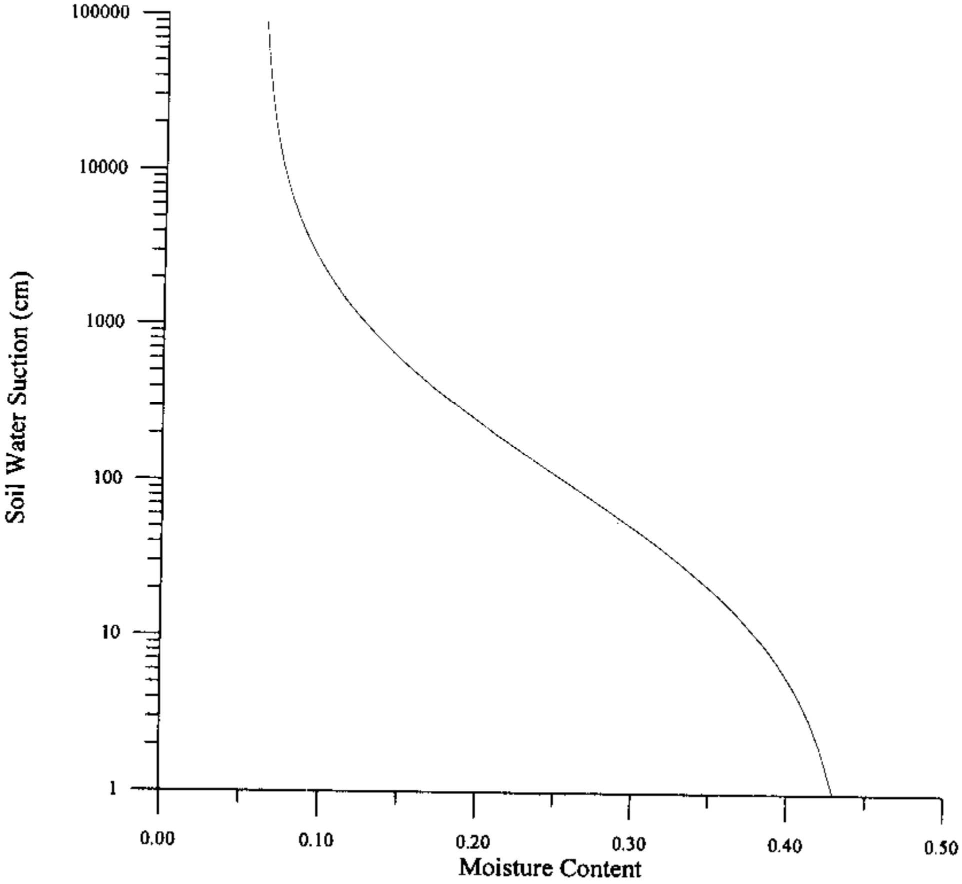

Figure 5 : Soil Moisture Retention Curve at Aurangabad (A4)

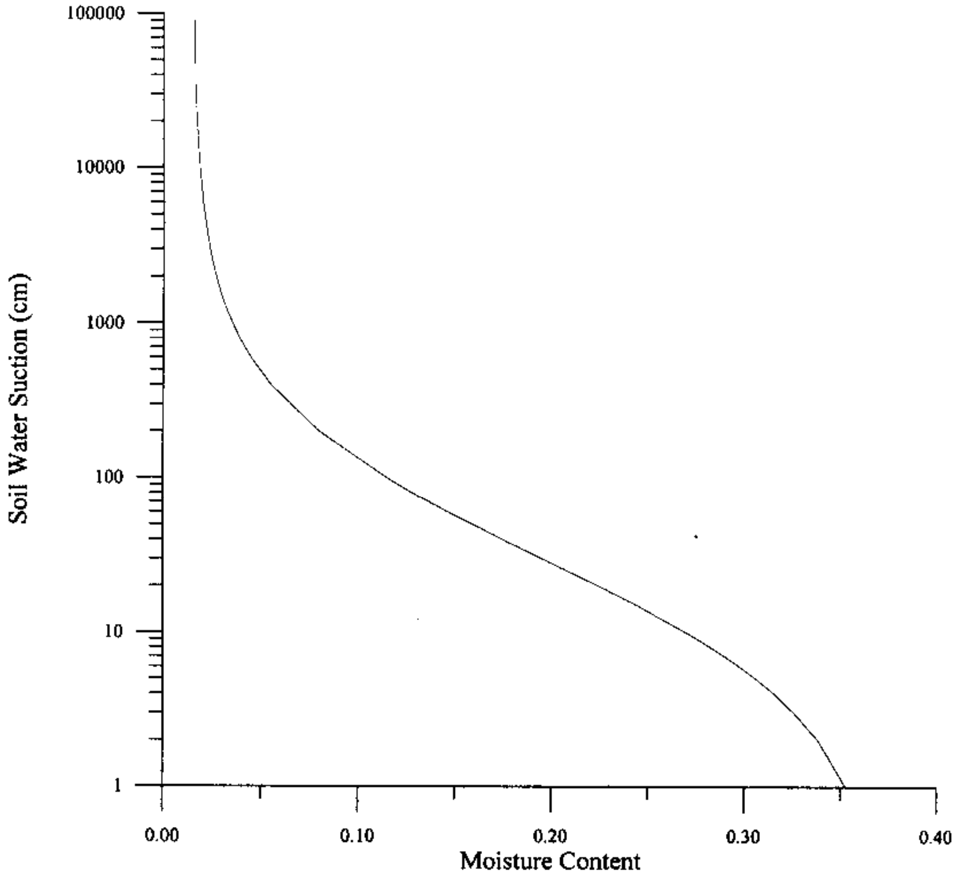

Figure 6 : Soil Moisture Retention Curve at Kamalpur (K1)

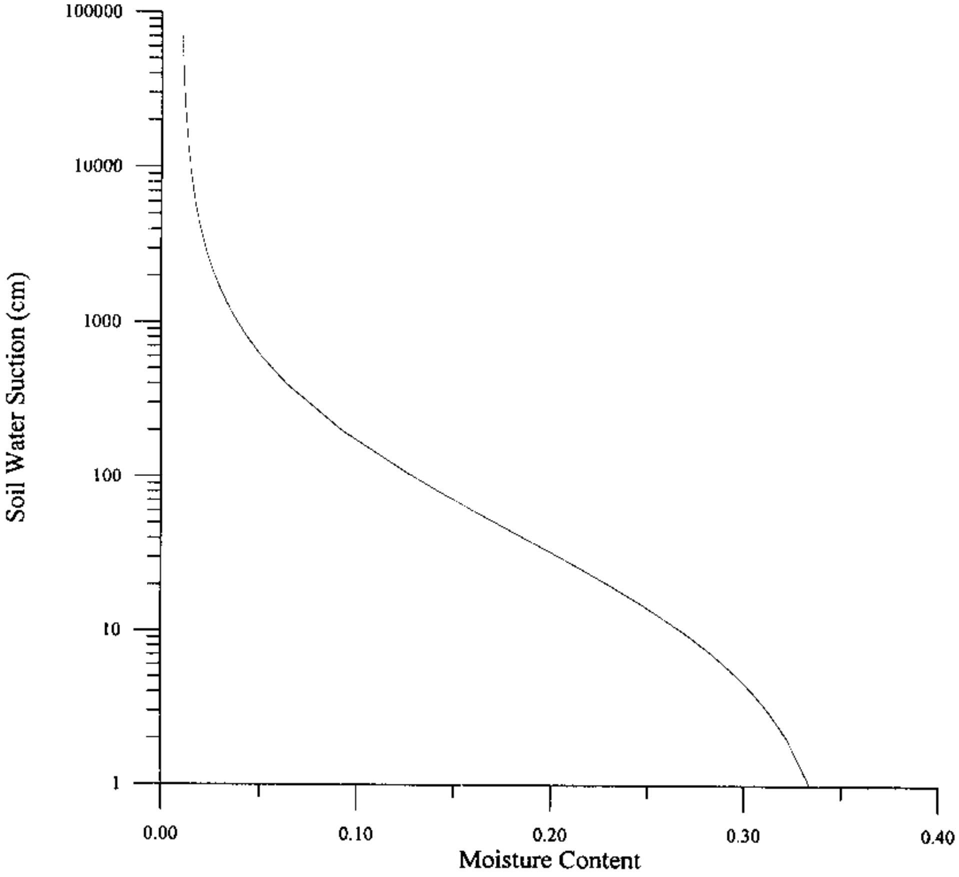

Figure 7 : Soil Moisture Retention Curve at Kamalpur (K2)

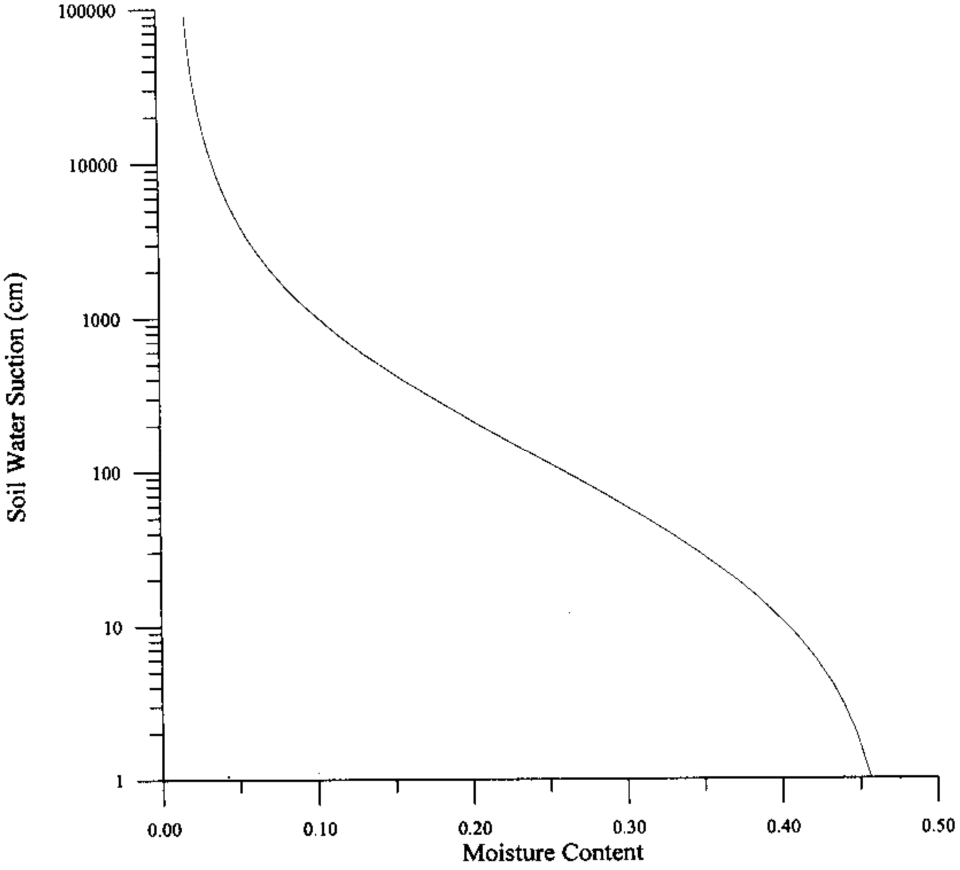

Figure 8 : Soil Moisture Retention Curve at Kamalpur (K3)

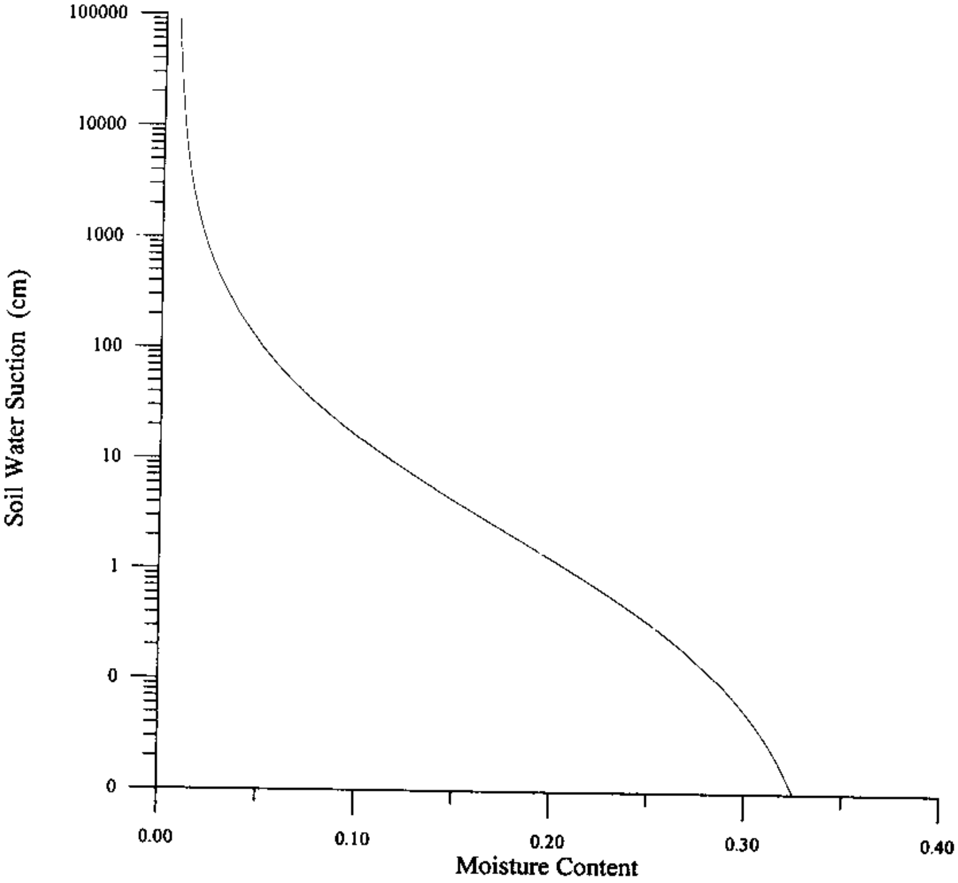

Figure 9 : Soil Moisture Retention Curve at Kamalpur (K4)

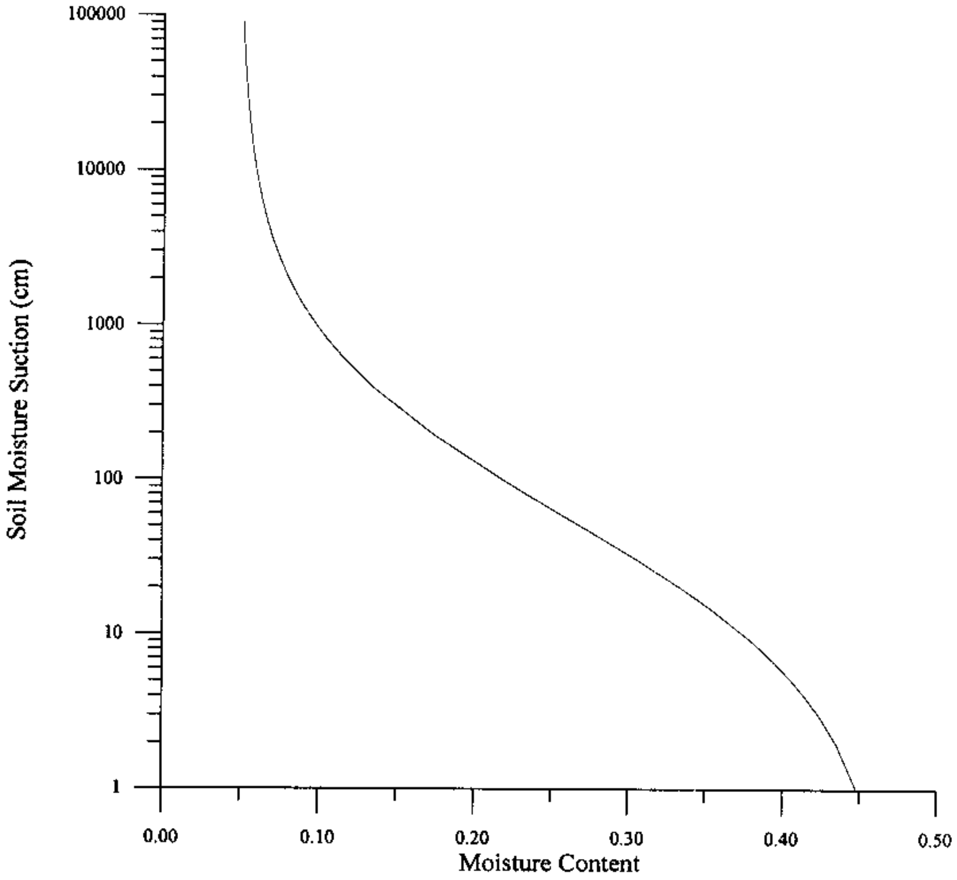

Figure 10 : Soil Moisture Retention Curve at Kamalpur (K5)

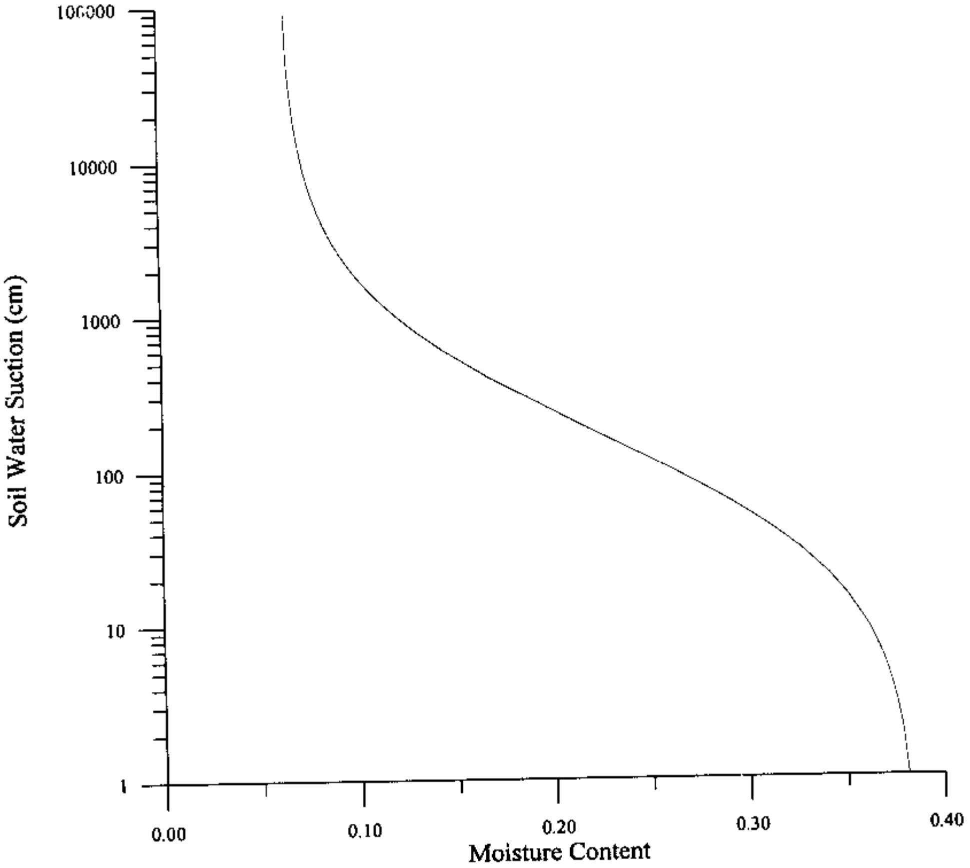

Figure 11 : Soil Moisture Retention Curve at Kamalpur (K6)

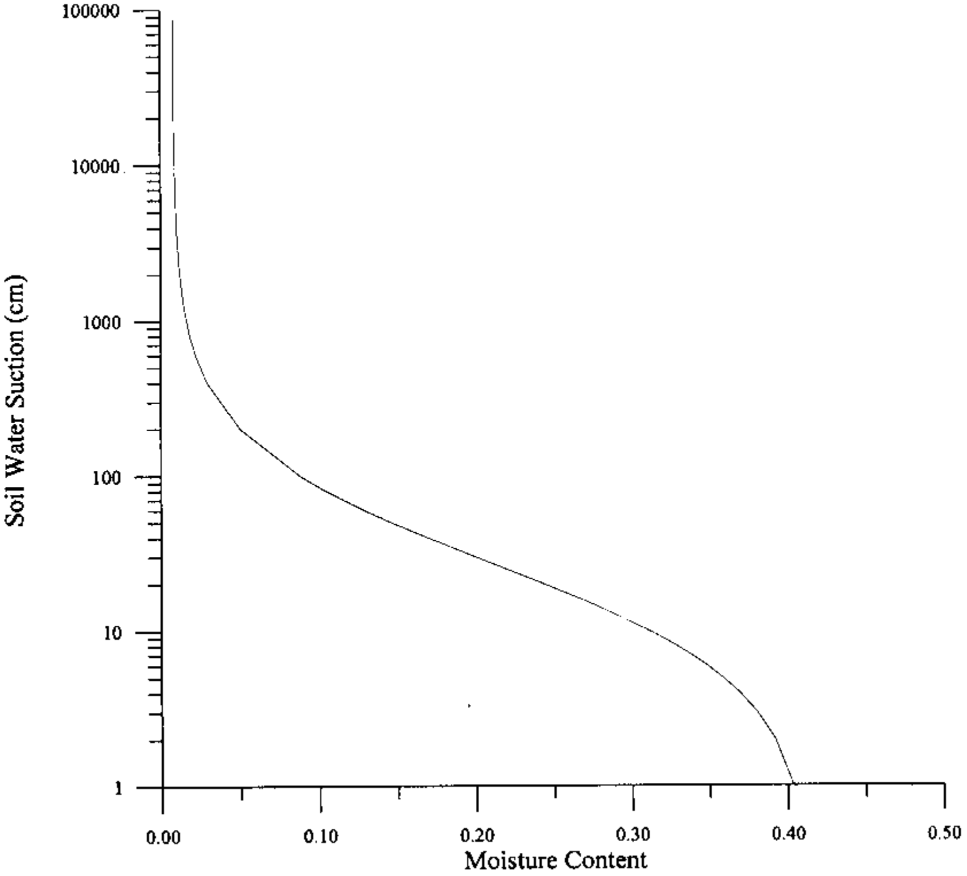

Figure 12 : Soil Moisture Retention Curve at Budhakhera

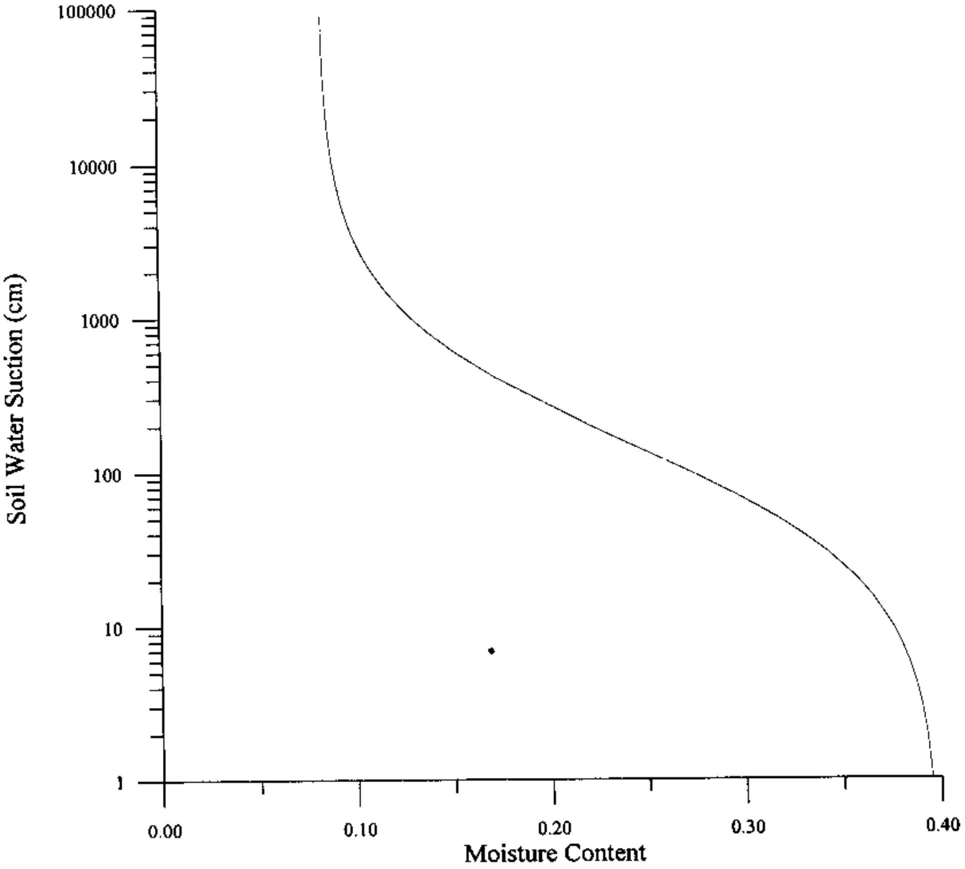

Figure 13 : Soil Moisture Retention Curve at Gagalheri

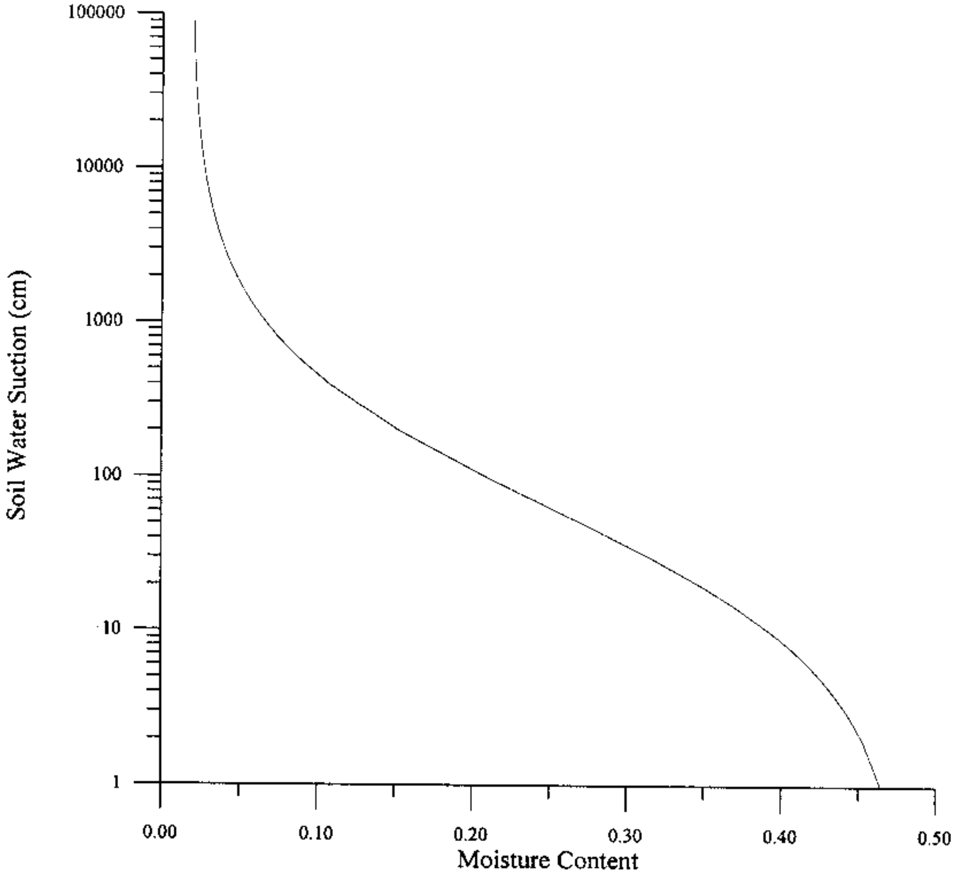

Figure 14 : Soil Moisture Retention Curve at Dudhil Bukhara

Table 5 : Parameters of Haverkamp K – h Function

Sample No.	θ_r	θ_s	K_s (cm/hour)	Van Genuchten Retention Parameters			Haverkamp K-h Function Parameters		
				α_v	N	Proportion of Variance Explained	A	β_1	Proportion of Variance Explained
A11	0.072	0.415	0.041	0.0142	1.3884	93.67	7.645	1.255	99.32
A12	0.088	0.439	0.010	0.0112	1.5193	97.12	17.530	1.270	99.28
A1 (Average)	0.050	0.427	0.026	0.0185	1.3284	95.65	5.029	1.316	99.43
A21	0.077	0.436	0.080	0.0088	1.7714	99.18	86.035	1.435	99.48
A22	0.101	0.408	0.022	0.0058	1.8370	98.60	176.590	1.420	99.64
A23	0.037	0.433	0.588	0.0134	1.3812	94.62	7.345	1.230	99.31
A2 (Average)	0.086	0.426	0.230	0.0078	1.7100	91.61	63.324	1.342	99.48
A31	0.095	0.377	0.058	0.0057	2.1278	99.60	1196.988	1.747	99.79
A32	0.117	0.420	0.080	0.0063	1.8294	97.76	156.263	1.425	99.63
A33	0.076	0.420	0.036	0.0124	1.6643	99.42	38.729	1.426	99.29
A3 (Average)	0.098	0.406	0.058	0.0074	1.8622	82.87	169.768	1.492	99.61
A41	0.039	0.469	1.884	0.0207	1.7457	99.41	48.347	1.688	99.32
A42	0.055	0.416	0.175	0.0273	1.3312	99.22	5.006	1.488	99.60
A43	0.045	0.451	0.412	0.0138	1.6006	99.14	26.279	1.406	99.27
A4 (Average)	0.058	0.445	0.824	0.0210	1.5725	59.22	20.685	1.552	99.37
K11	0.008	0.380	33.753	0.1728	1.5520	98.59	9.731	2.925	100.00
K12	0.015	0.374	16.157	0.0479	1.7156	99.61	40.794	2.190	99.84
K13	0.014	0.368	17.785	0.1089	1.5384	98.69	14.323	2.606	99.99
K1 (Average)	0.015	0.374	22.565	0.0591	1.7022	94.05	39.957	2.357	99.91
K21	0.026	0.387	0.677	0.0200	1.7937	98.99	61.501	1.716	99.30
K22	0.002	0.330	24.984	0.8721	1.4431	98.80	0.120	3.054	100.00
K23	0.006	0.342	14.430	0.0867	1.5714	98.22	19.504	2.495	99.97
K2 (Average)	0.009	0.353	13.364	0.0536	1.6099	57.31	24.870	2.163	99.88

Table 5 (continued) ...

Sample No.	θ_r	θ_s	K_s (cm/hour)	Van Genuchten Retention Parameters			Haverkamp K-h Function Parameters		
				α_v	N	Proportion of Variance Explained	A	β_1	Proportion of Variance Explained
K31	0.042	0.471	0.303	0.0142	1.6234	99.06	29.492	1.436	99.27
K32	0.034	0.474	0.350	0.0151	1.6272	98.94	29.537	1.461	99.27
K33	0.011	0.473*	4.603	0.0486	1.7927	99.91	57.832	2.284	99.85
K3 (Average)	0.013	0.473	1.752	0.0311	1.4824	69.47	12.565	1.678	99.62
K41	0.006	0.348*	84.992	0.4259	1.5619	99.71	1.486	3.269	100.00
K42	0.006	0.348	48.204	0.6204	1.4641	98.43	0.339	3.076	100.00
K4 (Average)	0.005	0.348	66.598	0.7309	1.4639	95.27	0.214	3.092	100.00
K51	0.018	0.471*	20.196	0.0910	1.7243	99.07	46.113	2.799	99.98
K52	0.048	0.471*	0.421	0.0269	1.7350	98.34	43.189	1.808	99.47
K53	0.075	0.471	0.245	0.0246	1.4396	97.51	9.976	1.523	99.50
K5 (Average)	0.048	0.471	6.954	0.0474	1.5506	43.19	18.148	2.006	99.83
K61	0.059	0.380	0.845	0.0148	1.7622	99.74	60.798	1.576	99.28
K62	0.076	0.391	0.230	0.0242	1.4583	98.92	11.109	1.529	99.49
K6 (Average)	0.064	0.385	0.538	0.0178	1.5956	93.20	23.988	1.499	99.30
B11	0.010	0.409	14.937	0.0219	2.4113	99.69	1108.457	2.396	99.43
B12	0.007	0.437	5.493	0.0781	1.9931	97.11	178.926	3.077	99.98
B13	0.004	0.400	17.588	0.2128	1.5754	96.61	8.015	3.084	100.00
B1 (Average)	0.008	0.415	12.673	0.0519	1.9764	83.26	128.839	2.547	99.89
G11	0.127	0.391	17.270	0.0079	1.7607	98.88	86.032	1.397	99.52
G12	0.109	0.414	0.177	0.0088	1.8348	97.86	126.838	1.503	99.53
G13	0.023	0.391	8.519	0.0334	1.8370	97.53	65.564	2.026	99.62
G1 (Average)	0.083	0.398	8.655	0.0164	1.6898	49.91	39.859	1.546	99.27
G21	0.004	0.414	N.A.	--	--	--	--	--	--
D11	0.016	0.539	0.207	0.0594	1.3853	96.55	6.634	1.960	99.89
D12	0.007	0.507	66.640	0.0597	1.6970	97.50	39.022	2.360	99.92
D13	0.036	0.418	70.013**	0.0070	2.2241	99.66	1712.531	1.892	99.81
D14	0.003	0.465	89.857	0.3957	1.5793	95.83	1.971	3.298	100.00
D1 (Average)	0.018	0.482	56.679	0.0392	1.6279	56.19	26.398	1.950	99.73

* Assumed

** From Guelph Permeameter (ICW Permeameter result not available)

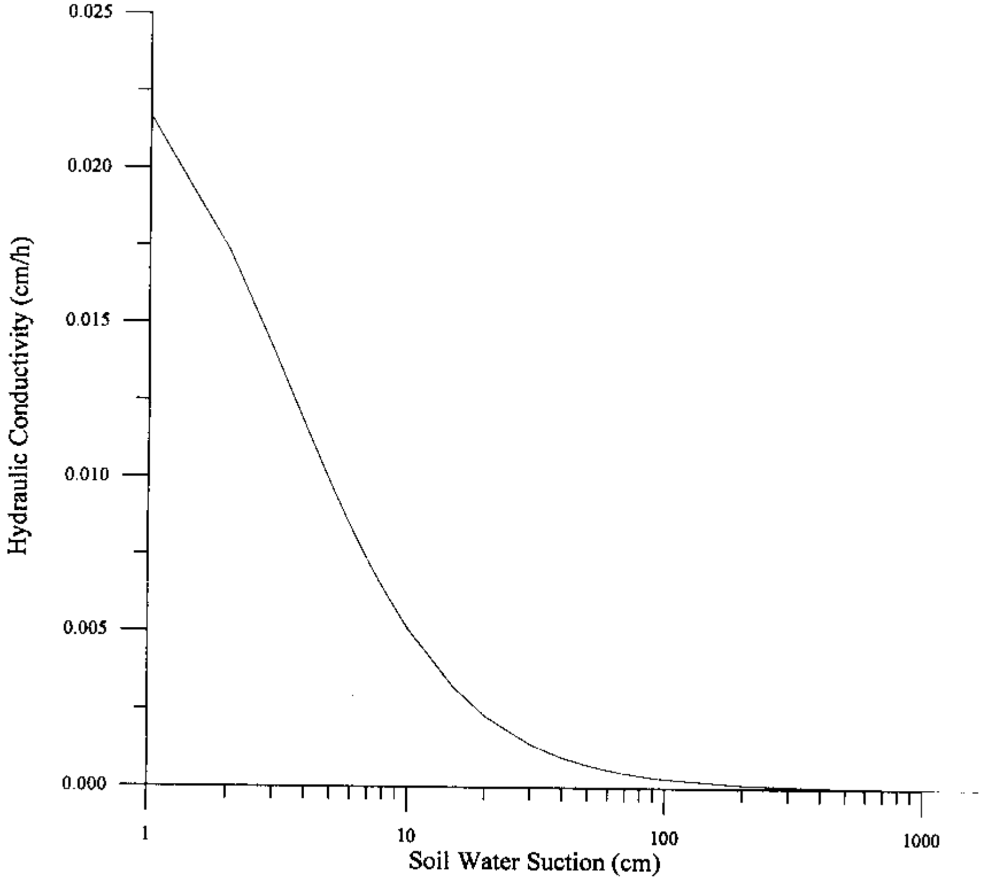

Figure 15 : Variation of Hydraulic Conductivity K with
Soil Water Suction (-h) at Aurangabad (A1)

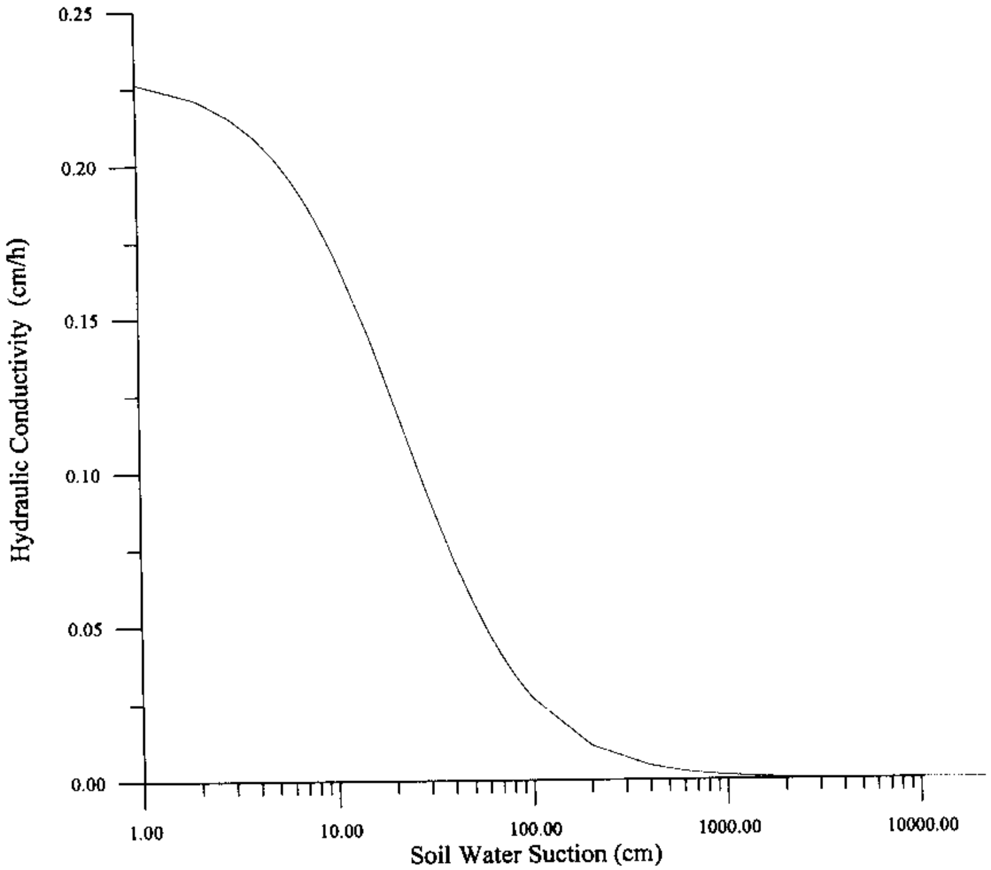

Figure 16 : Variation of Hydraulic Conductivity K with Soil Water Suction (-h) at Aurangabad (A2)

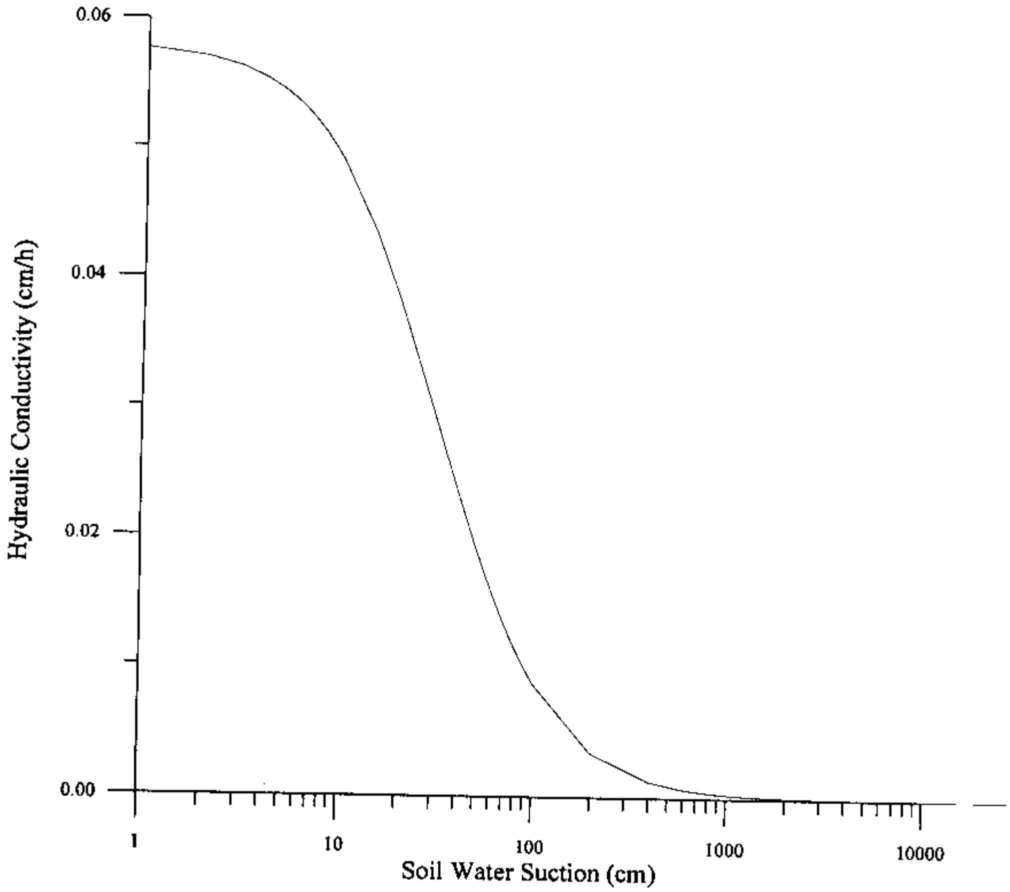

Figure 17 : Variation of Hydraulic Conductivity K with Soil Water Suction (-h) at Aurangabad (A3)

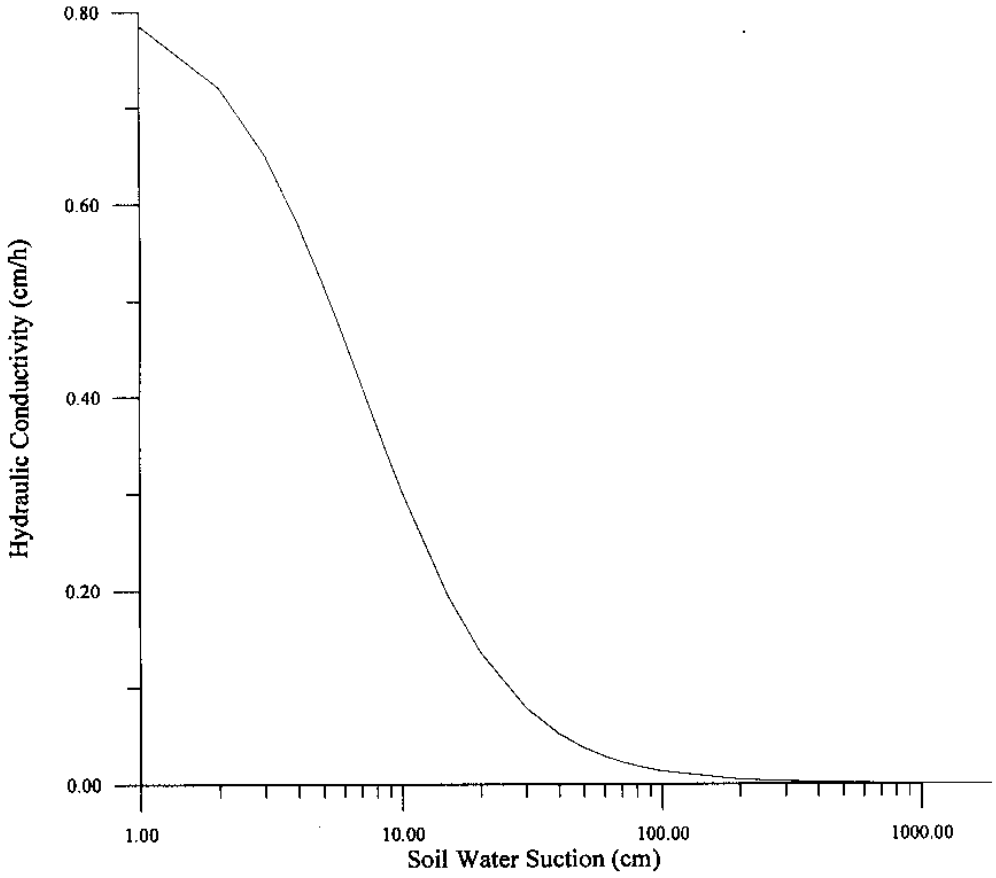

Figure 18 : Variation of Hydraulic Conductivity K with Soil Water Suction (-h) at Aurangabad (A4)

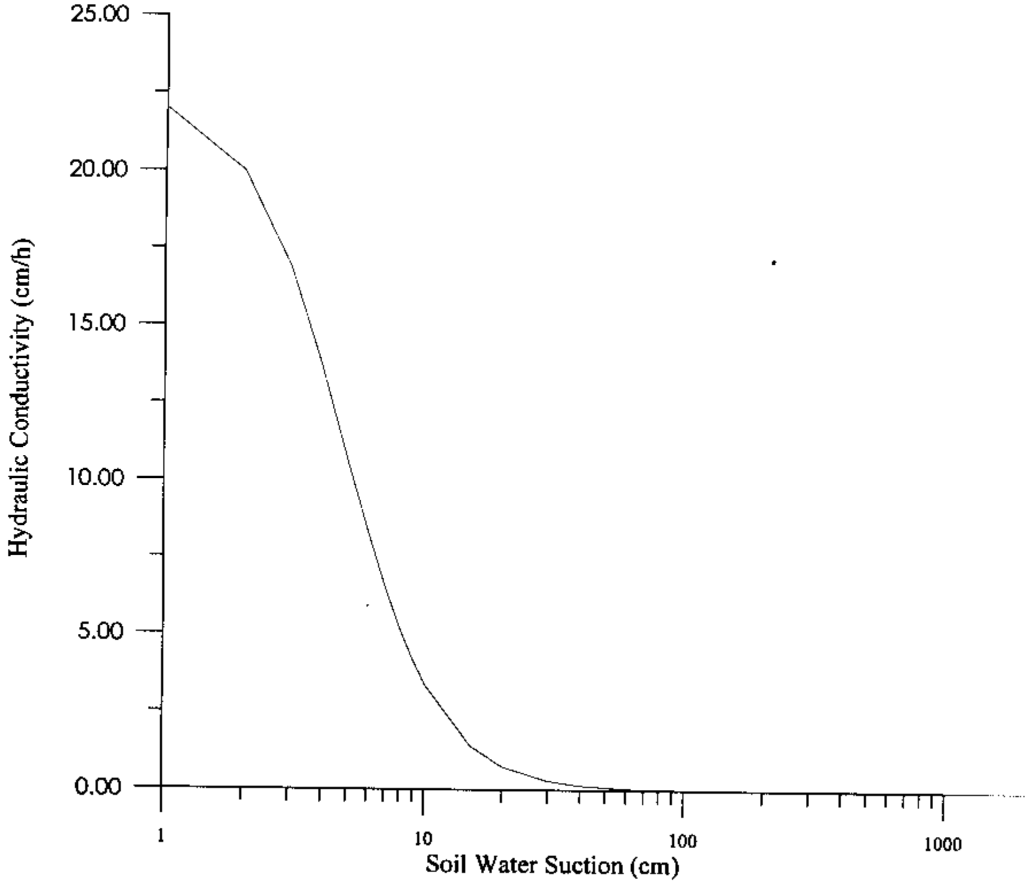

Figure 19 : Variation of Hydraulic Conductivity K with Soil Water Suction (-h) at Kamalpur (K1)

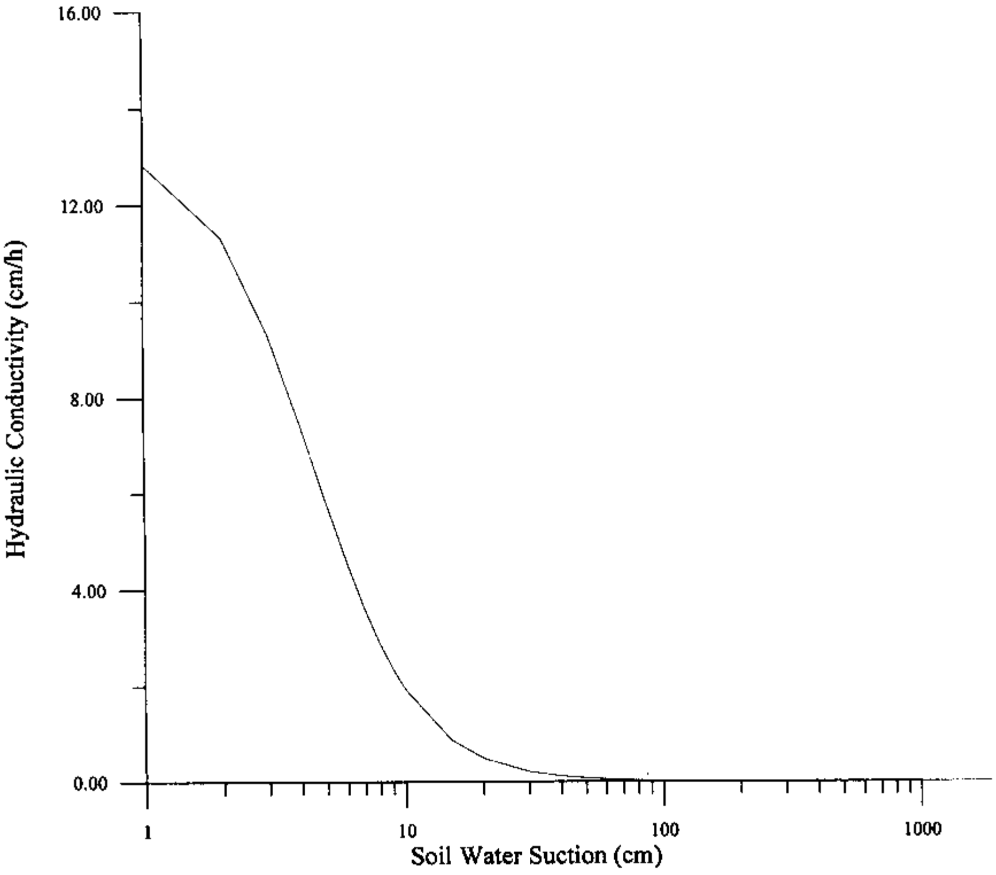

Figure 20 : Variation of Hydraulic Conductivity K with Soil Water Suction (-h) at Kamalpur (K2)

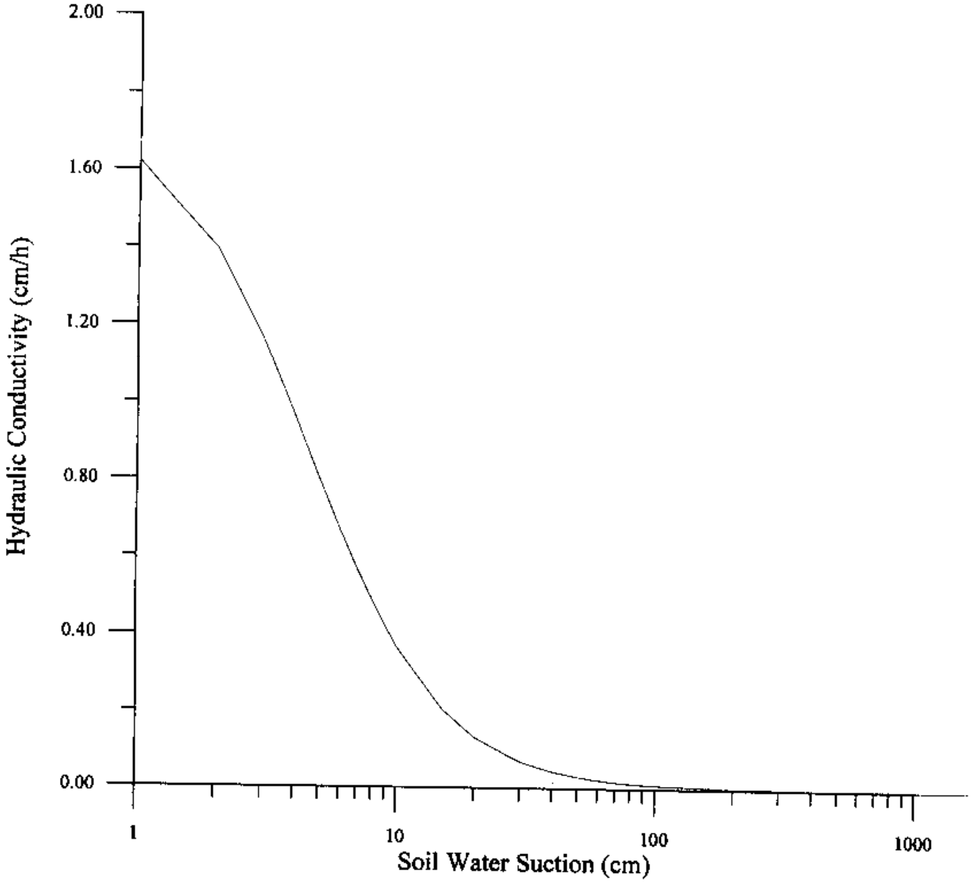

Figure 21 : Variation of Hydraulic Conductivity K with Soil Water Suction (-h) at Kamalpur (K3)

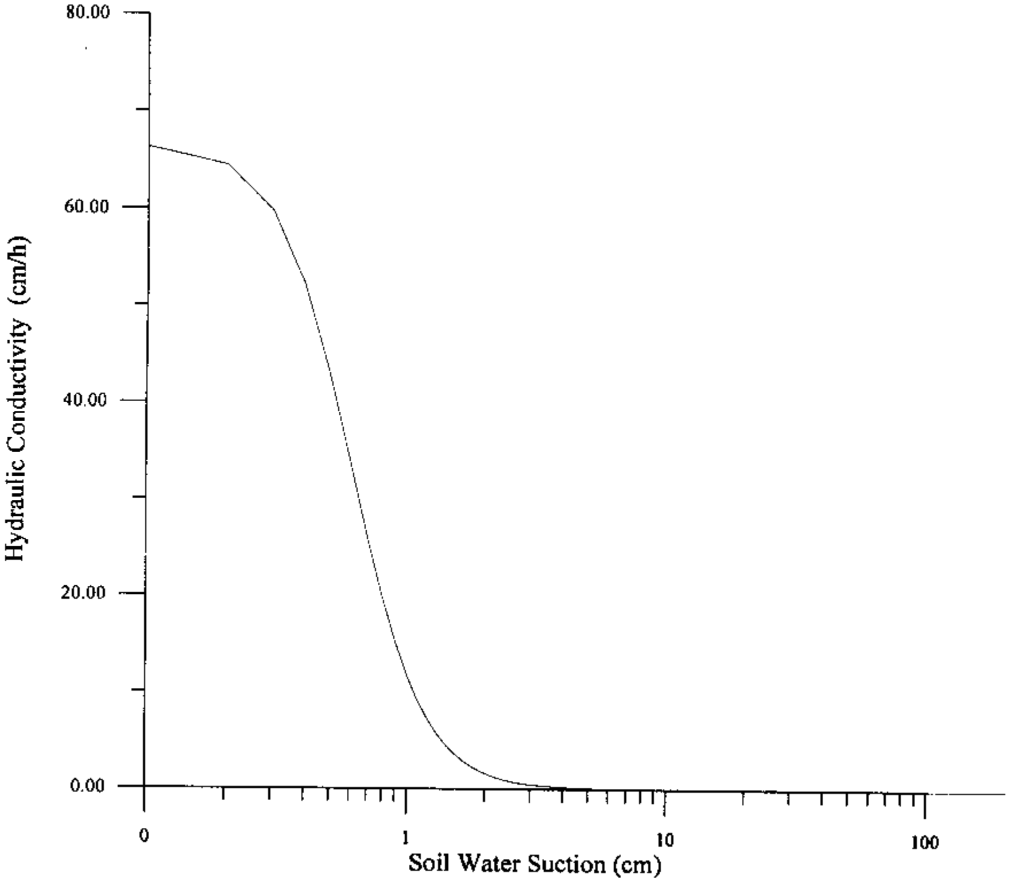

Figure 22 : Variation of Hydraulic Conductivity K with Soil Water Suction (-h) at Kamalpur (K4)

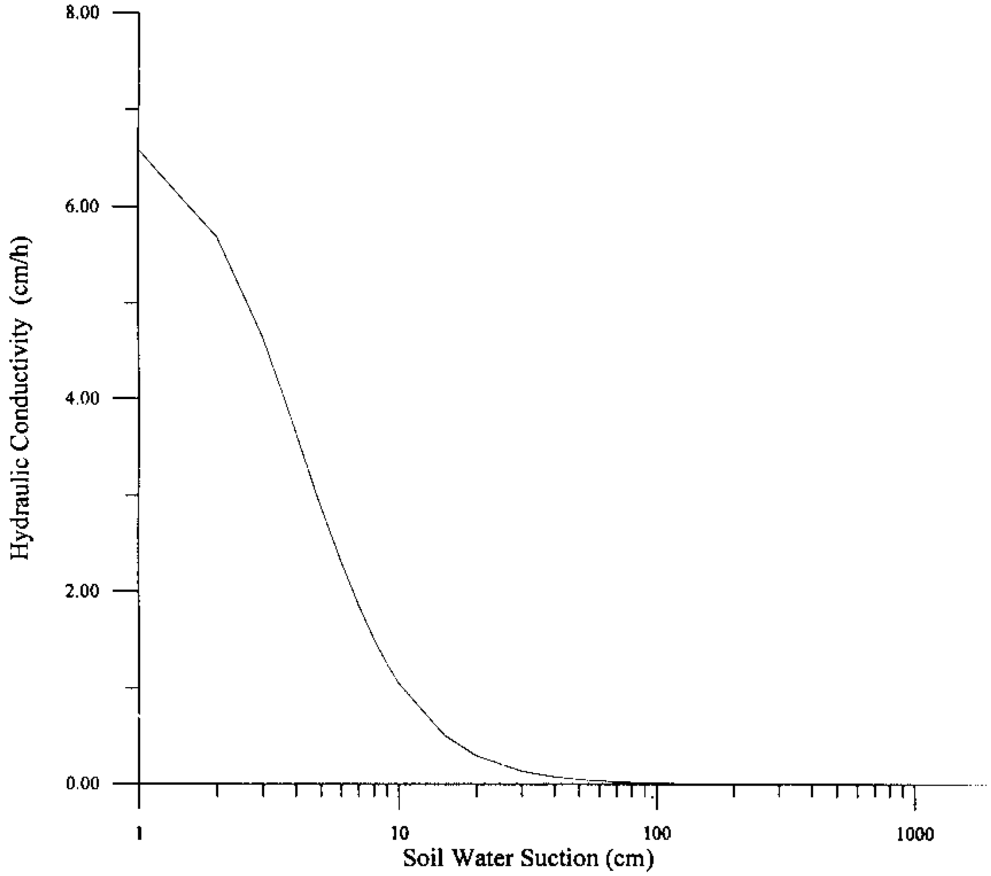

Figure 23 : Variation of Hydraulic Conductivity K with Soil Water Suction (-h) at Kamalpur (K5)

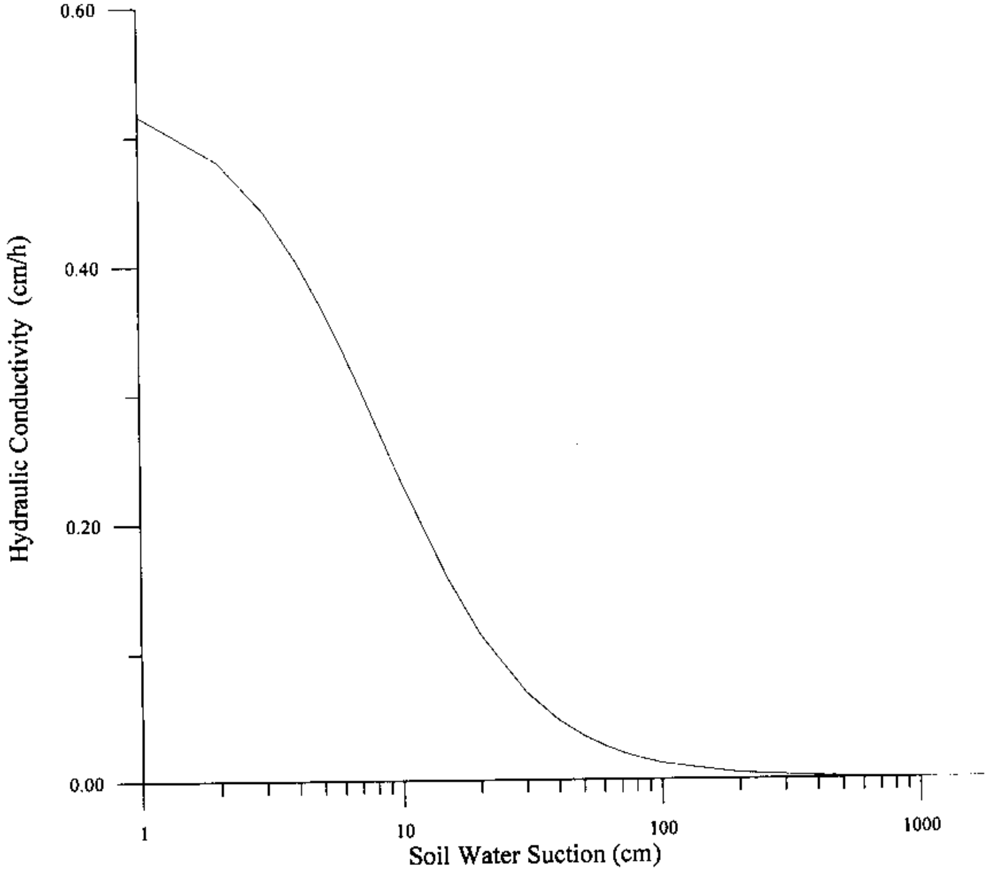

Figure 24 : Variation of Hydraulic Conductivity K with Soil Water Suction (-h) at Kamalpur (K6)

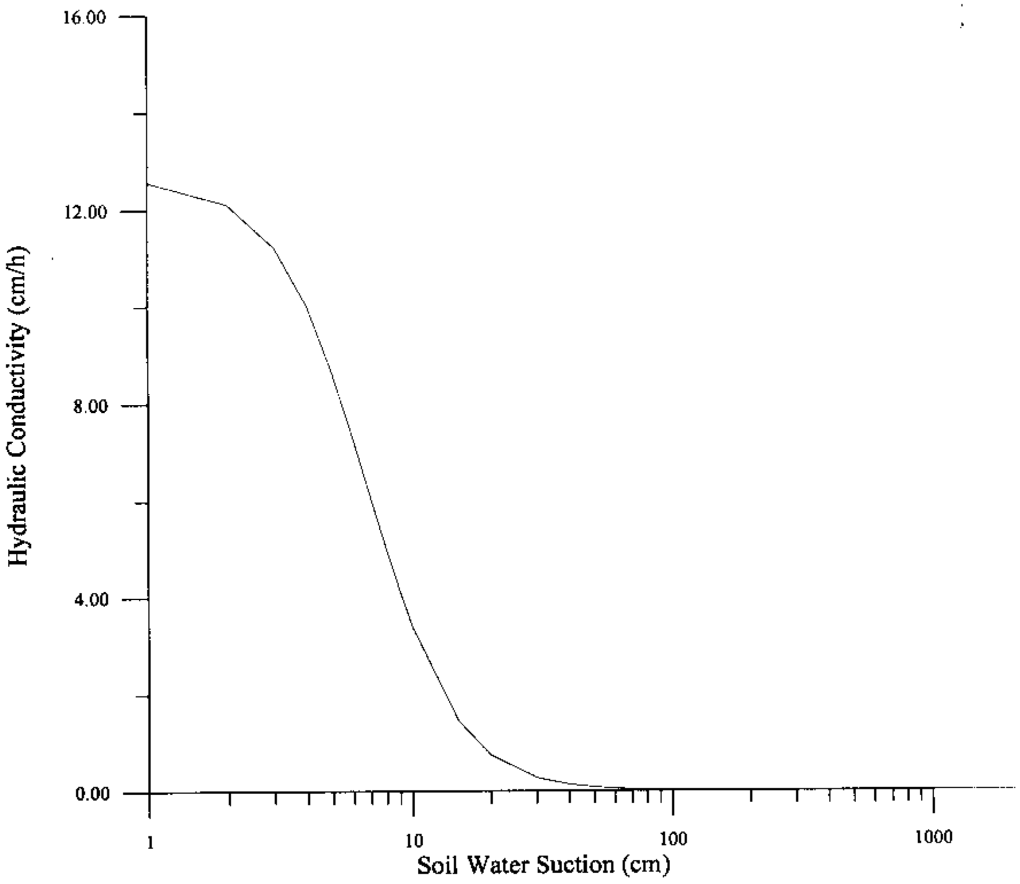

Figure 25 : Variation of Hydraulic Conductivity K with Soil Water Suction (-h) at Budhakhera

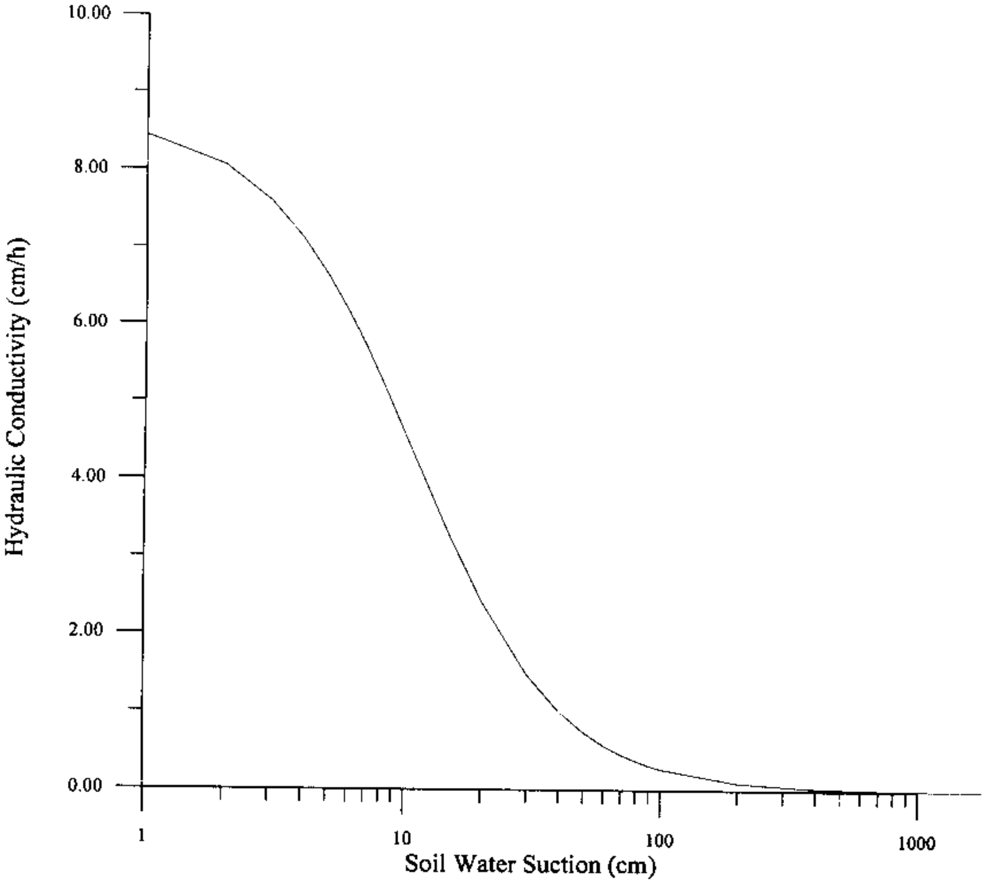

Figure 26 : Variation of Hydraulic Conductivity K with
Soil Water Suction (-h) at Gagalheri

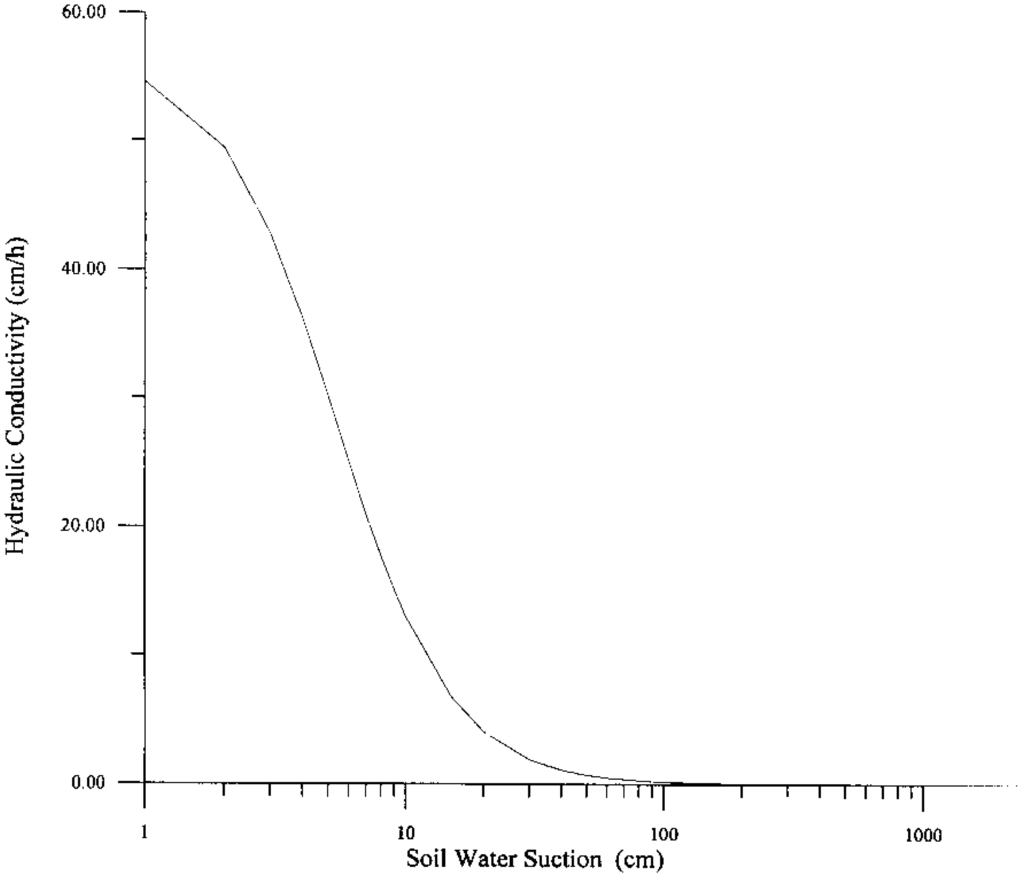

Figure 27 : Variation of Hydraulic Conductivity K with Soil Water Suction (-h) at Dudhil Bukhara

4.5 Concluding Remarks

The physical principles of soil water movement elucidated by theory and experiment are not easily applied in the field because of the complex functional relationships between soil water properties and the difficulties of their measurement, and because of complicating factors that often do not allow soils to approximate to the uniform inert porous materials assumed in most theoretical analyses. An attractive alternative to direct measurement is to calculate the soil functions from more easily determined soil properties such as texture, bulk density, organic matter and clay mineralogy. Models of soil water movement in hydrological systems have therefore progressed by making intelligent estimates of soil water properties and by ignoring complications.

5.0 CONCLUSION

The planning and execution of hydrological and soil technical projects (for instance drainage and irrigation) is almost always preceded by geo-hydrologic research. The utilization of rain and irrigation water received at the soil surface for the growing crops is controlled by the hydrophysical properties of the soil profile. Water enters the soil by infiltration, moves through it by percolation and leaves it by drainage, each of these processes being governed by well-defined physical forces and transmission parameters.

Water relations are among the most important physical phenomena that affect the use of soils for agricultural or engineering purposes. During the recent years, mathematically sophisticated theories of transport in porous material have been proposed. However, the difficulties of making reliable field measurements at an appropriate scale and using them in physically realistic predictive models are undiminished.

In this study, field and laboratory based soil investigations were carried out for the uppermost part of Hindon river catchment. Soil characteristics such as particle size distribution, soil moisture retention curve and saturated hydraulic conductivity were measured at various locations along the Hindon river. The parameters of soil moisture retention function were obtained through non-linear regression analysis. The parameters of hydraulic conductivity function were indirectly derived from the van Genuchten model. Soil characteristics were found to vary widely both spatially as well as along the depth.

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