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SOIL MOISTURE MEASUREMENT AND MOVEMENT IN AGRICULTURAL FIELDS

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PREFACE

The understanding of water movement in natural soil profiles under vegetation cover is of great importance for soil problems (irrigation & drainage) and for problems in hydrology and hydrometeorology. However, in many cases, such water movement investigations are only partly carried out in the field because of difficulties in measurig and analysing. For a critical examination, experiments with simultaneous field measurements of soil water content and soil moisture potential as a function of time and depth are needed. Several hydrologists and soil physicists all over the world have identified some methods which are helpful in this regard.

The National Institute of Hydrology established the Hydrological Investigation Division in 1985 with the major objectives of studying the hydrological parameters using geophysical and nuclear techniques. In this report an attempt has been made to review the present status of the methods available, with particular emphasis on the one which makes use of neutron moisture gauge and gamma ray transmission method, for the study of soil moisture measurement and movement in agricultural fields.

The report has been prepared by Dr. C.K. Jain, Scientist in Hydrological Investigation Division. He was supported by Sh. Rm.P. Nachiappan, S.R.A.

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SUMMARY

Soil moisture content is an important variable that determines the response of a soil plant system to any water input. Continual monitoring is therefore, of significance in irrigation management. Different agricultural practices cause varying changes in soil moisture status in the fields. Determination of soil moisture content, its variation in time and space and redistribution during and after rainfall or irrigation are necessary in order to decide when to irrigate and what is the optimum quantity of water needed in agricultural fields. As successful crop production requires an adequate supply of soil moisture throughout the growing season, it is essential to study the factors influencing the soil moisture movement in agricultural fields such as variation on land cover, soil hydrologic properties etc.

In this report a brief discussion on several methods available for the measurement of soil moisture content and soil moisture tension with particular emphasis on the methods making use of neutron probe, gamma-ray spectrometer and tensiometer have been given, followed by a comprehensive review on the effective applicability of the methods for the purpose citing several Indian and foreign examples.

1.0 INTRODUCTION

1.1 General

A significant and vital phase of the hydrological cycle is the entry and movement of water in the soil profile. In field situations, infiltration of rainfall or irigation water is generally a case of water movement into soil profiles of non-uniform water content and hydraulic conductivity. When water is supplied to the soil surface, whether by precipitatin or irrigation, some of the arriving water penetrates in the surface and is absorbed into the soil, while some occur at the surface or flow over it. The water which does penetrate is itself latter partitioned between that amount which returns to the atmosphere by evapotranspiration and that which seeps downward, with some of the latter re-emerging as streamflow while the remainder/recharges the groundwater reservoirs. Soil moisture studies provide necessary information in determining the optimum irrigation regime. Basically there are two main problems, firstly, the quantity of water required to the crop for maximum yield and secondly, knowledge of optimum irrigation rate, frequency, and also the method by which water can be made available to the plant, utilising the natural storage of the soil. On the other hand, tendency of farmers to use as much water as they can get for irrigation without understanding the soil moisture storage create serious problems as over irrigation can cause water logging and thereby reducing its productivity. As water resources are becoming increasingly scare and more expensive to develop, more precise information on soil moisture storage and movement in the unsaturated zone is required.

The first problem, that of determining the consumptive use of the crop can be studied from a soil moisture approach by meeting certain *boundary conditions. The second problem, that of making water available to the plant with maximum efficiency, can be studied effectively only through investigation of the soil regime. Therefore, measurement of soil moisture content and soil moisture hydraulic potential are necessary for a full understanding of the movement of water in the soil.*

Information of the movement of water in the unsaturated zone is needed whenever one tries to set up a water balance either for the unsatured zone itself or for the groundwater in the saturated zone beneath it. The kowledge of spatial distribution of soil moisture may yield information on the water movement as well. However, the relation between potential gradient and flow rate known as Darcy's law is more complicated in the case of unsaturated flow than in saturated flow. In the saturated zone, the hydraulic conductivity is usually constant with time and even if its numerical value is unknown, the relative changes in flow are strictly proportional to the corresponding changes of the hydraulic gradient. In the unsaturated zone, however conductivity is a variable dependent on moisture content.

The concept of water movement through soils, termed as piston flow model was developed by Zimmermann et al.(1967) and Munnich (1968) with the assumption that the soil moisture moves downwards in discrete layers. Any fresh layer of water added on the surface, due to precipitation or irrigation, would percolate by pushing on equal amount of water beneath it further down, and so on, such that the moisture of the *last layer in the unsaturated zone is added to the water table. Datta et al.(1973) and Athavale et al.(1980 and 1983) used the tritium tagging technique to understand the soil moisture movement and estimated recharge to ground water. This assumption of piston flow model was used by many other subsequently. Under this assumption, soil water or infiltrated water cannot by pass or short cut the moisture of underlying layers in either direction and leads to a downward displacement of it like a movig piston.*

1.2 Uptake of Soil Moisture by Plants

Successful crop production requires an adequate supply of soil moisture throughout the growing season. A major portion of the soil moisture supply comes from precipitation events which man has been trying to modify in order to insure his water supply. In dry climates, plants growing in the field may consume hundreds of tons of water for each ton of vegetative growth. That is to say the plants must *inevitable transmit to an unquenchably thirsty atmosphere most of the water they extract from the soil. The loss of water vapor by plants, a process called transpiration, is not in itself an essential physiological function, nor a direct result of the living processes of the plants. In fact, plants can thrive in an atmosphere saturated or nearly saturated with vapor and hence requiring very little transpiration. Rather than by plant growth per se, transpiration is cused by the vapor pressure gradient between the normally water saturated leaves and the often quite dry atmosphere.*

In other words, it is exacted of the plants by the evaporative demand of the climate in which they live. To grow successful, a plant must achieve a water economy such that the demand made upon it is balanced by the supply available to it. The problem is that the evaporative demand of the atmosphere is almost continuous, whereas rainfall occurs only occasionally and irregularly. To survive during dry spells between rains, the plant must rely upon the diminishing reserves of water contained in the pores of the soil, which itself loses water by direct evaporation and internal drainage.

Current approaches to the problem of soil water extraction and utilisation by plants are based on recognition that the field with all its parts-soil, plant, and atmosphere taken together forms a physically integrated, dynamic system in which various flow processes occur interdependently like links in a Chain. This unified system has been called the SPAC (soil -plant-atmosphere continum) by philip (1966). The universal principle which operates consistently throughout the system is that water flow always takes place spontaneously from region of higher to regios of lower potential energy.

In order to describe the interlinked processes of water transport throughout the SPAC, we must evaluate the pertinent components if the energy potential of water and their effective gradients as they very in space and time. As an approximation, the flow rate through each segment of the system can be assumed to be proportional directly *to the operating potential gradient, and inversely to the segment's resistance. The flow path includes liquid water movement in the soil towards the roots, liquid and perhaps vapor movement across the root-to-soil contact zone, absorption into the roots and across their membranes to the vascular tubes of the xylem, transfer through the xylem up the stem to the leaves, evaporation in the intercellular spaces within the leaves, vapor diffusion through the substomatal cavities and out the stomatal perforations to the quiescent boundary air layer in contact with the leap surface, and through it, finally, to the turbulent atmosphere which carries awy the water thus extracted from the soil.*

The rate of water uptake from a given volume of soil depends on rooting density (the effective length of roots per unit volume of soil), soil conductivity, and the difference between average soil-water suction and root suction. If the initial soil water suction is uniform throughout all depths of the rooting zone, but the active roots are not uniformly distributed, the rate of water uptake should be highest where the density of roots is greatest. However, more rapid uptake will result in more rapid depletion of soil moisture, and the rate will not remain constant very long.

Non-uniformity of water uptake from different soil depths has been found in the field (Ogata et al., 1960). In a non-uniform root system, suction gradients can form which may induce water movement from one layer to another in the soil profile itself. In general, the magnitude of this movement is likely to be small relative to the water uptake rate by the plants, but in some cases it can be considerable. As a rough approximation, it is sometimes possible to divide the rooting system into two layers, an upper layer, in which root density is greatest and nearly uniform and in which water depletion is similarly uniform, and a lower layer, in which the roots are relatively sparse and in which the rate of water depletion is slow as long as the water content of the upper layer is fairly high. The water content of the lower layer, is depleted by two simultaneous processes: uptake by the roots of that layer, and direct upward flow in the soil itself, caused by suction gradients, form the still moist lower layer to the more rapidly depleted upper layer.

A mature root system occupies a more or less constant soil volume of fixed depth so that uptake should depend mainly upon the size of this volume, its water content and hydraulic properties, and the density of the roots. On the other hand, in young plants, root extension and advance into deeper layers with moisture can play an important role in supplying plant water requirements (Kramer and coile, 1940; Wolf,1968).

Rose and stern (1967) presented an analysis of the time rate of water withdrawl from different soil depth zones in relations to soil wetness and hydraulic properties, and to the rate of plant root uptake. A similar field study of water extraction by a root system was carried out by van Bavel et al.(1968), using the instantaneous profile method of obtaining the hydraulic properties of a complete profile in situ (Watson, 1966; Hillel et al., 1972).

2.0 SOIL MOISTURE AND POTENTIAL

The variable amount of water contained in a unit mass or volume of soil, and the energy state of water in the soil are important factors affecting the growth of plants. In clayey soils, swelling and shrinkage associated with addition or extraction of water change the overall specific volume (or bulk density) of the soil as well as its pore-size distribution. Soil water content also governs the air content and gas exchange of the soil, thus affecting the respiration of roots, the activity of micro-organisms, and the chemical state of the soil (e.g. oxidation-reduction potential).

The per mass or per volume fraction of wter in the soil can be characterised in terms of soil moisture. Te physico-chemical condition or state of soil water is characterised in terms of its free energy per unit mass termed the potential. Of the various components of this potential, it is the pressure of matric potential which characterises the tenacity with which soil water is held by the soil matrix.

2.1 Soil Moisture

The fractional content of water in the soil can be expressed in terms of either mass or volume ratios, i.e.,

$$w = M_w / M_s$$

and $$\Theta = V_w / V_t = V_w / (V_s + V_a + V_m)$$

Where w, the soil moisture by mass, is the dimensionless ratio of water mass M_w to dry soil mass M_s, whereas Θ, the soil moisture by volume, is the ratio of water volume V_w to total (bulk) soil volume V_t. The latter is equal to the sum of the volumes of soilds (V_s), water (v_w), and air (V_a). Both Θ and w are usually multiplied by 100 and reported as percetages by volume or mass.

The two expressions can be related to each other by means of the bulk density ρ_b and the density of water:

$$Q = w\ (\rho_b/\rho_w) = w\ \Gamma_b$$

Where Γ_b is the bulk specific gravity of the soil (a dimensionless ratio which usually lies in the range between 1.1 and 1.7).

2.2 Determination of Soil Moisture

The need to determine the amount of water contained in the soil arise frequently in many agronomic, ecological and hydrological investigations aimed at understanding the soil's chemical, mechanical, hydrological and biological relationships. There are direct and indirect methods to measure soil moisture. Some of the most prevalent methods for the determination of soil moisture are as follows:

2.2.1 Gravimetric method

The traditional gravimetric method of measuring soil moisture consists of removing a sample by augering into the soil and then determining its moist and dry weights. The moist weight is determined by weighing the sample at the time of sampling, and the dry weight is obtained after drying the sample to a constant wieght in an oven. The more or less standard method of drying is to place the sample in an oven at 105°C for 24 hr.

$$\text{Moisture content 'W'(\%)} = \frac{(\text{wet weight}) - (\text{dry weight})}{\text{dry weight}} \times 100$$

$$= \frac{\text{weight loss in drying}}{\text{weight of dried sample}} \times 100$$

If volumetric water content (Q) is required, the gravemetric value is multiplied by the bulk density of the soil, i.e.,

$$Q = W = \frac{y_d}{y_w}$$

where y_d is the oven dried bulk density in g/cm^3 and y_w is the density of of water in g/cm^3.

The gravimetric method is laborious and time consuming, since a period of at least 24 hours is usually considered necessary for complete oven drying. The standard method of oven drying is itself arbitrary. Some clays may still contain appreciable amounts of adsorbed water even at 105°C. On the other hand some organic matter may oxidize and decompose at this temperature so that the weight loss may not be due entirely to the evaporation of water. Also, during the weighing to the oven dried soil sample, it absorbs hygroscopic moisture from air, thus does not give real values of moisture content. The errors in the gravimetric method can be reduced by increasing the size and number of sample. However, now a days, a new approach is used for the determination of moisture content using gravimetric method employing infrared radiations to heat the soil sample. An equipment known as infrared moisture balance is used for this purpose in which a small amount of soil sample (about 5-10 gm) is used. After drying the sample with these radiations, the equipment gives direct value of moisture percentage on weight basis. In this way, time consuming process and absorption of hygroscopic moisture is removed. Even than, the sampling method is destructive and may disturb the observation or experimental plot sufficiently to distort the results. For these reasons, many worker prefer indirect methods which permit making frequent or continuous measurements at the same point.

2.2.2 Electrical resistance method

The electrical resistance of a soil volume depends not only upon its water content, but also upon its composition, texture and soluble salt concentration. On the other hand, the electrical resistance of porous *bodies placed in the soil and left to equilibrate with soil moisture can sometimes be calibrated against soil moisture. Such units (generally called electrical resistance blocks) generally contain a pair or electrodes embedded in gypsum (Bouyouces and mick, 1940) nylon, or fiberglass (Colman and hendrix, 1949).*

The electrical conductivity of moist porous block is primarly due to the permeating fluid rather than the soil matrix.

Thus it depends upon the electrolytic solutes present in the fluid as well as upon the volume content of the fluid. blocks made of such inert materials as fiberglass, for instance, are highly sensitive to even small variations in salinity of the soil solution. On the other hand, blocks made of plaster of paris (gypsum) maintain a nearly constant electrolyte concentration corresponding primarily to that of a saturated solution of calcium sulfate. This tends to mask, or buffer the effect of small or even moderate variations in the soil solution (such as those due to fertilization or low levels of salinity). However, an undesirable consequence of the solubility of gypsum is that these blocks eventually deteriorate in the soil. Hence the relationship between electrical resistance and moisture suction varies not only from block to block but also for each block as a function of time, since the gradual dissolution of the gypsum changes the internal porosity and pore-size distribution of the blocks.

For these and other reasons (e.g. temperature sensitivity), the evaluation of soil moisture by means of electrical resistance blocks has limited accuracy. On the other hand, the advantage of these blocks is that they can be connected to a recorder to obtain a continuous indication of soil moisture changes in situ, even than this method is not generally used for the determination of soil moisture.

2.2.3 Neutron scattering method

First developed in the 1950s, this method has gained widespread acceptance as an efficient and reliable technique for monitoring soil moisture in the field. Its principal advantages over the gravimetric method are that it allows less laborious, more rapid, nondestructive, and periodically repeatable measurements, in the same locations and depths. The method is practically independent of temperature and pressure. Its main disadvantages, however, are the high initial cost of the instrument, low degree of spatial resolution, difficulty of measuring moisture in the soil surface zone, and health hazard associated with exposure to neutron and gamma radiation.

The instrument, known as a neutron depth moisture gauge (Fig.1) consists essentially of a probe containing fast neutron source and a slow neutron detector adjacent to the source. The probe contains a radio active source which emits fast neutrons into the surrounding soil.

A source of fast neutrons is generally obtained by mixing a radioactive emitter of alpha particles(helium nuclei) with beryllium. Frequently used is a 5-10 millicurie pelletize mixture of radium and beryllium or americium and beryllium.

Both radiumn and americium incidentally emit gamma radiation, but that of the americium is lower in energy and hence less bazardous than that of the radium. The source materials are chosen for their longevity (e.g. radium-beryllium has a half - life of about 1620 yr.) so that they can be used for a number of years without an appreciable change

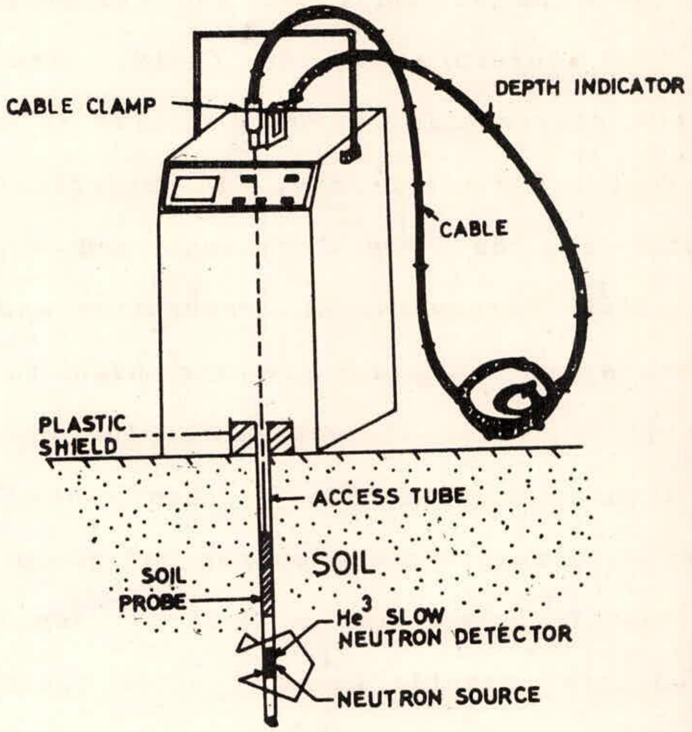

Figure 1 : Diagram of Neutron Depth Moisture Gauge

in radiation flux.

The fast neutrons are emitted radially into the soil where they encounter and collide elastically with various atomic nuclei. Through repeated collisions, the neutrons are deflected and "scattered", and they gradually lose some of their kinetic energy. As the speed of the initially fast neutrons diminishes, it approaches a speed which is characteristic for paracticles at the ambient temperature. For neutrons this is about 2.7 km/sec. corresponding to an energy of about 0.03 ev. Neutrons that have een slowed to such a speed are said to be thermalized and are called slow neutrons. Such slow neutrons to interact with the soil and are eventually absorbed by the nuclei present.

The effectiveness of various nuclei present in the soil in moderating or thermalizing fast neutrons varies widely. The average loss of energy is maximal for collisions between particles of approximately the same mass. of all nuclei encountered i the soil, the ones most nearly equal in mass to neutrons are the nuclei of hydrogen, which are therefore the most effective fast neutron moderators of all soil constituents. If the soil contains an appreciable concentration of hydrogen, the emitted fast neutrons are thermalized before they get very far from the source, and the slow neutron thus produced scatter randomly in the soil quickly forming a cloud of constant density around the probe. The equilibrium density of the slow neutron clouds is determined by the rate of emission by the source and the rates of thermalization and absorption by the medium (i.e. soil) and is established within a small fraction of a second.

As the thermalized neutrons repeatedly collide and bounce randomly, a number of them (proportional to the density of neutrons thus thermalized and scattered, and hence approximately linearly related to the concentra-

tion of soil moisture) return to the probe where they are counted by the detector of slow neutrons.

For the sake of safety and also to provide a convenient means of making standard readings, the probe containing the fast neutron source is normally carried inside a protective shield, which is a cylindrical container filled with lead and some hydrogenous material such as paraffin or polyethylene designed to prevent the escape of fast neutrons. The shield should also protect users of the neutron soil moisture meter against emitted gamma radiation. improper or excessive use of the equipment can be hazardous. The danger from exposure to radiation depends upon the strength of the source, the quality of the shield, the distance from source to operator, the direction of radiation and the duration of contact.

It is also suggested that the use of radio-active source having more than 225 millicurie activity should be avoided.

Any neutron source having a surfce dose equivalent rate of 200 mrem/h 92 mSv/h) or a dose equivalent rate of more than 10 mrem/h (0.1 mSv/h) at 1 meter should be stored in a labelled container conformig with the following requirements.

- *i) When the source is in its storage container, less than 200 mrem/h (2 mSv/h) shall be delivered at any container surface and less than 10 mrem/h (0.1 mSv/h) at 1 m from the container.*
- *ii) Neutron sources with low gamma intensities should be stored in paraffin wax or polyethylene container of thickness such that above requirements are met. The paraffin and polyethylene in turn should be confined in the mild steel outer containers. In case of sources with sufficient gamma hozard also should firstly be place in lead containers of suitable thickness*

and then surrounded by a hydrogeneous material.

iii) The source container should be kept in a separate room or enclosure and kept under lock and key. The keys of the room should be kept in the custody of a responsible person.

iv) The source container should be duly labelled indicating the activity, half-life, date of measurement of activity, surface dose rate and identity of the source i.e. its source number, particularly in case of pu-be sources. The source container should be used for storing sources upto its rated capacity only.

v) Radiation symbols should be posted outside the source container and the room housing the source container.

2.2.4 Gamma ray attenuation method

The gamma ray attenuation method is a technique that can be used to determine soil moisture content within a 1 to 2 cm soil layer. This method assumes that scattering and absorption of gmma rays are related to the density of matter in their path and that the specific gravity of a soil remains relatively constant as the wet density changes with moisture content increases or decreases. Changes in wet density are measured by the gamma transmission technique and the moisture content determined from this density change. The mass absorption coefficient above 600/keV energy of gamma rays for heavy - clay, sand clay, well graded clay and grable sand clay is almost the same. Also, the mass absorption coefficient is quite large for hydrogen compared to the other elements found in the soil for gamma radiations above 600 keV. Therefore, this property may be exploited, since the change in counting rate is to be quite large with and without moisture in the soil water system.

The observation of each day and each time is to be correlated which is possible if gamma ray spectrometer is standarized and every time compared with the standard. kumar and Singh (1981) has suggested a method for its standarization.

Gamma rays may be collimated to a narrow beam, which permits a representative reading to be obtained at any position in the soil. Gurr (1962), Ferguson and Gardner (1962) and Davidson et al. (1963) were instrumented in developing the theoretical basis and procedures for its use.

Basic equipment includes a gamma ray source surrounded by a collimator, a detector with a collimator and a scaler. Gurr (1962) used a 25 - mCi ^{137}*CS source with a lead collimator. The beam emerged from a circular hole 4.8 mm in diameter. A scientillation counter, used as a detector, was shielded by a lead collimator having a 12.5 mm diameter hole. Mansell et al. (1973) stated that collimated radiation from 300 mCi each of* ^{241}*Am and* ^{137} *Cs provided a high intensity beam comprising 60 and 62 - kev photons. Count rates measured by a single detector and a two - channel gamma spectrometer were corrected for coincidence losses due to pulse - resolving time. They concluded that error in soil water content measurement by the dual energy gamma ray attenuation method will probably not exceed a standard diviatiin of 1%.*

besides, Kumar and Singh (1979) have introduced a new approach for the calibration of gamma ray transmission method. Kumar and Singh (1988) have also developed a new approach for the automatic count rate stabilization of gamma ray spectrometer. Thus properly calibrated and standarized (using automatic count rate stabilization unit) gamma ray transmission method can be used for the measurement of soil moisture accurately in laboratory as well as in -situ. The theoretical aspect of the method is as given below.

When gamma rays are allowed to pass through soil water system of thickness X cm having volumetric moisture content Q_v, the attenuation can be written as:

$$Nsw = N_0 \exp [- (\mu s/\rho s) x \rho s + (\mu w/\rho w) \rho w x C Qv] \qquad ....1/-$$

where N_0 and Nsw are the counting rates initially and after attenuation through a soil water system of thickness x. μs and μw are the main absorption coefficients of the soil and water respectively. ρs and ρw are the density of soil and water and C is factor introduced by Singh and Chandra (1977) to account for the effect of scattering. For a soil system having volumetric moisture content Qv', the attenuation equation can be written in a similar manner as:

$$Nsw' = No \exp - [(\mu s/\rho s) \rho s x + (\mu w/\rho w) \rho w C x Qv'] \qquad ...2/-$$

taking logarithem and subtracting eq. (2) from eq.(1) we have

$$\ln Nsw - \ln N'sw = (\mu w/\rho w) x C (Q'v-Qv)$$

Thus, change in natural logarithem of counting rates is directly proportional to change in moisture content provided (μw, x and C) remains constant. Kumar and Singh (1979) have shown that ($\mu w/\rho w$) x C can be taken to be a calibration factor. Therefore, the change in counting rates can be correlation with change in moisture content. For more theoretical aspects, the details given by Saxena et (1974) and Kumar and Singh (1988), may be consulted. The experimental set up for the measurement and movement of soil moisture in laboratory as well as in fields are shown in fig.2 and 3 respectively.

2.2.5 Other methods

Additional approaches to the measurement of soil moisture include -ray absorptio, the dependence of soil thermal properties upon water content, and the use of ultrasonic waves radar waves, dielectric properties

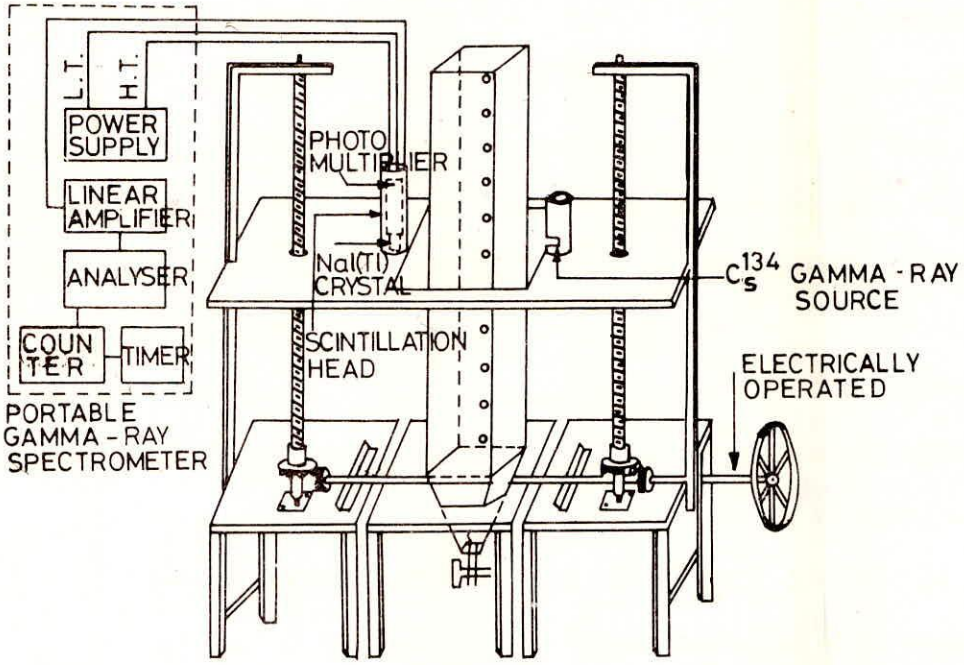

Figure 2: Laboratory set up for the Study of Soil Moisture Measurement and Movement by Gammaray Transmission Method.

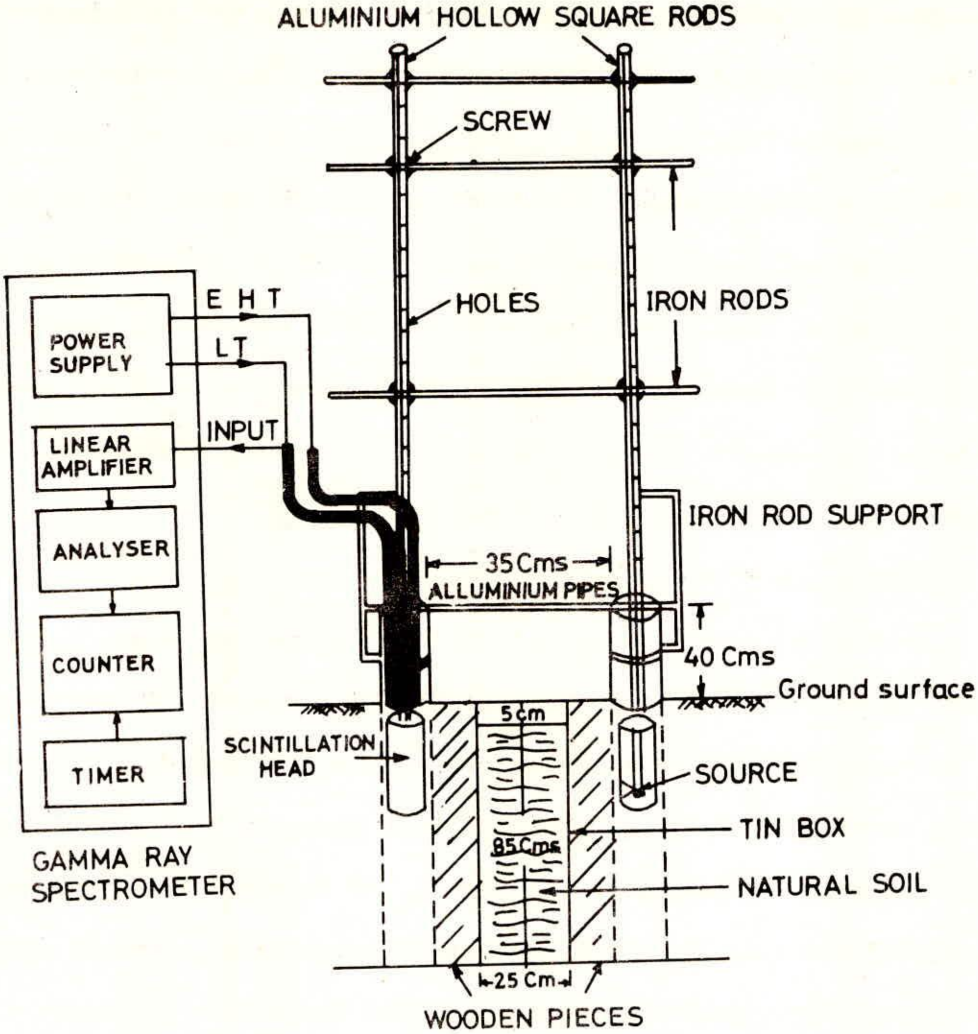

Figure 3: Experimental set up for the Study of Soil Moisture Measurement in-situ by Gamma-ray Transmission Method

and hygrometric techniques using several types of hygrometers like electrical resistance, capacitance, piezoelectrical resistance, capacitance, piezoelectric sorption infrared absorption and transmission, dimensionally varying element, dew point and psychrometric hygrometers. Some of these and other methods have een tried in connection with the remote sensing of land areas from aircraft or satellites. However, most of these methods developed or under development are not yet practical for routing use in the field. For details of these methods article by Schmegge et al. (980) may be consulted.

2.3 Soil Moisture Potential

Soil water, like other bodies in nature can contain energy in different quantities and forms. Classical physics recogizes two principal forms of energy,kinetic and potential. Since the movement of water in the soil is quite slow, its kinetic energy which is proportional to the velocity squared, is generally considered, to be negligible, on the other hand, the potential energy, which is due to position or internal condition is of primary importance in determining the state and movement of water in the soil.

The potential energy of soil water varies over a very wide range. Differences in potential energy of water between one point and another give rise to the tendency of water to flow within the soil. In the soil, water moves constantly in the direction of decreasing potential energy. The rate of decrease of potential energy with distance is in fact the moving force causing flow.

2.4 Determination of Soil moisture Potential

The measurement of soil moisture is obviously not sufficient to provide a description of the state of soil water. To obtain such a description, evaluation of the energy status of soil water (soil moisture potential, or suction) is necessary. In general the twin variables, soil moisture and potential, should be measured directly.

Total soil - moisture potential is often thought of as the sum of matric and osmotic (solute) potentials and is a useful index for characterizing the energy status of soil water with respect to plant water uptake. The sum of the matric and gravitational (elevation) head is generally called the hydraulic head (or hydraulic potential) and is useful in evaluating the directions and magnitudes of the water moving forces throughout the soil profile. Methods are available for measuring matric potential as well as total soil moisture potential, separately or together (Black, 1965). To measure matric potential in the field, an instrument known as the tensiometer is used, whereas in the laboratory use is often made of tension plates and of air-pressure extraction cells. Total soil moisture potential can be obtained by measuring the equilibrium vapor pressure of soil water by means of thermocouple psychrometers.

2.4.1 Tensiometer

Tensiometer has won wide spread acceptance as a practical device for in-situ measurement of matric suction, hydraulic head and hydraulic gradient. The essential parts of a tensiometer are shown in Fig.4. The tensiometer consists of a prous cup, generlly of ceramic material, connected through a tube to a manometer with all parts filled with water. When the cup is placed in the soil where the suction measurement is to be made, the bulk water inside the cup comes into hydraulic contact and tends to equilibrate with soil water through the pores in the ceramic walls. When initially placed in the soil, the water contained in the tensiometer is generally at atmospheric pressure, soil water being generally at sub-atmospheric pressure, exercises a suction

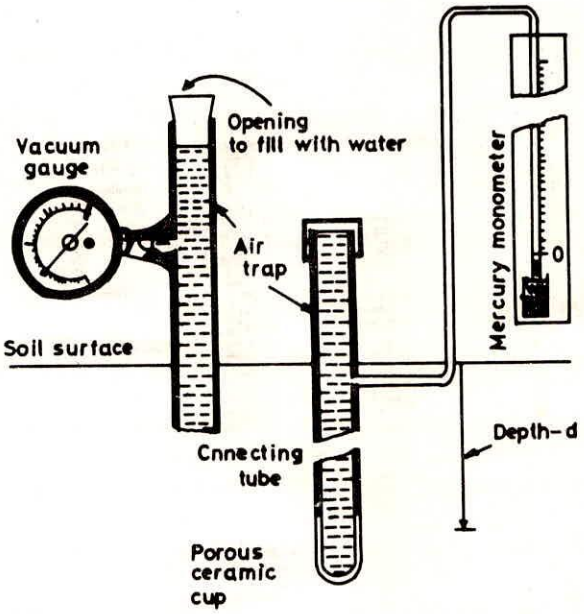

Figure 4: Schematic Illustration of the Essential Parts of Tensiometer

which draws out a certain amount of water from the rigid and airtight tensiometer, thus causing a drop in its hydrostatic pressure. This pressure is indicated by a manometer, which may be a simple water or mercury filled u tube, a vaccum gauge, or an electrical transducer.

A tensiometer left in the soil for a long period of time tends to follow the changes in the matric suction of soil water. As soil moisture is depleted by drainage or plant uptake, or as it is replenished by rainfall or irrigation, corresponding readings on the tensiometer gauge occur. Owing to the hydraulic resistance of the cup and the surrounding soil, or of the contact zone between the cup and the soil, the tensiometer response may lag behind suction changes in the soil.

This lag time can be minimized by the use of full type device or of a transducer type manometer with rigid tubing, so that practically no flow of water need take place as the tensiometer adjusts to changes in the soil matric suction.

Since the porous cup walls of the tensiometer are permeable to both water and solutes, the water inside the tensiometer tends to assume the same solute composition and concentration as soil water, and the instrument does not indicate the osmotic/suction of soil water (unless equipped with some type of an auxiliary salt sensor).

Suction measurements by tensiometry are generally limited to matric suction values of below 1 atm This due to the fact that the vaccum gauge or manometer measures a partial vaccum relative to the external atmospheric pressure, as well as to the general failure of water columns in macroscopic system to withstand tensions exceeding 1 bar. Furthermore, as the ceramic material is generally made of the most permeable and porous material possible, too high a suction may cause air entry into the cup, which would equalise the internal pressure to the atmospheric pressure. Under such conditions, soil suction will continue to increase even though the tensiometer fails to show it.

With properly designed tensiometers it may perhaps be possible to measure soil suction upto a range of 0.85-0.9 bax of maximal suction. To measure higher suctions, the use of an osmometer with a semi-permeable membrance at the wall has been proposed, but this instrument is still in the experimental stage. However, the lmited range of suction measurable by the tensiometer is not a serious problem as it may seem at this sight. Though the suction range of 0-0.8 bar is not a small pat of the total range of suction variation encountered in the field, it generally encompasses the greater part of the soil wetness range. In many agricultural soils the tensiometer range accounts for more than 50% (and in coarse textured soils 75% or more) of the amount of soil water taken up by plants. Thus, where soil management (particularly in irrigation) is aimed at maintaining low suction conditions which are most favourable for plant growth, tensiometer are definitely useful.

Despite their many shortcomings, tensiometers are practical instruments, available commercially, and, when operated and maintained by a skilled worker, are capable of providing reliable data on the insitu state of soil moisture profile and their changes with time.

Tensiometer radings reflect soil - moisture tension only, that is, they indicate the relative wetness of the soil surrounding the porous tip. They do not provide direct information on the amount of water held in the soil. Tnesion measurements are useful in deciding when to irrigate,but they do not indicate how much water should be applied. A special moisture characteristic curves indicating relationship between moisture tension and available moisture percentage for different type of soils like sand, clay and loam are shown in Figure 5. A general practice is to place tensiometers at one or more soil depths representing the root zone, and to irrigate when the tensiometers indicate that the matric suction has reached some prescribed value. The use of several tensiometers at different depths can allow calculation of the hydraulic gradients in the soil profile. if $\Psi_1, \Psi 2, \Psi 3, \ldots \Psi n$ are the matric suction values in centimeters of water head ($\cong$ milibars) at depths d_1, d_2, d_3,..... d_n measured in centimeters below the surface, the average hydraulic gradient i between depths d_n and d_{n+1} is;

$$i = \left[(\Psi_{n+1} + d_{n+1}) - (\Psi_n + d_n) \right] / (d_{n+1} - dn)$$

Measurement of the hydraulic gradient is particularly important in the region below the root zone, where the direction and magnitude of water movement cannot easily be ascertained otherwise.

The still considerable cost of tensiometers may limit the number of instruments used below the number needed for characterizing the often highly variable distribution of moisture and hence the pattern of suction in heterogeneous soils. Air diffusion through the porous cup into the vaccum gauging system requires frequent purging with deaired water. Tensiometers are also sensitive to temperature gradients between their various parts. Hence the above - ground parts should preferably be shielded from direct exposure to the sun. When installing a tensiometer, it is important that good contact be made between the cup and the soil so that equilibration is not hindered by contact zone impedance to flow.

2.4.2 Thermocouple psychrometer

At equilibrium, the potential of soil moisture is equal to the potential of the water vapor in the ambient air. If thermal equilibrium

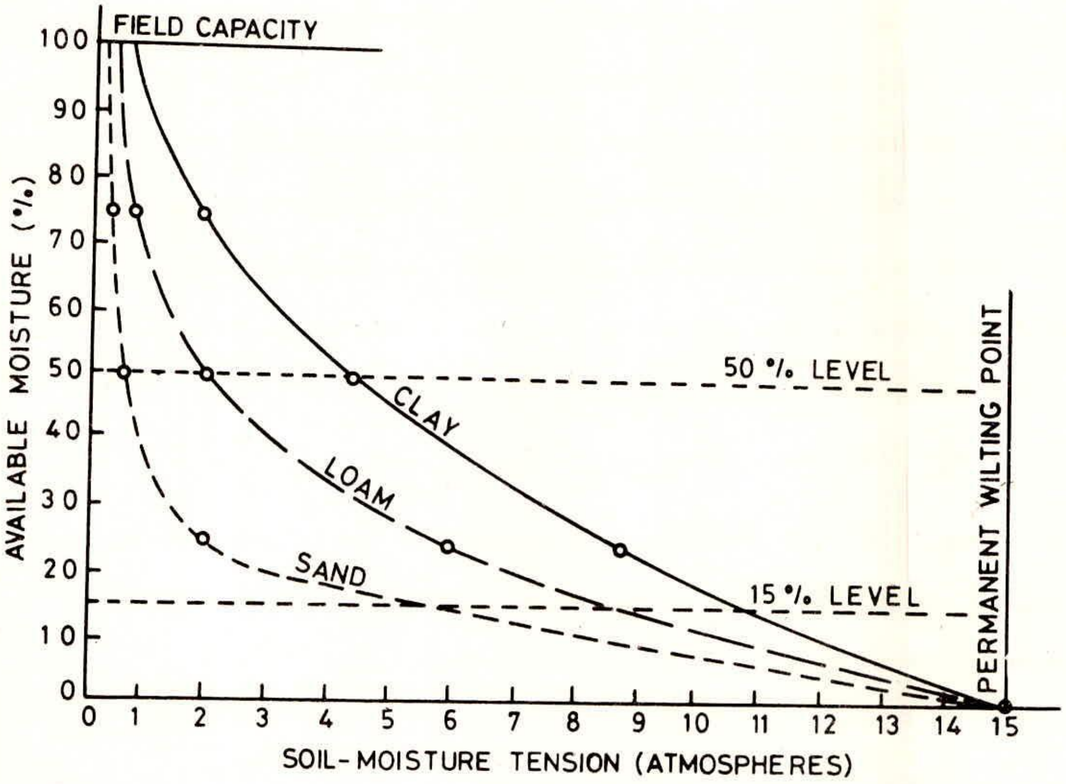

Figure 5: Moisture Characteristic Curves for Clay, Loam and Sand

is assured and the gravitational effect is neglected, the vapor potential can be taken to be equal to the sum of the matric and osmotic poentials, since air acts as in ideal semi-permeable membrane in allowing only water molecules to pass (provided that the solutes are nonvolatile).

Fortunately, recent years have witnessed the development of highly precise, miniaturized thermocouple psychrometers which indeed make possible the in-situ measurement of soil moisture potential (Dalton and Rawlins 1968; Brown, 1970). A thermocouple is a double junction of two dissimilar metals. If the two junctions are subjected to different temperatures they will generate a voltage difference. If, on the other hand, an electromotive force (emf) is applied between the junctions, a difference in temperature will result; depending on which way a direct current is applied, one junction can be heated while the other is cooled, and vice versa. The soil psychrometer (Fig.6) consists of a fine wire thermocouple one junction of which is equilibrated with the soil atmosphere by placing it inside a hollow porous cup embedded in the soil, while other junction is kept in an insulated medium to provide a temperature lag. During operation, an emf is applied so that the junction exposed to the soil atmosphere, is cooled to a temperature below the dew point of that atmosphere, at which point a droplet of water condenses on the junction, allowing it to become, in effect, a wet bulb thermometer. This is a consequence of the so-called Peltier effect (Yavorsky and Detalf, 1972). The cooling is then stopped, and as the water from the droplet reevaporates the junction attains a wet bulb temperature which remains nearly constant until the junction dries out, after which it returns to the ambient soil temperature. While evaporation takes place, the difference in temperature between the wet bulb and the insulated junction serving as dry bulb generates an emf which is indicative of the soil moisture

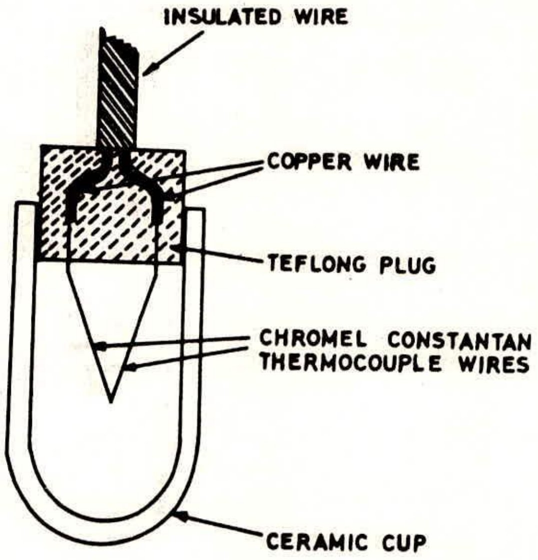

Figure 6: Cross Section of a Thermocouple Psychrometer Contained in an Air-filled Ceramic cup.

potential. The relative humidity (i.e. the vapor pressure depression relative to that of pure, free water) is related to the soil-water potential according to

$$\Phi = RT \ln (p/p_o)$$

Where p is the vapor pressure of soil water, P_o the vapor pressure of pure, free water at the same temperature and air pressure, and R is the specific gas constant for water vapor.

3.0 REVIEW

The understanding of water movement in natural soil profiles under vegetation cover is of great importance for soil problems (water supply of plants, drainage, irrigation and for problems in hydrology (groundwater recharge) and agrometeorology (evapotranspiration). However, in many cases, such water flow investigations are only partly carried out in the field because of difficulties in measuring and analysing. For instance, soil water contents of various depths are determined in the field, and the other data required for water movement calculations are derived from the relations between soil water content and hydraulic conductivity, which are determined on core samples in the laboratory. This procedure may cause several errors, so for a critical examination, experiments with simultaneous field measurements of soil water content and soil water suction as a function of time and depth are needed (Gardner 1967). An analysis of these field data by computer gives evidence of the water flow, and also of the above mentioned basic relations in the soil horizons or layers of a natural profile under non-equilibrium conditions. The procedure and some preliminary results of such simultaneous soil water content and soil water suction measurements in a loose soil profile under arable cultivation are described by Giesel et al. (1970). Similar studies have been carried out by various workers (Gardner, 1960; Rose et al; 1967; Van Bavel et al., 1968; Wesseling, 1961.

Gee and Kirkhan (1984) used moisture profiles obtained by neutron proble logging, and calculated tht 8.5 out of 28 cm of annual precipitation drained from 1.0 to 3.5 m depth at a sandy site near Richland, Washington, vegetated with shallow-rooted cheat grass. They also estimated deep drainage to be 5.2 cm yr using the in situ water content and unsaturated conductivity calculated by the instantaneous profile method.

Stephons and knowlton (1986) conducted some field experiments at a sparsely vegetatted, dry-looking, sandy site on the sevilleta National Wildlife Refuge neare socorro, New Mexico to determine saturated hydraulic conductivity above the water table using borehole infiltration tests.

In situ unsaturated hydraulic conductivity was determined by the instantaneous profile method recommended by Hillel et al. (1972). The opined that soil moisture measurements and in situ hydraulic conductivities below about the 2m depth, but above the influence of water table fluctuations, are necessary for substantiating the recharge estimates based on relatively shallow data. Alternative approaches, such as isotope tracers in the unsaturated zone, may be useful in investigation average soil wter flux over long periods. Isotopic methods offer the advantage of directly monitoring long term soil moisture movement, but they do not provide information on the dynamics of the infiltration and recharge processa that is afforded by soil water monitoring.

Gvirtzman and Magaritz (1986) presented a new approach employing the natural tritium profiles to study the mechanism of water transport in the unsaturated zone under irrigated fields. This makes it possible to continue the use of natural tritium as a tracer, in spite of the fact that the major atmospheric pulse has almost disappeared. This method involves measurement of the profile of soil moisture which is created by two sources of water input that differ in their tritium content and which alternate seasonally: rain during the winter with the atmosheric tritium level and irrigation water during the summer having a near zero tritium level. These two sources of water penetrate the soil surface alternately, and create layers with different tritium composition, along the soil column. This methodology enables seasonal resolution in the unsaturated zone as reported by Bath et.al. (1982) in the profiles of oxygen-18 and deuterium.

Van Bavel et al. (1968) demonstrated that when a bare soil is irrigated the depletion rate is always greater than the true evaporation rate. When the soil contained a sorghum crop with a normally developed root system, the initial depletion rate was also greater than the measured evaporation rate, but later, as water moved upward into the root zone, the depletion rate was an underestimate of the evaporation rate. Correction of the depletion figures by extrapolation of known drainage rates of a covered, bare plot with the same water content as the planted plot, or by estimation of the flux from unsaturated flow characteristics, did not yield satisfactory results (van Bavel et al., 1968). Recently Black et al. (1969) successfully predicted the changes in water storage for a bare sand, by combining evaportion and drainage values, calculated by means of simplified flow equation, with rainfall data.

Penman (1962) suggested that sugar beet gives little response to irrigation because it has a deep and efficient root system. This may allow the crop to draw on the reserve of moisture at depth when the growth of shollow-rooted crops is restricted by water shortage. Previous report of Penman (1952) and Harvey (1962) showed tht, relative to other crops, increases, in sugar yield were usually small.

In recent decades research in soil physics has resulted in the development of mathematical theories and models describing the state and movement of water in both saturated and unsaturates soil bodies. Moreover, experimental work has resulted in the development of more precise and reliable techniques for the measurement of flow phenomena and of pertinent soil parameters. Application of actual processes in the field depends upon knowledge of the pertinent hydraulic characteristics of the soil, including the fundamental relation of hydraulic conductivity and of matric suction to soil wetness as well as the spatial and temporal variation of these in the heterogeneous field situation.

The prediction of the behaviour of the soil-water plant system may be considered with a description of the moisture regime existing in the soil as a first approximation. Mathematical modelling and simulation techniques have been developed to describe the dynamic nature of the moisture regime in the soil water plant system (Nimah and Hanks, 1973; Feddes et al. 1976; Hillel, 1977). The techniques generally involve the solution of a finite difference approximation to the moisture flow equation, including a root extraction or sink term. The precidtion of the unsaturated hydraulic conductivity from pore size distribution data has been explored by several investigators (Millington and Quirk 1961; Jackson et al., 1965). A simulation model describing water movement through field cropped soils have been developed by Jong and Cameron (1979). Feddes et.al., (1978) developed a model for simulation of field wter uptake by plants using a soil water dependent root extraction function. Hillel et.al. (1976), Gupta et.al., (1978) Dejong and Camerin (1979), Hayhoe and Dejong (1982) and Idike et.al., (1982) developed models for predicting soil water content at various depths, taking into consideration water uptake by the root system.

Measurement of water uptake by plants has been attempted on macroscopic and microscopic bases. In macroscopic models (Molz and Remson, 1970; Feddes et.al., 1976; Hillel et.al. 1976; Molz, 1987), the uptake by the whole roots system is considered while in microscopic models (philip 1957; cowan, 1965), the uptake only by a single root is taken into account. Both macroscopic and microscopic models can be useful to describe plant water uptake under appropriate conditions. Jain and Murty (1985) has developed a macroscopic model to simulate soil water profiles under crops taking soil crop and climatic parameters into consideration and used the model fo scheduling. Data on soil moisture content at a field experiment on sandy loam soil under wheat were used to test the model. The observed moisture contents in the field were compared with the values predicted by the model and were found in close agreement. The model can be used for other crops and other locations by replacing the crop characteristics of wheat by that of the crop under consideration and the climatic parameters.

Molz (1981) has presented a detiled review of physically based models of water transport in the soil-plant root system. But these models rely on several simplifying assumptions and extensive experimental information for their parameters which restricts their applicability directly at the field level. This is why simple conceptual models of soil water balance based on empirical observtions of soil plant responses have been preferred in commercial irrigation services (Jonsen et.al., 1970; Stegman et.al., 1980). Also, when the soil water balance model is only a component of irrigation optimization models with limited water supplies, the soil water transport models, based on numerical solutions of differential equations of flow, present difficulties with respect to computer storage and time. Rao et.al.(1987) presented a conceptual model of soil water balance which monitors the soil moisture conditions at weekly intervals in an irrigation season by estimating the actual evapotranspirtion during a week. The model is based on empirically established results of plant response to available soil water (Doorenbos and Kassam, 1979). It is tested by application to the field conditions of a case study area in the Nagarjan Sagar Irrigation Project Area. Andhra Pradesh, India in order to evaluate its use in irrigation optimization models which output the optimal weekly irrigation programmes (Rao, 1985).

kilute and Peters (1969) have reviewed the analysis of flow of water to roots. The single root models have all a) assumed cylindrical geometry in a soil homogeneous with depth, so that one-dimensional flow results, b) neglected gravity, and c) assumed constant diffusivity and/or steady state flow. Analytical solutions for unsteady flow of water from a finite cylinder assumed constant diffusivity(Shih, 1969) or that diffusivity is an exponential function of moisture content (Singh and Franzini, 1967). Philip (1957) and Gardner (1960) assumed a constant flux into the root as a boundary condition to obtain water potentials in the root-soil system. The plant factor influencing the flow of water in plants have been discussed by cowan and Mithorpe (1968) and by Slatyer (1967). Gardner (1965) and Cownan (1965) have attempted to model the soil and plant resistances to flow, but both of these models force a flux rate to exist, either across the root or leaf surface, and assume steady - state type water potential of the soil.

The performance of different soil moisture deficit models have been assessed by calder et al. (1983) by comparing model predictions with over 3000 neutron probe observations of soil moisture content at six grassland experimental sites operated by Institute of Hydrology, Wallingford, Oxan. The models were formulated using combinations of different equations *for estimating potential evaporation and different regulating functions relating actual to potential evaportion via the moisture status of the soil.*

Surface soil moisture variations on small agricultural watersheds at Chickasha Oklahoma have been studied by Hawley et.al. (1983). Statistical analysis showed that topography is the most important factor controlling the distribution of soil moisture. The presence of vegetation tends to diminish the soil moisture variations caused by topography, while the effect of minor variations in soil type were usually insignificant.

4.0 REMARKS

A significant and vital phase of the hydrological cycle is the entry and movement of water in the soil profile. In field situations, infiltration of rainfall or irrigation water is generally a case of water movement into soil profiles of nonuniform water content and hydraulic conductivity. The understanding of water movement in natural soil profiles under vegetation cover is of great importance for soil problems e.g. water supply of plants, drainage and irrigation and for problems in hydrology. One of the most important parameters influencing crop production is the water available to plants either by rainfall or through irrigation. The amount of irrigation water to be applied is directly related with the depth of the root zone and the water present in the soil. The behaviour of the soil water plant system may be considered with a description of the moisture regime existing in the soil. However, it is possible that while the total soil water content in the root zone appears to be adequate for plant growth, the distribution of water in layers of the soil is not optimal. Therefore, continual monitoring of soil moisture content is of great significance in irrigation management. The methods described in the report measure the soil water status at a given soil depth. Each method has its own limited applicability under field conditions. However, these methods are of some importance in scheduling of irrigtin and in providing approximate estimates of amount of water to be applied in each irrigation with respect to a fixed soil depth.

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