HYDROLOGICAL RESPONSE OF UNSATURATED ZONE UPTO WATER TABLE

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submitted in fulfilment of the
requirements for the award of the degree
of
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in
HYDROLOGY

BY

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled HYDROLOGICAL RESPONSE OF UNSATURATED ZONE UPTO WATER TABLE in fulfilment of the requirement for the award of the Degree of Doctor of Philosophy, submitted in the Department of Hydrology of the University is an authentic record of my own work carried out during a period from Dec'83 to Dec'86 under the supervision of Dr. Satish Chandra and Dr. Deepak Kashyap.

The matter embodied in this thesis has not been submitted by me for the award of any other degree.

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SYNOPSIS

The rainfall and applied irrigation excite the unsaturated zone, extending from ground surface upto the water table, at the ground surface. The hydrological response to this excitation comprises amongst others, the return flow from the applied irrigation and rainfall, change in soil moisture storage and ponding of water. The return flow is an important component of groundwater resource of an unconfined aquifer. The soil moisture status in the root zone and the ponding of water has an important bearing on the evapotranspiration of vegetation. The evapotranspiration in case of agricultural crops determines the necessity of supplementing rainfall by irrigation, for maintaining a predefined moisture level in part of/entire root zone or for maintaining a range of ponded depth of water. Thus, a quantitative estimate of the response of the unsaturated zone is a prerequisite for carrying out ground water, crop water requirement and other related studies.

The response is governed by the unsteady state moisture flow in the zone. Current practice, of simulating the flow process, is mostly based upon soil moisture accounting (SMA) models considering the entire zone as a unit. However, these models suffer from many restrictive assumptions. Prominent amongst them is the assumption of existence of a threshold moisture content (termed as field capacity), below and at which there occurs no moisture movement and above which the excess moisture is drained in the basic accounting period, irrespective of the soil drainability. This could lead to discrepancies in time distribution as well as periodical totals of return flow. Many of these assumptions can be eliminated by solving the governing differential equation of the unsteady state flow of moisture in the zone. This equation is known as Richards equation. Since, solution of the equation can provide time and space distribution of the response, the models governed by this equation would be distributed models.

The present work is an attempt, to develop a one dimensional (vertical) distributed numerical model, to simulate the unsteady flow of water in the unsaturated zone involving evapotranspiration. The model is based upon solution of the Richards equation by Crank-Nicolson finite difference scheme. An algorithm has been developed for identification and assignment of the upper boundary condition (ground surface boundary condition). However, the overland flow is not simulated. The lower boundary condition is assigned accounting for the time variant position of water table. Further, a piecewise continuous functional relation for capillary suction head versus moisture content and an empirical criteria for specifying variable time step of simulation have been developed. Calculations of the model are performed with the assistance of a digital computer. The computer code has been written in FORTRAN IV.

The moisture profiles simulated by the model compare well with those given by the Philips quasi-analytical solution (Philip 1969), for a soil(yolo light clay) under identical conditions. Further, the model has been operated to simulate moisture profiles of a layered soil under field situation. The simulated moisture profiles compare will with the observed profiles. Statistical evaluation, of the model simulation, in respect of moisture profiles, by calculating coefficient of correlation, F and t statistics indicates a satisfactory performance of the model.

The model has been operated to schedule irrigation for a few soil-crop conditions, under daily rainfall series of a normal rainfall year reported from a local rainguage station. The soil crop conditions considered were: rice-wheat cropping on clay as well as on loam and sugarcane on loam. Irrigation criterion considered for wheat and sugarcane was 50 percent allowable average moisture depletion in the entire root zone. For rice two different criterion have been considered. These are:no allowable average moisture depletion in the entire root zone (upland cultivation), and requirement of maintaining a minimum ponding of 50 mm (low land or submergence cultivation). Time distributions of the return flow (from the rainfall and the scheduled irrigation) have been worked out, for the rice-wheat cropping on clay as well as on loam.

The model scheduled irrigation totals in case of upland rice, wheat and sugarcane, are generally lower than the generally existing local practice. The major reason for this deviatior was suspected to be the farmers' practice of irrigating by 'feeling' the moisture depletion in the upper part of the root zone only, where the moisture depletion would be relatively faster. In order to verify this argument the model was re-operated for the wheat cropping on loam, with a modified irrigation criterion of no allowable average moisture depletion in the top 30 cms (usual tillage depth) of the root zone . The irrigation so scheduled was quite close to the generally existing local practice. The model scheduled total irrigation in case of low land rice cultivation has been in the reported range of the existing practices in India. Annual return flows have worked out to 71.61 percent and 50.67 percent, of the rainfall and applied irrigation, incase of rice-wheat cropping on clay and on loam respectively. It has been noticed that due to a time lag (between occurence of input at ground surface and occurence or return flow at the water table), the return flow in certain time periods (months) are disproportionate to the corresponding inputs.

The current practice of quantifying field capacity by adopting the moisture content corresponding to 0.1 to 0.5 bar tension may not always be consistent with it s hydraulic implication in the SMA models. So a method has been proposed to quantify field capacity as a flow parameter, to be more objective. This method is more suitable for coarser soils.

A SMA model has been operated to route infiltration through the unsaturated zone. Field capacity in this model is quantified as per the proposed method. The daily infiltration series generated while calculating return flows (for the rice-wheat cropping on clay and on loam) by the distributed model, have been routed through the unsaturated zone, by this model.

The SMA model over estimated the return flow rates during the early (rice crop) period, in comparison to the return flow rates given by the distributed model. Subsequently, these return flow rates were lower. This situation is more pronounced with the clay soil. This descrepancy is due to the fact that, the SMA model doesn't account for the time lag in occurrence of the return flow. As a result of such an underestimation and over estimation of return flow during different simulation periods the errors in the estimates of seasonal totals got compensated to some extent. Thus, the seasonal totals of return flows computed by the SMA model tended to match with the corresponding totals arrived at by the distributed model.

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LIST OF SYMBOLS

Symbol	Description	Dimension
AI	Applied Irrigation	$[L]$
C	Specific Moisture Capacity	$[L^{-1}]$
$\bar{\bar{C}}_{i,j}$	Representative C, for the finite difference scheme, at the i^{th} node during Δt_j.	$[L^{-1}]$
D	Moisture diffusivity	$[L^2T^{-1}]$
D_j	Instantaneous depth to watertable at j^{th} simulation level	$[L]$
D_{p_j}	Instantaneous ponding depth at j^{th} simulation level	$[L]$
$D_{p_{max}}$	Prescribed maximum ponded water depth.	$[L]$
Dp_{min}	Prescribed minimum ponded water depth	$[L]$
$D_{t_{i,j}}$	Rate of change of h at the i^{th} node, in Δt_j, in the finite difference form.	$[LT^{-1}]$
E	Actual evapotranspiration rate per Unit volume of soil	$[T^{-1}]$
E_J	Actual evapotranspiration rate in J	$[LT^{-1}]$
ET	Actual evapotranspiration in td	$[L]$
$\bar{\bar{E}}_{i,j}$	Representative E, for the finite differences scheme, at the ith node, during Δt_j.	$[T^{-1}]$
E_j	Instantaneous rate of Actual evapotranspiration in Δt_j	$[LT^{-1}]$
$\hat{F}$	Total infiltration in td.	$[L]$
θ	Volumetric moisture content	
F' and F	Flow rate per unit horizontal area in downward direction.	$[LT^{-1}]$

FC	Field capacity	
F_J	Infiltration in the J^{th} period (In the SMA model)	[L]
F_j	Infiltration in the j^{th} time step	[L]
IF_j	Instantaneous rate of Infiltration	$[LT^{-1}]$
$\bar{F}_{i,j}$	Representative flow rate, from i^{th} node to (i+1)th node during Δt_j	$[LT^{-1}]$
h	Capillary suction head	[L]
h_b	Air entry value (bubbling pressure)	[L]
I	Total Input in t_d	[L]
I_o	Infiltration capacity rate	$[LT^{-1}]$
i	Depth node index in the finite difference scheme	
J	Basic accounting period index in the SMA model	
j	Time level Index in the finite difference scheme	
K	Capillary conductivity	$[LT^{-1}]$
K_s	Saturated capillary conductivity	$[LT^{-1}]$
$K_{i,j}$	Capillary conductivity of the soil layer between ith and (i+1)th depth nodes	$[LT^{-1}]$
ℓ	iteration index	
NR_{t_j}	The node number at which the root zone ends, in jth time step of simulation.	
n	Number of nodes	
p	The factor as per Doorenbos et al (1979) to be used in the AET, PET and θ submodel of Doorenbos et al (1979)	
Q_j	Constant input intensity during Δt_j	$[LT^{-1}]$

R	Total recharge at the water table in t_d	[L]
R_d	Uncovered fall of watertable	[L]
R_J	Return flow in Jth period of accounting in the SMA model	[L]
R_j	Instantaneous rate of recharge at the water table	$[LT^{-1}]$
RR_j	Recharge in jth time step	[L]
R_r	Uncovered rise of water table	[L]
R_{t_j}	Depth of root zone (in the irrigation criteria)	[L]
S	Sink term: Algebraic sum of point abstraction and accretion rates per unit volume of soil.	$[T^{-1}]$
S_J	Moisture storage at the start of J^{th} period (In the SMA model)	[L]
$S_r(h)$	Surface runoff intensity as a function of ponded water depth.	$[LT^{-1}]$
S_y	Specific yield	
S_{m_j}	Uniform maximum moisture that can be held in the root zone.	[L]
T_j	Flow from the ground surface node to the node immediately below it	[L]
t	Time	[T]
t_{max}	Limit on the time step	[T]
t_d	Time period in which input intensity is constant	[T]
t_J	Basic accounting period (In the SMA model)	[T]
U	Vector flow velocity (in Darcy law)	$[LT^{-1}]$
u_j	Return flow in the jth time step	[L]

v_j	Flow caused by variation of water table in jth time step	[L]
WP	Wilting point	
x,y,z	Cartesian coordinates with z positive upward	[L]
z	Elevation above water table (positive upward)	[L]
Δh	Change in ponded water depth in t_d	[L]
Δs	Change in moisture storage in t_d	[L]
Δt_j	Time step of simulation between jth and (j+1)th simulation levels	[T]
Δt_ℓ	ℓth time step in td	[T]
Δt_u	Uniform time step in t_d	[T]
$\Delta t'_u$	First time step by the empirical criteria.	[T]
Δz_i	Dept interval between ith and (i+1)th node in the finite difference scheme.	[L]
θ_a	Average moisture content of part of entire root zone in irrigation scheduling excercises	
$\theta_{i,j}$	Volumetric moisture content at ith node and at jth level of simulation	
θ_p	Moisture content at the permissible moisture depletion level	
θ_r	residual moisture content	
θ_t	Threshold moisture content upto which actual evapotranspiration is equal to potential evapotranspiration.	
θ_ω	Gravimetric moisture content	
γ_d	Dry density of the soil	$[FL^{-3}]$
f	Level of moisture depletion (in irrigation scheduling excercise)	
f_{max}	Maximum permissible level of soil moisture depletion (in irrigation scheduling excercise)	

ε_1	Percentage error in mass balance of ponding.	
ε_2	Percentage error in mass balance of flow in the unsaturated zone	
τ	Total head (-h+z)	[L]
∇	Gradient of scalar	
$\nabla \cdot$	Divergence operator	
[ ]	Vector of a variable	
ε_c	Prescribed tolerable error on convergence in the Picard iteration method of solving the system of nonlinear simultaneous equation.	[L]
ε_{de}	Prescribed small positive value in the establishment of dynamic equilibrium.	[L]
ε_d	Prescribed tolerable error in the algorithm for identifying and assigning the upper boundary condition.	[L]
ε_f	Infinitismly small positive value in field capacity quantification as flow parameter.	
ϕ	Porosity.	

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CHAPTER - I

INTRODUCTION

For the survival of human race, it is necessary to meet the food requirements of rapidly growing population by enhancing the agricultural production. The continuous depletion of available moisture in the root zone, due to evapotranspiration caused by agricultural crops, needs to be replenished for a healthy growth. The major natural water resource, namely, rainfall may not be sufficient to replenish the entire depletion and may not occur in sufficient quantity at required time. Irrigation is the principal artificial means, to supplement rainfall, to replenish the depletion. So large number of irrigation projects are being planned and implemented these days. However, the total irrigation water that a project can supply is always limited. Nevertheless, benefits from such an irrigation project, in terms of agricultural produce (yield from various crops), can be enhanced if the cropping pattern and allowable moisture depletion levels in the root zone are optimally planned. Such an yield enhancement study needs a quantitative estimation of evapotranspiration and irrigation requirements, of a trial cropping pattern, with a set of allowable moisture depletion levels, for various crops in the trial cropping pattern.

The return flow, from the applied irrigation, may cause an excessive rise of water table in case the natural sub surface drainage is not adequate. The excessive rise has severe consequences in the form of water logging and possible salt accumulation. These consequences are so grave that they threaten the viability of the water project. So preventive measures, in the form of artificial subsurface drainage, must be planned. The artificial sub surface drainage can be implemented by a conjunctive use of ground and surface waters in case the ground water is of acceptable quality. Else, tile or ditch drains may be used. Planning of any one or more of these measures, for adequate drainage, needs a quantitative estimation of time distribution of the return flows from the proposed irrigation.

The root zone of the agricultural crops, generally lie in the unsaturated zone, which extends from ground surface up to the water table. The irrigation water passes through the unsaturated zone, before part of it is available as return flow. Therefore, a quantitative estimation of the irrigation requirements and return flows, needs a study of the hydrological response of the unsaturated zone. The hydrological response comprising ponding, infiltration, evapotranspiration, change in moisture storage of the zone and return flows, is governed by unsteady state flow of water in the zone.

The current practice, of simulating this flow process, is mostly based upon soil moisture accounting models considering the entire unsaturated zone as a unit. However, these models involve many restrictive assumptions relating to the flow process.

These assumptions are i. no movement of moisture at moisture contents less than or equal to field capacity ii. complete drainage of excess moisture at moisture contents greater than field capacity, in the basic accounting period irrespective of the soil drainability iii. Uniform distribution of moisture in the root zone and uniform extraction of moisture by plant roots, in the basic accounting period iv. homogeneous soil medium v. the part of the unsaturated zone below the root zone acts as a passive pathway in draining the excess moisture vi. the water table is sufficiently deep so that the concept of field capacity is not invalidated and the position of water table is time invariant. The assumption (i) could lead to under estimation of return flow (Richardson et al1973, Miller 1967, Rushton et al1979, Chandra 1979) and assumption (ii) could lead to discrepancies, in time distribution of returnflow, due to the fact that the time lag in occurance of return flow is not properly accounted for (Fox et al1976, Rushton et al1979).

The handicaps of soil moisture accounting models can be overcome, by solving the governing differential equation for one dimensional (vertical) unsteady state flow of water through the unsaturated zone. The equation is called Richards equation (Philip 1969). Reported works, on the study of the flow process by solving the Richards equation (Staple 1966, Thomas et al 1982, Wang et al1968, Philip 1969,74 Morel Seytoux 1978, 84, Singh et al1986, Remson 1965,67,Pikul et al 1974,Horenberger et a
1969

Babu 1976^b, Kafri et al1978, Krishnamurty et al 1977, Feddes et al1978) are extensive. However, full potential of the equation has not been realized so far.

In the present work an attempt has been made, to develop a one dimensional (vertical) distributed numerical model, to simulate the unsteady state flow of water in the unsaturated zone, involving evapotranspiration. Richards equation, in capillary suction head form, assuming no hysterisis in the flow, is the governing equation of the model. The equation is solved by Crank-Nicolson finite difference scheme. The resulting system of nonlinear simultaneous equations are linearized explicitly. The solution obtained is verified at prescribed time intervals, by comparing with the solution obtained by solving the nonlinear system using Picards iteration method (Remson et al1971). The model can account for, heterogeneity in the form of layering, time variant-position of water table, vegetal root zone depth, input (rainfall and applied irrigation) intensity and evapotranspiration. The boundary condition at the ground surface is automatically identified and assigned. The outputs of the model are the moisture content as well as capillary suction head distribution at prescribed time levels of simulation. Apart from this, abstracts of ponded depth of water, infiltration, actual evapotranspiration, change in moisture storage of the zone and recharge (return flow in a special case), at prescribed periods are also included in the output. As a part of the proposed work, a piecewise continuous functional relation has been developed for $h-\theta$ relation. The relation is based on well defined soil parameters viz. residual moisture content, porosity and air entry value (bubbling pressure) of the soil. Further, an empirical criteria has been developed for specifying variable time step of simulation. Calculations of the model are performed with the assistance of a digital computer. The computer code has been written in FORTRAN IV.

The model has been operated for the soil yololight clay under the conditions of homogeneous and semi-infinite soil medium, uniform initial moisture content and instantaneous surface saturation. The model simulated moisture profiles were compared with those given by Philip's quasi-analytical solution (Philip 1969), for the same soil under identical conditions.

The model has been operated to schedule irrigation for a few soil- crop conditions, under rainfall series of a normal rainfall year. The soil-crop conditions considered were:rice-wheat cropping on clay as well as on loam and sugarcane on loam. Irrigation criterion considered, for wheat and sugarcane was 50 % allowable average moisture depletion in the entire root zone. For rice two different criterionhave been considered. These are, 0 % percent allowable average moisture depletion in the entire root zone (upland cultivation) and requirement of maintaining a minimum ponding of 50 mm (low land or submergence cultivation). The associated return flows were also computed.

The model has been operated to simulate moisture profiles of a layered soil under field situation. Subsequently, the simulated and the observed moisture profiles (in the field) were compared.

Soil moisture accounting models, though require far less computational efforts, are based upon rather empirical concept of field capacity. So a method has been proposed, to quantify field capacity as a flow parameter, in order to be more objective. The infiltration series generated, while calculating the return flows by the distributed model, was routed through the unsaturated zone under indentical conditions, by a soil moisture accounting model. The field capacity in this model was quantified in accordance with the proposed procedure

CHAPTER - II

LITERATURE REVIEW

2.1 GENERAL

Rainfall and irrigation excite the unsaturated zone, extending from ground surface up to the water table, at the ground surface (Fig.4.1). The hydrological response to this excitation comprises infiltration, ponded water, surface runoff (overland flow), change in soil moisture storage, evapotranspiration (enveloping evaporation and transpiration) and return flow (Generally termed as ground water recharge) from rainfall and applied irrigation. The hydrological response study is of paramount importance in crop water requirement, ground water and other related studies. This response is governed by the unsteady state flow of water (moisture) in the unsaturated zone. Engineering hydrologists untill recently evinced relatively little attention to the study, of unsteady state flow of moisture in the unsaturated zone, unlike their counterparts namely soil physicists.

2.2 SOIL MOISTURE ACCOUNTING

Current practice of simulating the flow process is mostly based upon soil moisture accounting models considering the entire zone as a unit (Mc Whorter et al 1977, Satish Chandra 1979). The conventional method of estimating return flow is based on the studies of Penman and Grindley (Rushton et al 1979). Return flow is viewed as a function of effective rainfall

(Rainfall- Evapotranspiration) which is distributed according to a simple land use model. It is significant that Penman and Grindley were not primarily concerned with the water balance from the view point of estimating return flow but rather they attempted to determine actual evapotranspiration and soil moisture deficits. However, their work precipitated much literature on the meteorological and agricultural aspects of the water balance.

In principle these methods involve a book keeping of various mass balance components of the unsaturated zone, taken as a unit (Mc Whorter et al 1977, Satish Chandra 1979), Thus, in a given period the mass balance can be written as

$$PAI = SRF + IFL \tag{2.1a}$$

$$IFL = AET + \Delta Sm + RECH \tag{2.1b}$$

where

PAI : Rainfall and applied irrigation (after accounting for all losses like interception).

SRF : Surface run off

IFL : Infiltration

AET : Actual evapotranspiration

ΔSm : Change in moisture storage of unsaturated zone

RECH: Return flow

Usually, only water movement in the root zone (root zone: Bear 1972) is modelled. Rest of the unsaturated zone is assumed to be at the maximum water holding capacity at all times (i.e. field capacity times depth of the root zone). The surface run off is evaluated by some land use model (Victor 1964, Reeves 1975, Ive et al 1976, Li et al 1977, Thomas et al 1981). The infiltration is determined after deducting the runoff from rainfall and applied irrigation. The excess infiltration (above the maximum water holding capacity and after accounting for actual evapotranspiration) is assumed to be available as return flow, instantaneously. Thus, if no excess infiltration is available there will be no return flow in the time period.

It may be seen from the above operational details that, the soil moisture accounting (SMA) modelling involves the following assumptions.

Group A

i. The porous medium is stable and isotropic.
ii. The flow is immiscible and two phase (air and water).
iii. The air phase is at atmospheric pressure (arbitrarily taken as zero) through out the zone at any time and the air phase flow is negligible.
iv. The water is pure and incompressible.
v. The flow is under isothermal conditions.

Group B

i. No moisture movement at moisture contents less than or equal to field capacity.
ii. Complete drainage of excess moisture, at moisture contents greater than field capacity, in the basic accounting period.

iii. Uniform extraction of moisture by plant roots throughout the root zone and uniform distribution of moisture in the root zone, in the basic accounting period.

iv. Homogeneous soil medium.

v. The part of the unsaturated zone below the root zone acts as a passive path way, in draining the excess moisture.

vi. The water table is sufficiently deep so that the concept of field capacity is not invalidated and position of water table is time invariant.

Prominent among the assumptions is the existance of a threshold moisture content, namely, field capacity (ie., assumptions i and ii of gr.B.).Bear (1972), Hillel (1980) pointed out the inadequacy of the definition of field capacity. Miller (1967) and Smith et al (1970), Kitching et al (1974, 1977) (Rushton et al 1979) observed occurence of considerable return flow, even at moisture contents below field capacity. Thus, as per the implication of the concept of field capacity, there will be under estimation of return flow by the SMA modelling. The current practice of quantifying field capacity by adopting the moisture content corresponding to 0.1 to 0.5 bar tension may not always be consistent with its hydraulic implications, in the soil moisture accounting models. Miller (1964) observed that 0.33 bar moisture content can not reasonably provide the magnitude of field capacity. Richards (1960) expressed the desire of imposing moratorium on the concept. Moreover, the concept of field capacity is applicable, if the water table is deep enough; a situation which is not met always. Sykes et al (1967) have stressed the need for quantifying field capacity as a flow parameter.

Apart from the above restrictive assumptions, another complication is the accurate assesment of the mass balance components. Among the components, the evapotranspiration is difficult for an accurate assesment (Penman 1969, Rushton et al 1979). Rouse (1970) and Miller et al (1971) verified the sensitivity of accuracy of field measurement of mass balance components. They concluded that neglecting deep drainage creates large errors in the estimates of actual evapotranspiration.

Bair et al (1966) proposed a soil moisture budget model. Richardson et al (1973), by actual measurement of the surface runoff, could succeed in simulating the soil moisture content. Saxton et al (1974) developed and operated a soil moisture accounting model applicable layer by layer. The excess moisture of a layer is routed to the layer below it by applying Darcy-Buckingham law, under steady state condition. In this study also the runoff was measured. Rushton et al (1979) proposed alternate mechanisms for the estimation of return flow. They observed pronounced effect of root reservoir, time period of accounting, on the estimates of return flows. Fox and Rushton (1976) recognised the importance of incorporating a time lag factor in the occurence of return flow to overcome the assumption of instantaneous availability of excess moisture as return flow. Kashyap et al (1986) evaluated the performance of a soil moisture accounting model for the estimation of return flow. In the study they proposed a method for quantifying field capacity as a flow parameter. Thus, they could succeed in simulating the seasonal totals of return flow to an acceptable degree.

The SMA models can be put to use for scheduling irrigation, based on allowable depletion levels of the moisture, as the SMA models can provide the estimates of moisture content (though lumped) of the root zone, in time domain. However, since, the SMA models can not provide the estimates of ponded water depth, irrigation scheduling can be done only for crops of upland cultivation and irrigation scheduling for crops of low land cultivation (submergence cultivation) can not be done. Doorenbos et al (1975) gives a scheduling procedure using an SMA model. Jensen et al (1971), Wright et al (1978) used SMA models for estimating soil moisture depletion, from climate crop and soil data, in order to schedule irrigation.

2.3 DISTRIBUTED MODELLING

Handicaps of soil moisture accounting models associated with group B assumptions can be overcome, by solving the governing differential equations of unsteady state flow of water through the unsaturated zone. The equation is called Richards equation (Philip 1969). Since, solution of the equation can provide time and space distribution of moisture content, the models governed by the equation can be called as distributed models.

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Considering only hydrostatic forces, apart from gravity, the equation governing the flow is as follows:

$$\frac{\partial\theta}{\partial t} = \frac{\partial\left[K\,\frac{\partial(-h)}{\partial x}\right]}{\partial x} + \frac{\partial\left[K\,\frac{\partial(-h)}{\partial y}\right]}{\partial y} + \frac{\partial\left[K\,\frac{\partial(-h+z)}{\partial z}\right]}{\partial z} \qquad 2.2a$$

Richards equation is a nonlinear Fokker-Planck equation (Philip 1969), which is classical in the heat flow problems.A sink term may be added to the equation to account for point abstractions (accretions). Further, assuming that the sink term constitutes only of actual evapotranspiration, the equation takes the following form

$$\frac{\partial\theta}{\partial t} = \frac{\partial\left[K\,\frac{\partial(-h)}{\partial x}\right]}{\partial x} + \frac{\partial\left[K\,\frac{\partial(-h)}{\partial y}\right]}{\partial y} + \frac{\partial\left[K\,\frac{(-h+z)}{\partial z}\right]}{\partial z} - E \qquad 2.2b$$

where,

h : Capillary suction head $(h=f(\theta))$

z : Elevation head (Gravity head) (+ve upwards)

E : Actual evapotranspiration rate per unit soil volume

$K(h,x,y,z)$: Capillary conductivity

x,y,z : Cartesian coordinates

θ : Volumetric moisture content

t : time

The Richards equation is a second order nonlinear parabolic partial differential equation. The equation is applicable to layered soils also by simply making the characteristics, a function of depth. Solution of the equation can give depth wise distribution of cap. suction head (or moisture content) which can be used to evaluate the return flow, infiltration etc.,. For the solution, initial and boundary conditions are needed to be specified. The initial condition is the depthwise distribution of cap. suction head (or moisture content) at the start of simulation. Boundary conditions are the conditions at the bounds of flow domain throughout the simulation time. These may be of Dirichlet type or Neuman type. (Types of boundaries: Remson et al 1971).

Analytical solution for the equation (2.2b) may not be possible. Even numerical solutions may be prohibitively elaborate. Therefore, it is desirable to drop some of the terms which do not claim a significant role. First and second terms on the right hand side of equation (2.2b) represent the horizontal flows and the third term represents the vertical flow. The horizontal flows would be smaller than the vertical flows due to the fact that, the gradients of flow in horizontal direction are smaller than the gradients of flow in vertical direction. Absence of gravity head in horizontal plane makes the flow gradient (in horizontal direction) to be smaller than the flow gradient in vertical direction. Therefore, dropping the first two terms, on the right hand side, the equation can be simplified as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial \left[K \frac{\partial}{\partial z}(-h+z)\right]}{\partial z} - E \qquad 2.3$$

Further, assuming that the flow is nonhysteritic, terms specific moisture capacity and moisture diffusivity can be defined as follows:

$$C = \frac{d\theta}{dh} \qquad 2.4a$$

$$D = K\,\frac{dh}{d\theta} \qquad 2.4b$$

where

$C(h,z)$: Specific moisture capacity $[L^{-1}]$

$D(\theta,z)$: Moisture diffusivity $[L^{2}T^{-1}]$

Using equation (2.4) the equation (2.3) can be written as follows -

$$C\frac{\partial h}{\partial t} = \frac{\partial \left[K \frac{\partial(-h+z)}{\partial z}\right]}{\partial z} - E \qquad 2.4c$$

$$\frac{\partial \theta}{\partial t} = \frac{\partial\left(-D\,\frac{\partial \theta}{\partial z} + K\right)}{\partial z} - E \qquad 2.4d$$

The equation (2.4c) is known as head form and the equation (2.4d) is known as moisture content form.

It may be observed from the above discussion that there are two basic requirements to make the Richards equation ready for solution. These are i. h vs θ relation and K vs h relation (or K vs θ relation as h is a function of θ) ii. The actual evapotranspiration distributed in space and time. The requirement i is the specification of characteristics of the soil. A detailed development of the Richards equation has been given in chapter III.

2.3.1 Characteristics

The relations h vs θ and K vs h(or K vs θ as h is a function of θ) are called as characteristics of the soil. The characteristics show the phenomenon of hysterisis. This is due to rain drop effect (Bear 1972). An other mechanism leading to hysterisis is the ink bottle effect on account of many bottle necks in the geometry of pore space (Bear 1972). The hysterisis in the K-θ relation is usually small (Bear 1972). Fig. 2.1 shows a typical h-θ relation. The two curves marked by A and B are drainage and imhibition curves (Drainage and imhibition: Bear 1972). The paths marked by broken lines between these boundary curves are called as scanning curves. Selection of proper scanning curve can be made by studying, whether the point under consideration is draining or getting imbibed (Bear 1972). The characteristics can be determined by pure absorption or desorption experiments (absorption and desorption: Bear 1972).

Many investigators used empirical and semi-empirical relations to describe the characteristics. Levert (1941) (cited by Bear 1972) using dimensional analysis suggested a semi-emperical approach for the h-θ relation. Few of the other contributions are Wind (1955) Gardner (1958,60b), Brooks and Corey (1964), Vesser (1966), Brutsaert (1967),

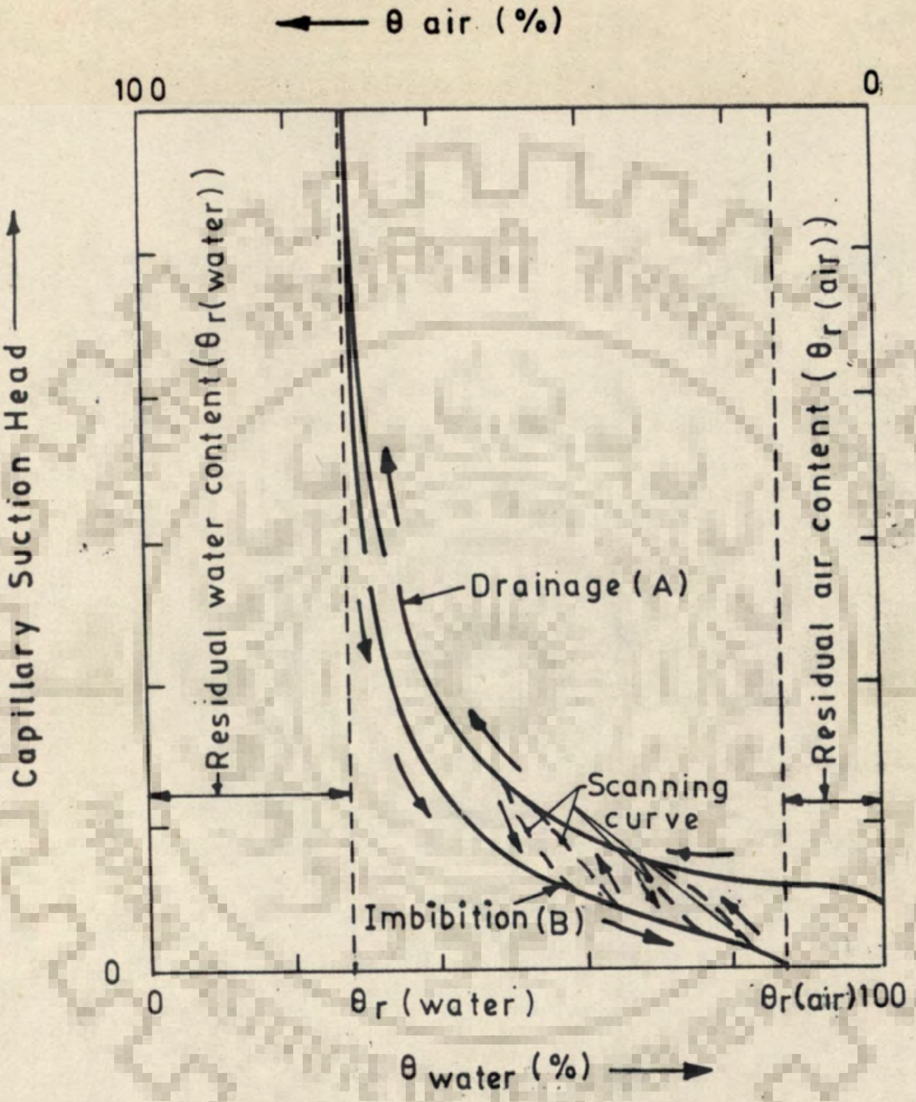

FIG. 2·1 - TYPICAL 'h CHARACTERISTIC' SHOWING HYSTERESIS

Taylor and Luthin (1969), Campbell (1974), Gillham (1976) and Clapp (1978) used a piecewise continuous relation for the $h-\theta$ characteristic. Cameron (1978) discussed the variability of soil water detention curves and predicted hydraulic conductivities on a small plot. Gupta and Larson (1979) presented regression models for determining characteristics of the soil from particle size distribution, percent of organic matter and bulk density. Ghosh (1980) proposed methods for estimating soil moisture characteristics from mechanical properties. Some investigators calibrated the coefficients of the relation describing characteristics by a proposed (or adopted) relation (eg. Hoover et al 1983).

In addition to the above discussed empirical and semi-empirical methods, some investigators conducted experiments to determine the characteristics of the soil. Rose et al (1965) proposed a method of in situ determination of K as a function of θ and z. Salter et al (1967) discussed the influence of texture on the $h-\theta$ characteristic. Klute et al (1969) has proposed a strain gauge pressure transducer for hydraulic and pressure head measurements. Wesseling et al (1969) proposed an experimental method, based on infiltration, for the determination of $K-\theta$ characteristic. Campbell (1974) proposed a method for determining unsaturated conductivity from moisture retention data. Boels et al (1978) described a laboratory method for determination of characteristics of the soil. The method involves lysimeter experimentation in which comparision of loss of moisture due to evaporation by actual measurement and by Darcy-Buckingham flux law are made. Dane (1980) compared field and laboratory determined hydraulic conductivity values. He concluded that method developed by Libardi et al (1980) can be extended to Coarse texture soils and that undisturbed core samples may give K-θ relation comparable to field tests. Nakano (1980) discussed the effect of pore structure on h-θ relation. Busscher (1981) used a finite difference model to estimate capillary conductivity for a drying soil. Ragab et al (1981) have made a comparative study of numerical and laboratory methods for determing hydraulic conductivity function of a sand. Dane et al (1983) calibrated closed form relations for h-θ and K-θ relations in a moisture content simulation study of a drainage problem. Hoover et al (1983) used least squares approach to determine coefficients in the Taylor and Luthin (1969) relations. Jaynes et al (1984) concluded that Gardner equation (Gardner 1958) well suited to the experimental data. Few of the other contributions are Salter et al (1965), Klute (1972), Bruce (1972), Mualem (1976), Gillham et al (1976), Van Genuchten (1980), Ghong et al (1981), Scotter et al (1983), Field et al (1984), Malik et al (1984), and Talsma (1985)

2.3.2 Evapotranspiration

The atmospheric diurnal evaporative demand creates a transient potential at the root surface and in the soil surrounding it. Vanden Hornet (1948) put forward a hypothesis that, the potential difference across each path way divided by the transpiration rate equals the resistance to water flow of that component. This is simply an analogy of Ohms law in electric current studies. Various aspects of water availability to plants have been discussed by Richards and Wadleigh (1952) Kelly (1954), Jamison (1956), Bonner (1959). Importance of water availability to plants has been discussed long ago by Livingston and Koketsu (1920) (cited by Gardner 1960a). They proclaimed the usage water supplying power of soils. Richards (1928) (Gardner 1960a) pointed out that availability involves both the ability of the plant to absorb water and the readiness of soil surrounding it to supply water.

2.3.2.1 Transpiration - Models for transpiration can be grouped under two heads. The microscopic models wherein flow to each root is analysed. The macroscopic models where in flow to individual root is not analysed, but the macroscopic outcome from a volume of soil containing roots is analysed. Few of the noteworthy contributions in the microscopic transpiration models are Gardner (1960a,62). Cowan (1965), Passioura et al (1968), Raats (1976), Lomen and Warrick (1976), Slatyer (1956,67,77,81a,b), Slack et al (1977), Dejong and Cameron (1979), Mc Coy et al (1984). Few of the prominent contributions on the macroscopic transpiration models are Whisler et al (1968), Nimah et al (1973a,b), Herkelrath et al (1977), Taylor and Klepper (1975,78). Molz (1981) has documented many of the works, in chronological order, on the macroscopic transpiration models.

2.3.2.2 Evapotranspiration - In the transpiration models, only transpiration from vegetal roots is obtained. The direct evaporation from soil needs to be evaluated seperately (e.g. Feddes et al 1978). Moreover, some of the models require the potential transpiration to be specified. It is often necessary to evaluate the Evapotranspiration (Direct evaporation and transpiration). For instance, evapotranspiration is very nearly equal to consumptive use of crops.

In the macroscopic actual evapotranspiration (AET) models, the AET is functionally related to the cap suction head (or moisture content) depth and time. Also, usually, these models require the potential evapotranspiration of crop (PET (crop)) to be specified. The PET (crop) can be evaluated, for instance, as per Doorenbos et al (1979), Debruin (1981). The procedure involves firstly the calculation of PET of the reference crop. The reference crop is defined to be green grass, actively growing (8 to 15 cms tall), completely shading the ground surface and not short of water. Using the methods of Penman, Radiation, Pan evaporation etc., the reference cropPET can be calculated. Subsequently, using crop coefficients (eg.Doorenbos et al 1979), the PET (crop)can be determined. The crop coefficients will differentiate crops, stage of growth and climatic conditions. Doorenbos et al (1979) made a full length discussion on calculation of PET(crop) from weather data. Once the PET (crop) is available a model can be formulated to calculate PET relating functionally the PET (crop), AET, depth of soil, moisture content and the time. Thus, the 'availability' concept of Richardson (1928) and 'Supplying power of soil', concept of Livingston and Koketsu (1920) are indirectly become effective. Important attraction of these types of models is that the all the parameters are easy to evaluate. The cap. suction (or moisture content) is simultaneously evaluated, when this AET model forms a sub model, in the model describing the unsteady state flow of water through the unsaturated zone. So, once the relation between AET and cap. suction (or moisture content) is prescribed, the AET can be evaluated by an iterative procedure.

Veihmeyer and Hendrickson (1950) held the view that the ET is always at potential rate irrespective of the soil moisture level. However, a number of later experiments showed that this view is not correct and ET is dependent on soil moisture level. Stanhill (1957), Denmead et al (1962) observed that actual transpiration decreased with decreasing soil moisture content and increasing transpiration. Rose et al (1967) proposed a calibration type of method for the determination of withdrawal of water from soil by crop roots, as a function of depth and time. Rouse (1970) studied the effects of soil water movement on actual ET from soil moisture budget for a grass covered sandy loam soil. They observed the average actual ET to exceed that of Penman and Thornthwhite. They attributed it to deep seepage losses. Eagleson et al (1965) plotted the observed ET and soil moisture deficit. A curvilinear relation (nearly linear) was obtained with correlation coefficient of 0.72.Stricker (1981) has presented methods for calculation of AET from meteorological data. Sermer (1969) has proposed methods and formulae for determination of soil evaporation and soil moisture content from hydrometeorological data. Hansen (1984) presented a model for AET of agricultural crops, from routine weather data. An important drawback of the model is that, it did not consider the wind speed. Minhas et al (1974) proposed a parametric empirical relation between AET, PET and moisture content. Different values of the parameter reasonably approximate relations proposed by few researchers (Fig.2.2). The relation is as follows.

$$\frac{ET}{PET} = (1- e^{-rx}) / (1-2e^{-r\bar{x}} + e^{-rx}) \qquad (2.5)$$

where

x : θ - WP

r : Parameter

$\bar{x}$: Available soil moisture (FC-WP)

FC : Field capacity

WP : Wilting point

θ : Volumetric moisture content

In the case of Evapotranspiration models and models for characteristics a well substantiated evaluation is not possible, as these models act as submodels in the model describing the unsteady state flow of water through unsaturated zone.

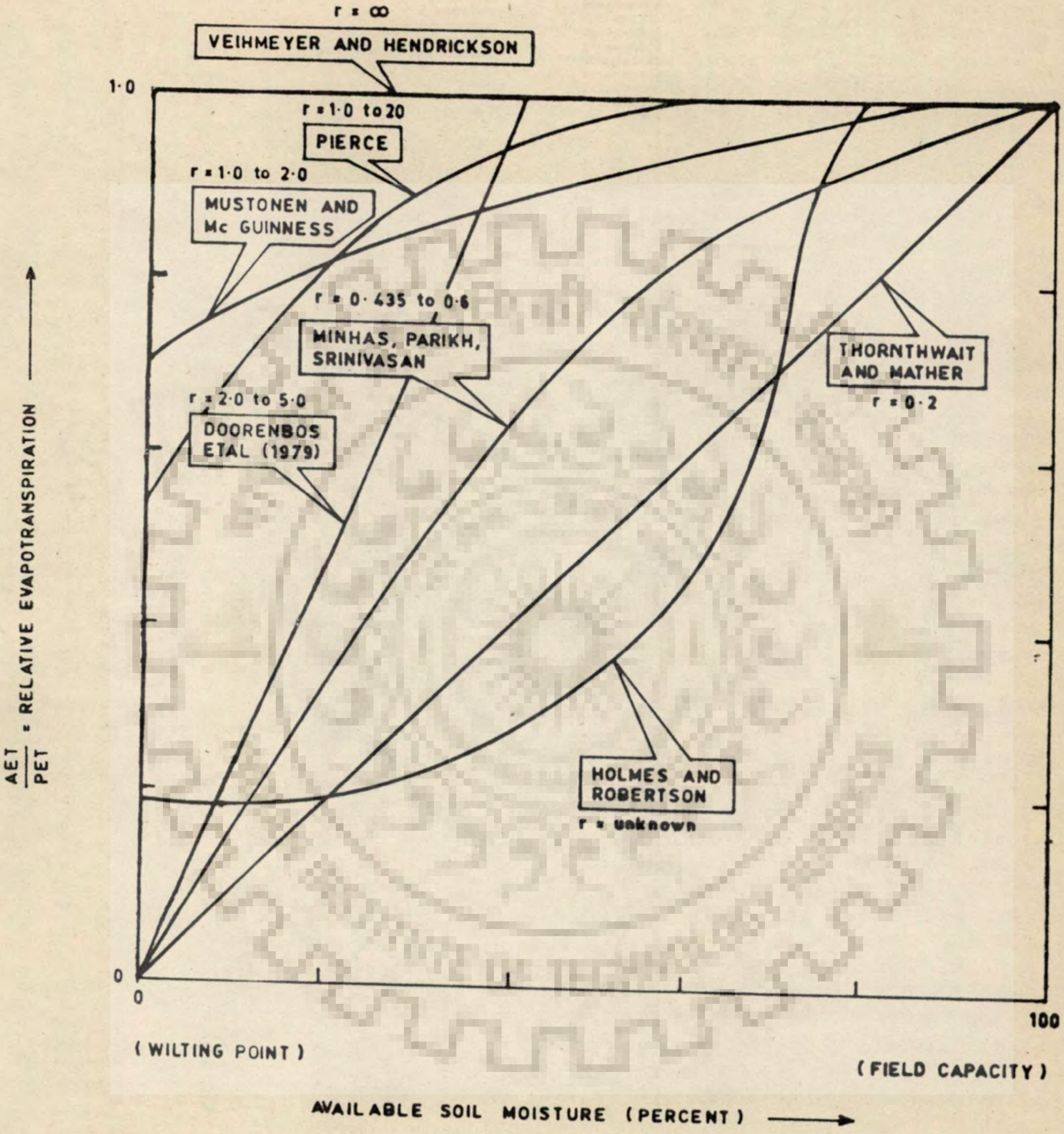

FIG. 2·2 – RESULTS OF VARIOUS STUDIES THAT SHOW THE DEPENDENCE OF RELATIVE EVAPOTRANSPIRATION ON SOIL MOISTURE

2.4 SOLUTION TECHNIQUES FOR RICHARDS EQUATION

The two requirements, namely, the characteristics of the soil and a submodel for AET will make the Richards equation ready for solution. The solution techniques for the Richards equation can be grouped under two heads, i.Analytical and ii. Numerical.

Analytical solutions are the solutions in which a solution can be completely found by mathematical analysis. There is yet no analytical solution available for the Richards equation . Quasi-analytical solution are those in which the methods of mathematical analysis are used to establish the basic form of the solution, even though some coefficients that appear in the solution may be required to be evaluated (by numerical methods). Usually, similarity substitution (Boltzman transformation: Remson et al 1971) is used to reduce the partial differential equation into an ordinary differential equation. Then perturbation (Van Dyke 1964) techniques are used to solve the equation.

2.4.1 Quasi-analytical solutions

Philip (1969) proposed a quasi-analytical solution to the Richards equation. The soil medium is assumed to be homogeneous, Semi-infinite with initial uniform moisture content and instantaneous prescribed moisture content at the ground surface. The equation was as follows.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[D \frac{\partial \theta}{\partial z}\right] - \frac{dk}{d\theta} \cdot \frac{\partial \theta}{\partial z} \qquad 2.6a$$

with

$$t = 0 \qquad z > 0 \quad \theta = \theta_o \qquad 2.6b$$

$$t \geq 0 \qquad z = 0 \quad \theta = \theta_s \qquad 2.6c$$

where,

$D = K \frac{d\psi}{d\theta}$

z : Vertical distance (+ve down wards) from ground surface.

θ_s : Moisture content prescribed

K : Capillary conductivity

ψ : Moisture potential (= - h)

Firstly, the gravity term (second term of the R.H.S.) is dropped. Thus, equation (2.6a) becomes

$$\frac{\partial \theta}{\partial t} = \frac{\partial \left[D \frac{\partial \theta}{\partial z}\right]}{\partial z} \qquad 2.7$$

Using the similarity substitution

$$\phi = z\ t^{-1/2} \qquad 2.8a$$

equation 2.7 reduces to

$$\frac{-\phi}{2} \frac{d\theta}{d\phi} = \frac{d}{d\phi}\left[D \frac{d\theta}{d\phi}\right] \qquad 2.8b$$

with

$$\phi = 0 \qquad \theta = \theta_s \qquad 2.8c$$

$$\phi \to \infty \qquad \theta = \theta_o \qquad 2.8d$$

Thus, solution of equation (2.7) subject to (2.6b) and (2.6c) becomes,

$$z(\theta, t) = \phi(\theta)t^{1/2} \qquad 2.9$$

Equation (2.7) may be re-written as

$$- \frac{\phi}{2} = \frac{d}{d\theta}\left[D \frac{d\theta}{d\phi}\right] \qquad 2.10$$

Integrating equation (2.10) yields

$$\int_{\theta_o}^{\theta} \phi d\theta = -\ 2D\ d\theta/d\phi \qquad 2.11a$$

subject to

$$\theta = \theta_s \quad \phi = 0 \qquad 2.11b$$

Equation (2.11) is an integro-differential equation. Solution of the equation yields ϕ. Thus, from equation (2.9) the movement of moisture $(Z(\theta,t))$ can be evaluated.

At this stage, pressuming that the contribution by the gravity term to be small (i.e., in small time), the solution to the equation (2.6a) is sought in the following form.

$$Z(\theta,t) = \phi_1 t^{1/2} + \phi_2 t + \phi_3 t^{3/2} + \phi_4 t^2 + \ldots \qquad 2.12$$

where,

$$\phi_1 = \phi$$

Using perturbation techniques (Van Dyke 1964), following integro differential equations were derived for the evaluation of the ϕs (in equation 2.12).

These are

$$\int_{\theta_o}^{\theta} \phi_1\ d\theta = \frac{-2D}{\phi_1'} \qquad 2.13a$$

$$\int_{\theta_o}^{\theta} \phi_2 d\theta = \frac{D\phi_2'}{(\phi_1')^2} + (K-K_o) \qquad 2.13b$$

$$\int_{\theta_o}^{\theta} \phi_3 d\theta = \frac{2D}{3}\left[\frac{\phi_3'}{(\phi_1')^2} - \frac{(\phi_2')^2}{(\phi_1')^3}\right] \qquad 2.14c$$

$$\int_{\theta_o}^{\theta} \phi_4 d\theta = \frac{D}{2}\left[\frac{\phi_4'}{(\phi_1')^2} - \frac{(\phi_2')^2}{(\phi_1')^3}\left(2\frac{\phi_3'}{\phi_2'} - \frac{\phi_2'}{\phi_1'}\right)\right] \qquad 2.14d$$

$$\int_{\theta_o}^{\theta} \phi_n d\theta = \frac{2D}{n}\left[\frac{\phi_n'}{(\phi_1')^2} - R_n(\theta)\right] \qquad (n \geq 3) \qquad 2.14e$$

where,

$\phi_n' = \frac{d\phi_n}{d\theta}$

$K_o = K(\theta_o)$

$K = K(\theta)$

R_n may be determined from $\phi_1 \ldots \phi_{n-1}$. Since $\phi_1 \equiv \phi$ (Known) ϕ_2 can be found from 2.14b. Thus, $\phi_3, \phi_4 \ldots$etc., can be found. Subsequently, he derived equations applicable for large times. The solution was

$$Z(\theta,t) = \frac{K_s - K_o}{\theta_s - \theta_o} + (\theta_s - \theta_o)\int_{\theta}^{\theta_s - \varepsilon_a} \frac{D\, d\theta}{(K_s - K_o)(\theta - \theta_o) - (K - K_o)(\theta_s - \theta_o)} \qquad 2.15$$

where,

ε_a : small positive quantity

K_s : $K(\theta_s)$

Irmay (1969), starting from a physically unacceptable model arrived at the same solution. Babu (1976a,b) used perturbation method to solve the equation analytically. Few of the other contributions are by Parlange (1971,80a,b,c,82, 84a,b,85), Dagan (1971), Liu (1976).

Braster (1963) solved the linearized form (by assigning constant value for terms causing nonlinearity) of the Richards equation by a quasi-analytical method. The simulated results were compared with the numerical solution of Rubin et al (1963). The comparison of the results obtained by the numerical solution and the linearized solution showed small differences for the variation of the water content at the soil surface with time. The agreement between the water content profiles is less satisfactory. Better results were obtained in the upper region of the soil profile (large values of the water content) and for small times. In the lower region, the profile obtained by solution of the linearized equation extended deeper than the profiles obtained by numerical solution because of the relatively large diffusivity value, which was taken to be constant for the entire profile. Thus, it may be observed that the flow nature is nonlinear.

Delta function solution : In this type of solutions, the Green ampt equations (Morel- Seytoux 1981) are classical. Few prominent other studies have been made by Whisler and Bower (1970), Mein et al (1971), Morel-Seytoux and his coworkers (1974, 75,76,78), Chu et al (1981), Rawls et al (1981b), Brakensiek et al (1977, 1982), Zirbel et al (1982).

The available quasi-analytical solutions to the Richards equation can not serve the purpose of estimating all the components of response on account of the following reasons.

i. Homogeneity of the soil (scale Heterogeneity is a very special and rare case).

ii. Semiinfinite medium

iii. Prescribed moisture content at the ground surface (eg. Philip 1969), or

Constant flux at the ground surface (eg.Babu 1976b, Parlange 1985).

iv. Pure infiltration and subsequent propagation of wetting front always down wards. In real life situations though(in some cases)transpiration is not present, the direct evaporation is present.

2.4.2 Numerical Solutions

Two distinct types of digital computer based methods are available for obtaining the numerical solution of Richards equation. These are finite difference and finite element methods.

2.4.2.1 Finite difference method - Finite differences as a numerical solution technique., for solving the partial differential equations, has been introduced by Richardson in 1910 (Remson et al 1971). The implicit finite difference form of Richards equation gives a set of nonlinear simultaneous equations at every time step. These nonlinear simultaneous equations can be solved by a suitable algorithm (eg. Brown 1969, Ortega 1970). These algorithms require the hint solution. The hint solution can be generated by any rational subjective or objective reasoning. The iteration process can be accelerated by procedures like Aitekan Δ^2(Henrici 1964).

Formulation : The following convention is followed for the finite difference scheme (for the discussion, equation 2.4 c is used).

i. The depth interval between ith and (i+1)th node is designated by Δz_i and will be referred to either as Δz_i or ith interval. The soil between ith and (i+1)th depth node will be referred to as ith link.

ii. The time step between jth and (j+1)th level of simulation is designated by Δt_j and will be referred to either as Δt_j or jth time step.

iii. The capillary conductivity of the ith link, at simulation level j, is designated as $K_{i,j}$ and will be referred to as $K_{i,j}$.

Fig. 4.2 shows the convention diagramatically.

The equation 2.4c written in finite difference form for an internal ith node will be as follows:

$$\bar{C}_{i,j} D_{t_{i,j}} = \frac{\Delta\bar{F}_{i,j}}{\Delta z_i} - \bar{E}_{i,j} \qquad 2.16a$$

where

$$\Delta\bar{F}_{i,j} = \bar{F}_{i-1,j} - \bar{F}_{i,j}$$

$\bar{F}_{i-1,j}$: Representative flow rate, from (i-1)th node to ith node, during Δt_j.

$\bar{F}_{i,j}$: Representative flow rate, from ith node to (i+1)th node, during Δt_j.

$$\overline{\Delta z_i} = \frac{\Delta z_{i-1}+\Delta z_i}{2}$$

$\bar{E}_{i,j}$: Representative E at ith node during Δt_j.

$$D_{t_{i,j}} = \frac{h_{i,j+1}-h_{i,j}}{\Delta t_j}$$

$\bar{C}_{i,j}$: Representative C at the ith node in Δt_j.

Equation 2.16a written for all interior nodes (i.e.,2 to n-1) will lead to (n-2) number of equations. One equation can be written for node number 1 (ie., ground surface) from the known boundary condition (henceforth, called as upper boundary condition). The equation will be:

Dirichlet condition:

$$h_{1,j+1} = H_{j+1} \tag{2.16b}$$

where

H_{j+1} : known capillary suction head at ground surface.

Neuman condition:

$$\bar{C}_{1,j}\cdot D_{t_{1,j}} = \frac{\overline{\Delta F}_{1,j}}{\overline{\Delta z}_1} - \bar{E}_{1,j} \tag{2.16c}$$

where

$$\overline{\Delta F}_{1,j} = Q_j - \bar{F}_{1,j}$$

Q_j : constant input intensity during Δt_j

$\bar{E}_{1,j}$: Representative E at node 1 during Δt_j

$$\overline{\Delta z_1} = \frac{\Delta z_1}{2}$$

Another equation can be written, from the known lower boundary condition (for instance water table, which is Dirichlet type always).

$$h_{n,j+1} = 0 \qquad 2.16d$$

Thus, there will be 'n' number of equations for the 'n' number of nodes, which make the system of equations determinate.

The three types of finite difference forms are(Remson etal 1971) i)Writting in forward difference form ii) Backward difference form iii) Weighted difference form (giving weightages to the forward and backward difference forms. Giving a 50 percent weightage is central difference or Crank-Nicolson form).

Explicit scheme : In this scheme the representative values in equation 2.16 are adopted as per jth level of simulation. Thus

$$\bar{F}_{i-1,j} = K_{i-1,j} \frac{(h_{i,j}-h_{i-1,j}+\Delta z_{i-1})}{\Delta z_{i-1}} \qquad 2.17a$$

$$\bar{F}_{i,j} = K_{i,j} \frac{(h_{i+1,j}-h_{i,j}+\Delta z_{i})}{\Delta z_{i}} \qquad 2.17b$$

$$\bar{C}_{i,j} = \frac{d\theta}{dh}\Big|_{h=h_{i,j}} \qquad 2.17c$$

$$\bar{E}_{i,j} = E(\theta_{i,j}) \qquad 2.17d$$

$K_{i-1,j}$: Capillary conductivity of the (i-1)st link at jth level

$K_{i,j}$ = Capillary conductivity of the ith link at jth level.

Thus, the $h_{i,j+1}$ may be solved explicitly, for the n number of nodes, using the 'n' equations. However, the scheme is stable and convergent only conditionally. The conditions are available only for homogeneous soil medium. Apart from this, the freedom of choosing 'Δt' independent of 'Δz' is reduced.

Implicit Scheme : In this scheme the representative values in equation (2.16) are adopted as per (j+1)th level of simulation. Thus

$$\bar{F}_{i-1,j} = K_{i-1,j+1} \frac{(h_{i,j+1}-h_{i-1,j+1}+\Delta z_{i-1})}{\Delta z_{i-1}} \qquad 2.18a$$

$$\bar{F}_{i,j} = K_{i,j+1} \frac{(h_{i+1,j+1}-h_{i,j+1}+\Delta z_{i})}{\Delta z_{i}} \qquad 2.18b$$

$$\bar{C}_{i,j} = \frac{d\theta}{dh}\Big|_{h=h_{i,j+1}} \qquad 2.18c$$

$$\bar{E}_{i,j} = E(\theta_{i,j+1}) \qquad 2.18d$$

$K_{i-1,j+1}$: Capillary conductivity of the (i-1)th link at (j+1)th level.

$K_{i,j+1}$: Capillary conductivity of the ith link at (j+1)th level.

The equation (2.16) with the values defined as per (2.18) results in a system of 'n' nonlinear simultaneous equations. The solution of the nonlinear system of equations will yield the $h_{i,j+1}$ at the n number of nodes. The scheme is unconditionally stable and convergent. However, the adoption of representative values as per (2.18) may not be appropriate, when change in h in the jth time step is significant.

Crank - Nicolson Scheme : Since, in the present work, the Crank-Nicolson scheme is used, a detailed discussion on the scheme has been given in section 4.2.2. The nonlinear system of equations resulting from implicit schemes like that of Crank-Nicolson scheme may give an oscillatory solution (Ames 1969, Krishnamurty et al 1978). Moreover, the nonlinear system will be difficult to solve (Ralston 1969). The system (of equations) can be linearized, which has been detailed in the sections 4.2.3.1 and 4.2.3.2.

It seems that relatively little work has been reported on numerical attack on Richards equation. The situation is particularly true in the context of estimation of recharge at the water table. Most of the reported works are with different basic purposes like estimation of infiltration, simulation of moisture profiles, estimation of actual evapotranspiration.

Klute (1952), used the numerical method for solving the Richards equation, considering a semi-infinite medium. Basic purpose is to simulate moisture distribution. Evapotranspiration was not considered.

Hanks and Bowers (1962), Rubin and Steinhardt (1963, 64a,64b) Whisler and Klute (1965), Pikul et al (1974) used local form of Richards equation i.e.

$$C \frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K \frac{\partial(-h+z)}{\partial z}\right] \qquad 2.19$$

Molz and Remson (1970), used decomposed form i.e., illustrating explicitly the two driving forces for water transfer ie., diffusive and convective.

$$C\frac{\partial h}{\partial t} = K\frac{\partial^2 h}{\partial z^2} + \frac{dk}{dh}\cdot\frac{\partial h}{\partial z}\left(\frac{\partial h}{\partial z}+1\right) \qquad 2.20$$

Gardner (1958), Rubin (1969), Raats and Gardner (1974), Jeppson (1974) employed Kirchoff transformation (Kirchoff transformation: Remson et al 1971).

$$\frac{C}{K}\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial z^2} + \frac{1}{k}\frac{dk}{dh}\cdot\frac{\partial u}{\partial z} \qquad 2.21$$

where,

$$\Psi = \int_{h_0}^{h} K\,dh$$

Gupta and Staple (1964), Staple (1966) used explicit scheme for solution of Richards equation, without evapotranspiration. The criteria for time step has been

$$\frac{D_{max}\Delta t}{(\Delta z)^2} \le r \qquad (r = 0.5) \qquad 2.22$$

Corey et al (1965) solved 2-D Richards equation by Crank-Nicolson finite difference scheme. The runoff is linked to the ponded depth. However, apart from not considering ET, the medium was assumed to be semi-infinite. Remson et al (1965, 67), Horenberger et al (1969) modelled the soil moisture flow by the numerical method. Green (1970) numerically modelled an unsaturated ground water flow and compared the results with a field experiment.

Freeze (1971) proposed an unsaturated-saturated flow model. This model did not contain ET term.

Wang and Lakshminarayana (1968) simulated water movement through unsaturated, non homogeneous semi-infinite soils, using moisture form of the equation (equation 2.5b). They used explicit implicit FD scheme and recommended a time step of simulation to be

$$\Delta t_{j+1} \leq \frac{1}{2} \quad \frac{(\Delta z)^2}{K(z,\theta)\, \frac{\partial h}{\partial \theta}\, (z,\theta)} \qquad 2.23$$

Pikul et al (1974) proposed a numerical model based on coupled one dimensional Richards and Boussinesq equations. The parallel vertical flows through the unsaturated zone are linked to one dimensional horizontal saturated flows. Beese et al (1977) conducted field experiments to determine the simulation capability of the Richards equation in field condition. The conclusion was positive.

Krishnamurti et al (1977) developed a Crank-Nicolson finite difference model for the estimation of return flow from rain fall. They modified the Richards equation as a result of assuming (considering) a linear variation in the associated characteristic curves. They did not consider the ET (sink term). Krishnamurti et al (1978) developed a criteria for time step of simulation in the numerical solution of the modified Richards equation (Krishnamurty et al 1977). The criteria is as follows:

$$\{[(C_{1j} - \theta_j^t \; C_{3j})/\Delta z^2] + \frac{C_{6j}}{2}\} > 0 \qquad 2.24a$$

and

$$\frac{C_{1j}\theta_j^t - C_{3j}}{(C_{45j} - C_{2j}\theta_j^t)\Delta z} > \frac{(C_{45j} - C_{2j}\theta_j^t)\Delta z}{C_{1j}\theta_j^t - C_{3j}} > 0 \qquad 2.24b$$

$$0 < \Delta t \leq 2/\max \mu_j \qquad 2.24c$$

where

Δz : uniform depth interval

μ : positive Eigen value of the coefficient matrix.

j : Depth node ; t : simulation time level

Feddes et al (1978) used Crank-Nicolson finite difference scheme for solving the Richards equation with ET. The equation was taken up in cap. suction form. The lower boundary was specified as time varient water table. However, the prime concern of this work is to estimate ET and not the returnflow. Moreover the run off needs to be externally specified. They used a time step of simulation as recommended by Zaradny (1978) which is as follows.

$$\Delta t^{i+1} < \frac{\varepsilon \Delta z}{|q|^{i}} \qquad 2.25$$

where,

q : Input intensity

Δz : Uniform space interval

ε : A coefficient varying from 0.015 to 0.035

Δt : Time step

i : Index of simulation level

Kafri et al (1978) modelled the flow in soil water zone for the estimation of return flow. The lower boundary condition (ie., bottom of soil water zone) has been set such that the moisture moves only by gravity, which however, is an artificial imposition. Surface run off was not considered, since the rain intensities never exceeded the infiltration capacity rate of the soil. They considered the ET (sink term). Resulting system of nonlinear simultaneous equations have been solved by N-R method (Ralston 1965). Its real life application (except for few isolated cases) seems to be doubtful.

Dejong et al (1979) using moisture form with ET term have simulated the flow, using fluctuating water table as lower boundary. Surface run off and ponding could not be accounted for as the equation is in moisture form.

Richter (1980) modelled the vertical unsaturated flow of water through unsaturated soils by the numerical method. Reeder et al (1980) modelled the infiltration problem under rapidly varying ponded depth, by numerical solution of Richards equation for a semi-infinite soil medium. Dane etal (1981) proposed an adaptive finite difference scheme. The upper boundary condition was fixed (flux or concentration type) by expressing it with relations involving constants. The constants are to be supplied. The scheme can handle variable grid and time spacing. They demonstrated the effect of different combinations of $\Delta z, \Delta t$. The space increment changes in time domain also as per the requirement. They concluded that variable space and time can give more realistic results. Heverkamp et al (1981) made a study on comparative performance of models having three forms of Richards equation (Local form, decomposed form and Kirchoff transformed form) as governing equation and concluded that the performance of these three models are independent of boundary conditions. Further, they concluded that Kirchoff form worked better in general and local form is good for calculating mass balance components like infiltration. Zachaman et al (1981) presented methods for calibrating Richards flow equation, for a draining column by parameter identification.

Thomas et al (1982) used finite difference methods to simulate the rain infiltration into layered field soils, using the head form of the equation. The soil was assumed to be semi infinite. Regab et al (1982) using numerical methods (finite difference methods), simulated infiltration profiles. Further, they compared the simulation profiles with an experimental study.

Kunze et al (1983) compared infiltration profiles obtained experimentally and numerically using moisture form of Richards equation for a semi-infinite medium.

Reynolds et al (1984) developed and validated a numerical model for simulating evaporation from short cores. Besbes et al (1984) proposed a methodology for the identification of the spatial variability of the infiltration transfer function using common climatic and piezometric data. A parametrization of the transfer functions using gamma distribution as basic functions has been suggested. Morel-Seytoux (1984) proposed and verified with field evidences, an approximate unit hydrograph method to estimate temporal variation of return flow from excess infiltration. The developed tool was physical and practical. The parameters have physical meaning.

2.4.2.2 Finite element method: Recently increased interest is being shown on the implementation of finite element methods, in the numerical solution of ground water flow problems. Whisler (1970), Feddes (1975) used finite element technique for solving the (Richards equation) ground water flow problems. Singh et al (1986) used Galerkin finite element (Remson 1971) solution for 2D Richards equation incorporating aquiter compressibility and thereby to develop a general model to simulate saturated-unsaturated flow.

From the review, it may be observed that the thrust on estimation of recharge (return flow) is less. Many of the reported works are with different purposes like estimation of infiltration, moisture distribution, evapotranspiration etc., Mostly the thrust is on the estimation of infiltration.

CHAPTER - III

MODELLING OF FLOW THROUGH UNSATURATED ZONE

3.1 GENERAL

The unsaturated zone of an aquifer is bounded by ground surface at top and by water table at bottom. Soil (porous medium) constituting the zone may be heterogeneous and anisotropic. The roots of usual agricultural crops are confined to this zone. The fluid flow in the zone is multiphase- air, water, water vapour and various gases. The soil skelton shows the properties of swelling and shrinking, degree of which varies from soil to soil.

While rainfall and applied irrigation (after accounting for interception and direct evaporation losses) excite the zone at the ground surface, temporal variation of water table excites it at the water table. Response of the zone to these excitations are recharge at the water table, infiltration, ponding of water at the surface, evapotranspiration and change in the soil moisture storage.

This hydrological excitation-response process is governed by the unsteady state flow of water (moisture) in the zone, which is very complex. Mathematical modelling, being a flexible tool, can be put to use to reasonably approximate the flow process.

3.1.1 Current practice

The current practice, of modelling the flow process is mostly based upon soil moisture accounting. These models, involving treatment of the problem on lumped basis, are generally of the following form (for a Jth period).

A. Estimation of infiltration in Jth period, by seperating surface run off, detention, interception etc., from rainfall, and applied irrigation.

B. Routing of infiltration through the unsaturated zone.

i. The infiltration in the Jth period t_J (F_J), is added to the soil moisture storage (S_J) at the start of the Jth period. Thus, the revised uniform moisture (S'_J) will be:

$$S'_J = S_J + F_J \qquad 3.1a$$

ii. The uniform actual evapotranspiration rate in Jth period (E_J) is calculated with the aid of a submodel. The uniform moisture (S''_J) after accounting for the actual evapotranspiration depth will be:

$$S''_J = S'_J - E_J \cdot t_J \qquad 3.1b$$

iii. The Uniform maximum moisture that can be held (S_{m_J}) (corresponding to field capacity) in the root zone, in Jth period, is calculated as follows:

$$S_{m_J} = FC \cdot R_{t_J} \qquad 3.1c$$

where

FC : Field capacity

R_{t_J} : Depth of root zone in Jth period.

iv. The return flow (R_J) is the excess of moisture above (S_{m_J}).

$$R_J = S''_J - S_{m_J} \qquad \text{if } S''_J > S_{m_J} \qquad 3.1d$$

$$R_J = 0 \qquad \text{if } S''_J \leq S_{m_J} \qquad 3.1e$$

v. If R_J evaluated at step iv is positive, the uniform moisture in the root zone is set equal to (S_{m_J}). Else, the uniform moisture in the root zone is unaltered. Thus

$$S'''_J = S_{m_J} \qquad \text{if } R_J > 0 \qquad 3.1f$$

$$S'''_J = S''_J \qquad \text{if } R_J \leq 0 \qquad 3.1g$$

vi. If the depth of the root zone increases in the subsequent period (i.e., J+1), it is assumed that the enhanced root zone will be at field capacity. Thus, the uniform initial condition (S_{J+1}) for (J+1)th period will be

$$S_{J+1} = S'''_J + (R_{t_{J+1}} - R_{t_J}) \ \text{FC} \qquad 3.1h$$

vii. If the depth of root zone decreases in the subsequent period (i.e., J+1), the S_J is reduced in proportion of the root zone depth in (J+1)th and Jth periods to arrive at initial condition on (J+1)st period.

$$S_{J+1} = S'''_J \cdot R_{t_{J+1}} / R_{t_J} \qquad 3.1i$$

It may be observed from the above operational details that, the Soil moisture accounting (SMA) modelling involves the following assumptions.

Group A

i. The porous medium is stable and isotropic.

ii. The flow is immiscible and two phase (air and water).

iii. The air phase is at atmospheric pressure (arbitrarily taken as zero) throughout the zone at any time and the air phase flow is negligible.

iv. The water is pure and incompressible.

v. The flow is under isothermal conditions.

Group B

i. No moisture movement at moisture contents less than or equal to field capacity.

ii. Complete drainage of excess moisture at moisture contents greater than field capacity, in the basic accounting period.

iii. Uniform extraction of moisture by plant roots through out the root zone and uniform distribution of moisture in the root zone, in the basic accounting period.

iv. Homogeneous soil medium.

v. The part of the unsaturated zone, below the root zone, acts as a passive path way in draining the excess moisture.

vi. The water table is deep enough so that the concept of field capacity is not invalidated and position of water table is time invarient.

3.1.2 Distributed Modeling

The assumptions listed under group B can be eliminated if the governing differential equation of the flow is solved. This type of modelling is called as distributed modelling.

3.1.2.1 Governing equation : Almost all the equations describing the flow of water through unsaturated zone, are based upon the Darcy law as applicable to unsaturated flow. Assuming that the flow involves only hydrostatic pressure apart from gravity the Darcy law (as applicable to unsaturated flow) in cartesian co-ordinate system can be written as follows:

$$U = - K \nabla \tau \qquad 3.2$$

U : Vector flow velocity $[LT^{-1}]$

τ : Total head = $-h + z$ $[L]$

z : Elevation head (gravity head) $[L]$

$-h$: Hydrostatic pressure head $[L]$

h : Capillary suction head $[L]$

$K(h,x,y,z)$: Capillary conductivity $[LT^{-1}]$

∇ : Gradient of a scalar

x,y,z: Cartesian coordinates with z taken positive upward. $[L]$.

A combination of principle of continuity and the Darcy law (equation 3.2) provides a formal equation (Richards equation) describing the unsteady state flow of moisture in the unsaturated zone.

Principle of continuity

$$\frac{\partial\theta}{\partial t} = -\nabla \cdot U \qquad 3.3$$

where

$\theta(h)$: Volumetric moisture content

t : time [T]

∇ : Divergence operator.

Richards equation (by putting equation 3.2 into equation 3.3).

$$\frac{\partial\theta}{\partial t} = \nabla \cdot (K \nabla \tau) \qquad 3.4$$

A sink term may be added to the equation (3.4) to account for point abstractions (or accretions). Thus, equation (3.4) will take the following form.

$$\frac{\partial\theta}{\partial t} = \nabla \cdot (K \nabla \tau) - S \qquad 3.5$$

or

$$\frac{\partial\theta}{\partial t} = \frac{\partial\left[K \frac{\partial(-h)}{\partial x}\right]}{\partial x} + \frac{\partial\left[K \frac{\partial(-h)}{\partial y}\right]}{\partial y} + \frac{\partial\left[K \frac{\partial(-h+z)}{\partial z}\right]}{\partial z} - S \qquad 3.6$$

where

S : Algebraic sum of point abstraction and accretion rates per unit volume of soil $[T^{-1}]$.

Analytical solution for the equation (3.6) may not be possible. Even numerical solutions may be prohibitively elaborate. Therefore, it is desirable to drop some of the terms which do not claim a significant role. First and second terms on the right hand side of equation (3.6) represent the horizontal flows and the third term represents the vertical flow. The horizontal flows would be smaller than the vertical flows due to the fact that, the gradients of flow in horizontal direction are smaller than the gradients of flow in vertical direction. Absence of gravity head in horizontal plane makes the flow gradient in horizontal direction to be smaller than the flow gradient in vertical direction. Therefore, dropping the first two terms on the right hand side, the equation can be simplified as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial \left[K \frac{\partial(-h+z)}{\partial z} \right]}{\partial z} - S \qquad 3.7$$

Assuming that, 'S' consists of only actual evapo - transpiration, the equation takes the following form

$$\frac{\partial \theta}{\partial t} = \frac{\partial \left[K \frac{\partial(-h+z)}{\partial z} \right]}{\partial z} - E \qquad 3.8$$

where

E : Actual evapotranspiration rate per unit volume of soil $[T^{-1}]$.

Further, assuming that the flow is nonhysteritic (refer Chap.2 pp. 16), terms specific moisture capacity and moisture diffusivity can be defined as follows:

$$C = \frac{d\theta}{dh} \qquad 3.9a$$

$$D = K\,\frac{dh}{d\theta} \qquad 3.9b$$

where

$C(h,z)$: Specific moisture capacity $[L^{-1}]$

$D(\theta,z)$: Moisture diffusivity $[L^{2}T^{-1}]$

Using equation (3.9) the equation (3.7) can be written as follows:

$$C\,\frac{\partial h}{\partial t} = \frac{\partial\left[K\,\frac{\partial}{\partial z}(-h+z)\right]}{\partial z} - E \qquad 3.10a$$

$$\frac{\partial\theta}{\partial t} = \frac{\partial\left(-D\,\frac{\partial\theta}{\partial z} + K\right)}{\partial z} - E \qquad 3.10b$$

Letting $F = K\,\frac{\partial(-h+z)}{\partial z}$ and $F' = -D\,\frac{\partial\theta}{\partial z} + K$ the equation may be rewritten as

$$C\,\frac{\partial h}{\partial t} = \frac{\partial F}{\partial z} - E \qquad 3.11a$$

$$\frac{\partial\theta}{\partial t} = \frac{\partial F'}{\partial z} - E \qquad 3.11b$$

where,

F' and F: Flow rate per unit horizontal area in downward direction $[LT^{-1}]$.

In the light of discussion made in Chapter 2 pp 19-23, the rate of actual evapotranspiration 'E' is a function of z, θ and t.

Equation 3.11 is a second order nonlinear parabolic partial differential equation. Initial, boundary conditions and the rate of evapotranspiration will be required for solving the equation.

CHAPTER IV

MODEL DEVELOPMENT

4.1 PROBLEM IDENTIFICATION

The present study is aimed at developing a mathematical model for simulation of one dimensional (vertical) unsteady state flow of moisture through unsaturated zone (extending from ground surface upto water table) involving evapotranspiration. Objective of the simulation is to compute response of the unsaturated zone to a known excitation (Fig. 4.1). Governing equation of the model is:

$$C \frac{\partial h}{\partial t} = \frac{\partial F}{\partial z} - E \qquad 4.1$$

4.1.1 Statement of the problem

Given the following data -

i. The time domain in which the simulation is to be carried out.

ii. The initial condition ie., depth distribution of h(or θ) at zero time of simulation.

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* Refer pp 46-49 for definition of symbols.

$$C = \frac{d\theta}{dh} \qquad 3.9a$$

$$D = K\,\frac{dh}{d\theta} \qquad 3.9b$$

where

$C(h,z)$: Specific moisture capacity $[L^{-1}]$

$D(\theta,z)$: Moisture diffusivity $[L^2T^{-1}]$

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$$C\,\frac{\partial h}{\partial t} = \frac{\partial\left[K\,\frac{\partial}{\partial z}(-h+z)\right]}{\partial z} - E \qquad 3.10a$$

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$$C\,\frac{\partial h}{\partial t} = \frac{\partial F}{\partial z} - E \qquad 3.11a$$

$$\frac{\partial\theta}{\partial t} = \frac{\partial F'}{\partial z} - E \qquad 3.11b$$

where,

F' and F: Flow rate per unit horizontal area in downward direction $[LT^{-1}]$.

In the light of discussion made in Chapter 2 pp 19-25, the rate of actual evapotranspiration 'E' is a function of z, θ and t.

Equation 3.11 is a second order nonlinear parabolic partial differential equation. Initial, boundary conditions and the rate of evapotranspiration will be required for solving the equation.

Equations 3.11a and 3.11b are known as head form and moisture content form, of the Richards equation, respectively. However, the equations are not completely equivalent. Equation (3.11a) may still be applicable for h zero or negative (saturation and ponding), where as equation (3.11b) can not. Thus, the ponded water condition can be implemented by equation 3.11a only. Moreover, in equation 3.11b the first term on right hand side involves differentiation on θ. Numerical methods may introduce large errors when θ in z direction varies marginally. On the other hand, in the equation 3.11a the differentiation is on (-h+z) and even for marginal variation in θ(in z direction), the variation in (-h+z) may be significant. This will help in reducing numerical differentiation errors.

3.2 PRESENT STUDY

The present study is mainly aimed at developing a distributed model, for estimating the hydrological response of the unsaturated zone by solving equation 3.11a.

3.2.1 Basic Data for the Study

The model has been verified with the depth and time distribution of moisture content given by a quasi analytical solution. Annexture I-a shows the moisture profiles given by the analytical solution. Further, a field experimentation programme has been taken up to observe depth and time distribution of gravimetric moisture content on 9 days, in the rainy season months - Sep and Oct of 1985 (Annex I-b), in the open lawn of the department. Annexure I-C and I-D show the observed contineous rainfall record, twice daily class A pan evaporation and daily depth to water table data for the above period. Annexures I-e shows the litholog of the site. The model simulated moisture profiles were verified with this field evidence. Subsequently, the model has been operated to schedule irrigation and to estimate the associated return flows under three different vegetal covers (crops) and two soil textures. Annexure I-f shows the daily rainfall, monthly potential evapotranspiration of reference crop and monthly depth to water table. Annexure I-g shows fortnightly root zone depth of the three crops.

CHAPTER IV

MODEL DEVELOPMENT

4.1 PROBLEM IDENTIFICATION

The present study is aimed at developing a mathematical model for simulation of one dimensional (vertical) unsteady state flow of moisture through unsaturated zone (extending from ground surface upto water table) involving evapotranspiration. Objective of the simulation is to compute response of the unsaturated zone to a known excitation (Fig. 4.1). Governing equation of the model is:

$$C \frac{\partial h}{\partial t} = \frac{\partial F}{\partial z} - E \qquad 4.1$$

4.1.1 Statement of the problem

Given the following data -

i. The time domain in which the simulation is to be carried out.

ii. The initial condition ie., depth distribution of h(or θ) at zero time of simulation.

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* Refer pp 46-49 for definition of symbols.

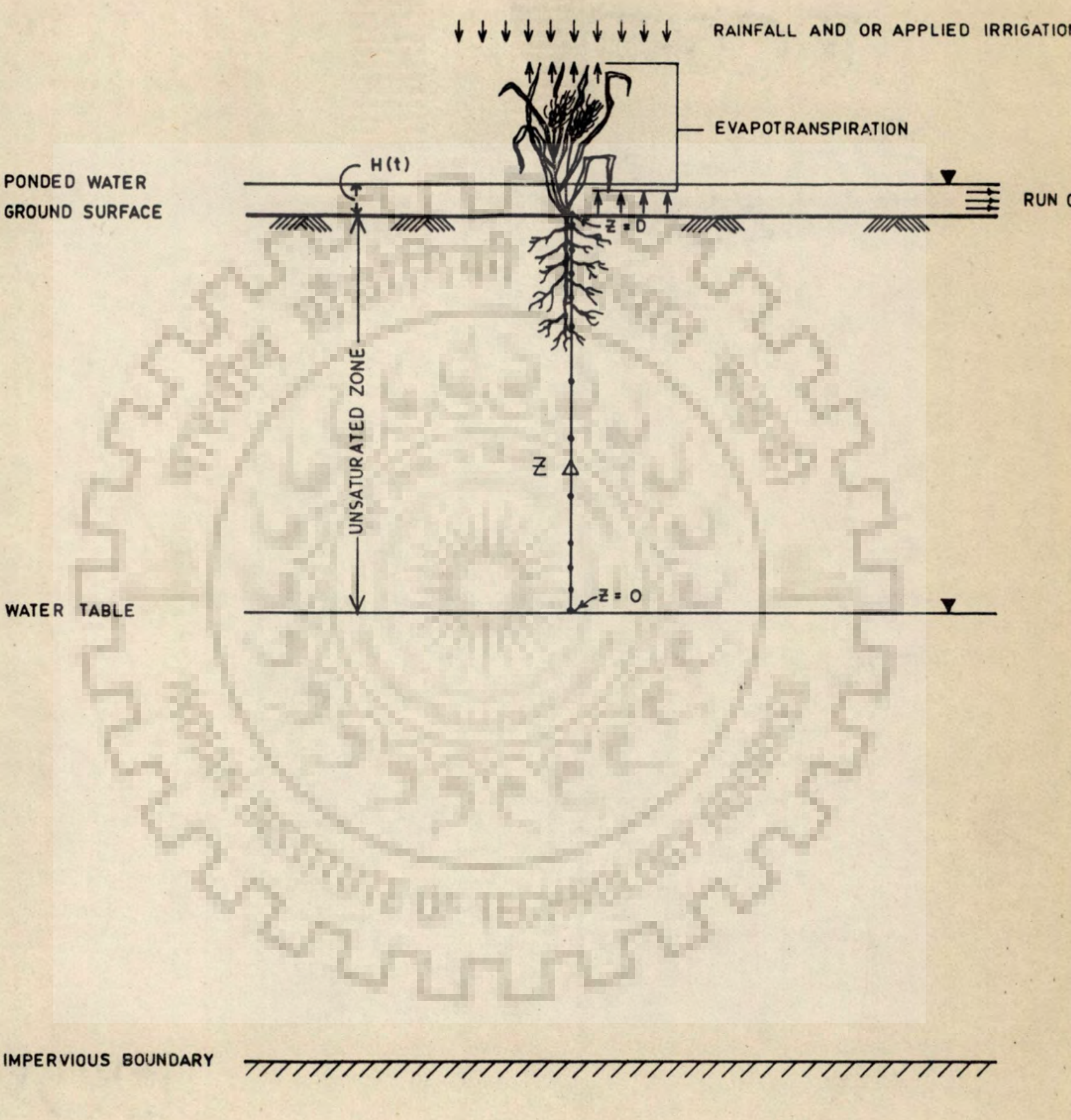

FIG. 4·1.a.- DEFINITION DIAGRAM OF UNSATURATED ZONE

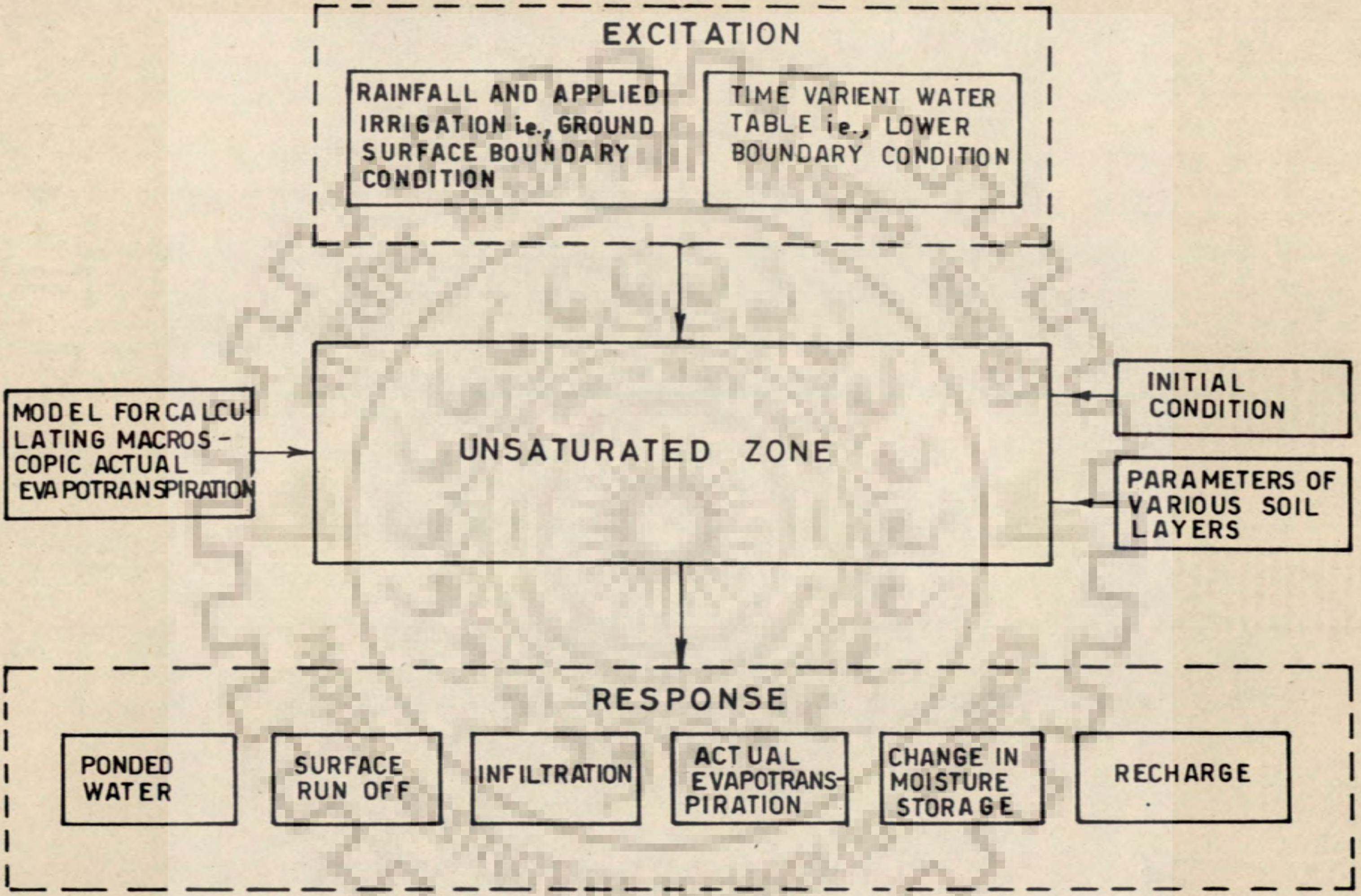

FIG. 4.1b–HYDROLOGICAL RESPONSE OF UNSATURATED ZONE UPTO WATERTABLE

iii. Variation of the following data in the entire simulation time period.

   a. Input at the ground surface ie., Rainfall and applied irrigation, adjusted for losses on surface.

   b. Depth to water table

   c. Depth of root zone

   d. Potential evapotranspiration due to vegetation.

iv. $K - \theta$ or $K-h$ relation

v. $h - \theta$ relation or the following soil parameters to define the relation

   θ_r : residual moisture content

   h_b : air entry value (bubbling pressure) [L]

   ϕ : porosity

vi. A submodel to evaluate actual evapotranspiration rate.

Compute the following (objectives):

   i. h/θ distribution in depth and time

   ii. Time distribution of recharge at the water table.

   iii. Time distribution of actual evapotranspiration

   iv. Time distribution of infiltration and ponded water depth.

4.2 FINITE DIFFERENCE SOLUTION

There is no analytical solution available for equation (4.1) to satisfy the requirements of present problem. Few reported analytical solutions (Philip 1969, Babu 1976, Parlange 1982, Morel Seytoux 1978) are restrictive in scope of application. Therefore, in the present work, the equation is solved numerically by finite difference method.

4.2.1 Formulation

The following convention is followed for the finite difference scheme.

i. The depth interval between ith and (i+1)th node is designated by Δz_i and will be referred to either as Δz_i or ith interval. The soil between ith and (i+1)th depth node will be referred to as ith link.

ii. The time step between jth and (j+1)th level of simulation is designated by Δt_j and will be referred to either as Δt_j or jth time step.

iii. The capillary conductivity of the ith link, at simulation level j, is designated as $K_{i,j}$ and will be referred to as $K_{i,j}$. The $K_{i,j}$ is evaluated using the 'K characteristic' and the average moisture content in the ith link at jth level.

Fig. 4.2 shows the convention diagramatically.

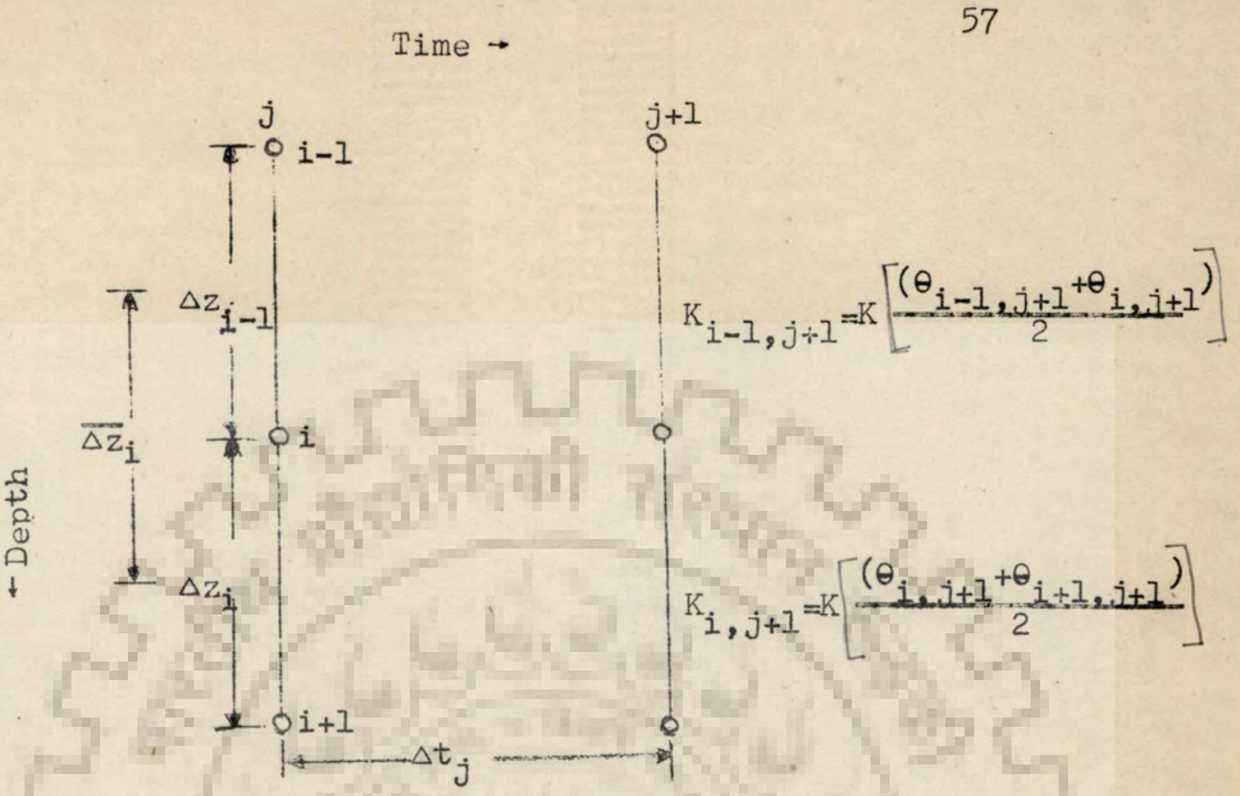

Fig. 4.2 DEFINITION DIAGRAM OF THE FINITE DIFFERENCE SCHEME.

The equation (4.1), written in finite difference form for an internal ith node will be as follows:

$$\bar{C}_{i,j}\, D_{t_{i,j}} = \frac{\Delta\bar{F}_{i,j}}{\overline{\Delta Z}_i} - \bar{E}_{i,j} \tag{4.2a}$$

where,

$$\Delta\bar{F}_{i,j} = \bar{F}_{i-1,j} - \bar{F}_{i,j}$$

$\bar{F}_{i-1,j}$: Representative flow rate, from (i-1)th node to ith node, during Δt_j.

$\bar{F}_{i,j}$: Representative flow rate, from ith node to (i+1)th node, during Δt_j.

$$\overline{\Delta z}_i = \frac{\Delta z_{i-1} + \Delta z_i}{2}$$

$\bar{E}_{i,j}$: Representative E at ith node during Δt_j.

$$D_{t_{i,j}} = \frac{h_{i,j+1} - h_{i,j}}{\Delta t_j}$$

$\bar{C}_{i,j}$: Representative C at the ith node in Δt_j.

Equation 4.2a written for all interior nodes (ie., 2 to n-1) will lead to (n-2) number of equations. One equation can be written for node number 1 (ie., ground surface) from the known boundary condition (henceforth, called as upper boundary condition). The equation will be:

Dirichlet condition:

$$h_{1,j+1} = H_{j+1} \qquad 4.2b$$

where,

H_{j+1} : known capillary suction head at ground surface.

Neuman condition,

$$\bar{C}_{1,j} \cdot D_{t_{i,j}} = \frac{\Delta\bar{F}_{1,j}}{\Delta\bar{z}_1} - \bar{E}_{1,j} \qquad 4.2c$$

where,

$\Delta\bar{F}_{1,j} = Q_j - \bar{F}_{1,j}$

Q_j = constant input intensity during Δt_j

$\bar{E}_{1,j}$: Representative E at node-1 during Δt_j

$\Delta\bar{z}_1 = \frac{\Delta z_1}{2}$

Another equation can be written from the known lower boundary condition (water table , which is Dirichlet type always).

$$h_{n,j+1} = 0 \qquad 4.2d$$

Thus, there will be 'n' number of equations for the 'n' number of nodes, which make the system of equations determinate.

4.2.2 Crank - Nicolson Scheme

In the explicit scheme, $\bar{F}$s, $\bar{C}$ and $\bar{E}$(in equation 4.2) are evaluated at jth level of simulation, where as, in implicit scheme these are evaluated at (j+1)th level of simulation. In the Crank-Nicolson scheme, $\bar{F}$s are adopted as the arithematical mean of flow rates evaluated at jth and (j+1)th level of simulation, $\bar{C}$ and $\bar{E}$ are adopted as the values computed using the arthematical mean of capillary suction head at jth and (j+1)th level of simulation. Thus, the representative values take the following form:

$$\bar{F}_{i-1,j} = \frac{1}{2}\left[K_{i-1,j}\frac{(h_{i,j}-h_{i-1,j}+\Delta z_{i-1})}{\Delta z_{i-1}} + K_{i-1,j+1}\frac{(h_{i,j+1}-h_{i-1,j+1}+\Delta z_{i-1})}{\Delta z_{i-1}}\right] \qquad 4.3a$$

$$\bar{F}_{i,j} = \frac{1}{2}\left[K_{i,j}\frac{(h_{i+1,j}-h_{i,j}+\Delta z_{i})}{\Delta z_{i}} + K_{i,j+1}\frac{(h_{i+1,j+1}-h_{i,j+1}+\Delta z_{i})}{\Delta z_{i}}\right] \qquad 4.3b$$

$$\bar{C}_{i,j} = \frac{d\theta}{dh}\bigg|_{h = \frac{h_{i,j}+h_{i,j+1}}{2}} \qquad 4.3c$$

$$\bar{\bar{E}}_{i,j} = E\left(\frac{\theta_{i,j} + \theta_{i,j+1}}{2}\right)^{1} \qquad 4.3d$$

Equation 4.2, with the representative values defined as per equation 4.3, results in a system of 'n' nonlinear simutaneous equations. Solution of the nonlinear system of equations will yield $h_{i,j+1}$ for i varying from 1 to n. This scheme is stable and convergent unconditionally. The arthematic mean values will be more representative than either as per jth level or (j+1)th level (explicit and implicit scheme respectively). Jeppson, after conducting a number of numerical studies, observed that the Crank-Nicolson scheme is relatively more efficient (Krishna Murthy et al 1978). So in the present study the Crank-Nicolson scheme is used.

4.2.3 Solution of the nonlinear system of equations

Solution of the system of nonlinear simultaneous equations require the hint solution. Further, the system of nonlinear simultaneous equations will have more than one solution. The algorithms available are mostly problem dependent and iterative. So, two questions arise i) whether the iterative scheme converges ii) if converges what is the rate of convergence. Though answers for the above two questions are positive,

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[1] For brevity $E(\theta(h), z, t)$ will be written as $E(\theta)$.

since, there will be more than one solution to the system, the hint solution may lead the iterative scheme to converge to an undesired solution. Thus, specification of hint solution itself will be difficult, particularly in a problem like that is being dealt in the present work. On the other hand, the algorithms for solution of system of linear simultaneous equations are mostly problem independent and require no hint solution. Moreover, solution of the system will be unique. Many of the algorithms for solution of system of linear simultaneous equations are well tested. Thus, it is desirable to linearize the system.

Fortunately, the terms causing non-linearity namely $K, \bar{C}$ and $\bar{E}$ are appearing seperately (in the equation 4.3). So the system can be linearized in the following two ways.

4.2.3.1 Explicit linearization : In this method, the terms causing nonlinearity namely $K, \bar{C}$ and $\bar{E}$ are evaluated as per the known values of h(or θ) at the jth level. Thus, the representative values (equation 4.3) to be used (in equation 4.2) will be as follows:

$$\bar{F}_{i-1,j} = \frac{1}{2} \left[K_{i-1,j} \frac{(h_{i,j} - h_{i-1,j} + \Delta z_{i-1})}{\Delta z_{i-1}} + K_{i-1,j} \frac{(h_{i,j+1} - h_{i-1,j+1} + \Delta z_{i-1})}{\Delta z_{i-1}} \right] \quad 4.4a$$

$$\bar{F}_{i,j} = \frac{1}{2} \left[K_{i,j} \frac{(h_{i+1,j} - h_{i,j} + \Delta z_{i})}{\Delta z_{i}} + K_{i,j} \frac{(h_{i+1,j+1} - h_{i,j+1} + \Delta z_{i})}{\Delta z_{i}} \right] \quad 4.4b$$

$$\bar{C}_{i,j} = \frac{d\theta}{dh}\Big|_{h=h_{i,j}} \qquad 4.4c$$

$$\bar{E}_{i,j} = E(\theta_{i,j}) \qquad 4.4d$$

The resulting system of equations given by equation (4.2), with representative values defined by equation (4.4), will be linear. An examination of the finite difference equation for ith node, will reveal that the system has a tridiagonal coefficient matrix as follows:

Interior node

$$A_i\, h_{i-1,j+1} + B_i h_{i,j+1} + C_i h_{i+1,j+1} = D_i \qquad 4.5a$$

Lower boundary node

$$0.0 h_{n-1,j+1} + 1.0 h_{n,j+1} = 0.0$$

Upper boundary node

Dirichlet type

$$1.0 h_{1,j+1} + 0.0\, h_{2,j+1} = H_{j+1} \qquad 4.5c$$

Neuman type

$$B_1 h_{1,j+1} + C_1 h_{2,j+1} = D_1 \qquad 4.5d$$

The tridiagonal system can be solved by Thomas algorithm (Remson et al 1971). The algorithm is extremely stable with respect to round off errors as per Douglas (Remson et al 1971) and the computer memory requirement is reduced to (3n) from (n^2+2n).

4.2.3.2 Picard iteration method (Remson et al 1971): In this method of implicit linearization, a hint solution is specified. Let the hint solution be $[h]^{(0)}$. Let the values of $[K]$, $[\overline{C}]$ and $[\bar{\bar{E}}]$(in equation 4.3) evaluated using $[h]^{(0)}$ be $[K]^{(0)}$, $[\overline{C}]^{(0)}$ and $[E]^{(0)}$. Then, the representative values (equation 4.3) to be used (in equation 4.2) will result in a system of linear simultaneous equations. The coefficient matrix of the system will be tridiagonal. The tridiagonal system can be solved as mentioned in the preceeding paragraph. Solution of the linear system will yield $[h]^{(1)}$. Once $[h]^{(1)}$ is obtained $[K]^{(1)}$ $[\overline{C}]^{(1)}$ and $[E]^{(1)}$ can be determined using $[h]^{(1)}$. Subsequently, $[h]^{(2)}$ can be obtained on the same lines of obtaining $[h]^{(1)}$. Thus, general form of representative values in the $(\ell+1)$st iteration will be as follows.

$$\bar{\bar{F}}_{i-1,j} = \frac{1}{2}\Big[K_{i-1,j} \frac{(h_{i,j} - h_{i-1,j} + \Delta z_{i-1})}{\Delta z_{i-1}} + K^{(\ell)}_{i-1,j+1} \frac{(h^{(\ell+1)}_{i,j+1} - h^{(\ell+1)}_{i-1,j+1} + \Delta z_{i-1})}{\Delta z_{i-1}}\Big] \qquad 4.6a$$

$$F_{i,j} = \frac{1}{2}\Big[K_{i,j} \frac{(h_{i+1,j} - h_{i,j} + \Delta z_i)}{\Delta z_i} + K^{(\ell)}_{i,j+1} \frac{(h^{(\ell+1)}_{i+1,j+1} - h^{(\ell+1)}_{i,j+1} + \Delta z_i)}{\Delta z_i}\Big] \qquad 4.6b$$

$$\bar{C}_{i,j} = \frac{d\theta}{dh}\Big|_{h = \frac{h_{i,j}+h^{(\ell)}_{i,j+1}}{2}} \qquad 4.6c$$

$$\bar{E}_{i,j} = E\left[\frac{\theta(h_{i,j})+\theta(h^{(\ell)}_{i,j+1})}{2}\right] \qquad 4.6d$$

As the iteration index ℓ approaches infinity, the [h] is expected to converge to the true solution of the system of nonlinear simultaneous equations. However, a large number of iterations mean more CPU time. So the iterations can be stopped, if the following check is satisfied.

$$\max_{i=1 \text{ to } n-1} \left| h^{(\ell+1)}_{i,j+1} - h^{(\ell)}_{i,j+1} \right| \leq \varepsilon_o \qquad 4.7$$

where,

ε_o : Prescribed tolerable error (small positive value)

In the present model, the explicit linearization is adaopted. The solution obtained (by explicit linearization) will be verified by the solution obtained by picard iteration method, using the solution obtained by explicit linearization for the hint solution $[h]^{(o)}$, at specified time intervals.

4.3 BOUNDARY CONDITIONS

Operation of the model described in the preceeding paragraphs requires a complete knowledge of the boundary conditions (ie., the type along with necessary relevant value). In a real life problem, the upper boundary condition switches from Dirichlet type to Neuman type and Viceversa. In one condition itself the relevant values (infiltration or ponding) may vary on account of the variation in excitation and response of the unsaturated zone, in time domain. So, except under controlled conditions, the boundary condition (along with the relevant value) can not be specified before hand. Similarly, the time varient position of the lower boundary causes the 'n' in the equation 4.2 (ie., depth of flow domain) to be a function of time.

In the present work algorithms have been developed, to identify the type (Dirichlet or Neuman), to assign the relevant value (Ponded water depth or infiltration), for the upper boundary and to account for the variable lower boundary position. The algorithms are described in the following paragraphs.

4.3.1 Upper boundary

In case of a pure infiltration and redistribution problem (No abstractions and accertions) in a deep homogeneous soil medium (ie., water table at infinite depth), most of the text book infiltration curves are as shown in Figure 4.3.

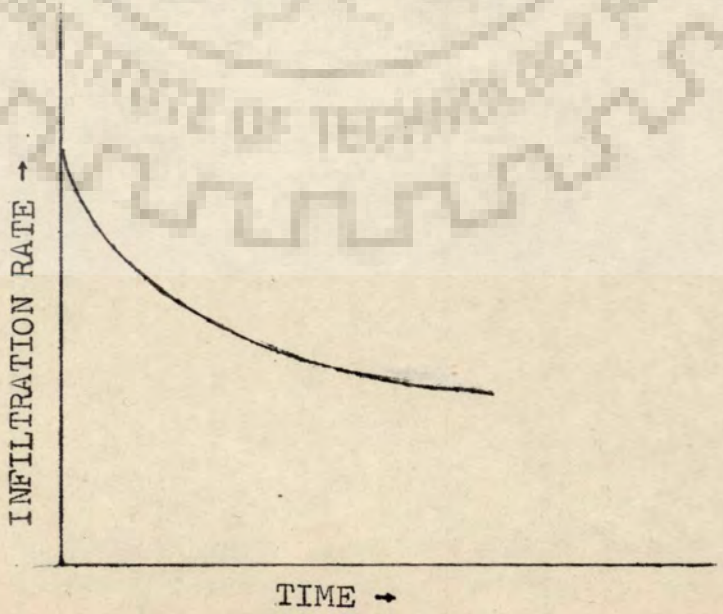

FIG 4.3 TYPICAL TEXT BOOK INFILTRATION CURVE

The curve shows that ponding (or saturation) occurs instantaneously. This situation may be realistic, for instance, incase of input like flood irrigation. In case of input like rainfall, there always occur a period (howso-ever small) in which the entire input infilters (if the ground surface is not already saturated). The occurence of ponding (or saturation) depends on input intensity (Q), infiltration capacity rate (Ic) and saturated capillary conductivity (K_s) of the soil medium. Assuming Q to be constant for sufficiently longer period, there will be three general cases of infiltration.

i. $Q < K_s$: In this case no ponding can occur and the entire input infilters (curve 1 of Fig. 4.4).

ii. $K_s < Q < I_c$: In this case just saturation occurs. The time to saturation will be different for different intensities of input.(Horizontal portion of curve 2 Fig. 4.4).

iii. $Q > I_c$: In this case saturation and even ponding occurs at some time (Decreasing portion of the curve 2 Fig. 4.4).

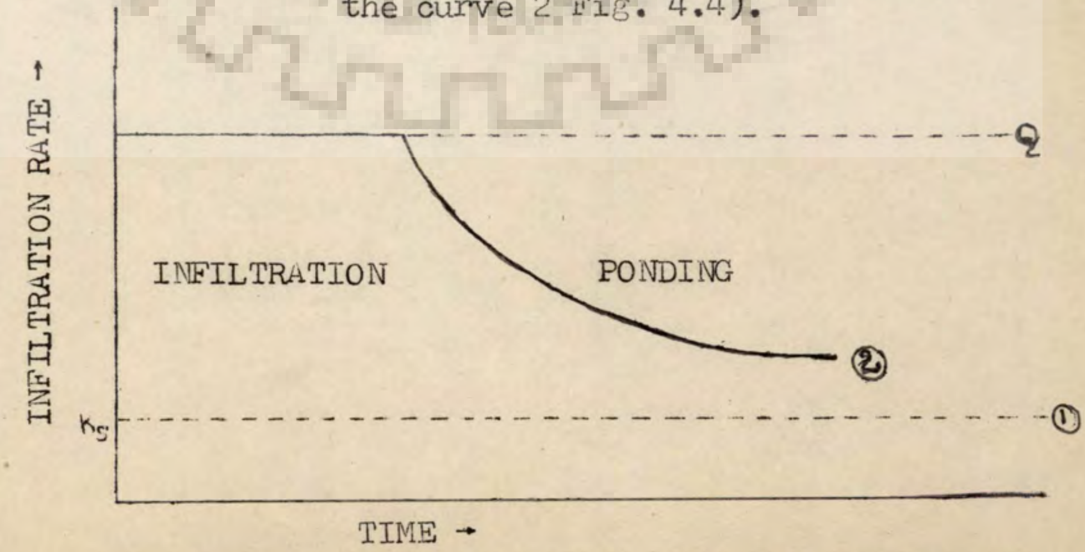

FIG. 4.4 INFILTRATION CURVES FOR DIFFERENT INPUT INTENSITIES AND SOIL HYDRAULIC SITUATIONS.

In the above situation simple algebric formule, like that of Mein-Larson formule (Mein-Larson 1971), may be used to calculate pre saturation infiltration, time to saturation and post saturation infiltration. However, in reality the problem is not that straight as the soil medium is often heterogeneious, the water table is not very deep, the evapotranspiration is present and the input intensity Q varies in time domain.

4.3.1.1 Algorithm : The infiltration part of the input, in the jth time period, would build up soil moisture in the surface layer (node 1) and contribute to the flow of water from node 1 to node 2. The algorithm is based on the principle of suppose and correct. The stepwise operation is as follows.

Step A- Simulation in the time till saturation: If the $h_{1,j}$ is positive (or zero in a special case: refer step B), for the simulation at (j+1)th level, it is supposed that, the entire input infilters. The simulation is carried out under Neuman type of boundary condition. If the supposition is correct, the $h_{1,j+1}$ will be either positive or zero. If $h_{1,j+1}$ turns out to be negative, (Ponding) the supposition is incorrect. So the Δt_j, is successively reduced (to Δts_j), till the $h_{1,j+1}$ turns out to be zero (and the supposition becomes correct). The time $(\sum_{p=1}^{j-1} \Delta t_p + \Delta ts_j)$ with $\Delta ts_j \leq \Delta t_j$ is the time to surface saturation. If $h_{1,j+1}$ (with $\Delta t_j = \Delta t_j$) is positive, the step A itself repeated for subsequent simulation (in Δt_{j+1}).

If $h_{1,j+1}$ is zero (with $\Delta t_j = \Delta t_j$ or $\Delta t_j = \Delta ts_j$), subsequent simulation is carried out as per step B. The case of Δt_{sj} being very nearer to zero may occur, when $h_{1,j}$ is very nearer to zero. In such a case, after confirming that Δt_{sj} is very small, the simulation for Δt_j is done as per step B by considering $h_{1,j}$ to be zero.

B. Simulation in the time between two successive pairs of saturation and desaturation : If $h_{1,j}$ is zero or negative, it is supposed that the input can sustain the ponding or at least saturation (of the ground surface layer). Thus, the simulation is carried out under Dirichlet type of boundary condition by modifying $h_{1,j+1}$ iteratively. Let the hint value of $h_{1,j+1}$ be $h^{(o)}_{1,j+1}$. The simulation is carried out and $h^{(1)}_{1,j+1}$ is generated by performing the mass balance of ponded water in Δt_j as follows.

$$h^{(1)}_{1,j+1} = h_{1,j} - I_j + F^{(o)}_j + [S_r(h_{1,j}) + S_r(h^{(o)}_{1,j+1})] \times \frac{\Delta t_j}{2}$$

(∵ ponded water means h_1 is -ve) 4.8

Using the $h^{(1)}_{1,j+1}$, $h^{(2)}_{1,j+1}$ can be generated by repeating the simulation in Δt_j and using the equation 4.8. Thus, the general form of equation (for generating $h_{1,j+1}$) can be written as follows:

$$h^{(\ell+1)}_{1,j+1} = h_{1,j} - I_j + F^{(\ell)}_j + [S_r(h_{1,j}) + S_r(h^{(\ell)}_{1,j+1})] \frac{\Delta t_j}{2} \qquad 4.9$$

where,

I_j : Input (rainfall + applied irrigation) in the jth time step = $Q_j \cdot \Delta t_j$

$F^{(\ell)}_j$: Infiltration depth in the jth time step using $h^{(\ell)}_{1,j+1}$, $K^{(\ell)}_{1,j+1}$ and the corresponding simulated $h^{(\ell)}_{2,j+1}$ (with $h^{(\ell)}_{1,j+1}$ as the boundary condition).

$$F^{(\ell)}_j = T^{(\ell)}_j + \bar{E}^{(\ell)}_{1,j} \cdot \Delta\bar{z}_1 \cdot \Delta t_j + \Delta\theta^{(\ell)}_{1,j} \cdot \Delta\bar{z}_1$$

$T^{(\ell)}_j$: Flow from node 1 to node 2 in Δt_j.

$$= \frac{\Delta t_j}{2}\left[K_{1,j} \frac{(-h_{1,j} + h_{2,j} + \Delta z_1)}{\Delta z_1} + K^{(\ell)}_{1,j+1} \frac{(-h^{(\ell)}_{1,j+1} + h^{(\ell)}_{2,j+1} + \Delta z_1)}{\Delta z_1}\right]$$

$\bar{E}^{(\ell)}_{1,j}$: Representative evapotranspiration at node 1 during Δt_j (using $\theta(h^{(\ell)}_{1,j+1})$)

$\Delta\theta^{(\ell)}_{1,j}$: Change in the moisture content at node 1=0 ($\because$ the moisture content is already equal to ϕ).

$S_r(h)^{*}$: Surface run off intensity as a function of ponded waterdepth.

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* The algorithm has been tested only for $S_r(h)=0$ ie., no surface runoff (overland flow). However, it can easily be extended to account for over land flow as well, by appropriate $S_r(h)$ relation.

The iterative scheme is initiated by prescribing $h_{1,j}$ for $h^{(o)}_{1,j+1}$. The iterations are stopped, if the following check is satisfied.

$$|h^{(\ell+1)}_{1,j+1} - h^{(\ell)}_{1,j+1}| \leq \varepsilon_d \qquad 4.10$$

where,

ε_d : prescribed tolerable error.(small positive value)

In any iteration if $h_{1,j+1}$ becomes positive, it means that the surface has got desaturated somewhere in Δt_j. In this case, the Δt_j is succesively reduced (to Δtd_j) till $h_{1,j+1}$ is zero in the aforesaid iterative scheme. The time $\sum_{p=1}^{j-1} (\Delta t_p) + \Delta td_j$ is the time to desaturation, in the corresponding pair of saturation desaturation. If such a desaturation is found, the simulation for subsequent time step is done according to the step A. Else, the simulation for subsequent time step is done according to the present step (i.e., step B). The case of Δtd_j being very nearer to zero, may occur when the ponding depth at jth level is very small (even zero ie., saturation). In such a case, after confirming that Δtd_j is very small, the simulation in the Δt_j is carried out as per step A by considering $h_{1,j}$ equal to zero, and $\sum_{p=1}^{j-1} \Delta t_p$ will be the desaturation time, in the pair of saturation- desaturation times.

Thus, the simulation is carried out switching from step A to step B and vice versa (i.e., from Neuman type to Dirichlet type and vice versa) with properly identifying and assigning the boundary condition. Since $h_{1,1}$ is known (from the initial condition), using j=1, the logic of the algorithm can be initiated from the appropriate step (A or B). Subsequently, without any manual interference, the boundary condition is identified and assigned automatically.

4.3.2 Lower boundary

Equation 4.2 describes the lower boundary condition, at (j+1)th time level, in terms of h at the nth node. In case of time varient position of water table, the depth to water table will very and so the position of nth node will also vary. The continuous variation of depth to water table is accounted for in the model by a stepwise discretization. The discretization involves the assumption of a constant water table position during the jth time step, with the depth to water table being the instanteneous value at jth level. The resulting changes in the flow domain are incorporated as follows.

4.3.2.1 Algorithm : In the simulation for (j-1)th time step 'h' at n_{j-1} nodes at j, for a flow domain with a depth of D_{j-1} (Depth of water table) is generated. Since, the flow domain has a depth of D_j at jth level, for the simulation in jth time step, the distribution of h up to D_j is required. Thus there arise three cases.

i. $D_j=D_{j-1}$: In this case there, is no need to workout any thing and n_j will be equal to n_{j-1}.

ii. $D_j < D_{j-1}$: In this case, the flow domain is reduced. So, a total of $(n_{j-1}-n_j)$ number of nodes from bottom are ignored and h_{n_j} is prescribed as zero.

iii. $D_j > D_{j-1}$: In this case, the flow domain is enhanced. So, a total of (n_j-n_{j-1}) number of nodes are added and h at all these additional nodes is prescribed as zero (ie., $h_{p_j}=0$ for p varying from $n_{j-1}+1$ to n_j).

a. In case of $D_j > D_{j-1}$ the additional number of nodes along with the depth interval will be arrived at as follows:

Let

$$L = \frac{D_j - D_{j-1}}{\Delta z_{n-1_{j-1}}}^{*} \qquad 4.11$$

If L is not an integer number, then L is rounded to the nearest lower integer. Thus

$$R_d = D_j - D_{j-1} - L \cdot \Delta z_{n-1_{j-1}} \qquad 4.12$$

where,

R_d : the uncovered fall.

If R_d is equal to or more than half of $\Delta z_{n-1_{j-1}}$, then L is increased to (L+1) and

$$n_j = L + n_{j-1} \qquad 4.13$$

with $\Delta z_\ell = \Delta z_{n-1_{j-1}}$ for ℓ from n_{j-1} to $(n-2)_j$

and

$$\Delta z_{n-1_j} = R_d$$

---

* 1st subscript for depth node, 2nd subscript for simulation time level.

If R_d is less than, half of $\Delta z_{n-1_{j-1}}$ then L is unaltered. In this case,

$$n_j = L + n_{j-1} \tag{4.15}$$

with $\Delta z_\ell = \Delta z_{n-1_{j-1}}$ for ℓ from n_{j-1} to $(n-2)_j$

and $\Delta z_{n-1,j} = R_d + \Delta z_{n-1_{j-1}}$

In case L is an integer number

$$n_j = L+n_{j-1} \tag{4.17}$$

with $\Delta z_\ell = \Delta z_{n-1_{j-1}}$ for ℓ from n_{j-1} to $(n-1)_j$

b. If $D_j < D_{j-1}$ the number of nodes that are ignored and the last depth interval will be arrived at as follows:

$$L = \frac{D_{j-1}-D_j}{\Delta z_{n-1_{j-1}}} \tag{4.18}$$

If L is an integer number then

$$n_j = n_{j-1} - L$$

with $\Delta z_{n-1,j} = \Delta z_{(n_{j-1}-L-1)_{j-1}}$

If L is not an integer number, then L is rounded to the nearest lower integer number. Subsequently, the uncovered rise R_r is calculated as below.

$$R_r = D_{j-1} - D_j - L \cdot \Delta z_{n-1_{j-1}} \tag{4.20}$$

If R_d is equal to or more than half of $\Delta z_{n-1_{j-1}}$, then L is increased to L+1.

In this case

$$n_j = n_{j-1}-L \qquad 4.21$$

with $\Delta z_{n-1,j} = \Delta z(n_{j-1}-L-1)_{j-1} + R_r$

If R_r is less than half of $\Delta z_{n-1 \, j-1}$ then L is unaltered.

In this case

$$n_j = n_{j-1}-L \qquad 4.22$$

with

$$\Delta z_{n-1 \, j} = \Delta z(n_{j-1}-L-1)_{j-1} - R_r$$

4.4 PROCESSING OF SIMULATED [h]

The simulated $h_{i,j}$ matrix is processed to meet the objectives listed in 4.1.1, as follows:

i. Using the appropriate h characteristic the matrix $\theta_{i,j}$ can be determined.

ii. The instantaneous rates of recharge, evapotranspiration, infiltration and instantaneous ponded water depth can be arrived at as follows:

a. Recharge : By applying the Darcy law at the water table

$$R_j = K_{n-1,j} \left[\frac{\Delta z_{n-1} - h_{n-1,j}}{\Delta z_{n-1}} \right] \quad (\because h_{n,j} = 0)$$

4.23a

b. Infiltration : By applying the Darcy law at ground surface

$$IF_j = K_{1,j} \left[\frac{-h_{1,j}+h_{2,j}+\Delta z_1}{\Delta z_1} \right] + \bar{E}_{1,j} \cdot \overline{\Delta z_1} (\text{if } h_{1,j} \leq 0) \quad 4.23b$$

$$= Q_j \qquad \text{if } h_{1,j} > 0 \quad 4.23c$$

c. Evapotranspiration: summing up the instantaneous rates at all the nodes in the root zone.

$$E_j = \sum_{\ell=1}^{NRt_j} \bar{E}_{\ell,j} \cdot \overline{\Delta z_\ell} \quad 4.23d$$

where

NRt_j: The last node number of the root zone.

d. Ponded water depth:

$$D_{p_j} = -h_{1,j} \qquad \text{if } h_{1,j} \leq 0 \quad 4.23e$$

$$= 0 \qquad \text{if } h_{1,j} > 0$$

The instantaneous values will be numerically integrated, in time domain, to get the depths.

4.5 TIME STEP OF SIMULATION

Errors, due to discritization of time become critical when rapid variations in capillary suction head, caused by a sudden change in the input intensity occur. Among the several available methods, decreasing the size of the time step has been the prefered method in the present model. The adequacy of the size of the step for explicit linearization has been decided as follows:

Let

i. t_d be a time period in which input intensity is constant.

ii. ε_1 and ε_2 be the percentage errors in mass balance of ponding water and flow in the unsaturated zone respectively. Thus;

$$\varepsilon_1 = [(I-\hat{F}-\Delta h)/I] \times 100 \qquad 4.24a$$

$$\varepsilon_2 = [(\hat{F}-\Delta S-R-ET)/\hat{F}] \times 100 \qquad 4.24b$$

where,

I : Total input in t_d. [L]

$\hat{F}$: Total infiltration in t_d. [L]

Δh : Change in ponded depth of water (if any) in t_d [L]

ΔS : Change in moisture storage in t_d. [L]

R : Total Recharge at the water table in t_d. [L]

ET : Actual evapotranspiration in t_d. [L]

A time step, which can provide ε1 and ε2 in the prescribed limits, is adequate and so accepted as the time step of simulation.

4.5.1 Uniform Time Step

Trial numerical studies have been conducted using the model with five soil textures namely sand, loamy sand, loam, siltly clay loam and clay and input intensities (in the t_d) ranging from 6.944×10^{-4} mm/sec. to 5.555×10^{-3} mm/sec. The depth to water table in all the studies was considered to be 5m (which is the average value in the studies presented

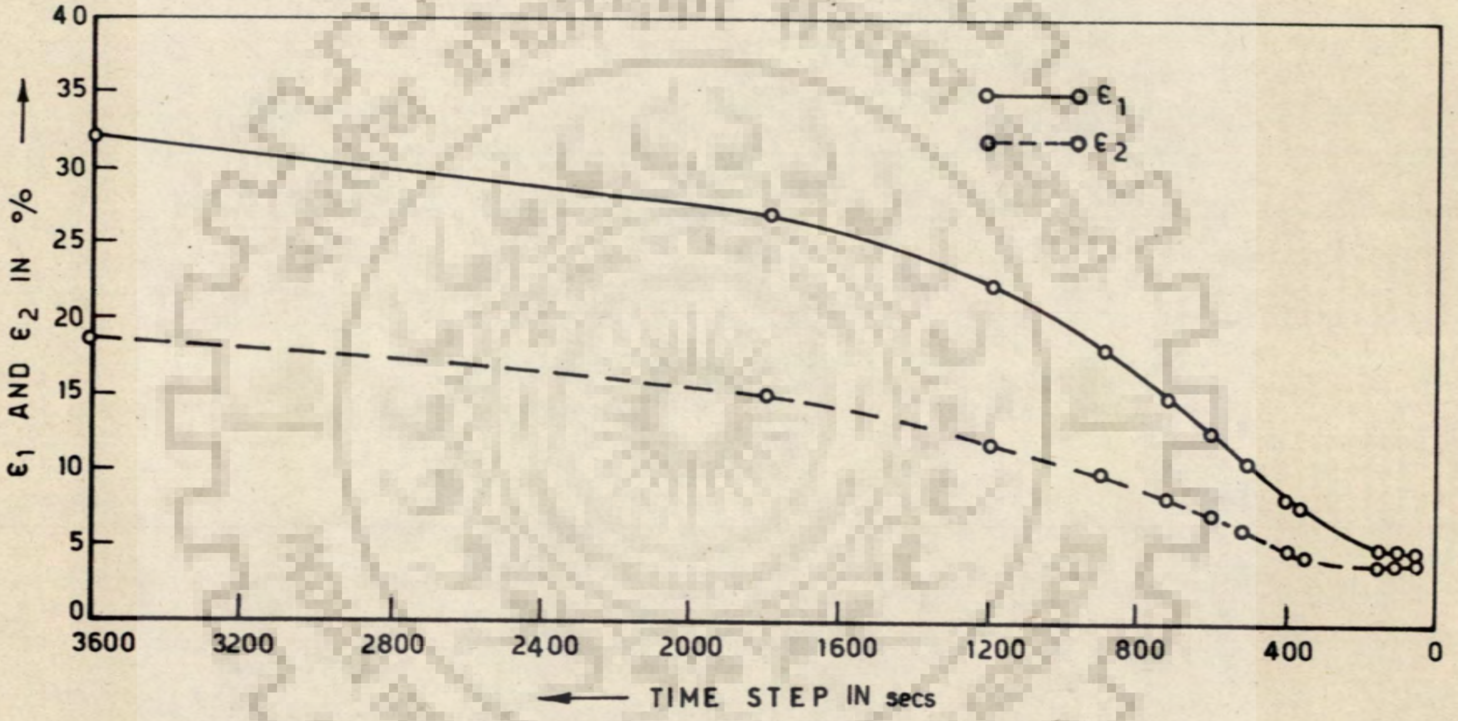

FIG. 4.5 _ UNIFORM TIME STEP OF SIMULATION: PLOTS OF ϵ_1 AND ϵ_2

The uniform time step (Δt_u) with which both ε1 and ε2 are limited to 5 percent, is accepted as the adequate time step.

4.5.2 Sequence of non uniform time steps

Although small time steps are needed for accuracy when [h] varies rapidly (with a sudden change in the input intensity), the small step becomes less and less important as the time goes on with the same intensity of input, since, the time variation in [h] will become milder. Thus, as rapid variation in [h] dissipates, it is desirable to attempt to use larger time steps, This can reduce the CPU time requirement also. However, there can be number of sequences of non uniform time steps which can provide ε1 and ε2 in the desired limits. So it requires number of trial numerical studies for selecting a feasible sequence. On the other hand, if equation(s) are designed to generate the sequence, the task will become easier.

Following empirical equations have been designed, to generate the sequence of nonuniform time steps in t_d

$$\Delta t_1 = \Delta t_u \qquad 4.27a$$

$$\Delta t_\ell = \sqrt{\Delta t_1 \cdot \sum_{p-1}^{\ell-1} \Delta t_p} \quad \text{for } \ell \geq 2 \qquad 4.27b$$

subject to

$$\text{If } \sum_{p=1}^{\ell} \Delta t_p > t_d \text{ then } \Delta t_\ell = t_d - \sum_{p=1}^{\ell-1} \Delta t_p \qquad 4.27c$$

where,

Δt_ℓ : ℓth time step in t_d

Δt_u : uniform time step generated in the excercise 4.5.1.

It is evident that, the time step generated by equation 4.27 would continue to increase unboundedly, if t_d is large and the input intensity in t_d remains constant. It may be desirable to limit this unbounded growth. This can be done by limiting the step to a t_{max}. It is suggested that the t_{max} could be the permissible uniform time step in Picard iteration method and can be evaluated on the same lines of determing the Δt_u in explicit linearization.

All the studies described in para have been redone using the sequence of nonuniform time steps given by equation 4.27. In these studies both $\varepsilon 1$ and $\varepsilon 2$ were in the range of 5 to 6 percent. Thus, it may be observed that, inspite of increasing the time step, there has been no substantial increase in $\varepsilon 1$ and $\varepsilon 2$. Fig. 4.6 shows the graphical implementation of equation 4.27 for a given Δt_1. It may be observed from the figure that the time step gradually increases as time passes.

4.5.2.1 Empirical formula for Δt_u: The computation of Δt_u may require considerable CPU time. So it is desirable to generate Δt_u by some empirical equation. Intutively the Δt_u would be relatively small for a relatively large input intensity and relatively coarser soil. The following empirical equation has been designed to evaluate Δt_u (For clarity $\Delta t_u'$ will be used).

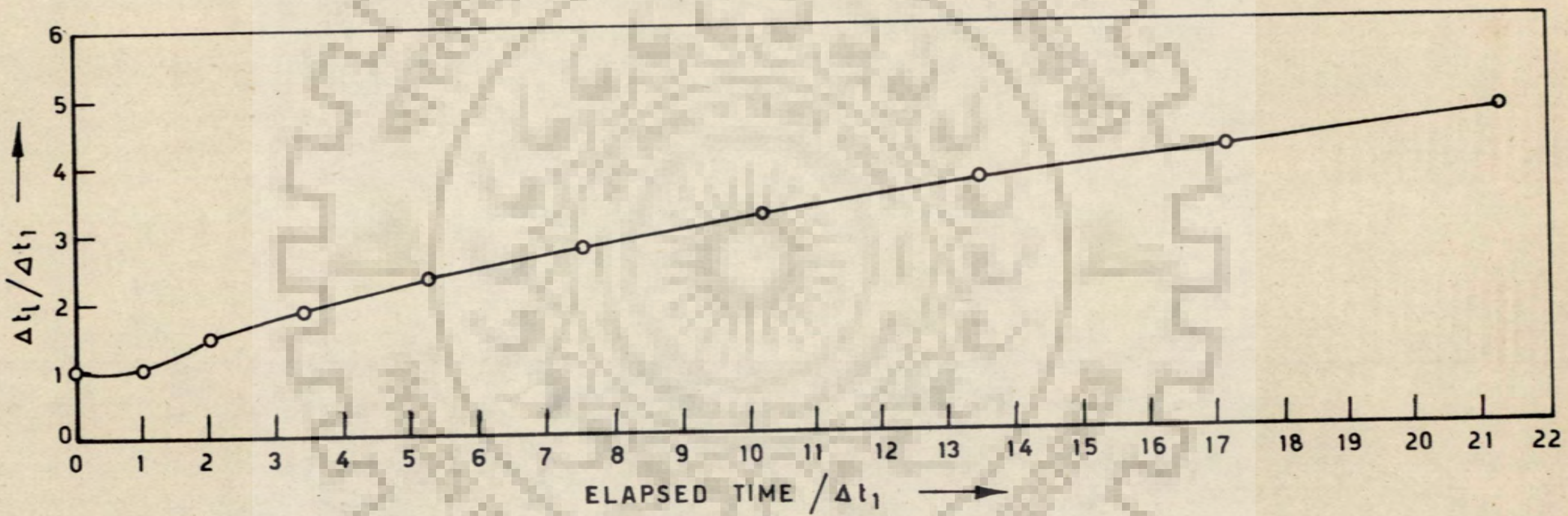

FIG. 4.6 _ GRAPHICAL IMPLEMENTATION OF EQUATION 4.27

$$\Delta t'_u = \frac{\theta_r \cdot t_{max}}{-0.059 \; \ln(Ks)} \cdot \frac{\ln(I)}{I} \qquad 4.28$$

where,

θ_r : Residual moisture content

K_s : Saturated capillary conductivity (< 1mm/sec)

I : Total input in t_d. (mm)

In the above equation if I is less than 2.5mm, a value of 2.5 is used.

Since, the soil properties used are time invarient the equation 4.28 can be rewritten as follows

$$\Delta t'_u = \varepsilon_1 \frac{\ln I}{I} \qquad 4.29$$

Fig. 4.7 shows the plot of $\Delta t'_u$ versus I. It may be observed from the figure that $\Delta t'_u$ decreases as I increases, which is the desired feature.

Fig. 4.8 shows the plots of $\Delta t'_u$ versus Δt_u in studies with clay and sand. The firm line passing through the origin with a slope of unity shows the ideal requirement (that $\Delta t'_u = \Delta t_u$). Results of the studies with other soil textures are similar.

Fig. 4.9 shows the plots of ε1 and ε2, in the studies with clay and sand, using the sequence of nonuniform time steps given by equation 4.27 with Δt_u and $\Delta t'_u$ for Δt_1. The results with other studies were similar.

Though Fig. 4.8 shows scattering of points around the ideal line, Fig. 4.9 shows a satisfactory result with clustering of points around the ideal line.

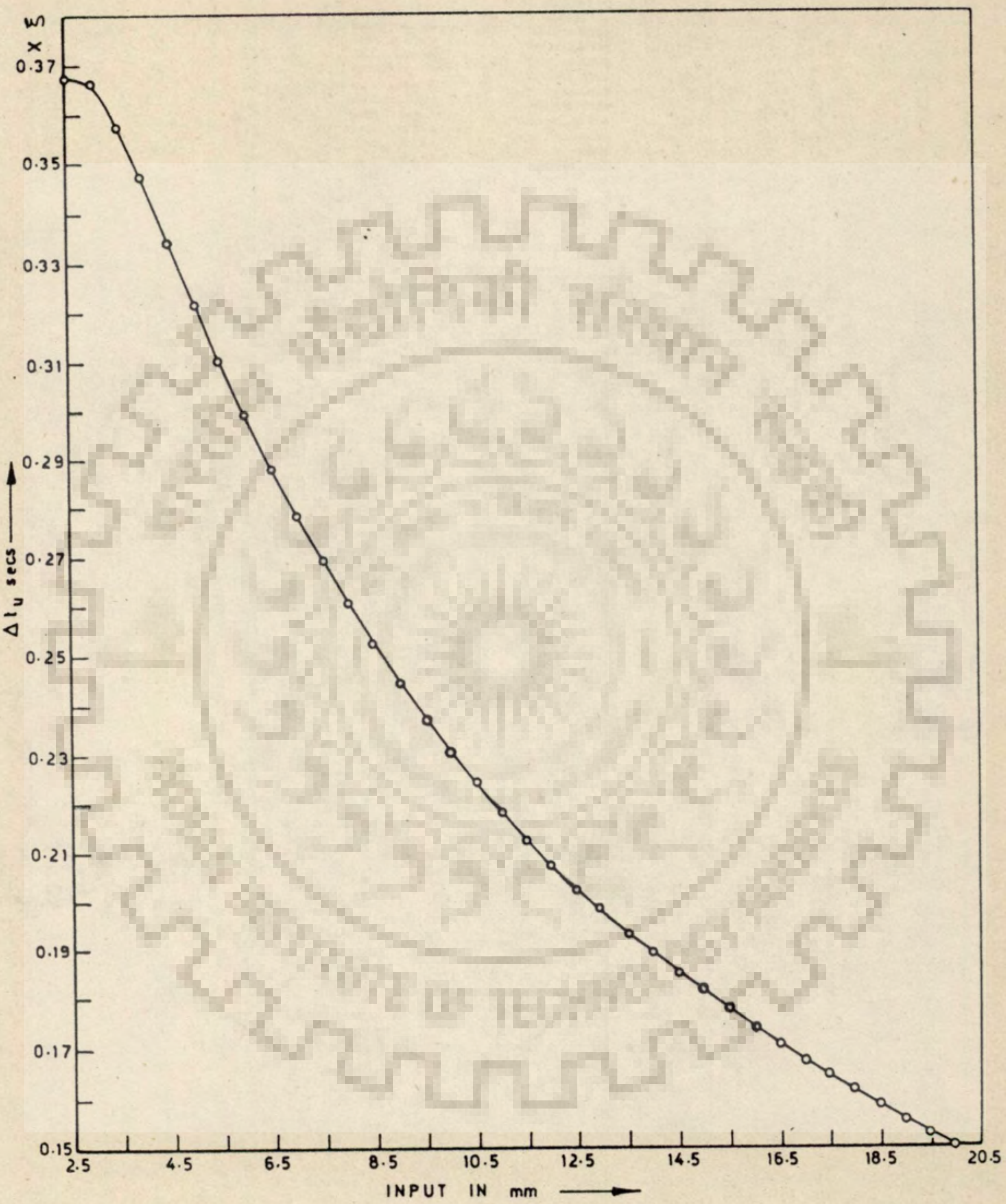

FIG. 4.7 _ PLOT OF $\Delta t'_u$ VS I

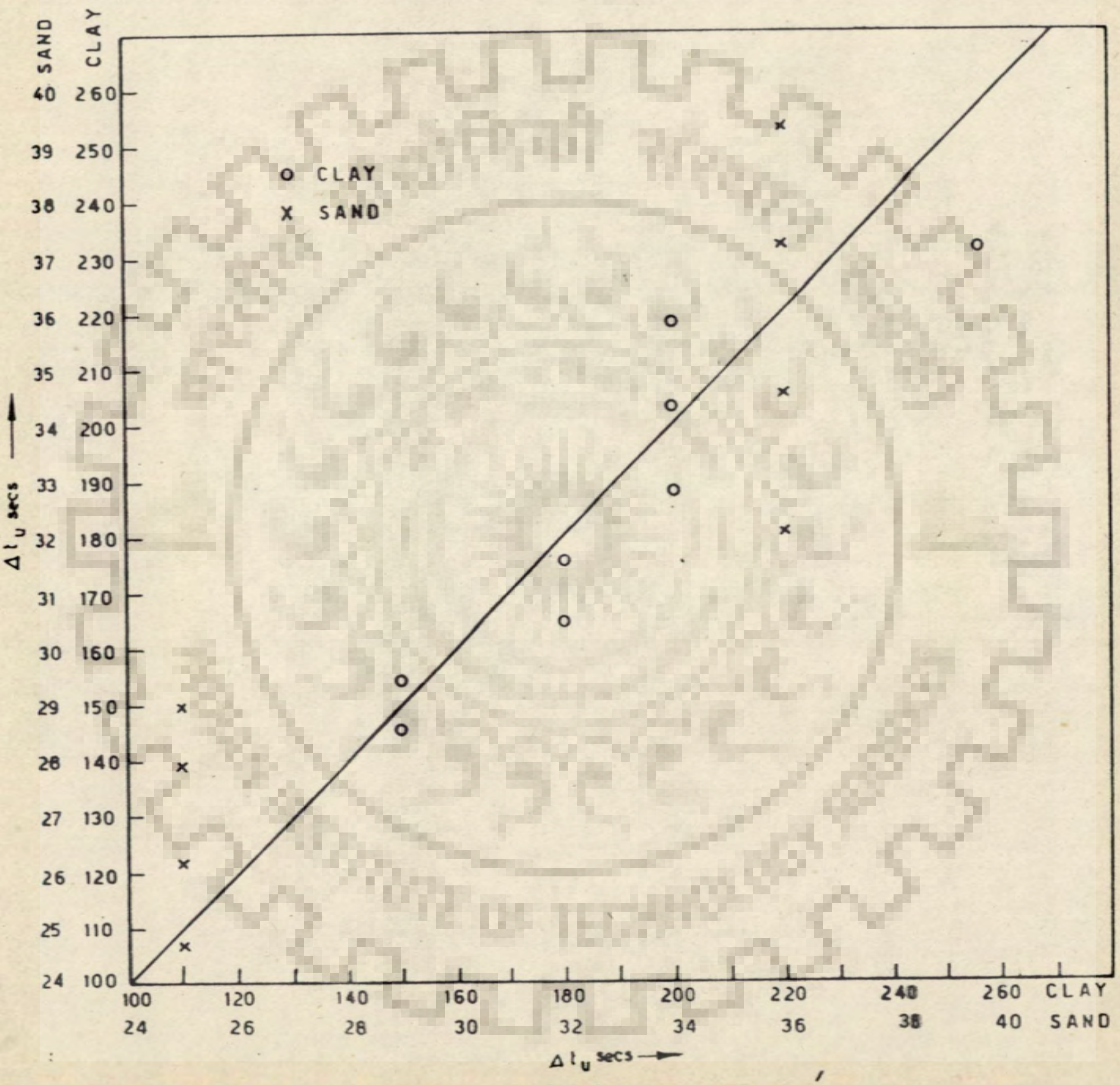

FIG. 4.8 _ PLOT OF Δt_u VS $\Delta t'_u$

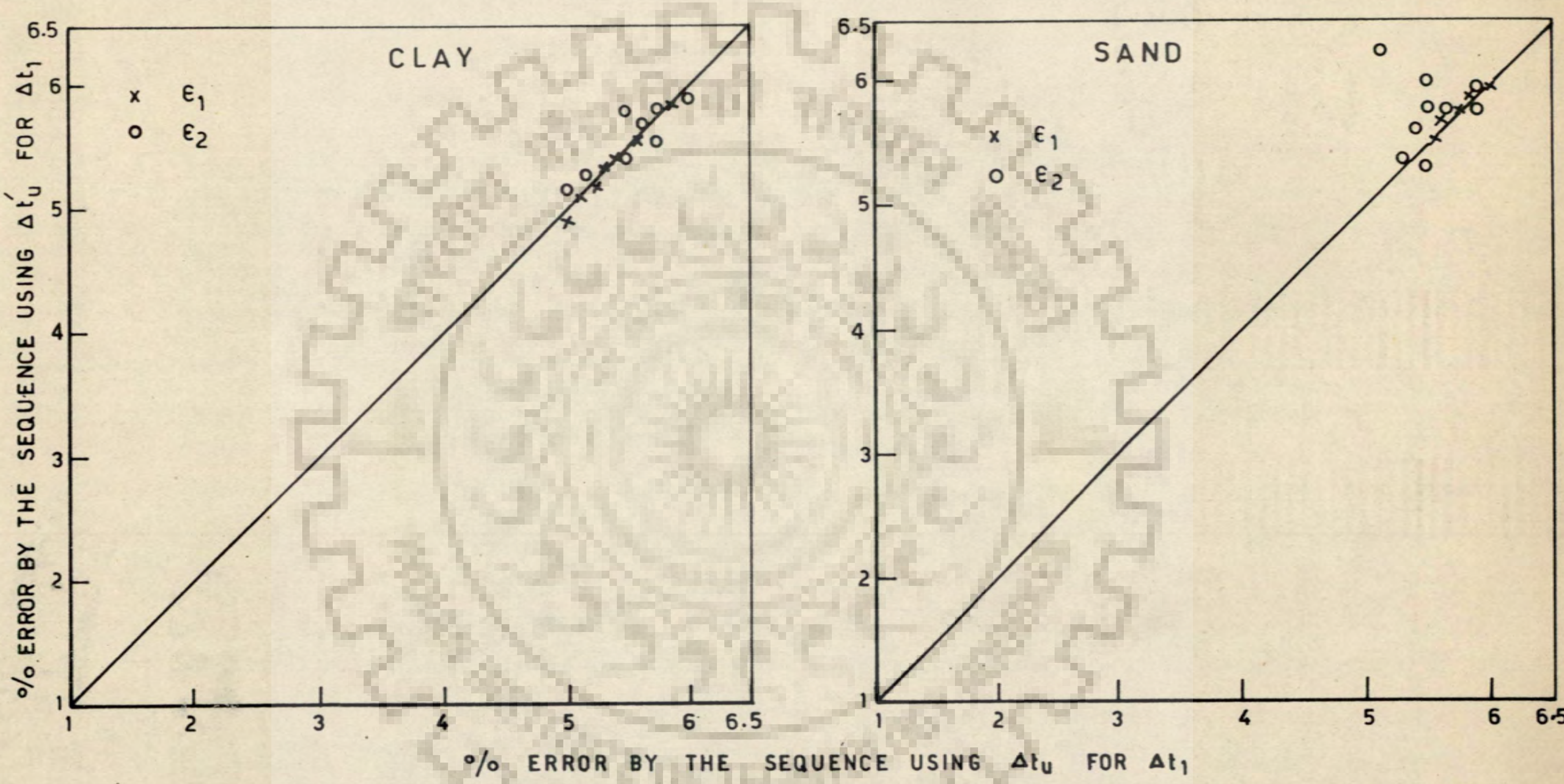

FIG. 4.9 _ PLOT OF ϵ_1 AND ϵ_2 WITH Δt_u AND $\Delta t'_u$ FOR Δt_1

In all the studies the Evapotranspiration has not been considered. However, this may not effect the results much as the usual values of evapotranspiration are much less than the input values considered.

The criteria has been developed for the studies reported in the subsequent chapters. Thus, it may not be applicable universally. Further, the criteria has been developed for homogeneous soil medium. However, the author could succeed in applying it to a case study involving heterogeneous soil medium (exercises 5.2 and 5.3) by specifying K_s, θ_r and t max values corresponding to upper soil layer. The success may be due to the fact that, in the case studies, the upper soil layer has a thickness of about 50 percent of the average depth of the flow domain. Thus, the author can not specify the applicability of the criteria for heterogeneous soil medium. Further, it is to be remembered that the units to be used (in the criteria) are mm and seconds.

4.6 DEPTH DISCRETIZATION

The model can be made more efficient by adopting a variable depth discretization. It is preferable to use finer depth interval at key parts of the zone. For instance, the depth intervals at the ground surface should be smaller, as the variation in 'h' near the ground surface will be rapid compared to those in the middle part of the zone. Since, the infiltration and recharge are calculated using the Darcy law, the depth interval should not cause numerical differentiation errors in calculating the flow gradient at the ground surface and water table. The time variation of the root zone depth and soil layering can more precisely be accounted by a variable discritization before hand. The time varient position of water table has been accounted for, by adding or deleting the required number of nodes. Thus, the last interval at any time of simulation is dependent on the last interval in the initial condition. So too small a value for the last interval, in initial condition, may lead to round off errors and too big a value may lead to truncation errors. Keeping in view the possible variation of the water table (in time), there should be sufficient number of nodes with a suitable Δz near the water table, in the initial condition. Thus, selection of the variable depth interval is problem dependent and may be decided by trial runs.

4.7 APPROXIMATE FUNCTIONAL RELATION FOR h CHARACTERISTIC

A finite number of discrete point data on h characteristic obtained by experimentation, may be used, for interpolation at non tabulated values, and for differentiation to determine the specific moisture capacity. However, it is well known that numerical differentiation may involve serious errors, especially when the discrete point data are not error free (Ralston et al, 1965). Even a small error in the basic data could lead to a very significant error in the computed derivatives. Therefore, the experimentation for the generation of discrete point data should involve barest minimum observational errors. This requirement would obviously need elaborate experimentation. If facilities for such an experimentation are available, it would certainly be desirable to generate adequate discrete point data (of h characteristic) and subsequently employ efficient numerical algorithms. However, such facilities may not always be available. In order to overcome this problem, the following procedure is proposed for evolving h characteristic.

Fig. 4.10 shows plot of a h characteristic, using the experimentally determined discrete point data, by Brooks etal (1964). It can be seen from the figure that with h increasing from zero to h_b, θ reduces marginally from ϕ to $(\phi - \delta)$, where δ is a small value. For values of h greater than h_b, the variation in θ resembles the classical exponential decay. From the inspection of plots, of h characteristic using the experimentally determined discrete h and θ values, the δ may be found to be nearly equal to θ_r, especially in case of coarser soils like sand. So, the general form of the characteristic has been approximated by a piece wise functional relation. The variation of θ from $h = 0$ to $h = h_b$ has been approximated by a linear relation, adopting θ_r for δ. Thus

$$\theta = \phi - \frac{\theta_r}{h_b} h \qquad 0 \le h \le h_b \qquad 4.30a$$

The variation of θ, for values of h greater than h_b, has been approximated by the classical exponential decay relation. Thus

$$\theta = e^{-\alpha h} + \theta_r \qquad \alpha > 0 \text{ and } h \ge h_b \qquad 4.30b$$

The exponential decay relation ensures, that, at higher values of h, θ tends to θ_r. The constant 'α' can

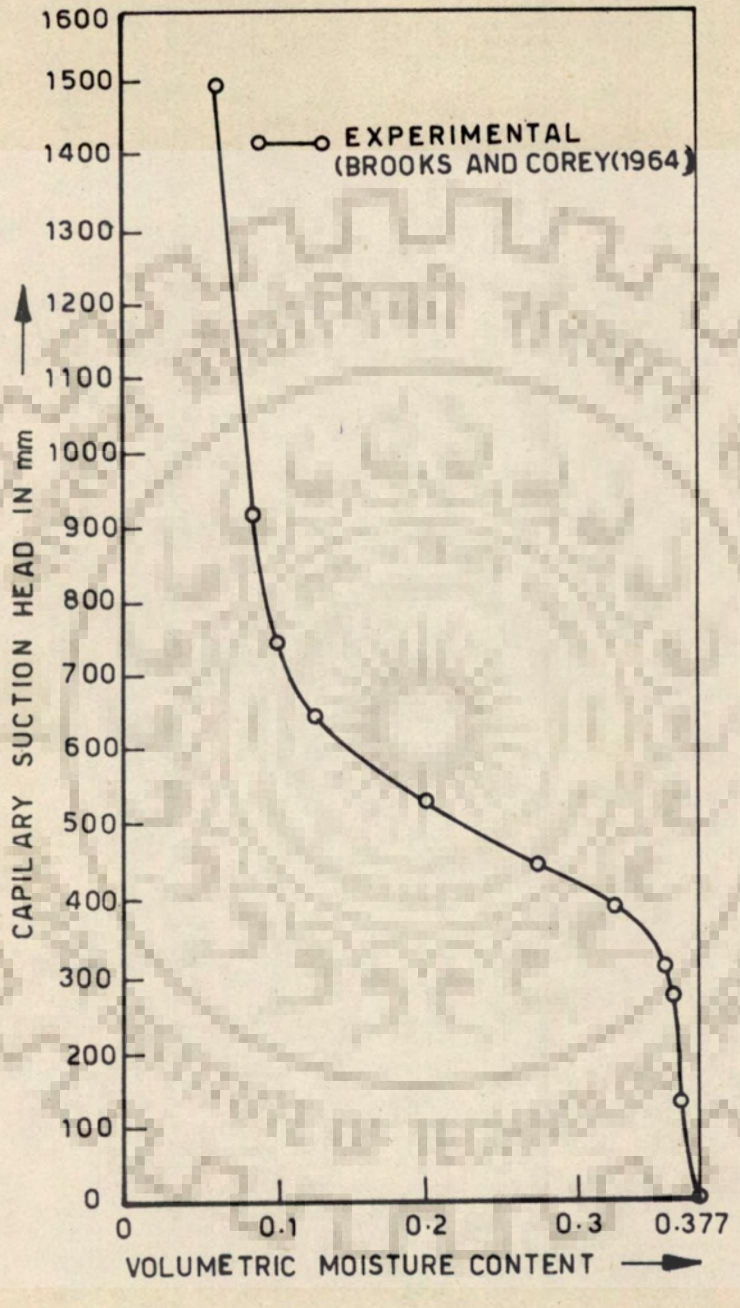

FIG. 4.10 _ PLOT OF 'h CHARACTERISTIC' USING THE EXPERIMENTALLY DETERMINED DISCRETE POINT DATA

be determined from the condition that θ is unique at h_b (since the flow is assumed to be nonhysteristic).

Thus,

$$\phi - \theta_r = e^{-\alpha h_b} + \theta_r$$

$$\alpha = \frac{-\ln(\phi - 2\theta_r)}{h_b}$$

Thus, the piece wise approximation will be

$$\theta = \phi - \frac{\theta_r}{H_b} h \qquad 0 \le h \le h_b \qquad 4.31a$$

$$\theta = \exp\left[\frac{\ln(\phi - 2\theta_r)}{h_b} h\right] + \theta r \qquad h \ge h_b \qquad 4.31b$$

The piecewise functional approximation given by equation (4.31) requires the well defined soil properties θ_r, ϕ and h_b. The relation is amenable for differentiation and interpolation.

Fig. 4.11 shows the plot of a reported experimental h and θ discrete point data by small circles. The firm line curve in the figure has been plotted using the equation with the (reported) experimentally determined θ_r, ϕ, h_b. Comparision of the plots is satisfactory.

4.8 A CRITICAL REVIEW OF THE SMA MODEL

Soil moisture accounting models require far less expertise and computational effort than the distributed model (described in the preceding paragraphs). In some cases, it may

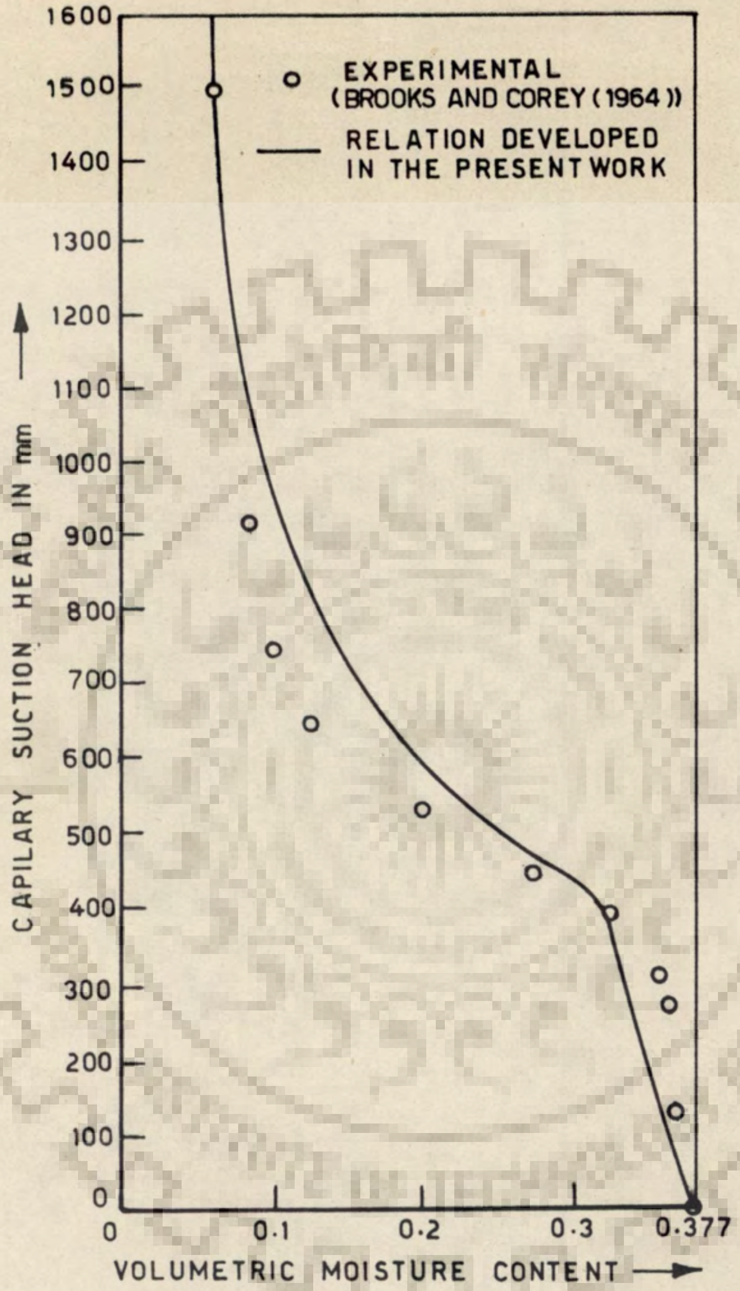

FIG. 4.11 _ COMPARISON OF PLOTS OF PROPOSED 'h CHARACTERISTIC' RELATION WITH THE PLOT USING EXPERIMENTALLY DETERMINED DISCRETE POINT DATA

even be possible to perform calculations manually. However, the SMA models involve many assumptions relating to the flow process. Prominent amongst them is the assumption of a threshold moisture content (which is termed as field capacity) below and at which there occurs no moisture movement and above which the rate of movement is such that all the excess moisture is drained in the basic accounting period. Thus, field capacity is in fact a flow parameter. However, current practice of quantifying it is to adopt the moisture content corresponding to a suction of 0.1 to 0.5 atmospheres. In the present work, a method has been proposed to quantify field capacity as a flow parameter.

4.8.1 Field capacity as a flow parameter

The concept of field capacity in the SMA model, implies that soil moisture movement occurs only if the moisture content exceeds it (field capacity). In other words, there will be no movement of soil moisture below field capacity. Theoretically, this is possible if K for θ upto field capacity is zero, as the gradients of flow (below field capacity) are not unconditionally zero. So, ensuring of no drainage of moisture contents upto field capacity and a drainability adequate to clear the excess moisture (above field capacity) may be possible if the K characteristic is in accordance with figure 4.12. The K characteristic shown in Figure 4.12 implies the quantification of field capacity as follows:

$$K(FC-\varepsilon_f) = 0 \qquad 4.32a$$

$$K(FC+\varepsilon_f) = Ks \qquad K_s >> (K_s \text{ large enough to provide adequate drainability}) \qquad 4.32b$$

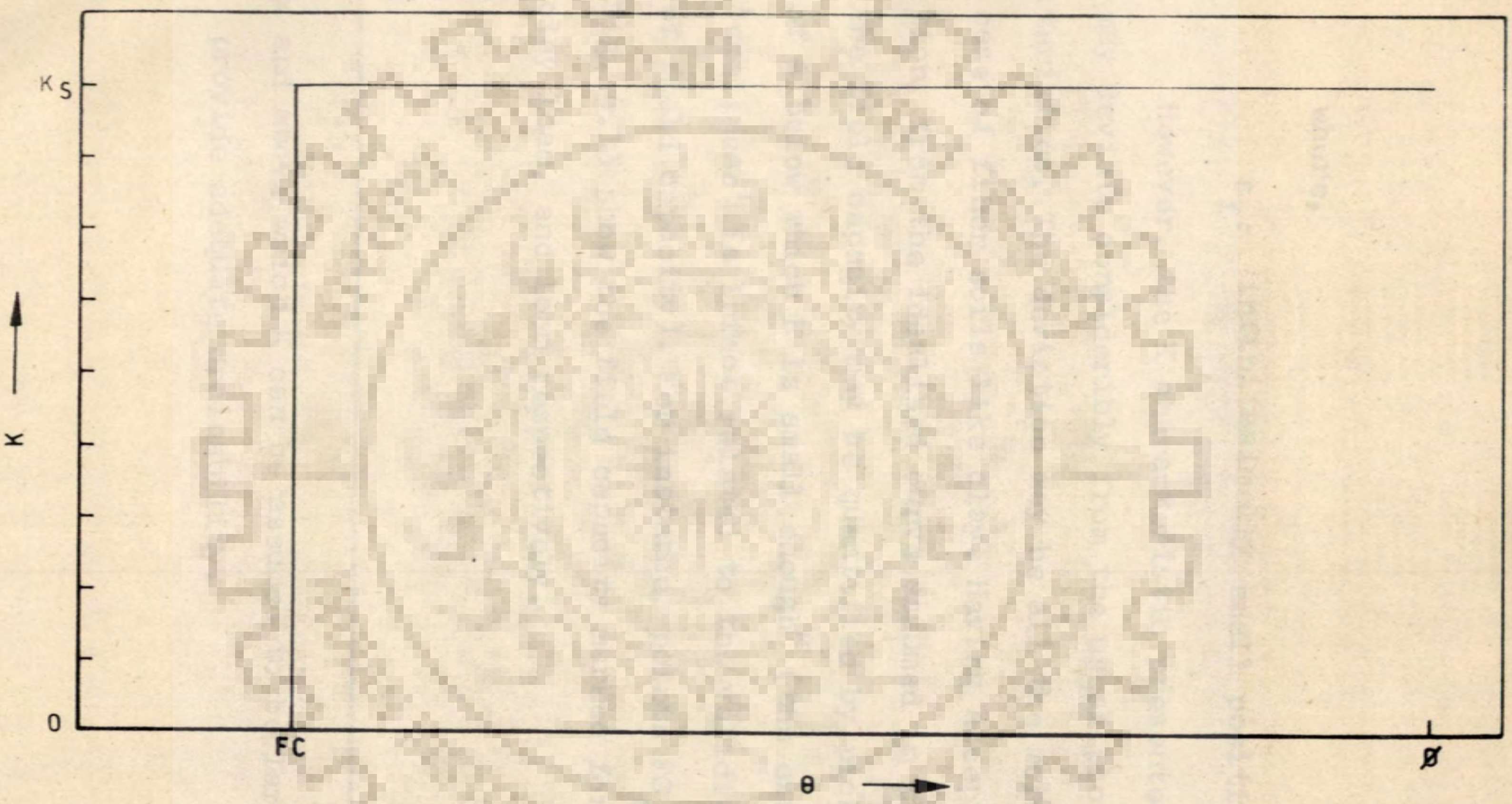

FIG. 4.12 — IDEAL 'K CHARACTERISTIC' FOR EXACT QUANTIFICATION OF FIELD CAPACITY

where,

ε_f: infinitesimally small positive value.

However, the K characteristic presented in Fig.4.12 may deviate consideribly from the usual plots of K characteristics. The deviation may be all the more severe, in case of finer soils like clay. Having accepted this deviation, from the idealised curve assumed in the SMA models, the field capacity may be quantified by picking such valu of θ below which K is small enough* (the extent of this 'smallness' is infact related to the validity of the concept of field capacity). For instance, points FC_a, FC_b, FC_c in Fig. 4.13 show the field capacity marked for clay, silty clay loam, and loam respectively.

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* and above which K can be assumed to be large enough to provide adequate drainability.

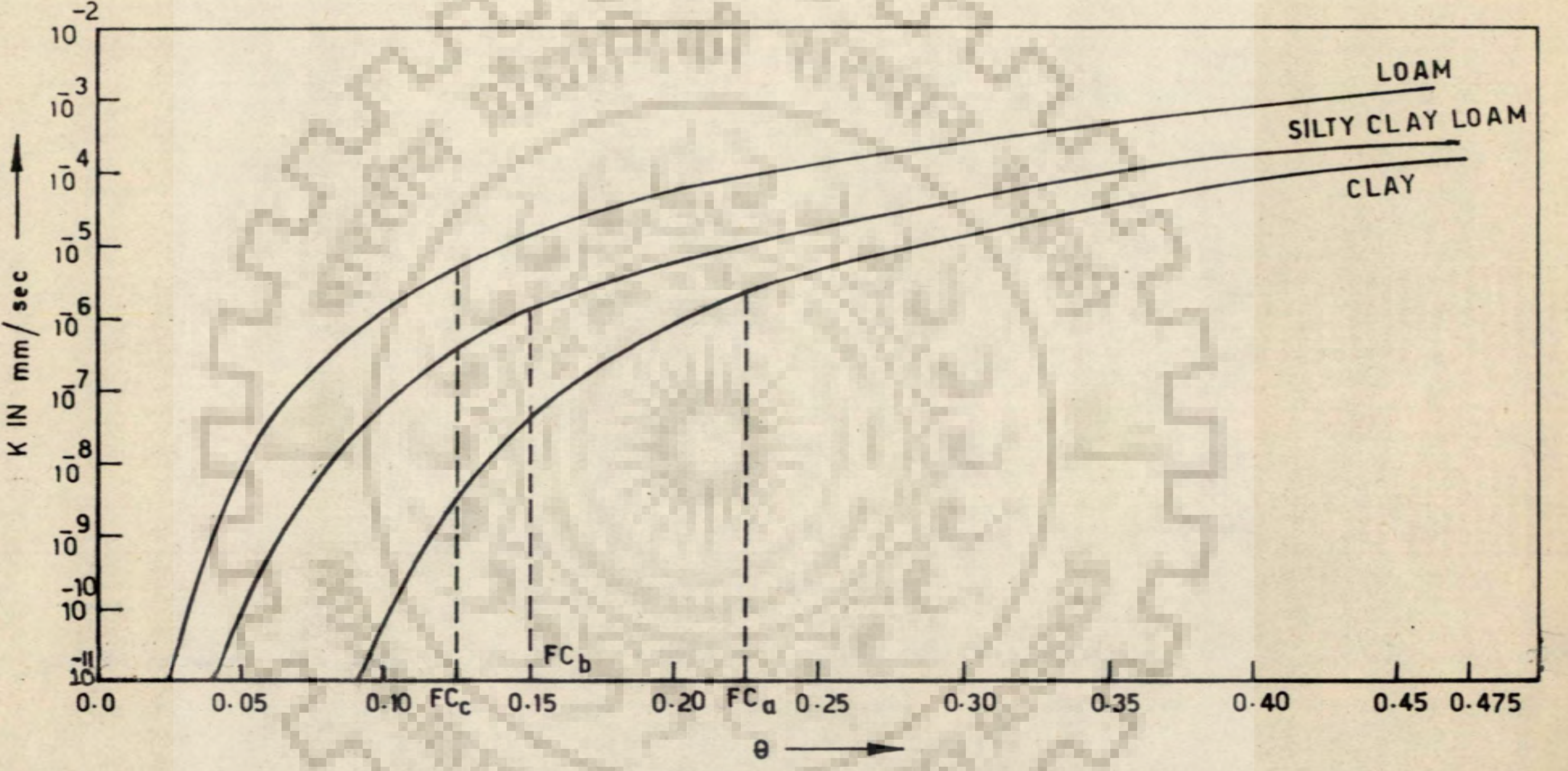


FIG. 4.13 – REAL LIFE 'K CHARACTERISTIC' WITH FIELD CAPACITY MARKED AS PER THE PROPOSED METHOD

4.9 COMPUTER CODE OF THE DISTRIBUTED MODEL

The computer code, for performing the calculations of the distributed model, has been written in FORTRAN IV. The programme consists of 10 subroutines and a main programme. Transfer of data from main programme to the subroutines and in between the subroutines, is made by labelled COMMON blocks. Dimensions of the variables are required to be changed according to the problem. Role of the main programme and each subroutine is described briefly in the following paragraphs.

MAIN PROGRAMME: In the main programme all the data and switches are read. The data are as follows:

Data:

- Length of total simulation period as an integer multiple of a suitable block of time (eg. a day).
- Time steps of simulation in each block of time (any step should be less than or equal to the block of time).
- A discretized series of rainfall (applied irrigation, if specified externally), potential evapotranspiration, depth to water table and depth of root zone. The block of time will be the period, corresponding to the highest frequent data among these data. For instance, Evapotranspiration, depth to water table, depth of root zone may be available on daily basis. The rainfall may be available as a continuous record (recording rain guage output), which might be discritized on hourly basis. The block of time in this case will be an hour.

- Number of depth nodes and interval at the initial condition.
- The number(s) of the node(s) at which the soil layer changes.
- Data of characteristics, either tabulated or coefficients in the closed form relation.
- Initial condition (ie. the vector of h at zero time).
- Various tolerable errors.
- Maximum number of iterations to be performed in assigning the upper boundary condition.

Options

- The times at which the simulated h(and θ) are to be reported. The time should be total sum of any subset of time steps. Default is never to report but for times of saturation and desaturation.
- The time interval at which the abstract of the simulated responses are to be reported. This should be an integer multiple of the block of time.
- Times at which the solution is to be verified by Picard's iteration method. This should coincide with the elapse of a specified time step. The number of iterations are to be specified as a data. Default is to never verify.
- Option regarding continuing the programme execution even if the upper boundary could not be assigned or the verification with picard iteration fails. Default is to continue. A message is given on the terminal screen regarding when (the simulation time from the begining) the failure occured, for subsequent interactive action (to continue or to exit or changing trial value in case of upper boundary condition failure and redefining time steps for verification in the picards iteration method).

- Option regarding by passing the algorithm for identifying and assigning the ground surface boundary condition. Default is algorithm operative.
- Option for simulation with lower boundary other than water table.
- Option to specify the time steps by any other suitable criteria.
- Option for writting the time steps of simulation actually taken, in a specified file.
- Option for getting failures of simulation on account of not satisfying the tolerable error limits. Message of when (the simulation time from the beginning) is given on the terminal screen. The execution is suspended temporarily for instructions from the user (to rectify the situation or to exit).

Subroutines called: DISBAL and THETA (if the initial condition is given interms of moisture content).

DISBAL : This is the principal monitoring routine of the programme. All options are recognized, data channeled for the use in the simulation. The irrigation is scheduled as per the given irrigation criteria (if the irrigation is also to be scheduled). The outputs are formated and written in specified files on specified devices. Algorithms for the upper and lower boundary are implemented. Messages, regarding failures of simulation other than the verification with the Picard iteration method are output on the terminal screen.

Subroutines called: THETA, COND, SOLVE, STEP,SIMU, RUNOFF.

THETA: In this subroutine, the θ for a given h is calculated. Data on the node(s) at which the soil layer changes is made available through labelled COMMON block. The node number is supplied as an argument, so that the appropriate characteristics is used. If tabulated values are provided, they should be made available in the subroutine through a COMMON block. In such a case (of tabulated values) the interpolation method needs to be programmed in the routine.

COND: In this subroutine conductivity is calculated (for the link) for the specified θ (or h). Other details are similar to the THETA subroutine.

SIMU: From this subroutine the depth to water table at the day is returned to the calling subroutine. If necessary suitable logic (saturated flow model) can be incorporated in this routine to compute and return the response (in the form of modified depth to water table) to the computed recharge.

RUNOFF: In this subroutine the trial 'h' at the ground surface node is generated.

STEP: The sequence of the time steps of simulation are generated in this subroutine by using the rain fall and the scheduled irrigation as input. The user may resort to another procedure to generate time steps of simulation by suitable programming in the subroutine.

SOLVE : In this subroutine the finite difference equations are formulated and solved. As per the option, the solution is verified (at the specified times) by picard iteration method. Message regarding failure on such a verification is given on terminal for interactive measures. The subsurface flow mass balance is performed to take action on the necessity of reducing the current time step.

Subroutines called: SINK, DIFU. TREP, THETA, COND.

TREP: In this subroutine, the change in moisture storage in the current time step of simulation is calculated.

DIFU: In this subroutine, the specific moisture capacity is calculated. Either numerical or closed form method should be programmed in this subroutine. Apart from supplying all the required data through labelled COMMON blocks the node number is supplied as an argument so that the appropriate characteristic is used.

SINK : In this subroutine, the actual evapotranspiration rate at all the nodes in the root zone are calculated. Necessary data should be made available through COMMON blocks. The actual ET, Potential ET and θ relation needs to be programmed.

Fig. 4.14 shows the flow chart of the computer code. In annexure II listing of the computer code has been presented.

CHAPTER - V

MODEL VERIFICATION

The model has been verified by comparing the simulated depth and time distribution of moisture content with that given by Philip's quasi analytical solution (Philip 1969) and with a field observation. Details of these two verifications are given in sections 5.1 and 5.2.

5.1 VERIFICATION WITH PHILIP QUASI-ANALYTICAL SOLUTION

A full length discussion on the analytical solution has been made in chapter on literature review (pp. 25 to 28). Philip has illustrated the solution for Yololight clay by presenting depth wise moisture distribution (Annexture I-a), for a time upto 2×10^6 seconds. The model has been operated to simulate the depth wise moisture content distribution upto the same time (i.e. up to 2×10^6 seconds), under identical conditions.

5.1.1 Data

In the illustrated analytical solution, initial and boundary conditions have been specified as follows.

Initial condition $\theta_{z,0} = \theta_i$ 5.1a

Lower boundary $\theta_{\infty,t} = \theta_i \quad t \geq 0$ 5.1b

Upper boundary $\theta_{0,t} = \theta_s \quad t > 0$ 5.1c

where

z : Depth measured from ground surface [L].

θ_s: Prescribed moisture content at the ground surface.

The boundary conditions (as per equations 5.1b and 5.1c) imply that, the medium is semi-infinite and the ground surface is brought to 'θ_s' instantaneously. Since, the present model is based upon head form of Richards equation, these moisture contents have been converted in to 'h' using the h-θ characteristic employed in the illustration. Further, the present model is based on numerical solution of the Richards equation. Hence, the time domain requires to be discritized by finite intervals. So, the instantaneous change in the moisture content (equation 5.1c) at the upper boundary has been simulated using a small time step of 10 seconds for Δt_1 and by prescribing 'h' at the boundary to be 10 mm (corresponding to θ_s in the illustrated analytical solution), for simulation levels of second and beyond. The illustrated analytical solution is valid for a semi-infinite medium (ie., lower boundary positioned at infinite depth), so that, the moisture content at that depth remains unchanged. However, the present model requires the lower boundary position to be at a finite depth. An examination of the illustrated analytical solution revealed that the moisture front moved up to a depth of 1.50 m by 2 x 10^6 seconds. Thus, upto this time, the moisture contents below 1.50 m did not change from the initial condition. Therefore, position of the lower boundary could be any where below 1.50m. with 'h' specified as initial condition itself. So a depth of 3 metres has been adopted to be on conservative side. The depth has been discritized with an interval of 50mm upto a depth of 2m and 100 mm for the remaining depth of 1m. Thus total number of nodes were 51. The initial and boundary conditions were as follows:

Initial condition: $h(i,1) = 3140$mm $i=1$ to 51 5.2a

Upper boundary condition

$h(1,j) = 10$ mm $j \geq 2$ 5.2b

Lower boundary condition

$h(51,j) = 3140$ mm 5.2c

The upper boundary condition has been prescribed explicitly before hand. So the algorithm for identifying and assigning the boundary condition has been made inoperative in the computer code.

5.1.1 Results

Fig. 5.1 shows the reported (Analytical solution) and simulated distribution of moisture content, in depth and time. The comparision is satisfactory. So, it can be concluded that, the numerical scheme used could give a solution fairly close to the quasi analytical solution. This could imply that the numerical errors are not significant.

5.2 VERIFICATION WITH FIELD OBSERVATION

In the preceeding exercise, only core part of the model involving the numerical scheme for solving Richards equation has been activated. Apart from the core, the model can account for the following.

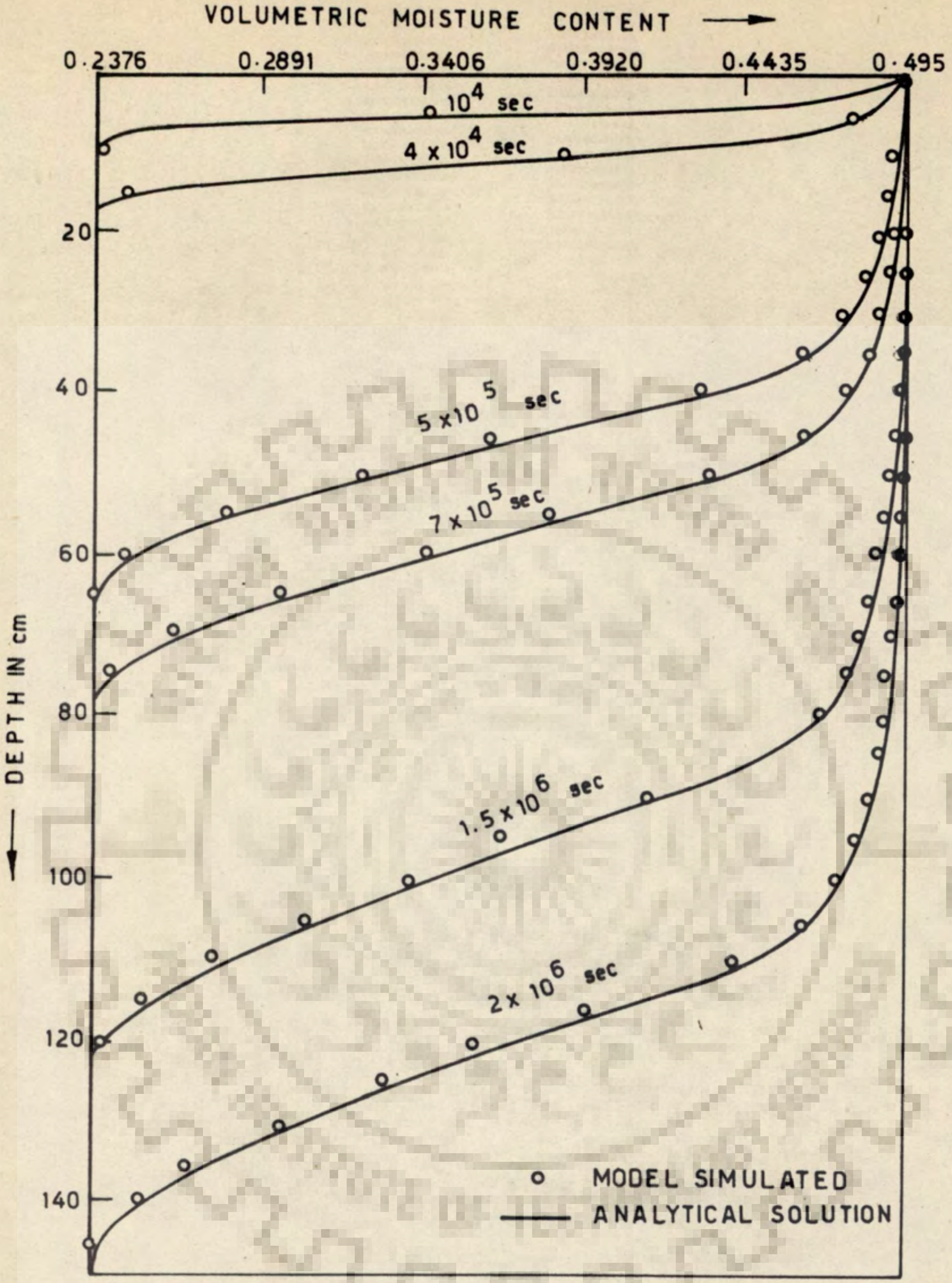


FIG. 5.1 _ MODEL VERIFICATION: MODEL SIMULATED AND PHILIP QUASI-ANALYTICAL SOLUTION, MOISTURE PROFILES

i. Heterogeneity of the soil in the form of layering

ii. Presence of evapotranspiration

iii. Time varient position of water table

iv. Time varient rainfall and applied irrigation at the ground surface

v. Time varient root zone of vegetation

vi. Automatic indentification and assignment of upper boundary condition.

These additional features enhance the capability of the model to simulate the flow more realistically. Present excercise is aimed at verification of these features with a field evidence. The field location is the open lawn of the department. In this location, depth wise gravimetric moisture content distribution has been observed in Sep - Oct 1985, for 9 days well distributed in the period (Annexure I-b). Assuming $\gamma_\omega = 1.0$, the discrete observations, of gravimetric moisture contents have been converted in to volumetric ones by the following relation.

$$\theta = \theta_\omega \cdot \gamma_d \qquad 5.3$$

where

θ_ω : Gravimetric moisture content (weight of water/ weight of dry soil)

γ_d : Dry density of the soil (weight of dry soil/ Total volume of the soil before drying) $[FL^{-3}]$

θ : Volumetric moisture content.

5.2.1 Data

5.2.1.1 Determination of γ_d: On Sept. 16, there has been ponding of water at the surface throughout the day. So the soil sample at the ground surface should have had saturated volumetric moisture content (Numerically equal to porosity). Thus, equation 5.3 contains only one unknown γ_d which can be evaluated by solving the equation. Similarly, γ_d for the lower soil layer has been determined using a soil sample taken at the water table. The values arrived at for γ_d are 1.311 g/cm^3 for upper soil and 1.52 g/cm^3 for lower soil.

5.2.1.2 Rainfall : Recording rain gauge outputs have provided continuous record of rainfall from Sep 1, 8.30 A.M. (IST) to Nov. 1, 8.30 AM (IST) (i.e., for the period of Sep - Oct. (Annexure I-C). The continuous records of rainfall have been used to evaluate the hourly distribution. The interception and direct evaporation losses have been not accounted for.

5.2.1.3 Evapotranspiration : Class A Pan evaporation at 8.30 AM (IST) and 5.30 PM (IST) every day (Annexure I-d) provided half daily evaporation. Based on the recommendations of Doorenbos etal (1979), a pan coefficient of 0.75 has been used to convert the class A pan evaporation rate (on half daily basis) into potential evapotranspiration rate of reference crop. The field has actively growing green grass. A depth of 30 cm from ground surface has been considered to be effective for evapotranspiration. Thus, the root zone depth has been considered to be time invarient at 30 cms. From the observed moisture content distribution, it has been concluded that, the moisture content in the root zone has been above the field capacity of 0.15 (refer Fig. 4.13) throughout the period of interest (Sep-Oct 85). Thus, there has never been a short supply of water. So the crop in the location has been considered to be the reference crop and so $\bar{E}$, at any node in the root zone has been taken equal to the proptionate (uniformly distributed) potential evapotranspiration rate. However, the E has been restricted such that, the evapotranspiration (depth) in Δt_j will not exceed the moisture stock available. at the node calculated at jth level for simulation at (j+1)st level.

5.2.1.4 Depth to water table: Depth to water table at 8.30 AM (IST) every day, observed in a bore well near by the ground point (Annexure I-d) provided the data requirement of depth of flow domain as a function of time.

5.2.1.5 Depth discretization : Litholog of the bore well (Annexure I-e) shows two soil textures. These have been classified as silty clay loam and loamy sand (Singhal 1985). So, to account for the two layers and the root zone more precisely, the depth has been discretized with an interval of 50 mm upto 400 mm, 100 mm between 400 mm to 3800 mm, 50 mm between 3800 mm to 4100 mm and 30 mm (last depth interval).

5.2.1.6 Characteristics: In the absence of necessary instrumentation, the characteristics of the soil layers have been approximated by the following relations.

$$K = K_s \left(\frac{\theta-\theta_r}{\phi-\theta_r}\right)^{4.0} \quad \theta \geq \theta_r \quad \text{(Brooks et al 1964)} \qquad 5.4a$$

$$= 0 \qquad 5.4b$$

$$\theta = \exp\left[\frac{\ln(\phi-2\theta_r)}{h_b} h\right] + \theta_r \quad h \geq h_b \qquad 5.5a$$

$$\theta = \phi - \frac{\theta_r}{h_b} \times h \quad 0 \leq h \leq h_b \qquad 5.5b$$

where,

θ_r : Residual moisture content
ϕ : Porosity
h_b : Air entry value (bubbling pressure)[L]
h : Capillary suction head [L]
K_s : Capillary conductivity at saturation [LT^{-1}]
θ : Volumetric moisture content

Reported values of θ_r, ϕ, h_b, K_s, based on soil texture (Rawls et al 1981a) have been used to define the relations However, the K_s and h_b of upper soil layer have been slightly modified from the reported values to get better match between the simulated and observed moisture profiles. Table below shows the finally used values of θ_r, ϕ, h_b, and K_s.

Soil layer	θ_r	ϕ	h_b	K_s
Silty clay loam	0.04	0.471	650.0 mm	3.167E-4mm/sec.
Loamy Sand	0.035	0.437	205.8 mm	1.697E-2mm/sec.

5.2.1.7 Initial conditions: On Sep Ist, the gravimetric moisture contents have been observed upto water table. Using appropriate h characteristic, the discrete volumetric moisture contents have been converted in to a set of discrete 'h'. Subsequently, a smooth curve has been plotted and 'h' at other (depth) nodes have been interpolated graphically. This nodal distribution of 'h' has been assigned as initial condition. Fig. 5.2 shows the initial condition in terms of volumetric moisture content.

5.2.1.8 Boundary conditions: The algorithm developed for automatic identification and assignment of ground surface boundary condition, has been activated.

It has been assumed that the position of water table is constant in a day and the variation takes place instantaneously, at the turn of the day. Thus, the records of daily depth to water table (Annexure I-d) have been used to prescribe the position of lower boundary at all levels of simulation.

After specifying all the required data, using a maximum time step of simulation of 3600 seconds the model has been operated for the two months period of Sep. and Oct. 85.

5.2.2 Results:

In Table 5.1 the node (i.e., depth) and day(i.e. time) wise observed and simulated moisture contents have been presented. Fig. 5.3 shows the observed and simulated moisture distribution graphically. It may be observed from figure 5.3 that the simulated moisture contents are close to the observed. However, the following statistical tests also have been performed.

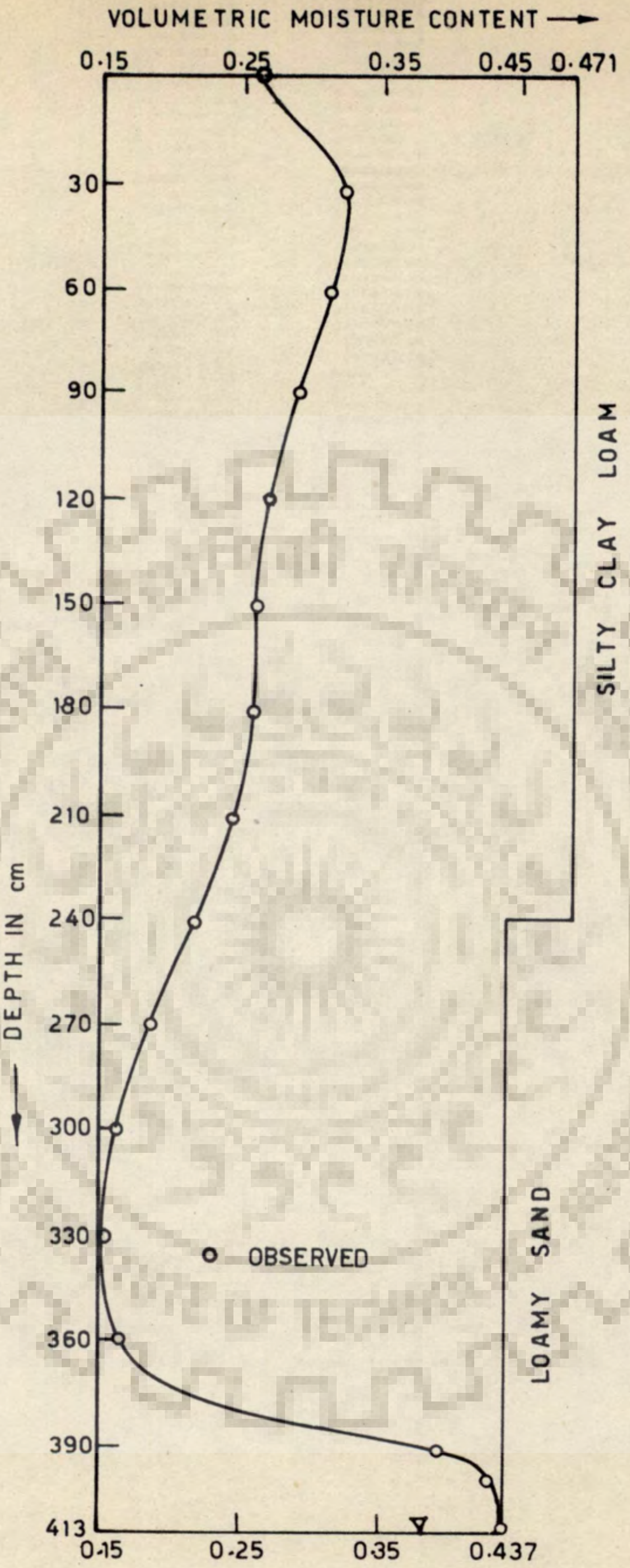


FIG. 5.2 _ MODEL VERIFICATION WITH FIELD EVIDENCE: INITIAL CONDITION

Table 5.1 : MODEL VERIFICATION WITH FIELD EVIDENCE: SIMULATED AND OBSERVED MOISTURE CONTENTS

Day	Description	Percentage moisture content at a depth of								R^2	F	t
		0 cm	30 cm	60 cm	90 cm	120 cm	150cm	180 cm	210 cm			
Sep 2	Simu	27.50	35.43	30.68	29.11	25.27	25.17	25.62	24.23	0.97	1.01	0.16
	Obsd	27.78	34.51	31.03	28.59	25.00	24.41	25.92	23.36			
9	Simu	21.25	34.43	30.34	28.81	24.16	24.66	24.30	24.23	0.96	1.05	0.32
	Obsd	20.45	33.47	30.33	28.24	24.17	23.82	23.71	22.55			
16	Simu	47.10	35.13	29.13	28.11	24.70	24.50	24.30	24.29	1.00	1.00	0.01
	Obsd	47.10	35.10	29.17	28.12	24.75	24.52	24.29	24.29			
24	Simu	42.00	34.44	31.44	28.78	25.50	24.92	24.66	27.30	0.99	1.03	0.01
	Obsd	41.95	34.98	31.73	28.70	25.00	25.22	25.00	26.50			
Oct 5	Simu	36.30	31.73	31.26	25.68	24.99	24.52	23.13	24.99	0.99	1.03	0.05
	Obsd	36.49	32.54	30.80	25.10	25.00	25.00	23.48	25.00			
12	Simu	39.25	36.84	31.49	27.31	27.08	29.17	25.61	28.24	0.99	1.04	0.07
	Obsd	39.28	36.72	31.49	26.61	26.26	28.47	26.03	28.70			
21	Simu	28.20	31.89	31.26	29.40	28.65	28.94	27.31	26.10	0.94	1.06	0.17
	Obsd	28.24	31.84	31.84	29.98	28.70	28.24	28.01	26.19			
31	Simu	21.00	30.24	31.10	30.60	29.10	28.30	26.80	27.50	0.96	1.17	0.06
	Obsd	19.99	29.40	31.26	29.98	29.98	29.70	27.54	27.54			

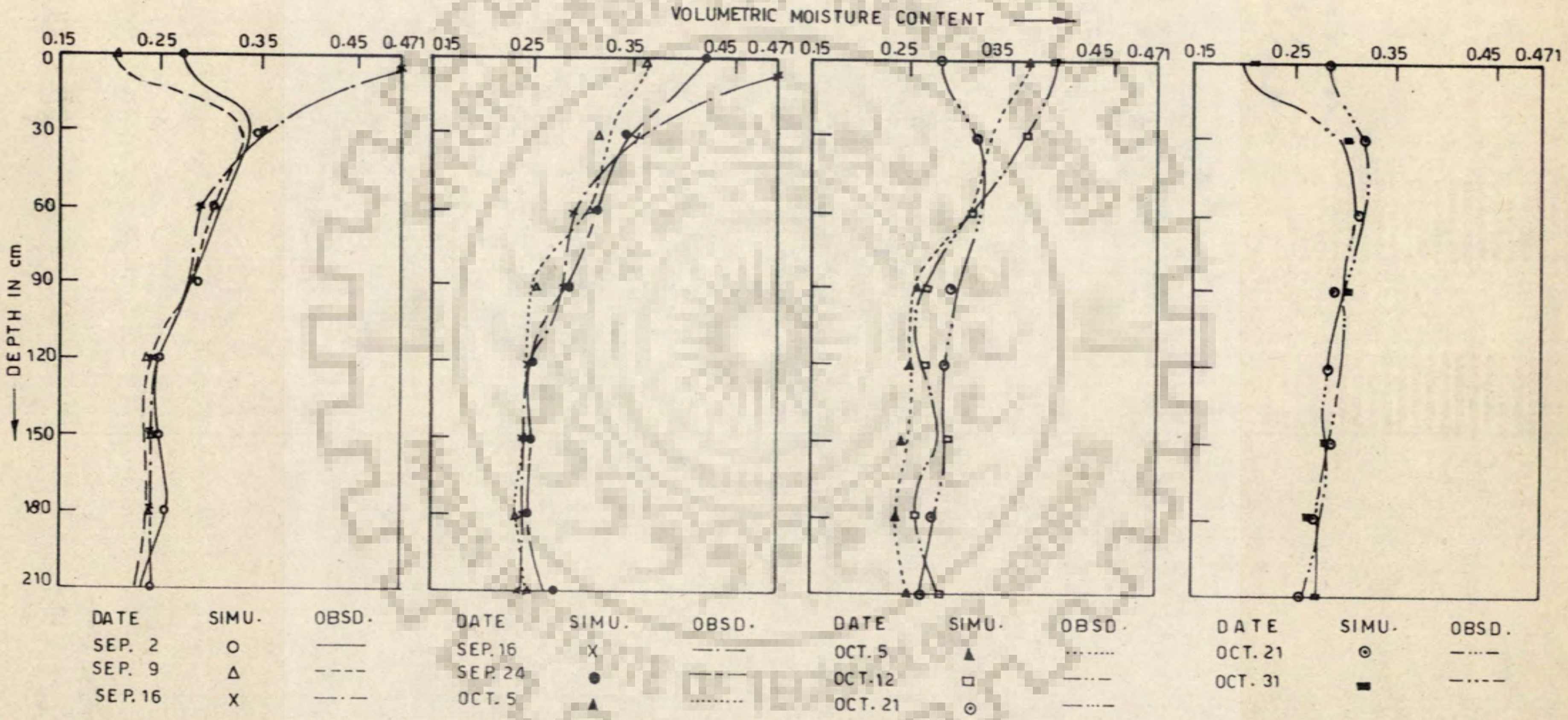


FIG. 5.3_MODEL VERIFICATION WITH FIELD EVIDENCE: SIMULATED AND OBSERVED MOISTURE PROFILES

5.2.2.1 Statistical tests:

Coefficient of correlation (R^2) (Nash 1970)

$$R^2 = 1.0 - \sum_{\ell=1}^{n_p} (\theta_{s\ell} - \theta_{o\ell})^2 \Big/ \sum_{\ell=1}^{n_p} (\theta_{o\ell} - \bar{\theta}_o)^2 \qquad 5.6$$

where,

$\theta_{s\ell}$: simulated moisture content at ℓth node

$\theta_{o\ell}$: observed moisture content at ℓth node

$\bar{\theta}_o$: mean of observed moisture contents

n_p : number of data points of comparision (8 in the present case).

Table 5.1 shows the R^2 calculated for the profiles on each day. It may be observed that the R^2 is quite high. However, since, the sample is small, it is necessary to confirm the match of simulated and observed profiles by small sample tests. The following tests have been taken up.

<u>F test</u> (Gupta et al 1980)

$$F = \frac{\theta_{sv}^2}{\theta_{ov}^2} \left(\text{or } \frac{\theta_{ov}^2}{\theta_{sv}^2}\right)^{*} \qquad 5.7$$

where,

θ_{sv}^2 : varience in the simulated series $= \dfrac{\sum_{\ell=1}^{n_p} (\theta_{s\ell} - \bar{\theta}_s)^2}{n_p - 1}$

θ_{ov}^2 : varience in the observed series $= \dfrac{\sum_{\ell=1}^{n_p} (\theta_{o\ell} - \bar{\theta}_o)^2}{n_p - 1}$

$\bar{\theta}_s$: mean of simulated moisture contents

under H_o (null hypothesis), the test static is

$$F_{cr(\nu_1,\nu_2)}\Big|_{\eta\%} \geq F \qquad 5.8$$

---

[*] The numerator will have large one among the θ_{sv}^2 and θ_{ov}^2

$F_{cr_{\nu_1,\nu_2}}$: Critical F with ν_1 and ν_2 degrees of freedom at η% level of significance

ν_1 and ν_2 : Degrees of freedom of the numerator and denominator (7,7 in the present case)

η : level of significance (usually 5 percent is taken)

The f_{cr} with (7,7) degrees of freedom at 5 percent level of significance is 3.79. It may be observed from the table 5.1 that the calculated F for each profiles is less than the tabulated critical F at 5 % level of significance. Thus, the null hypothesis at 5 % significance level is acceptable.

t test (Gupta et al 1980)

$$t = \frac{|\bar{\theta}_s - \theta_o|}{\sqrt{S^2\left(\frac{1}{n_p}+\frac{1}{n_p}\right)}} \qquad 5.9$$

where,

$$S^2 = \frac{1}{n_p+n_p-2}\left[\Sigma(\theta_{s\ell} - \bar{\theta}_s)^2 + \Sigma(\theta_{o\ell} - \bar{\theta}_o)^2\right]$$

under H_o (null hypothesis) the test static is

$$t_{cr_\nu}\Big|_\eta \geq t \qquad 5.10$$

where,

$t_{cr_\nu}\big|_\eta$: critical t with ν degrees of freedom at η% level of significance

ν : degree of freedom (14 in the present case)

η : level of significance

The t_{cr} with 14 degrees of freedom at 5 % level of significance is 1.761. It may be observed from the table 5.1 that the calculated t for each profile is less than the critical t at 5 % level of significance. Thus, the null hypothesis at 5% significance level is acceptable.

So the graphical and statistical evaluation of the model simulation are satisfactory.

5.3 ADEQUACY OF DATA OF DAILY RAINFALL AND EVAPORATION

In India continuous records of rainfall and of pan evaporation (or of potential evapotranspiration) are not available always. The data are generally available at a discrete interval of one day. Thus, it is interesting and necessary to see the effect of specifying daily data, on simulation of moisture distribution. For this excercise the data reported at 5.2 were employed as follows.

The continuous records of rainfall were used to arrive at daily depths, which were then distributed uniformly over the entire day. Similarly, the twice daily values of class A pan evaporation were added up to arrive at daily depths, which were then distributed uniformly over the day. Thus, a situation was simulated, in which, the observations on rainfall and pan evaporation are taken once in a day. The model operation described in section 5.2. has been repeated with the presently generated data, of rainfall and potential evapotranspiration. Since, the results given in 5.2 were based upon hourly values of rainfall and half daily values of pan evaporation, a comparision of these two sets of results (i.e. reported in 5.2 and the present excercise) shows the impact of coarser discretisation of rainfall and pan evaporation data on the simulation.

5.3.1 Results

In table 5.2 the observed and simulated day and depth wise moisture content distribution have been presented. Fig.5.4 shows the observed and simulated (in this excercise) moisture profiles. In order to quantify the effect of the coarser data discretization, the statistical tests (equations 5.6, 5.8 and 5.10) were performed for this excercise as well (Table 5.2). Comparision of the two set of the statistical tests (done for the present and the previous excercise) indicates that, the use of daily values of rainfall and pan evaporation results in a relatively low R^2, high F and high t (Table 5.3, below).

Table 5.3 Comparision of statistical tests

Day / Test	R^2		F		t	
	hourly	daily	hourly	daily	hourly	daily
Sep 2	0.97	0.85	1.01	1.43	0.16	0.04
9	0.96	0.95	1.05	1.25	0.32	0.02
16	1.00	0.94	1.00	1.16	0.01	0.21
24	0.99	0.93	1.03	1.08	0.01	0.15
Oct. 5	0.99	0.84	1.03	1.22	0.05	0.22
12	0.99	0.90	1.04	1.25	0.07	0.05
21	0.94	0.80	1.06	1.55	0.17	0.17
31	0.96	0.84	1.17	2.13	0.06	0.35

However, the computed F and t are still acceptable (low enough) at 5 percent level of significance. Thus, the null hypothesis at 5 % level of significance is acceptable in this case also.

Table 5.2 ADEQUACY OF DAILY RAINFALL AND PAN EVAPORATION: SIMULATED AND OBSERVED MOISTURE CONTENT

Day	Description	Percentage moisture content at a depth of								R^2	F	t
		0 cm	30 cm	60 cm	90 cm	120 cm	150 cm	180 cm	210 cm			
Sep 2	Simu	26.50	32.50	31.00	29.00	27.50	23.50	25.50	24.63	0.85	1.43	0.04
	Obsd	27.78	34.51	31.03	28.59	25.00	24.41	25.92	23.36			
9	Simu	20.01	33.31	31.80	29.00	25.50	22.60	22.80	22.16	0.95	1.25	0.02
	Obsd	20.45	33.47	30.33	28.24	24.17	23.82	23.71	22.55			
16	Simu	43.80	34.61	30.00	28.30	26.60	22.30	22.20	23.16	0.94	1.16	0.21
	Obsd	47.10	35.10	29.17	28.12	24.75	24.52	24.29	24.29			
24	Simu	41.85	33.92	31.61	28.86	27.60	23.30	23.10	25.11	0.93	1.08	0.15
	Obsd	41.95	34.98	31.73	28.70	25.00	25.22	25.00	26.50			
Oct 5	Simu	35.55	32.21	31.43	26.76	27.00	22.60	21.50	22.18	0.84	1.22	0.22
	Obsd	36.49	32.54	30.80	25.10	25.00	25.00	23.48	25.00			
12	Simu	37.60	36.60	31.40	29.11	27.86	27.40	26.03	26.67	0.90	1.25	0.05
	Obsd	39.28	36.72	31.49	26.61	26.26	28.47	26.03	28.70			
21	Simu	28.20	32.62	31.12	30.26	29.86	27.14	27.10	25.21	0.80	1.55	0.17
	Obsd	28.24	31.84	31.84	29.98	28.70	28.24	28.01	26.19			
31	Simu	20.00	27.93	31.12	32.00	31.00	37.16	26.14	26.12	0.84	2.13	0.35
	Obsd	19.99	29.40	31.26	29.98	29.98	29.70	27.54	27.54			

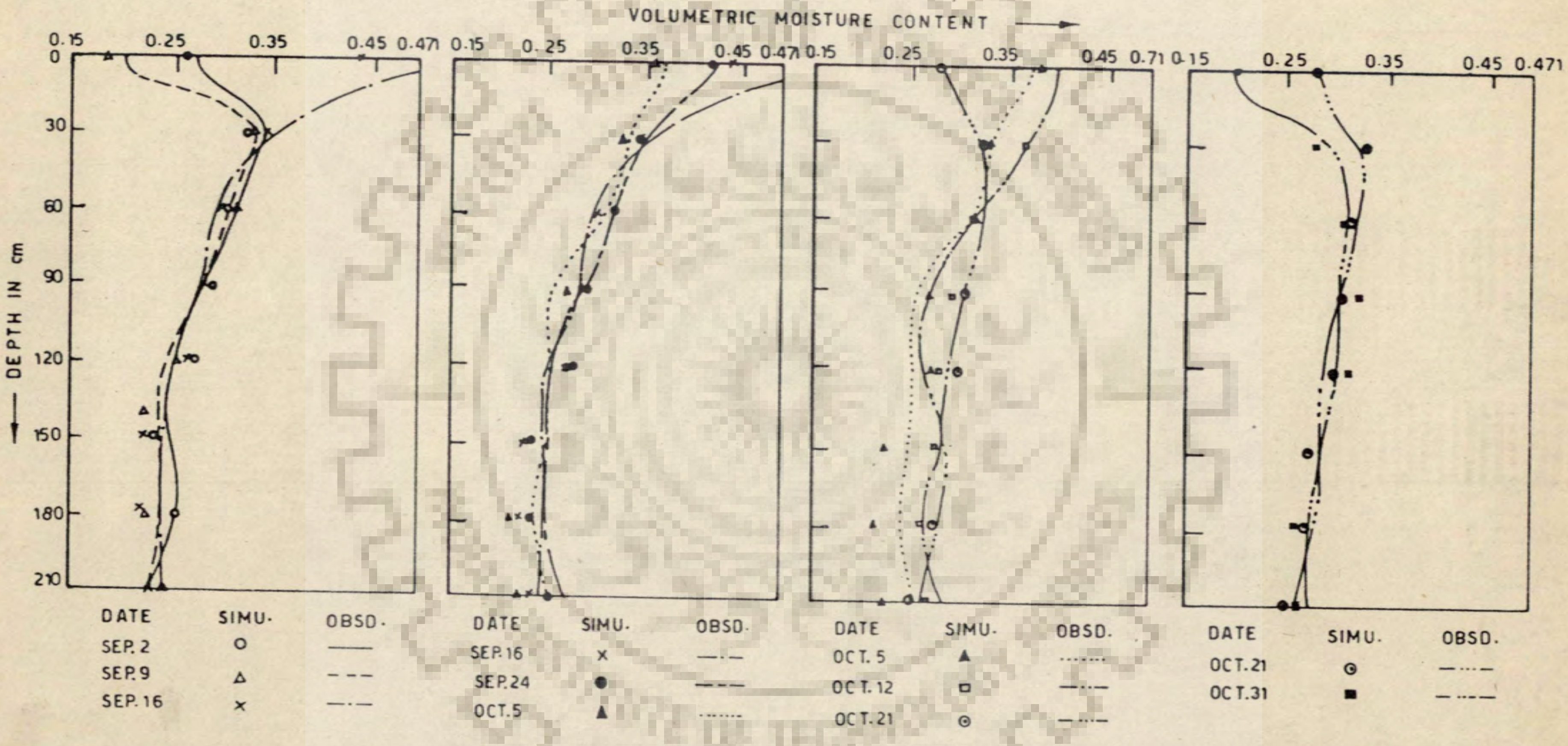


FIG. 5.4 – ADEQUACY OF DAILY RAINFALL AND CLASS A PAN EVAPORATION: SIMULATED AND OBSERVED MOISTURE PROFILES

CHAPTER - VI

MODEL APPLICATION

In this chapter, the model capabilities of scheduling irrigation and estimating time distribution of return flows are illustrated. A critical comparision of the return flows given by the soil moisture accounting model (chapter III pp 43-44) with those given by the present distributed model under identical condition is made. These three excercises are described in section 6.1, 6.2 and 6.3 respectively.

6.1 SCHEDULING IRRIGATION

This excercise is aimed at illustrating the model's capability of scheduling irrigation for a crop and an allowable depletion level of the available moisture of part of entire root zone or requirement of maintaining a minimum ponded water depth.

The level of depletion(f) is quantified in terms of field capacity (FC) wilting point (WP) and soil moisture content (θ_p).

$$f = \frac{FC - \theta_p}{FC - WP} \; 100 \qquad 0 \leq f \leq 100 \qquad 6.1$$

Rice is a semi-aquatic plant with shallow root zone. So moisture depletion even to a little extent is not desirable. Hence, in upland rice cultivation, moisture content of the root zone is maintained at field capacity where as in lowland rice cultivation (Submergence cultivation) water is kept ponded on the surface as a conservative measure, so that the moisture depletion is replenished immediately and automatically.

Thus, the criteria for irrigation schedule is fixed either interms of an allowable soil moisture depletion (f_{max}) of part of /entire root zone or in terms of ponding depth.

Apart from computing the irrigation schedule, the model provides time distribution of evapotranspiration. These data can be used to calculate yields (eg., Doorenbos et al 1979). Thus, the model can assist the planners in arriving at an optimal cropping pattern and allowable moisture depletion levels. For this exercise, the following data will be required.

i. Initial condition

ii. Characteristics of the soil layers

iii. Position of lower boundary at all levels of simulation

iv. Rainfall series for the entire period of simulation. (If the planner wishes to schedule irrigation for a drought year, the corresponding series may be specified. Similarly, the schedule can be decided for a normal year by specifying the rainfall series of the normal year).

v. A sub model for calculation of actual evapotranspiration rate as a function of depth, time and θ (or h).

6.1.1 Working Philosophy

The model simulates capillary suction head distribution as a function of depth and time. Simulation is continued in time domain till the irrigation criteria is met. The check can be made by constantly monitoring the simulated capillary suction head (and so the moisture content) distribution in root zone or the cap. suction head at the node representing the ground surface. Mathematically, this monitoring means to verify the following appropriate inequivality.

$$\theta_a < \theta_p \Big|_{f=fmax} \qquad 6.2a$$

$$h_{1,j} > -D_{p\,min} \qquad (h_{1,j} \leq 0) \qquad 6.2b$$

where

θ_a : Average moisture content of part of/ entire root zone

$D_{p\,min}$: The desired minimum ponded depth of water.

If the inequivality is satisfied, it means that, irrigation is required at the time of jth level of simulation. Ideally speaking, the irrigation dose will be just to dissatisfy the inequivality. But in such a case the frequency of irrigation increases. A higher irrigation may reduce the frequency, but at the same time the deep percolation of water may increase. However, the excessive deep percolation can be reduced by restricting the requirement to buildup soil moisture upto maximum water holding capacity. In case of ponded depth requirement also, irrigation dose will be to just dissatisfy the corresponding inequivality. In such a case, in this case also, the frequency increases. A higher irrigation may reduce the frequency but buildup of the ponded depth of water may lead to a situation wherein bunds of the irrigated plot are over topped and surface runoff is initiated. In such a situation, the valuable irrigation water is lost in the form of overland flow (runoff). So, in case of ponded water requirement, the irrigation may be restricted to buildup a maximum depth, so that runoff losses are minimum and preferably zero. Thus, the irrigation requirement may be calculated as

$$AI = (FC - \theta_a) \; R_{t_j} \qquad 6.3a$$

or

$$AI = D_{p\,max} + h_{1,j} \qquad (h_{1,j} \leq 0) \quad 6.3b$$

where

R_{t_j} : length of prescribed part of root zone (eg. Top 30 cms) $= \sum_{l=1}^{NR_j} \overline{\Delta z_l}$

$D_{p\,max}$: Prescribed maximum ponded depth of water

NR_j : The last depth node number of the root zone for the prescribed R_{t_j}

The requirement calculated may be a floating point value. Depending on the local practice, it may be rounded to a standard value. The duration and pattern of the application can be specified in accordance with the local practice. Beyond this duration, the simulation is continued with rainfall as input, till the irrigation criteria is again met with.

6.1.2 Illustration

The capability of the model, to schedule irrigation has been illustrated by the following examples.

6.1.2.1 Soils and Crops: Three crops, namely, Rice, Wheat and Sugarcane have been used for illustration. In the context of North India Rice is a 'Kharif' (Rainy season) crop, Wheat is a 'Rabi' (Winter season) crop and sugarcane is a perennial (11 months) crop. Two soils clay and loam are considered. The illustration consists of the following crop combinations.

Rice followed by what on clay
Rice followed by wheat on loam
Sugarcane on loam.

6.1.2.2 Conditions of operation: The model has been operated under the following conditions.

i. Rice and Wheat are grown on the same plot.
ii. In the fallow period, casual unirrigated crops which are as good as reference crop are grown.
iii. In the period of presowing operations, the crop is as good as the reference crop. However, the effects of presowing operation like tillage etc. are not considered.
iv. Application of irrigation is ceased, even if the criteria demands, before 15 days from the harvest date.

v. The irrigation is applied uniformly for a period of 6 hours from the start of the day. Thus, the simulated moisture content distribution of the root zone or ponded water depth is monitored at the beginning of every day for checking the appropriate inequivality (ie., eqn. 6.2).

vi. In case of rice grown on clay the criteria is to apply irrigation if ponded water depth falls below 50 mm(ie., $D_{p_{min}}$). Maximum depth of ponding is prescribed as 100 mm (ie., $D_{p_{max}}$). The requirement is rounded to the nearest higher integer multiple of 25 mm.

vii. For rice grown on loam, no depletion of the moisture (in the entire root zone on the day) is allowed (ie., $f_{max} = 0$).

$$AI = (FC - \theta_a) \times R_{tj} \quad \text{if } \theta_a < FC$$

where

θ_a : Average moisture content of root zone at the start of the day.

The requirement is rounded to the nearest higher integer multiple of 75 mm (3").

viii. For wheat and sugarcane on either loam or clay, a depletion of moisture (in the entire root zone on the day) by 50 percent is allowed (ie., $f_{max} = 50$).

Thus, irrigation is applied if the average moisture content of root zone (θ_a) falls below θ_p, calculated from equation 6.1 with f equal to 50

$$AI = (FC - \theta_a) \times R_t \quad \text{if } \theta_a < \theta_p \big|_{f = 50}$$

The requirement is rounded to the nearest higher integer multiple of 75 mm (3").

ix. The interception and direct evaporation losses from irrigation are not accounted.

x. The irrigation is uniform on the entire plot.

6.1.3 Data

6.1.3.1 Crop activities: As per Tripathi (1985) and as per local practice, the crop activity details adopted are as follows:

Activity Crop	Pre-sowing (Field preparation)	Sowing	Harvesting
Rice	1 to 5 Jul.	6 Jul.	15 Oct.
Wheat	15 to 19Nov.	20 Nov.	15 Mar.
Sugarcane	15 to 19Mar.	20 Mar.	15 Feb.

6.1.3.2 Rainfall : A real life data of daily rainfall (Annexure I-f), corresponding to normal average year of a station has been used. The rainfall has been assumed to be uniform through out the day. The interception and direct evaporation losses (from rainfall) have been not accounted.

6.1.3.3 Evaluation of $\bar{E}$: Monthly values of potential evapotranspiration (reference crop) monitored close to the rainguage station (annexure I-f) have been adopted. It has been assumed that the monthly values are uniformly distributed throughout the respective month. Using the crop coefficients (based on crop and stage of growth) advocated by Doorenbos et al (1979), potential evapotranspiration rates (E_p) of crop in each day have been calculated for the three crops. In Table 6.1 the daily potential evapotranspiration of reference crop, the crop coefficients (as a function of crop and stage of growth) and the daily potential evapotranspiration of the crops have been presented. For sugarcane, wheat and fallow period crop, the E_p, θ, and $\bar{E}$ are related as shown in Fig. 6.1.

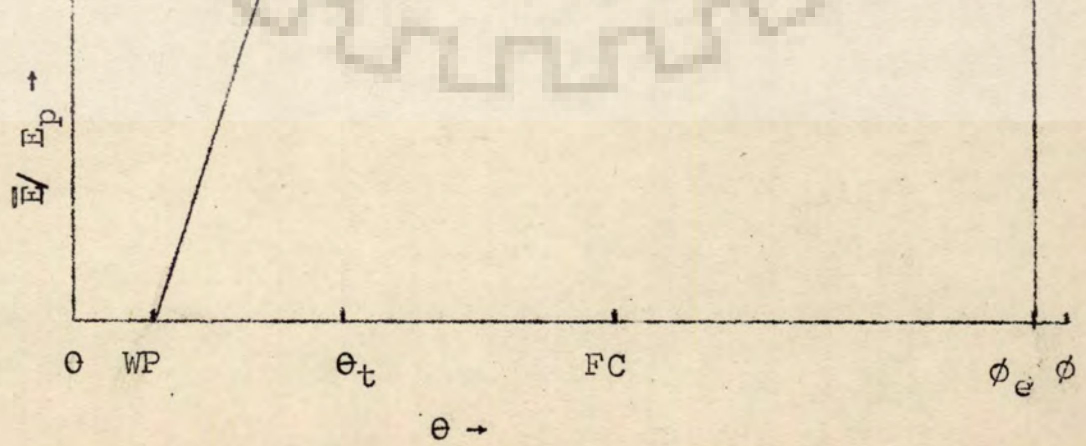


Fig. 6.1 RELATION BETWEEN E_p, $\bar{E}$ AND θ.

Table 6.1 Stage of growth, crop coefficient, factor 'P' and daily potential evapotranspiration of crops.

Rice

Stage of growth	Initial	Development	Mid	Late		Harvest
Period	6-20 Jul	21-31 Jul	Aug	1-15 Sep	16-30 Sep	1-15 Oct
Crop Coeff KC	1.125	1.3	1.2	1.2	1.0	1.0
Factor p		Doesn't arise (Refer the text)				
PET mm	5.91	6.84	5.5	5.69	4.74	3.59

Wheat

Stage of growth	Initial	Development	Mid	Late	Harvest
Period	20-30 Nov	Dec	Jan	Feb	1-15 Mar
Crop Coeff. KC	0.35	0.75	1.125	0.7	0.225
Factor p	0.8	0.8	0.8	0.8	0.8
PET mm	0.77	1.05	1.93	1.88	0.92

Table 6.1

Sugar Cane

Stage of growth	Initial		Development			Mid				Late		Harvest
Oeriod	20 -31 Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec	Jan	1-15 Feb
Crop Coeff KC	0.45	0.45	0.85	0.85	0.85	1.15	1.15	1.15	1.15	0.775	0.775	0.55
Factor of P	0.875	0.829	0.55	0.531	0.653	0.59	0.58	0.687	0.836	0.875	0.875	0.875
PET mm	1.85	2.62	6.09	6.38	4.47	5.27	5.45	4.13	2.52	1.09	1.33	1.47

Fallow (reference Crop)

Stage of growth	Doesn't arise											
Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crop Coeff. KC	Doesn't arise											
Factor p	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PET m	1.71	2.68	4.1	5.83	7.16	7.50	5.26	4.58	4.74	3.59	2.20	1.40

The relation implies that $\bar{E}$ will be zero for moisture contents at or below wilting point and at or above effective porosity ie, $(\phi - \theta_r)$ (because of development of anaerobic conditions).

Further the relation implies that, $\bar{E}$ will be at potential rate even if the moisture content falls below field capacity, by certain extent. Thus, factor p can be quantified as

$$p = \frac{FC - \theta_t}{FC - WP} \qquad 6.4$$

where,

θ_t : The threshold moisture content upto which the $\bar{E}$ is at potential rate.

The factor p for sugarcane and wheat in the relation (equation 6.4) have been adopted from Doorenbos et al (1979) and are presented in table 6.1. In case of the fallow period crop p has been taken as zero. The $\bar{E}$ at any node has been calculated using the moisture content at the node, and the proportionate (uniformly distributed) E_p. In case of rice, the $\bar{E}$ at any node in the root zone has been assigned as the proportionate (uniformly distributed) potential rate. Reported values (Rawls et al 1981) have been adopted for the wilting point. These are 0.15 and 0.055 for the clay and the loam respectively. Field capacity has been quantified from the K characteristic (refer 6.1.3.5) as per the proposed method described in Chapter iv pp.92 to 94. These are 0.225 and 0.125 for the clay and the loam soils respectively.

6.1.3.4 Root zone depth : Fortnightly increase in root zone depth for various crops have been adopted from Tripathi (1985) The root zone depth has been assumed to be constant in the fortnight at the starting value(in the fortnight)and the change has been assumed to be instantaneous at the turn of the fortnight. If the root zone depth in any fortnight is less than 30cms, the depth has been adopted to be 30 cm by assuming that the direct evaporation from soil takes place from top 30 cms. Thus, a minimum root zone depth of 30 cms has been considered to be effective for evapotranspiration. Annexure I-g shows the fortnight wise. discritized root zone depth of the three crops. For fallow period crop a time invarient root zone depth of 30 cms has been adopted.

6.1.3.5 Characteristics: In the absence of experimental or specific data availability, following relations have been adopted.

$$K = K_s \left(\frac{\theta - \theta_r}{\phi - \theta_r} \right)^{4.0} \qquad \theta \geq \theta_r \quad \text{Brooks-Corey (1964)}$$

$$= 0.0 \qquad \theta < \theta_r \qquad 6.5$$

$$\theta = \phi - \frac{\theta_r}{h_b} h \qquad 0 \leq h \leq h_b$$

$$\theta = \exp\left[\frac{\ln(\phi - 2\theta_r)}{h_b} h\right] + \theta_r \qquad h \geq h_b \qquad 6.6$$

Reported values (Rawls etal 1980) **have been used for** θ_r, ϕ, K_s and h_b, to define the relations. These are 0.09, 0.475, 1.667E - 4 mm/sec and 850 mm respectively for clay and 0.027, 0.463, 1.889 E-3mm/sec and 401.2 mm respectively for loam. Fig. 4.13 shows the plots of the K characteristics.

6.1.3.6 Boundary conditions: The available monthly depth to water table of an observation well (Annexure I-f), near by the raingauge station, have been used to arrive at the daily depths by linear interpolation. It has been assumed that the water table is stationary during a day and the variation takes place instantaneously at the turn of the day. The upper boundary condition is identified and assigned using the algorithm developed.

6.1.3.7 Initial conditions and model operation: Ideally speaking, the initial condition should be available through actual measurement. In the absence of such a measured information, the initial conditions have been generated as follows:

Imagining an idealistic situation, of indefinite stationary water table, of no input and of no evapotranspiration, if the unsaturated zone is left to its course of redistribution, an ultimate situation will arise where in capillary suction head is balanced by gravity head. Strictly speaking, it may require an infinite time to attain such a depthwise distribution of capillary suction head. However, depending on soil properties, the practical attainment (of the ultimate situation) may require different finite time periods. In this ultimate position, the capillary suction head distribution in depth is known, as it is numerically equal to elevation (i.e. gravity head). If the depth wise moisture contents are measured at this stage, the h-θ relation can be obtained. In other words, the h-θ relation itself is the ultimate moisture profile, wherein the moisture content at a depth is the minimum that can be held by the soil at that depth. So this may be called as the equilibrium profile (Bear 1972). The equilibrium distribution has been adopted as the initial condition. But this may not be a correct specification as the equilibrium profile is very idealistic. However, the errors incurred by such specification of initial condition can be over come by operating the model for number of years , using the same data, till the initial condition used, in the simulation, in two consecutive years are practically nearer. This approach is analogus to the concept of dynamic equilibrium (Kashyap 1981) in the saturated flow zone literature. Hereinafter, the initial condition of the first year of the two consecutive years, will be refered as dynamic equilibrium condition and the first year (of the two consecutive years) will be refered as dynamic equilibrium year. Mathematically, the procedure for obtaining the dynamic equalibrium can be expressed as

$$\text{Minimize } \varepsilon_{de} = \max_{i} \left| h_{i,j}^{(n)} - h_{i,j}^{(n-1)} \right| \qquad 6.7$$

where,

ε_{de} : prescribed small positive value

n = number of year.

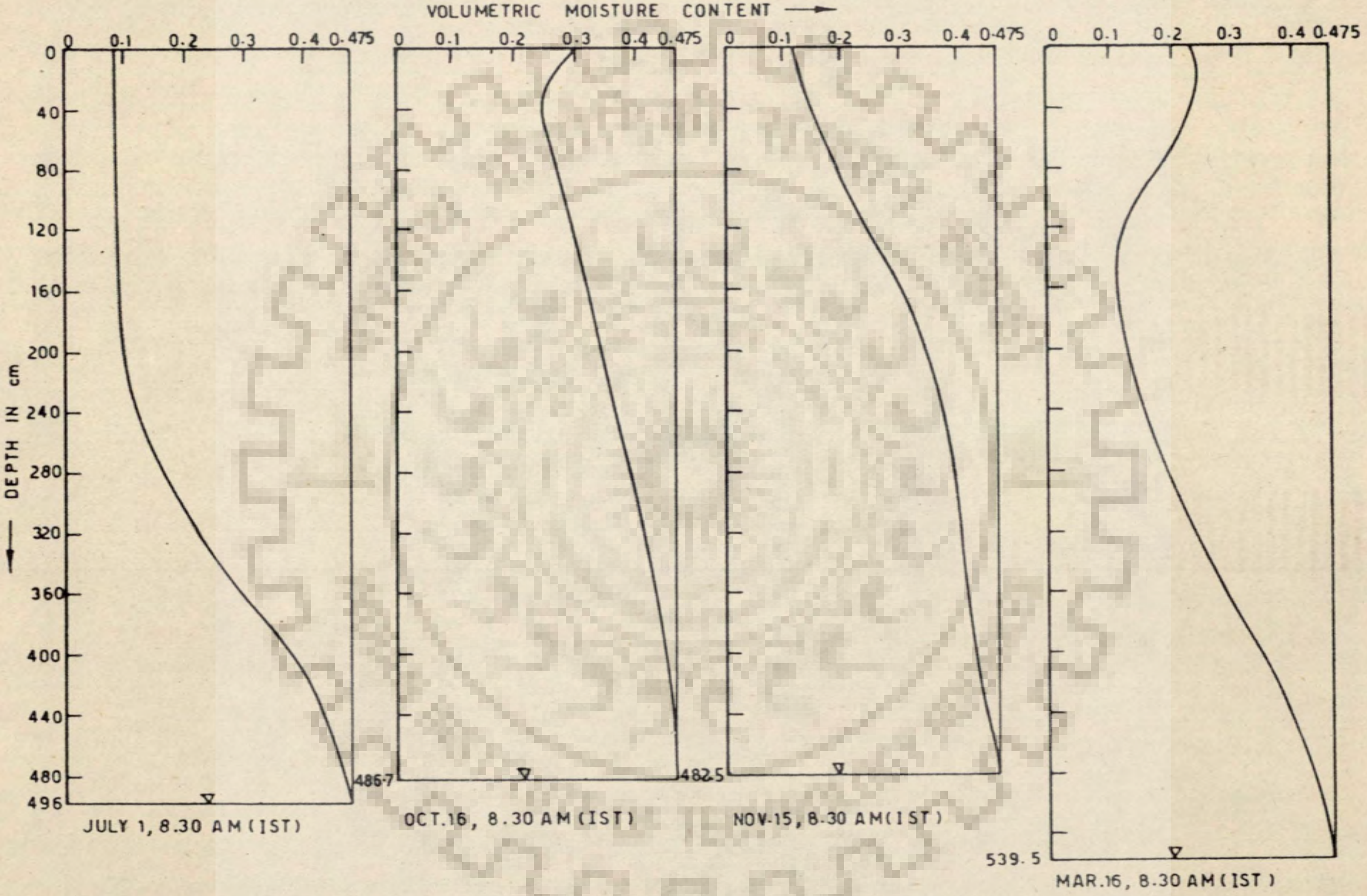
The irrigation scheduling done for the first year may be heavy, on account of relatively drier initial condition. The heavy irrigation reduces gradually from second year onwards. Subsequent to the dynamic equilibrium stage, the irrigation schedule repeats. Thus, the schedule in the dynamic equilibrium year will be nearer to reality. So, using the equilibrium distribution of 'h' as initial condition for the first year, the model has been operated with the same data for number of years, till the dynamic equilibrium is established. Factually, scheduling the irrigation in the dynamic equilibrium year completes the excercise.

6.1.4 Results

Figs 6.2, 6.3, 6.4 show the establishment of dynamic equilibrium for Rice-Wheat grown on clay, Rice-Wheat grown on loam and sugarcane grown on loam respectively. Table 6.2 and 6.3 show periodical abstracts (obtained from daily abstracts) of the rainfall, scheduled irrigation and actual evapotranspiration, in the dynamic equilibrium year, for Rice-Wheat grown on loam and sugarcane grown on loam, respectively. In Annexure III daily abstracts of rainfall, scheduled irrigation, infiltration, ponded water depth, evapotranspiration, change in moisture storage and recharge, for rice-wheat grown on clay, for the dynamic equilibrium year, have been presented.

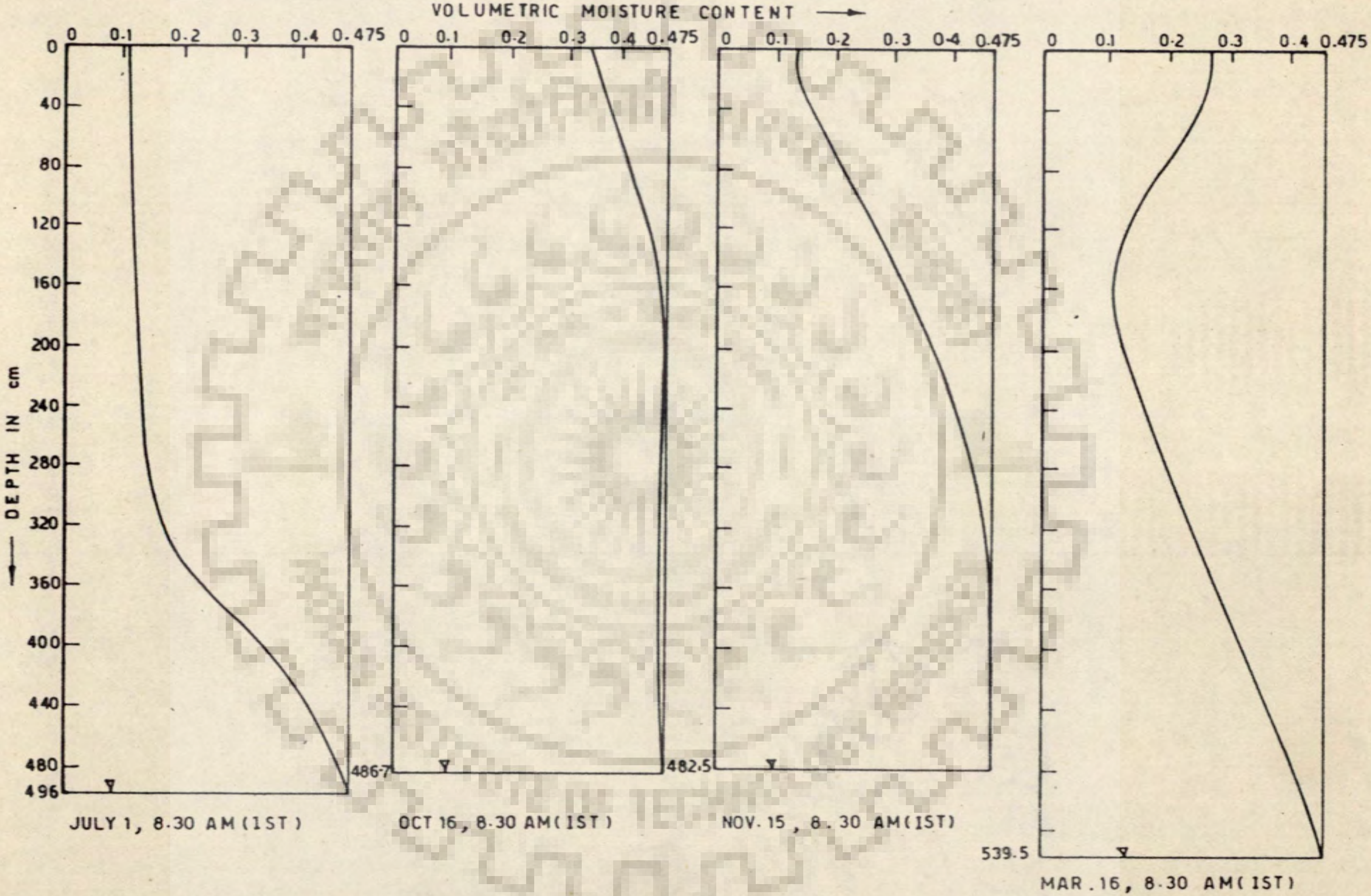
6.1.4.1 Discussion : The irrigation schedules have been arrived at for a specific irrigation criteria, soil type, series of rainfall, evapotranspiration, depth to water table. The studies have been done under the following conditions.

i. Unit dose of irrigation for the submergence rice cultivation is an integer multiple of 25 mm.



JULY 1, 8.30 AM (IST)   OCT.16, 8.30 AM (IST)   NOV-15, 8.30 AM (IST)   MAR.16, 8.30 AM (IST)

FIG. 6.2 a _ ESTABLISHMENT OF DYNAMIC EQUILIBRIUM: RICE-WHEAT CROPPING ON CLAY, Ist YEAR



JULY 1, 8.30 AM (IST)

OCT 16, 8.30 AM (IST)

NOV. 15, 8.30 AM (IST)

MAR. 16, 8.30 AM (IST)

FIG.6.2b ESTABLISHMENT OF DYNAMIC EQUILIBRIUM: RICE - WHEAT CROPPING ON CLAY, 2nd YEAR

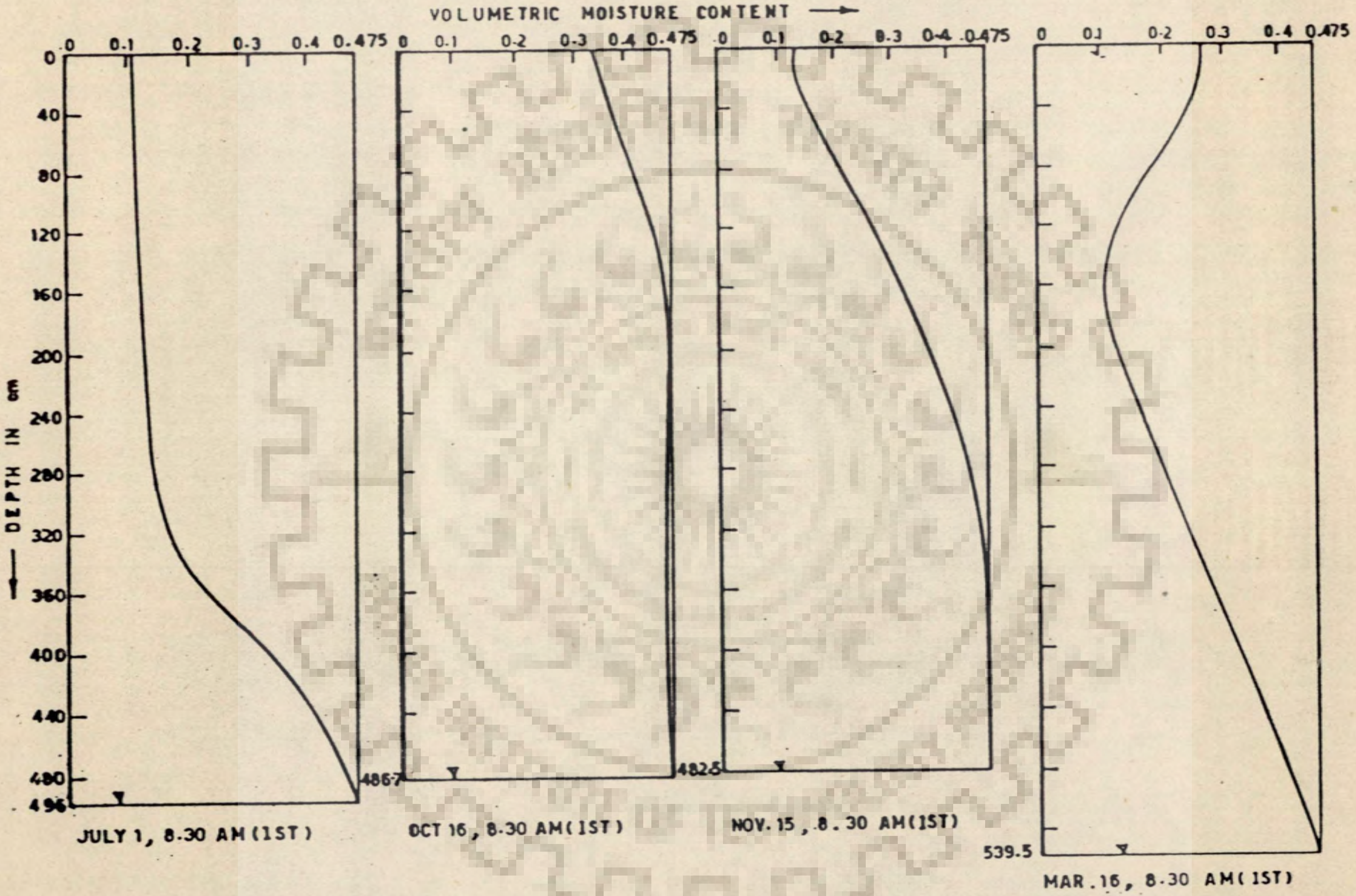
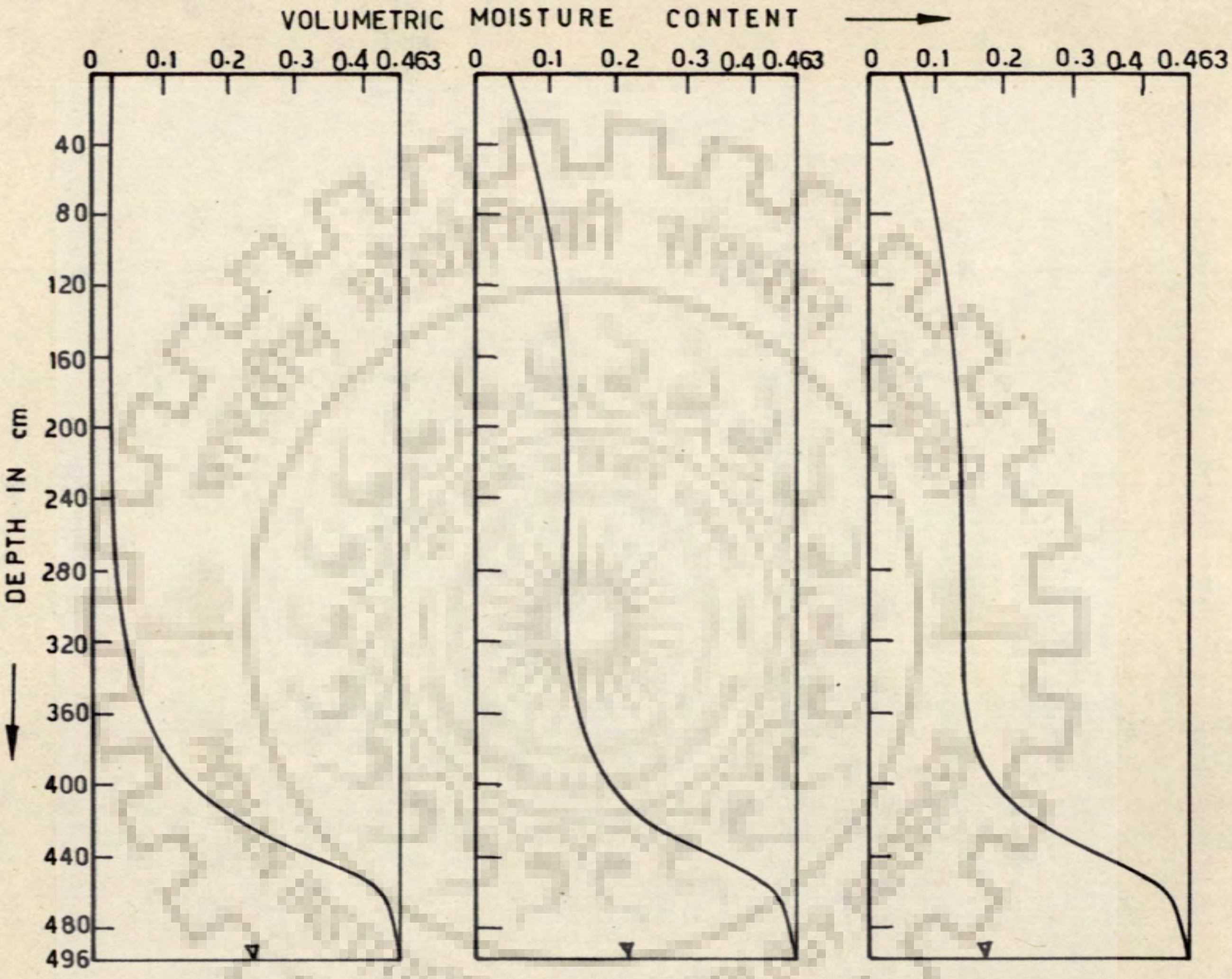
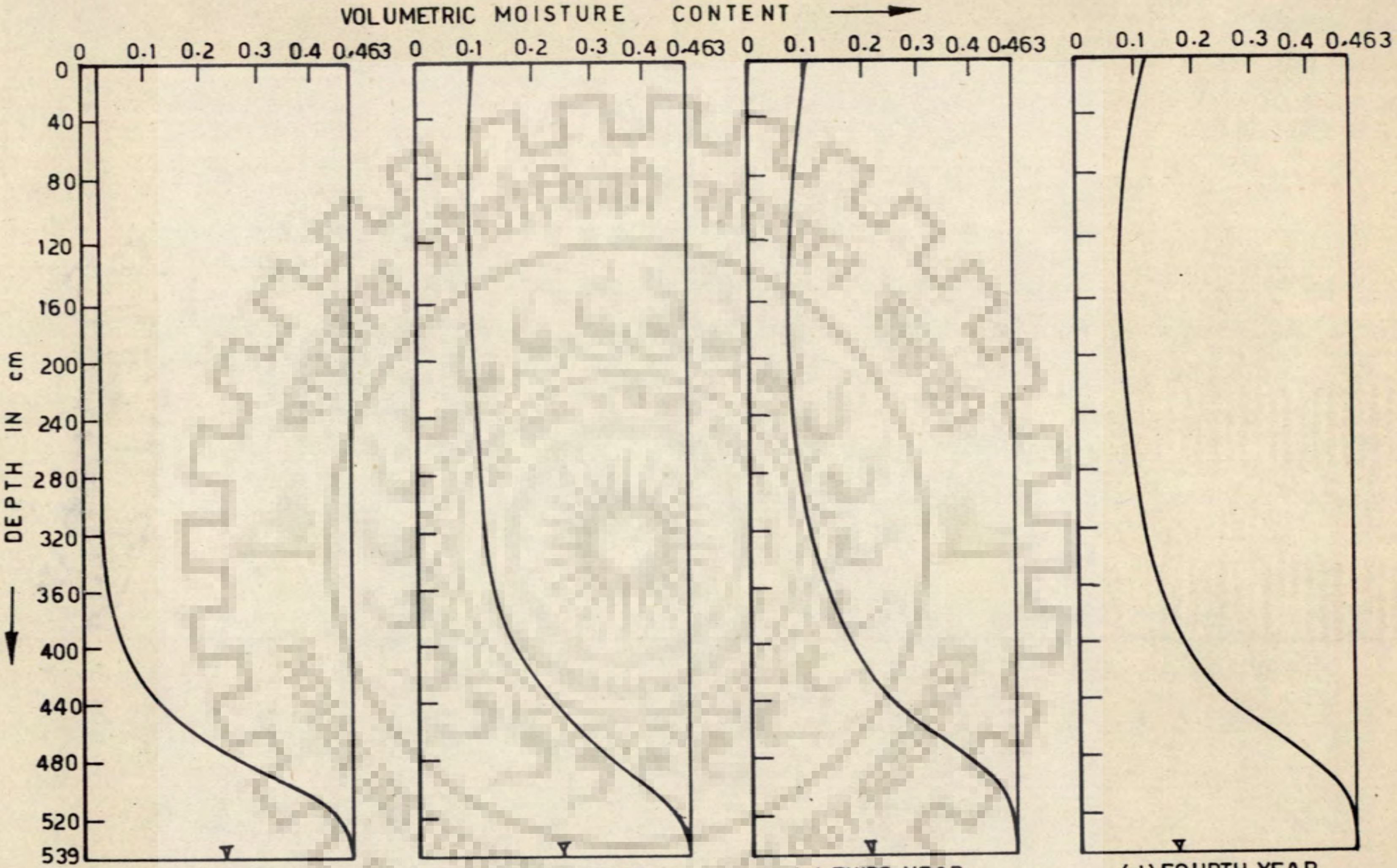


FIG.6.2C ESTABLISHMENT OF DYNAMIC EQUILIBRIUM: RICE-WHEAT CROPPING ON CLAY, 3rd YEAR



(a) FIRST YEAR (b) SECOND YEAR (c) THIRD YEAR

FIG. 6.3 _ ESTABLISHMENT OF DYNAMIC EQUILIBRIUM: RICE-WHEAT CROPPING ON LOAM



(a) FIRST YEAR (b) SECOND YEAR (c) THIRD YEAR (d) FOURTH YEAR

FIG. 6. 4 _ ESTABLISHMENT OF DYNAMIC EQUILIBRIUM : SUGARCANE CROPPING ON LOAM

Table 6.2 Periodical abstracts of rainfall, scheduled irrigation and simulated evapotranspiration: Rice-wheat cropping on loam.

Crop	Period	Rainfall mm	Irrigation mm	Evapotranspiration mm	Potential ET mm
Rice					
Presowing	1-5 Jul	11.0	75(1)	20.42	26.30
	6-31Jul	363.20		163.89	163.89
	Aug	142.20	75(27)	170.50	170.50
	Sep	130.10	75(22)	156.45	156.45
	1-15 Oct.	9.60		53.85	53.85
Fallow	16-31 Oct.	0.0		5.44	57.28
	1-14 Nov.	1.20		0.58	30.80
Wheat					
Presowing	15-19 Nov.	0.0	75(15)	10.61	11.00
	20.30 Nov.	1.0		8.47	8.47
	Dec	0.0	75(29)	32.55	32.55
	Jan	43.5		59.83	59.83
	Feb	13.0		52.64	52.64
	1-15 Mar	0.0		13.22	13.80
Fallow	16-31 Mar	0.0		9.60	65.60
	Apr	38.70		28.87	174.90
	May	0.0		12.86	221.96
	June	0.0		0.20	225.00

Note - Fig. in brackets indicates the date of irrigation application in the month.

Table 6.3 Periodical abstracts of rain fall, scheduled irrigation and simulated evapotranspiration. Sugar cane cropping on loam.

Crop	Period	Rainfall mm	Irrigation mm	ET mm	PET mm
Sugarcane					
PresoWing	15 Mar-19 Mar	5.0	75(1)	19.48	20.50
	20 -31 Mar	5.5	75(30)	22.20	22.20
	Apr	4.0	75(14),75(30)	78.60	78.60
	May	11.0	75(13) 75(26)	188.79	188.79
	Jun	70.20	75(13)	191.40	191.40
	Jul	374.2	75(10)	138.57	138.57
	Aug	142.20		163.37	163.37
	Sep	130.10		163.50	163.50
	Oct	9.60	75(9)	128.03	128.03
	Nov	2.20	75(7)	75.60	75.60
	Dec	0.0		33.79	33.79
	Jan	43.50	75(4)	41.23	41.23
	1-15 Feb	13.0		22.05	22.05
Fallow	16-28 Feb	0.0		18.39	34.84
	1-14 Mar	0.0		5.90	57.40

Note - Fig. in brackets indicates the date of irrigation application in the month.

ii. Unit doese of irrigation for the upland rice, wheat and sugarcane is an integer multiple of 75 mm.

iii. The field preparation and leaching requirements are not accounted for.

iv. The interception and direct evaporation losses from irrigation and rainfall are not accounted for.

v. There is no overland flow.

vi. The application of irrigation is uniform on the entire plot.

vii. Lateral surface as well as subsurface (in the unsaturated zone) flows are not accounted for.

The irrigation criteria are as follows.

S.No.	CROPPING	SOIL	IRRIGATION CRITERIA
1.	Rice followed by wheat	Clay	Rice-requirement of maintaining ponded water depth between 50 mm to 100 mm, up to harvest subseason. Wheat-requirement of maintaining average moisture content, of the entire root zone, at or above the mid value, between wilting point and field capacity, up to harvest subseason
2.	Rice followed by wheat	Loam	Wheat-as above Rice-requirement of maintaining average moisture content, of the entire root zone, at or above field capacity upto harvest subseason.
3.	Sugarcane	Loam	Same as wheat

A comparision of the results with the available data on generally existing local practice,under near identical conditions of rainfall, evapotranspiration and soil type are given in table 6.4.

It may observed, from the table that,incase of the upland rice, wheat and sugarcane, the computed irrigation totals are on the lower side (compared to the general local practice). This systematic deviation, could have been due to the operative conditions, from iii. through vi. Another, perhaps,major reason could be the irrigation criteria ie., permitting moisture depletion (upto the allowable extent) in the entire root zone before irrigation is applied. The farmer, on the other hand, determines the necessity to irrigate by 'feeling' the moisture depletion in the top soil only. To check this argument, the model has been re-operated for the wheat cropping on loam with a modified irrigation criterion. The criterion was the requirement of maintaining average moisture content of upper 30 cms (usual tillage depth), of the root zone, at or above field capacity. In Table 6.5 the periodical abstracts of rainfall, irrigation, evapotranspiration have been presented. Table 6.6 below shows the computed irrigation along with the generally existing local practice.

Table 6.4 Comparision of Model Scheduled fortnightly irrigation with the generally existing local practice

Soil and Cropping	Description	Fortnightly irrigation in mm																						Source for data on generally existing local practice
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Total	
Rice[illegible] Loam (up land cultivation) 1Jul-15Oct	Generally existing local practice	375 x	75	75	75	75	75																750	Tripathi[4] (1985)
	Model scheduled	75	0	0	75	0	75																275	
Rice on clay (Submergence cultivation) [illegible]t.	Generally existing local practice		Distribution not available																				1800-4400	Rajput (1984) Tripathi(1985)
	Model scheduled	500	300	425	500	450	450																2625	
Wheat on loam 15 Nov-15Mar	Generally existing local practice	175xx	75	75	75	75	75	75															625	Tripathi (1985)
	Model scheduled	75	0	75	0	0	0	0															150	
Wheat on clay 15Nov-15Mar	Generally existing local practice		Distribution as well as total not available																					
	Model scheduled	75	0	0	0	0	0	75															150	
Sugarcane on loam 15Mar-15Feb	Generally existing local practice	225xxx	75	150	75	150	75	150	75	150	0	0	0	0	0	150	75	150	75	75	75	0	1725	Tripathi (1985)
	Model scheduled	75	75	75	75	75	75	75	0	75	0	0	0	0	0	75	0	75	0	0	75	0	825	

x Including field preparation requirement of 300 mm.

xx Including Palewa (Preirrigation) requirement of two 50mm doses.

xxx Including field preparation requirement of 150mm.

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Table 6.5 Periodical abstracts of rainfall. Scheduled irrigation and simulated evapotranspiration with the modified irrigation criteria, wheat cropping on loam.

Crop	Period	Rainfall mm	Irrigation mm	Evapotranspiration mm	Potential evapotranspiration mm
Wheat					
Presowing	15 Nov-19 Nov	0.0	75(15)	10.62	11.00
	20 Nov-30 Nov	1.0	75(27)	8.47	8.47
	Dec	0.0	75(11),75(26)	32.55	32.55
	Jan	43.5	75(17)	59.83	59.83
	Feb	13.0	75(16)	52.64	52.64
	1-15 Mar	0.0		13.80	13.80

Note : Fig. in brackets indicate the date of application of irrigation in the month.

Table 6.6 Fortnightly irrigation:Generally existing local practice and model scheduled wheat cropping on loam.

Fortnight	1	2	3	4	5	6	7
Generally Existing local practice (Tripathi 1985)	175*	75	75	75	75	75	75
Total Irrigation Computed	150	75	75	0	75	0	75

* Including two irrigations of 50 mm each for field preparation.

It may be seen from the above table that, the computed irrigation distribution as well as amounts are very close to the generally existing local practice.

In case of the submergence rice cultivation also, the model operative conditions serial numbered iii. through iv. may lead to an under estimation of irrigation requirements. However, in case the lateral surface and the subsurface inflows are significant (eg. Majority of the rice fields in Andhra Pradesh and Karnataka of the Indian union) the model may over estimate the irrigation requirements. This is corroborated by a few reported figures of irrigation requirements for submergence rice cultivation. However, this argument could not be cross checked by any subsequent model studies, as the model is not capable of simulating the lateral surface and subsurface flows.

The operative conditions given in i. through iv. can be varied in accordence with the requirements of the problem. For instance, the adequacy of return flow in providing the necessary leaching can be checked by the theory of leaching (Lecture notes ICLD 1973, Hoffman 1985). However, the effects of violation of the other conditions v through vii. may possibly be compensated subjectively, by adopting appropriate multiplication factors.

6.2 ESTIMATION OF RETURN FLOWS

Operation of the saturated flow models is done, by assuming that, the net excitation comprises of algebraic sum of withdrawls and the return flows, from rainfall and applied irrigation. In the present model, the computed time distribution of recharge, with a varying water table, is not identically equal to the return flow. This is due to the fact that, any fall of water table hastens the process of vertical drainage. This excess should not be attributed to the return flow. Integration of this excess in time (up to ∞) will obviously be equal to specific yield times the fall. Incidentally, this will far exceed the release of water from the desaturated zone (Fig. 6.5). Similarly, in case of rising water table, the vertical drainage is impeded, resulting in a reduction of recharge. In this situation also the reduction (in recharge) should not be attributed to the return flow. For the sake of understanding,

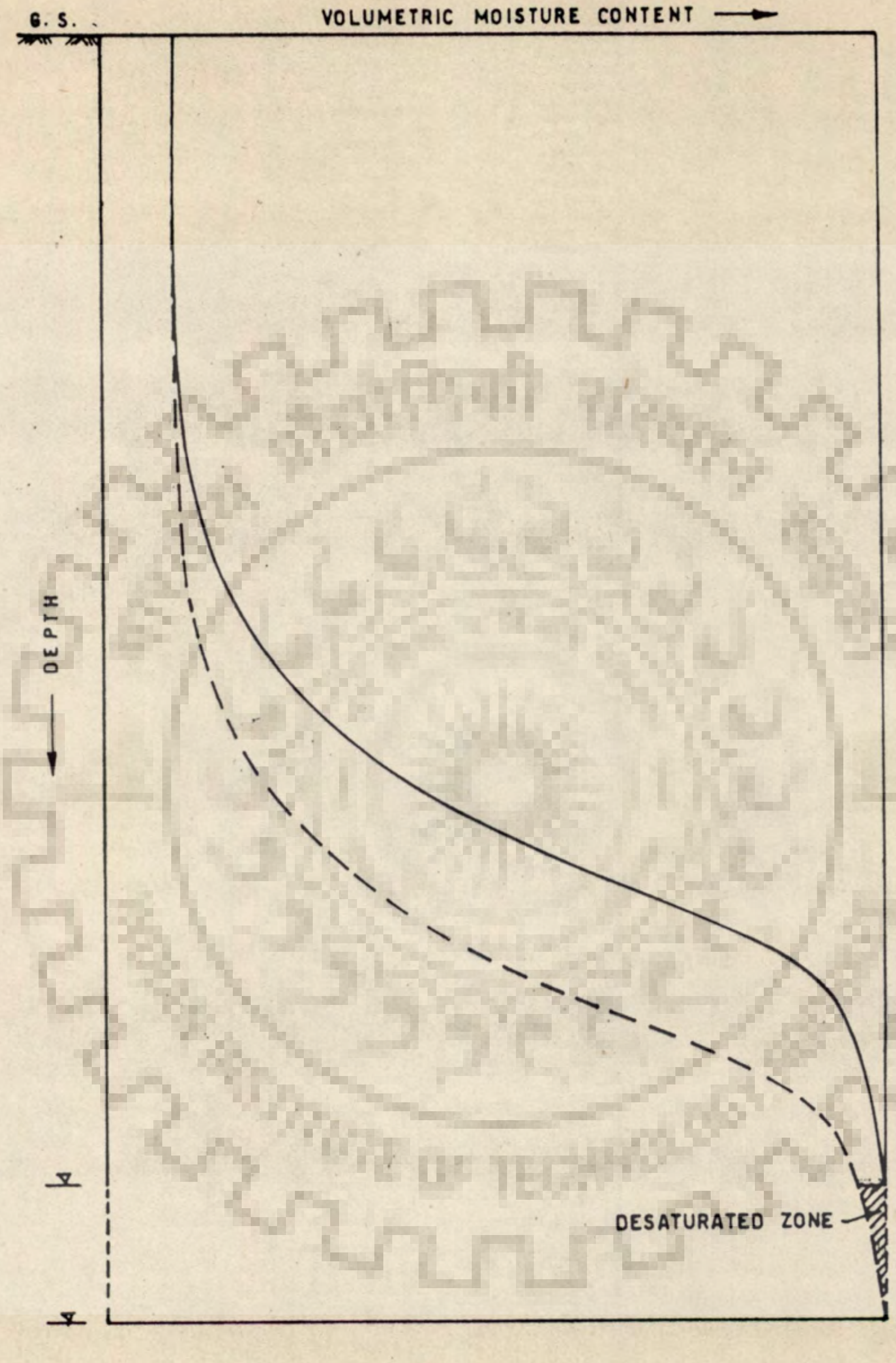

FIG. 6.5 _ EFFECT OF FALLING (RISING) WATER TABLE

the recharge RR_j in any jth time step may be written as follows.

$$RR_j = u_j + v_j$$

where

u_j : Return flow in the jth time step [L]

v_j : Flow caused by variation of water table in jth time step. [L]

These two components are not discriminated in the physical process of flow and it may not be possible to seperate them explicitly. As already mentioned, the total volume of water released on account of the excess recharge will be equal to the specific yield times the net change in water table position (i.e., $\sum_{j=1}^{\infty} v_j = Sy \times \delta h$). Thus, the total amount of return flow (only) can be estimated. However, this may not meet the input data requirement of a time distributed saturated flow model. In this context, the author suggests the following approximate method for the estimation of return flow.

6.2.1 Approximate method :

If the (time) variations of the water table are small, they may be neglected and an average depth of flow domain may be assigned. In the light of discussion made earlier, it is obvious that, under Dirichlet upper boundary condition, the hastened vertical drainage associated with a falling water table, results in increased infiltration rates. Similarly, the rising water table is associated with a decrease in infiltration rates. The falling water table postpones the surface saturation and prepones the surface desaturation. The rising water table gives a diametrically opposite effect (the surface saturation is preponed and surface desaturation is postponed). Obviously, this approach can not account for these effects of changing water table.

6.2.2 Estimation of time distribution of return flow

This study is aimed at illustrating the model's capability of estimation of the return flows, with the aid of the suggested method. The data of the dynamic equilibrium year (refer study 6.1) has been used for this study also. The simulation has been carried out again for the dynamic equilibrium year. Operational details of the model are same as per 6.1 but for the following.

i. The initial condition has not been generated. The dynamic equilibrium profile has been taken as initial condition.

ii. The irrigation schedule was not arrived at. The dates and doses as obtained in 6.1 have been used directly.

iii. The position of lower boundary (Water table) has been prescribed to be time invarient. The depth of time invarient water table used has been 4960 mm (depth at the initial condition).

6.2.3 Results -

Fig.6.6 shows the superposed moisture profiles, the rice wheat cropping on clay, obtained in the previous and present excercises. It may be observed that the computed moisture profile with stationary water table are affected only marginally, by the assumption of a stationary water table.

Table 6.7 shows the relative change of water table position, periodical recharge estimated as per excercise 6.1 and periodical recharge (return flow) estimated in the present excercise, for the Rioe-Wheat cropping on the clay and the loam soil. It may be seen that, the results are in confirmation with the discussion made.

Fig. 6.6 and 6.7 show the moisture profiles obtained in the present excercise, for the rice-wheat cropping on the clay and the loam respectively. It may be observed from the figures that, there is a build up of moisture by the end of rice crop season. This build up is reletively high in case of clay soil (Fig. 6.6) due to its low conductivity and relatively large input.

Table 6.8 and 6.9 show the periodical abstracts of, rainfall, applied irrigation, return flow and percentage of return flow to the rainfall and applied irrigation, for the studies with clay and loam soils respectively. It may be seen from the tables that, the percentage of return flow in some advanced periods exceeds 100 percent of the inputs in

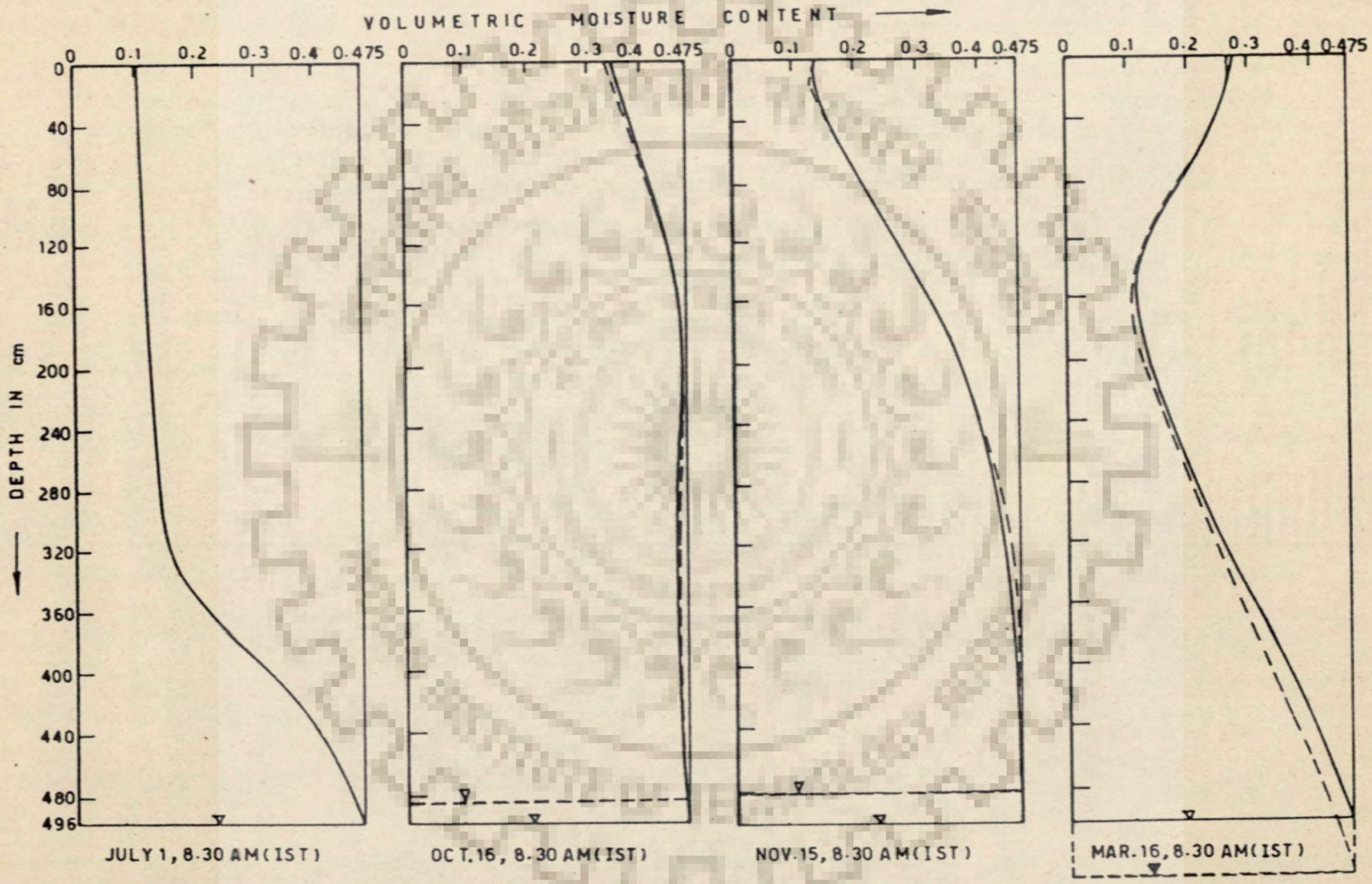

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FIG.6.6 _ ESTIMATION OF RETURN FLOWS– MOISTURE PROFILES: RICE-WHEAT CROPPING ON CLAY (BROKEN LINES SHOW THE PROFILES WITH TIME VARIENT WATER TABLE)

Table 6.7 Periodical abstracts of the return flows: Rice-wheat cropping on clay as well as on loam.

Crop	Period	Relative change of depth of watertable* mm	Clay Soil Recharge mm		Loam soil Recharge mm	
			Variable watertable	Stationary watertable	Variable watertable	Stationary watertable
Rice presowing	1 - 5 July	- 5.16	11.58	23.58	- 15.14	7.01
	6 -31 July	-32.55	287.11	291.14	- 29.17	9.66
	Aug	-117.42	449.32	453.62	- 32.99	12.79
	Sep.	92.40	771.76	762.11	134.24	100.27
	1 -15 Oct.	- 27.83	200.08	200.21	45.74	46.88
Fallow	16 -31 Oct.	- 35.61	159.00	163.26	38.73	45.65
	1 -14 Nov.	- 7.00	95.83	100.47	36.25	37.57
Wheat Presowing	15 -19 Nov.	- 0.83	23.29	24.07	9.71	13.44
	20 -30 Nov.	- 5.03	55.70	58.56	18.43	42.11
	Dec.	537.69	166.50	132.39	143.00	57.42
	Jan.	- 94.32	107.33	110.20	22.28	51.09
	Feb.	111.97	73.16	56.90	53.81	44.81
	1 - 15 Mar	17.84	33.41	26.65	33.17	22.77
Fallow	16 -31 Mar	15.48	28.90	27.30	21.48	17.63
	Apr.	242.64	68.27	34.56	75.61	25.38
	May	47.04	54.95	32.33	46.25	21.29
	June	-714.04	-54.23	29.24	-200.64	16.06

* -ve value means rise.

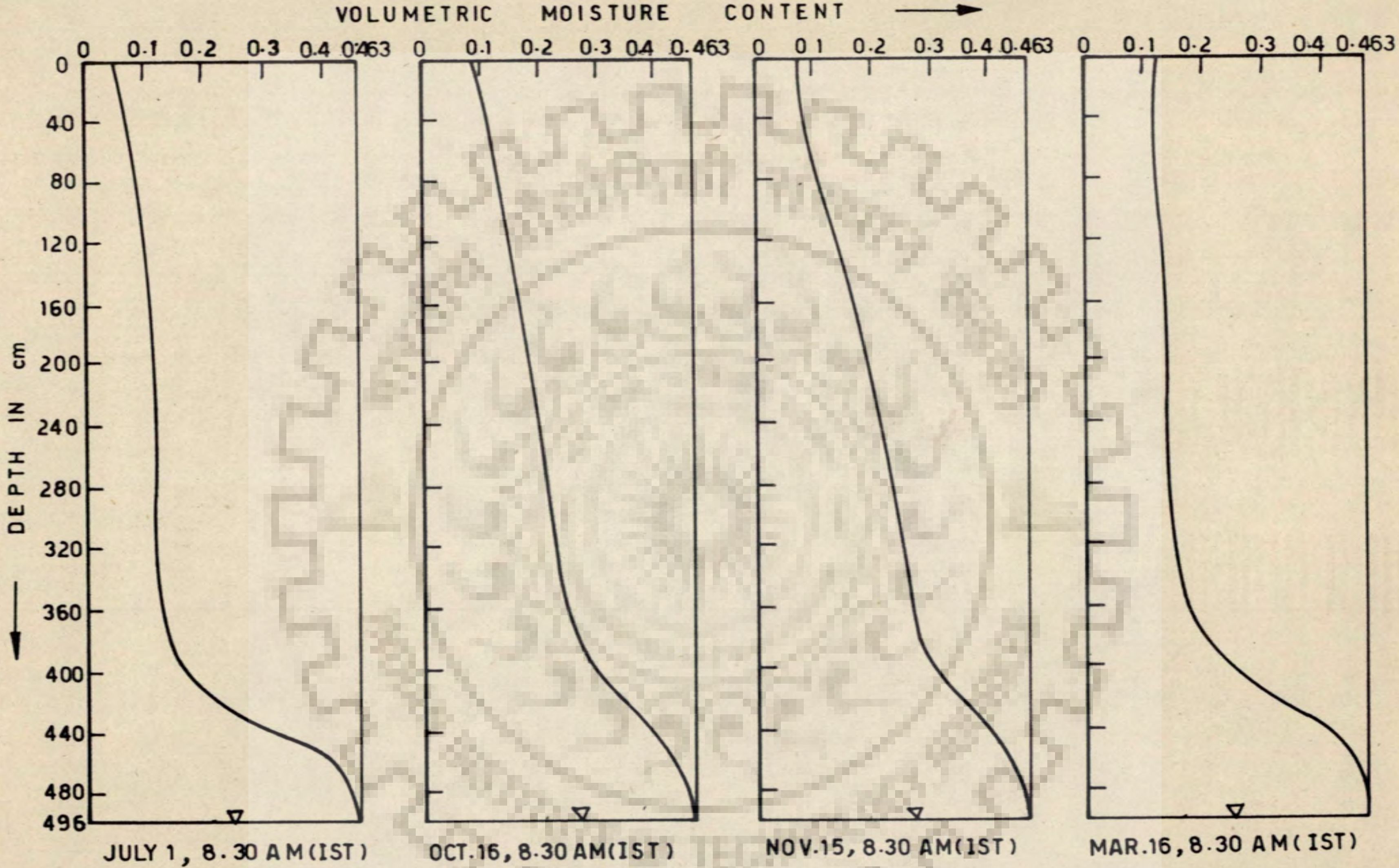

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FIG. 6.7 _ ESTIMATION OF RETURN FLOWS-MOISTURE PROFILES: RICE-WHEAT CROPPING ON LOAM

Table 6.8 Periodical percentage return flow Rice-wheat cropping on clay.

Crop	Period	Rainfall	Applied irrig.	Return flow	of return flow(%)
Rice	July	374.20	800	314.72	26.80
	Aug	142.20	925	453.62	42.51
	Sep	130.10	900	762.11	73.98
	1-15 Oct.	9.60	0.0	200.21	>100
Fallow	16 Oct-14 Nov	1.20	0.0	263.73	>100
Wheat	15 Nov-30 Nov.	1.0	75.0	82.63	>100
	Dec	0.0	0.0	132.39	>100
	Jan	43.5	0.0	110.20	>100
	Feb.	13.0	75.0	56.90	64.66
	1 -15 Mar	0.0	0.0	26.65	>100
	16-31 Mar	0.0	0.0	27.30	>100
	Apr	38.70	0.0	34.56	89.30
	May	0.0	0.0	32.33	>100
	June	0.0	0.0	29.24	>100
	Total	753.5	2775	2526.59	71.61 %

Table 6.9 Periodical percentage return flow: Rice-Wheat cropping on loam.

Crop	Period	Rainfall	Appl. Irrgn.	Return flow	% return flow
Rice	July	374.20	75	16.67	3.71
	Aug	142.20	75	12.79	5.89
	Sep	130.10	75	100.27	48.89
	1-15 Oct.	9.60	0.0	46.33	>100
Fallow	16-Oct-14 Nov.	1.20	0.0	83.22	>100
Wheat	15 Nov-30 Nov.	1.00	75	55.55	73.09
	Dec.	0.0	75	57.42	76.56
	Jan	43.50	0.0	51.09	>100
	Feb.	13.00	0.0	44.81	>100
	1-15 Mar	0.0	0.0	22.77	>100
Fallow	16-31 Mar	0.0	0.0	17.63	>100
	Apr	38.70	0.0	25.38	65.58
	May	0.0	0.0	21.29	>100
	June	0.0	0.0	16.06	>100
	Total	753.5	375.0	571.83	50.67

the corresponding period. This is due to the fact that, part of the build up moisture storage is drained in the subsequent periods as well. This causes a time lag in occurence of the return flow.

6.3 EVALUATION OF THE SMA MODEL

This study is aimed at evaluating the routing of infiltration, through the unsaturated zone, by the SMA model described (Chapter III pp 43-44) with accounting period a day. The evaluation has been done, by comparing the return flows with those given by the distributed model, under identical conditions (refer study 6.2). The daily infiltration (depths) generated in the study 6.2 (for the clay and loam) under the cropping rice followed by wheat have been assigned. Thus, the difference between the estimates of return flows, as computed by the SMA and the distributed models, will be exclusively on account of different routing procedures. The initial condition for this excercise has been prescribed by integrating the initial moisture profiles (in the preceeding excercise) in the root zone. Other data, namely, potential evapotranspiration of crops, submodel for calculation of actual evapotranspiration, the crop activity details and time variation of root zone depth, wilting point and field capacity, used in the SMA model, have been same as those used in the preceeding excercise with the distributed model.

6.3.1. Results

Figures 6.8 and 6.9 show the daily cumulative return flows obtained by the distributed model and by the soil moisture accounting model, for the rice-wheat cropping on clay and loam respectively. Slope of the cumulative curve will provide daily rates.

It may be observed from the figures that, the curves of the SMA model have many kinks, where as the curves of the distributed model are smooth. Thus, it means that the SMA model leads to a pulse type of return flow and the distributed model leads to a continuous return flow.

Further, it may be observed that, the SMA model tends to over estimate the return flow rates during the early period, which is the period of peak infiltration (rainy season with rice cultivation). This behaviour is due to the fact that, the SMA model does not account for the time lag in occurence of return flow. Moreover, rice is a shallow rooted crop. So the moisture deficiency to be filled up by the infiltrated water is less. Thus, as the infiltration decreases subsequently (winter season with wheat crop), the SMA model provides lower rates of return flows*. Thus, the seasonal totals of the return flow tend to match with those given by the distributed model. Following table shows the seasonal totals given by the SMA model and the distributed model.

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* This situation is more pronounced in case of the clay soil. In general, the loam (coarser soil) gave results closer to the results of the distributed model, than the clay (finer soil). This can lead to an inference of relatively better applicability of the concept of field capacity in case of coarser soils.

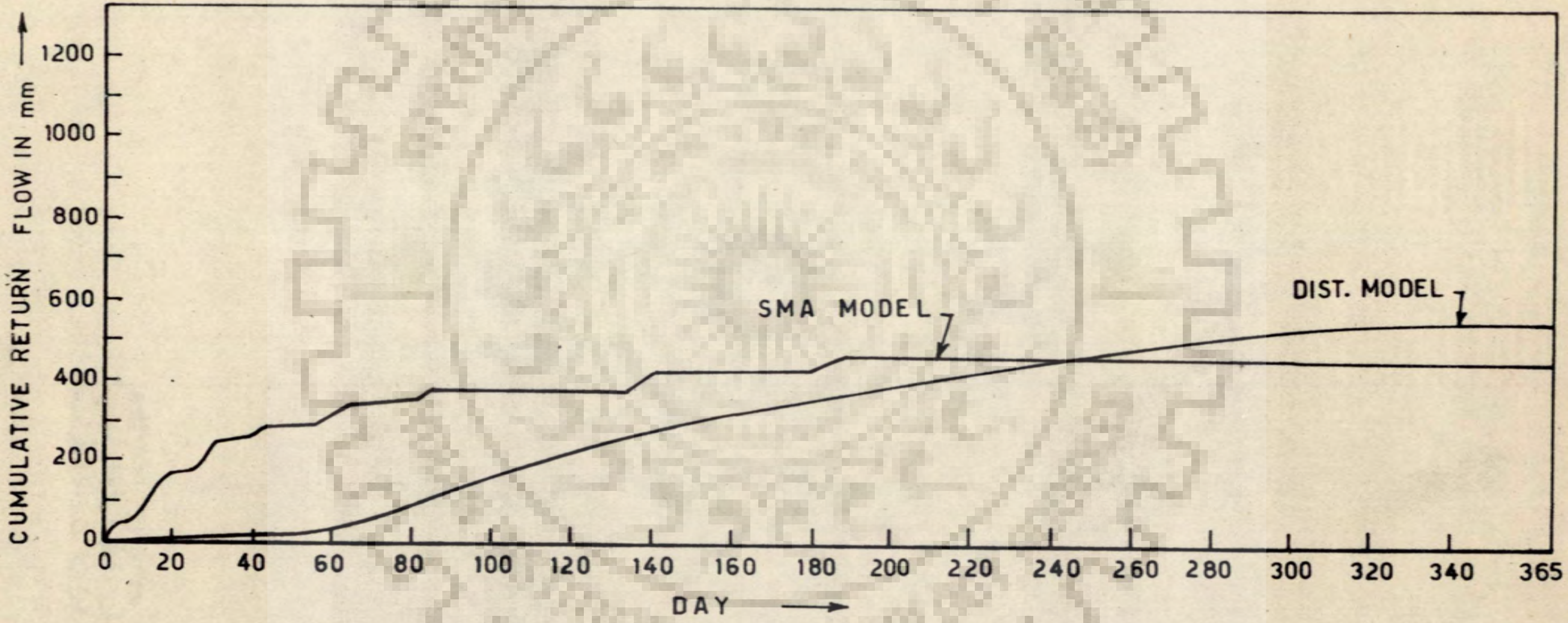

FIG. 6.9 DAILY CUMULATIVE RETURN FLOW BY THE SMA MODEL AND BY THE DISTRIBUTED MODEL: RICE-WHEAT CROPPING ON LOAM

6.3.1. Results

Figures 6.8 and 6.9 show the daily cumulative return flows obtained by the distributed model and by the soil moisture accounting model, for the rice-wheat cropping on clay and loam respectively. Slope of the cumulative curve will provide daily rates.

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[x] This situation is more pronounced in case of the clay soil. In general, the loam (coarser soil) gave results closer to the results of the distributed model, than the clay (finer soil). This can lead to an inference of relatively better applicability of the concept of field capacity in case of coarser soils.

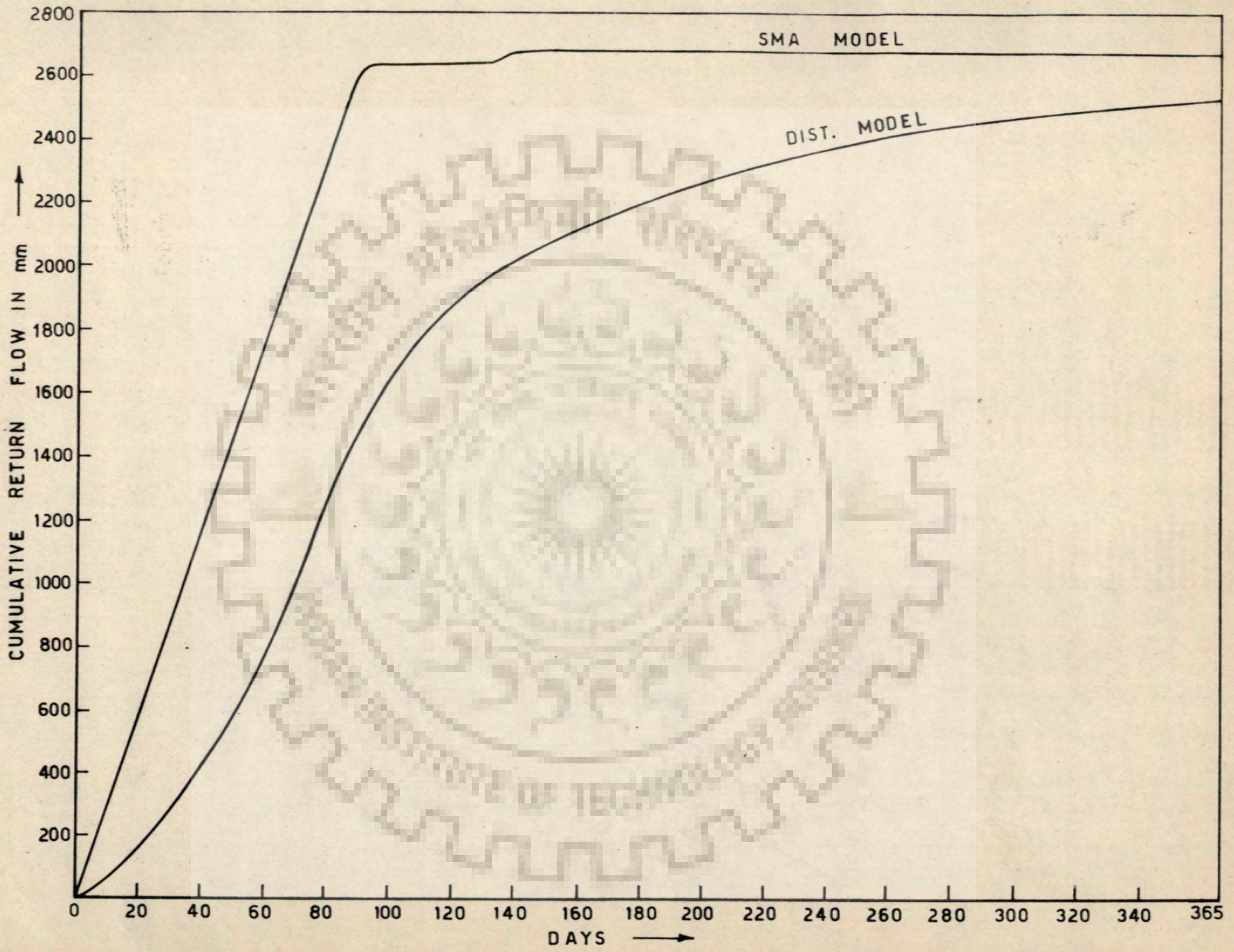


FIG. 6.8 _ DAILY CUMULATIVE RETURN FLOW BY THE SMA MODEL AND BY THE DISTRIBUTED MODEL; RICE-WHEAT CROPPING ON CLAY

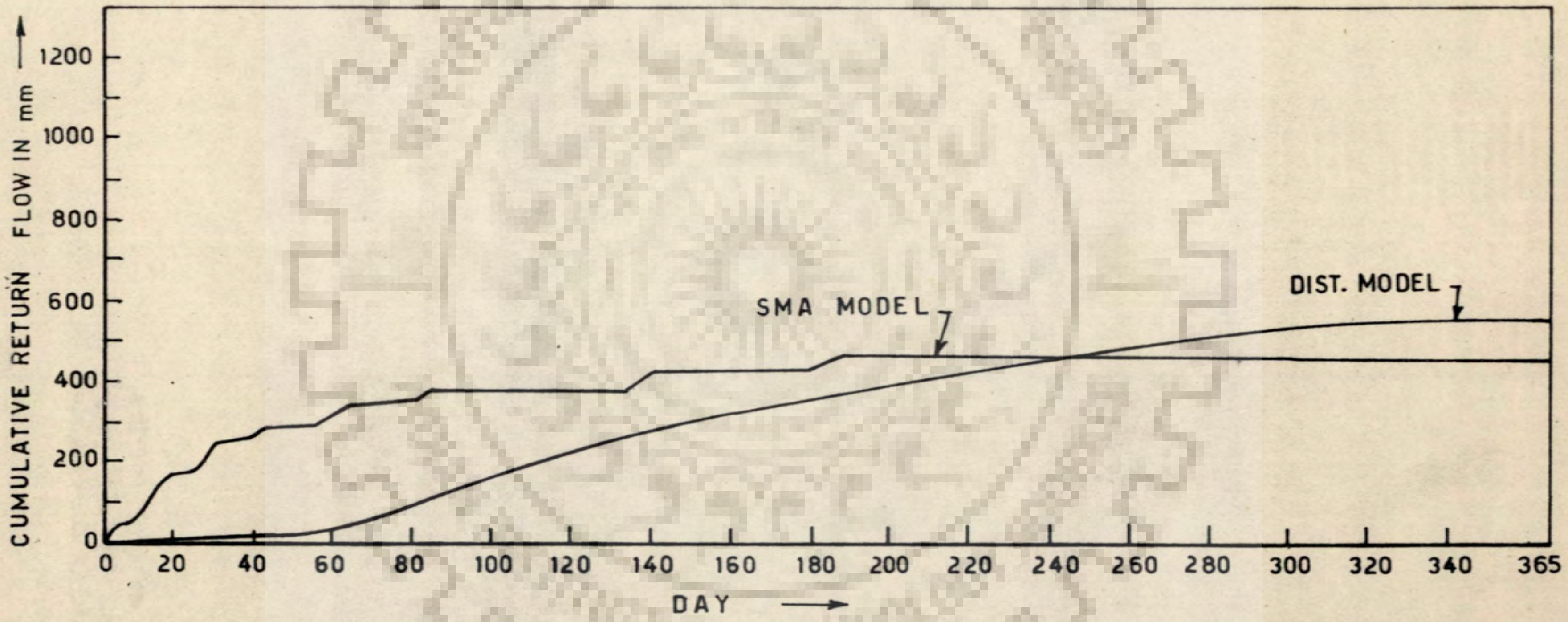


FIG. 6.9 DAILY CUMULATIVE RETURN FLOW BY THE SMA MODEL AND BY THE DISTRIBUTED MODEL: RICE - WHEAT CROPPING ON LOAM

Soil and cropping	Return flow in mm by the end of		
	Rice season	Wheat season	One year
Rice-wheat on clay			
SMA model	2625.32	2675.66	2675.66
Dist model	1730.66	2403.16	2526.59
Rice-wheat on loam			
SMA model	395.65	470.65	470.65
Dist model	176.61	491.47	571.83

CHAPTER- VII

CONCLUSION

The present work is mainly aimed, at developing a one dimensional (vertical) distributed numerical model, to simulate unsteady state flow of water in the unsaturated zone extending from ground surface upto water table. Aim of the simulation is to estimate, the hydrological response of the unsaturated zone constituting. ponding of water, infiltration, actual evapotranspiration, recharge and soil moisture as well as capillary suction head variation. The model permits automatic identification and assignment of ground surface boundary condition, under no overland flow condition. The model provides an option for using a proposed piecewise continuous relation for 'h characteristic', defined in terms of tabulated soil properties viz., residual moisture content, porosity and air entry value. Further, another option is provided to adopt nonuniform time steps of simulation, generated through a proposed empirical criteria. The model can account for time variant position of water table and soil layering.

Following are the prominent conclusions from the studies conducted.

1. The hydrological response of the unsaturated zone can be estimated by solving the Richards equation numerically (Refer annexure III for a sample output of the model). The return flow from rainfall and applied irrigation can be estimated under time invariant water table condition.

2. The model simulated moisture profiles, for yolo light clay, compared well with those given by Philip (1969) quasi-analytical solution.

3. The irrigation schedules, for a predefined criteria, can be computed along with the computation of the hydrological response. However, the model computed irrigation will not include field preparation and leaching requirements but constitutes only the consumptive use requirements. Further, the interception, direct evaporation losses, lateral surface and subsurface (unsaturated zone) flows are not accounted for and the irrigation is considered to be applied uniformly on the entire plot.

The model has been operated to schedule irrigation for a few soil cropping conditions. Subsequently, the associated return flows (from the rainfall and the scheduled irrigation) have been calculated by assigning a stationary water table position. For this excercise two of the soil-cropping conditions have been used.

i. Soil and cropping: Rice followed by wheat on clay. Irrigation criteria for rice: Requirement of maintaining a minimum ponding of 50 mm up to harvest sub season(submergence or lowland rice cultivation).

Irrigation criteria for wheat: 50 percent allowable average moisture depletion in the entire root zone.

Fortnightly computed irrigation was as follows

Fortnight Crop	1	2	3	4	5	6	7
Rice (1 Jul-15 Oct.)							
Rainfall mm	179.0	195.2	122.0	20.20	120.7	9.4	
Irrigation mm	500	300	425	500	450	450	
Wheat (15 Nov-15 Mar)							
Rainfall mm	1.0	0.0	0.0	18.0	25.5	13.0	0.0
Irrigation mm	75	0	0	0	0	0	75

There has been a heavy build-up of moisture, during the rice period, due to large input and low conductivity of the soil (refer Fig. 6.6). Receding of this build-up, in the subsequent wheat and fallow periods, resulted in a time lag in the occurence of return flow. Following are the monthly return flows.

Month	Jul	Aug	Sep	Oct	Nov	Dec.
Total input mm (Rainfall +Irrigation)	1174.2	1067.2	1030.10	9.60	77.2	0.0
Return flow mm	314.72	453.62	762.11	363.47	183.10	132.39

...contd

Month	Jan.	Feb	Mar	Apr	May	Jun
Total input mm. (Rainfall +Irrigation)	43.5	88.0	0.0	38.7	0.0	0.0
Return flow mm.	110.2	56.9	53.95	34.56	32.33	29.24

ii. **Soil** and Cropping : Rice followed by wheat on loam Irrigation criteria for rice: 0 % allowable average moisture depletion in the entire root zone (up land rice cultivation).

Irrigation criteria for wheat: 50 percent allowable average moisture depletion in the entire root zone.

Fortnightly computed irrigation was as follows:

Fortnight / Crop	1	2	3	4	5	6	7
Rice (1 Jul-15 Oct)							
Rainfall mm	179.0	195.2	122.0	20.20	120.7	9.4	
Irrigation mm	75	0	0	75	0	75	
Wheat (15 Nov-15 Mar)							
Rainfall mm	1.0	0.0	0.0	18.0	25.5	13.0	0.0
Irrigation mm.	75	0	75	0	0	0	0

In this excercise also, there has been a build up of soil moisture, in the rice period (Fig.6.7). However, the build up is less pronounced, due to reletively small input and high conductivity of the soil. Receding of this build-up, in the subsequent wheat and fallow periods, resulted in a time lag in the occurence of return flow. Following are the monthly return flows.

Month	Jul	Aug	Sep	Oct	Nov
Total input mm(rainfall+ irrigation)	449.20	217.20	205.10	9.60	77.20
Return flow mm	16.67	12.79	100.27	92.53	93.12

contd..

Month	Dec	Jan	Feb	Mar	Apr	May	Jun
Total input mm (rainfall+ irrigation)	75	43.5	13.0	0.0	38.70	0.0	0.0
Return flow mm.	57.42	51.09	44.81	40.40	25.38	21.29	16.06

iii. **Soil** and Cropping : Sugar cane on loam

Irrigation criteria: 50 percent allowable average moisture depletion in the entire root zone.

Fortnightly computed irrigation was as follows

Fortnight / Crop.	1	2	3	4	5	6
Sugarcane (15 mar-15 Feb)						
Rainfall mm	10.5	4.0	0.0	11.0	0.0	34.20
Irrigation mm	75	75	75	75	75	75

contd..

Fortnight	7	8	9	10	11	12	13	14
Rainfall mm	36.0	179.0	195.20	122.0	20.20	120.7	9.4	9.6
Irrigation mm	75	0	75	0	0	0	0	0

contd...

Fortnight	15	16	17	18	19	20	21	22
Rainfall mm	0.0	1.2	1.0	0.0	0.0	18.0	25.5	13.0
Irrigation mm	75	0	75	0	0	75	0	0

4. The computed total irrigation for the lowland (submergence) rice cultivation has been 2625 mm(refer table 6.4). The reported total irrigation on generally existing local practice (Rajput 1984, Tripathi 1985), under comparable conditions vary from 1800 mm to 4400mm.

5. The computed total irrigation, in case of upland rice, wheat and sugarcane, have been less than the generally existing local practice (refer table 6.4). This systematic deviation could be on account of operative conditions, described in conclusion no.3. However, a predominent reason might be that, in the computation of the irrigation, the depletion of soil moisture (upto the predefined level)is permitted in the entire root zone before irrigation is applied. The farmer, on the other hand, usually determines the necessity (of irrigation) by 'feeling' the moisture depletion of top soil only. This argument has been checked by the following study.

6. Soil and Cropping: Wheat on loam
   Irrigation criteria 0 % allowable average moisture depletion, in the top 30 cms of root zone.

Fortnightly computed irrigation was as follows

Fortnight Crop	1	2	3	4	5	6	7
Wheat (15 Nov-15 Mar)							
Rainfall mm	1.0	0.0.	0.0	18.0	25.5	13.0	0.0
Irrigation mm	150	75	75	0	75	0	75

The computed total as well as the distribution, of irrigation, is close enough to the generally existing practice locally (refer table 6.6).

7. The model simulated moisture profiles, for the layered soil field situation have compared well with those observed. Statistical tests (R^2, F and t) also supported this observation.

8. Current practice of quantifying field capacity, by 0.1 to 0.5 bar tension, may not always be consistent with its definition. So, a method has been proposed to quantify field capacity as a flow parameter. This method is better applicable to coarse soils.

9. A daily soil moisture accounting (SMA) model has been operated to route a given daily infiltration series through the unsaturated zone. Field capacity, in this model, is quantified as per the proposed method. The daily infiltration series generated, while calculating the return flows by the distributed model, were routed through the unsaturated zone under identical conditions.

The daily rates, of return flows given by the SMA model, in case of the clay, departed severely from those given by the distributed model. In case of the loam, departure in the daily rates (given by the SMA model and the distributed model) is not that severe (refer Figs. 6.8 and 6.9).

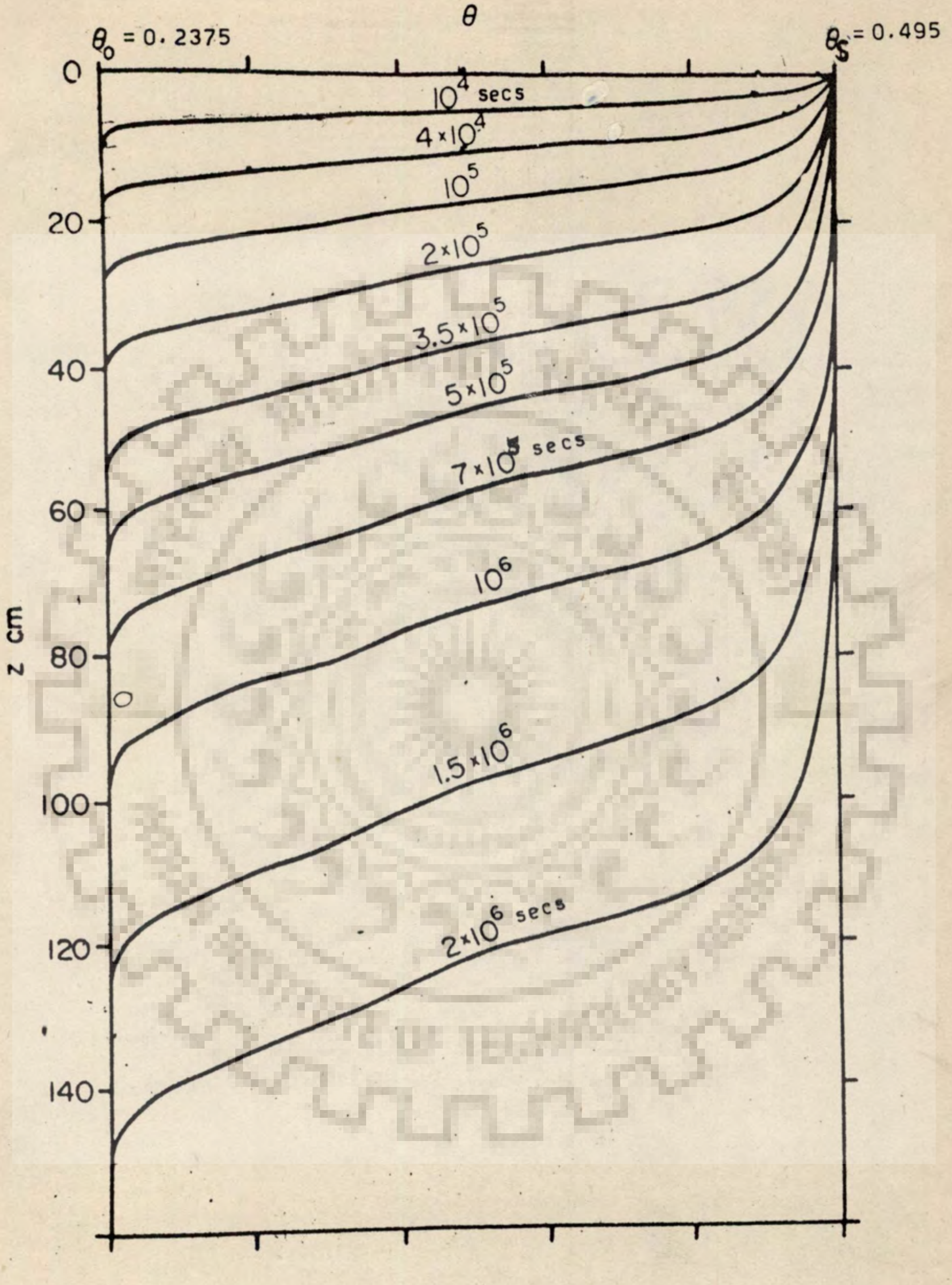
Following are the seasonal totals of return flows given by the SMA model and the distributed model.

Soil and cropping	Return flow in mm by the end of		
	Rice season	Wheat season	The year
Rice wheat on clay			
Dist model	1730.66	2403.16	2526.59
SMA model	2625.32	2675.66	2675.66
Rice-Wheat on loam			
Dist Model	176.61	491.47	571.83
SMA Model	395.65	470.65	470.65

ANNEXTURE - I

BASIC DATA FOR THE STUDIES

ANNEXURE I - a



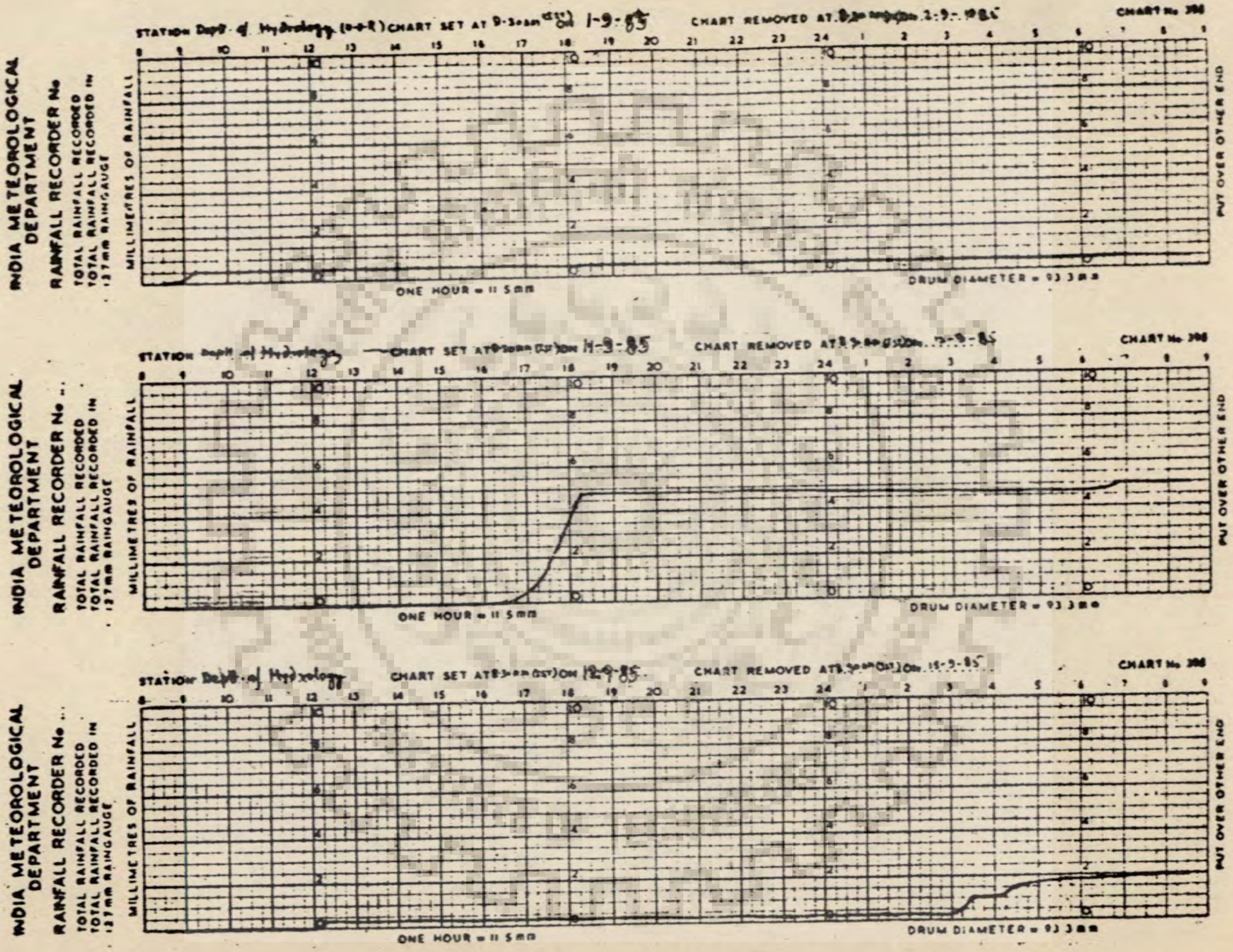
PHILIP QUASI - ANALYTICAL SOLUTION: MOISTURE PROFILES

Annexure I-b

Observed gravimetric moisture contents (%)

Location: Open lawn, Dept. of Hydrology, UOR, Roorkee

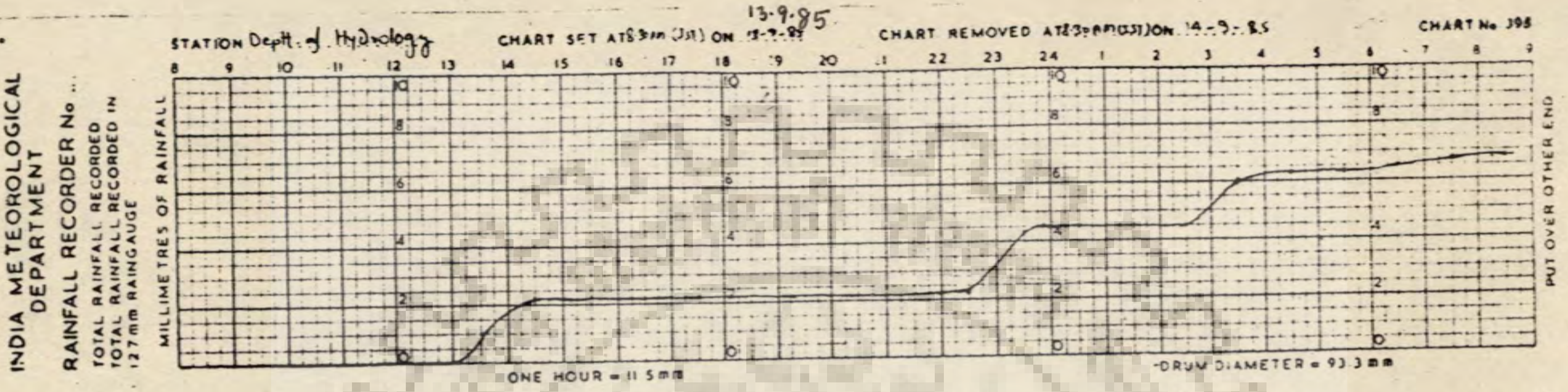
								Observation depth from ground surface in cms.								
Date	0	30	60	90	120	150	180	210	240	270	300	330	360	390	402	413
Sep 85 1.	20.59	24.79	23.87	22.35	20.40	19.83	19.64	18.54	14.14	12.17	10.53	10.20	10.72	25.86	28.29	28.75
2.	21.19	26.32	23.67	21.81	19.07	18.61	19.77	17.82								
9.	15.60	25.53	23.14	21.54	18.44	18.17	18.09	17.21								
16.	35.93	26.77	22.25	21.45	18.88	18.70	18.53	18.53								
24.	32.00	26.68	24.20	21.88	19.07	19.24	19.07	20.21								
Oct.85 5	27.83	24.82	23.49	19.15	19.07	19.07	17.91	19.07								
12	29.96	28.01	24.02	20.30	20.03	21.72	19.86	21.89								
21	21.54	24.29	24.29	22.87	21.89	21.54	21.37	19.98								
31	15.25	22.43	23.84	22.87	22.87	22.65	21.01	21.01								



Recording rainguage outputs

Observatory: Dept. of Hydrology, UOR, Roorkee.

13.9.85


INDIA METEOROLOGICAL DEPARTMENT

RAINFALL RECORDER No ..

TOTAL RAINFALL RECORDED

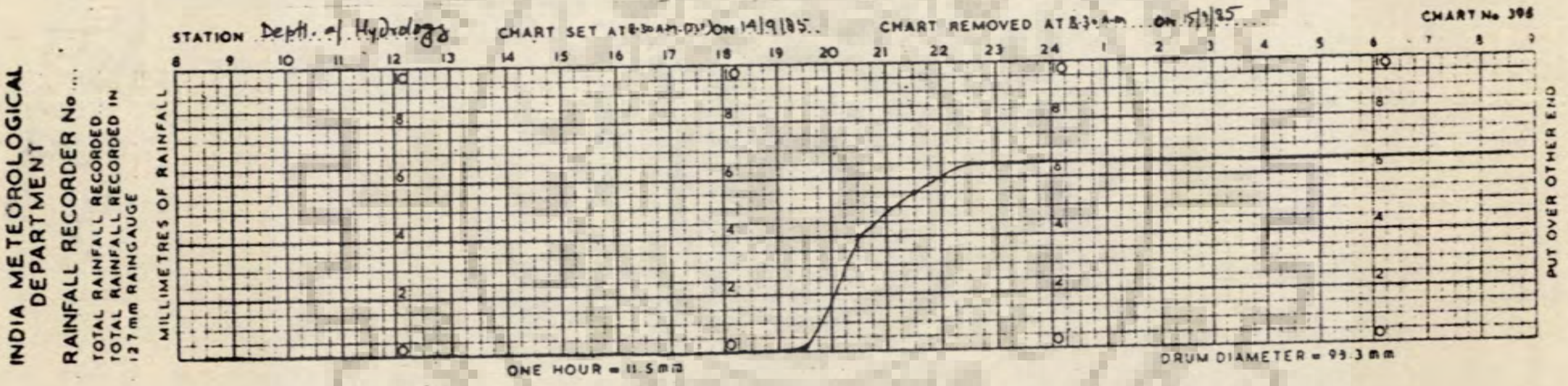
TOTAL RAINFALL RECORDED IN 127 mm RAINGAUGE

STATION Deptt. of. Hydrology CHART SET AT 8.30 a.m (IST) ON 13-9-85 CHART REMOVED AT 8.30 a.m (IST) ON 14-9-85 CHART No 395

ONE HOUR = 11.5 mm

DRUM DIAMETER = 93.3 mm

PUT OVER OTHER END


INDIA METEOROLOGICAL DEPARTMENT

RAINFALL RECORDER No ..

TOTAL RAINFALL RECORDED

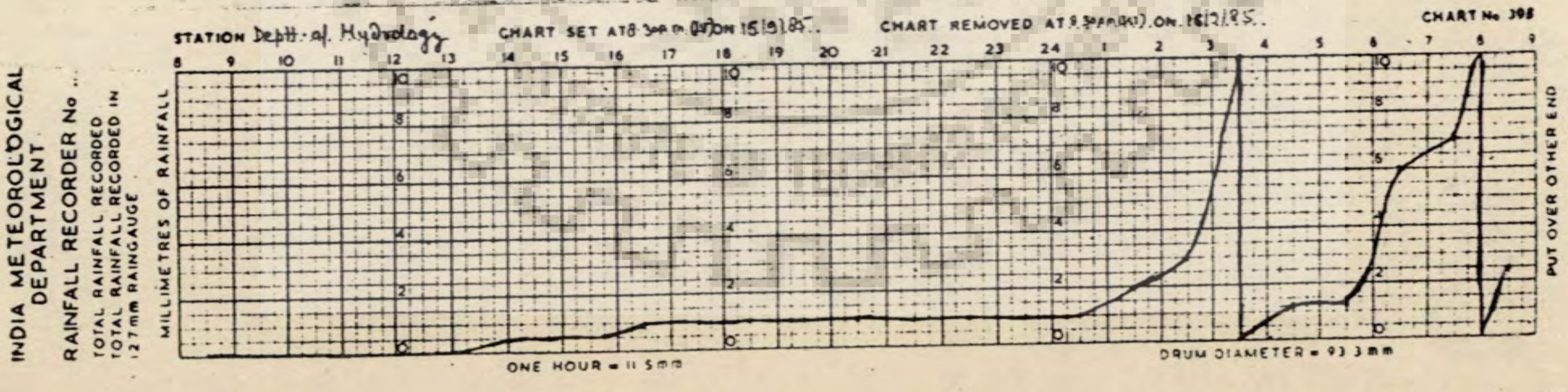
TOTAL RAINFALL RECORDED IN 127 mm RAINGAUGE

STATION Deptt. of Hydrology CHART SET AT 8.30 AM (IST) ON 14/9/85.. CHART REMOVED AT 8.30 A.M ... ON 15/9/85.... CHART No 395

ONE HOUR = 11.5 mm

DRUM DIAMETER = 93.3 mm

PUT OVER OTHER END


INDIA METEOROLOGICAL DEPARTMENT

RAINFALL RECORDER No ..

TOTAL RAINFALL RECORDED

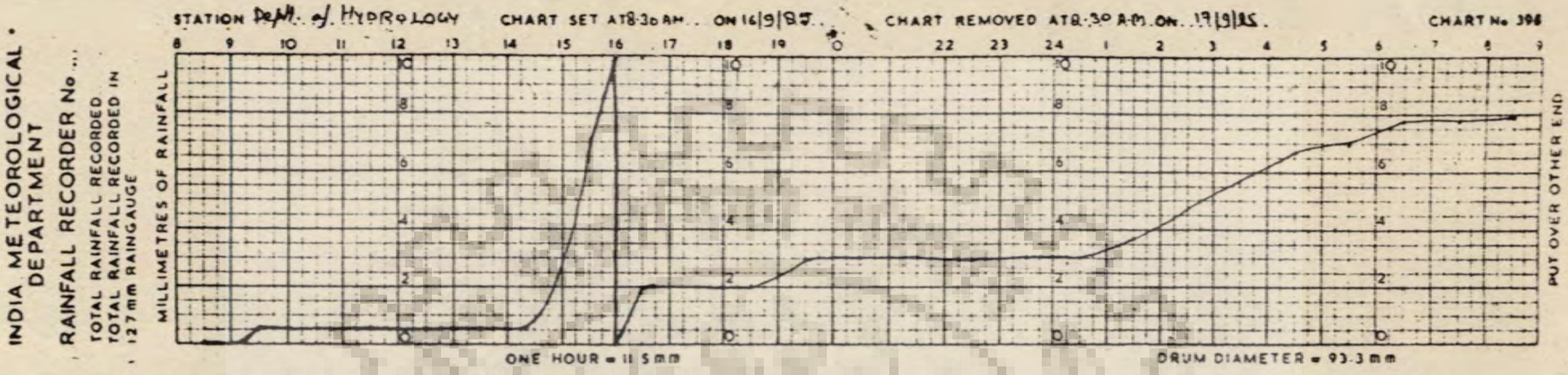
TOTAL RAINFALL RECORDED IN 127 mm RAINGAUGE

STATION Deptt. of. Hydrology CHART SET AT 8.30 a.m (IST) ON 15/9/85.. CHART REMOVED AT 8.30 a.m (IST). ON. 16/9/85.. CHART No 395

ONE HOUR = 11.5 mm

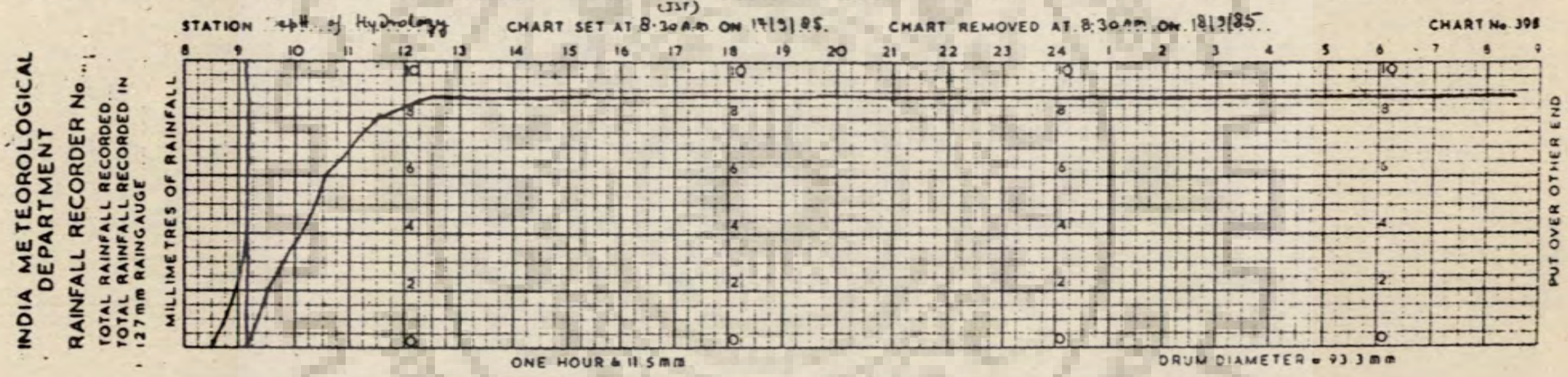
DRUM DIAMETER = 93.3 mm

PUT OVER OTHER END



INDIA METEOROLOGICAL DEPARTMENT
RAINFALL RECORDER No ...
TOTAL RAINFALL RECORDED
TOTAL RAINFALL RECORDED IN 127mm RAINGAUGE

STATION Deptt. of HYDROLOGY CHART SET AT 8·30 AM.. ON 16|9|85.. CHART REMOVED AT 8·30 A.M. ON. 17|9|85. CHART No. 398



INDIA METEOROLOGICAL DEPARTMENT
RAINFALL RECORDER No ...
TOTAL RAINFALL RECORDED
TOTAL RAINFALL RECORDED IN 127mm RAINGAUGE

(IST)
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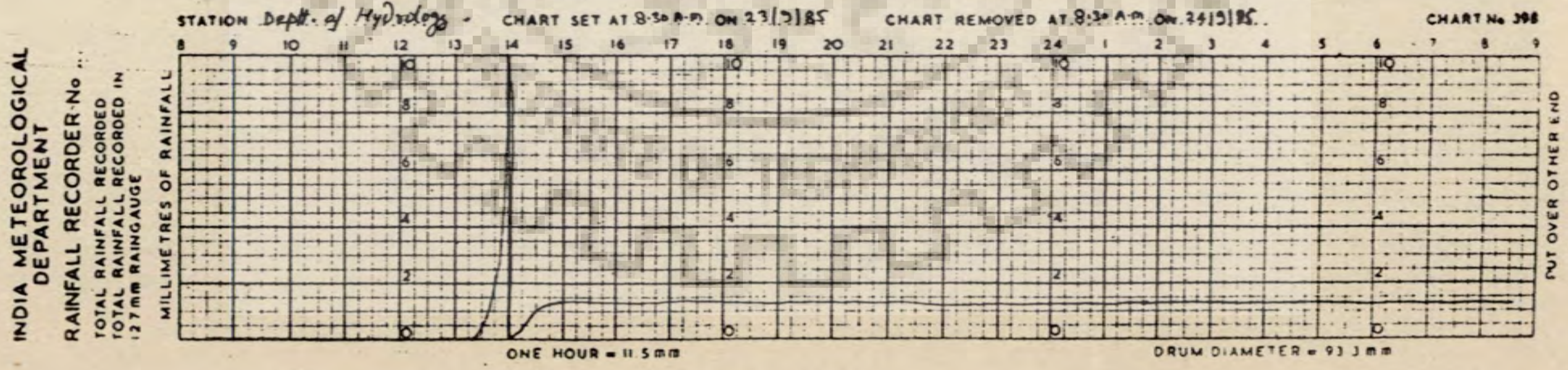
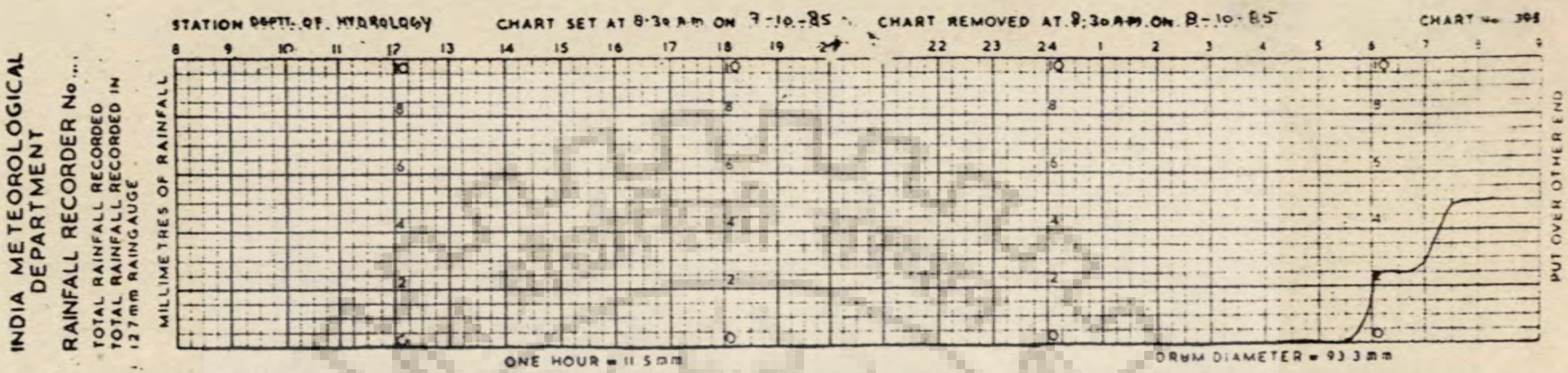
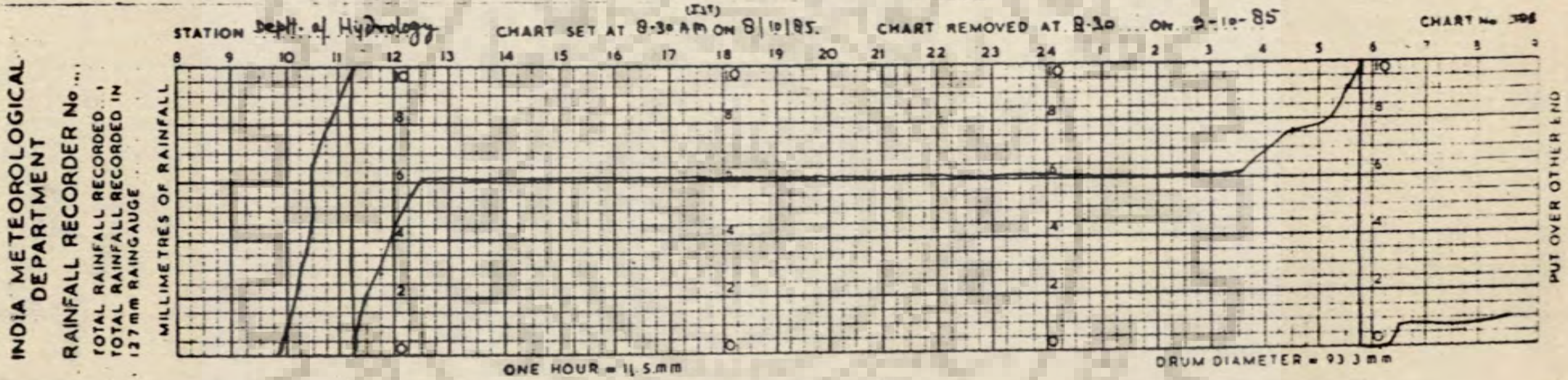
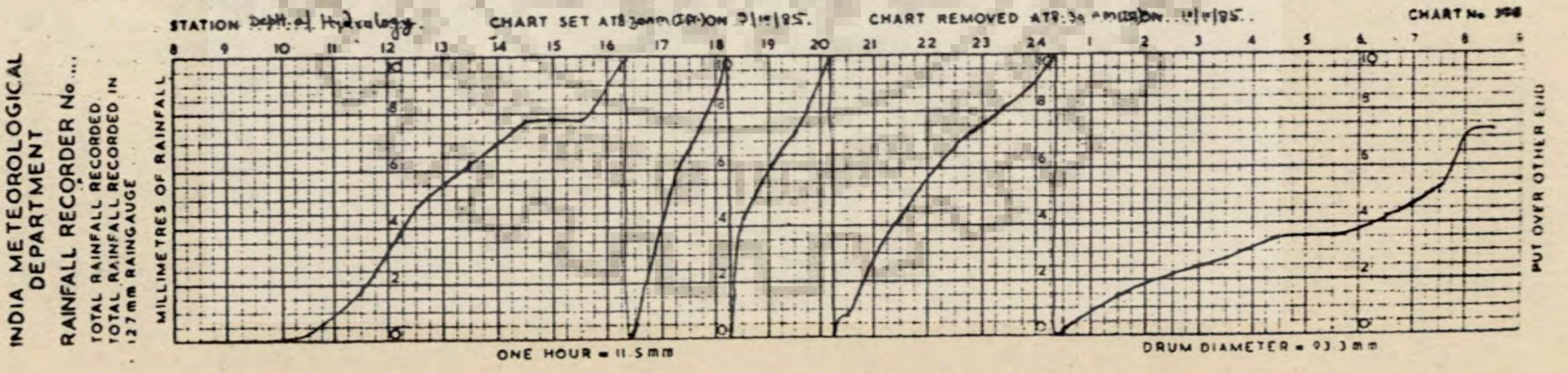


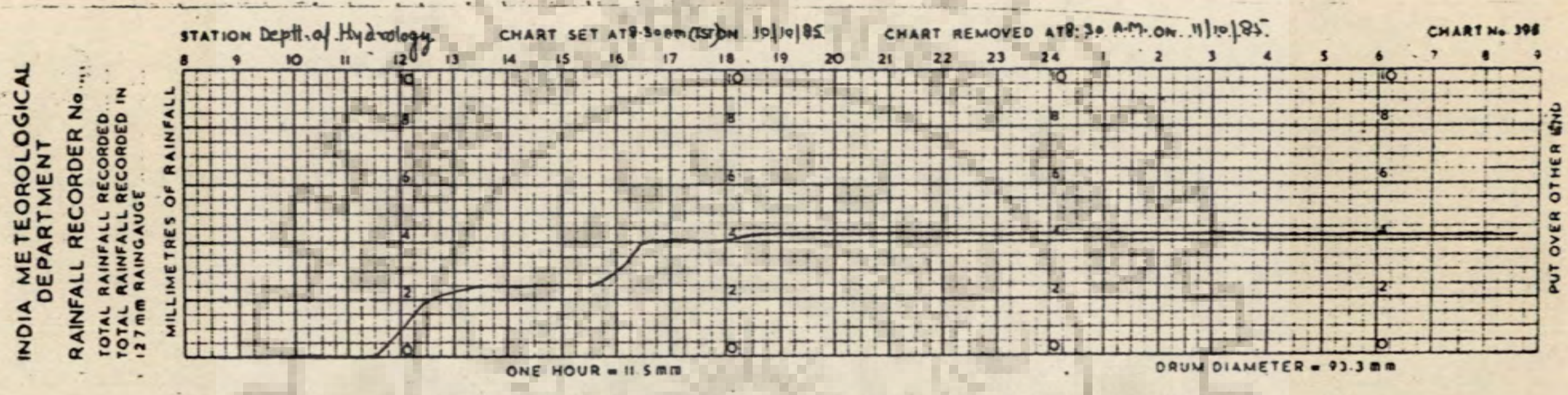
INDIA METEOROLOGICAL DEPARTMENT
RAINFALL RECORDER No ...
TOTAL RAINFALL RECORDED
TOTAL RAINFALL RECORDED IN 127mm RAINGAUGE

STATION Deptt. of Hydrology - CHART SET AT 8·30 A.m. ON 23|9|85 CHART REMOVED AT 8:30 A.m. ON. 24|9|85.. CHART No. 398


STATION DEPTT. OF. HYDROLOGY CHART SET AT 8-30 A.M ON 7-10-85 CHART REMOVED AT 8:30 A.M. ON 8-10-85 CHART No. 395


STATION Deptt. of Hydrology CHART SET AT 8-30 AM (IST) ON 8/10/85. CHART REMOVED AT 8-30 ... ON 9-10-85 CHART No. 396


STATION Deptt. of Hydrology. CHART SET AT 8.30 am (IST) ON 9/10/85. CHART REMOVED AT 8:30 am (IST) ON 10/10/85. CHART No. 398



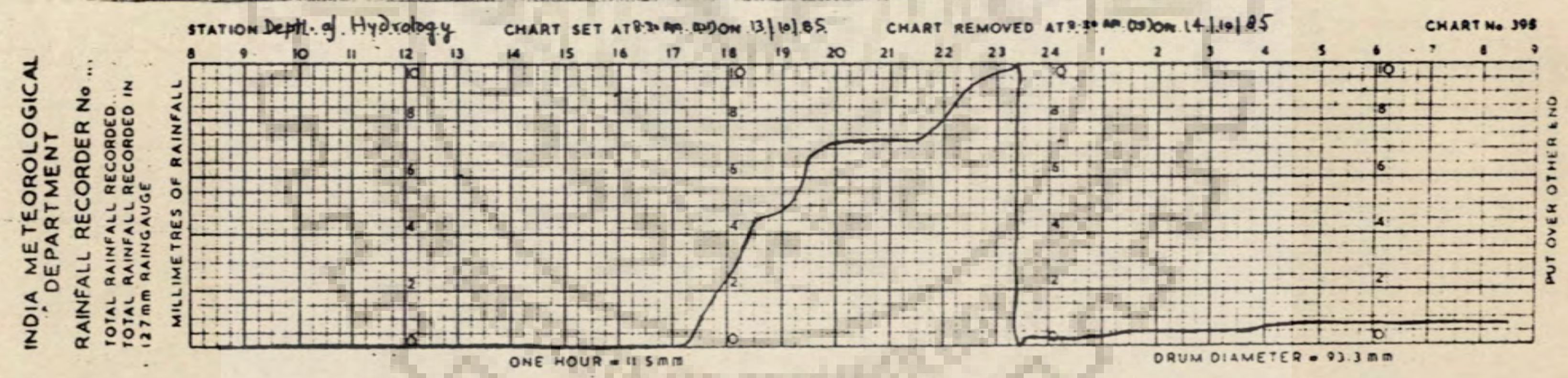
INDIA METEOROLOGICAL DEPARTMENT

RAINFALL RECORDER No ...

TOTAL RAINFALL RECORDED ...

TOTAL RAINFALL RECORDED IN 127 mm RAINGAUGE ...

STATION Deptt. of Hydrology CHART SET AT 8·30 am (IST) ON 10|10|85 CHART REMOVED AT 8:30 A.M. ON 11|10|85 CHART No. 398



INDIA METEOROLOGICAL DEPARTMENT

RAINFALL RECORDER No ...

TOTAL RAINFALL RECORDED ...

TOTAL RAINFALL RECORDED IN 127 mm RAINGAUGE ...

STATION Deptt. of Hydrology CHART SET AT 8·30 AM (IST) ON 13|10|85 CHART REMOVED AT 8·30 AM (IST) ON 14|10|85 CHART No. 395

DEPTH TO WATERTABLE (IN BOREWELL) AND CLASS A PAN EVAPORATION

LOCATION: DEPT. OF HYDROLOGY, U.O.R.ROORKEE(INDIA)

ANNEXURE I-d

SEPT 1985

DATE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
DTW	4130	4130	4130	4150	4150	4180	4180	4200	4220	4380	4430	4370	4330	4300	4300
E	0.7	0.6,0.9	0.6,0.7	0.7,0.8	0.6,1.2	0.6,5.0	2.2,3.4	2.0,2.8	2.0,3.2	1.0,4.0	2.1,0.9	0.9,0.7	0.0,0.6	0.3,0.7	0.5,1.2

DATE	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
DTW	4220	4150	4120	4120	4070	4070	4050	4050	4050	4000	4000	4050	4050	4050	4150
E	0.2,1.5	0.0,1.6	0.0,1.0	0.7,1.8	1.8,1.8	1.4,3.0	1.3,1.8	1.0,0.7	0.7,0.9	0.7,1.5	0.6,2.4	2.0,1.8	0.8,1.8	1.0,1.2	1.0,1.7

OCT 1985

DATE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
DTW	4120	4120	4190	4210	4230	4220	4210	4210	4150	4070	4070	4000	3980	4000	4120	3960
E	1.0,1.6	1.0,1.3	1.4,1.5	1.4,1.8	1.8,1.8	0.9,1.8	0.9,1.0	4.0,1.20	1.0,0.5	0.5,2.8	1.3,2.8	1.7,2.8	1.7,1.8	1.8,2.9	1.6,2.0	3.0,1.6

DATE	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	1 NOV
DTW	4040	4100	4050	3900	4000	4000	4000	4050	3980	3950	3930	3920	3900	3890	3910	
E	2.0,1.0	2.1,1.0	3.0,1.7	2.0,1.4	2.0,1.5	1.5,1.7	0.7,1.3	1.2,1.3	1.3,0.8	0.4,0.8	0.6,0.9	0.5,0.4	0.9,0.6	0.6,0.6	0.5,0.5	0.5

DTW: DEPTH TO WATER TABLE IN mm

E: CLASS A PAN EVAPORATION AT 8-30 A.M(IST) AND 5-30 P.M(IST)

LITHOLOG OF THE BORE WELL
FIELD LOCATION: DEPT. OF HYDROLOGY, UNIVERSITY OF ROORKEE

DAILY RAIN FALL, MONTHLY POTENTIAL EVAPOTRANSPIRATION OF REFERENCE CROP AND MONTHLY DEPTH TO WATERTABLE

Annexure I-f

RAINFALL in mm

Date	Mar	Apr	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec	Jan.	Feb.	Mar	Apr	May	June
1.	2.5			7.5			15.5									
2.	4.8			2.6		1.2	39.7									
3.	1.5			1.6			12.0					1.0				
4.	0.2	4.0		1.2		9.0	1.0				3.0	12.0				
5.				0.6	11.0	5.0					15.0					
6.				1.0		15.5										
7.			11.0				9.2							5.5		
8.							21.5							9.0		
9.				2.4		35.0	1.2	9.6								
10.				6.5	16.8											
11.				1.2			0.2									
12.				0.8			2.1		1.2							
13.	1.2			1.2			7.3									
14.	2.6				129.0	55.1	10.0									
15.	5.0			7.6	22.2	1.2	1.0									
16.				2.0	3.8	10.0										
17.				3.4	28.4									3.2		
18.				1.0	1.0		0.4									
19.					16.0		2.0									
20.	1.6															
21.	3.9					10.2										
22.				0.7												
23.				1.9	21.0						0.4					
24.				4.6												
25.				4.3							9.0					
26.				15.6			7.0				1.0			4.0		
27.				1.3							15.1			9.5		
28.				0.8	85.4				1.0					1.5		
29.				0.4	38.5									6.0		
30.					1.1											
31.																
Potential evapotranspiration reference crop in mm	127	175	222	225	163	142	142	111	66	44	53	75	127	175	222	225
DTW at the start of the month in mm	5380	5410	5660	5700	4960	4920	4800	4900	4831	4820	5376	5260	5380	5410	5660	5700

Note: Blank entries indicate zero value.

Annexure I-8

GROWTH OF ROOT ZONE IN MM IN VARIOUS FORTNIGHTS

FORTNIGHT CROP	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Wheat																						
Original data	125-725	725-1025	1025-1325	1325-1425	1425-1525	1525-1625	1625-1725	1725-1800														
Adopted data	325	725	1025	1325	1425	1525	1625	1725														
Rice																						
Original data	100-625	625	625	625	625	625	625															
Adopted data	325	625	625	625	625	625	625															
Sugar cane	100																					
Original data	100-225	225-325	325-425	425-525	525-625	625-725	725-825	825-925	925-1025	1025-1125	1125-1225	1225-1325	1325-1425	1425-1475	1475-1525	1525-1575	1575-1625	1625-1675	1675-1725	1725-1775	1775-1825	1825-1875
Adopted data	325	325	325	425	525	625	725	825	925	1025	1125	1225	1325	1425	1475	1525	1575	1625	1675	1725	1775	1825

ANNEXURE - II

COMPUTER CODE

THIS IS A VERY BRIEF DOCUMENTATION

INPUTS

ALP: TITLE

ATIM:COEFFICIENT IN THE EMPERICAL CRITERIA FOR TIME STEP OF SIMULATION

FALL: RAIN FALL (MONTH & DAY WISE)

NDP: NO.OF DEPTH NODES

NODE:NODE NUMBER AT WHICH SOIL LAYER CHANGES (PRESENTED IS FOR HOMOGENIOUS SOIL; SO NODE IS SET TO A NEGATIVE NUMBER)

BTIM: TOLERABLE ERROR ON MASS BALANCE OF UNSATURATED ZONE FLOW (ABSOLUTE VALUE)

HPR: INITIAL CONDITION IN TERMS OF H

DELZ: VECTOR OF DELTA-Z

PF: FACTOR 'P' IN THE DOORENBOS ETAL (1979) 'ET' RELATION

DTB:DEPTH TO WATER TABLE

SAT; SATURATED CAPILARY CONDUCTIVITY

WP: WILTING POINT

THR:THETA-R

POR: POROSITY

SSM: AIR ENTRY VALUE

PET: POTENTIAL ET OF CROP

NOROOT: NODE NO.AT WHICH ROOT ZONE ENDS

AKJT: TIME(S) AT WHICH MOISTURE PROFILES ARE TO BE OUTPUT

MONDAY, DAYS IN THE MONTH

NDAYS: LENGTH OF SIMULATION IN INTEGER MULTIPLE OF A BLOCK OF TIME (HERE PRESENTED IS A DAY)

IOPT: WHETHER SURFACE IS SATURATED AT INT.COND (>0)

INSTAN:(=1)BYPASS UPPER BOUNDARY ALGORITHM

JE: TIME INTERVAL AT WHICH VERIFICATION IS SOUGHT BY PICARD ITERATION (REMSON ET AL 1971)METHOD

ITOPT: OPTION FOR WRITTING TIME STEPS ACTUALLY TAKEN

COINEX: OPTION SWITCH ON ACTION TO BE TAKEN INCASE OF FAILURE ON ASSIGNING UPPER BOUNDARY CONDITION (=1 FOR GIVING MESSAGE AND STOP (PAUSE); = 0 FOR BATCH OPERATION)

COIMEX:OPTION SWITCH ON VERIFICATION WITH PICARD ITERATION METHOD

JDOP: INTERVAL AT WHICH ABSTRACT OF RESPONSE COMPONENTS ARE TO BE WRITTEN

OUTPUTS

MOISTURE PROFILES

THE: VECTOR OF MOISTURE CONTENT

HAD: VECTOR OF CAPILLARY SUCTION HEAD

THEDAY: TIME AT WHICH THE VECTOR OF MOISTURE CONTENT IS BEING WRITTEN

ABSTRACT

IZUD: DATE

DTVB: DEPTH TO WATER TABLE

XXRAI: RAINFALL

XAI:APPLIED IRRIGATION

XHTED1: CHANGE IN PONDED WATER DEPTH

BENH: CUMULATIVE PONDING

XETLD: EVAPOTRANSPIRATION

XSTO1 : CHANGE IN MOISTURE STORAGE

XOUT: RECHARGE

ERR: MASS BALANCE ERROR IN PONDING (ABSOLURE VALUE)

PERIODICAL ABSTRACT

TORAI: RAINFALL

TOAI : APPL.IRRIGATION

TOFILT: INFILTRATION

TOHTED: PONDED WATER DEPTH

TOETL: EVAPOTRANSPIRATION

TOSTO: CHANGE IN STORAGE

TXOUT: RECHARGE

ERR: ERROR IN BALANCE OF PONDED WATER DEPTH

BANDA: TIME STEPS ACTUALLY TAKEN

NOTE: 1. TOLERABLE ERROR ON MASS BALANCE OF PONDED WATER HAS BEEN SET TO 0.01; REFER SUBROUTINE RUNOFF

2. TOLERABLE ERROR ON CONVERGENCE IN PICARD ITERATION METHOD HAS BEEN SET TO 0.02(EPS IN SUBROUTINE SOLVE)

```
      DIMENSION MONDAY(24),FALL(24,31),DTB(24)
      DIMENSION ALP1(3,80),PF(24,31),AI(31)
      COMMON/DAT/RAI(1000),NDP,DELZ(100),NODE,NDAYS,ALP(84),IOPT,
      1DE,ITR,AKJT(1000),HPR(100),JE,IRUN,COINEX,COIMEX,DEAL,IFLOW
      2,ILIN
      COMMON/NEW1/HAD(100),STO(100),RAIN,DELTAT,SUM,THE(100)
      COMMON/ETS/NOROOT(1000),FM(31),WP,PET(1000)
      COMMON/CONST/THR,POR,AM,POW,AC,SSM,SAT
      COMMON/RSLTS/TOFILT,TORUN,TOETL,TOSTO,TOREC,MON,ISTAD,BANG,
      1ATIM,BTIM,INSTAN,SKF,ROG1,JDOP,ITOPT
      COMMON/DUD/DTW(1000)
      COMMON/CUMLAT/VT1,VT2,VT3,VT4,VT5,VT6,VT7,BENH,FACTOR
      DATA MONDAY/31,28,14,17,30,31,30,31,31,30,31
      1,30,31,31,15,13,14,17,30,31,30,31,31,30/
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      OPEN(UNIT=1,DEVICE='DSK',FILE='RAIN.DAT')
      OPEN(UNIT=20,DEVICE='DSK',FILE='ABT.DAT')
      OPEN(UNIT=22,DEVICE='DSK',FILE='CABT.DAT')
      READ(1,80)(ALP1(1,I),I=1,80)
      READ(1,80)(ALP1(2,I),I=1,80)
      READ(1,*)ATIM
80    FORMAT(80A1)
      DO 1 I=4,17
1     READ(1,*)(FALL(I,J),J=1,MONDAY(I))
      THR=0.027;POR=0.463;SSM=401.2;AM=-THR/SSM
      SAT=1.889E-3;POW=4.0;EFC=0.125;WP=0.055
      NDP=56;NODE=-100
      BTIM=0.2;DE=1.0;IRUN=1
      DE=-DE
      ACCEPT*,IGM
      IPD=1
      HPR(NDP)=0.0;SUM1=0.0
      DO 2 I=1,NDP-1
      K=NDP-I
      SUM1=SUM1+DELZ(K)
      HPR(K)=SUM1
2     CONTINUE
```

```
      AC=-ALOG(SSM*AM+POR-THR)/SSM
      DO 35 I=4,17
      READ(1,*)(PF(I,J),J=1,MONDAY(I))
35    CONTINUE
      READ(1,*)(DTB(I),I=4,18)
      ISTAD=15
      OPEN(UNIT=21,DEVICE='DSK',FILE='INT.DAT')
      READ(21,*)NDP
      READ(21,*)(HPR(I),I=1,NDP)
      READ(21,*)(DELZ(I),I=1,NDP-1)
      CLOSE(UNIT=21)
998   IGM=IGM+1
      DO 98 LP=1,IPD
      VT1=0.0;VT2=0.0;VT3=0.0;VT4=0.0;VT5=0.0;VT6=0.0;VT7=0.0
      BENH=0.0
      DO 66 MON=4,17
      TYPE*,MON
      NDAYS=MONDAY(MON)+1
      DO 67 I=1,NDAYS
      DTW(I)=0.0;RAI(I)=0.0;AI(I)=0.0;PET(I)=0.0
      NOROOT(I)=0.0;AKJT(I)=0.0
67    CONTINUE
      AF=DTB(MON+1)-DTB(MON)
      AF=AF/FLOAT(MONDAY(MON))
      DO 68 I=1,NDAYS
68    DTW(I)=DTB(MON)+AF*FLOAT(I-1)
      RAI(1)=FALL(MON-1,MONDAY(MON-1))
      DO 69 I=2,NDAYS
69    RAI(I)=FALL(MON,I-1)
      READ(1,*)(PET(I),I=1,NDAYS-1)
      READ(1,*)(NOROOT(I),I=1,NDAYS-1)
      DO 45 I=1,NDAYS-1
45    FM(I)=FFC-(FFC-WP)*PF(MON,I)
      IF(MON.EQ.4)AKJT(5)=24.0
      AKJT(NDAYS-1)=24.0
      KK=2
      IF(MON.LE.15)KK=1
```

```
      DO 70 I=1,80
 70   ALP(I)=ALP1(KK,I)
      IF(IGM.EQ.1.AND.MON.LE.16)GO TO 66
      CALL DISBAL
 66   CONTINUE
 98   CONTINUE
      IF(IGM.EQ.1)GO TO 998
      STOP;END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      FUNCTION COND(TUF,JTL)
      COMMON/DAT/RAI(1000),NDP,DELZ(100),NODE,NDAYS,ALP(84),IOPT,
     1DE,ITR,AKJT(1000),HPR(100),JE,IRUN,COINEX,COIMEX,DEAL,IFLOW
     2,ILIN
      COMMON/CONST/THR,POR,AM,POW,AC,SSM,SAT
      COND=SAT*((TUF-THR)/(POR-THR))**POW
      RETURN;END
      FUNCTION THETA(TUF,JTL)
      COMMON/DAT/RAI(1000),NDP,DELZ(100),NODE,NDAYS,ALP(84),IOPT,
     1DE,ITR,AKJT(1000),HPR(100),JE,IRUN,COINEX,COIMEX,DEAL,IFLOW
     2,ILIN
      COMMON/CONST/THR,POR,AM,POW,AC,SSM,SAT
      IF(TUF.GT.SSM)GO TO 100
      THETA=AM*TUF+POR
      GO TO 101
 100  THETA=EXP(-AC*TUF)+THR
 101  IF(THETA.GT.POR)THETA=POR
      RETURN;END
      SUBROUTINE RUNEX(RUG,XXX,YYY,IDLI)
      COMMON/RUNOF/R1,RUNX,IDIOT,XBZ
      IF(IDLI.NE.1)GO TO 60
      RUG=0.0;RETURN
 60   RR1=R1;IF(RR1.LT.0.0)RR1=0.0;XXX=RR1-XBZ
      RETURN;END
      SUBROUTINE SIMU(REC,DT,JA)
      COMMON/DUD/DTW(1000)
      DT=DTW(JA)
      RETURN;END
```

```
      SUBROUTINE SINK
      DIMENSION B(100)
      COMMON/DAT/RAI(1000),NDP,DELZ(100),NODE,NDAYS,ALP(84),IOPT,
     1DE,ITR,AKJT(1000),HPR(100),JE,IRUN,COINEX,COIMEX,DEAL,IFLOW
     2,ILIN
      COMMON/NEW1/HAD(100),STO(100),RAIN,DELTAT,SUM,THE(100)
      COMMON/NEW4/JAYA,ITRT,HPR1(100)
      COMMON/CONN/S(100),BB(100),PAT
      COMMON/ETS/NOROOT(1000),FM(31),WP,PET(1000)
      KM=JAYA
      DO 600 I=1,NDP
      B(I)=BB(I)
      IF(ITRT.GT.0)B(I)=(BB(I)+THE(I))/2.
600   CONTINUE
      DO 30 I=1,NDP
30    S(I)=0.0
      FFC=FM(KM);AVA=FFC-WP
      SIG=0.0
      DO 10 I=1,NOROOT(KM)-1
10    SIG=SIG+DELZ(I)
      SIG=SIG+DELZ(NOROOT(KM))/2.0
      SSS=PET(KM)/(PAT*SIG)
      DO 20 I=1,NOROOT(KM)
      IF(AVA.EQ.0.0)S(I)=SSS
      IF(AVA.EQ.0.0)GO TO 60
      S(I)=SSS*(B(I)-WP)
      S(I)=S(I)/AVA
60    DEP=(DELZ(I-1)+DELZ(I))/2.
      IF(I.EQ.1)DEP=DELZ(1)/2.
      IF(B(I).GT.FFC)S(I)=SSS
      IF(B(I).LT.WP.OR.B(I).GE.0.436)S(I)=0.0
      S(I)=S(I)*DEP
      SVR=S(I)*DELTAT
      AVSM=(B(I)-THR)*DEP
      IF(SVR.GT.AVSM)SVR=AVSM
      S(I)=SVR/DELTAT
20    CONTINUE
```

```
     RETURN;END
     SUBROUTINE STEP(RONAK)
     COMMON/DAT/RAI(1000),NDP,DELZ(100),NODE,NDAYS,ALP(84),IOPT,
     1DE,ITR,AKJT(1000),HPR(100),JE,IRUN,COINEX,COIMEX,DEAL,IFLOW
     2,ILIN
     COMMON/NEW3/KO,KOUNT,BUZ(500),LAPAZ,DUBBA,CRET,RAO(31,300)
     1,JJVK
     COMMON/NEW4/JAYA,ITRT,HPR1(100)
     COMMON/RSLTS/TOFILT,TORUN,TOETL,TOSTO,TOREC,MON,ISTAD,BANG,
     1ATIM,BTIM,INSTAN,SKF,ROG1,JDOP,ITOPT
     A1=RONAK*0.25;B1=0.75*RONAK
     A2=RAI(JAYA+1)-RONAK
     A3=A1+A2
     TMAXI=2700.0
     IF(A3.LT.2.5)A3=2.5
     RAO(JAYA,1)=ATIM*ALOG(A3)/A3
     IF(RAO(JAYA,1).GT.TMAXI)RAO(JAYA,1)=TMAXI
     ASUMI=0.0
     JJVK=2
     ASUMI=ASUMI+RAO(JAYA,1)
8687 CONTINUE
     RAO(JAYA,JJVK)=SQRT(RAO(JAYA,1)*ASUMI)
     IF(RAO(JAYA,JJVK).GT.TMAXI)RAO(JAYA,JJVK)=TMAXI
     ASUMI=ASUMI+RAO(JAYA,JJVK)
     IF(ASUMI.GT.21600.0)RAO(JAYA,JJVK)=21600.0-ASUMI+RAO(
     1JAYA,JJVK)
     IF(ASUMI.GE.21600.0)GO TO 8686
     JJVK=JJVK+1
     GO TO 8687
8686 JJVK=JJVK+1
     IF(B1.LT.2.5)B1=2.5;KLOCK=JJVK
     RAO(JAYA,JJVK)=ATIM*ALOG(B1)/B1
     IF(RAO(JAYA,JJVK).GT.TMAXI)RAO(JAYA,JJVK)=TMAXI
     ASUMI=0.0;JJVK=JJVK+1
     ASUMI=ASUMI+RAO(JAYA,JJVK-1)
8689 CONTINUE
     RAO(JAYA,JJVK)=SQRT(RAO(JAYA,KLOCK)*ASUMI)
```

```
      IF(RAO(JAYA,JJVK).GT.TMAXI)RAO(JAYA,JJVK)=TMAXI
      ASUMI=ASUMI+RAO(JAYA,JJVK)
      IF(ASUMI.GT.64800.0)RAO(JAYA,JJVK)=64800.0-ASUMI+RAO(
     1JAYA,JJVK)
      IF(ASUMI.GE.64800.0)GO TO 9696
      JJVK=JJVK+1;GO TO 8689
9696  IF(JJVK.GT.300)STOP'CAUTION TIME STEPS'
      RETURN;END
```

Subroutine

```
      SUBROUTINE DISBAL
      DIMENSION AP(100),SA(100),DG(100),BIG(100),BANDA(2000)
     1,PORO(100),DOT(100),HVD(100),KAV(100),FLOWER(100),ZETA(100)
     2,BETA(100),THY(100),BB(100),ADZ(100)
      COMMON/DAT/RAI(1000),NDP,DELZ(100),NODE,NDAYS,ALP(84),IOPT,
     1DE,ITR,AKJT(1000),HPR(100),JE,IRUN,COINEX,COIMEX,DEAL,IFLOW
     2,ILIN
      COMMON/NEW1/HAD(100),STO(100),RAIN,DELTAT,SUM,THE(100)
      COMMON/CONN/S(100),B1(100),PAT
      COMMON/NEW2/C1,G1,C2,G2,COM,OUT,STOR,ETL,ERR
      COMMON/NEW3/KO,KOUNT,BUZ(500),LAPAZ,DUBBA,CRET,RAO(31,300)
     1,JJVK
      COMMON/NEW4/JAYA,ITRT,HPR1(100)
      COMMON/RSLTS/TOFILT,TORUN,TOETL,TOSTO,TOREC,MON,ISTAD,BANG,
     1ATIM,BTIM,INSTAN,SKF,ROG1,JDOP,ITOPT
      COMMON/RUNOF/R1,RUNX,IDIOT,XBZ
      COMMON/DINF/TOR,TOF,TOR1,TORX,TOHX,TOEL,TOST,
     1TOSTI,TOUT,BTOR,BTOF,BTOR1,BTORX,BTOHX,
     2BTOEL,BTOST,BTOSTI,BTOUT,VAIP
      COMMON/IRRG/AI(1000)
      COMMON/EXTER/ZUTA(100),AUMMU
      COMMON/ETS/NOROOT(1000),FM(31),WP,PET(1000)
      COMMON/TADI/NFC,BHAMA
      COMMON/CUMLAT/VT1,VT2,VT3,VT4,VT5,VT6,VT7,BENH,FACTOR
      TOFILT=0.0;TORUN=0.0;TOETL=0.0;TOSTO=0.0;TOREC=0.0;TORAI=0.0
      TORUND=0.0;TOHTED=0.0;TXOUT=0.0;DXCHR=0.0;XBENH=0.0;TOAI=0.0
      SUM=0.0;CRET=BTIM
      DO 2160 I=1,NDAYS-1
      AKJT(I)=AKJT(I)*3600.
```

```
 2160 CONTINUE
      KOUNT=1;SSM=0.0;LAPAZ=LAPAZ+1
      IF(LAPAZ.NE.1)GO TO 2166
      DO 8671 I=1,100
      JTL=I
      PORO(I)=THETA(0.0,JTL)
 8671 CONTINUE
      DUMMU=DELZ(NDP-1)
      AUMMU=DUMMU
      DO 8081 I=1,500
 8081 BUZ(I)=0.0
      DO 8097 I=1,NDP
      THE(I)=0.0
      HAD(I)=0.0
 8097 CONTINUE
      DELF=DELZ(NDP-1);DBN=0.0
      DO 77777 JB=1,NDP-1
      FLOWER(JB)=DELZ(JB)
      IF(IFLOW.NE.0)FLOWER(JB)=0.0
77777 CONTINUE
      IF(JE.EQ.0)JE=100000*3600
      IF(ITR.EQ.0)ITR=10
      IF(INSTAN.EQ.1)IRUN=0
      JE=-JE
      PAT=86400.0
      IF(ROG1.NE.0.0)PAT=ROG1
      MUDD=1
      IF(JDOP.NE.0)MUDD=JDOP
      VAT69=PAT/86400.0*24.0
      IF(IOPT.GT.0)HAD(1)=SKF
      DO 386 I=1,NDP
      JTL=I
      B1(I)=THETA(HPR(I),JTL)
 386  CONTINUE
      WRITE(3,86882)
      WRITE(20,86882)
6882 FORMAT(40X,52('='))
```

```
      WRITE(20,906)
      BUNI=PAT/3600.0
      WRITE(20,888)BUNI
      WRITE(3,888)BUNI
      IF(IFLOW.NE.0)WRITE(20,99999)
      IF(IFLOW.NE.0)WRITE(3,99999)
      IF(IFLOW.EQ.0)WRITE(20,88888)
      IF(IFLOW.EQ.0)WRITE(3,88888)
      IF(ILIN.NE.0)WRITE(20,66666)
      IF(ILIN.NE.0)WRITE(3,66666)
      IF(ILIN.EQ.0)WRITE(20,55555)
      IF(ILIN.EQ.0)WRITE(3,55555)
      IF(IRUN.NE.1)WRITE(20,996)
      WRITE(3,86882)
      WRITE(3,2167)
      WRITE(20,86882)
 2166 CONTINUE
      HPR(NDP)=BANG
      B1(NDP)=THETA(BANG,NDP)
C     WRITE(3,2167)
 2167 FORMAT(1H1)
      WRITE(3,102)(ALP(I),I=1,80),MON
      WRITE(3,101)
      IF(LAPAZ.NE.1)GO TO 2168
      WRITE(3,100)THEDAY
      WRITE(3,9999)(B1(I),I=1,NDP)
      WRITE(3,640)(HPR(KL),KL=1,1)
      STORI=-TREP(AR)
      SAPOTA=STORI
      ATOSTI=STORI
 2168 WRITE(20,2167)
      WRITE(20,102)(ALP(I),I=1,80),MON
      WRITE(20,101)
      WRITE(20,103)
      WRITE(20,101)
      IF(LAPAZ.NE.1)GO TO 1000
C     WRITE(20,99)STORI
```

```
 99   FORMAT(79X,F8.2)
      DO 800 I=1,NDP-1
      JTL=I
      IF(I.EQ.NODE)JTL=JTL+1
      AP(I)=COND((B1(I)+B1(I+1))/2.,JTL)
 800  CONTINUE
      STO(1)=(-HPR(1)+HPR(2)+FLOWER(1))/DELZ(1)*AP(1);C1=STO(1)
      G1=(-HPR(NDP-1)+HPR(NDP)+FLOWER(NDP-1))/DELZ(NDP-1)*AP(NDP-1)
      STO(NDP-1)=G1-(-HPR(NDP-2)+HPR(NDP-1)+FLOWER(NDP-2))/DELZ(NDP-2)
     1*AP(NDP-2)
      DO 1000 I=2,NDP-2
      STO(I)=(-HPR(I)+HPR(I+1)+FLOWER(I))/DELZ(I)*AP(I)
     1-(-HPR(I-1)+HPR(I)+FLOWER(I-1))/DELZ(I-1)*AP(I-1)
 1000 CONTINUE
      BEM=0.0
      DO 7771 JB=1,NDP-1
 7771 BEM=BEM+DELZ(JB)
      IF(LAPAZ.EQ.1)BHAMA=BEM
      IF(LAPAZ.EQ.1)NFC=NDP
      DO 200 J=1,NDAYS-1
      XXHPR=HPR(1);IF(XXHPR.GE.0.0)XXHPR=0.0
      AI(J)=0.0
      IF(MON.GE.15)GO TO 19838
      GO TO 19832
      IF(MON.GE.17)GO TO 19838;IF(MON.GE.13)GO TO 19832
      IF(HPR(1).LE.-50.0)GO TO 19838
      AI(J)=100.0-ABS(HPR(1))
      IF(HPR(1).GE.0.0)AI(J)=100.0
      IF(MON.EQ.10)AI(J)=0.0
      GO TO 19838
19832 SUMST=0.0;RTDP=0.0
      DO 19833 ICKK=2,NOROOT(J)
      RTDP=RTDP+DELZ(ICKK)
19833 SUMST=SUMST+(DELZ(ICKK-1)+DELZ(ICKK))*B1(ICKK)/2.0
      SUMST=SUMST+DELZ(1)*B1(1)/2.0
      RTDP=RTDP+DELZ(1)-DELZ(NOROOT(J))/2.0
      CONM=SUMST/RTDP;AVASI=(0.125+WP)/2.0
```

```
      IF(CONM.GT.PORO(1))STOP'ERROR'
      IF(CONM.GE.AVASI)GO TO 19838
      AI(J)=RTDP*0.125-SUMST
19838 CONTINUE
      ZIPP=RAI(J+1)/4.0
      AI(J)=AI(J)-ZIPP
      IF(AI(J).LT.0.0)AI(J)=0.0;IF(AI(J).EQ.0.0)GO TO 99963
      KAJU=AI(J)/75.0
      IF(FLOAT(KAJU)*75.0.EQ.AI(J))AI(J)=AI(J)-75.0
      IBOGI=AI(J)/75.0+1
      AI(J)=FLOAT(IBOGI)*75.0
99963 RONAK=RAI(J+1)
      RAI(J+1)=RONAK+AI(J)
      JAYA=J
      CALL STEP(RONAK)
      JAY=JAYA+1
      CHORI=0.0
      IF(BANG.NE.0.0)GO TO 5252
      IF(J.EQ.1.AND.LAPAZ.EQ.1)GO TO 5252
      JAYAL=JAYA
      CALL SIMU(REC,DTW,JAYAL)
      DZ1=0.0
      DO 22222 JB=1,NDP-1
22222 DZ1=DZ1+DELZ(JB)
      DO 8882 JB=1,NDP
      THY(JB)=B1(JB)
      BETA(JB)=DELZ(JB)
 8882 CONTINUE
      NDS=NDP
      BEM=DZ1
      IF(DTW-DZ1)6262,5252,4242
 6262 CONTINUE
      DBN=0.0
      DZL=DZ1-DTW
      KAVI=0;DZX=0.0
      DO 33333 JB=1,NDP-1
      KBL=NDP-JB
```

```
      DZX=DZX+DELZ(KBL)
      IF(DZL.GE.DZX)GO TO 33333
      DELZ(KBL)=DZX-DZL
      GO TO 2221
33333 KAVI=KAVI+1
      STOP'W.T RACHED SURFACE'
 2221 NDP=NDP-KAVI
      DO 6263 JB=1,NDP-1
      FLOWER(JB)=DELZ(JB)
      IF(IFLOW.NE.0.0)FLOWER(JB)=0.0
 6263 CONTINUE
      HPR(NDP)=0.0;HAD(NDP)=0.0
      B1(NDP)=THETA(HPR(NDP),NDP)
      THE(NDP)=B1(NDP)
      UGL=(B1(NDP)+B1(NDP-1))/2.0
      JTL=NDP-1
      IF(JTL.EQ.NODE)JTL=NDP
      AP(NDP-1)=COND(UGL,JTL)
      UGL=(B1(NDP-1)+B1(NDP-2))/2.0
      JTL=NDP-2
      IF(JTL.EQ.NODE)JTL=NDP-1
      AP(NDP-2)=COND(UGL,JTL)
      G1=(-HPR(NDP-1)+HPR(NDP)+FLOWER(NDP-1))/DELZ(NDP-1)*AP(NDP-1)
      STO(NDP-1)=G1-(-HPR(NDP-2)+HPR(NDP-1)+FLOWER(NDP-2))/DELZ(NDP-2)
      1*AP(NDP-2)
      DEMP=DZL;KOUR=0
      DO 3 JB=1,NDS-1
      MOUR=KOUR
      JBXY=NDS-JB
      IF(DEMP.GT.BETA(JBXY))KOUR=KOUR+1
      IF(DEMP.GT.BETA(JBXY))DEMP=DEMP-BETA(JBXY)
      IF(MOUR.EQ.KOUR)GO TO 4
 3    CONTINUE
 4    CONTINUE
      ARC=0.0
      IF(KOUR.EQ.0)GO TO 12
      DO 11 JB=NDS-KOUR,NDS-1
```

```
      AA1=(THY(JB)-THY(JB+1))*BETA(JB)/2.0
 11   ARC=ARC+AA1
 12   CONTINUE
      MNQP=NDS-KOUR-1
      MNVP=MNQP+1
      AA1=THY(MNQP)/BETA(MNQP)
      AA2=THY(MNVP)/BETA(MNQP)
      AA3=AA1*DEMP-AA2*DEMP
      AA1=AA3+THY(MNVP)
      AA1=(AA1-THY(MNVP))*DZL/2.0
      ARC=ARC+AA1
C     CHORI=ARC
      DUMMU=DELZ(NDP-1)
      BHAMA=0.0;DO 771 JB=1,NDP-1
 771  BHAMA=BHAMA+DELZ(JB);NFC=NDP;TXCHR=0.0
      GO TO 5252
 4242 CONTINUE
      DZL=DTW-DZ1
      LNDP=NDP
      DBN=DBN+DZL
      DVN=DBN
      IF(DBN.LT.DELF)DELZ(NDP-1)=DELZ(NDP-1)+DZL
      IF(DBN.LT.DELF)GO TO 12345
      DELZ(NDP-1)=DUMMU
      KAS=DBN/DELF
      DO 2286 JB=NDP,NDP+KAS-1
 2286 DELZ(JB)=DELF
      DIFT=DBN-FLOAT(KAS)*DELF
      DELZ(NDP+KAS-1)=DELZ(NDP+KAS-1)+DIFT
      DBN=0.0
      LNDP=NDP
      NDP=NDP+KAS
      DUMMU=DELZ(NDP-1)
12345 CONTINUE
      DO 6264 JB=1,NDP-1
      FLOWER(JB)=DELZ(JB)
      IF(IFLOW.NE.0.0)FLOWER(JB)=0.0
```

```
 6264 CONTINUE
      HPR(NDP)=0.0;HAD(NDP)=0.0;B1(NDP)=THETA(0.0,NDP)
      THE(NDP)=B1(NDP)
      IF(DVN.LT.DELF)GO TO 12347
      DO 12347 JB=LNDP,NDP-1
      JBB=JB;HPR(JB)=HPR(LNDP)
      B1(JB)=THETA(HPR(JB),JBB)
12347 CONTINUE
      UGL=(B1(NDP)+B1(NDP-1))/2.
      JTL=NDP-1
      IF(JTL.EQ.NODE)JTL=NDP
      AP(NDP-1)=COND(UGL,JTL)
      UGL=(B1(NDP-1)+B1(NDP-2))/2.
      JTL=NDP-2
      IF(JTL.EQ.NODE)JTL=NDP-1
      AP(NDP-2)=COND(UGL,JTL)
      G1=(-HPR(NDP-1)+HPR(NDP)+FLOWER(NDP-1))/
      1DELZ(NDP-1)*AP(NDP-1)
      STO(NDP-1)=G1-(-HPR(NDP-2)+HPR(NDP-1)+FLOWER(NDP-2))
      1/DELZ(NDP-2)*AP(NDP-2)
      IF(LNDP.EQ.NDP)GO TO 12349
      DO 12348 JB=LNDP-1,NDP-2
      JTL=JB
      IF(JTL.EQ.NODE)JTL=JTL+1
      AP(JB)=COND((B1(JB)+B1(JB+1))/2.0,JTL)
12348 CONTINUE
      DO 12349 JB=LNDP-1,NDP-2
      STO(JB)=(-HPR(JB)+HPR(JB+1)+FLOWER(JB))/DELZ(JB)
      1*AP(JB)-(-HPR(JB-1)+HPR(JB)+FLOWER(JB-1))
      2/DELZ(JB-1)*AP(JB-1)
12349 CONTINUE
 5252 CONTINUE
      DZ1=0.0
      DO 86881 JB=1,NDP-1
      DZ1=DZ1+FLOWER(JB)
86881 CONTINUE
      DTVB=DZ1
```

```
      IF(NDP.GT.100)STOP'NODES > 100'
 6087 CONTINUE
      JYOTI=1;HDAY1=HPR(1)
      JAYA=J
      AKO1=FLOAT(NDAYS)*PAT
      IF(AKJT(JAYA).NE.0)AKO1=AKJT(JAYA)
      STO1=0.0;ETLD=0.0;RUN=0.0;FILT=0.0;REC=0.0;RUND=0.0
      HTED=0.0
      ZAIIN=AI(J)/21600.0
      DELI=0.0
      DO 203 JK=1,JJVK
 6089 CONTINUE
      DELA=0.0;IVPT=0;IJPT=0;ISPT=0
      DE=RAO(J,JK)
      DELTAT=DE
      DELI=DELI+DELTAT
 60   CONTINUE
      MAN=0;IRMY=0
      IF(IJPT.EQ.1)DELTAT=DE-DELTAT
      IF(IVPT.EQ.1)DELTAT=DE-DELA
      IF(DELTAT.LE.2.0.AND.MANIS.EQ.1)MAN=1
      IF(DELTAT.LE.2.0)GO TO 6060
      RAIN=RONAK/PAT;DAIP=RAI(J)/PAT
      IF(DELI.LE.21600.0)RAIN=RAIN+ZAIIN
      IF(LAPAZ.NE.1.AND.J.EQ.1)DAIP=VAIP
      IF(INSTAN.EQ.1)GO TO 6060
      IF(IOPT.LE.0)GO TO 6060
 6547 CONTINUE
      TGF=R1;IF(ABS(TGF).LE.0.01)TGF=0.0
      ALOF=RAIN*DELTAT-TGF*DELTAT/DUBBA-C1*DELTAT
     1-S(1)*DELTAT
      HAD(1)=HPR(1)-ALOF
      IF(HAD(1).LE.0.0)GO TO 6060
      IOPT=0;IKLT=1;AMMO=DELTAT
 6060 CONTINUE
      HTEX=0.0
      HRET=HAD(1);IVIJ=0;VIJAYA=0.0
```

```
      BOMB=0.0
 607  CONTINUE
      IF(DELTAT.LE.2.0)GO TO 802
 6000 CONTINUE
      C11=C1;G11=G1
      DO 6008 ILT=1,NDP-1
      DG(ILT)=B1(ILT)
 6008 SA(ILT)=STO(ILT)
      CALL SOLVE
      C1=C2;G1=G2
      IF(IOPT.GT.0)GO TO 600
      IF(HAD(1).LT.SSM-0.01)DELTAT=DELTAT/2.
      IF(DELTAT.LE.2.0)GO TO 801
      IF(HAD(1).LT.SSM-0.01)GO TO 6070
      IF(HAD(1).GT.SSM+0.01)GO TO 600
 801  CONTINUE
      IF(DELTAT.LE.2.0.AND.HAD(1).LT.0.0)HAD(1)=0.0
      IOPT=2
      IGLT=0
      IF(IKLT.EQ.1)IGLT=1
      IF(IGLT.NE.1)GO TO 6001
 6070 CONTINUE
      C1=C11;G1=G11
      DO 6009 ILT=1,NDP-1
      B1(ILT)=DG(ILT)
 6009 STO(ILT)=SA(ILT)
      IF(IKLT.EQ.1.AND.DELTAT.EQ.AMMO/2.)BUAM=HAD(1)
      IF(IRUN.NE.1.AND.DELTAT.EQ.AMMO/2.)BUAM=HGG
      IF(VIJAYA.EQ.1.0)HAD(1)=0.0
      IF(IVIJ.EQ.1)GO TO 607
      IF(DELTAT.LE.2.0.AND.IGLT.EQ.1)DELTAT=AMMO
      IF(DELTAT.LE.2.0.AND.IGLT.EQ.1)HAD(1)=BUAM
      GO TO 607
 6001 CONTINUE
      SUM=SUM+DELTAT
      DELA=DELA+DELTAT
      ISPT=1
```

```
      MUR=SUM/AK01
      DO 7878 ILT=1,NDP-1
      BIG(ILT)=B1(ILT)
 7878 CONTINUE
      DO 7879 ILT=1,NDP-1
      B1(ILT)=DG(ILT)
 7879 CONTINUE
      STOR=TREP(AR)
      DO 7880 ILT=1,NDP-1
 7880 B1(ILT)=BIG(ILT)
      ETL=0.0
      DO 6856 LAT=1,NDP-1
      ETL=ETL+S(LAT)
 6856 CONTINUE
      ETL=ETL*DELTAT
      COM=RAIN*DELTAT
      OUT=(G1+G11)*DELTAT/2.
      R1=0.0;HTEX=0.0;RUNX=0.0
      ETLD=ETLD+ETL
      FILT=FILT+COM
      REC=REC+OUT
      ERR=0.0
      INGU=0
      CAR=STOR;BIR=0.0
 8677 CONTINUE
      STORI=STORI+BIR+CAR
      STO1=STO1+BIR+CAR
      ERR1=COM-OUT-ETL-BIR-CAR
      STOR=CAR
      JUND=0
      DO 7 JB=1,NDP
      ZUTA(JB)=THE(JB)
 7    CONTINUE
      TOR=TOR+COM
      TOF=TOF+COM
      TOR1=TOR1+R1
      TORX=TORX+RUNX
```

```
      TOHX=TOHX+HTEX
      TOEL=TOEL+ETL
      TOST=TOST+STOR
      TOSTI=TOSTI+STORI
      TOUT=TOUT+OUT
      IF(HPR(1).GT.SSM+0.01)GO TO 1202
      JJKL=IFIX(SUM);ISUN=MUR*IFIX(AKO1)
      IF(WE.LT.0.0)GO TO 1201
      IF(JJKL.NE.ISUN)GO TO 1201
      THEDAY=SUM/PAT
      WRITE(3,100)THEDAY
      MANIS=1
 1202 CONTINUE
      THEDAY=SUM/PAT
C     IF(HPR(1).GT.SSM+0.01)WRITE(3,106)THEDAY
C     WRITE(3,9999)(THE(KL),KL=1,NDP)
C     WRITE(3,640)(HAD(KL),KL=1,1)
      ATOR=TOR-BTOR;ATOF=TOF-BTOF;ATOR1=TOR1-BTOR1
      ATORX=TORX-BTORX;ATOHX=TOHX-BTOHX;ATOEL=TOEL-BTOEL
      ATOST=TOST-BTOST
      ATOSTI=ATOSTI+ATOST;ATOUT=TOUT-BTOUT
      ERR1=ATOF-ATOUT-ATOEL-ATOST
      ERR=ATOR-ATOR1-ATOHX-ATOF
C     WRITE(3,107)ATOR,ATOF,ATOR1,ATORX,ATOHX,ATOEL,ATOST,
C     1ATOUT,ERR1,ERR
      BTOR=TOR;BTOF=TOF;BTOR1=TOR1;BTORX=TORX;BTOST=TOST
      BTOHX=TOHX;BTOEL=TOEL;BTOSTI=TOSTI;BTOUT=TOUT
 1201 CONTINUE
      DO 67888 JB=1,NDP-1
      B1(JB)=BIG(JB)
67888 CONTINUE
      DO 601 I=1,NDP-1
      HPR(I)=HAD(I)
      B1(I)=THE(I)
 601  CONTINUE
      IJPT=1
      IF(ITOPT.EQ.0.OR.JYOTI.GT.2000)GO TO 6072
```

```
      DO 6072 JJV=1,KOUNT-1
      BANDA(JYOTI)=BUZ(JJV)
      JYOTI=JYOTI+1
      IF(JYOTI.GT.2000)GO TO 60720
 6072 CONTINUE
60720 CONTINUE
      DUBBA=DELTAT
      GO TO 60
 600  CONTINUE
      IF(IOPT.GT.0)GO TO 6040
      IGLT=0
      IF(IKLT.EQ.1)IGLT=1
      IF(IGLT.NE.1)GO TO 6040
      DELTAT=DELTAT/2.
      IF(DELTAT.LE.4.0)VIJAYA=1.0
      IF(DELTAT.LE.4.0)GO TO 801
      C1=C11;G1=G11
      DO 6042 ILT=1,NDP-1
      B1(ILT)=DG(ILT)
      STO(ILT)=SA(ILT)
 6042 CONTINUE
      IVIJ=1
      GO TO 607
 6040 CONTINUE
      CH1=RAIN*DELTAT
      COM=CH1
      IF(IOPT.GT.0)COM=(C1+C11)*DELTAT/2.0
      R1=CH1-COM
      IF(IRUN.NE.1.AND.IOPT.GT.0)R1=R1-S(1)*DELTAT
      IF(IRUN.NE.1)GO TO 6050
      IF(IOPT.LE.0)GO TO 6050
      ETL=ETL+S(1)*DELTAT
      R1=R1-S(1)*DELTAT-(HPR(1)-HAD(1))
      IF(R1.LT.0.0)R1=0.0
      XBZ=HAD(1)
      AJANTA=HPR(1);IF(AJANTA.GT.0.0)AJANTA=0.0
      ELLORA=HAD(1);IF(ELLORA.GT.0.0)ELLORA=0.0
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```
      HTEX=AJANTA-ELLORA
      IDIOT=1
      IF(IRUN.EQ.1.AND.BOMB.LE.DEAL)CALL RUNOFF
      BOMB=BOMB+1.0
      IF(IDIOT.EQ.1)GO TO 6050
      IF(HAD(1).LE.0.0)GO TO 6080
      DELTAT=DELTAT/2.
      HAD(1)=HRET
      BOMB=0.0
      IF(DELTAT.GT.2.0)GO TO 6080
      IRMY=1
      IF(COINEX.EQ.0.0)GO TO 6050
      TYPE 6806,SUM
 6806 FORMAT(5X,'COMPATIBILITY FAILURE EXT.VS.INT.RUNOFF
     1 AT',5X,G12.5,5X,'TYPE "Y" TO PROCEED "N" TO STOP')
      ACCEPT*,YAMUNA
      IF(YAMUNA.EQ.'Y')GO TO 6050
      STOP
 6080 CONTINUE
      IF(DELTAT.LE.2.0)STOP'RUNOFF VER.FAILURE'
      C1=C11;G1=G11
      DO 6010 ILT=1,NDP-1
      B1(ILT)=DG(ILT)
      STO(ILT)=SA(ILT)
 6010 CONTINUE
      GO TO 607
 6050 CONTINUE
      IKLT=0;IGLT=0
      SUM=SUM+DELTAT
      MUR=SUM/AK01
      DO 8878 ILT=1,NDP-1
      BIG(ILT)=B1(ILT)
 8878 CONTINUE
      DO 8879 ILT=1,NDP-1
      B1(ILT)=DG(ILT)
 8879 CONTINUE
      STOR=TREP(AR)
```

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      DO 8880 ILT=1,NDP-1
      B1(ILT)=BIG(ILT)
 8880 CONTINUE
      COM=CH1
      IF(IOPT.GT.0)COM=(C1+C11)*DELTAT/2.
      OUT=(G1+G11)*DELTAT/2.
      ETL=0.0
      KMMR=1
      IF(IOPT.GT.0)KMMR=2
      DO 6866 LAT=KMMR,NDP-1
      ETL=ETL+S(LAT)
 6866 CONTINUE
      ETL=ETL*DELTAT
      RUN=RUN+R1
      RUND=RUND+RUNX
      HTED=HTED+HTEX
      FILT=FILT+COM
      ETLD=ETLD+ETL
      REC=REC+OUT
      ERR=CH1-R1-HTEX-COM
      INGU=0
      CAR=STOR;BIR=0.0
 9677 CONTINUE
      STORI=STORI+BIR+CAR
      STO1=STO1+BIR+CAR
      ERR1=COM-ETL-OUT-BIR-CAR
      DO 8 JB=1,NDP
 8    ZUTA(JB)=THE(JB)
      TOR=TOR+CH1
      TOF=TOF+COM
      TOR1=TOR1+R1
      TORX=TORX+RUNX
      TOHX=TOHX+HTEX
      TOEL=TOEL+ETL
      TOST=TOST+STOR
      TOSTI=TOSTI+STORI
      TOUT=TOUT+OUT
```

```
      JJKL=IFIX(SUM);ISUN=MUR*IFIX(AK01)
      IF(WE.LT.0.0)GO TO 1200
      IF(JJKL.NE.ISUN)GO TO 1200
      THEDAY=SUM/PAT
      WRITE(3,100)THEDAY
      MANIS=1
      WRITE(3,9999)(THE(KL),KL=1,NDP)
C     WRITE(3,640)(HAD(KL),KL=1,1)
      ATOR=TOR-BTOR;ATOF=TOF-BTOF;ATOR1=TOR1-BTOR1
      ATORX=TORX-BTORX;ATOHX=TOHX-BTOHX;ATOEL=TOEL-BTOEL
      ATOST=TOST-BTOST
      ATOSTI=ATOSTI+ATOST;ATOUT=TOUT-BTOUT
      ERR1=ATOF-ATOUT-ATOEL-ATOST
      ERR=ATOR-ATOR1-ATOHX-ATOF
C     WRITE(3,107)ATOR,ATOF,ATOR1,ATORX,ATOHX,ATOEL,ATOST,
C    1ATOUT,ERR1,ERR
      BTOR=TOR;BTOF=TOF;BTOR1=TOR1;BTORX=TORX;BTOST=TOST
      BTOHX=TOHX;BTOEL=TOEL;BTOSTI=TOSTI;BTOUT=TOUT
 1200 CONTINUE
      DO 67777 JB=1,NDP-1
      B1(JB)=BIG(JB)
67777 CONTINUE
      IF(ITOPT.EQ.0.OR.JYOTI.GT.2000)GO TO 6073
      DO 6073 JJV=1,KOUNT-1
      BANDA(JYOTI)=BUZ(JJV)
      JYOTI=JYOTI+1
      IF(JYOTI.GT.2000)GO TO 802
 6073 CONTINUE
 802  CONTINUE
      DO 701 I=1,NDP-1
      HPR(I)=HAD(I)
      B1(I)=THE(I)
 701  CONTINUE
      IF(DELTAT.LE.2.0)SUM=SUM+DELTAT
      IF(DELTAT.GT.2.0.OR.MAN.EQ.1)GO TO 8050
      MUR=SUM/AK01
      JJKL=IFIX(SUM);ISUN=MUR*IFIX(AK01)
```

```
      IF(JJKL.NE.ISUN)GO TO 8050
      THEDAY=SUM/PAT
      WRITE(3,100)THEDAY
      WRITE(3,9999)(THE(KL),KL=1,NDP)
C     WRITE(3,640)(HAD(KL),KL=1,1)
      ATOR=TOR-BTOR;ATOF=TOF-BTOF;ATOR1=TOR1-BTOR1
      ATORX=TORX-BTORX;ATOHX=TOHX-BTOHX;ATOEL=TOEL-BTOEL
      ATOST=TOST-BTOST
      ATOSTI=ATOSTI+ATOST;ATOUT=TOUT-BTOUT
      ERR1=ATOF-ATOUT-ATOEL-ATOST
      ERR=ATOR-ATOR1-ATOHX-ATOF
C     WRITE(3,107)ATOR,ATOF,ATOR1,ATORX,ATOHX,ATOEL,ATOST,
C    1ATOUT,ERR1,ERR
      BTOR=TOR;BTOF=TOF;BTOR1=TOR1;BTORX=TORX;BTOST=TOST
      BTOHX=TOHX;BTOEL=TOEL;BTOSTI=TOSTI;BTOUT=TOUT
 8050 CONTINUE
      IF(MAN.EQ.1)MANIS=0
      HEY=HAD(1)
      IF(IRMY.EQ.1)GO TO 8644
      IF(DELTAT.LE.2.0.OR.DELTAT.EQ.DE)GO TO 201
 8644 CONTINUE
      IF(IVIJ.EQ.1)IOPT=0
      DUBBA=DELTAT
      IVPT=1;DELA=DELA+DELTAT;GO TO 60
 201  IF(DAYSUM.EQ.PAT)GO TO 6999
 203  CONTINUE
 6999 CONTINUE;PORIX=STORI
      CALL TEST(JAY,REC,DELF,NZNDP,ZETA,ADZ,CHORI,NDS,BEM)
      DO 6061 JB=1,NDP
      BETA(JB)=DELZ(JB)
      THY(JB)=THE(JB)
 6061 BB(JB)=B1(JB)
      DO 6062 JB=1,NZNDP
      B1(JB)=0.0;DELZ(JB)=ADZ(JB)
 6062 THE(JB)=ZETA(JB)
      NNDP1=NDP
      NDP=NZNDP
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      STORI=TREP(AR)
      NDP=NNDP1
      DO 16063 JB=1,NDP
      B1(JB)=0.0
      DELZ(JB)=BETA(JB)
      THE(JB)=ZUTA(JB)
16063 CONTINUE
      PORIX=TREP(AR)
      DO 6063 JB=1,NDP
      B1(JB)=BB(JB)
      THE(JB)=THY(JB)
 6063 CONTINUE
      IF(AKO1.GT.PAT)GO TO 1001
      THEDAY=SUM/PAT
      WRITE(3,100)THEDAY
      WRITE(3,9999)(THE(KL),KL=1,NDP)
C     WRITE(3,640)(HAD(KL),KL=1,1)
      ATOR=TOR-BTOR;ATOF=TOF-BTOF;ATOR1=TOR1-BTOR1
      ATORX=TORX-BTORX;ATOHX=TOHX-BTOHX;ATOEL=TOEL-BTOEL
      ATOST=TOST-BTOST
      ATOSTI=ATOSTI+ATOST;ATOUT=TOUT-BTOUT
      ERR1=ATOF-ATOUT-ATOEL-ATOST
      ERR=ATOR-ATOR1-ATOHX-ATOF
C     WRITE(3,107)ATOR,ATOF,ATOR1,ATORX,ATOHX,ATOEL,ATOST,
C     1ATOUT,ERR1,ERR
      BTOR=TOR;BTOF=TOF;BTOR1=TOR1;BTORX=TORX;BTOST=TOST
      BTOHX=TOHX;BTOEL=TOEL;BTOSTI=TOSTI;BTOUT=TOUT
 1001 CONTINUE;HTED=0.0
      IF(HEY.GE.0.0.AND.HDAY1.GE.0.0)GO TO 6071
      GHJ=HDAY1
      IF(HDAY1.GE.0.0)GHJ=0.0
      IF(HEY.GE.0.0)HEY=0.0
      HTED=GHJ-HEY
 6071 CONTINUE
      LAXMI=JYOTI-1
      IF(ITOPT.EQ.0)GO TO 6093
      WRITE(8,6076)LAXMI
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      TORUND=TORUND+XRUND;VT4=VT4+XRUND
      TOETL=TOETL+XETLD;VT5=VT5+XETLD
      TOSTO=TOSTO+XSTO1;VT6=VT6+XSTO1
      VT7=VT7+XOUT
      XRAI=0.0;XFILT=0.0;XRUN=0.0;XRUND=0.0;XHTED=0.0
      XETLD=0.0;XSTO1=0.0;XREC=0.0;XAI=0.0;XCHORI=0.0
 9856 CONTINUE
      WRITE(22,99951)VT1,VT2,VT3,BENH,VT4,VT5,VT6,VT7
99951 FORMAT(5X,8F10.2,/)
 200  CONTINUE
      WRITE(22,2167)
      ERR1=TOFILT-TOETL-TOREC-TOSTO
      ERR=TORAI+TOAI-TORUND-TOHTED-TOFILT
      WRITE(20,101)
      WRITE(20,903)TORAI,TOAI,TOFILT,TOHTED,TORUND,TOETL,TOSTO,
      1DXCHR,TXOUT,ERR
      WRITE(20,101)
      WRITE(20,99977)
99977 FORMAT(4X,'UNITS OF COLUMN 2 THROUGH 12 ARE MM')
99999 FORMAT(/,40X,'3. PARTIALLY SATURATED HORIZONTAL FLOW CONSI
      1DERED')
88888 FORMAT(/,40X,'3. PARTIALLY SATURATED VERTICAL FLOW
      1 CONSIDERED')
66666 FORMAT(/,40X,'4. LINEARIZED FORM OF GOVERNING EQN. CON
      1SIDERED')
55555 FORMAT(/,40X,'4. NON LINEAR FORM OF GOVERNING EQN. CON
      1SIDERED')
 888  FORMAT(/,40X,'2.  1 UNI=',2X,G9.5,2X,'HOURS')
 996  FORMAT(/,40X,'5. RUNOFEXT AND HDETAIND NOT APPLICABLE')
 100  FORMAT(10X,'UNI=',2X,G12.5)
 101  FORMAT(4X,123('-'))
 102  FORMAT(4X,80A1,31X,'PERIOD=',I5)
 103  FORMAT(4X,'DAY    DTW     RAINFALL  APPLIRRN  INFILTRE  DELTA--H
      1   PONDING  RUN--OFF  EVAPTRAN  DELTA--S   DESATRN
      2  RECHARGE  OVALDIFF')
 106  FORMAT(2X,5('='),'>> SURFACE SATURATION  UNI=',2X,G12.5)
 107  FORMAT(2X,10F10.2,/,2X,130('-'))
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 902  FORMAT(4X,I3,12(2X,F8.2),/)
 8656 FORMAT(1X,2F8.2,62X,F8.2)
 903  FORMAT(4X,'TOTAL',8X,4(2X,F8.2),12X,F8.2,2X,F8.2,2X,F8.2
      1,2X,F8.2,2(2X,F8.2))
 906  FORMAT(///,40X,'NOTES:',//,40X,'1. ALL THE COMPONENTS ARE IN MM.')
 640  FORMAT(13F10.2)
      VAIP=DAIP
 9999 FORMAT(18F7.4)
      RETURN;END
      SUBROUTINE SOLVE
      DIMENSION G(100),AP(100),BB(100),F(100),GH(100),SA(100)
      DIMENSION FLOWER(100)
      DIMENSION B(100),STO1(100),TH(100),ST(100),HE(100)
      COMMON/DAT/RAI(1000),NDP,DELZ(100),NODE,NDAYS,ALP(84),IOPT,
      1DE,ITR,AKJT(1000),HPR(100),JE,IRUN,COINEX,COIMEX,DEAL,IFLOW
      2,ILIN
      COMMON/NEW1/HAD(100),STO(100),RAIN,DELTAT,SUM,THE(100)
      COMMON/CONN/S(100),B1(100),PAT
      COMMON/NEW2/C1,G1,C2,G2,COM,OUT,STOR,ETL,ERR
      COMMON/NEW3/KO,KOUNT,BUZ(500),LAPAZ,DUBBA,CRET,RAO(31,300)
      1,JJVK
      COMMON/NEW4/JAYA,ITRT,HPR1(100)
      EPS=0.02;COM1=0.0;OUT1=0.0;STORY=0.0;ETLK=0.0
      ITRT=-1;DELA=0.0;DUM=DELTAT;ISBT=0;IJLT=0
      KOUNT=1
      DO 1060 JB=1,NDP-1
      FLOWER(JB)=DELZ(JB)
      IF(IFLOW.NE.0)FLOWER(JB)=0.0
 1060 CONTINUE
      DO 5856 JJV=1,500
      BUZ(JJV)=0.0
 5856 CONTINUE
      DO 968 I=1,NDP
 968  B(I)=B1(I)
 6800 CONTINUE
      DO 3800 I=1,NDP
      HPR1(I)=HPR(I)
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      B1(I)=B(I)
      STO1(I)=STO(I)
 3800 CONTINUE
      DELA=0.0;DUM=DELTAT
      C11=C1;G11=G1
 3600 CONTINUE
      DO 1266 I=1,NDP-1
      SA(I)=STO(I)
 1266 CONTINUE
      IDLT=NDP-2
      IDL=1
      IF(IOPT.GT.0)IDL=2
 900  CONTINUE
      DO 1 I=IDL,NDP
      HAD(I)=HPR1(I)
      THE(I)=B1(I)
      STO(I)=SA(I)
 1    CONTINUE
      STO(1)=SA(1)
      IF(IOPT.GT.0)THE(1)=THETA(HAD(1),1)
      IF(ITRT.LE.0)GO TO 860
      IF(IJLT.EQ.1)GO TO 860
      DO 861 ILT=IDL,NDP
      B1(ILT)=B(ILT)
      HPR1(ILT)=HPR(ILT)
 861  CONTINUE
 860  CONTINUE
      DO 110 M=1,ITRT+1
      IQ=0
      DO 10 I=1,NDP-1
      JTL=I
      IF(I.EQ.NODE)JTL=JTL+1
      AP(I)=COND((THE(I)+THE(I+1))/2.,JTL)
 10   CONTINUE
      CALL SINK
      IF(IOPT.GT.0)GO TO 66
      I=1
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      JTL=I
      FLOWE=AP(I)
      IF(IFLOW.NE.0)FLOWE=0.0
      DDT=DELZ(I)/DELTAT*DIFU(JTL)
      BB(I)=-AP(I)/(AP(I)-DELZ(I)*DDT)
      G(I)=(-DDT*HPR1(I)+2.*S(I)+STO(I)-2.*RAIN+FLOWE)
     1/(AP(I)/DELZ(I)-DDT)
      DO 20 I=2,NDP-2
      JTL=I
      FLOWE=AP(I)-AP(I-1)
      IF(IFLOW.NE.0)FLOWE=0.0
      DDT=(DELZ(I-1)+DELZ(I))/DELTAT*DIFU(JTL)
      T=AP(I-1)/DELZ(I-1)+AP(I)/DELZ(I)-DDT+AP(I-1)/DELZ(I-1)*BB(I-1)
      BB(I)=-AP(I)/(DELZ(I)*T)
      G(I)=STO(I)+2.*S(I)-DDT*HPR1(I)+FLOWE
     1+AP(I-1)*(G(I-1)/DELZ(I-1))
      G(I)=G(I)/T
20    CONTINUE
      I=NDP-1
      JTL=I
      FLOWE=AP(I)-AP(I-1)
      IF(IFLOW.NE.0)FLOWE=0.0
      DDT=(DELZ(I-1)+DELZ(I))/DELTAT*DIFU(JTL)
      T=AP(I-1)/DELZ(I-1)+AP(I)/DELZ(I)-DDT+AP(I-1)/DELZ(I-1)*BB(I-1)
      BB(I)=-AP(I)/(DELZ(I)*T)
      G(I)=STO(I)+2.*S(I)-DDT*HPR1(I)+FLOWE
     1+HAD(NDP)/DELZ(I)*AP(I)
     2+AP(I-1)*(G(I-1)/DELZ(I-1))
      G(I)=G(I)/T
      F(NDP-1)=G(NDP-1)
      GO TO 1200
66    CONTINUE
      I=2
      JTL=I
      FLOWE=AP(I)-AP(I-1)
      IF(IFLOW.NE.0)FLOWE=0.0
      DDT=(DELZ(1)+DELZ(2))/DELTAT*DIFU(JTL)
```

```
      BB(I)=-AP(I)/DELZ(I)
      BB(I)=BB(I)/(AP(I-1)/DELZ(I-1)+AP(I)/DELZ(I)-DDT)
      G(I)=-DDT*HPR1(I)+STO(I)+2.*S(I)+FLOWE+HAD(1)/DELZ(I-1)
     1*AP(I-1)
      G(I)=G(I)/(AP(I-1)/DELZ(I-1)+AP(I)/DELZ(I)-DDT)
      DO 201 I=3,NDP-2
      JTL=I
      FLOWE=AP(I)-AP(I-1)
      IF(IFLOW.NE.0)FLOWE=0.0
      DDT=(DELZ(I-1)+DELZ(I))/DELTAT*DIFU(JTL)
      T=AP(I-1)/DELZ(I-1)+AP(I)/DELZ(I)-DDT+AP(I-1)/DELZ(I-1)*BB(I-1)
      BB(I)=-AP(I)/(DELZ(I)*T)
      G(I)=STO(I)+2.*S(I)-DDT*HPR1(I)+FLOWE
     1+AP(I-1)*(G(I-1)/DELZ(I-1))
      G(I)=G(I)/T
  201 CONTINUE
      I=NDP-1
      JTL=I
      FLOWE=AP(I)-AP(I-1)
      IF(IFLOW.NE.0)FLOWE=0.0
      DDT=(DELZ(I-1)+DELZ(I))/DELTAT*DIFU(JTL)
      T=AP(I-1)/DELZ(I-1)+AP(I)/DELZ(I)-DDT+AP(I-1)/DELZ(I-1)*BB(I-1)
      BB(I)=-AP(I)/(DELZ(I)*T)
      G(I)=STO(I)+2.*S(I)-DDT*HPR1(I)+FLOWE
     1+HAD(NDP)/DELZ(I)*AP(I)
     2+AP(I-1)*(G(I-1)/DELZ(I-1))
      G(I)=G(I)/T
      F(NDP-1)=G(NDP-1)
      IDLT=NDP-3
      IDL=2
 1200 DO 500 I=1,IDLT
      K=NDP-1-I
      F(K)=G(K)-BB(K)*F(K+1)
      IF(ABS(HAD(K)-F(K)).LE.EPS)IQ=IQ+1
  500 CONTINUE
      IF(ABS(HAD(NDP-1)-F(NDP-1)).LE.EPS)IQ=IQ+1
      IF(ITRT.LE.0.OR.IQ.EQ.(IDLT+1))GO TO 1110
```

```
      IF(DELTAT.LE.2.0)GO TO 1110
      DO 600 I=IDL,NDP-1
      JTL=I
      HAD(I)=F(I)
      THE(I)=THETA(HAD(I),JTL)
600   CONTINUE
      GO TO 110
1110  CONTINUE
      DO 700 I=IDL,NDP-1
      JTL=I
      HAD(I)=F(I)
      IF(HAD(I).LT.0.0.AND.I.GT.1)HAD(I)=0.0
      THE(I)=THETA(HAD(I),JTL)
700   CONTINUE
      DO 800 I=1,NDP-1
      JTL=I
      IF(I.EQ.NODE)JTL=JTL+1
      AP(I)=COND((THE(I)+THE(I+1))/2.,JTL)
800   CONTINUE
      STO(1)=(-HAD(1)+HAD(2)+FLOWER(1))/DELZ(1)*AP(1);C2=STO(1)
      G2=(-HAD(NDP-1)+HAD(NDP)+FLOWER(NDP-1))/DELZ(NDP-1)
      1*AP(NDP-1)
      STO(NDP-1)=G2-(-HAD(NDP-2)+HAD(NDP-1)+FLOWER(NDP-2))/DELZ(NDP
      1-2)*AP(NDP-2)
      DO 1000 I=2,NDP-2
      STO(I)=(-HAD(I)+HAD(I+1)+FLOWER(I))/DELZ(I)*AP(I)
      1-(-HAD(I-1)+HAD(I)+FLOWER(I-1))/DELZ(I-1)*AP(I-1)
1000  CONTINUE
      COM=RAIN*DELTAT
      IF(IOPT.GT.0)COM=(C1+C2)*DELTAT/2.
      OUT=(G1+G2)*DELTAT/2.
      STOR=TREP(AR)
      ETL=0.0
      IDL=1
      IF(IOPT.GT.0)IDL=2
      DO 986 I=IDL,NDP-1
      ETL=ETL+S(I)
```

```
  986 CONTINUE
      ETL=ETL*DELTAT
      ERR=COM-OUT-ETL-STOR
CILIN IF(ILIN.NE.0)GO TO 12060
      IF(ABS(ERR).GT.CRET.AND.DELTAT.GT.2.0)GO TO 1206
12060 CONTINUE
      DELA=DELA+DELTAT
      DO 3700 I=IDL,NDP-1
      B1(I)=THE(I)
      HPR1(I)=HAD(I)
 3700 CONTINUE
      C1=C2;G1=G2
      IF(KOUNT.GT.500)GO TO 12345
      BUZ(KOUNT)=DELTAT
      KOUNT=KOUNT+1
12345 CONTINUE
      DELTAT=DUM-DELA
      IF(ITRT.GT.0)GO TO 9878
      COM1=COM1+COM
      OUT1=OUT1+OUT
      STORY=STORY+STOR
      ETLK=ETLK+ETL
 9878 CONTINUE
      IF(DELTAT.EQ.0.0)GO TO 4000
      IF(ISBT.EQ.1)IJLT=1
      GO TO 3600
 4000 CONTINUE
      ISBT=1
      DELTAT=DUM
      SUMI=SUM+DELTAT
      MUR=SUMI/FLOAT(JE)
      IF(JE*MUR.NE.IFIX(SUMI))GO TO 9010
      IF(ITRT.GT.0)GO TO 9000
      DO 102 I=1,NDP-1
      TH(I)=THE(I)
      HE(I)=HAD(I)
      ST(I)=STO(I)
```

```
102  CONTINUE
     C22=C2;G22=G2
     DO 4100 I=1,NDP-1
     STO(I)=STO1(I)
4100 CONTINUE
     C1=C11;G1=G11
     ITRT=ITR
     GO TO 6800
110  CONTINUE
1206 CONTINUE
     DELTAT=DELTAT/2.
     GO TO 900
9000 CONTINUE
     MANASA=0
     DO 9001 I=1,NDP-1
     AA=0.0
     ATUL=HE(I)
     IF(ATUL.EQ.0.0)ATUL=HAD(I)
     IF(ATUL.EQ.0.0)GO TO 9001
     AA=ABS((HE(I)-HAD(I))/HE(I))
     IF(AA.GT.0.05)MANASA=MANASA+1
9001 CONTINUE
     IF(MANASA.EQ.0)GO TO 2000
     IF(COIMEX.EQ.0.0)GO TO 2000
     TYPE 3000,MANASA,SUM
3000 FORMAT(5X,'COMPATIBILITY FAILURE EXPLI.VS,IMPLI
     1 ',2X,I5,2X,'TIMES AT ',5X,G12.5,5X,'TYPE "Y"
     2 TO PROCEED "N" TO STOP')
     ACCEPT*,YAMUNA
     IF(YAMUNA.EQ.'Y')GO TO 2000
     STOP
2000 CONTINUE
     WRITE(3,1001)
     WRITE(3,9999)(THE(IL),IL=1,NDP)
     WRITE(3,6750)(HAD(IL),IL=1,1)
     WRITE(3,23)SUMI
     WRITE(3,9999)(TH(IL),IL=1,NDP)
```

```
      WRITE(3,6750)(HE(IL),IL=1,1)
23    FORMAT(10X,'TIME=',G12.5,'SECS.')
1001 FORMAT(2X,'COMPARISION--IMPLICIT LINEARIZATION FOWLLED
     1 BY EXPLICIT LINEARIZATION',/)
9999 FORMAT(18F7.4)
6750 FORMAT(13F10.2)
      DO 103 I=1,NDP-1
      THE(I)=TH(I)
      HAD(I)=HE(I)
      STO(I)=ST(I)
103   CONTINUE
      C2=C22;G2=G22
9010 CONTINUE
      COM=COM1;OUT=OUT1;STOR=STORY;ETL=ETLK
      ERR=COM-OUT-ETL-STOR
      RETURN;END
      FUNCTION TREP(AR)
      COMMON/DAT/RAI(1000),NDP,DELZ(100),NODE,NDAYS,ALP(84),IOPT,
      1DE,ITR,AKJT(1000),HPR(100),JE,IRUN,COINEX,COIMEX,DEAL,IFLOW
      2,ILIN
      COMMON/NEW1/HAD(100),STO(100),RAIN,DELTAT,SUM,THE(100)
      COMMON/CONN/S(100),B(100),PAT
      COMMON/DINF/TOR,TOF,TOR1,TORX,TOHX,TOEL,TOST,
      1TOSTI,TOUT,BTOR,BTOF,BTOR1,BTORX,BTOHX,
      2BTOEL,BTOST,BTOSTI,BTOUT,VAIP
      AREA=0.0
      DO 100 KM=2,NDP-1
      AREA=AREA+(THE(KM)-B(KM))*(DELZ(KM-1)+DELZ(KM))/2.
100   CONTINUE
      TREP=AREA+(THE(1)-B(1))*(DELZ(1))/2.+(THE(NDP)-B(NDP))*DELZ
      1(NDP-1)/2.
      RETURN;END
      SUBROUTINE RUNOFF
      COMMON/DAT/RAI(1000),NDP,DELZ(100),NODE,NDAYS,ALP(84),IOPT,
      1DE,ITR,AKJT(1000),HPR(100),JE,IRUN,COINEX,COIMEX,DEAL,IFLOW
      2,ILIN
      COMMON/NEW1/HAD(100),STO(100),RAIN,DELTAT,SUM,THE(100)
```

```
      COMMON/RUNOF/R1,RUNX,IDIOT,XBZ
      IDIOT=0;RUNP=0.0;RUNA=0.0
      AA1=HPR(1);BB1=HAD(1)
      IF(AA1.LT.-0.01)CALL RUNEX(RUNP,XXX,-AA1,1)
      IF(BB1.LT.-0.01)CALL RUNEX(RUNA,XXX,-BB1,1)
      RUNX=(RUNP+RUNA)*DELTAT/2.
      IF(ABS(RUNX-R1).GT.0.01)GO TO 60
      IDIOT=1;RETURN
60    CONTINUE
      RUN2=2.*R1/DELTAT-RUNP
      XXX=0.0
      IF(RUN2.GE.0.0)CALL RUNEX(RUN2,XXX,-BB1,2)
      HAD(1)=-XXX
      IF(ABS(HAD(1)-XBZ).LE.1.E-25)GO TO 80
      RETURN
80    CONTINUE
      HAD(1)=12.0;RETURN;END
      FUNCTION DIFU(JTL)
      COMMON/DAT/RAI(1000),NDP,DELZ(100),NODE,NDAYS,ALP(84),IOPT,
      1DE,ITR,AKJT(1000),HPR(100),JE,IRUN,COINEX,COIMEX,DEAL,IFLOW
      2,ILIN
      COMMON/NEW1/HAD(100),STO(100),RAIN,DELTAT,SUM,THE(100)
      COMMON/CHAR/P(1),CO(1),T1(1),NT
      COMMON/CONST/THR,POR,AM,POW,AC,SSM,SAT
      COMMON/NEW4/JAYA,ITRT,HPR1(100)
      TUF1=HAD(JTL)
      IF(ITRT.GT.0)TUF1=(HPR1(JTL)+HAD(JTL))/2.0
      IF(TUF1.EQ.SSM)GO TO 887
      IF(TUF1.GT.SSM)GO TO 1000
      DIFU=AM
      RETURN
1000  DIFU=EXP(-AC*TUF1)*-AC
      IF(DIFU.GE.0.0)STOP'ERROR-SPEC'
      RETURN
887   CONTINUE
      A1=THETA(TUF1+0.001,JTL)/0.002
      A2=THETA(TUF1-0.001,JTL)/0.002
```

```
      DIFU=A1-A2
      IF(DIFU.GE.0.0)STOP'ERROR-SPEC';RETURN;END
      SUBROUTINE TEST(JAY,REVE,DELF,NZNDP,ZETA,ADZ,CHORI,NDS,BEM)
      DIMENSION CC(100),DD(100),EE(100),FF(100)
      1,ZETA(100),ADZ(100)
      COMMON/DAT/RAI(1000),NDP,DELZ(100),NODE,NDAYS,ALP(84),IOPT,
      1DE,ITR,AKJT(1000),HPR(100),JE,IRUN,COINEX,COIMEX,DEAL,IFLOW
      2,ILIN
      COMMON/NEW1/HAD(100),STO(100),RAIN,DELTAT,SUM,THE(100)
      COMMON/CONN/S(100),B1(100),PAT
      COMMON/NEW2/C1,G1,C2,G2,COM,OUT,STOR,ETL,ERR
      COMMON/NEW3/KO,KOUNT,BUZ(500),LAPAZ,DUBBA,CRET,RAO(31,300)
      1,JJVK
      COMMON/RSLTS/TOFILT,TORUN,TOETL,TOSTO,TOREC,MON,ISTAD,BANG,
      1ATIM,BTIM,INSTAN,SKF,ROG1,JDOP,ITOPT
      COMMON/RUNOF/R1,RUNX,IDIOT,XBZ
      COMMON/DINF/TOR,TOF,TOR1,TORX,TOHX,TOEL,TOST,
      1TOSTI,TOUT,BTOR,BTOF,BTOR1,BTORX,BTOHX,
      2BTOEL,BTOST,BTOSTI,BTOUT,VAIP
      COMMON/EXTER/ZUTA(100),AUMMU
      COMMON/TADI/NFC,BHAMA
      LND=NDP
      DO 100 I=1,NDP
      CC(I)=THE(I)
      DD(I)=B1(I)
      EE(I)=HPR(I)
      FF(I)=DELZ(I)
100   CONTINUE
      DO 30 I=1,NDP
      B1(I)=ZUTA(I)
      HPR(I)=HAD(I)
30    CONTINUE
      CALL SIMU(REVE,DTW,JAY)
      DZ1=0.0
      DO 60 JB=1,NDP-1
      DZ1=DZ1+DELZ(JB)
60    CONTINUE
```

```
      CEM=DZ1
      IF(DTW-DZ1)6262,6262,4242
6262  CONTINUE
      DBN1=0.0
      DZL=DZ1-DTW
      KAVI=0
      DZX=0.0
      DO 86 JB=1,NDP-1
      KBL=NDP-JB
      DZX=DZX+DELZ(KBL)
      IF(DZL.GE.DZX)GO TO 86
      DELZ(KBL)=DZX-DZL
      GO TO 22
86    KAVI=KAVI+1
      STOP'FROM TEST: W.T. REACHED SURFACE'
22    NDP=NDP-KAVI
      DO 666 I=1,NDP
      ZETA(I)=B1(I)
      ADZ(I)=DELZ(I)
666   CONTINUE
      NZNDP=NDP
      AUMMU=DELZ(NDP-1)
      GO TO 5252
4242  CONTINUE
      DZL=DTW-DZ1
      LNDP=NDP
      DBN1=DBN1+DZL
      DVN1=DBN1
      IF(DBN1.LT.DELF)DELZ(NDP-1)=DELZ(NDP-1)+DZL
      IF(DBN1.LT.DELF)GO TO 123
      DELZ(NDP-1)=AUMMU
      KAS=DBN1/DELF
      DO 228 JB=NDP,NDP+KAS-1
228   DELZ(JB)=DELF
      DIFT=DBN1-FLOAT(KAS)*DELF
      DELZ(NDP+KAS-1)=DELZ(NDP+KAS-1)+DIFT
      DBN1=0.0
```

```
RETURN
CONTINUE
A1=ZUTA(NDP)/DELZ(NDP-1)
A2=ZUTA(NDP-1)/DELZ(NDP-1)
A4=A2*AXE-A1*AXE
A5=-A4
CHORI=A5*AXE/2.0
IF(AXE.GE.BOX)GO TO 1002
CHORI=BOX/AXE*CHORI
BOX=AXE
RETURN;END
```

ANNEXURE - III

OUTPUT OF THE MODEL AS A SAMPLE

ANNEXURE-III

```
RICE CBLTIVATED UNDER PONDING
------------------------------------------------------------------------------------------------------------------------------------
                                                                                                                    PERIOD#      7
DAY    DTW      RAINFALL  APPLIRRN  INFILTRE  DELTA--H   PONDING  RUN--OFF  EVAPTRAN  DELTA--S   DESATRN  RECHARGE  OVALDIFF
------------------------------------------------------------------------------------------------------------------------------------
  1   4960.00      0.00    100.00     46.41     51.66     51.66      0.00      2.21     67.97      0.00      1.23      1.93
  2   4958.71      0.00      0.00     37.16    -38.15     13.51      0.00      4.32     31.39      0.00      1.14      0.99
  3   4957.42      0.00    100.00     37.85     61.09     74.60      0.00      4.41     31.99      0.00      1.00      1.05
  4   4956.13      0.00      0.00     29.91    -30.92     43.67      0.00      4.51     23.69      0.00      1.36      1.01
  5   4954.84     11.00     75.00     39.67     45.08     88.76      0.00      4.51     27.04      0.00      6.85      1.24
  6   4953.55      0.00      0.00     32.98    -33.85     54.91      0.00      5.91     22.44      0.00      4.23      0.86
  7   4952.26      0.00      0.00     25.00    -25.73     29.18      0.00      5.91     17.90      0.00      1.42      0.74
  8   4950.97      0.00     75.00     34.89     38.68     67.86      0.00      5.91     20.94      0.00      7.29      1.42
  9   4949.68      0.00      0.00     28.01    -28.79     39.07      0.00      5.91     19.31      0.00      2.57      0.78
 10   4948.39     16.80     75.00     39.28     50.83     89.90      0.00      5.91     19.92      0.00     12.20      1.69
 11   4947.10      0.00      0.00     33.26    -34.12     55.79      0.00      5.91     18.42      0.00      8.13      0.86
 12   4945.81      0.00      0.00     25.14    -25.86     29.93      0.00      5.91     17.38      0.00      1.77      0.72
 13   4944.52      0.00     75.00     35.07     38.50     68.42      0.00      5.91     18.18      0.00      9.99      1.43
 14   4943.23    129.00      0.00     43.82     82.78    151.20      0.00      5.91     17.95      0.00     19.98      2.40
 15   4941.94     22.20      0.00     50.53    -30.39    120.81      0.00      5.91     17.51      0.00     27.06      2.06
 16   4940.65      3.80      0.00     41.09    -38.88     81.92      0.00      5.91     16.67      0.00     16.81      1.59
 17   4939.35     28.40      0.00     34.81     -7.90     74.02      0.00      5.91     16.17      0.00     11.60      1.49
 18   4938.06      1.00      0.00     29.60    -29.41     44.62      0.00      5.91     15.70      0.00      7.33      0.81
 19   4936.77     16.00     75.00     40.50     48.77     93.38      0.00      5.91     16.17      0.00     16.71      1.73
 20   4935.48      0.00      0.00     34.09    -34.95     58.44      0.00      5.91     15.61      0.00     11.46      0.85
 21   4934.19      0.00      0.00     25.76    -26.54     31.90      0.00      6.84     14.41      0.00      4.25      0.77
 22   4932.90      0.00     75.00     35.54     38.01     69.91      0.00      6.84     15.43      0.00     12.17      1.45
 23   4931.61     21.00      0.00     31.05    -10.98     58.94      0.00      6.84     14.82      0.00      8.68      0.93
 24   4930.32      0.00      0.00     25.88    -26.66     32.28      0.00      6.84     14.33      0.00      4.47      0.77
 25   4929.03      0.00     75.00     35.63     37.92     70.20      0.00      6.84     15.06      0.00     12.58      1.45
 26   4927.74      0.00      0.00     28.56    -29.39     40.81      0.00      6.84     14.07      0.00      7.12      0.83
 27   4926.45      0.00     75.00     37.66     35.81     76.62      0.00      6.84     14.83      0.00     14.64      1.53
 28   4925.16     85.40      0.00     40.47     42.90    119.52      0.00      6.84     14.70      0.00     17.28      2.03
 29   4923.87     38.50      0.00     44.98     -8.41    111.11      0.00      6.84     14.58      0.00     23.58      1.94
 30   4922.58      1.10      0.00     38.45    -38.83     72.28      0.00      6.84     14.28      0.00     15.85      1.48
 31   4921.29      0.00      0.00     29.06    -29.89     42.39      0.00      6.84     13.67      0.00      7.94      0.83
------------------------------------------------------------------------------------------------------------------------------------
TOTAL            374.20    800.00   1092.13     42.39                0.00    183.85    612.52      0.00    298.71     39.68
------------------------------------------------------------------------------------------------------------------------------------
UNITS OF COLUMN 2 THROUGH 12 ARE MM
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RICE CULTIVATED UNDER PONDING                                                                              PERIOD=    8
-------------------------------------------------------------------------------------------------------------------------
DAY    DTW     RAINFALL  APPLIRRN  INFILTRE  DELTA--H   PONDING  RUN--OFF  EVAPTRAN  DELTA--S   DESATRN  RECHARGE  QVALDIFF
-------------------------------------------------------------------------------------------------------------------------
  1  4920.00      0.00     75.00     38.05     35.41     77.80      0,00      5,50     15,04      0,00     15,94      1,54
  2  4916.13      1.20      0.00     25.25    -24.89     52.90      0,00      5,50     14,48      0,00     10,32      0,84
  3  4912.26      0.00      0.00     24.45    -25.15     27.76      0,00      5,50     14,11      0,00      4,52      0,69
  4  4908.39      9.00     75.00     35.64     46.85     74.61      0,00      5,50     14,77      0,00     14,00      1,50
  5  4904.52      5.00      0.00     30.23    -26.04     48.57      0,00      5,50     14,37      0,00      9,50      0,82
  6  4900.65     15.50     50.00     36.03     27.95     76.52      0,00      5,50     14,60      0,00     14,51      1,52
  7  4896.77      0.00      0.00     30.07    -30.87     45.65      0,00      5,50     14,23      0,00      9,50      0,80
  8  4892.90      0.00     75.00     38.82     34.60     80.25      0,00      5,50     14,55      0,00     17,05      1,57
  9  4889.03     35.00      0.00     35.21     -1.76     78.49      0,00      5,50     14,12      0,00     14,20      1,54
 10  4885.16      0.00      0.00     30.54    -31.35     47.14      0,00      5,50     14,09      0,00     10,02      0,81
 11  4881.29      0.00     75.00     39.18     34.23     81.37      0,00      5,50     14,52      0,00     17,40      1,59
 12  4877.42      0.00      0.00     31.23    -32.05     49.32      0,00      5,50     14,10      0,00     10,62      0,82
 13  4873.55      0.00     75.00     39.70     33.69     83.02      0,00      5,50     14,43      0,00     19,78      1,61
 14  4869.68     55.10      0.00     38.32     15.01     98.03      0,00      5,50     14,31      0,00     16,82      1,77
 15  4865.81      1.20      0.00     35.34    -35.01     63.02      0,00      5,50     14,11      0,00     14,31      0,87
 16  4861.94     10.00      0.00     28.08    -18.87     44.15      0,00      5,50     13,96      0,00      7,92      0,79
 17  4858.06      0.00     75.00     38.47     34.97     79.13      0,00      5,50     14,24      0,00     17,02      1,56
 18  4854.19      0.00      0.00     30.69    -31.51     47.62      0,00      5,50     13,93      0,00     10,30      0,81
 19  4850.32      0.00     75.00     39.29     34.12     81.74      0,00      5,50     14,34      0,00     17,69      1,59
 20  4846.45      0.00      0.00     31.31    -32.14     49.60      0,00      5,50     13,78      0,00     11,01      0,83
 21  4842.58     10.20     50.00     35.63     23.09     72.69      0,00      5,50     13,79      0,00     14,89      1,48
 22  4838.71      0.00      0.00     29.16    -29.95     42.75      0,00      5,50     13,31      0,00      9,54      0,78
 23  4834.84      0.00     75.00     38.13     35.32     78.07      0,00      5,50     12,96      0,00     18,00      1,55
 24  4830.97      0.00      0.00     30.44    -31.25     46.82      0,00      5,50     11,32      0,00     12,67      0,81
 25  4827.10      0.00     75.00     39.10     34.31     81.13      0,00      5,50     10,48      0,00     21,35      1,58
 26  4823.23      0.00      0.00     31.17    -31.99     49.14      0,00      5,50      8,85      0,00     15,79      0,82
 27  4819.35      0.00     75.00     39.65     33.74     82.88      0,00      5,50      8,21      0,00     25,96      1,61
 28  4815.48      0.00      0.00     31.59    -32.42     50.46      0,00      5,50      6,84      0,00     18,18      0,83
 29  4811.61      0.00      0.00     23.87    -24.55     25.91      0,00      5,50      5,78      0,00     12,27      0,68
 30  4807.74      0.00     75.00     34.12     39.49     65.40      0,00      5,50      5,72      0,00     21,61      1,39
 31  4803.87      0.00      0.00     27.43    -28.18     37.22      0,00      5,50      4,66      0,00     16,61      0,75
-------------------------------------------------------------------------------------------------------------------------
TOTAL           142.20    925.00   1036.19     -5.17                0,00    170,50    388,02      0,00    449,32     36,18
-------------------------------------------------------------------------------------------------------------------------
UNITS OF COLUMN 2 THROUGH 12 ARE MM
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RICE CULTIVATED UNDER PONDING                                                                                      PERIOD=    9
--------------------------------------------------------------------------------------------------------------------------------
DAY   DTW      RAINFALL  APPLIRRN  INFILTRE  DELTA--H   PONDING  RUN--OFF  EVAPTRAN  DELTA--S   DESATRN  RECHARGE  OVALDIFF
--------------------------------------------------------------------------------------------------------------------------------
 1    4800.00    15.50     75.00     38.69     50.16     87.38     0.00      5.69      4.67      0.00     28.39      1.66
 2    4803.33    39.70      0.00     37.48      0.56     87.94     0.00      5.69      3.89      0.00     26.46      1.66
 3    4806.67    12.00      0.00     34.25    -23.16     64.78     0.00      5.69      3.30      0.00     24.12      0.91
 4    4810.00     1.00      0.00     27.40    -27.15     37.63     0.00      5.69      2.74      0.00     18.50      0.75
 5    4813.33     0.00     75.00     36.91     36.59     74.21     0.00      5.69      2.90      0.00     26.94      1.50
 6    4816.67     0.00      0.00     29.52    -30.31     43.90     0.00      5.69      2.20      0.00     20.95      0.79
 7    4820.00     9.20     75.00     39.51     43.04     86.94     0.00      5.69      2.46      0.00     31.57      1.65
 8    4823.33    21.50      0.00     35.16    -15.13     71.81     0.00      5.69      1.92      0.00     26.32      1.47
 9    4826.67     1.20      0.00     29.10    -28.68     43.13     0.00      5.69      1.54      0.00     21.23      0.79
10    4830.00     0.00     75.00     38.22     35.23     78.35     0.00      5.69      1.82      0.00     29.20      1.55
11    4833.33     0.70      0.00     30.53    -31.14     47.21     0.00      5.69      1.24      0.00     22.82      0.81
12    4836.67     2.10     75.00     39.45     36.04     83.25     0.00      5.69      1.55      0.00     32.41      1.61
13    4840.00     7.30      0.00     32.56    -26.13     57.12     0.00      5.69      1.04      0.00     24.85      0.87
14    4843.33    10.00      0.00     26.67    -17.44     39.69     0.00      5.69      0.81      0.00     19.77      0.76
15    4846.67     1.00     75.00     37.52     36.95     76.63     0.00      5.69      1.21      0.00     29.18      1.53
16    4850.00     0.00      0.00     30.10    -30.87     45.76     0.00      4.74      1.08      0.00     23.28      0.77
17    4853.33     0.00     75.00     38.85     34.57     80.33     0.00      4.74      1.29      0.00     32.81      1.57
18    4856.67     0.40      0.00     31.04    -31.39     48.94     0.00      4.74      0.79      0.00     24.40      0.79
19    4860.00     2.00     75.00     39.85     35.52     84.47     0.00      4.74      1.09      0.00     34.00      1.62
20    4863.33     0.00      0.00     31.97    -32.77     51.69     0.00      4.74      0.66      0.00     25.37      0.81
21    4866.67     0.00      0.00     24.17    -24.83     26.87     0.00      4.74      0.39      0.00     18.59      0.66
22    4870.00     0.00     75.00     34.35     39.25     66.11     0.00      4.74      0.88      0.00     27.32      1.40
23    4873.33     0.00      0.00     27.60    -28.32     37.79     0.00      4.74      0.41      0.00     21.68      0.72
24    4876.67     0.00     75.00     36.95     36.54     74.33     0.00      4.74      0.80      0.00     29.75      1.50
25    4880.00     0.00      0.00     29.56    -30.32     44.02     0.00      4.74      0.35      0.00     23.50      0.76
26    4883.33     7.00     75.00     39.27     41.10     85.11     0.00      4.74      0.72      0.00     33.79      1.63
27    4886.67     0.00      0.00     32.12    -32.93     52.18     0.00      4.74      0.33      0.00     25.83      0.81
28    4890.00     0.00      0.00     24.29    -24.94     27.24     0.00      4.74      0.08      0.00     19.01      0.66
29    4893.33     0.00     75.00     34.44     39.16     66.39     0.00      4.74      0.58      0.00     27.70      1.41
30    4896.67     0.00      0.00     27.67    -28.39     38.00     0.00      4.74      0.14      0.00     22.01      0.72
--------------------------------------------------------------------------------------------------------------------------------
TOTAL           130.10    900.00    995.21      0.78               0.00    156.45     42.86      0.04    771.72     34.15
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UNITS OF COLUMN 2 THROUGH 12 ARE MM
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```
RICE CULTIVATED UNDER PONDING                                                                                        PERIOD=   10
-----------------------------------------------------------------------------------------------------------------------------------
DAY    DTW      RAINFALL  APPLIRRN  INFILTRE  DELTA--H   PONDING  RUN--OFF  EVAPTRAN  DELTA--S   DESATRN  RECHARGE  OVALDIFF
-----------------------------------------------------------------------------------------------------------------------------------
  1  4900.00      0.00      0.00     20.92    -21.47     16.54      0.00      3.59      0.52      0.00     16.58      0.55
  2  4897.77      0.00      0.00     16.20    -16.54      0.00      0.00      3.59     -0.02      0.00     12.72      0.33
  3  4895.55      0.00      0.00      0.00      0.00      0.00      0.00      3.59    -16.90      0.00     13.30     -0.00
  4  4893.32      0.00      0.00      0.00      0.00      0.00      0.00      3.59    -16.91      0.00     13.32      0.00
  5  4891.10      0.00      0.00      0.00      0.00      0.00      0.00      3.59    -16.93      0.00     13.34      0.00
  6  4888.87      0.00      0.00      0.00      0.00      0.00      0.00      3.59    -17.00      0.00     13.35      0.00
  7  4886.64      0.00      0.00      0.00      0.00      0.00      0.00      3.59    -16.98      0.00     13.37      0.00
  8  4884.42      0.00      0.00      0.00      0.00      0.00      0.00      3.59    -17.01      0.00     13.38      0.00
  9  4882.19      9.60      0.00      9.60      0.00      0.00      0.00      3.59     -7.34      0.00     13.36      0.00
 10  4879.97      0.00      0.00      0.00      0.00      0.00      0.00      3.59    -17.31      0.00     13.29      0.00
 11  4877.74      0.00      0.00      0.00      0.00      0.00      0.00      3.59    -16.78      0.00     13.19      0.00
 12  4875.51      0.00      0.00      0.00      0.00      0.00      0.00      3.59    -16.66      0.00     13.04      0.00
 13  4873.29      0.00      0.00      0.00      0.00      0.00      0.00      3.59    -16.45      0.00     12.85      0.00
 14  4871.06      0.00      0.00      0.00      0.00      0.00      0.00      3.59    -16.23      0.00     12.62      0.00
 15  4868.84      0.00      0.00      0.00      0.00      0.00      0.00      3.59    -15.97      0.00     12.36      0.00
-----------------------------------------------------------------------------------------------------------------------------------
TOTAL                 9.60      0.00     46.72    -38.00                0.00     53.85   -207.99      0.00    200.08      0.88
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UNITS OF COLUMN 2 THROUGH 12 ARE MM
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FALLOW BETWEEN RICE-WHEAT OR WHEAT-RICE                                                                               PERIOD=   10
-----------------------------------------------------------------------------------------------------------------------------------
DAY     DTW      RAINFALL  APPLIRRN  INFILTRE  DELTA--H   PONDING  RUN--OFF  EVAPTRAN  DELTA--S   DESATRN  RECHARGE  OVALDIFF
-----------------------------------------------------------------------------------------------------------------------------------
 16   4866.61       0.00      0.00      0.00      0.00      0.00      0.00      3.59    -15.67      0.00     12.10      0.00
 17   4864.38       0.00      0.00      0.00      0.00      0.00      0.00      3.58    -15.37      0.00     11.79      0.00
 18   4862.16       0.00      0.00      0.00      0.00      0.00      0.00      3.52    -15.00      0.00     11.50      0.00
 19   4859.93       0.00      0.00      0.00      0.00      0.00      0.00      3.40    -14.58      0.00     11.19      0.00
 20   4857.71       0.00      0.00      0.00      0.00      0.00      0.00      3.23    -14.10      0.00     10.85      0.00
 21   4855.48       0.00      0.00      0.00      0.00      0.00      0.00      3.03    -13.59      0.00     10.55      0.00
 22   4853.26       0.00      0.00      0.00      0.00      0.00      0.00      2.81    -13.08      0.00     10.26      0.00
 23   4851.03       0.00      0.00      0.00      0.00      0.00      0.00      2.60    -12.59      0.00      9.97      0.00
 24   4848.80       0.00      0.00      0.00      0.00      0.00      0.00      2.40    -12.09      0.00      9.71      0.00
 25   4846.58       0.00      0.00      0.00      0.00      0.00      0.00      2.20    -11.62      0.00      9.47      0.00
 26   4844.35       0.00      0.00      0.00      0.00      0.00      0.00      2.02    -11.18      0.00      9.22      0.00
 27   4842.13       0.00      0.00      0.00      0.00      0.00      0.00      1.86    -10.77      0.00      8.97      0.00
 28   4839.90       0.00      0.00      0.00      0.00      0.00      0.00      1.71    -10.39      0.00      8.70      0.00
 29   4837.68       0.00      0.00      0.00      0.00      0.00      0.00      1.58    -10.02      0.00      8.49      0.00
 30   4835.45       0.00      0.00      0.00      0.00      0.00      0.00      1.46     -9.68      0.00      8.21      0.00
 31   4833.23       0.00      0.00      0.00      0.00      0.00      0.00      1.35     -9.36      0.00      8.01      0.00
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TOTAL                 0.00      0.00      0.00      0.00                0.00     40.31   -199.08      0.00    159.00      0.00
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UNITS OF COLUMN 2 THROUGH 12 ARE MM
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FALLOW BETWEEN RICE-WHEAT OR WHEAT-RICE                                                                      PERIOD=   11
--------------------------------------------------------------------------------------------------------------------------
DAY    DTW     RAINFALL  APPLIRRN  INFILTRE  DELTA--H   PONDING  RUN--OFF  EVAPTRAN  DELTA--S   DESATRN  RECHARGE  OVALDIFF
--------------------------------------------------------------------------------------------------------------------------
  1  4831.00      0.00      0.00      0.00      0.00      0.00      0.00      0.78     -8.58      0.00      7.82      0.00
  2  4830.63      0.00      0.00      0.00      0.00      0.00      0.00      0.74     -8.39      0.00      7.67      0.00
  3  4830.27      0.00      0.00      0.00      0.00      0.00      0.00      0.71     -8.19      0.00      7.50      0.00
  4  4829.90      0.00      0.00      0.00      0.00      0.00      0.00      0.68     -7.99      0.00      7.34      0.00
  5  4829.53      0.00      0.00      0.00      0.00      0.00      0.00      0.66     -7.81      0.00      7.18      0.00
  6  4829.17      0.00      0.00      0.00      0.00      0.00      0.00      0.63     -7.63      0.00      7.00      0.00
  7  4828.80      0.00      0.00      0.00      0.00      0.00      0.00      0.60     -7.45      0.00      6.85      0.00
  8  4828.43      0.00      0.00      0.00      0.00      0.00      0.00      0.58     -7.29      0.00      6.74      0.00
  9  4828.07      0.00      0.00      0.00      0.00      0.00      0.00      0.55     -7.13      0.00      6.61      0.00
 10  4827.70      0.00      0.00      0.00      0.00      0.00      0.00      0.53     -6.97      0.00      6.47      0.00
 11  4827.33      0.00      0.00      0.00      0.00      0.00      0.00      0.51     -6.83      0.00      6.31      0.00
 12  4826.97      1.20      0.00      1.20      0.00      0.00      0.00      0.52     -5.54      0.00      6.22      0.00
 13  4826.60      0.00      0.00      0.00      0.00      0.00      0.00      0.54     -6.63      0.00      6.10      0.00
 14  4826.23      0.00      0.00      0.00      0.00      0.00      0.00      0.52     -6.50      0.00      6.01      0.00
--------------------------------------------------------------------------------------------------------------------------
TOTAL                 1.20      0.00      1.20      0.00                0.00      8.56   -102.94      0.00     95.83      0.00
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UNITS OF COLUMN 2 THROUGH 12 ARE MM
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RABI WHEAT                                                                                                            PERIOD=   11
------------------------------------------------------------------------------------------------------------------------------------
DAY    DTW       RAINFALL  APPLIRRN  INFILTRE  DELTA--H   PONDING  RUN--OFF  EVAPTRAN  DELTA--S   DEBATRN  RECHARGE  OVALDIFF
------------------------------------------------------------------------------------------------------------------------------------
 15   4825.87      0.00     75.00     66.75      6.46      6.46      0.00      1.88     64.29      0.00      0.81      1.79
 16   4825.80      0.00      0.00      6.46     -6.46      0.00      0.00      2.00     -1.17      0.00      5.44      0.00
 17   4824.13      0.00      0.00      0.00      0.00      0.00      0.00      2.20     -7.73      0.00      5.61      0.00
 18   4824.77      0.00      0.00      0.00      0.00      0.00      0.00      2.20     -7.68      0.00      5.63      0.00
 19   4825.40      0.00      0.00      0.00      0.00      0.00      0.00      2.20     -8.08      0.00      5.80      0.00
 20   4824.03      0.00      0.00      0.00      0.00      0.00      0.00      0.77     -6.18      0.00      5.43      0.00
 21   4823.67      0.00      0.00      0.00      0.00      0.00      0.00      0.77     -6.10      0.00      5.36      0.00
 22   4823.30      0.00      0.00      0.00      0.00      0.00      0.00      0.77     -6.02      0.00      5.26      0.00
 23   4822.93      0.00      0.00      0.00      0.00      0.00      0.00      0.77     -5.95      0.00      5.19      0.00
 24   4822.57      0.00      0.00      0.00      0.00      0.00      0.00      0.77     -5.87      0.00      5.13      0.00
 25   4822.20      0.00      0.00      0.00      0.00      0.00      0.00      0.77     -5.80      0.00      5.06      0.00
 26   4821.83      0.00      0.00      0.00      0.00      0.00      0.00      0.77     -5.73      0.00      4.99      0.00
 27   4821.47      0.00      0.00      0.00      0.00      0.00      0.00      0.77     -5.66      0.00      4.92      0.00
 28   4821.10      1.00      0.00      1.00      0.00      0.00      0.00      0.77     -4.60      0.00      4.85      0.00
 29   4820.73      0.00      0.00      0.00      0.00      0.00      0.00      0.77     -5.54      0.00      4.79      0.00
 30   4820.37      0.00      0.00      0.00      0.00      0.00      0.00      0.77     -5.48      0.00      4.72      0.00
------------------------------------------------------------------------------------------------------------------------------------
TOTAL              1.00     75.00     74.21      0.00                0.00     18.95    -23.30      0.00     78.99      1.79
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UNITS OF COLUMN 2 THROUGH 12 ARE MM
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```
RABI WHEAT                                                                                                        PERIOD=   12
---------------------------------------------------------------------------------------------------------------------------------
DAY    DTW      RAINFALL  APPLIRRN  INFILTRE  DELTA--H   PONDING   RUN--OFF  EVAPTRAN  DELTA--S   DESATRN   RECHARGE  OVALDIFF
---------------------------------------------------------------------------------------------------------------------------------
  1   4820.00     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -5.72      0.00      4.68      0.00
  2   4837.94     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.12      0.06      5.04      0.00
  3   4855.87     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.20      0.00      5.22      0.00
  4   4873.81     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.27      0.06      5.14      0.00
  5   4891.74     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.25      0.07      5.26      0.00
  6   4909.68     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.30      0.10      5.25      0.00
  7   4927.61     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.64      0.12      5.57      0.00
  8   4945.55     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.33      0.14      5.29      0.00
  9   4963.48     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.27      0.15      5.22      0.00
 10   4981.42     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.27      0.18      5.28      0.00
 11   4999.35     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.39      0.22      5.12      0.00
 12   5017.29     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.06      0.16      5.28      0.00
 13   5035.23     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.90      0.00      6.10      0.00
 14   5053.16     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.36      0.14      5.29      0.00
 15   5071.10     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.06      0.13      4.93      0.00
 16   5089.03     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.35      0.20      5.28      0.00
 17   5106.97     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.26      0.21      5.21      0.00
 18   5124.90     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.19      0.22      5.20      0.00
 19   5142.84     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.87      0.00      5.88      0.00
 20   5160.77     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.13      0.13      5.31      0.00
 21   5178.71     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.26      0.16      5.26      0.00
 22   5196.65     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.09      0.15      5.16      0.00
 23   5214.58     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.04      0.19      5.23      0.00
 24   5232.52     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.22      0.24      5.11      0.00
 25   5250.45     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.74      0.00      5.87      0.00
 26   5268.39     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -5.91      0.12      4.80      0.00
 27   5286.32     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.13      0.16      5.26      0.00
 28   5304.26     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.20      0.19      5.17      0.00
 29   5322.19     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -5.71      0.16      4.58      0.00
 30   5340.13     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -5.89      0.21      4.69      0.00
 31   5358.06     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -6.72      0.00      5.99      0.00
---------------------------------------------------------------------------------------------------------------------------------
TOTAL             0.00      0.00      0.00      0.00                0.00     32.55   -193.87      3.86    162.64      0.00
---------------------------------------------------------------------------------------------------------------------------------
UNITS OF COLUMN 2 THROUGH 12 ARE MM
```

```
RABI WHEAT                                                                                                 PERIOD#   13
-------------------------------------------------------------------------------------------------------------------------
DAY     DTW     RAINFALL  APPLIRRN  INFILTRE  DELTA--H   PONDING  RUN--OFF  EVAPTRAN  DELTA--S   DESATRN  RECHARGE  OVALDIFF
-------------------------------------------------------------------------------------------------------------------------
  1   5376.00     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -6.89      0.13      5.30      0.00
  2   5372.26     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -6.24      0.00      4.37      0.00
  3   5368.52     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -5.82      0.00      3.98      0.00
  4   5364.77     3.00      0.00      3.00      0.00      0.00      0.00      1.93     -2.69      0.00      3.86      0.00
  5   5361.03    15.00      0.00     15.00      0.00      0.00      0.00      1.93      9.10      0.00      4.04      0.00
  6   5357.29     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -6.61      0.00      4.36      0.00
  7   5353.55     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -5.68      0.00      4.20      0.00
  8   5349.81     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -5.55      0.00      3.67      0.00
  9   5346.06     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -5.46      0.00      3.58      0.00
 10   5342.32     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -5.38      0.00      3.51      0.00
 11   5338.58     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -5.31      0.00      3.43      0.00
 12   5334.84     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -5.24      0.00      3.37      0.00
 13   5331.10     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -5.15      0.00      3.28      0.00
 14   5327.35     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -5.19      0.00      3.31      0.00
 15   5323.61     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -5.21      0.00      3.69      0.00
 16   5319.87     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -5.13      0.00      3.56      0.00
 17   5316.13     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -5.00      0.00      3.48      0.00
 18   5312.39     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -4.92      0.00      3.41      0.00
 19   5308.65     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -4.86      0.00      3.35      0.00
 20   5304.90     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -4.81      0.00      3.29      0.00
 21   5301.16     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -4.77      0.00      3.23      0.00
 22   5297.42     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -4.73      0.00      3.17      0.00
 23   5293.68     0.40      0.00      0.40      0.00      0.00      0.00      1.93     -4.29      0.00      3.11      0.00
 24   5289.94     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -4.65      0.00      3.05      0.00
 25   5286.19     9.00      0.00      9.00      0.00      0.00      0.00      1.93      4.57      0.00      2.99      0.00
 26   5282.45     1.00      0.00      1.00      0.00      0.00      0.00      1.93     -3.53      0.00      2.93      0.00
 27   5278.71    15.10      0.00     15.10      0.00      0.00      0.00      1.93     10.69      0.00      2.86     -0.00
 28   5274.97     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -5.01      0.00      2.80      0.00
 29   5271.23     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -4.42      0.00      2.73      0.00
 30   5267.48     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -4.39      0.00      2.67      0.00
 31   5263.74     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -4.35      0.00      2.60      0.00
-------------------------------------------------------------------------------------------------------------------------
TOTAL            43.50      0.00     43.50      0.00                0.00     59.83   -116.91      0.13    107.20     -0.00
-------------------------------------------------------------------------------------------------------------------------
UNITS OF COLUMN 2 THROUGH 12 ARE MM
```

```
                                                                                                  PERIOD=    14
RABI WHEAT
-----------------------------------------------------------------------------------------------------------------
DAY    DTW       RAINFALL  APPLIRRN  INFILTRE  DELTA--H   PONDING  RUN--OFF  EVAPTRAN  DELTA--S   DESATRN  RECHARGE  OVALDIFF
-----------------------------------------------------------------------------------------------------------------
  1   5260.00      0.00      0.00      0.00      0.00      0,00      0,00      1,88     -4,26      0,00      2,53      0,00
  2   5264.29      0.00      0.00      0.00      0.00      0,00      0,00      1,88     -4,42      0,10      2,63      0,00
  3   5268.57      1.00      0.00      1.00      0.00      0,00      0,00      1,88     -3,40      0,00      2,79      0,00
  4   5272.86     12.00      0.00     12.00      0.00      0,00      0,00      1,88      7,76      0,00      2,85      0,00
  5   5277.14      0.00      0.00      0.00      0.00      0,00      0,00      1,88     -4,95      0,01      2,91      0,00
  6   5281.43      0.00      0.00      0.00      0.00      0,00      0,00      1,88     -4,31      0,01      2,48      0,00
  7   5285.71      0.00      0.00      0.00      0.00      0,00      0,00      1,88     -4,28      0,01      2,46      0,00
  8   5290.00      0.00      0.00      0.00      0.00      0,00      0,00      1,88     -4,25      0,01      2,43      0,00
  9   5294.29      0.00      0.00      0.00      0.00      0,00      0,00      1,88     -4,31      0,01      2,49      0,00
 10   5298.57      0.00      0.00      0.00      0.00      0,00      0,00      1,88     -4,42      0,01      2,58      0,00
 11   5302.86      0.00      0.00      0.00      0.00      0,00      0,00      1,88     -4,24      0,01      2,42      0,00
 12   5307.14      0.00      0.00      0.00      0.00      0,00      0,00      1,88     -4,19      0,02      2,38      0,00
 13   5311.43      0.00      0.00      0.00      0.00      0,00      0,00      1,88     -4,15      0,02      2,35      0,00
 14   5315.71      0.00      0.00      0.00      0.00      0,00      0,00      1,88     -4,14      0,02      2,34      0,00
 15   5320.00      0.00      0.00      0.00      0.00      0,00      0,00      1,88     -4,87      0,02      3,15      0,00
 16   5324.29      0.00      0.00      0.00      0.00      0,00      0,00      1,87     -4,51      0,02      3,02      0,00
 17   5328.57      0.00      0.00      0.00      0.00      0,00      0,00      1,87     -4,36      0,03      2,94      0,00
 18   5332.86      0.00      0.00      0.00      0.00      0,00      0,00      1,86     -4,27      0,02      2,43      0,00
 19   5337.14      0.00      0.00      0.00      0.00      0,00      0,00      1,86     -4,71      0,03      2,92      0,00
 20   5341.43      0.00      0.00      0.00      0.00      0,00      0,00      1,85     -4,49      0,03      2,73      0,00
 21   5345.71      0.00      0.00      0.00      0.00      0,00      0,00      1,84     -4,37      0,03      2,72      0,00
 22   5350.00      0.00      0.00      0.00      0.00      0,00      0,00      1,84     -4,43      0,04      2,65      0,00
 23   5354.29      0.00     75.00     64.79      8.59      9,22      0,00      1,80     60,01      0,04      2,56      1,62
 24   5358.57      0.00      0.00      8.35     -8.59      0,00      0,00      1,81      5,45      0,03      1,20      0,24
 25   5362.86      0.00      0.00      0.00      0.00      0,00      0,00      1,81     -4,24      0,03      2,58      0,00
 26   5367.14      0.00      0.00      0.00      0.00      0,00      0,00      1,80     -4,47      0,03      3,08      0,00
 27   5371.43      0.00      0.00      0.00      0.00      0,00      0,00      1,79     -3,97      0,04      2,20      0,00
 28   5375.71      0.00      0.00      0.00      0.00      0,00      0,00      1,79     -4,43      0,05      2,66      0,00

-----------------------------------------------------------------------------------------------------------------
TOTAL             13.00     75.00     86.14      0.00                0,00     52,00    -35,22      0,68     72,48      1,86
-----------------------------------------------------------------------------------------------------------------
UNITS OF COLUMN 2 THROUGH 12 ARE MM
```

```
                                                                                                      PERIOD=   15
RABI WHEAT
------------------------------------------------------------------------------------------------------------------
DAY    DTW     RAINFALL  APPLIRRN  INFILTRE  DELTA--H   PONDING  RUN--OFF  EVAPTRAN  DELTA--S  DESATRN  RECHARGE  OVALDIFF
------------------------------------------------------------------------------------------------------------------
  1  5380.00     0.00      0.00      0.00      0.00      0.00      0.00      0.88     -3.50      0.05     2.57      0.00
  2  5380.97     0.00      0.00      0.00      0.00      0.00      0.00      0.88     -3.10      0.01     2.45      0.00
  3  5381.94     0.00      0.00      0.00      0.00      0.00      0.00      0.89     -3.00      0.01     2.44      0.00
  4  5382.90     0.00      0.00      0.00      0.00      0.00      0.00      0.89     -3.05      0.01     2.45      0.00
  5  5383.87     0.00      0.00      0.00      0.00      0.00      0.00      0.89     -3.39      0.02     2.38      0.00
  6  5334.84     0.00      0.00      0.00      0.00      0.00      0.00      0.89     -3.36      0.02     2.23      0.00
  7  5385.81     0.00      0.00      0.00      0.00      0.00      0.00      0.89     -3.11      0.01     2.15      0.00
  8  5386.78     0.00      0.00      0.00      0.00      0.00      0.00      0.90     -3.00      0.01     2.14      0.00
  9  5387.74     0.00      0.00      0.00      0.00      0.00      0.00      0.90     -2.91      0.01     2.14      0.00
 10  5388.71     0.00      0.00      0.00      0.00      0.00      0.00      0.90     -2.81      0.01     2.15      0.00
 11  5389.68     0.00      0.00      0.00      0.00      0.00      0.00      0.90     -2.89      0.01     2.17      0.00
 12  5390.65     0.00      0.00      0.00      0.00      0.00      0.00      0.90     -3.18      0.02     2.13      0.00
 13  5391.62     0.00      0.00      0.00      0.00      0.00      0.00      0.90     -3.28      0.02     2.00      0.00
 14  5392.58     0.00      0.00      0.00      0.00      0.00      0.00      0.90     -2.97      0.01     1.89      0.00
 15  5393.55     0.00      0.00      0.00      0.00      0.00      0.00      0.91     -2.87      0.01     1.88      0.00
------------------------------------------------------------------------------------------------------------------
TOTAL            0.00      0.00      0.00      0.00                0.00     13.42    -46.41      0.24    33.17      0.00
------------------------------------------------------------------------------------------------------------------
UNITS OF COLUMN 2 THROUGH 12 ARE MM
```

```
                                                                                                              PERIOD#   15
--------------------------------------------------------------------------------------------------------------------------
FALLOW BETWEEN RICE-WHEAT OR WHEAT-RICE
--------------------------------------------------------------------------------------------------------------------------
DAY   DTW       RAINFALL  APPLIRRN  INFILTRE  DELTA--H  PONDING  RUN--OFF  EVAPIRAN  DELTA--S  DESATRN  RECHARGE  OVALDIFF
--------------------------------------------------------------------------------------------------------------------------
 16   5394.52     0.00      0.00      0.00      0.00     0.00      0.00      3.92     -5.74      0.01     1.89      0.00
 17   5395.49     0.00      0.00      0.00      0.00     0.00      0.00      3.64     -5.53      0.01     1.89      0.00
 18   5396.46     0.00      0.00      0.00      0.00     0.00      0.00      3.28     -5.06      0.01     1.90      0.00
 19   5397.42     0.00      0.00      0.00      0.00     0.00      0.00      2.93     -4.73      0.01     1.91      0.00
 20   5398.39     0.00      0.00      0.00      0.00     0.00      0.00      2.63     -4.31      0.01     1.93      0.00
 21   5399.36     0.00      0.00      0.00      0.00     0.00      0.00      2.36     -4.12      0.01     1.94      0.00
 22   5400.33     0.00      0.00      0.00      0.00     0.00      0.00      2.12     -4.07      0.02     1.92      0.00
 23   5401.29     0.00      0.00      0.00      0.00     0.00      0.00      1.92     -4.20      0.03     1.80      0.00
 24   5402.26     0.00      0.00      0.00      0.00     0.00      0.00      1.73     -3.58      0.02     1.68      0.00
 25   5403.23     0.00      0.00      0.00      0.00     0.00      0.00      1.57     -3.34      0.01     1.66      0.00
 26   5404.20     0.00      0.00      0.00      0.00     0.00      0.00      1.42     -3.05      0.01     1.67      0.00
 27   5405.16     0.00      0.00      0.00      0.00     0.00      0.00      1.29     -2.88      0.01     1.69      0.00
 28   5406.13     0.00      0.00      0.00      0.00     0.00      0.00      1.17     -2.85      0.01     1.70      0.00
 29   5407.10     0.00      0.00      0.00      0.00     0.00      0.00      1.06     -2.63      0.01     1.71      0.00
 30   5408.07     0.00      0.00      0.00      0.00     0.00      0.00      0.97     -2.67      0.01     1.71      0.00
 31   540[illegible].03     0.00      0.00      0.00      0.00     0.00      0.00      0.89     -2.44      0.01     1.70      0.00
--------------------------------------------------------------------------------------------------------------------------
TOTAL             0.00      0.00      0.00      0.00               0.00     32.90    -61.20      0.21    28.69      0.00
--------------------------------------------------------------------------------------------------------------------------
UNITS OF COLUMN 2 THROUGH 12 ARE MM
```

```
                                                                                                    PERIOD=   16
FALLOW BETWEEN RICE-WHEAT OR WHEAT-RICE
-------------------------------------------------------------------------------------------------------------------
DAY    DTW      RAINFALL  APPLIRRN  INFILTRE  DELTA--H   PONDING  RUN--OFF  EVAPTRAN  DELTA--S   DESATRN  RECHARGE  OVALDIFF
-------------------------------------------------------------------------------------------------------------------
  1   5410.00     0.00      0.00      0.00      0.00      0.00      0.00      1.12     -2.65      0.01      1.71      0.00
  2   5418.33     0.00      0.00      0.00      0.00      0.00      0.00      0.98     -2.71      0.11      1.83      0.00
  3   5426.67     0.00      0.00      0.00      0.00      0.00      0.00      0.86     -2.96      0.12      1.88      0.00
  4   5435.00     0.00      0.00      0.00      0.00      0.00      0.00      0.76     -2.90      0.13      1.87      0.00
  5   5443.33     0.00      0.00      0.00      0.00      0.00      0.00      0.67     -2.65      0.13      1.86      0.00
  6   5451.67     5.50      0.00      5.50      0.00      0.00      0.00      0.98      2.70      0.13      1.91     -0.00
  7   5460.00     9.00      0.00      9.00      0.00      0.00      0.00      1.68      5.32      0.15      1.92      0.00
  8   5468.33     0.00      0.00      0.00      0.00      0.00      0.00      2.23     -4.08      0.15      1.93      0.00
  9   5476.67     0.00      0.00      0.00      0.00      0.00      0.00      2.21     -5.06      0.00      3.02      0.00
 10   5485.00     0.00      0.00      0.00      0.00      0.00      0.00      1.90     -4.05      0.09      2.15      0.00
 11   5493.33     0.00      0.00      0.00      0.00      0.00      0.00      1.63     -3.48      0.08      2.15      0.00
 12   5501.67     0.00      0.00      0.00      0.00      0.00      0.00      1.40     -3.65      0.09      2.19      0.00
 13   5510.00     0.00      0.00      0.00      0.00      0.00      0.00      1.20     -3.51      0.11      2.16      0.00
 14   5518.33     0.00      0.00      0.00      0.00      0.00      0.00      1.04     -3.07      0.11      2.12      0.00
 15   5526.67     0.00      0.00      0.00      0.00      0.00      0.00      0.90     -2.74      0.10      2.16      0.00
 16   5535.00     0.00      0.00      0.00      0.00      0.00      0.00      0.78     -2.55      0.11      1.72      0.00
 17   5543.33     3.20      0.00      3.20      0.00      0.00      0.00      0.93      0.10      0.12      2.28      0.00
 18   5551.67     0.00      0.00      0.00      0.00      0.00      0.00      1.05     -3.51      0.15      2.22      0.00
 19   5560.00     0.00      0.00      0.00      0.00      0.00      0.00      0.91     -2.90      0.13      2.18      0.00
 20   5568.33     0.00      0.00      0.00      0.00      0.00      0.00      0.79     -2.84      0.13      2.23      0.00
 21   5576.67     0.00      0.00      0.00      0.00      0.00      0.00      0.68     -3.17      0.16      2.23      0.00
 22   5585.00     0.00      0.00      0.00      0.00      0.00      0.00      0.59     -4.08      0.00      3.20      0.00
 23   5593.33     0.00      0.00      0.00      0.00      0.00      0.00      0.52     -2.73      0.09      2.30      0.00
 24   5601.67     0.00      0.00      0.00      0.00      0.00      0.00      0.45     -2.32      0.08      1.84      0.00
 25   5610.00     0.00      0.00      0.00      0.00      0.00      0.00      0.40     -2.38      0.08      2.37      0.00
 26   5618.33     4.00      0.00      4.00      0.00      0.00      0.00      0.65      0.90      0.10      2.40      0.00
 27   5626.67     9.50      0.00      9.50      0.00      0.00      0.00      1.30      5.75      0.12      2.35      0.00
 28   5635.00     1.50      0.00      1.50      0.00      0.00      0.00      1.93     -2.55      0.11      2.30      0.00
 29   5643.33     6.00      0.00      6.00      0.00      0.00      0.00      2.22      1.75      0.10      2.33      0.00
 30   5651.67     0.00      0.00      0.00      0.00      0.00      0.00      2.49     -5.34      0.13      2.34      0.00
------ ------------------------------------------------------------------------------------------------------------
TOTAL            38.70      0.00     38.70      0.00                0.00     35.24    -61.38      3.11     65.16      0.00
-------------------------------------------------------------------------------------------------------------------
UNITS OF COLUMN 2 THROUGH 12 ARE MM
```

```
FALLOW BETWEEN RICE-WHEAT OR WHEAT-RICE                                                                              PERIOD=   17
-----------------------------------------------------------------------------------------------------------------------------------
DAY    DTW      RAINFALL  APPLIRRN  INFILTRE  DELTA--H   PONDING  RUN--OFF  EVAPTRAN  DELTA--S   DESATRN  RECHARGE  OVALDIFF
-----------------------------------------------------------------------------------------------------------------------------------
  1   5660.00     0.00      0.00      0.00      0.00      0.00      0.00      2.88     -5.26      0.14      2.27      0.00
  2   5661.29     0.00      0.00      0.00      0.00      0.00      0.00      2.36     -4.69      0.04      2.16      0.00
  3   5662.58     0.00      0.00      0.00      0.00      0.00      0.00      1.93     -4.02      0.04      2.06      0.00
  4   5663.87     0.00      0.00      0.00      0.00      0.00      0.00      1.58     -4.01      0.04      1.99      0.00
  5   5665.16     0.00      0.00      0.00      0.00      0.00      0.00      1.30     -3.36      0.04      1.90      0.00
  6   5666.45     0.00      0.00      0.00      0.00      0.00      0.00      1.07     -3.13      0.04      1.83      0.00
  7   5667.74     0.00      0.00      0.00      0.00      0.00      0.00      0.88     -2.68      0.03      1.79      0.00
  8   5669.03     0.00      0.00      0.00      0.00      0.00      0.00      0.73     -2.58      0.03      1.77      0.00
  9   5670.32     0.00      0.00      0.00      0.00      0.00      0.00      0.61     -2.32      0.03      1.75      0.00
 10   5671.61     0.00      0.00      0.00      0.00      0.00      0.00      0.50     -2.11      0.02      1.74      0.00
 11   5672.90     0.00      0.00      0.00      0.00      0.00      0.00      0.42     -1.95      0.02      1.74      0.00
 12   5674.19     0.00      0.00      0.00      0.00      0.00      0.00      0.35     -2.37      0.03      1.72      0.00
 13   5675.48     0.00      0.00      0.00      0.00      0.00      0.00      0.30     -2.03      0.04      1.67      0.00
 14   5676.77     0.00      0.00      0.00      0.00      0.00      0.00      0.25     -2.07      0.03      1.63      0.00
 15   5678.06     0.00      0.00      0.00      0.00      0.00      0.00      0.22     -1.81      0.03      1.59      0.00
 16   5679.35     0.00      0.00      0.00      0.00      0.00      0.00      0.19     -1.67      0.03      1.58      0.00
 17   5680.65     0.00      0.00      0.00      0.00      0.00      0.00      0.16     -1.58      0.02      1.58      0.00
 18   5681.94     0.00      0.00      0.00      0.00      0.00      0.00      0.14     -1.51      0.02      1.58      0.00
 19   5683.23     0.00      0.00      0.00      0.00      0.00      0.00      0.12     -1.45      0.02      1.59      0.00
 20   5684.52     0.00      0.00      0.00      0.00      0.00      0.00      0.11     -1.41      0.02      1.60      0.00
 21   5685.81     0.00      0.00      0.00      0.00      0.00      0.00      0.10     -1.36      0.02      1.61      0.00
 22   5687.10     0.00      0.00      0.00      0.00      0.00      0.00      0.09     -1.33      0.02      1.61      0.00
 23   5688.39     0.00      0.00      0.00      0.00      0.00      0.00      0.08     -1.29      0.02      1.62      0.00
 24   5689.68     0.00      0.00      0.00      0.00      0.00      0.00      0.08     -1.26      0.02      1.63      0.00
 25   5690.97     0.00      0.00      0.00      0.00      0.00      0.00      0.07     -2.16      0.00      2.56      0.00
 26   5692.26     0.00      0.00      0.00      0.00      0.00      0.00      0.07     -1.46      0.02      1.71      0.00
 27   5693.55     0.00      0.00      0.00      0.00      0.00      0.00      0.06     -1.35      0.02      1.67      0.00
 28   5694.84     0.00      0.00      0.00      0.00      0.00      0.00      0.06     -1.25      0.01      1.65      0.00
 29   5696.13     0.00      0.00      0.00      0.00      0.00      0.00      0.06     -1.20      0.01      1.18      0.00
 30   5697.42     0.00      0.00      0.00      0.00      0.00      0.00      0.06     -1.71      0.02      1.64      0.00
 31   5698.71     0.00      0.00      0.00      0.00      0.00      0.00      0.05     -1.73      0.03      1.59      0.00
-----------------------------------------------------------------------------------------------------------------------------------
TOTAL             0.00      0.00      0.00      0.00                0.00     16.90    -68.12      0.93     54.02      0.00
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UNITS OF COLUMN 2 THROUGH 12 ARE MM
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FALLOW BETWEEN RICE-WHEAT OR WHEAT-RICE                                                          PERIOD#   18
---------------------------------------------------------------------------------------------------------------
DAY   DTW      RAINFALL  APPLIRRN  INFILTRE  DELTA--H   PONDING  RUN--OFF  EVAPTRAN  DELTA--S   DESATRN  RECHARGE  OVALDIFF
---------------------------------------------------------------------------------------------------------------
  1   5700.00    0.00      0.00      0.00      0.00      0.00      0.00      0.06     -1.39      0.02      1.53      0.00
  2   5675.33    0.00      0.00      0.00      0.00      0.00      0.00      0.05     -0.48      0.00      0.70      0.00
  3   5650.67    0.00      0.00      0.00      0.00      0.00      0.00      0.05     -0.12      0.00      0.31      0.00
  4   5626.00    0.00      0.00      0.00      0.00      0.00      0.00      0.05      0.05      0.00      0.01      0.00
  5   5601.33    0.00      0.00      0.00      0.00      0.00      0.00      0.05      0.17      0.00     -0.25      0.00
  6   5576.67    0.00      0.00      0.00      0.00      0.00      0.00      0.05      0.16      0.00     -0.38      0.00
  7   5552.00    0.00      0.00      0.00      0.00      0.00      0.00      0.05      0.33      0.00     -0.65      0.00
  8   5527.33    0.00      0.00      0.00      0.00      0.00      0.00      0.05      0.53      0.00     -0.90      0.00
  9   5502.67    0.00      0.00      0.00      0.00      0.00      0.00      0.04      0.82      0.00     -1.15      0.00
 10   5478.00    0.00      0.00      0.00      0.00      0.00      0.00      0.04      0.75      0.00     -1.43      0.00
 11   5453.33    0.00      0.00      0.00      0.00      0.00      0.00      0.04      0.60      0.00     -0.73      0.00
 12   5428.67    0.00      0.00      0.00      0.00      0.00      0.00      0.04      1.35      0.00     -1.75      0.00
 13   5404.00    0.00      0.00      0.00      0.00      0.00      0.00      0.04      1.57      0.00     -1.93      0.00
 14   5379.33    0.00      0.00      0.00      0.00      0.00      0.00      0.04      1.18      0.00     -1.30      0.00
 15   5354.67    0.00      0.00      0.00      0.00      0.00      0.00      0.04      1.56      0.00     -1.66      0.00
 16   5330.00    0.00      0.00      0.00      0.00      0.00      0.00      0.04      1.87      0.00     -2.34      0.00
 17   5305.33    0.00      0.00      0.00      0.00      0.00      0.00      0.04      2.10      0.00     -2.48      0.00
 18   5280.67    0.00      0.00      0.00      0.00      0.00      0.00      0.04      2.25      0.00     -2.59      0.00
 19   5256.00    0.00      0.00      0.00      0.00      0.00      0.00      0.04      2.23      0.00     -2.39      0.00
 20   5231.33    0.00      0.00      0.00      0.00      0.00      0.00      0.04      2.46      0.00     -2.77      0.00
 21   5206.67    0.00      0.00      0.00      0.00      0.00      0.00      0.04      2.71      0.00     -2.92      0.00
 22   5182.00    0.00      0.00      0.00      0.00      0.00      0.00      0.04      2.86      0.00     -3.03      0.00
 23   5157.33    0.00      0.00      0.00      0.00      0.00      0.00      0.04      2.78      0.00     -3.28      0.00
 24   5132.67    0.00      0.00      0.00      0.00      0.00      0.00      0.04      3.23      0.00     -3.30      0.00
 25   5108.00    0.00      0.00      0.00      0.00      0.00      0.00      0.03      3.39      0.00     -3.41      0.00
 26   5083.33    0.00      0.00      0.00      0.00      0.00      0.00      0.03      3.54      0.00     -3.48      0.00
 27   5058.67    0.00      0.00      0.00      0.00      0.00      0.00      0.03      3.37      0.00     -3.30      0.00
 28   5034.00    0.00      0.00      0.00      0.00      0.00      0.00      0.03      3.09      0.00     -3.13      0.00
 29   5009.33    0.00      0.00      0.00      0.00      0.00      0.00      0.03      3.08      0.00     -3.10      0.00
 30   4984.67    0.00      0.00      0.00      0.00      0.00      0.00      0.03      3.15      0.00     -3.12      0.00
---------------------------------------------------------------------------------------------------------------
TOTAL            0.00      0.00      0.00      0.00                0.00      1.23     49.20      0.02    -54.25      0.00
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UNITS OF COLUMN 2 THROUGH 12 ARE MM
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