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ESTIMATION OF SURFACE SOIL PROPERTIES IN MALAPRABHA COMMAND AREA

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

Soil and water are the two main resources of our earth. Soil is a complex of mineral and organic substances. It is a product of development or evolution. It has evolved from a parent material, which is the mantle rock, by a slow process of physical and chemical weathering in addition to the influence of living organisms. The essential ingredients of soil are mineral substances, organic compounds, living organisms, water, and air.

Physical properties of soils such as texture, structure, capacity to retain and transmit water are some of the properties which are important from a hydrologist's point of view, apart from its chemical properties. The soil, located at the atmosphere-lithosphere interface, plays an important role in determining the amount of precipitation that runs off the land and the amount that enters the soil for storage and future use. Soil plays a key role in water retention and storage. Water movement in soils occurs as a liquid flow in saturated soils, and as a liquid and vapour flow in unsaturated soils.

The unsaturated soil zone occupies the centre stage in the hydrological cycle. The ability of the soil to absorb, retain, and transmit water gives rise to the notion of this zone behaving as a leaky reservoir. Input at the surface is in the form of precipitation or irrigation, of which a part is absorbed and the other runs off. The water that infiltrates into the soil is later partitioned between that amount which returns to the atmosphere by evapotranspiration and that which seeps downward and recharges the saturated zone. Flow of water in the unsaturated zone has also been described by Beven (1991) as a complex phenomenon involving transfers of water, air, vapour, and solutes through dynamic flow paths under the influence of hydraulic, temperature, density, and osmotic gradients in a compressible porous medium.

Knowledge about the factors controlling water storage and movement in the soil has been gained through contributions from a wide spectrum of sciences including: soil science, agronomy, geomorphology, environmental engineering, ecology, and hydrology. Soil physics in particular offers an excellent theory for describing water movement in the unsaturated zone, that has been validated through several laboratory experiments.

Water existing in the soil strata is known as subsurface water and can be separated into soil water and groundwater. The soil water occurs in unsaturated zone, and groundwater occurs in saturated zone. In the groundwater zone, all the soil or rock pores are completely filled by water and the upper limit of this zone is termed as water table. The soil water zone occupies the space above the water table which extends upto the soil surface. In this zone, some soil pores are filled with water, some are partially filled, and some are essentially empty, which are filled by air. The unsaturated zone is a transition zone, which supplies water for vegetation growth and through which water moves down to recharge groundwater. The water in this zone can remain in storage, move downwards by gravity to the water table and the groundwater, or move upwards through evaporation and transpiration.

The retention and movement of water in soil and plants involve energy transfers of various types, generally categorized as free energy of water. Water molecules are attracted to each other in a polymer like grouping, forming an open tetrahedral lattice structure. This asymmetrical arrangement results from the dipolar nature of the water molecules. The hydrogen atom of one molecule attracts the oxygen atom of the adjacent molecule in a kind of hydrogen bonding. Hydrogen bonding accounts for the forces of adhesion, cohesion, and surface tension that largely regulate the retention and movement of water in soils.

Water tends to move from a zone of high free energy to one of low free energy - from a wet soil to a dry soil. The energy status of soil water is expressed by the soil water potential. The total water potential consists of several subpotentials, such as matric, gravity, gas pressure, osmotic, and overburden potentials. However, the amount of movement depends on the differences in the energy states (potential) between the two zones.

Gravitational potential is a positive force, but both matric and osmotic potentials are negative forces because they reduce the free energy level of water. The energy required to remove water from soil pores or from the attraction of soil particles can be measured by applying suction to a saturated soil sample placed over a permeable membrane, and is expressed either in atmospheres (or bar) of pressure or height of a water column needed to create such pressure.

Study of water in the unsaturated or vadose zone of the soil is important, since it is the direct source of moisture for vegetation and an integral part of hydrological cycle. Soil moisture movement studies provide potential information in the field of hydrology. These studies are important for understanding the mechanism of recharge through the soil and to provide soil moisture storage data for water balance. The allocation of net precipitation, at the soil surface into either surface or sub surface flow determines, the timing and amount of stream flow that occurs. The surface runoff, soil moisture storage and deep percolation due to infiltration from a storm are influenced by the soil characteristics of the watershed. Infiltration rate, the runoff, the evaporation rate and the storage available for infiltration water prior to groundwater recharge all influence the water balance of an area.

It is required to have a detailed knowledge of hydraulic properties of the soil to quantitatively predict the movement of water through variably saturated soils. Since the water content and its energy status vary from place to place, these measurements have received a great deal of attention. Several direct and indirect methods have been developed to evaluate and measure the soil hydraulic properties and several alternative ways are available to express these quantitatively. Such an evaluation is, however, difficult to make under field conditions but is possible under controlled laboratory conditions. Even under field conditions, if the basic principles governing the state and movement of soil water are known, the appropriate measurement and evaluation technique suited for the purpose can be selected.

There has been a considerable progress in the last decade or two in the understanding of the retention and movement of water in soil mass. There is, however, a large gap between these fundamental studies and their application to the understanding of the role of soils in basin hydrology. The number of measurements required to characterise several horizons of each of the soil types present in a basin requires the use of relatively simple and rapid methods to assess the properties, texture and structure, conductivity, suction in the soil, moisture content, and its moisture retention capacity.

2.0 PHYSICAL AND HYDRAULIC SOIL PROPERTIES

The physical properties of a soil have much to do with its suitability for the uses to which it is put. The rigidity and plasticity, drainage and moisture storage capacity, ease of penetration by roots, aeration, and retention of plant nutrients are all connected with the physical condition of the soil.

The soil located at the atmosphere-lithosphere interface, plays an important role in determining the amount of precipitation that runs off the land and the amount that enters the soil for storage and future use. The moisture status and the movement in soil depend on the pore characteristics and the difference between the water potential. So it is important to estimate the hydraulic properties of the soil in this zone.

The major physical and hydraulic properties of the soil are enumerated below.

2.1 SOIL TEXTURE (PARTICLE SIZE)

Surface soil consists of a mixture of inorganic and organic particles varying greatly in size and shape. Soil texture refers to the coarseness or fineness of the soil. Specifically, texture is the relative proportions of sand, silt, and clay or the particle-sized groups smaller than gravel (less than 2 mm in diameter). The particle size groups are called soil separates or textural separates. The sizes of the mineral particles and the relative proportion of size groups vary greatly among soils, but they are not easily altered in a given soil. Thus, soil texture is considered as a basic property of soil.

A knowledge of distribution of different size groups of the particles is essential for physical characterisation of the soil.

There is sometimes a broad correlation between texture and hydrologic behaviour of soils. Limits of sizes have been fixed differently under different classification systems. Particles less than 0.02 mm are classified as silt and clay in all systems, particle sizes between 0.02 to 2 mm are generally known as sand and particle above 2mm are known as gravel. Schemes for classifying soil separates have been developed in number of countries. The classification used by the USDA, based on diameter limits in millimeters, is given in the table shown below.

Name of Separate	Diameter Limits, mms
SAND	0.05-2.00
Very coarse	1.00-2.00
Coarse	0.50-1.00
Medium	0.25-0.50
Fine	0.10-0.25
Very fine	0.002-0.10
SILT	0.002-0.05
CLAY	Less than 0.002

The determination of particle size distribution in soils is normally called a mechanical analysis. There are several techniques for determining the percentage distribution of particle size, but most of them involve the complete dispersion of soil samples in water, separating them into size classes by physical and chemical processes, and calculating the percentages of each class by weight. Once the particles are separated, depending upon the methods used, several arbitrary criteria can be applied to define the particle size. The coarser particles can be separated into desired size groups through direct sieving. Sand fractions can be separated into arbitrary groups by sieving. The hydrometer and the pipette methods are the two most widely used systems for determining silt and clay fractions. These methods are based on the principle that the particles suspended in water tend to settle in relation to their size.

The result of particle size analyses can be expressed in two ways: (1) percentage distribution, and (2) summation curves.

The percentage distribution method to classify the textural soil type does not provide a complete picture of particle size distribution in different soils. The same textural soil types may have a completely different particle size distribution and may exhibit different properties. A better way is to present the results of particle size distribution analysis is graphically as curves known as summation curves.

Summation curve is a graphical method of reproducing size distribution of soil particles. The result of particle size analysis are expressed by a graph showing the cumulative percentage of weight of all particles smaller than any given diameter as ordinate to an arithmetic scale and diameter of particles to a logarithmic scale as abscissa. With such a graphic representation, it is easy to compare the gradations of soils of different sizes.

The textural class of a soil can be estimated in the field with reasonable accuracy after some experience. A more accurate method of determining textural class designation is by use of the textural triangle. This system is used in most parts of the world, but its use depends first on the determination of particle size distribution.

2.2 SOIL STRUCTURE

Soil structure is defined as the physical constitution of a soil material as expressed by the size, shape and arrangement of the solid particles and voids. Structure refers to the combination or arrangement of primary soil particles (sand, silt, clay) into secondary particles or aggregates.

Soil characteristics such as water movement, aeration, bulk density, and porosity are greatly influenced by the overall aggregation or arrangement of the primary soil separates.

Structure modifies the influence of texture with regard to moisture and air relationships. The macroscopic size of most aggregates results in the existence of spaces in between, which are much larger than that can exist between adjacent sand, silt, and clay particles within an aggregate. It is this structural effect on the pore space relationships that makes structure so important. Field descriptions of soil structure usually give the type or shape, class or size, and grade or distinctness of soil materials contained in each horizon of the soil profile. So the complete description of soil structure consists of combination of these three variables.

The combining of individual particles into structural aggregates is influenced by a number of factors. Among these the nature and origin of the parent materials and the physical and biochemical processes of soil formation are most important. Of particular note are the presence of salts, growth and decay of roots, freezing and thawing, wetting and drying, and the activity of soil organisms. Soil texture has considerable influence on the development of aggregates. Soil aggregates are generally more stable under forested conditions than under cultivated conditions.

2.3 BULK DENSITY

Bulk density is the ratio of dry weight of a given volume of undisturbed soil to the weight of an equal volume of water. Sine it is a weight measurement by which the entire soil volume is taken into consideration, it is influenced by soil structure. Unlike particle density, which is concerned with the solid particles only, bulk density measurement includes air space, as well as soil volume, and this measurement is thus related to porosity. Soil which are high in organic matter have lower bulk densities than soil low in this component. Soil that are loose and porous have low weights per unit volume (bulk density) while those that are compacted have high values.

2.4 PORE VOLUME

The quantity, size and continuity of voids are particularly important in Hydrology, since it is in them that water is stored or transmitted during the subsurface phase of the hydrological cycle.

Pore volume is that part of the soil volume not occupied by solid particles. The soil pores normally contain both air and water, but the relative proportions of each are constantly changing. In a dry soil, the pore spaces are largely occupied by air, but in a waterlogged soil they are filled with water. The coarse textured soils have large pores but their total pore space is less than that of fine textured soils. Because clay soils have greater total pore space than sands, they are normally lighter per unit volume (or have a lower bulk density). If bulk density is known, the pore space of mineral soil can be calculated using the formula:

pore space(%)=100-(bulk density/particle density)X100
(porosity)

Pore volume is conveniently divided into capillary and noncapillary pores. Soils with a high proportion of capillary (small diameter) pores generally have high moisture holding capacity, slow infiltration of water, and perhaps a tendency to waterlog. On the other hand, a soil with large proportion of noncapillary (large diameter) pores generally has good aeration, rapid infiltration, and a low capacity to retain moisture.

Since water molecules are strongly adsorbed onto soil surfaces, pore characteristics are of great importance with regard to the flow or movement of water into (infiltration) and through (percolation) soil.

2.5 SOIL MOISTURE AND SOIL MOISTURE RETENTION

The soil moisture characteristic (SMC) expresses the functional relationship between the volumetric moisture content (θ) and the matric potential (h), in an unsaturated porous medium.

The SMC has been the subject of considerable research activity for many years now and several laboratory, field, and theoretical methods have been developed for its estimation. Laboratory determination of the SMC involves desorption of a saturated soil sample to a specified pressure and then determination of its equilibrium water content. Field determination involves simultaneous insitu measurement of matric potentials and moisture contents at the depth of interest. Both the laboratory and field procedures are tedious, expensive and cannot be used to characterise large area, because of the known spatial variability of soil properties. Also, the insitu and laboratory SMCs will defer, since the laboratory samples can never fully duplicate field conditions.

Measurement of water content are needed in hydrological studies for direct knowledge of the quantity of the available soil water for interpretation of physical and chemical measurements, and for determination of water retention and hydraulic conductivity curves. Soil water content can be expressed as a dimensionless mass or volume ratio. Gravimetric and volumetric soil water content are related to each other as $\theta = \gamma_s\theta_g$, where θ is volumetric water content, γ_s is dry bulk density and θ_g is gravimetric soil water content.

The direct and indirect methods of measuring soil water content can be broadly classified into following main groups:

a) Thermo-gravimetric, which can be used as standard for calibration of other methods,
b) Lysimetric, for measuring the change in soil moisture with time,
c) Penetrometer,
d) Electrical,
e) Nuclear, includes neutron scattering methods which are most accurate and time consuming,
f) Acoustic (ultrasonic),
g) Chemical and
h) Thermal.

Matric potential of the water in unsaturated soil layer arises from local interactions between soil and water. When this potential changes, its water content will also change. After exerting a certain pressure head or suction upon a soil sample, the equilibrium soil moisture content can be determined. Applying different pressure heads step by step, a curve of pressure head versus moisture content can be obtained. This is generally called the soil moisture retention curve.

Investigators have long attempted to device useful equilibrium points or constants in describing soil moisture. Such terms as field capacity, moisture equivalent, hygroscopic coefficient, and permanent wilting point have found their way into soils literature over the years. When water from a heavy rain passes through the soil surface, air is displaced and the soil pores, both large and small, become filled with water. At this point, the upper part of the soil is saturated and is at its maximum retentive capacity. With the cessation of rains, there is a relatively rapid downward movement of some of the water until, after a day or so, this movement will essentially cease and gravitational water is drained away.

Field capacity describe the amount of water held in the soil after gravitational water has drained away and, for all practical purposes, the downward movement has stopped. It is an excellent concept for expressing the upper limit of available soil moisture for plants. The factors such as soil texture and structure, organic matter content, and water table significantly influence the values. The presence of soil layers of different pore size markedly influences water flow and, hence, field capacity. The amount of moisture retained by exerting a pressure of about 0.33 bar, for silt loam soils and one-tenth bar for sands, are often used to approximate field capacity.

The amount of water held in a sample of sieved soil after it has been subjected to a centrifugal force of 1000 times gravity is termed as **moisture equivalent**. It is sometimes used as an approximation of field capacity.

Hygroscopic coefficient describes the amount of hygroscopically bound water in soils. It is sometimes used to mark the lower limit of available water. It is the moisture content of a soil that has lost its liquid water from even the smallest of micropores.

The moisture content of a soil at which plants remain permanently wilted unless water is added to the soil is called **permanent wilting point**. This is used to refer the lower limit of soil water storage for plant growth. The amount of moisture retained at a tension of 15 bars exerted by a pressure membrane apparatus is probably the best approximation of this moisture content.

Retention and detention are two constants used to describe soil water storage in watershed studies. Retention storage refers to water that can be held in soil capillary pores, expressed as centimeters of water per given depth of soil. It is termed retention storage because this water is retained in the soil and does not contribute directly to stream flow or groundwater. Water in the noncapillary pores is called detention storage because it is only temporarily held. Depending on permeability of horizons, detention water will either flow laterally to stream channels or downward to satisfy capillary moisture deficits and eventually to the water table.

2.6 HYDRAULIC CONDUCTIVITY

Hydraulic conductivity is defined as the volume rate of flow of water through a unit area of soil under a unit gradient and is a measure of the ability to conduct water under a unit hydraulic potential gradient. Saturated conductivity represents the soil conductivity when the soil is saturated. Field saturated hydraulic conductivity refers to the saturated hydraulic conductivity of soil containing entrapped air. It is more appropriate than the truly saturated hydraulic conductivity for vadose (unsaturated) zone investigations because, by definition, positive pressure heads do not persist in unsaturated conditions long enough for entrapped air to dissolve.

The hydraulic conductivity curve defines the relationship between the hydraulic conductivity of the soil and its water content, $K(\theta)$ or water potential $K(h)$. The conductivity of a soil depends to a large extent on the pore geometry which is determined by soil texture and structure. It is at its maximum when the soil is saturated and decreases with decreasing water content or increasing water tension. Conductivity curves can be used in the analysis of infiltration, drainage and water transport towards roots of transpiring plants.

Both in field and laboratory, hydraulic conductivity can be measured under steady or transient flow conditions with a number of methods. With a steady state method, all boundary conditions remain constant in time and the conductivities are directly calculated from flux and hydraulic potential measurements.

Therefore, these methods are more accurate than transient ones. However, at low fluxes in slowly permeable soils, the flow system will take a very long time to reach a steady state. Transient methods are generally faster than steady state methods and cover a wider range of soil water retention.

In saturated soils, conductivity may be measured in the field by a number of methods or in laboratory on soil cores taken with a minimum of disturbance. Most of these methods are based on the Darcy's equation and calculate the saturated conductivity by measuring soil water flux and the hydraulic gradient. Commonly used laboratory methods to estimate saturated hydraulic conductivity, are constant head method and falling head method. Several field methods have been developed to measure saturated conductivity below and above groundwater table. The most common methods below water table are piezometer method and auger hole method. Methods used above groundwater table are shallow well pump-in method, ring permeameter method, double tube method, guelph permeameter, and disc permeameter. These methods take considerable time and effort, since a large quantity of water is required to saturate the soil under investigation.

Attempts have been made to calculate the conductivity of unsaturated soils (capillary conductivity) from the pore size distribution. The techniques are, however, difficult and subject to improvement in many ways. Important laboratory methods are steady state head control, steady state flux control, and transient one step out flow. The important steady state methods in field are crust and sprinkler imposed flux methods and the most important transient method is unsteady drainage flux. These methods are suitable for field measurements if the topography is reasonably level, the soil is not too stony and vertical flow dominates during the experiment. The crust method is a field variant of the steady state flux method used in the laboratory. It can also be obtained from field studies of water movement using tensiometers to follow changes in suction.

Disc permeameter is an instrument developed at CSIRO, Canberra, to measure both saturated and unsaturated hydraulic conductivity under field conditions. Details are given in next chapter.

Empirical evidence and intensive reasoning indicate that conductivity increases with increasing particle size. It was generally found that hydraulic conductivity is proportional to the second power of particle size. Later on, researchers replaced the particle diameter with the effective diameter since the diameter of soil particles is not uniform. Small particles mixed into a soil will decrease its hydraulic conductivity. It is obviously affected by structure as well as by texture, being greater if the soil is highly porous, fractured, or aggregated.

2.7 INFILTRATION

Infiltration is the process of water entry into soil profile through the soil surface. It is usually expressed in units of depth per hour. Infiltration might best be regarded as a concept because one cannot see or directly measure it without influencing its value. The infiltration process is of great importance and it affects many aspects of Hydrology and Agriculture. Runoff, one of the important component of the hydrologic cycle, is determined by subtracting the abstractions that occurring the drainage basin, from rainfall. The most important abstraction affecting runoff is the portion of precipitation that is lost to infiltration.

Infiltration results from the combined forces of capillary and gravity. The initial high rate is due to the physical attraction of soil particles to water or the metric potential gradient. The maximum rate at which water can enter the soil surface is called infiltration capacity. The actual infiltration rate equals the infiltration capacity only when the rainfall rate equals or exceeds the infiltration capacity. When rainfall intensity is less than the infiltration capacity the rate of infiltration equals rainfall intensity. Only when rainfall intensity exceeds the infiltration capacity of a soil can runoff occur.

The infiltration rate as a function of time defines the infiltration curve. Since the capillary forces are strong, when the soil is dry, the rate of infiltration is more at the beginning of the precipitation, for a soil type and antecedent moisture condition. As the time progress, the resistance to the forces acting on the water increases and the rate of infiltration decreases. As a result, a constant infiltration rate attains after some interval, when the soil is fully saturated. This rate is known as ultimate infiltration capacity.

Horton infiltration equation is,

$f = f_c + (f_0 - f_c)\, e^{-kt}$, where f_0, f_c and k are parameters to be estimated from data.

The infiltration capacity of a soil depends on several factors, including texture, structure, surface conditions, nature of soil colloids, organic matter content, soil depth or presence of impermeable layers, and presence of micropores within the soil. Soil water content, soil frost, and the temperature of the soil and water all influence infiltration characteristics of a soil at any point in time. Many of the above factors are also influenced by landuse and vegetation management practice.

Measuring infiltration and infiltration capacity is difficult, since both are influenced by the rate of application. However, the generally used methods are given below.

Flooding Infiltrometers - Most often, a double ring infiltrometer is used which is easy and relatively inexpensive to apply. But the positive head of water due to ponding causes higher infiltration rates than might occur from rainfall. So these are useful for obtaining comparisons of infiltration rates for different soils, sites, vegetation types, and treatments.

Rain Simulators - This method will avoid the effect of ponding and the effect of raindrop impact on soil is taken care of. These, either apply water to the soil surface in a manner that simulates rainfall (sprinklers) or provide a system for which natural rainfall events can be evaluated. The runoff plot has a boundary strip that forces any surface runoff to flow through a measuring device. Rainfall simulators can be adjusted to represent different drop sizes and rainfall intensities. The approach is more costly and difficult to apply in remote areas. Infiltration capacities determined by this approach should be more representative of actual infiltration capacities than those determined by flooding type infiltrometers. However, studies have shown that there is a consistent relationship between infiltration capacities determined by the two methods.

Hydrograph Analysis - By analysing the runoff hydrograph and the rainfall data, it is possible to obtain a reasonable estimate of infiltration of a drainage basin . The hydrologic budget requires accounting for evapotranspiration, depression storage, and interception.

Correlation with related variables - Drainage basin infiltration can be related to such variables as median-grain diameter, drainage density, runoff volume, and sediment yield.

Infiltration indices - ϕ-index is the mean infiltration rate occurring for the duration of the storm. This means, infiltration rate is the rainfall rate above which the rainfall volume is equal to the runoff volume. W-index defines the ϕ-index, by including interception and depression storage.

3.0 DISC PERMEAMETER

The CSIRO Disc Permeameter, developed in the CSIRO Centre for Environmental Mechanics, Canberra, Australia, is designed to measure the insitu hydraulic properties of field soils. It enables rapid measurement of hydraulic conductivity, sorptivity, macroscopic capillary length or α-parameter, and characteristic pore size with minimal soil disturbance. The contribution of preferential flow paths, such as biopores, to field infiltration can be assessed quantitatively with the permeameter. Its principal application is in measurements on surface soils, particularly in relation to soil management and land degradation studies.

When a source of water, such as a wet circular disc or shallow pond, is placed on the soil surface, the initial stages of flow into the soil are dominated by the soil's capillary properties. As the time progress, both the size or geometry of the water source and the force of gravity influence the water flow rate. For a uniform soils, a time will eventually reach where the flow rate from the source becomes steady. This steady state flow is governed by capillarity, gravity, the size of the disc, and the pressure at which water is supplied to the soil surface.

In this technique, both the initial and steady state flow rates are used to separate the capillarity and gravity contributions to soil water flow.

The method for determining soil hydraulic properties from disc permeameter measurements in the field is given by White, Sully, and Perroux (1989) and is based on an analysis (Wooding, 1968) of the three dimensional flow from a shallow circular pond or surface disc.

For a pond or disc of radius r_0, on a homogeneous soil, Wooding showed that when water is supplied at a potential of ψ_0 the steady state volumetric flow rate q is;

$$q = \pi r_0^2(K_0-K_n) + 4r_0\varphi$$

The first term on the right essentially represents the contribution of gravity to the total flow from the surface disc and the second term contains the contribution due to capillarity. In the gravity term, K_0 is the hydraulic conductivity at the supply potential ψC, and K_n is the hydraulic conductivity at the initial soil water potential ψ_n. For relatively dry materials, K_n is much smaller than K_0 and can be safely ignored. The capillary term contains the matric flux potential φ, which is related to the conductivity by $\varphi = K_0\ \lambda_c$.

The macroscopic capillary length λ_c is related to the sorptivity S_0 and the hydraulic conductivity,

$$\lambda_c = bS_0^2/(\theta_0-\theta_n)\ K_0$$

where, θn is the initial moisture content at ψ_n, θ0 is the moisture content at the supply potential ψ0 and b is a dimensionless constant whose value lies between 0.5 and π/4. For field soils, a good mean value for b is 0.55.

The above equation can be rewritten as,

$$q = \pi r_0^2 K_0 + 4\ r_0 bS_0^2/(\theta_0-\theta_n)$$

or $$q/\pi r_0^2 = K_0 + 4\ bS_0^2/(\theta_0-\theta_n)\pi r_0$$

Rearranging,

$$K_0 = q/\pi r_0^2 - 4\ bS_0^2/(\theta_0-\theta_n)\pi r_0$$

During the early stages of flow from the disc, capillarity dominates flows irrespective of the size of the disc. At short infiltration times, the system behaves as if it were one dimensional. In this case, the cumulative infiltration is given by (Philip, 1969),

$$Q/\pi r_0^2 = S_0\ t^{0.5}$$

where, Q is the total volume of water infiltrated and t is the time from the commencement of infiltration. Sorptivity, then, is the slope of the cumulative infiltration Vs $t^{0.5}$ plot.

To calculate the hydraulic conductivity, the measurements required are the sorptivity, the steady state flow rate, the initial volumetric moisture content and the volumetric moisture content at supply potential.

The design of the disc permeameter used to make saturated (ponded, positive water potentials) and unsaturated (negative water potentials) measurement are given in Fig.1.

Prior to use, each reservoir must be calibrated.

The initial water content and the bulk density are needed to calculate hydraulic conductivity. Measurements are made on cores taken approximately 250 mm from the centre of the disc permeameter surface.

Saturated Permeameter:

The potential for the ponded permeameter is adjusted by means of the height adjusting screws on the base of the disc. The potential at the soil surface is the distance from the bottom of the air entry tube to the soil surface. The usual supply potential for ponded infiltration is +10 mm.

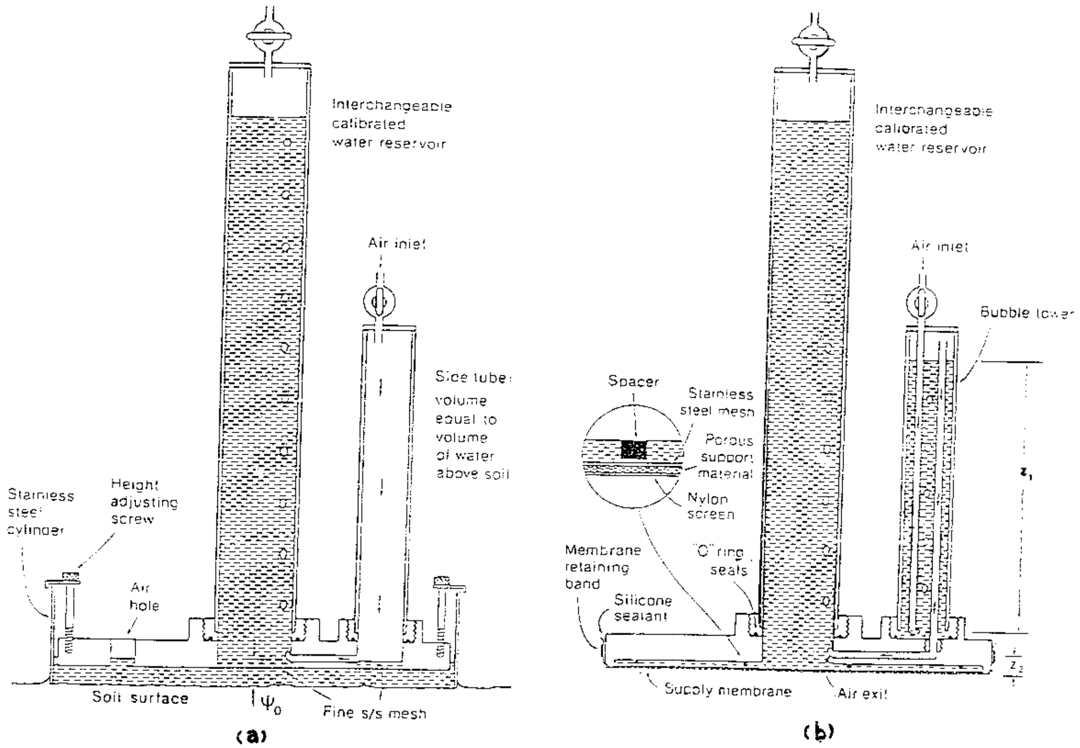

FIG. 1: DISC PERMEAMETER SETUP FOR
(a) SATURATED HYD. CONDUCTIVITY
(b) UNSATURATED HYD. CONDUCTIVITY

Clear a thin band on the soil surface where the edge of the steel ring will be in contact with the soil. Remove from the centre of the ring, any large stones that would interfere with the disc and clip the vegetation to a height below the level of the bottom of the disc.

Insert the ring about 4 mm into the soil surface by placing a cover plate over the ring until the cover plate contacts the spacer. The depth of insertion must be constant as it affects the supply potential. Remove the cover plate and spacer and seal the ring on the outside with a bentonite or local clay paste.

Set the empty permeameter on the ring and check that the permeameter is level and the supply potential is properly adjusted.

Remove the permeameter from the ring and place in a bucket of water. Fill the side tube to the required volume (as that of supply potential). Fill the reservoir tube with water.

Infiltration Measurement: Carefully place the permeameter in the ring. To begin the measurement, open the stopcock on the side of the tube. Start the stop watch when the side tube empties. It is essential that the seal on the outside of the ring does not leak.

With the recording stop watch, record times at constant predetermined scale increments on the reservoir tube, usually 5 to 10 mms. It is important to record as many accurate measurements as possible during the early stages of flow. The scale increment used depends on the soil and is best determined by experience. After the early stages, measurements can be recorded continuously or interrupted until flow approaches steady state. At least 10 measurements have to be taken to ensure that an accurate value for steady state flow is obtained. In some soils, several reservoir volumes are required before steady state flow is reached.

At the end of infiltration measurements, close the stopcock and remove the permeameter. Collect a soil sample off the soil surface as soon as free water disappears from the surface, which can be used to calculate supply surface water content.

Unsaturated Permeameter:

Water potential is set by altering the water level in the bubbling tower. The water potential at the membrane is $z_2 - z_1$. The value of z_2 is fixed for each disc so that the potential is varied by altering z_1, the height of the water above the bottom of the air inlet tube.

The unsaturated permeameter is not air-tight unless the disc is soaked in water for several hours prior to the measurements.

If the soil is not bare and flat, it will be necessary to prepare a cap of contact material. Place the ring on the surface, fill with a suitable contact material such as fine sand and smooth the surface. Carefully remove the ring. Infiltration measurements should be made as soon as possible to prevent the contact material surface from drying. Fill the disc reservoir.

Infiltration Measurement: The same scale increments are used for the unsaturated measurements as are used for the ponded measurements. When placing the disc directly on the soil surface, begin timing as soon as the bubbling begins. If the disc is placed on a cap of contact material, timing does not begin until the wetting front moved through the cap. The time taken depends on the cap material, the thickness and the value of the water potential set by the bubbling tower.

Record times as often as possible during the early stage of infiltration. Continue making reading until the flow rate is constant.

Soil sample should be taken immedietly after removing the disc, to determine the supply water potential.

Both the duration of the sorptivity phase and the time of approach to steady state depend on the soil. The duration of the sorptivity-dominated phase can range from 0.02 to 1 hour. The time required to approach steady state flow ranges from 0.2 to 6 hours.

Data Analysis:

The sorptivity S_0 is calculated from the early time data. To find S_0, plot scale reading on the Y axis against the square root of time on the X axis. The slope of the straight line portion multiplied by (the reservoir calibration/Area) is the sorptivity and has units length/time$^{0.5}$.

The steady state flow rate can be found by plotting the scale against t and multiplying the slope of that line by (the reservoir calibration/Area).

The hydraulic conductivity of the soil at the potential at which the measurement is being made is calculated from the equation;

$$K_0 = q/\pi r_0^2 - 4\ r_0 b S_0^2/(\theta_0-\theta_n)\pi r_0^2$$

Macroscopic capillary length is calculated by using the equation;

$$\lambda_c = bS_0^2/(\theta_0-\theta_n)K_0$$

and the mean pore size is calculated using the equation;

$$\lambda_m = 7.4/\lambda_c$$

4.0 PRESENT STUDY

4.1 STUDY AREA

The Malaprabha and Ghataprabha projects have been conceived by the Karnataka Government as part of the State's long term development programme to irrigate the drought prone Northern districts of Belgaum, Bijapur, and Dharwad. Though the storage dams were completed in early 70's and both the schemes have been in operation since 1974, their canal systems are still incomplete and under construction.

The Command Area Development Authority, Malaprabha & Ghataprabha Projects, Belgaum, has been established under the provisions of the Karnataka Command Area Development Act, 1980, for comprehensive and systematic development of the area which are benefitted by the above major irrigation projects.

These projects in the northern part of the Karnataka State play a very important role, extending irrigation benefits to vast areas covering 19 taluks in Belgaum, Bijapur, and Dharwad Districts.

The Malaprabha project consists of a storage dam near Navilutheerth in Belgaum district with gross storage of 1068 M cum and construction of canal system to irrigate an area of 218191 ha. in the district of Belgaum, Dharwad, and Bijapur. The main components of Malaprabha project are Malaprabha dam, Malaprabha Left Bank Canal (MLBC), Malaprabha Right Bank Canal (MRBC) and Kolachi Right Bank Canal.

The command area of Malaprabha is located between 15° 24' 02'' to 16° 36' 09'' N latitudes and 74° 26' 43'' to 75° 56' 33'' E longitudes covering 218191 ha of land out of which 64786 ha lies in Belgaum district, 30873 ha in Bijapur district, and 122532 ha in Dharwad district of Karnataka, as shown in Fig.2.

Bailhongal, Ramdurg, and Saundatti taluks in Belgaum district; Nargund, Navalgund, Ron, and Hubli taluks in Dharwad district; and Badami taluk in Bijapur district are benefited by the canal systems of Malaprabha project.

The Malaprabha left canal command is nearly level to undulating lands with elevation ranging from 1900 to 2200 ft. above MSL. The main canal runs along the ridge line south to north from Manoli to Bannur, then traverses to the east upto Badami and takes a turn to the north upto Katageri. The general slope of the area is towards the south-east.

The climate of the project area is semi-arid with moderate to severe summer and moderate winter and low erratic rainfall. The rainfall in the project region shows considerable variations with annual rainfall averaging more than 1500 mm near Belgaum to less than 600 mm on the eastern side. About 60-70 % rain occurs between June to September.

The greater part of the command area is underlain by crystalline rocks comprising granite, gneiss, and schist in the southern part and shale, quartzite, sandstone, limestone, and dolomite in the northern part. Basalts are found as outliers surrounded by older rocks in the northern part of the command.

The groundwater occurs under unconfined and semi-confined conditions in the weathered, semi-weathered and interconnected fracture zones and under confined conditions in deep seated fractures. The basalts have comparatively better yields. The yields are lower in schists, phyllites, and shales. Dug wells and bore wells are extensively used for irrigation, domestic and drinking water supplies.

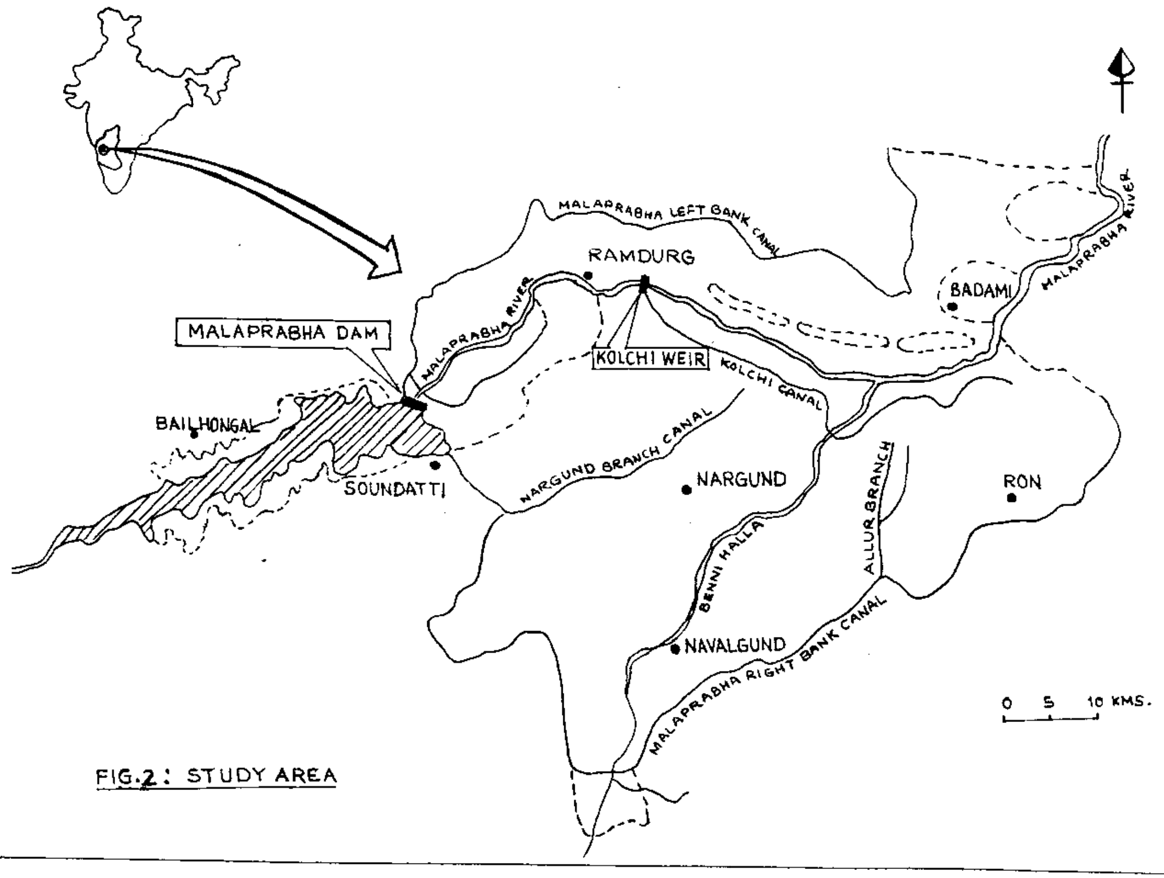

FIG.2: STUDY AREA

Season-wise, the following are the main cropping pattern;

Kharif - Hy. Maize, Kh. Jower, Ground nut, Sun flower
Bi-season - Cotton
Rabi - Rabi Jower, Wheat

Hydrogeological survey and mapping work carried out by the CADA has indicated that low lying area have become waterlogged, since there are no proper drainage to transport excess water applied for irrigation. Also, the natural drains existed in the irrigated areas have been silted up causing drainage problem. An area of 709.30 Ha of waterlogged area have been demarcated and efforts are on for the reclamation of the waisted land and to avoid future waterlogging by various types of drains.

4.2 METHODOLOGY

Spatial variations in the soil properties arise not only due to the variation in the properties of the soil matrix, but also due to many factors such as land use pattern, soil, geology, etc. In order to have a general idea about the hydraulic behaviour of the soils in a region, it is required to measure these properties in as many as possible sites within the area, which represents the spatial variation in that region. In the present study, 16 sites were selected by considering the soils, topography, and uniform distribution within the command area.

The CSIRO Disc permeameter is used to measure the major hydraulic properties such as saturated conductivity, sorptivity, infiltration, and pore characteristics. Double ring infiltrometer has also been used to have a cross check on the estimated value of infiltration rate. Soil samples have been brought to laboratory and soil texture analysis have been dine using pipette method. Pressure plate apparatus has been used to get the soil moisture retention curves for the different soil samples.

The location of the test sites is shown in Fig. 3.

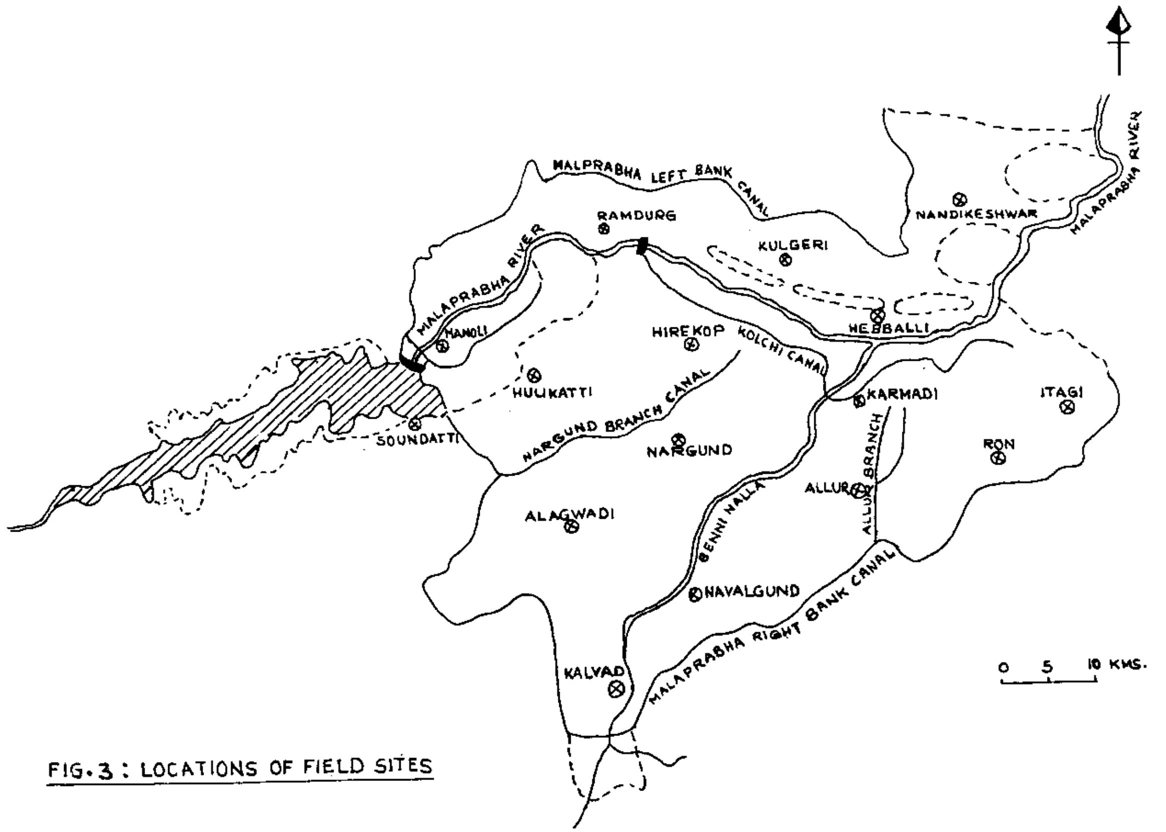

FIG.3 : LOCATIONS OF FIELD SITES

4.3 SITE DESCRIPTION

SOUNDATTI: Soundatti is located at about 60 km. east of Belgaum at an elevation of 658 m. Navilutheertha dam across Malaprabha river is situated in Soundatti taluk.

The test were performed on an agricultural land (Tur Daal cultivation) situated about 1 km from Soundatti on Belgaum-Soundatti road, near to the reservoir. Soil at the site is of black in colour and heavy loam in texture. Lot of mud cracks were present at the test site, which caused a very high initial infiltration.

MANOLI: Manoli is located about 10 kms north of Soundatti, across the dam, in Soundatti taluk. Malaprabha river, downstream of the dam is passing through this village. The soil is light brown in colour and of medium loam texture. The test site was a maze cultivated land, about 1 km from Manoli on Manoli-Hulikati road.

HULIKATTI: This test site is situated 10 kms east of Soundatti (Soundatti taluk), 1 km from Hulikati, on Nargund road. The soil is brownish black in colour and heavy loam in texture. The land is used for maze cultivation.

NARGUND: Nargund is about 100 kms east of Belgaum. The tests were conducted on a land which lies behind APMC campus, used for cotton plantation. Soil is light black and sandy in texture.

HIREKOP: Lies about 15 kms north of Nargund, in Ramdurg taluk. Test site was on a maze cultivated land. Soil is of light black in colour with trace of lime content.

RAMDURG: Situated about 80 kms east of Belgaum at an altitude of 557 m. Red, black and mixed soils occur in these area. Malaprabha passes through this area. The test site was located on Ramdurg-Badami road. The land is presently not used for cultivation because of water logging and salinity problems, probably due to overirrigation. Soil is light black in colour.

KULGERI: Kulgeri is located about 25 kms from Ramdurg in Badami taluk. Soil is reddish brown in colour.

NANDIKESWAR: Located about 15 kms north of Badami in Badami taluk. Soil is reddish brown in colour. Tests was conducted in a sun flower cultivated land. This area forms the north-eastern extreme of the command area.

HEBBALLI: Hebballi is located at 15 kms south-west of Badami on Badami-Nargund road (Badami taluk). Malaprabha passes through this place. Soil is red in colour and sandy in texture. Site showed a very high infiltration, and because of this, the disc permeameter cylinder had to be filled three times for getting somewhat constant reading.

KARMADI: The site is located about 25 kms north-east of Nargund, on black soil, groundnut cultivated land (Ron taluk). The site is on the bank of Kolchi canal.

ITAGI: Located about 20 kms east of Ron in Ron taluk. This is the farthest point of the command area and found to be very dry. Soil is black in colour with trace of lime and the land is used for maze cultivation.

RON: Ron is located about 150 kms east of Belgaum. Tests were performed on cotton cultivated land where soil is black in colour and sandy in texture.

ALLUR: Located 25 kms west of Ron in Ron taluk on Ron-Nargund road. Test site was near to Allur branch canal on sunflower cultivated land. Soil is of black in colour.

ALAGWADI: Located about 15 kms from Navalgund (in Navalgund taluk) on Navalgund-Soundatti road. The land is used for jower cultivation and the soil is found to be black in colour.

NAVALGUND: Situated about 120 kms south-east of Belgaum. The test is performed on a land where black soil with very deep mud cracks were present. The land is used for khushmi cultivation.

KALWAD: Located at 15 kms from Navalgund on Navalgund-Hubli road in Navalgund taluk. Soil is black in colour and the test site is an agricultural land with bajra cultivation.

5.0 RESULTS AND DISCUSSION

To analyse the soil characteristics and its spatial variability in a command area, 16 test sites were selected within the Malaprabha command area. Field tests were conducted using Disc permeameter, for estimating infiltration, conductivity, and pore characteristics. In order to have a comparison of the infiltration values determined by this new instrument, a double ring infiltrometer was also used side by side. Soil samples were collected from each site and laboratory tests were conducted on these samples to estimate bulk density, insitu moisture content, and moisture content at saturated condition. Pressure plate apparatus was used to determine soil moisture retention values at different pressures. Pipette analysis was performed on the samples to find out the textural classification. The results from the above studies are presented below.

5.1 DISC PERMEAMETER EXPERIMENT

Disc permeameter is used in the field to measure saturated hydraulic conductivity, infiltration, sorptivity, and pore characteristics. It can also be used to estimate conductivity values for various supply potentials, which was not performed in the present study.

In order to estimate the insitu hydraulic properties of soils, it is important to have an idea of the physical condition of the soil, which is expressed by bulk density and moisture status. Core samples were collected and the above properties have been determined by gravimetry in the laboratory. These values are given in table 1, which is further used to calculate infiltration, conductivity, etc.

TABLE 1: BULK DENSITY AND MOISTURE STATUS OF SOILS AT DIFFERENT EXPERIMENTAL SITES

TEST SITE	BULK DENSITY	MOISTURE STATUS (%) θ_0	 θ_n
SOUNDATTI	1.60	35.12	15.22
MANOLI	1.51	39.03	3.02
HULIKATI	1.07	35.11	3.40
NARGUND	1.57	48.59	5.62
HIREKOP	1.55	41.01	7.70
RAMDURG	1.85	50.43	3.69
KULGERI	1.68	43.00	1.62
NANDIKESAR	1.50	16.00	1.50
HEBBALLI	1.59	14.54	0.45
KARMADI	1.64	43.08	9.96
ITAGI	1.56	36.70	6.70
RON	1.49	52.17	19.03
ALLUR	1.47	32.24	7.41
ALAGWADI	1.40	53.08	8.11
NAVALGUND	1.78	55.42	7.25
KALWAD	1.37	62.66	9.22

θ_0 - moisture content at the supply potential
θ_n - In-situ moisture content

With the steady state flow rate obtained from the field experiment using the disc permeameter, soil properties such as sorptivity, infiltration, saturated conductivity, and the pore characteristics were calculated for each site and the same are tabulated in table 2. The soil was sandy in nature at Hebballi, where infiltration was very high. Calculation was not possible with the noted readings from the disk permeameter experiment. Also, tests were conducted on a waterlogged land at Ramdurg, where absurd results were obtained.

TABLE 2: SOIL HYDRAULIC PROPERTIES MEASURED WITH THE USE OF DISC PERMEAMETER

TEST SITE	INFILTRATION mm/hr	CONDUCTIVITY mm/hr	SORPTIVITY mm/hr	PORE CHARACTERISTIC	
				λc mm	λm mm
SOUNDATTI	53.48	25.28	28.38	87.62	0.09
MANOLI	74.55	34.24	45.52	92.46	0.08
HULIKATI	122.95	32.13	64.42	222.00	0.03
NARGUND	31.25	16.17	30.43	73.25	0.10
HIREKOP	55.86	20.52	40.81	135.27	0.06
RAMDURG	+	+	+	+	+
KULGERI	226.89	60.75	98.63	214.81	0.03
NANDIKESAR	70.32	36.51	34.04	72.73	0.10
HEBBALLI	*	*	*	*	*
KARMADI	75.91	24.82	44.38	161.65	0.05
ITAGI	66.68	14.37	47.34	285.92	0.03
RON	142.25	23.04	74.95	406.36	0.02
ALLUR	53.72	44.27	18.36	16.75	0.44
ALAGWADI	68.75	28.72	50.72	109.48	0.07
NAVALGUND	41.44	20.68	37.72	78.83	0.10
KALWAD	31.83	17.46	33.29	64.65	0.12

* calculation was not possible due to very high infiltration rate
\+ test was conducted on a waterlogged plot and so the results are not reliable

λc - macroscopic capillary length
λm - characteristic mean pore size

5.2 COMPARISON OF INFILTRATION VALUES ESTIMATED USING DOUBLE RING INFILTROMETER AND DISC PERMEAMETER

Accurate estimation of infiltration is difficult since these values are influenced by rate of application and the extent of disturbance created by the instrument used. So most of the methods used, except for rain simulator to some extent, will not be considered to give an absolute infiltration value. However, a general concept is that, by using a double ring infiltrometer, it is possible to have an idea of behaviour of the soil and can have a comparison of drainage capacity of different soils.

By introducing a new instrument for the estimation of infiltration, it is necessary to have a comparison of results obtained using it, with the values from the conventional double ring infiltrometer. So, a double ring infiltrometer is used simultaneously with the disc permeameter, and infiltration values have been calculated. The results are given in Table 3.

TABLE 3:INFILTRATION RATE (mm/hr) ESTIMATED USING DISC PERMEAMETER AND DOUBLE RING INFILTROMETER

TEST SITE	DISC PERMEAMETR	DOUBLE RING INFILTROMETER
SOUNDATTI	53.48	96.00
MANOLI	74.55	24.00
HULIKATI	122.95	54.00
NARGUND	31.25	60.00
HIREKOP	55.86	18.00
RAMDURG	+	+
KULGERI	226.89	42.00
NANDIKESAR	70.32	60.00
HEBBALLI	*	216.00
KARMADI	75.90	30.00
ITAGI	66.68	12.00
RON	142.25	24.00
ALLUR	53.72	30.00
ALAGWADI	68.75	33.00
NAVALGUND	41.44	36.00
KALWAD	31.83	12.00

From the results, it can be seen that the infiltration estimates obtained using disc permeameter is higher than that from double ring infiltrometer, except at Soundatti and Nargund where large mud cracks were present. An attempt has been made to perform a correlation between these values, and it is found that the correlation is very poor with an R-square vale of less than 0.1. The difference in the estimated values may be because of the manner in which the water is being applied in each method; the difference in soil surface area which is exposed to water application and its physical condition; etc.

In disc permeameter, some quantity of water accounts for macro pore saturation, whereas in the case of double ring infiltrometer, saturation of the buffer zone will be done in the initial stage of infiltration process and the final value does not account for the macro pore contribution. This may be the reason for the higher infiltration values obtained from the disc permeameter experiment. However, a detailed study has to be taken up for the comparison of the performance of different methodology and for justifying the difference in the infiltration values.

5.3 PRESSURE PLATE EXPERIMENT

Pressure plate apparatus is used to get the soil moisture retention curves, using the samples collected from the field sites. Percentage moisture retained by the samples for various pressures (ranging from 0 bar to 15 bars) were calculated and tabulated as shown in table 4.

Results show that black soils are having very high moisture retention capacity, whereas, red soils drain water very quickly. Typical moisture retention curves for different types of soils from the study area are shown in Fig. 4.

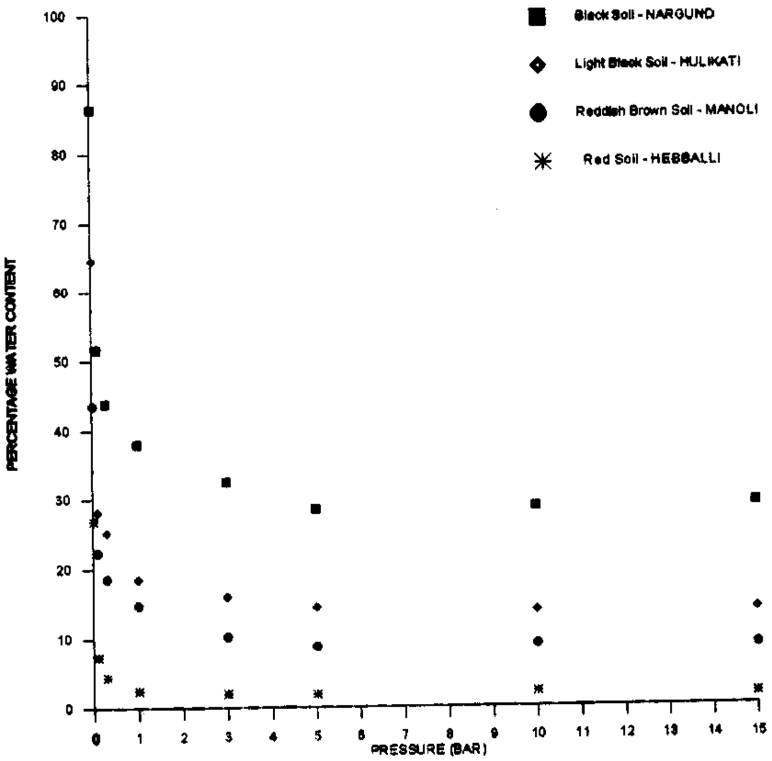

FIG. 4 : TYPICAL MOISTURE RETENTION CURVES FOR DIFFERENT SOILS

TABLE 4: PERCENTAGE SOIL MOISTURE RETENTION FOR DIFFERENT PRESSURES (BAR)

TEST SITE	0	0.1	0.3	1	3	5	10	15
SOUNDATTI	79.43	38.02	35.42	28.06	25.21	26.31	23.21	24.15
MANOLI	43.52	22.25	18.51	14.66	10.13	8.70	8.93	8.78
HULIKATI	64.54	28.18	25.18	18.48	15.92	14.40	13.76	13.85
NARGUND	86.37	51.68	43.84	38.00	32.46	28.53	28.70	29.14
HIREKOP	84.81	39.44	35.18	26.59	27.01	24.25	25.53	21.78
RAMDURG	54.95	25.01	23.95	15.94	15.22	12.89	13.15	12.19
KULGERI	27.57	13.81	11.86	6.88	6.03	4.84	4.29	4.46
NANDIKESWAR	38.81	15.51	14.33	7.96	7.50	7.08	6.26	5.24
HEBBALLI	26.77	7.26	4.47	2.47	2.00	1.94	2.12	1.64
KARMADI	94.23	46.26	45.87	36.41	32.34	32.75	27.34	26.66
ITAGI	58.20	33.30	30.55	24.56	19.62	22.41	19.15	21.52
RON	85.53	35.75	29.05	28.18	24.41	24.68	23.64	23.43
ALLUR	92.41	47.13	32.78	36.48	32.81	32.89	31.20	30.64
ALAGWADI	81.94	36.89	34.93	30.41	24.00	24.63	23.46	23.54
NAVALGUND	96.49	50.58	45.76	33.77	27.45	32.30	27.01	31.02
KALWAD	93.86	44.10	38.76	32.86	27.09	27.60	26.94	29.26

5.4 TEXTURE ANALYSIS

Textural analysis and its interpretation has a fundamental role in irrigation, hydraulics, geomorphology, and sedimentology. Using pipette analysis, the percentages of textural classes contained in soil samples have been estimated and the results are as shown in table 5.

In order to verify the hypothesis regarding the correlation between particle size and the major hydraulic soil properties, %(silt + clay) has been correlated with infiltration, hydraulic conductivity, and soil-moisture retention (at 0.3 and 15 bar), which are shown in Fig. 5, 6, 7, and 8. It can be seen that infiltration and conductivity values show a decreasing trend with increase in (silt + clay) content whereas, soil moisture retention shows an increasing trend. The retention values show a good correlation with (clay+silt) values with R-square value ranging between 0.88-0.92.

TABLE 5: PARTICLE SIZE DISTRIBUTION FOR THE STUDY AREA

TEST SITE	% SAND	% SILT	% CLAY
SOUNDATTI	18.96	28.42	52.62
MANOLI	47.64	13.13	39.23
HULIKATI	48.35	20.98	30.67
NARGUND	20.03	21.37	58.60
HIREKOP	31.36	25.46	43.18
RAMDURG	45.26	7.90	37.36
KULGERI	69.12	10.17	20.71
NANDIKESAR	66.03	4.84	29.13
HEBBALLI	92.87	0.61	6.52
KARMADI	10.87	27.59	61.54
ITAGI	20.23	26.95	52.82
RON	21.07	27.52	51.41
ALLUR	16.63	42.51	40.86
ALAGWADI	25.43	31.93	42.64
NAVALGUND	7.43	28.90	63.67
KALWAD	14.01	22.49	63.50

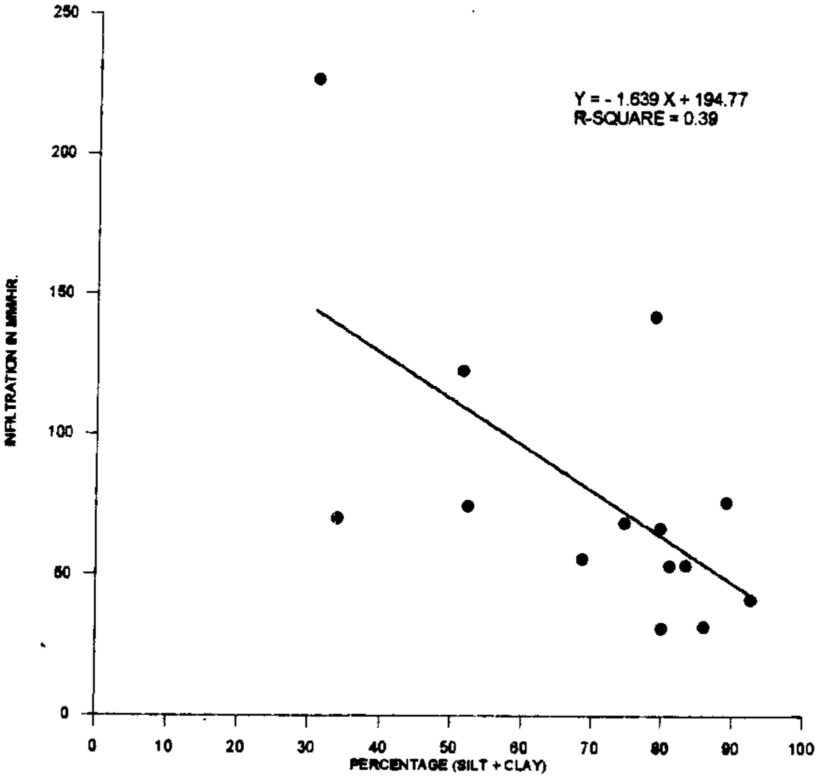

FIG. 5: CORRELATION BETWEEN PERCENTAGE (SILT+CLAY) AND INFILTRATION (DISK PERMEAMETER)

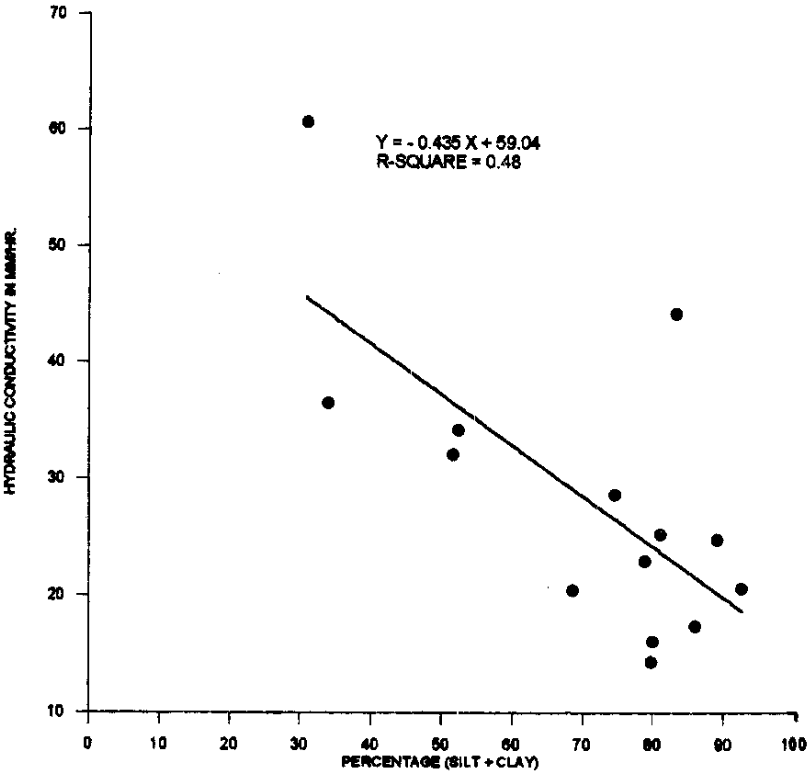

FIG. 6: CORRELATION BETWEEN PERCENTAGE (SILT + CLAY) AND HYDRAULIC CONDUCTIVITY

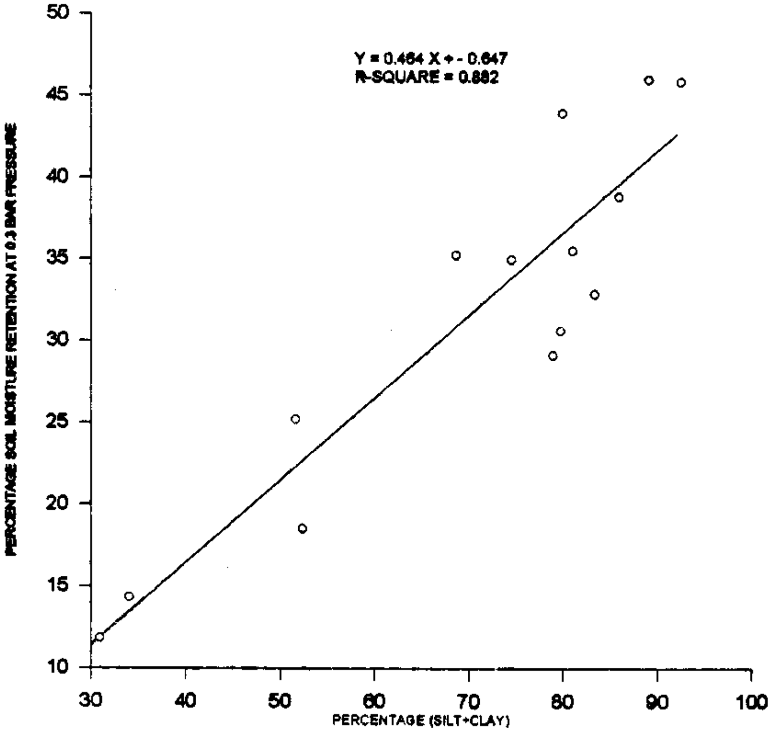

FIG. 7 : CORRELATION BETWEEN PERCENTAGE (SILT+CLAY) AND SOIL MOISTURE RETENTION AT 0.3 BAR PRESSURE

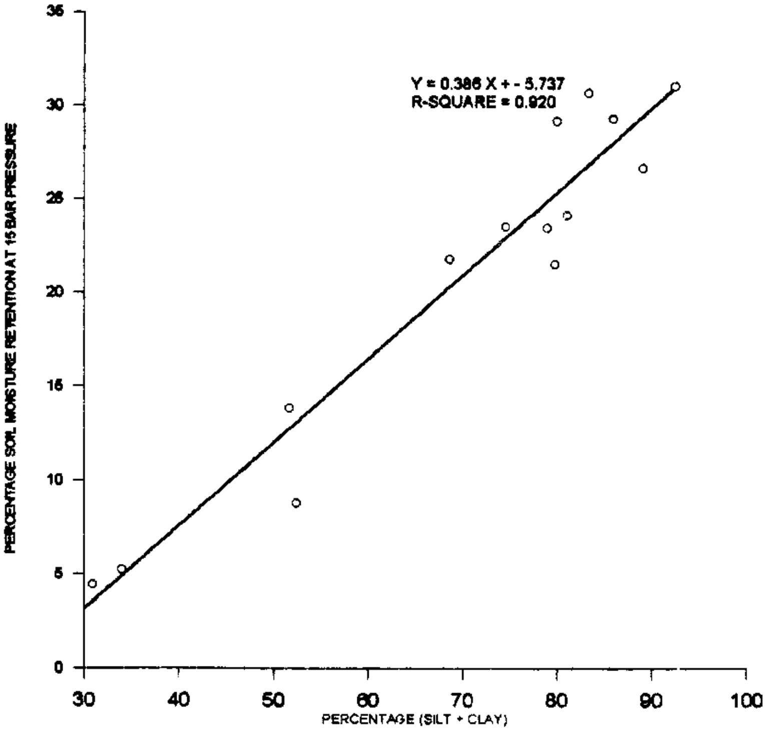

FIG. 8: CORRELATION BETWEEN PERCENTAGE (SILT + CLAY) AND SOIL MOISTURE RETENTION AT 15 BAR PRESSURE

5.5 CONCLUSIONS

From this study, it can be broadly concluded that generalisation of soil properties for an area is difficult since the soil and landuse type varies drastically from one point to another in a short distance. It is only possible to have a average value for a particular type of soil. Also, it can be seen from the results that the percentage of (silt+clay) plays an important role in shaping the hydraulic properties of a soil.

It is found that the new instrument (Disc permeameter) used is having the following advantages;(a)it is easy to handle compared to the conventional double ring infiltrometer, and (b)estimation of various soil hydraulic properties like infiltration, saturated and unsaturated conductivity, sorptivity, pore characteristics, etc. can be done simultaneously. However, from experience, it is noted that this instrument is not suited for extreme conditions of infiltration, and its calculation procedure is not fool proof. Also, The estimates of soil hydraulic properties obtained from the calculations are highly sensitive to θ_0 and θ_n and hence, insitu measurement of these moisture content values are essential for better results.

It is necessary to conduct a detailed study using all the available instruments and methodologies, to find out the most accurate field method to estimate the soil hydraulic properties like infiltration and conductivity. Eventhough, the use of rain simulators, which is considered as the most accurate method, involve high expenditure, it is always better to establish some relationship between soil properties estimated using various instruments and rain simulator. Such empirical equations can be used to convert the field estimates to more practical values, which can be used for our hydrologic studies.

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