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DROUGHT ANALYSIS USING SOIL MOISTURE SIMULATION APPROACH

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

A number of drought indices have been developed in past. Most of these indices appear to be adhoc and consider either rainfall alone or take some account of soil water storage and loss of water from this storage by evapotranspiration. An operational definition of drought could best be one that compares daily rainfall values to evapotranspiration rates to determine rate of soil moisture depletion to give upto date status of available soil moisture after correcting for surface runoff, and expresses these relationships in terms of drought effects on crop growth at various stages of crop development. An attempt has been made in this paper to discuss a simple approach for development of a soil water budgeting model to simulate daily soil moisture in dry lands using historical rainfall and climatic data and moisture characteristics of the soil. The severity of drought for a given crop can be studied by defining different levels of drought definition (i.e. different levels of soil moisture content corresponding to different soil water deficits). The incidence of drought can be characterised by determining the number of days during the growing season of a crop when simulated soil moisture is below a value which is known to impede crop growth appreciably. This operational definition can be used to analyse drought frequency, severity and duration for a particular crop in a given watershed.

1.0 INTRODUCTION

The variability of meteorological, hydrological and agroclimatological conditions over space and time have created a situation that nearly one third of the geographical area and 29% population of the country are affected by drought. The occurrence of drought leads to depletion of soil moisture, reduction in stream flow and consequent reservoir and tank levels and depletion of groundwater. It also affects the water quality adversely. This on a continued basis leads to reduced domestic and industrial water supply, reduced availability of fodder and decline in agricultural production. Nearly 25% of the cropped area of the country is under assured irrigation whereas rest of the area under dry land agriculture/rainfed agriculture is subject to the vagaries of nature. Therefore, substantial amount of cropped area suffers from the problem of drought.

Drought starts slowly, has long duration, is of the creeping and pervasive nature covering vast areas. Drought is generally viewed as a sustained regionally extensive occurrence of below normal water availability. It can be best defined by using properties of water deficit conceived or experienced in the different time series of water supply minus water demand. Characteristics of droughts are described by a selected set of variables depending upon the particular water user or interest. There are different types of drought i.e. meteorological, agricultural and hydrological, and all are caused due to lack of water availability. Hydrological drought which means lack of water resources, and agricultural drought, which may be defined as a time when crop growth is restricted due to lack of soil moisture do not necessarily coincide with periods of meteorological drought.

Soil is the store house of water from where plants extract moisture for their evapotranspirational needs. It is an established fact that the soil moisture deficit beyond a certain limit adversely affects the plant growth and causes wilting of plants. This results in declined agricultural production which can be taken as a physical measure of drought. The severity of drought can be studied by defining different levels of soil moisture deficits. Therefore, availability of soil moisture to the plants has been considered as an indicator for agricultural drought analysis and planning drought management measures in this report.

A conceptual approach for simulation of soil moisture in unirrigated areas on daily basis using historical records has been discussed in the report to allow prediction of soil moisture to analyse drought severity, duration and frequency for a particular crop in a given drought prone area.

2.0 REVIEW

2.1 General

Scores of drought definitions and indices have been developed and documented by a variety of disciplines as reported by WMO (1975). Most of the drought indices developed in past are adhoc and work in isolation. Rainfall analysis alone has been the main criteria in earlier drought studies. Accumulated rain in itself is not an adequate index of drought condition as drought is a relative measure and is resulted due to many other interracting variables representing hydrologic process, soils and crop aspects. The definitions of drought based on rainfall amount alone are concerned with meteorological drought. Hydrological drought, meaning depletion of water resources, and agricultural drought, which may be defined as depletion of soil moisture affecting the crop growth do not necessarily agree with meteorological drought. Availability of useful moisture in either of these forms e.g. i) shallow soil moisture, ii) deeper soil moisture, iii) water available in ground water storage, and iv) streamflow can be an appropriate index for drought analysis and planning drought management strategies.

2.2 Soil Moisture and Drought Concept

The soil moisture is one of the important elements of land phase of hydrologic cycle as most of the hydrological activities take place in unsaturated zone. The soil acts simply as a reservoir for the moisture from where plants extract moisture to satisfy their evapotranspirational needs. Deficiency in soil moisture adversely affects plant growth, and governs infiltration and storm runoff. Water in the soil profile is held with variable tensions and moisture held in between identified tensions are called different types of hydrological storages : i) detention storage which is the amount of water held between field capacity and maximum water holding capacity. This vilume of water finds its way through the soil profile and gets absorbed by the soil profile or released into the channel system or ground water storage much after the rain, ii) the retention storage (i.e. available soil moisture capacity) which is difference between permanent wilting point and field capacity. Water from this storage does not flow out of profile but gets utilised through the process of evapotranspiration, iii) the storage below permanent wilting point which is, not generally available for any of the two purposes indicated above. The soil moisture availability in difference soil types is shown in figure 1.

The soil moisture deficit is defined as the difference between field capcity and actual soil moisture (i.e. current soil moisture). Estimation of moisture deficit is made on the basis of certain fundamental concepts in connection with gain and loss of moisture by soil. It has been also well established that soil moisture deficit beyond a certain limit adversely affects plant growth and causes wilting of plants. This results in declined agricultural production which is normally taken as a measure of agricultural drought. When soil moisture

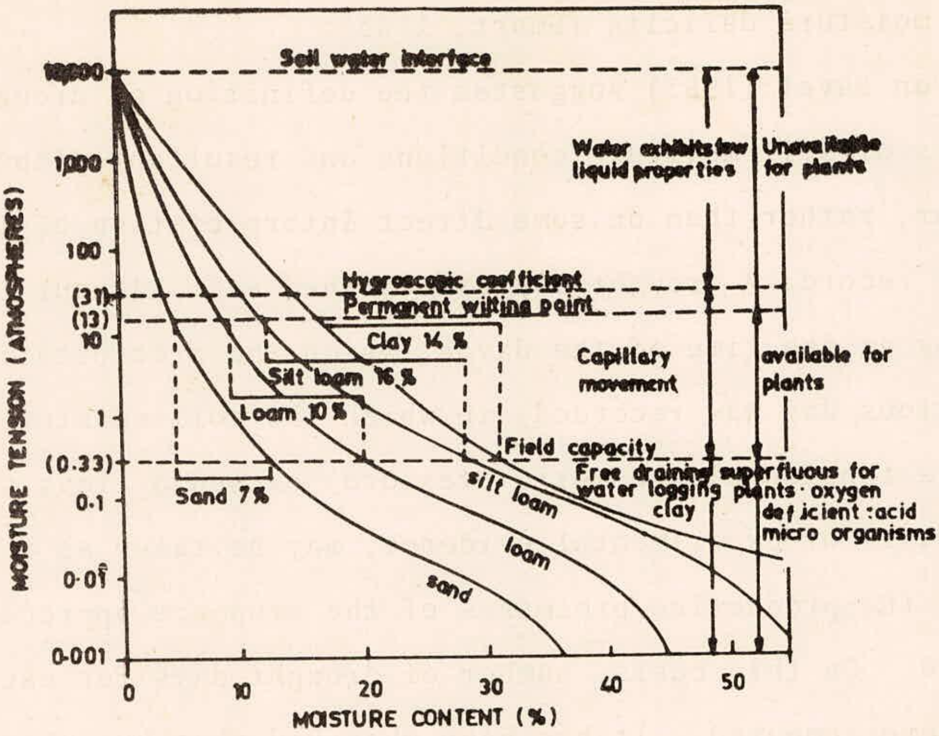

FIG.1. RELATIONSHIP BETWEEN MOISTURE CONTENT AND MOISTURE TENSION IN FOUR DIFFERENT TYPES OF SOIL, INDICATING THE RANGE OF MOISTURE AVAILABLE FOR PLANTS

falls below 'permanent wilting point', the crop will normally sustain permanent injury from which it cannot recover and this may lead to situation of severe or disastrous drought. The severity of drought can be studied by defining different levels of soil moisture deficits (Smart, 1983).

Van Bavel (1953) suggested the definition of drought on the basis of soil moisture conditions and resultant plant behaviour, rather than on some direct interpretation of the rainfall record. A drought day was defined as a 24-hour period (starting at the time of the day at which the precipitation of the previous day was recorded) in which the soil moisture stress (moisture tension plus osmotic pressure) exceed a limit which, on the basis of experimental evidence, may be taken as a point at which the productive processes of the crop are appreciably decreased. On this basis, number of drought days for each season were computed. It has been observed that by increasing the moisture storage capacity of the soil, the number of drought days could be reduced significantly. Wilhite and Glantz (1985) quoted the studies done by Kulik in 1960 which represented drought intensity as the difference between plant water demand and available soil water. It was reported that the upper 0.2 m of soil was critical to plant growth because of nutrient supplies, root activity and activities of micro-organisms. Therefore, drying of this soil layer was taken as an early indicator for loss of production i.e. a measure of drought intensity.

The total amount of soil moisture available to a crop depends both on the soil type and the crop as different soils have different soil moisture characteristics and different crops root to different depths. Figures 2(a) to 2(d) show the soil moisture deficit pattern of typical loamy sand, sandy loam, sandy clay loam and clay loam soils at different soil moisture tensions (Ray and Sharma, 1983). The figures indicate that maximum soil moisture deficit at PWP i.e. 15 bar soil moisture tension are about 1.3, 1.6, 1.7 and 3.02 mm/cm soil depth respectively. It shows that different soil types have different soil moisture deficits at a given soil moisture tensions. Percentage reduction in yield of crops like Wheat, Cotton, Sugarcane, Corn, Potato etc. at different soil moisture tension are shown in Figure 3. Gardner and Ehlig (1983) have concluded that the root zone should be divided roughly into two moisture zones namely upper and lower zone. The upper zone contains many roots and is depleted of water at a rate in proportion to remaining water in the soil. The lower zone containing fewer roots is depleted of water at a slower rate until most of the water in the upper layer is lost.

2.3 Soil Moisture Depletion in Forests and Grass Land

Soil moisture behaviour in forests and grass lands is also equally important. Forage production in arid and semi-arid parts is an important factor in watershed resources management programmes. Soil water deficiency influences forest and herbage production. It may be possible to estimate vegetative growth through evaluation of soil moisture regimes using simulation approach. Owtadlajam (1982) and Khalili (1984)

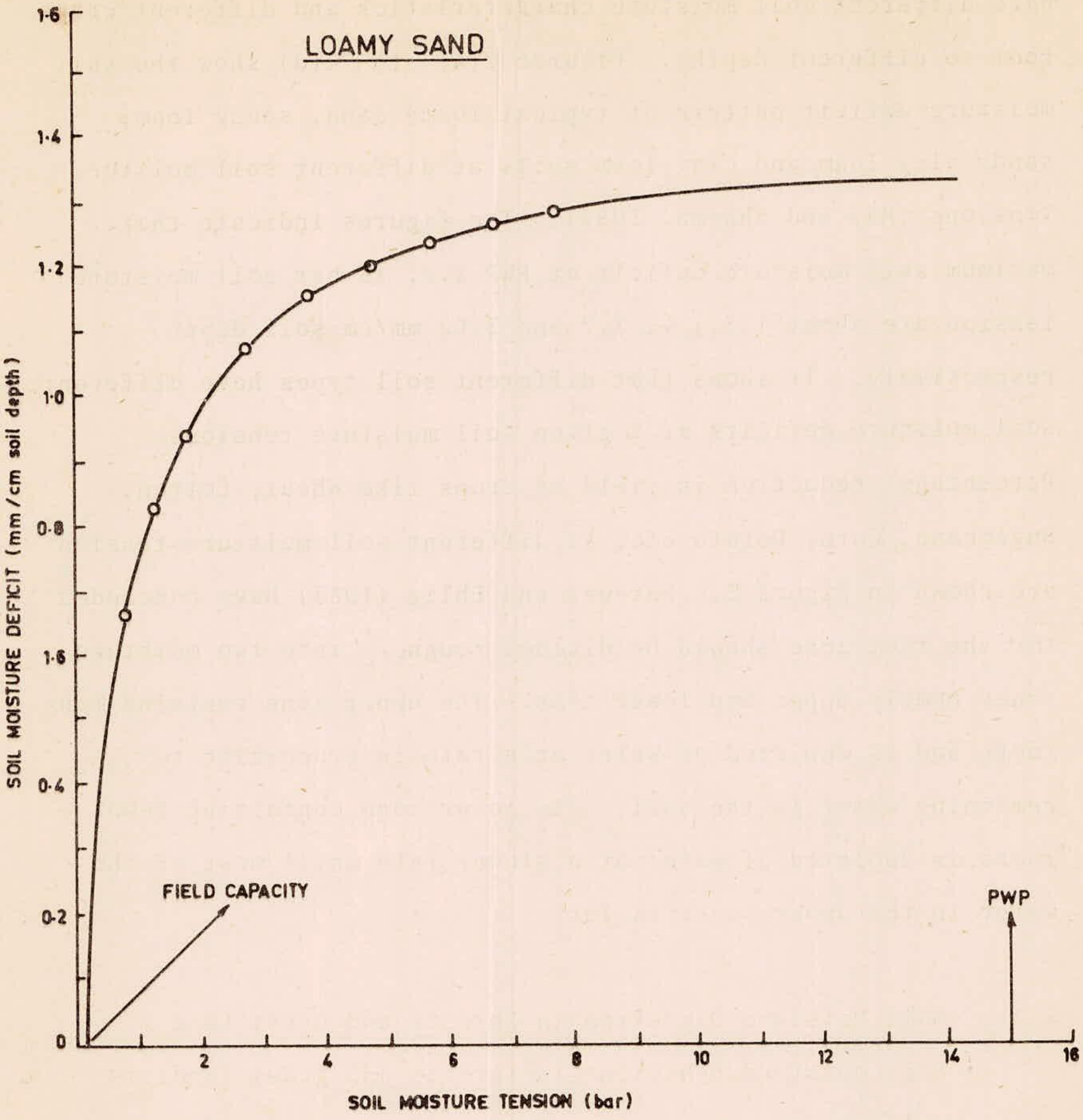

FIG. 2(a) SOIL MOISTURE RELEASE PATTERN OF LOAMY SAND

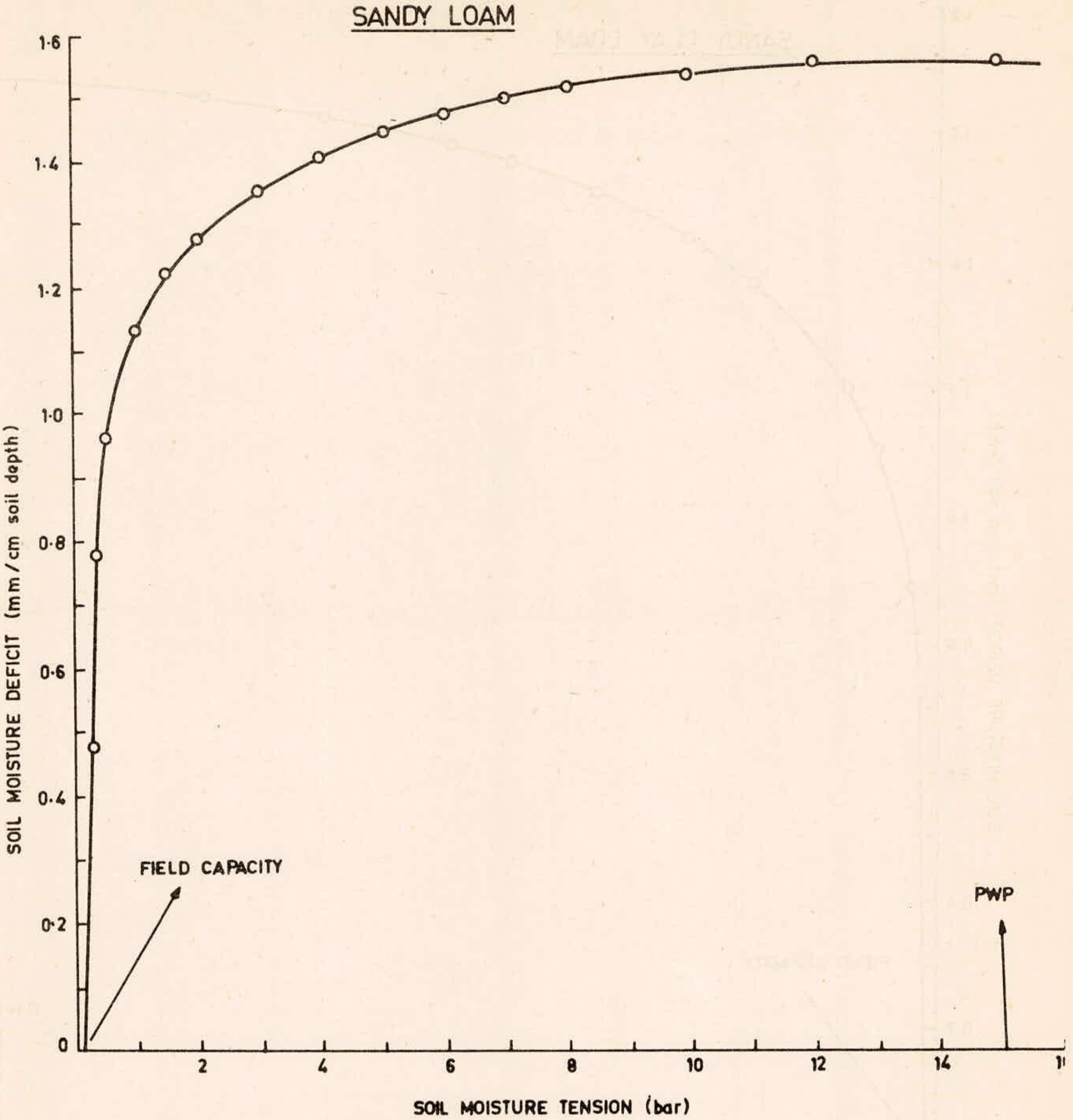

FIG. 2(b) SOIL MOISTURE RELEASE PATTERN OF SANDY LOAM

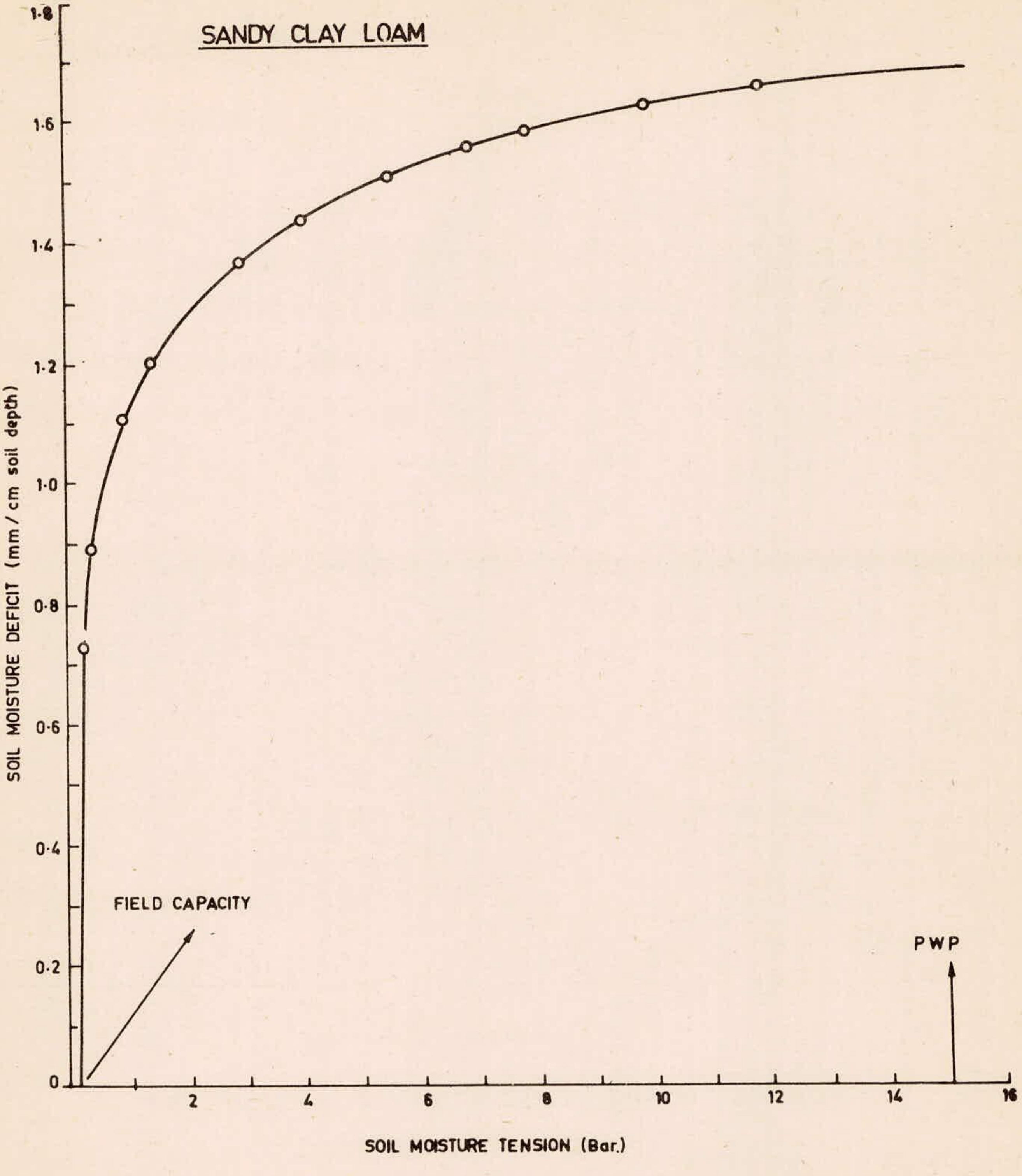

FIG 2(c) SOIL MOISTURE RELEASE PATTERN OF SANDY CLAY LOAM

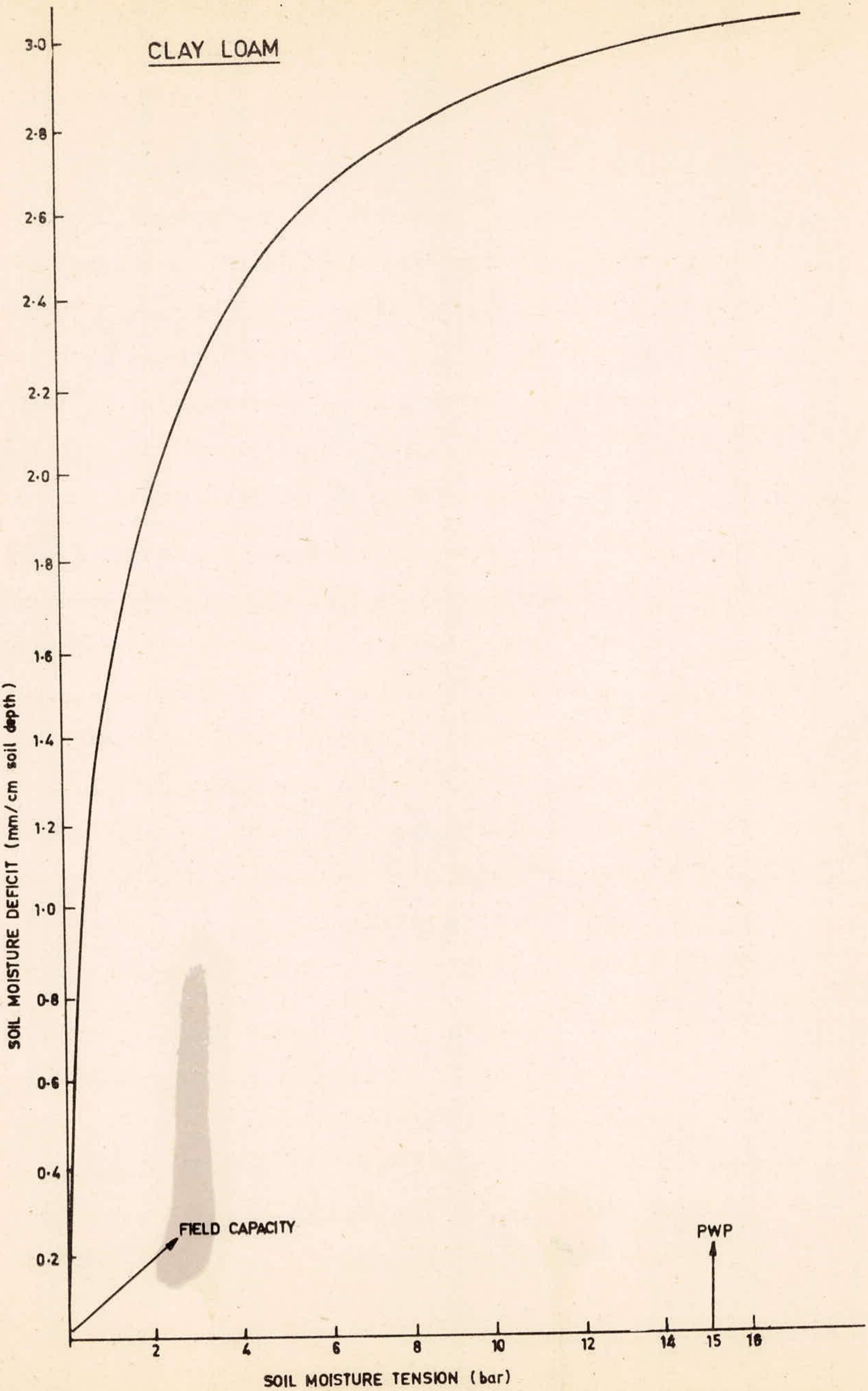

FIG. 2(d) SOIL MOISTURE RELEASE PATTERN OF CLAY-LOAM

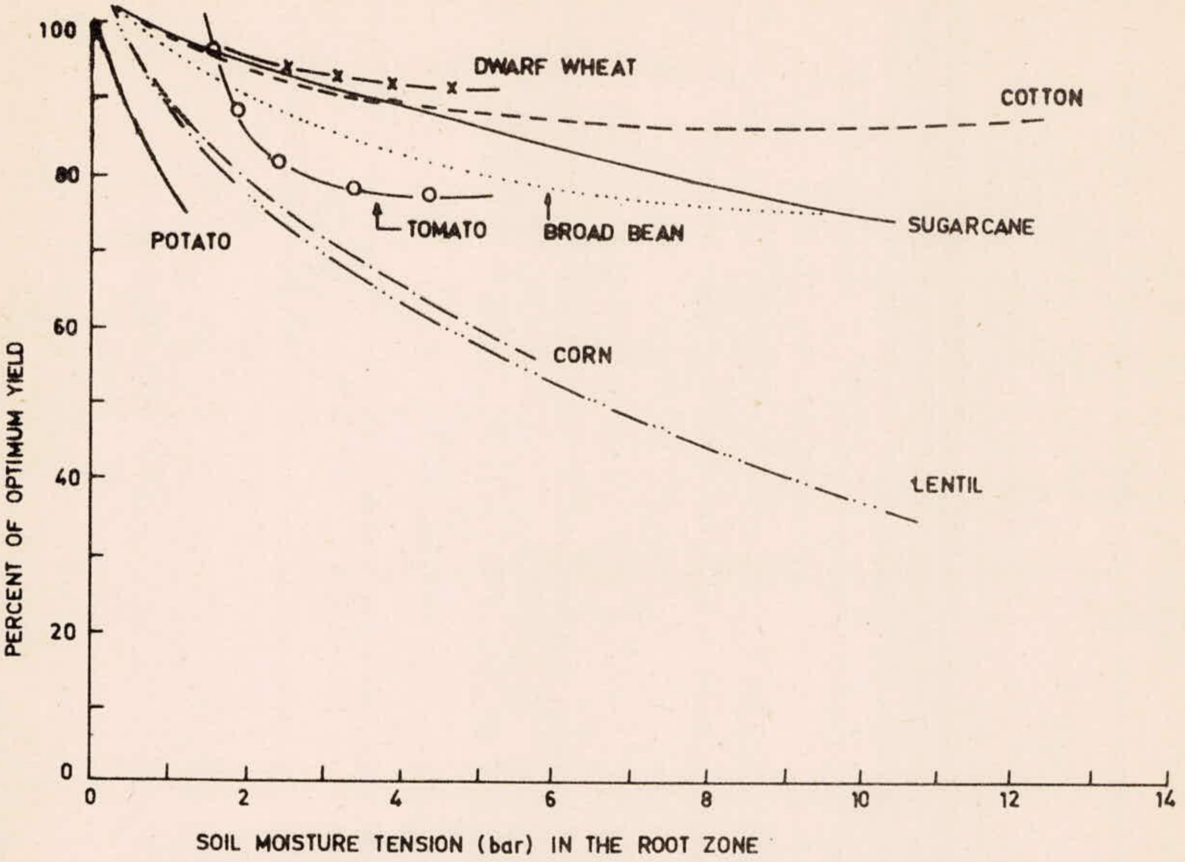

FIG. 3. PERCENT REDUCTION IN YIELD AT DIFFERENT SOIL MOISTURE TENSIONS

empolyed a soil-water budgeting model to simulate soil moisture stress (i.e. the difference between potential and actual evapotranspiration) on forage and rangeland production in semi-arid and arid areas of USA. Single layer soil model applying the concept of Budyko-Sellers water balance approach was used. The general form of regression model of soil moisture stress to yield was:

$$\text{Yield} = a_o + \text{Sum } (a_i \times \text{Stress}_i) \text{ .... } (1)$$

Equation (1) presents annual herbage production as a linear function of the individual stresses from various months or seasons. The coefficients a_o and a_i indicate the relative influence of various monthly or seasonal stresses on herbage production. Annual grass production was regressed against soil moisture stress. Perennial grass production alone was correlated against soil moisture stress in various groupings.

Dahl, (1962, cited from owtadolajam, 1982) found that the soil water content and the depth of soil wetting on April 15th of the year were good indicators for predicting the amount of grass which would be produced by the end of August in a site in East Central Colorado. Passey et al. (1964, cited from owtadolajam, 1982) also reported that the herbage production was correlated to available water in the soil at the end of March.

The behaviour of soil moisture depletion under various vegetative covers have been studied to a limited extent by researchers. In a study at Dehradun, the forest watershed gave relatively higher soil moisture values in top 45 cm soil depth as compared to agricultural watershed(Dhruvanarayana & Sastry, 1983). The long term studies on soil moisture regime conducted at Dehradun under forests and grass land with woil samples drawn from depths of 0.30-1.20 m twice a month indicated that soil moisture remains at a higher level under forest than grass (Ghosh et al., 1979). Soil moisture content remained at a higher level under bamboo (14-102 mm) followed by teak (30-73mm), Chir pine (20-77 mm), Sal (20-108 mm) and grass (9-95 mm). Chir recorded lower accretion and depletion rates as compared to teak and sal. Maximum soil moisture was observed in August whereas minimum in May. A serious soil moisture stress starts building from March to April resulting in soil moisture deficit during May and June. The maximum soil moisture deficit occured in the month of May.

The studies carried out in West Bengal (Ghosh, 1967) indicate that the soil moisture retained by bushy sal forest was maximum followed by sal coppice and barren waste land. In another study, Bansal et al. (1977) used non-weighing type undisturbed lysimeters to asses the soil moisture depletion and deep percolation for grass, soyabean, wheat, maize and cultivated fallow land. The results of the study are summarised in Table 1.

2.4 Soil Water Models

A multitude of soil moisture accounting models have been developed by several investigators (Holmes and Robertson,1959; Baier and Robertson, 1966; Saxton et al. 1974; Thornthwaite and Mather, 1955; Smart, 1983 & Jain & Murty, 1985 but less attention has been paid to application of these models for drought

TABLE 1 Soil Moisture Depletion and Deep Percolation

Period	Treatment	Rainfall (mm)	Irrigation (mm)	Soil Moisture depletion (mm)	Deep Percolation (mm)
December-April	Grass	56	-	158	Nil
	Wheat(Soyabean, Wheat rotation)	56	150	244	Nil
	wheat (Maize, wheat rotation)	56	150	298	Nil
	Bare (Cultivated)	56	150	174	Nil
May-October	Grass	1188	-	249	245
	Soyabean	1188	-	234	5
	Maize	1188	-	199	52
	Bare	1188	-	265	Nil

analysis and management. The available soil moisture models differ from each other due to different methods used for computing potential evapotranspiration, actual evapotranspiration, infiltration and runoff, temporal definition of evaporative demand and due to number of soil layers considered in the model.

Some of the investigators have tried to use soil moisture models in drought related studies (Cordery , 1981; Owtadolajam, 1982; Smart, 1983; Khalili, 1984; and Others). Cordery (1981) used a simple water balance model to estimate monthly catchment soil water deficit (SWD). In this model SWD is the difference between the actual soil water storage and the field capacity and drought is assumed to occur when there is large value of SWD. The model is run separately to obtain SWD for each root zone capacity area and then the catchment weighted average SWD is obtained. Evaporation loss as 70 percent of pan evaporation value has been considered in calibrating the model. The probability distributions of monthly catchment SWD using long term rainfall and evaporation data have been used for short term drought forecasting. Smart (1983) used a conceptual daily soil moisture accounting model run with daily rainfall and evaporation inputs to simulate soil moisture levels for the top 10 cm soil under irrigated and unirrigated conditions for drought studies in rye grass pasture at New Zealand The simulated soil moisture values were used to illustrate statistical procedures for drought frequency, duration and severity. Soil moisture content (% by weight) below which severity of drought was defined, included 10, 12, 14, 16, 18 and 20%. The model assumes that if rainfall is less than soil moisture deficit, all the rain-fall would go to recharge the soil which may not be true when intensity of rainfall is greater than infiltration rate of soil and in such case surface runoff will take place. The model also do not differentiate between surface runoff and percolation losses below the root zone.

Holmes and Robertson (1959) developed the modulated soil moisture model which was improvement of their earlier single-layer soil moisture model. This model uses a two-layer soil system and considers that actual evaporation will generally not equal the potential due to moisture deficits. The two are set equal until the moisture in the upper zone is depleted. Thereafter, moisture is extracted from the lower zone at a reduced rate proportional to the moisture level. The model assumes that the rain is first used to recharge the upper zone and surplus, if any, is used to recharge lower zone. Any further surplus remaining is assumed to be available for runoff or deep percolation beyond the root zone. Baier and Robertson (1966) improved these models with development of a versatile soil moisture budget model. In this model soil is divided into several layers and the available water capacity of each layer is taken to be the difference between soil's field capacity and wilting point. A much more comprehensive models to simulate soil-plant-atmosphere-water systems have been developed by Saxton at al. (1974) and many others for agricultural and hydrological studies. Saxton et al. (1974)developed a digital simulation model to relate the numerous meteorological crop and soil moisture relationships on a daily basis throught the year. In this model some processes, like soil moisture redistribution are modelled usig a physics based approach, whereas other like plant transpiration are semi-empirical. There are several physically based complex models capable of simulating soil-plant-atmosphere-water systems as described by Hillel (1977), Hanks et al. (1969), Nimah and Hanks (1973) and many others. These models generally use modified form of Hanks et al. (1969) equation by introducing a plant root extraction term.

$$\frac{\partial \phi}{\delta t} = \frac{\partial}{\delta z}\left(K(\phi)\,\frac{\partial H}{\partial z}\right) + A\,(z,\,t) \qquad \ldots \quad (2)$$

in which,

ϕ is volumetric water content,
t is the time,
z is depth,
$K(\phi)$ is hydraulic conductivity
H is hydraulic head, and
$A\,(z,t)$ is plant root extraction term

A comprehensive description of each model is beyond the scope of this report.

Soil moisture deficit at 30 and 45 cm depths in some climatic stations in India has been computed by Biswas and Mhalskar (1977) from rainfall and potential evapotranspiration for water budgeting and irrigation scheduling. The approach basically uses the water balance concept of Thornthwaite and Mather (1955) which relies heavily on the threshold concept that runoff does not occur until soil has attained its field capacity. This assumption limits its application as a water balance model.

The watershed models developed by hydrologists also include a component of soil moisture. State of the art examples of the approaches used in hydrologic modelling can be found in the USDA Hydrograph Laboratory (USDAHL) model (Holtan et al., (1975) and National Weather Service River Forecast (NWSRFS) model (Peck., 1976). In the USDAHL model, the spatial variability of soils and vegetation is accounted for by using zones within which the hydrologic parameters are averaged. Within each zone the soil is subdivided into several homogeneous layers determined from hydraulic properties. Evapotranspiration is computed daily using an empirical equation which considers the crop and soil characteristics, as well as the current soil moisture. Evapotranspiration is drawn from the first two layers, which are considered to be the root zone. These computations are performed daily. Infiltration is also based on soil and crop characteristics and the current soil moisture. A 1-hour time step is used for these computations. The procedure used for soil moisture redistribution and percolation only considers gravity flow.

In the NWSRFS Model, two zones are used to simulate soil water storage and movement. The upper layer responds quickly to rainfall and controls overland flow. It is usually very shallow. The lower layer is the balance of the soil column extending to the water table. Soil hydraulic properties are averaged within each layer. Moisture is stored as either tension or free water. Infiltration, percolation and soil moisture redistribution involve the free water. They are computed with empirical equations that use a controlling factor the ratio of the free water present to the field capacity of the layer involved. Evapotranspiration is also computed using an empirical procedure. Actual evapotranspiration is set equal to potential until all moisture in the upper layer is depleted. When this occurs, moisture is extracted from the lower zone using an equation that considers the moisture deficit and the crop characteristics. A 6-hour time step is used for simulation.

3.0 PROBLEM DEFINITION

A schematic diagram depicting soil-plant-water system is shown in Figure 4. The maximum root zone depth consisted of two layers which differ in respect of their field capacities. The root growth takes place linearly with respect to time after its emergence till the full canopy development and thereafter it remains constant till harvest. The evapotranspiration on any day is governed by the linear relationship of Thornthwaite and Mather (1955) as below

$$AE = PE \left(\frac{AW}{AWC}\right) \qquad \ldots (3)$$

in which,

AE and PE = actual and potential evapotranspiration
AW = available soil moisture, and
AWC = available soil water capacity

It is required to find the soil moisture in the root zone depth to find soil water deficit to quantify drought characteristics.

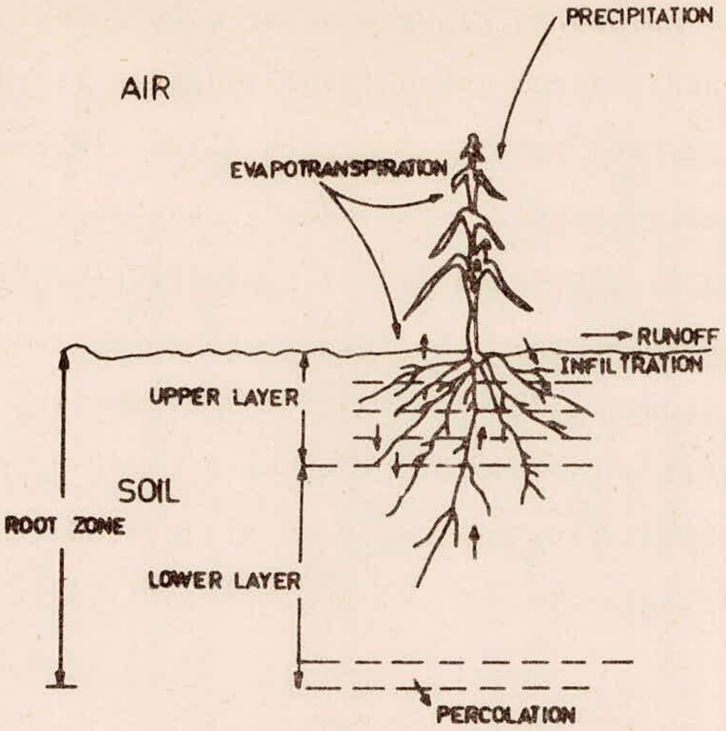

FIG. 4: SOIL PLANT WATER SYSTEM WHICH ENCOMPASSES THE WATER MOVEMENT MODELLED

4.0 METHODOLOGY

4.1 Soil Water Budgeting Model

The quantity of water available in the soil for plant growth can be estimated by accounting for inputs (i.e. rainfall) outputs (i.e. deep percolation, runoff and evaporation and transpiration from the soil column) and the initial quantity of water stored in the soil column. Soil moisture available for plant growth in the system at any time can be determined using the soil water balance equation:

$$Q_{(t+1)} = Q_{(t)} + P - R - S - AE \quad \ldots (4)$$

in which,

$Q_{(t)}$ = soil moisture at begining of t^{th} day in mm,

$Q_{(t+1)}$ = soil moisture at the end of t^{th} day in mm,

P = precipitation during t^{th} day in mm,

R = surface runoff during t^{th} day in mm,

S = deep percolation below root zone in mm, and

AE = actual evapotranspiration during t^{th} day in mm.

The procedure for determining the variables used in Equation (4) is discussed in the following sections.

4.1.1 Evapotranspiration

The extraction of soil moisture on any day during the growing sea son is known to be dependent on the soil moisture characteristics of different layers and the rooting depth.

Dpending upon the root zone depth, the depth of soil can be taken as around 1 to 1.5 m. The depth of soil can further be divided into upper and lower layer depending upon the soil characteristics.

i) Root growth model

On the basis of experimental data a linear root growth model can be evolved for estimating daily root growth. The root zone can be assumed to linearly extend from depth (Yo) at the time (to) i.e. time of plant emergence and to reach its full extension to depth (Ymax) at time (t_f) i.e. when canopy is fully developed. The rooting depth is normally assumed to remain constant thereafter until harvest. Figure 5 shows schematic view of root growth model considered in the water balance calculations. The soil volume and consequently the available soil moisture to crop above the root depth increase in proportion to the increment in the rooting depth. The soil moisture extraction can be assumed to take place from the upper soil layer through soil evaporation till the time of plant emergence. This assumption is made to take care of soil evaporation which is part of evapotranspiration before the plant emergence when the soil is relatively wet. Thereafter, depending upon rooting depth moisture extraction can be accounted.

Daily root growth after plant emergence can be calculated as,

$$DRG = \frac{Ymax - Yo}{t_f - to} \qquad \ldots (5)$$

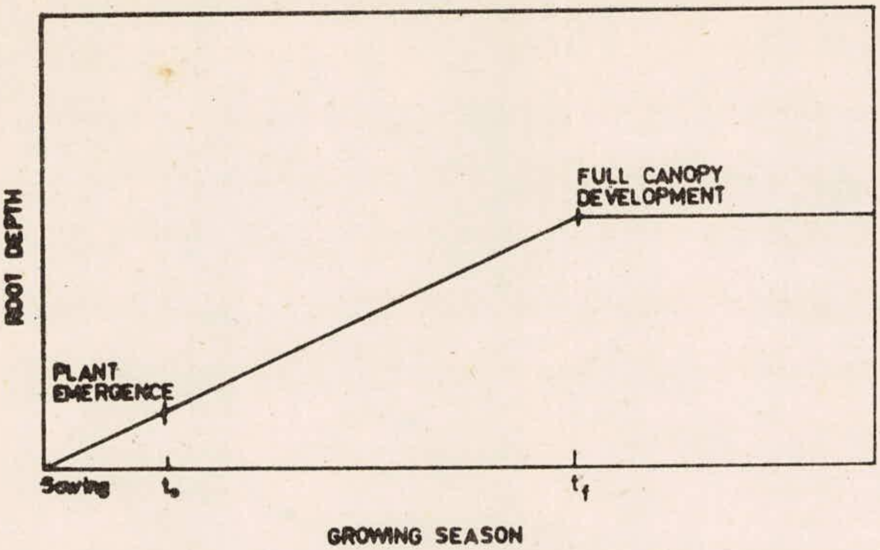

FIG. 5 SCHEMATIC VIEW OF ROOT GROWTH PATTERN

The cummulative root growth on any day t, after sowing can be calculated as,

$$Y_{(t)} = Yo + \left(\frac{Ymax - Yo}{t_f - to}\right) to \qquad \ldots (6)$$

The soil depth is considered to consist of two layers namely upper and lower. The plant will start extracting moisture from both the layers after the root has entered into the lower layer. If the depth of upper layer from soil surface is D_1, the time (t_1) when root reaches the lower layer can be calculated as,

$$t_1 = to + \frac{(D_1 - Yo)}{(Ymax - Yo)} (t_f - to) \qquad \ldots (7)$$

At time $t > t_i$, the root zone will enter the second layer.

ii) Actual evapotranspiration (AE)

It is difficult to measure AE under normal field conditions and the computation procedures for AE are the subject of debate. The widely used method of estimating AE is through the calculation of potential evapotranspiration (PE). Daily PE can be estimated from climatic data using available models like Thornthwaite, Penman and modified Penman, Blaney - Criddle and methods based upon pan evaporation data using suitable pan co-efficient and time varient crop coefficient values. The type of PE model to be used would depend upon the availability of data and terrain condition. AE is governed by vegetation and soil factors when water supply to plant is limited. When soil is at field capacity AE $\simeq$ PE, and when soil is dried out to wilting point, the plant can no longer extract moisture. The reasonably good linear relationship between AE/PE ratio to the ratio of amount of available soil water to available soil moisture capacity given by Thornthwaite and Mather (1955) can be used to compute daily AE, i.e.

$$AE_{(t)} = PE_{(t)} \frac{(AW_t)}{(AWC_t)} \qquad \ldots (8)$$

in which

$AE_{(t)}$ & $PE_{(t)}$ = actual & potential evapotranspiration of t^{th} day in mm,

AW_t = available soil moisture on t^{th}day in mm, and

AWC_t = available soil water capacity or water holding capacity on t^{th} day in mm.

AW_t and AWC_t can be computed using following relationships:

$$AW_t = (Q_t - Q_w) \times Y_{(t)} \qquad \ldots (9)$$

$$AWC_t = (Q_{fc} - Qw) \times Y_{(t)} \qquad \ldots (10)$$

in which,

$Y_{(t)}$ = root zone depth on t^{th} day in m,

Q_t = soil moisture content on t^{th} day in mm/m soil depth

Q_w = soil moisture content at permanent wilting point (PWP) in mm/m soil depth

Q_{fc} = soil moisture content at field capacity in mm/m soil depth

To convert soil moisture content from percentage on dry weight basis to volumetric basis, following relationships is used

$$Q_{(vol)} = Q_{(weight)} \times BD$$

in which,

BD is bulk density in gm/cc

$Q_{(vol)}$ thus obtained expresses value of soil moisture in cm/m soil depth

The value of AW_t & AWC_t would be different for both upper and lower layers depending upon the root growth and soil characteristics. As long as root is upto the upper layer one value each of AW_t & AWC_t can be assumed. As the plant sends root in the lower layer, AW_t & AWC_t values for both upper and lower layers are calculated depending upon the root depth, soil type and soil moisture contents of the respective layers. Computation of AE is started preferably from a day when soil is at field capacity or soil moisture is known. As assumed earlier, evapotranspiration will take place from the upper soil layer till the plant emergence. After the plant emergence, knowing the rooting depth of the crop on the day being simulated total soil water available to crop above the root depth is calculated to compute AE. After the rooting depth has entered into the lower layer, the following scheme of moisture extraction may be adapted.

a) Calculate total AW_t & AWC_t i.e. sum of both upper layer (1) and lower (2) till root growth

b) Calculate AE_t using total AW_t & AWC_t values above root growth

c) Calculate AE_{t1}(i.e. AE_t from upper layer)

d) Calculate AE_{t2}(i.e. AE_t from lower layer) = $AE_t - AE_{t1}$

Thus AE_t can be computed and withdrawn from both the layers.

To compute the soil moisture status in preparation of next day's computations, next step is to consider infiltration and its redistribution.

4.1.2 Surface runoff and infiltration

Surface runoff in small watersheds can be estimated by the standard soil conservation service (SCS) curve number technique using easily available rainfall and watershed data. Since agricultural drought studies are generally required to be taken on relatively smaller watersheds, SCS curve number technique can be applied to compute surface runoff. The procedure to compute daily runoff using SCS technique is given in Appendix - I.

Daily infiltration is computed as difference in the average rainfall of watershed and computed or observed watershed runoff expressed as depth.

$$I = P - R$$

in which,

I = Daily infiltration, mm

P = Daily rainfall, mm

R = Daily runoff from watershed, mm

No time distribution is given to the infiltration. It is considered stored in the upper soil layer unless this layer reached its field capacity;then the excess over field capacity is cascaded to succeeding lower layer with the same restriction untill sufficient storage is available. The infiltrating water is added to each soil layer till the soil attains field capacity. Any excess is added to subsequent layer untill all the available infiltration water has been added to the soil or both the layers are filled to field capacity. Any excess water available after satisfying the field capacity of lower layer, is lost as deep percolation.

The soil moisture status is up dated at the end of each day and this up-dated soil moisture becomes the initial or known soil moisture of the next day. Actual evapotranspiration (AE) is subtracted from the known initial soil moisture at the end of day before any effective rainfall (i.e. infiltration) is added to the soil to up-date the soil moisture at the end of the day. It is then used to simulate soil moisture of the following day and so on. Thus, using this approach through digital simulation soil moisture can be simulated.

4.2 Mathematical Model for Soil Moisture

Development of a mathematical model to determine soil moisture content or available soil moisture on any day after sowing (i.e. the beginning of budget period) has been also presented below using the concept as discussed in preceding sections.

The following expression is derived for soil moisture accounting for

$$0 > t < t_1$$

Available soil moisture on t^{th} day (i.e. the day counted from the date of sowing) can be given by following expression.

$$AW_{(t)} = \int_{o}^{y(t)} \left[\epsilon_i(Y, t_r) - \theta_w\right] d_y \qquad \ldots (11)$$

$$- \int_{o}^{t} \frac{AW(\tau)\ PE(\tau) d\tau}{y(\tau)\ (\theta_{fc} - \epsilon_w)}$$

$$= \int_{o}^{y(t)} \left[\theta_i(y, t) - \theta_w\right] dy$$

$$- \int_{o}^{t} \frac{AW(\tau)\ PE(\tau) d_\tau}{(\theta_{fc} - \epsilon_w) \left[y_o + (Y_{max} - Y_o) \frac{(\tau - to)}{(t_f - to)}\right]}$$

in which,

t is counted from the date of sowing and θ_i is the moisture content on the date of sowing. It is assumed that θ_i is invariant with depth till there is infiltration. After occurrence of first rainfall, the infiltrated quantity will bring the soil moisture to field capacity starting from the top. t_r represents the day when it rains. Discretising the time step and assuming that the available soil moisture and potential evaporation demand can be represented by some average values, which are constants during a particular time step but vary from step to step, equation (11) can be written as

$$Aw(n) = \int_{o}^{y(n)} \left[\epsilon_i(y, t_r) - \epsilon_w\right] dy \qquad \ldots (12)$$

$$- \left[\int_{o}^{1} \frac{Aw(1)\ P_E(1)}{(\epsilon_{fc} \quad \epsilon_w)} \frac{d\tau}{y_o} + \int_{1}^{2} \frac{Aw(2)\ P_E(2)}{(\theta_{fc} - \epsilon_w)} \frac{d\tau}{y_o} \right.$$

$$+ \int_{\gamma-1}^{r} \frac{Aw(\gamma)\ P_E(\gamma)}{(\epsilon_{fc} - \epsilon_w)} \frac{d\tau}{y_o} + \ldots + \int_{t_{o-1}}^{t_o} \frac{Aw(t_o)\ P_E(t_o) d\tau}{(\theta_{fc} - \theta_w)\ y_o}$$

$$+ \int_{t_o}^{t_o+1} \frac{Aw(t_o + 1)\ P_E(t_o + 1) \qquad d\tau}{(\epsilon_{fc} - \epsilon_w)\ (y_o + (y_{max} - y_o)\frac{\tau - t_o}{t_f - t_o}}$$

$$+ \ldots\ldots\ldots\ldots +$$

$$+ \int_{n-1}^{n} \frac{Aw(n)\ P_E(n) \qquad d\tau}{(\epsilon_{fc} - \theta_w)\ (y_o + (y_{max} - y_o)\ (\frac{\tau - t_o}{t_f - t_o})}$$

Thus for $n < t_o$, where n is integer

$$Aw(n) = \int_0^{y_o} \theta_i(Y, t_r) - \theta_w \ dy \qquad \ldots (13)$$

$$\sum_{\gamma=1}^{n-1} \frac{Aw(\gamma)\ P_E(\gamma)}{(\theta_{fc} - \theta_w)\ y_o} - \frac{Aw(n)\ P_E(n)}{(\theta_{fc} - \theta_w)\ y_o}$$

$$Aw(n) \left[1 + \frac{PE\ (n)}{(\epsilon_{fc} - \epsilon_w)y_o}\right]$$

$$= \int_0^{y_o} \left[\theta_i(Y, t_r) - \epsilon_w\right] dy$$

$$- \sum_{\gamma=1}^{n-1} \frac{Aw(\gamma)\ P_E(\gamma)}{(\theta_{fc} - \theta_w)\ y_o}$$

$$\text{or } Aw(n) = \frac{1}{1 + \frac{P_E(n)}{(\epsilon_{fc} - \theta_w)y_o}} \left[\int_0^{y_o} \left[\epsilon_i(Y, t_r) - \theta_w\right] dy - \sum_{\gamma=1}^{n-1} \frac{Aw(\gamma)\ P_E(\gamma)}{(\theta_{fc} - \epsilon_w)y_o}\right.$$

<u>For $n > t_o$</u>

$$Aw(n) = \int_0^{y(n)} \left[\epsilon_i(Y, r_r) - \theta_w\right] dy \qquad \ldots (14)$$

$$- \sum_{\gamma=1}^{n_o} \frac{Aw(\gamma)\ P_E(\gamma)}{(\epsilon_{fc} - \epsilon_w)y_o}$$

$$- \sum_{\gamma=n_o+1}^{n} \int_{\gamma-1}^{\gamma} \frac{Aw(\gamma)\, P_E(\gamma) \quad d\tau}{(\epsilon_{fc} - \epsilon_w) \quad y_o + (y_{max} - y_o)\frac{\tau - to}{t_f - t_o}}$$

$$\int_{\gamma-1}^{\gamma} \frac{d\tau}{Y_o + (Y_{max} - Y_o)\frac{\tau - to}{t_f - to}}$$

$$= \int_{\gamma-1}^{\gamma} \frac{d\tau}{Y_o + \frac{(Y_{max} - Y_o)}{t_f - to} (\tau - to)}$$

$$= \frac{(t_f - to)}{(Y_{max} - Y_o)} \int_{\gamma-1}^{\gamma} \frac{\left(\frac{Y_{max} - Y_o}{t_f - to}\right) d\tau}{Y_o + \frac{Y_{max} - Y_o}{t_f - to}(\tau - to)}$$

$$= \frac{t_f - to}{Y_{max} - Y_o} \left[\log_e \left[Y_o + \frac{Y_{max} - Y_o}{t_f - to}(\tau - to) \right] \right]_{\gamma-1}^{\gamma}$$

$$= \frac{t_f - to}{Y_{max} - Y_o} \left[\log_e \left[Y_o + \frac{Y_{max} - Y_o}{t_f - to}(\gamma - to \right] \right.$$

$$\left. - \log \left[Y_o + \frac{Y_{max} - Y_o}{t_f - to}(\gamma - 1 - to) \right] \right]$$

$$= \left[\frac{t_f - to}{Y_{max} - Y_o} \right] \log_e \left[\frac{Y_o + \frac{Y_{max} - Y_o}{t_f - t_o}(\gamma - t_0)}{Y_o + \frac{Y_{max} - Y_o}{t_f - t_o}(\gamma - 1 - t_o)} \right]$$

$$Aw(n) = \int_{o}^{Y(n)} \left[\epsilon_i(Y, t_r) - \epsilon_w \right] dY \qquad \ldots (15)$$

$$- \sum_{\gamma=1}^{no} \frac{Aw(\gamma)\, P_E(\gamma)}{(\epsilon_{fc} - \epsilon_w)\, Y_o}$$

$$- \sum_{\gamma = n_o + 1}^{n-1} \frac{Aw(\gamma)\ P_E(\gamma)}{(\epsilon_{fc} - \epsilon_w)} \frac{t_f - t_o}{Y_{max} - Y_o}$$

$$\log_e \frac{Y_o + \frac{Y_{max} - Y_o}{t_f - t_o}(\gamma - t_o)}{Y_o + \frac{Y_{max} - Y_o}{}(\gamma - 1 - t_o)}$$

$$- \frac{P_E(n)\ Aw(n)}{(\theta_{fc} - \theta_w)} \frac{t_f - t_o}{Y_{max} - Y_o} X$$

$$X \log_e \left\{ \frac{Y_o + \frac{Y_{max} - Y_o}{t_f - t_o}(n - t_o)}{Y_o + \frac{Y_{max} - Y_o}{t_f - t_o}(n - 1 - t_o)} \right\}$$

$$Aw(n) + \frac{P_E(n)\ Aw(n)}{\theta_{fc} - \theta_w} \frac{t_f - t_o}{Y_{max} - Y_o} \log_e \frac{Y_o + \frac{Y_{max} - Y_o}{t_f - t_o}(n - t_o)}{Y_o + \frac{Y_{max} - Y_o}{t_f - t_o}(n - 1 - t_o)}$$

$$= \int_0^{y(n)} \theta_i(Y,\ t_r)\ dY$$

$$- \sum_{\gamma = 1}^{no} \frac{Aw(\gamma)\ P_E(\gamma)}{(\theta_{fc} - \theta_w)\ Y_o}$$

$$- \sum_{\gamma = n_o + 1}^{n-1} \frac{Aw(\gamma)\ P_E(\gamma)}{(\theta_{fc} - \theta_w)} \frac{t_f - t_o}{Y_{max} - Y_o} \log_e \frac{Y_o + \frac{Y_{max} - Y_o}{t_f - t_o}(\gamma - t_o)}{Y_o + \frac{Y_{max} - Y_o}{t_f - t_o}(\gamma - 1 - t_o)}$$

$$Aw(n) = \frac{1}{1 + \frac{P_E(n)}{\theta_{fc} - \theta_w} \, \frac{t_f - to}{Y_{max} - yo} \log_e \frac{Y_o + \frac{Y_{max} - Y_o}{t_f - t_o}(n - t_o)}{Y_o + \frac{Y_{max} - Y_o}{t_f - t_o}(n-1-t_o)}} \quad \ldots (16)$$

$$X \left[\int_0^{Y(n)} \left[\theta_i(Y, t_r) \, dY \right. \right.$$

$$- \sum_{\gamma=1}^{no} \frac{Aw(\gamma) \; P_E(\gamma)}{(\theta_{fc} - \theta_w) \; Y_o}$$

$$\left. - \sum_{\gamma=n_o+1}^{n-1} \frac{Aw(\gamma) P_E(\gamma)}{(\theta_{fc} - \theta w)} \, \frac{t_f - to}{Y_{max} - Y_o} \log_e \frac{Y_o + \frac{Y_{max} - Y_o}{t_f - to}(\gamma - to)}{Y_o + \frac{Y_{max} - Y_o}{t_f - to}(\gamma - 1 - to)} \right]$$

When $t > t_r$

$$Aw(t) = \int_0^{y(t)} \left[\theta_i(Y, t_{r+1}) - \theta_w\right] dY \quad \ldots (17)$$

$$- \int_{t_r}^{t} \frac{Aw(\tau) \; P_E(\tau) \, d\tau}{y(\tau) \; (\theta_{fc} - \theta_w)}$$

Soil moisture distribution with depth from t_{r+1} onward till next rain

$$\frac{Aw(t_r)}{y(t_r)} = \theta(t_r)$$

$$\left[\theta_{fc} - \theta(t_r)\right] \; Y = i(t_r)$$

$$Y = \frac{i(t_r)}{\theta_{fc} - \theta(t_r)}$$

Soil moisture on t_{r+1}th day

$$Aw(t) = \int_{o}^{y(t)} \left[\theta_i (Y, t_{r+1}) - \theta_w\right] dy \qquad \ldots (18)$$

$$- \int_{t_r}^{t} \frac{Aw(\tau)\ P_E(\tau)\ d\tau}{(\theta_{fc} - \theta_{w1}) D_1 + y(\tau) - D_1 (\theta_{fc2} - \theta_{w2})}$$

In which subscript 1 and 2 present upper and lower layer respectively. Solution of this equation can be obtained in the similar way as above.

4.3 Drought Analysis Approach

The simulated soil moisture levels can be used to investigate drought characteristics. The simulated soil moisture levels need to be verified with observed field data at some sample sites to test the authenticity of the appraoch described earlier. It is also necessary to specify the depth of soil profile being considered for analysing drought. One of the simplest way to investigate drought is to assume certain level of soil moisture below which crop growth gets adversely affected. The number of days soil moisture level goes below this threshold value, would be the number of drought days. This threshold value would be different for different soils and crop types. The other methods are based on soil water deficit and soil moisture stress concept.

4.3.1 Soil water deficit & incidence of drought

The plant growth and yields are essentially governed by the availability of water in the right quantity and at the right time. Due to physiological changes the effects of water deficits on crop growth and yield may vary from crop to crop. Soil water deficit defined as the difference of field capacity and current soil moisture level on daily basis is taken as an indicator of drought as it affects plant growth and provides an estimate of water availability to crop. According to the field experiments based on the soil water regime concept, the water content at field capacity (i.e. the upper limit of the regime) is considered as 100 percent available for crop growth and that at the permanent wilting point (PWP) as zero percent available for crop growth. Soil water between field capcity and PWP is known as available soil water capacity (AWC). Even in this range entire soil moisture is not easily extracted by plants due to increased soil moisture tension when soil starts drying.

The safe limit of allowable soil water depletion (i.e. the lower limit of soil water regime) for a crop is determined by field experimentation. Number of experiments have been done to indentify this limit for various crops and soils as criterion for irrigation scheduling. It has been also experimentally found that when soil moisture level reaches at or below PWP (nearly 15 bar) plants get wilted resulting in crop failure. The general practise in irrigated areas is to apply water when about 40-50% of available soil water capacity (AWC) is depleted. The results of few experiments have been presented in the table 2 to illustrate the affect of soil

TABLE 2

Optimum Levels of Soil Water Depletion in Irrigated Agriculture

Sl No.	Crop	Soil Type & region	Levels of soil water depletion before irrigation (% of AWC)	Crop yield (q/ha)	Optimum soil water depletion (% of AWC)
1.	Wheat	a) Sandy loam (60 cm depth) at Delhi	40-50	-	40-50
		b) Light soils in AP & Rajasthan (30 cm depth)	-	-	25
2.	Maize	a) Sandy loam (15-30 cm depth) at Hisar	i) 50 ii) 75	37.6 30.5	50 for 30-60 cm soil depth in Sandy loam to clay loam soils
		b) Light soils	20-25	-	
		c) Clay loam (active root zone)	25 (during vegetative stage) 50 (thereafter)	-	
3.	Sorghum	a) Black clay (30 cm), Karnataka	i) 25 ii) 50 During Kharif iii) 50 During Summer	32.5 29.5	50
		b) Rahuri & Hyderabad	-	-	75(0-30 cm soil depth)in Kharif
		c) Tamil Nadu	-	-	50 in Rabi
4.	Pearl millet (Bajra)	a) Heavy black clay (0-30 cm depth) of Karnataka & Sandy loam of Delhi	-	-	75
		b) Sandy loam Anand (Gujarat)	i)0.2bar tension ii)0.4 -do- iii)0.6 -do- iv)0.8 -do-	24.5 19.6 15.4 11.6	
5.	Barley	Sandy & Sandy loam	-	-	50
6.	Finger millet (Ragi)	a) Heavy black clay soil(30 cm depth) Karnataka	i)25 ii)50 iii)75 (summer season)	21.4 19.4 12.4	50 in top 30 cm soil layer
		b) Sandy loam (Tirupathi)	50	good yield	

AWC = Available Soil Water Capacity (i.e. difference of field capacity & permanent wilting point)

Source: Extracted from various references cited "Water Requirement & Irrigation Management of Crops in India", IARI Monograph No.4. WTC, IARI, New Delhi, 1977.

moisture deficit on crop yield so as to provide some basis for deciding the threshold limit for defining drought.

It is evident from the table 2 that generally 50% depletion of AWC is the optimum soil water depletion level in irrigated areas to maintain good crop yields. In drought hard crops like Sorghum, pearl millet etc. even soil water depletion up to 75% is allowable to obtain satisfactory yields in heavy soils. However in dry lands or rainfed agriculture the same criteria may not hold good to define the threshold limits of soil water depletion for drought studies as the crops grown are normally drought hardy. In view of this, the following criteria has been proposed using soil water deficit (SWD) values to define a day as a drought day with different severity levels.

If SWD/AWC = 0.7 to $<$ 0.8 Moderate drought
SWD/AWC = 0.8 to $<$ 0.9 Severe drought
SWD/AWC $\geqslant$ 0.9 Disastrous drought

These are the suggested tentative limits to define various drought severity levels and would depend on the crop and soil type. The number of drought days during the growing season can be determined using this approach and drought days could be classified in different severity groups.

This alone may not be sufficient to quantify drought unless deficit during the crop growth stages is considered. It is therefore appropriate to incorporate the stage of crop development because the extent to which crop yield is affected, depends on the crop growth stages at which deficit occurs. Water deficit may either occur continuously over the total growing period of the crop or it may occur during any one of the growth periods i.e. establishment, vegetative, flowering, yield formation or ripening period. The critical or sensitive growth periods for water deficit of few crops are given in table 3 (FAO, 1979). Even the mild deficit during critical growth stage may be more detrimental as compared to severe deficit during non-critical stage of crop growth. Therefore, while computing daily drought index, appropriate weightage factor or yield susceptibility factor should be introduced to take care of such growth stages. An approach to incorporate this aspect is suggested as below:

Daily Drought Index (DDI) = SWD x weightage factor or yield susceptibility factor

Depending upon the sensitivity of the growth stage, appropriate weightage factors have to be assigned. For example, in wheat, crown root initiation stage is the most critical stage followed by flowering, jointing, milking, tillering and dough stage. The yield response factor which relates relative yield decrease to relative water deficit (i.e. ratio of AE to PE) during individual crop growth periods have been given by FAO (1979) which could be appropriately considered for adaptation in assigning weights to various growth stages. The yield response factor for few crops is given in table 4 as an example. An accumulated weighted drought index for the growing season can thus be computed by summing the daily drought index values.

The beginning and termination of drought can be

TABLE 3 Sensitive Growth Periods for Water Deficit

Alfalfa	just after cutting (and for seed production at flowering)
Banana	throughout but particularly during first part of vegetative period, flowering and yield formation
Bean	flowering and pod filling; vegetative period not sensitive when followed by ample water supply
Cabbage	during head enlargement and ripening
Citrus	
grapefruit	flowering and fruit set > fruit enlargement
lemon	flowering and fruit set > fruit enlargement; heavy flowering may be induced by withholding irrigation just before flowering
orange	flowering and fruit set > fruit enlargement
Cotton	flowering and boll formation
Grape	vegetative period, particularly during shoot elongation and flowering > fruit filling
Groundnut	flowering and yield formation, particularly during bod setting
Maize	flowering > grain filling; flowering very sensitive if no prior water deficit
Olive	just prior flowering and yield formation, particularly during the period of stone hardening
Onion	bulb enlargement, particularly during rapid bulb growth > vegetative period (and for seed production at flowering)
Pea	flowering and yield formation > vegetative, ripening for dry peas
Pepper	throughout but particularly just prior and at start of flowering
Pineapple	during period of vegetative growth
Potato	period of stolonization and tuber initiation, yield formation > early vegetative period and ripening
Rice	during period of heat development and flowering > vegetative period and ripening
Safflower	seed filling and flowering > vegetative
Sorghum	flowering yield formation > vegetative; vegetative period less sensitive when followed by ample water supply
Soybean	yield formation and flowering; particularly during pod development
Sugarbeet	particularly first month after emergence.

Sugarcane	vegetative period, particularly during period of tillering and stem elongation> yield formation
Sunflower	flowering> yield formation> late vegetative, particularly period of bud development
Tobacco	period of rapid growth > yield formation and ripening
Tomato	flowering> yield formation> vegetative period, particularly during and just after transplanting
Watermelon	flowering, fruit filling> vegetative period, particularly during vine development
Wheat	flowering>yield formation> vegetative period; winter wheat less sensitive than spring wheat

TABLE . 4 Yield Response Factor (ky)

Crop	Vegetative period(1) early (1a)	late (1b)	total	Flowering period (2)	Yield formation (3)	Ripening (4)	Total growing period
Alfalfa			0.7-1.1				0.7-1.1
Banana							1.2-1.35
Bean			0.2	1.1	0.75	0.2	1.15
Cabbage	0.2				0.45	0.6	0.95
Citrus							0.8-1.1
Cotton			0.2	0.5		0.25	0.85
Grape							0.85
Groundnut			0.2	0.8	0.6	0.2	0.7
Maize			0.4	1.6*	0.5	0.2	1.25*
Onion			0.45		0.8	0.3	1.1
Pea	0.2			0.9	0.7	0.2	1.15
Pepper							1.1
Potato	0.45	0.8			0.7	0.2	1.1
Safflower		0.3		0.55	0.6		0.8
Sorghum			0.2	0.55	0.45	0.2	0.9
Soybean			0.2	0.8	1.0		0.85
Sugarbeet							
beet							0.6-1.0
sugar							0.7-1.1
Sugarcane			0.75		0.5	0.1	1.2
Sunflower	0.25	0.5		1.0	0.8		0.95
Tobacco	0.2	1.0			0.5		0.9
Tomato			0.4	1.1	0.8	0.4	1.05
Water melon	0.45	0.7		0.8	0.8	0.3	1.1
Wheat							
winter			0.2	0.6	0.5		1.0
spring			0.2	0.65	0.55		1.15

evaluated depending upon the period when soil moisture status is continuously below the critical level (i.e. pre-decided severity levels) or above the critical level during the crop growing season.

4.3.2 Drought duration

It is necessary to determine the length of time (period) during which soil water deficit continuously runs above or below a given drought definition level to examine whether it is a temporary dry spell or serious long term drought event. This can be done by run length analysis, i.e. setting a drought definition level and scanning a time series of SWD levels to generate a new time series of the numbers of consecutive days for which the defined drought level is exceeded. The long term historic data of rainfall and potential evapotranspiration can be used for this purpose. The exercise of evaluating length of drought can be done for different severity levels and number drought days and frequency distributions of each of drought duration series can be plotted for different severity levels.

4.4 Data Requirement

The following data would be required to carryout this study:

i. Daily rainfall data (long term 50 years)
ii. Daily potential evapotranspiration or pan evaporation
iii. Soil characteristics eg. Bulk density, field

capacity, permanent wilting point

iv. Hydrologic soil group & land use practices/ treatments

v. Initial soil moisture content

vi. Rooting characteristics e.g. maximum rooting depth, rooting depth at plant emergence. Experimental results of the research of the specific crop could be used.

vii. Observeds oil moisture data for couple of years (5-8 years) to verify the simulated soil moisture values

ix. Type & variety of crop grown

x. Length of growing season

xi. Crop production of couple of years to test the validity of the approach.

5.0 APPLICATION

Soil water deficit which is an indicator of water availability to crop, affects agricultural production and can be considered as an index of drought. Soil moisture simulation using this improved soil water budgeting approach could allow prediction of soil moisture levels during growing season using daily rainfall and potential evapotranspiration inputs. The simulated soil moisture level is used to study the incidence, frequency, duration and severity of drought in unirrigated or dry land areas. Since soil moisture is being hardly measured at few locations, the simulation approach can be applied for computing soil water deficit to evaluate drought. In order to test the validity of the simulation model, it could be checked using observed field data. It would be desirable to use experimentally found threshold values of soil water deficit which affect crop growth appreciably. The methodology can be applied for drought studies in the following manner.

1. Incidence of drought can be studied by determining for a particular crop the number of days during its growing season on which soil water deficit exceeds a predetermined value which is known to impede crop growth appreciably.
2. Duration of drought can be studied for a given crop in a watershed by examining the length of time the soil moisture continuously runs above or below a given drought level (i.e. drought severity level). In doing so, the available time series of simulated daily soil

moisture levels can be examined and the number of days soil moisture remains below a drought definition level before rising above this definition level, are counted and stored as another time series containing the durations of consecutive drought (e.g. drought length n days) at definition level. The frequency distributions of each of the drought duration series for various drought severity levels can be done.

3. The frequency of exceedance of various levels of soil moisture as simulated by this soil water budgeting approach using historical records can be done during the growing season of the crop. Probability distributions of soil water deficits for each month of the growing season can be worked out using the past data to examine the monthly distribution of drought periods.

4. It is also possible to estimate the distribution of soil water deficits for the subsequent months, if given initial value of SWD is known. It means that if the current SWD is known, the probabilistic forecasts of SWD for next few months (say 2-4) can be made by this approach which could be of great use in planning drought management measures in advance.

5. The generated precipitation using some tested stochastic precipitation model can be coupled with this soil water simulation model to predict the future SWD pattern.

6. Using soil moisture simulation approach past historical data can be analysed to examine the distribution of soil

moisture availability over the growing season for various soil types to determine the safe growing season, critical moisture deficit periods and plan suitable cropping pattern in drought prone areas.

7. The soil moisture simulation approach described in the report can be modified to suit to shallow rooted grasses and deep rooted forest plantations to develop the procedure for diagnosing critical moisture conditions in relation to drought and mortality of trees and predict forage yield for given set of climatic conditions.

It could be generally mentioned that the models which use a 1-day averaging can produce accurate weekly average results; however, daily results will show some deviation on any given day. The soil moisture simulation model can provide timely soil moisture information without the necessity of field visits. However, a general disadvantage is the error of their estimates due to limitations and assumptions of the model.

6.0 CONCLUSION

The soil moisture is influenced by hydrologic processes (i.e. rainfall, runoff, infiltration and evapotranspiration), soils and land use characteristics. The availability of soil moisture to vegetation to meet the evapotranspirational needs appears to be a better indicator for analysing drought (specially agricultural drought) and planning drought management strategies. An operational definition of drought as considered in this report compares daily rainfall values to evapotranspiration rates to determine rate of soil moisture depletion to give up-to-date status of available soil moisture after correcting for surface runoff, and expresses these relationships in terms of drought affects on crop growth at various stages of crop development. An approach for development of a simple soil moisture accounting model on daily basis taking into account soil and root growth characteristics discussed in the report to simulate soil moisture levels in a dryland area using daily precipitation and potential evapotranspiration inputs appears to be a good tool for analysing and understanding drought conditions.

The incidence of drought can be characterised by determining the number of days during the crop growing season on which the soil water deficit (i.e. field capacity minus current soil moisture) corresponding to simulated soil moisture level falls below drought definition level (i.e. a value which impeds crop growth appreciably). The different levels of drought severity based on different soil water deficits (e.g. SWD/AWC = 0.7 to < 0.8, 0.8 to < 0.9 & ≥ 0.9) can be useful in finding out the frequency of droughts of varying severity. The duration of drought for different degrees of severity can be determined by run-length analysis (i.e. length of time soil moisture continuously runs above or below a given drought definition level). The expected seasonal occurrence of drought periods will define the probability of the number of droughts at different time of the growing season. The incorporation of sensitive crop growth stages and yield response factor increases the usefulness of the study.

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APPENDIX

Runoff using SCS curve Number Technique

The SCS equation is as follows:

$$R = \frac{(P - as)^2}{(P + bs)} \qquad \ldots 1$$

in which,

R = surface runoff, mm

P = rainfall, mm

S = potential maximum retention, mm

The values of co-efficients a and b have been given as 0.2 and 0.8 respectively by SCS from the results of small exerimental watersheds in USA. The central unit of Soil Conservation, Ministry of Agriculture, in India has developed these coefficents for Indian watersheds which modify the equation as :

$$R = \frac{(P - 0.3\ s)^2}{(P + 0.7\ s)} \qquad \ldots 2$$

$$R = \frac{(P - 0.1\ s)^2}{(P + 0.9\ s)} \qquad \ldots 3$$

The equation (2) is applicable for all the regions including black soils region with AMC I whereas equation (3) is applicable only for black soils region with AMC II and III (i.e. Antecedent Moisture Condition II & III). Antecedent moisture condition (AMC) is determined by the total rainfall in the 5 day period preceding a storm. Three levels of AMC used are: AMC I i.e. the lower limit of moisture or the upper limit of S., AMC II i.e. the average, and AMC III i.e. the upper limit of moisture or the lower limit of S. The criteria of classifying AMC-I, II & III is given below.

Rainfall limits for estimating antecedent moisture condition

Antecedent moisture Condition	5 days total antecedent rainfall, cm Dormant season	Growing season
I	less than 1.25	less than 3.5
II	1.25 to 2.75	3.5 to 5.25
III	over 2.75	over 5.25

The value of S is obtained using curve numbers which have been related to soil and vegetation characteristics of the watershed. The relationship between curve number, CN and S is given by:

$$CN = \frac{25400}{254+S} \qquad \ldots (4)$$

or

$$S = 254 \left(\frac{100}{CN} - 1\right) \qquad \ldots (5)$$

The curve numbers for Indian conditions have been published in the Hand Book of Hydrology, Central Unit of Soil Conservation, Ministry of Agriculture, Govt. of India (1972). Table A-1 gives the curve numbers for various hydrologic soil groups (A,B,C & D) under different land use practices for AMC-II. Conversion tables for converting AMC-II to AMC-I & AMC-III are given in tables A-2 & A-3. A hydrologic soil group map of India is given in Figure A-1

TABLE A-1 RUNOFF CURVE NUMBERS FOR HYDROLOGIC SOIL COVER COMPLEXES

LAND USE	Cover		Antecedent Moisture Condition-II			
	Treatment or Practice	Hydrologic Condition	Ia = 0.3S		Ia = 0.1S	
			A	B	C	D
Cultivated	Straight Row		76	86	90	93
Cultivated	Contoured)	Poor	70	79	84	88
	)	Good	65	75	82	86
Cultivated	Contoured) &) Terraced)	Poor	66	74	80	82
			62	71	77	81
Cultivated	Bunded)	Poor	67	75	81	83
	)	Good	59	69	76	79
Cultivated	Paddy		95	95	95	95
Orchards	-(with understorey cover)		39	53	67	71
	-(without understorey cover)		41	55	69	73
Forest	-	Dense	26	40	58	61
	-	Open	28	44	60	64
	-	Scrub	33	47	64	67
Pasture	-	Poor	68	79	86	89
	-	Fair	49	69	79	84
	-	Good	39	61	74	80
Tree Crops (Non-Agricultural)	-					
Wasteland	-		71	80	85	88
Roads (Dirt)	-		73	83	88	90
Hard Surface Area	-		77	86	91	93

TABLE A-2: CONVERSION OF CURVE NUMBER (CN) FROM ANTECEDENT MOISTURE CONDITION, AMC-II TO AMC-I & III

I a = 0.3S

CN for condition II	CN for condition I	CN for condition III
100	100	100
95	87	98
90	78	96
85	70	94
80	63	92
75	57	88
70	51	85
65	45	82
60	40	78
55	35	74
50	31	70
45	26	65
40	22	60

TABLE A-3: CONVERSION OF CURVE NUMBER (CN) FROM AMC II TO AMC III

I a = 0.1S

CN for condition II	CN for condition III
100	100
95	98
90	96
85	94
80	92
75	88
70	85
65	82
60	78
55	74
50	70
45	65
40	60

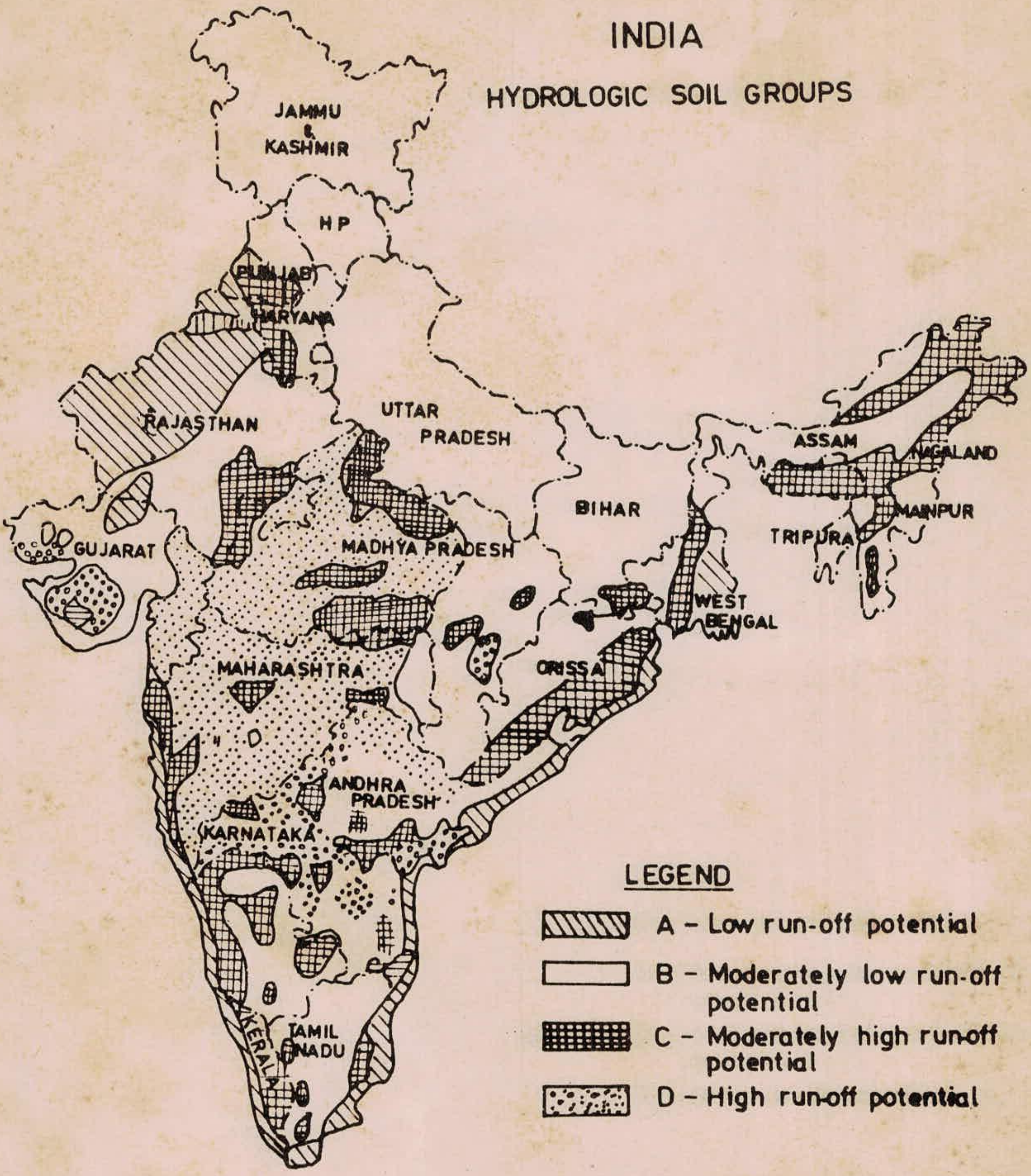

FIG. A-1 HYDROLOGIC SOIL GROUPS IN INDIA