WATER BALANCE STUDY IN A HILLY WATERSHED

A DISSERTATION

submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF ENGINEERING
in
IRRIGATION WATER MANAGEMENT

By
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CANDIDATE'S DECLARATION

I hereby certify that the work, which is being presented in this dissertation entitled *" WATER BALANCE STUDY IN A HILLY WATERSHED"* in partial fulfillment of the requirement for the award of the Degree of ***Master of Engineering*** in ***Irrigation Water Management*** submitted in the Department of Water Resources Development Training Centre of the University, is an authentic record of my own work carried out during a period from July 2000 to February 2001 under the supervision of ***Dr. G. C. Mishra,*** Professor, Water Resources Development Training Centre, Universityof Roorkee, Roorkee, Uttaranchal, India.

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

February 22, 2001 **(Viswambhar Kumar Chaturvedi)**

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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Roorkee, February 22, 2001 **(VISWAMBHAR KUMAR CHATURVEDI)**

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NOTATIONS

? - unknown value,

S – potential storage,

a – constant relating initial abstraction and potential storage, .

E - evaporation ,

P - precipitation,

F - actual storage,

Q – run off,

t - time,

I_a - initial abstraction,

A.M.C. – antecedent moisture content,

C.N. - curve number,

f_p – infiltration capacity rate,

f_a – average infiltration rate,

K – capillary conductivity,

$\overline{K}$ – saturated conductivity,

K_{rw} - relative conductivity for water,

θ - moisture content,

θ_f – moisture content at field capacity,

θ_s - moisture content at saturation,

θ_i – antecedent moisture content,

h_c – suction head,

Z_f – depth of saturation front from the ground surface,

H_f – weighted average or representative suction head at the saturation front,

H – ponding height,

τ - dummy variable,

w - cumulative infiltration

I – infiltration rate,

C_R – cumulative rainfall

V - velocity of overland flow,

n	-	co – efficient of rughosity, in contxt of the Manning's equation,
ρ	-	specific weight of water,
R	-	hydraulic radius of the sheet of overland flow,
S	-	slope of watershed,
O.T.I.	–	opportunity time for infiltration,
t_c	–	time of concentration,
A	–	area of the watershed,
V	-	volume ,
D	-	diffusivity,
h_a	-	atmospheric pressure head,
S_{GA}	-	Green and Ampt sorptivity,
t_p	-	ponding time,
η	-	porosity, in contxt of infiltration equations' derivation

LIST OF TABLES

In modern era, owing to population explosion, rapid, industrialization, urbanization and many diversified reasons, availability of water has reduced considerably. Water is not available adequately and timely.

For successful planning, design, construction, operation , maintenance and sustainability of any project or human activity , specially , irrigation , a reasonably realistic water balance study of the area is necessary to achieve proper co- ordination between surface and sub- surface water use .

On the basis of conceptual model of Ben Zvi and Gold Stoff, a soil-water balance method is used to compute the rainfall recharge. Soil Conservation Services method is used to get initial abstraction. Rainfall minus initial abstraction gives effective rainfall amount, a fraction of which infiltrates into root -zone and this is calculated by using Green & Ampt infiltration method. Thus rainfall minus initial abstraction minus infiltration gives the amount of water that emerges out as surface run-off. Infiltrated water increases the soil moisture. Soil moisture in excess of field capacity is deep percolation and regarded as recharge to ground water

To take into account of slope of a catchment in a hilly watershed, the opportunity time for infiltration after stoppage of rainfall is computed from time area diagram. Assuming that the infiltration rate towards the end of the rainfall is equal to saturated conductivity, the quantity that infiltrates from the entire catchment during post rainfall is computed.

In the thesis an in depth study on ponding time is made. Ponding time could be computed either using Morel Seytoux approach or using an approximate value of capacity rate which is computed using Green and Ampt sorptivity.

The infiltration after ponding has been computed considering an average value of cumulative rainfall depth during a time period. The average depth varies from period to period. The expression of cumulative depth of infiltrated water has been derived starting from Green and Ampt infiltration equation.Using an iteration procedure, the variation of cumulative infiltration is computed. The run off volume can be computed fairly using the method described in the thesis.

CHAPTER—I
INTRODUCTION

1.1 GENERAL

From the very conception stage to the design, construction, operation and maintenance of any project, the quantification of the available water resource inside an area is a pre-requisite. Many undesirable after-effects of improper utilization of the available water resources for want of reasonably accurate estimate of water balance of an area, have been noticed many times in past. Massive investments by the Tughlaks in building a great fort in Delhi, resulted in fiasco and it had to be abandoned for want of water and now we see that many irrigation projects and industrial areas are doing very well even in arid and semi-arid zones of India by properly regulating and controlling the water use in their areas supported by latest technological know-how about water balance quantification. Water balance studies enable us to categorize areas into stages of ground water development and regulate them accordingly.

1.2 SCOPE

At present methodology recommended by the 'Ground Water Estimation Committee' (G.E.C.-1997) is adopted as the basis of the water balance study in India. G.E.C.—1997 does not specifically provide a unit for assessment but it implies from its discussions that it is to be conducted for an administrative unit, selection of which is good for development point of view. But since it is not a natural unit, it has been recommended by G. E. C.- 97 that water-shed should be selected in a more desirable way for the larger interest and also for the sake of the simplicity of a more focussed study on soil water balance. To include the slope effects and special variability in a watershed, a hilly zone was considered to be proper.

Many variables influence the water balance of a study unit, namely:soil characteristics of the area, slope of the area, evapo-transpiration, root zone depth, ground water draft, ground water recharge from irrigation water, canals and other water bodies, built-up areas, aquifer geometry and aquifer characteristics etc. All these factors may vary in time and space. Sub-surface conditions also have a great impact on water balance. All these variables acting simultaneously make the job very complex. We focus our attention to rainfall, soil classification, topographical slope, root zone depth and evapo-transpiration which have the maximum weightage.

For the purpose of study of the soil water balance, a method based on conceptual model of Ben Zvi and Goldstoff (vide Bear, 1979) and recommended by G.E.C.—1997 has been used. Infiltration is calculated using Green and Ampt's infiltration method. Infiltrated water increases the soil-moisture up to field capacity. Infiltrated water, more than the field capacity requirement, meets ground water table and is regarded as recharge.

Soil depth below the root zone has not been taken into consideration because of its least capacity to hold water. This acts only as a transmission zone. Manning's equation is used to calculate opportunity time for infiltration. Also using time area diagram of a catchment, the opportunity time for infiltration after rainfall is computed. The fraction of precipitation which infiltrates during a rainfall event has been computed.

REVIEW OF LITERATURE

2.1 HYDROLOGIC SYSTEMS

2.1.1 Introduction

In physical approach towards a water-balance study of a water shed, the primary motivation is that of understanding the physical phenomenon and explaining how things happen in a hydrologic system and how they behave. In this chapter, we focus our attention to the various ways in which the hydrologic system behaves.

Hydrologic cycle that pertains to water in natural state, can be regarded as hydrologic system. Its various component parts include precipitation, interception, evaporation, transpiration, infiltration, detention storage or retention storage, surface run-off inter flow and ground water flow. Each component itself is a sub-system. It is quite relevant to mention some of the hydrologic sub - systems also in order to have a complete view of the scenario of what is happening and how inside a water -shed. Following figures illustrate this.

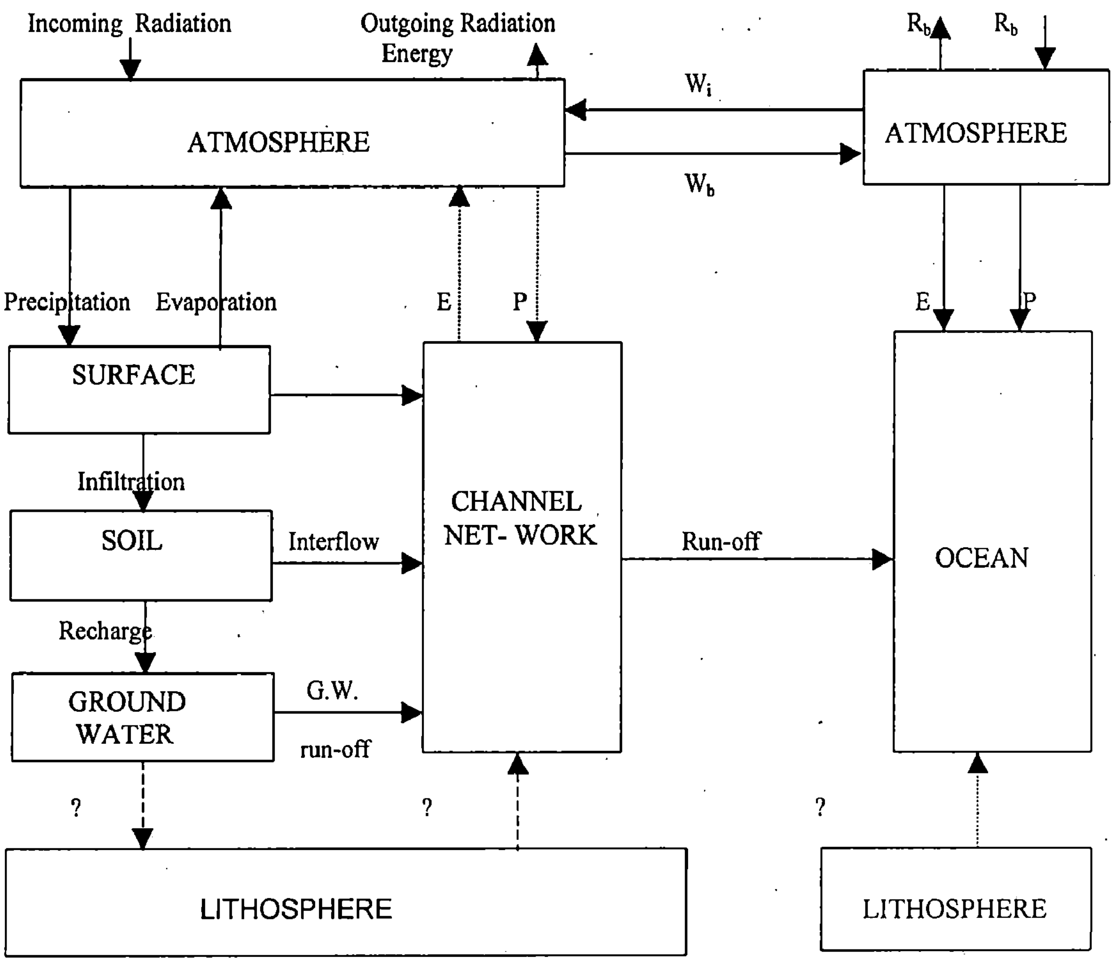

Fig: 2 . 1 .1 A system representation of hydrologic cycle (Dooge, 1973)

2.1.2 Run off System

Rainfall excess produces surface run off. Infiltration replenishes soil moisture storage and extracted by evapo–transpiration. Interception is consumed by evapo-transpiration. Depression storage goes into infiltration and evapo- transpiration. Infiltration in excess of soil moisture storage recharges ground water and emerges initially as base flow.

Run off is divided into (1) surface run off, (2) inter flow, (3) ground water flow.

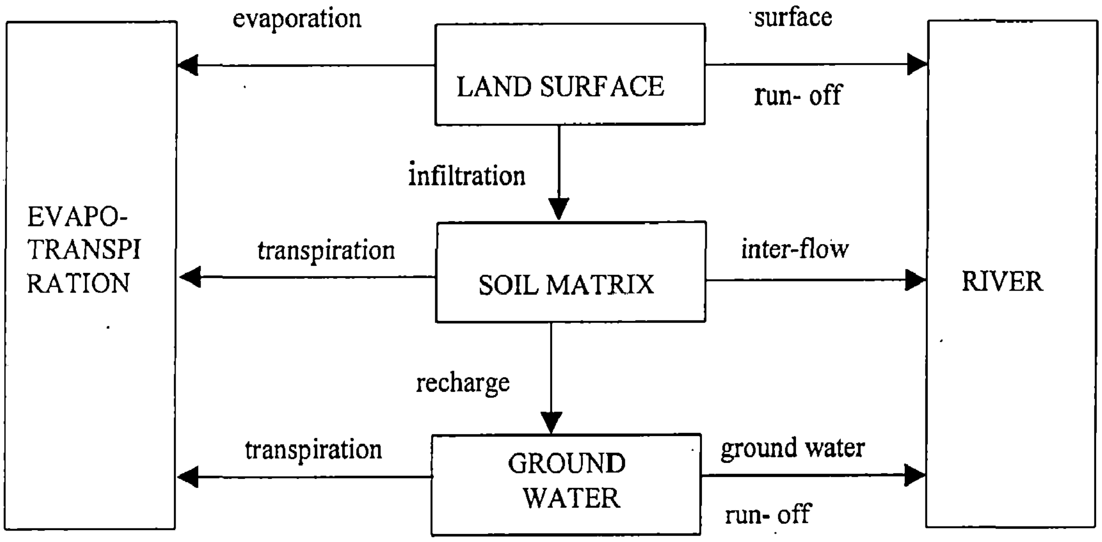

Fig:2. 1. 2 A system representation of water-shed run-off

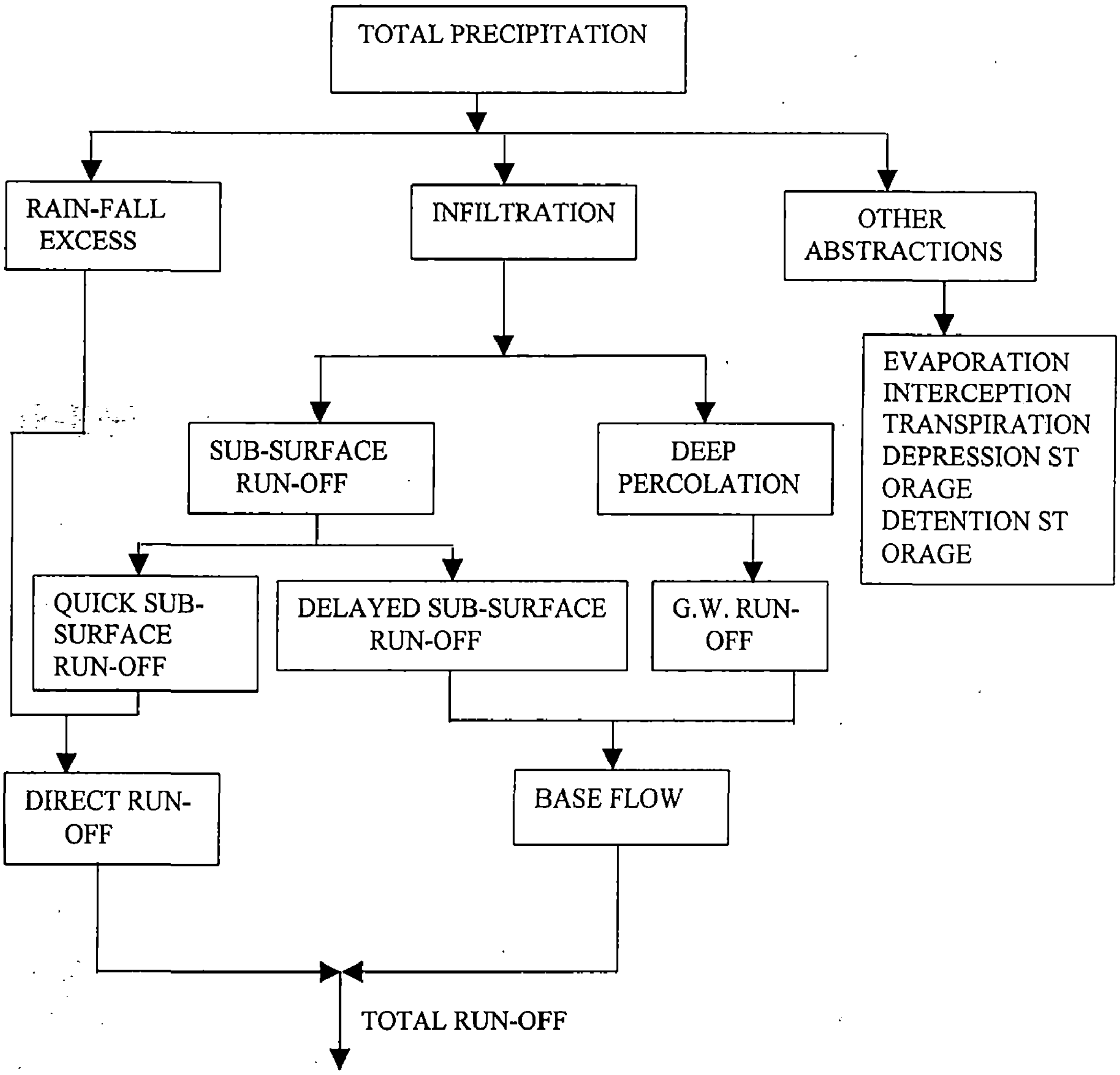

Fig: 2. 1. 3 A system representation of water-shed run-off (Chow, 1964)

2.2 ABSTRACTIONS

Abstractions include interception of precipitation on vegetation above the ground, depression storage on the ground surface as water accumulates in hollows over the surface; and infiltration of water into the soil. Interception and depression storage abstractions are estimated based on the nature of the vegetation and ground surface or are assumed to be negligible in a large storm.

2.2.1 Interception

A portion of precipitation falling in a water shed is intercepted by vegetal cover and other ground objects such as roofs etc. which is defined as interception.

A part of the intercepted precipitation wets and adheres to these objects and returns to atmosphere through evaporation. This part is called interception loss.

The intercepted precipitation may be retained on leaves, flow down the plant stems becoming stem flow, or drop off the leaves to become part of the through fall. In initial periods of the storm, we observe the most interception loss, thereafter the rate of interception rapidly declines and reaches to zero.

While studying major storms interception loss is often neglected but it becomes quite significant in water balance studies which are conducted by taking into consideration the nature, type and density of the vegetal cover, precipitation characteristics and season of the year.

2.2.2 Depression Storage

There are many depressions of varying characteristics such as area, volume, depth and numbers in a watershed. This depends on the topography, land form and land use practices inside the specific water shed.

During the rainfall, a certain portion of it gets retained in these depressions, without any possible escape in the form of run off. This volume of retained water is called depression storage.

Actually, small depressions fill first and thereafter over land flow begins. Next, large depressions get filled. Depressions of various different sizes are super imposed and are interconnected among themselves. This way depression storage has a role to play in any water balance study.

2.2.3 SCS Method For Computing Abstractions

For computing abstractions from any given rain fall, a method called 'Soil Conservation Services (1972) Method' also known as 'Curve Number Method' was developed. This method is based on following three assumptions:--

(1) There is a maximum amount of water S that a watershed can hold through depression & soil storage.

(2) Ratio of actual storage, (F) to potential storage, (S) is equal to the ratio of run off to rain-fall minus initial abstraction.

$$i.e. \frac{Actual\ Storage}{Potential\ Storage} = \frac{F}{S} = \frac{Run - off}{Rain\ fall - Initial\ abstraction} = \frac{Q}{P - Ia}$$

'Initial Abstraction' is a part of rainfall abstractions that occurs before ponding and there is no run off associated with it.

$$or\ \frac{F}{S} = \frac{Q}{P - Ia} \qquad \ldots(2.1)$$

where P, Q and I_a are rainfall, run off and initial abstraction respectively .

(3) I_a and S are linearly related , i.e.

$$I_a = a\,.\,S \qquad \ldots(2.2)$$

where 'a' is a constant which is originally taken as 0.2 which is satisfactory for large storms. But this leads to under estimating run off for small to medium storms.

Therefore, taking the value of a, as o.2 equation (2.2) takes following form: -

$$I_a = 0.2.\,S \qquad \ldots(2.3)$$

From mass balance, we have;

$$F = P - I_a - Q \qquad \ldots(2.4)$$

Combining equations (2.1) and (2.3);

$$or\ \frac{P - 0.2\,S}{S} = \frac{Q}{P - 0.2\,S} + \frac{Q}{S}$$

$$\frac{P - 0.2\,S - Q}{S} = \frac{Q}{P - 0.2\,S}$$

$$or\ \frac{P - 0.2\,S}{S} = Q\,.\left[\frac{S + P - 0.2\,S}{S(P - 0.2\,S)}\right]$$

$$or\ Q = \frac{(P - 0.2\,S)^2}{(P - 0.8\,S)}\ ; \qquad \ldots(2.5)$$

Parameter S is related to curve number in the following way;---

$$S = \frac{1000}{C_N} - 10\ ; \qquad \ldots(2.6)$$

where S is in inches

Substituting equation (2.5) in equation in equation (2.4), we get:---

$$F = P - Ia - \frac{(P - 0.2\,S)^2}{(P - 0.8\,S)} \qquad \ldots(2.7)$$

The curve number shown in equation (2.6) takes into account most of the water shed run-off producing characteristics that are mentioned below: --

(1) Soil type,

(2) Land use ,

3) Hydrologic conditions,

(4) Antecedent moisture content.

Curve numbers have been given in form of a table for various soil types and land use. For this four soil types have been categorized in four different groups that are mentioned below: ---

Group A: Deep sand, deep loess, aggregated silts

Group B: Shallow loess, sandy loam

Group C: Clay loams, shallow sandy loam, soils low in organic content and soils usually high in clay

Group D: Soils that swell significantly when wet, heavy plastic clays and certain Saline soils.

2.2.3.1 Classification of Antecedent Moisture Classes (AMC) For The SCS Method of Rainfall Abstractions

Table: 2.1

AMC group	Total 5-day antecedent rain-fall (in)	
	Dormant Season	Growing Season
I	Less than 0.5	Less than 1.4
II	0.5 to 1.1	1.4 to 2.1
III	Over 1.1	Over 2.1

2.2.3.2 Run off Curve Numbers for Selected Agricultural and Urban Land Uses (Antecedent Moisture Condition II, $I_a = 0.25$)

Table: 2.2

Land Use Description	Hydrologic Soil Group			
	A	B	C	D
Cultivated land; without conservation treatment	72	81	88	91
With conservation treatment	62	71	78	81
Pasture or range land : poor condition	68	79	86	89
Good condition	39	61	74	80
Meadow good condition	30	58	71	78
Wood or forest land : thin sand, poor cover, no mulch	45	66	77	83
Good cover(no grazing, litter or cover soil)	25	55	70	77
Open spaces, lawns ,parks, golf courses, cemeteries;				
Good condition: grass cover over 75% or more of area	39	61	74	80
Fair condition: grass cover over 50% to 75% of area	49	69	79	84
Commercial and business areas (85% impervious)	89	92	94	95
Industrial districts (72% impervious)	81	88	91	93
Residential:				
Average lot size — Average % impervious				
1/8 acre or less — 65	77	85	90	92
¼ acre — 38	61	75	83	87
1/3 acre — 30	57	72	81	86
½ acre — 25	54	70	80	85
1 acre — 20	51	68	79	84
Paved parking lots, roofs, driveways etc	98	98	98	98
Streets and roads; paved with curbs and storm sewers	98	98	98	98
Gravel	76	85	89	91
Dirt	72	82	87	89

Note:- (1) curve numbers have been computed by assuming that run-off from houses etc. moves directly to streets and is not intercepted by lawns .

(2) In warm climates for the pave parking lots roofs drive ways etc., a curve number of 95 is recommended.

Above description gives us an idea of the curve numbers but one can find more agricultural land use curve numbers from 'Soil Conservation Service, 1972'.

Carefully examining equation (F) we draw following important inferences; ---

(1) If CN=100 (maximum value), S=0, it means that100% of the precipitation goes as run off and there is no infiltration.

(2) If CN reduces from 100%, it shows that run-off is reducing and infiltration is on increase.

2.3 INFILTRATION

2.3.1 Introduction

In previous sections, we have so far discussed, how certain parts of the rainfall are consumed as initial abstraction and evaporation. Next physical phenomenon to take place is infiltration. Nearly seventy percent of the annual precipitation infiltrates into the soil and about thirty percent becomes available as runoff. Computation of infiltration is useful in determination of Effective Rainfall (also referred as Rainfall Excess) and direct run-off. Infiltration study is imperative in soil erosion problems, ascertaining soil water component of watershed system and in studies of many other hydrologic problems.

2.3.2 Definition

Infiltration is defined in many ways like,

(1) Infiltration is the process of entry of water into a soil through the soil surface.

(2) Infiltration is the phenomenon of water penetration from the surface of the ground into the sub surface soil.

(3) Infiltration is the phenomenon of water crossing from the airside to the soil side of the air soil interface.

(4) It is the evolution of water content in the soil resulting from the occurrence of rain or of a pond of water at the surface.

2.3.2.1 Other Infiltration Related Definitions

Percolation

It is the process of water movement within the soil profile. This process starts just after infiltration.

Infiltration Rate (f)

It is the rate at which water enters into the soil surface expressed as volume per unit area per unit time and thus dimensions of length per unit time.

Cumulative Infiltration (F)

This shows the volume of infiltration since the beginning of the rainfall time 't' or the rainfall event.

$$F(t) = \int_0^t f(x).dx\,; \qquad f(t) = \frac{dF}{dt}$$

Infiltration Capacity Rate (f_p)

It is the maximum rate at which soil can absorb water through its surface and has the dimensions of length per unit time.

One should see the difference between 'f' and 'f_p' which is as stated below:,

$$0 \leq f \leq f_p$$

The Average Infiltration Capacity Rate, (f_a)

This is given as; $f_a = \dfrac{f_{pi} + f_{pi+1}}{2}$; also ; $f_a = \dfrac{F(T)}{T}$

Capillary Potential

It is the hydraulic head due to the capillary forces and is measured in the units of length.

It is known as capillary pressure head, moisture tension, suction head, negative pressure head, capillary suction, or negative hydraulic head.

Capillary Conductivity (K)

This is defined as volume rate of flow of water through the soil under a unit hydraulic gradient in sub atmosheric pressure conditions.

Its dimensions are length per unit time. This is also called ' the hydraulic conductivity ' or simply the 'conductivity'.

Saturated Conductivity (K_s)

It represents the capillary conductivity when the soil is saturated and has the dimension of length per unit time.

Relative Conductivity (K_{rw})

It is the ratio of capillary conductivity to the saturated conductivity, for a given moisture content.

$$K_{rw}(\theta) = \frac{K(\theta)}{Ks}$$

2.3.3 Flow Of Water Through Soil

Flow of water through the porous media of soil can be visualized to take place in two different ways, namely (1) Unsaturated Flow and

(2) Saturated Flow

2.3.3.1 Comparison of Unsaturated and Saturated Flows in Soils

In general, we observe that mostly processes related to soil-water interactions in the field are of unsaturated nature, playing their role in the root zone of the plants and trees above the ground water level. These are complex in nature involving relationships among variables like; hydraulic conductivity, soil water content, suction head, hydraulic gradient etc. So this requires use of indirect method of analysis involving approximations, assumptions, numerical techniques, theoretical and experimental methods. Contrary to it, saturated flow cases are not so much complicated.

Hydraulic gradient of positive pressure potential is the force behind saturated flows, whereas in case of the unsaturated flow case suction pressure potential is the force which arises due to the attraction of water to the soil particle surfaces and capillary pores. Water is sucked or drawn from the zones where the water film enveloping the soil particles is thicker to where it is thinner in other words from less curved menisci areas to highly curved menisci areas. Water flows in the direction of higher suction from lower suction zones. A stage is reached when suction becomes uniform all along the horizontal column and then the suction gradient and the moving force both cease to exist. Now in this case, water flows through the fully water filled pores at existing suction and will creep along the hydration films over the soil particle surfaces.

This moving force is maximum at the wetting front zone where water invades and advances into the originally dry soil zone ahead where suction gradient may be enormous in magnitude some times thousands of times greater than the gravitational force. This is a boon of nature in face of extremely low hydraulic conductivity and relatively dry soils.

Major difference, with regard to unsaturated and saturated flows lies in hydraulic conductivity. Incase of saturated flows all the pore space contributes to flow. Hence, continuity and hydraulic conductivity are maximum. But as the soil desaturates, air replaces the water inside the pore space and the conducting part of it gets reduced . Consequentially suction increases and firstly large pores are emptied which are more conducive to flow.

content. This creates a distinct saturation front. Advancement of this front is shown in the following figure:

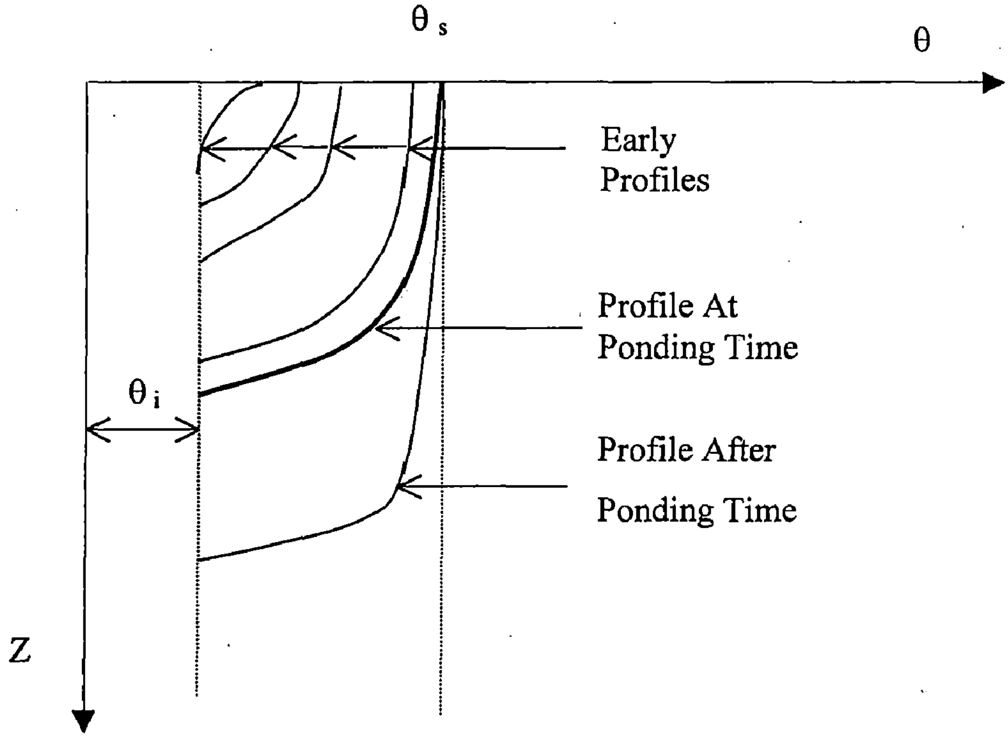

Fig: 2.3.4 Water content profiles showing advancement of saturation front during a uniform intensity rainfall.

When the rain just starts, difference in head causing the saturation front movement acts over a very small distance. This results in a very high hydraulic gradient. So initially infiltration capacity rate is very high. In this condition even a high intensity rainfall will get infiltrated.

With the continued rainfall, more and more water goes into the soil and saturation front moves deeper and deeper, thereby increasing the thickness of the wetted zone. This in turn reduces the hydraulic gradient and this way the infiltration rate capacity goes on decreasing with the passage of time. This phenomenon is shown in the following figure. -----

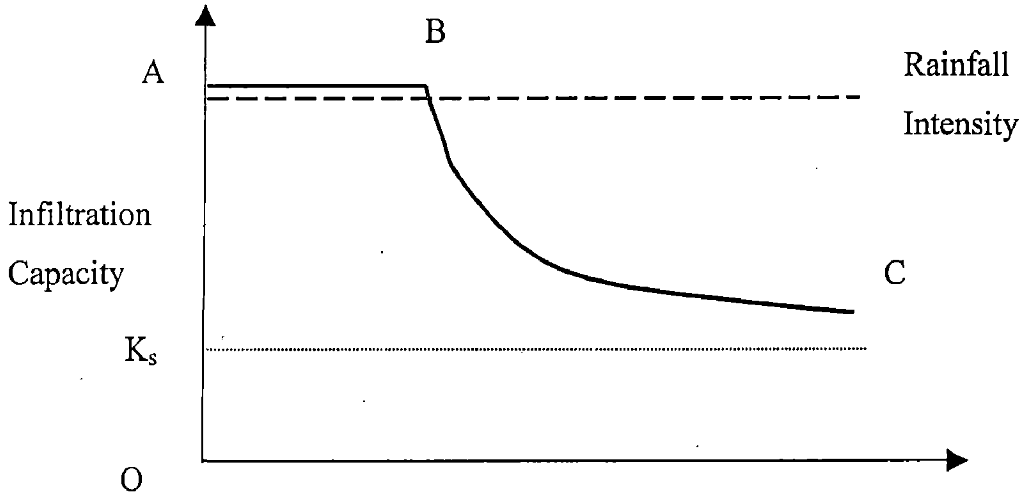

Fig: 2.3.5 Variation of infiltration capacity rate with time.

2.3.3.3 Infiltration, Ponding Time and Run off

As we see in the above figure from A to B, all the rain water gets infiltrated and after point B when infiltration capacity rate reduces and becomes less than the rainfall intensity. At this point ponding starts. The time period from beginning of rainfall to the instant when ponding starts, is called 'Ponding Time'. After ponding, next process to take place is run off. This is depicted as portion B C in the above figure.

2.3.3.4 Determination of weighted average value of suction head

Value of suction head h_c used in Green and Ampt equation can not be related to the varios soil characteristics curves. As a matter of fact , h_c is an average representative capillary pressure head which is determined by calibration curves drawn for infiltration rates from actual experiments conducted for infiltration rates on a soil. Aweighted average value of h_c called H_f has to be used in computations, formula for which is given below:

$$H_F = \int_{O}^{h_{ci}} K_{rw}(\theta)\,.\,dh_c$$

Where $h_{ci} = h_c(\theta_i)$

This has been shown graphically in figure 2.3.6 as under:

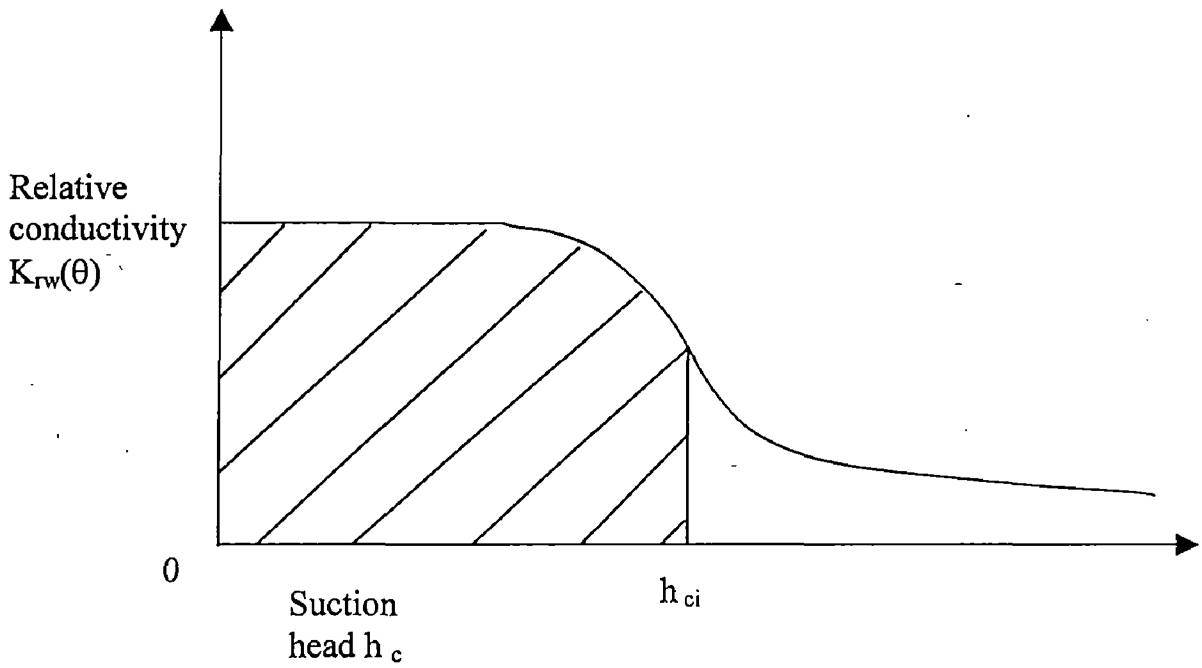

Fig:2.3.6 Relative conductivity v_s suction head relationship showing hatched Area as representative or weighted average capillary suction head Across the wetting front.

CHAPTER –III
ANALYSIS

3.1 Introduction

The most important aspect of any water balance study lies in calculating volume of ground water recharge due to rainfall. In the previous chapter, we have discussed about rainfall abstractions. In appendix -I derivations of the various equations and discussions about the infiltration related aspects such as ponding time and infiltration up to ponding time which are most important, are included.

In the following discussion, we will see how Green and Ampt equation is used to get the infiltration volume after ponding time by considering the ponding height also.To calculate the infiltration volume after stoppage of the rainfall in the area under consideration, time area graph method is employed in order to include the slope and surface characteristics of the hilly watershed.

3.2 Infiltration after ponding time

As the rainfall intensifies more and more after the ponding time, run off volume increases correspondingly. This volume of run off can be represented as height of ponding in terms of the units of length. Effect of this height of poinding has been accounted for calculating infiltration after ponding using Green and Ampt method.

3.2.1 Derivation of Equation For Infiltration After The Ponding Time

We know that after the lapse of ponding time period during the rain fall event , rain fall intensity is more than the infiltration capacity rate. Rainfall volume in excess of the infiltration capacity rate is available as run off on ground and this can be expressed in form of ponded height of water (H) in unit of length.

Cumulative infiltration up to time t since on set of rainfall:

$w(t) = \int_0^t I(\tau).d\tau$ and τ is a dummy variable.

From Green and Ampt equation for infiltration:

$$I(t) = \overline{K}.\frac{h_c + H + Z_f}{Z_f}$$

$$= \overline{K}.\frac{h_c(\theta_s - \theta_i) + H(\theta_s - \theta_i) + Z_f(\theta_s - \theta_i)}{Z_f(\theta_s - \theta_i)}$$

$$= \overline{K}.\frac{h_c(\theta_s - \theta_i) + \left[\int_0^t r(\tau).d\tau - \int_0^t I(\tau).d\tau\right](\theta_s - \theta_i) + Z_f(\theta_s - \theta_i)}{Z_f(\theta_s - \theta_i)}$$

$$= \overline{K}.\frac{h_c(\theta_s - \theta_i) + [C_R(t) - w](\theta_s - \theta_i) + Z_f(\theta_s - \theta_i)}{Z_f(\theta_s - \theta_i)};$$

here $C_R(t)$ = Cumulative rain fall and w(t) = cumulative infiltration

Since $I(t) = \frac{dw}{dt}$, hence,

$$\frac{dw}{dt} == \overline{K}.\frac{h_c(\theta_s - \theta_i) + [C_R(t) - w](\theta_s - \theta_i) + w}{w}$$

$$or \frac{w.dw}{\left[h_c(\theta_s - \theta_i) + [C_R(t) - w](\theta_s - \theta_i) + w\right]} = \overline{K}.dt \qquad ...(3.1)$$

Let us consider that at time t_1 and t_2, volume of infiltrated water be w_1 and w_2 respectively. So integrating and putting these limits on both sides of the equation (3.1), we get:--

$$\int_{w_1}^{w_2} \frac{w.dw}{h_c.(\theta_s - \theta_i) + (\theta_s - \theta_i).C_R(t) + w.\ (1 - \theta_s + \theta_i)} = \int_{t_2}^{t_1} \overline{K}.dt$$

$$\frac{1}{(1 - \theta_s + \theta_i)} \int_{w_1}^{w_2} \frac{w.dw}{w + \frac{(\theta_s - \theta_i).C_R(t)}{(1 - \theta_s + \theta_i)} + \frac{h_c.(\theta_s - \theta_i)}{(1 - \theta_s + \theta_i)}} = \int_{t_2}^{t_1} \overline{K}.dt$$

Asasuming $a = \frac{(\theta_s - \theta_i)}{(1 - \theta_s + \theta_i)}$: and $b = \frac{h_c.(\theta_s - \theta_i)}{(1 - \theta_s + \theta_i)}$;

The equation takes the following form:

$$\frac{1}{(1 - \theta_s + \theta_i)} \int_{w_1}^{w_2} \frac{w.dw}{w + a.C_R(t) + b} = \int_{t_2}^{t_1} \overline{K}.dt`$$

$$\text{or } \int_{w_1}^{w_2} \frac{w.dw}{w + a.C_R(t) + b} = (1 - \theta_s + \theta_i) \int_{t_2}^{t_1} \overline{K}.dt$$

$$\text{or } \int_{w_1}^{w_2} \frac{w + a.C_R(t) + b - a.C_R(t) - b}{w + a.C_R(t) + b}.dw = (1 - \theta_s + \theta_i).\overline{K}.(t_2 - t_1)$$

$$\text{or}(w_2 - w_1) - \int_{w_1}^{w_2} \frac{a.C_R(t) + b}{w + a.C_R(t) + b}.dw = (1 - \theta_s + \theta_i).\overline{K}.(t_2 - t_1) \qquad ...(3.2)$$

Let $C_R(t)$ be approximated as: $C_R(t) = \dfrac{C_R(t_1) + C_R(t_2)}{2} = \overline{C_R}$

While proceeding forward for the calculatios for each time step, t_1 and t_2 are encountered in succession. Hence only a very small difference in the magnitudes of $C_R(t_1)$ and $C_R(t_2)$ can be envisaged. So taking average of the two,($\overline{C_R}$) compensates for that small difference too. Since this average value does not vary from time t_1 to t_2, it is being regarded as a constant in the foregoing part of the derivation.

Substituting $\overline{C_R}$ in place of $C_R(t)$ in equation (3.2):

$$(w_2 - w_1) - \int_{w_1}^{w_2} \frac{a.\overline{C_R} + b}{w + a.\overline{C_R} + b}.dw = (1 - \theta_s + \theta_i).\overline{K}.(t_2 - t_1)$$

$$\text{or } (w_2 - w_1) - (a.\overline{C_R} + b).\left[l_n\left(w + a.\overline{C_R} + b\right)\right]_{w_1}^{w_2} = (1 - \theta_s + \theta_i).\overline{K}.(t_2 - t_1)$$

$$\text{or } (w_2 - w_1) - (a.\overline{C_R} + b)\, l_n \frac{(w_2 + a.\overline{C_R} + b)}{(w_1 + a.\overline{C_R} + b)} = (1 - \theta_s + \theta_i).\overline{K}.(t_2 - t_1)$$

Above equation can be written as:

$$w_2 - w_1 - \left[a.\left\{\frac{C_R(t_1) + C_R(t_2)}{2}\right\} + b\right].l_n \frac{w_2 + a.\dfrac{C_R(t_1) + C_R(t_2)}{2} + b}{w_1 + \dfrac{C_R(t_1) + C_R(t_2)}{2} + b}$$

$$= (1 - \theta_s + \theta_i).\overline{K}.(t_2 - t_1) \qquad ...(3.3)$$

Now for $t_1 = t_p$, considering time step t_2 being just next to time of ponding t_p and volume of infiltrated water up to pondding time as $w(t_p)$, equation (3.3) takes following form:

$$w_2 - w(t_p) - \left[a.\left\{\frac{C_R(t_p) + C_R(t_2)}{2}\right\} + b\right].l_n \frac{w_2 + a.\dfrac{C_R(t_p) + C_R(t_2)}{2} + b}{w(t_p) + \dfrac{C_R(t_p) + C_R(t_2)}{2} + b}$$

$$= (1 - \theta_s + \theta_i).\overline{K}.(t_2 - t_p) \qquad ...(3.4)$$

Equation(3.4) can be solved by trial and error method to give the value of w_2 during time immediately after ponding. In a similar manner, cumulative infiltration w_2 at various time steps can be calculated using equation (3.3).

3.3 Infiltration after stoppage of rainfall

Whenever the ponded depth happens to flow down over an area of the water shed, a part of overland flow gets infiltrated into the soil through its top surface. The post rainfall infiltration is estimated as follows:

3.3.1 Velocity of the run off water

As stated in the previous sections, run off starts after the ponding time. It appears over a relatively large area and hence, cosidered here to be moving down as a thin sheet of water. Its velocity downwards can be calculated with the help of the well known ' Manning's Equation' given as under,

$$V = \frac{1}{n} . R^{\frac{2}{3}} . S^{\frac{1}{2}} \qquad \ldots(3.5.)$$

Here n is co efficient of rughosity of the flow path of the sheet of water, R the hydraulic radius of the thin sheet of water and S longitudinal slope of the flow path.

Due to great width and a small height, hydraulic radius of the sheet of water can be assumed as ponded depth.

3.3.2Opportunity time for infiltration

Time taken by the run off water to reach the bottom most point of the water shed from any catchment boundary, is termed as the opportunity time for infiltration which can be calculated by dividing the length of flow by the velocity of flow of the run off water as above.

3.3.3 Isochrones

These are imaginary lines drawn on the topographical map of a water shed by joining all the points of equal time of opportunity for infiltration.

These lines start and terminate only inside the boundary of the water shed, do not cross each other and are continuous except near the ridge lines where run off patterns may be different on either side.

3.3.4 Derivation of equation of infiltration after stoppage of rainfall

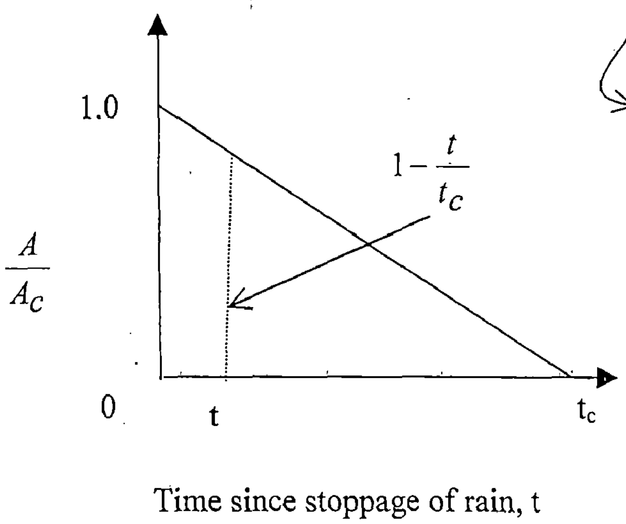

Fig: 3.1 (a) Time area curve of watershed.

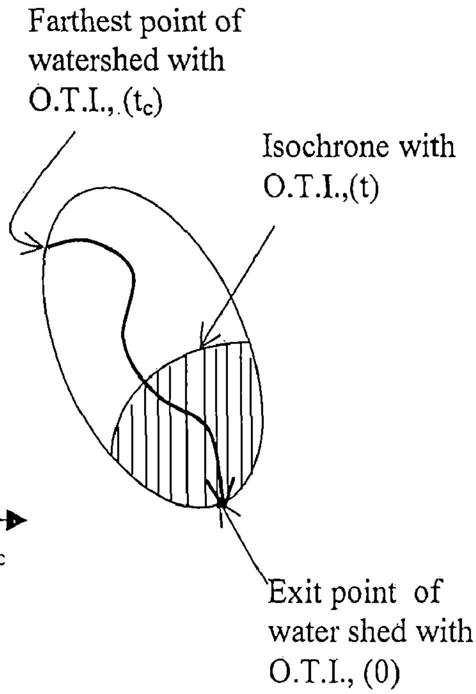

Fig:3.1(b) Sketch of watershed showing an isochrone and area under it.

In above figure:3.1(a), an idealized linear relationship between time since stoppage of rainfall and corresponding area contributing to flow has been shown which pertains to the hypothetical watershed in figure:3.1(b), where A_c is the area of catchment and A , the area contributing to infiltration after the rain stops.

We assume that rate of infiltration is $\overline{K}$.

The volume of water that infiltrates during an incremental time interval dt at t is given by :

$$dw_{pr} = \overline{K} . \left(1 - \frac{t}{t_c} \right) . dt . A_c$$

Therefore the volume of infiltrated water in time interval t_c is

$$w_{pr} = \int_0^{t_c} \overline{K} . \left(1 - \frac{t}{t_c} \right) . dt . A_c$$

$$= A_c . \overline{K} . \left[t - \frac{t^2}{2.t_c} \right]_0^{t_c}$$

$$= \overline{K} . \left[t_c - \frac{t_c^2}{2.t_c} \right]$$

$$= \frac{1}{2} . Ac . \overline{K} . t_c$$

RESULT AND DISCUSSIONS

4.1 INTRODUCTION

For the water balance study of any area under consideration, authentic relevant data are a basic pre- requisite. Due to non availability of data, we are taking some hypothetical data which is being used in order to demonstrate the inherent capabilities of the various equations and methodologies in this dissertation. As our chief objective is to compute the value of recharge to the ground water by means of infiltration, the data required for the same is being used for the purpose.

4.2 DATA

For the purpose of study, following data are assumed for use.

(1) Length of the hill slope - 100000 cms

(2) Hill slope - 0.36

(3) Time of concentration - 15 minutes

(4) Co- efficient of rughosity (n) of the flow path - 0.030

(5) Moisture content at saturation (θ_s) - 0.453

(6) Field capacity (θ_f) - 0.412

(7) Antecedent moisture content - 0.40

(8) Representative suction head at saturation front (H_F) - 11.02 cm

(9) Saturated conductivity (K_S) - 1.09 cm per hour

(10) Potential evapo-transpiration . 0.004 cm per 10 minutes

(11) Root zone depth . 300 cm.

(12) Rainfall data;

(a) Number of rainfall events - 1

(b) Length of each time step - 10 minutes

(c) Number of time steps - 18

(d) Rainfall data starting from time step 1 to 18 consecutively.

0.18, 0.21, 0.26, 0.32, 0.37, 0.43, 0.64, 1.14, 3.18, 1.65,
0.81, 0.52, 0.42, 0.36, 0.28, 0.24, 0.19, 0.17, .

4.3 Results :

Table : 4.1 Results without considering ponding height after ponding.

Time Step	Rain(I)	Rain(J)	Infiltration capacity rate CAPINF(J)	Infiltration rate INF(J)
1	0.18	0.176	0.412	0.176
2	0.21	0.26	0.3445	0.206
3	0.26	0.25	0.3146	0.256
4	0.32	0.316	0.2968	0.2968
5	0.37	0.366	0.2847	0.2847
6	0.43	0.426	0.2757	0.2757
7	0.64	0.636	0.2687	0.2687
8	1.14	1.136	0.2631	0.2631
9	3.18	3.176	0.2584	0.2584
10	1.65	1.646	0.2545	0.2545
11	0.81	0.806	0.2511	0.2511
12	0.52	0.516	0.2482	0.2482
13	0.42	0.416	0.2455	0.2455
14	0.36	0.356	0.2432	0.2432
15	0.28	0.276	0.2411	0.2411
16	0.24	0.236	0.2392	0.236
17	0.19	0.186	0.2375	0.186
18	0.17	0.166	0.236	0.166

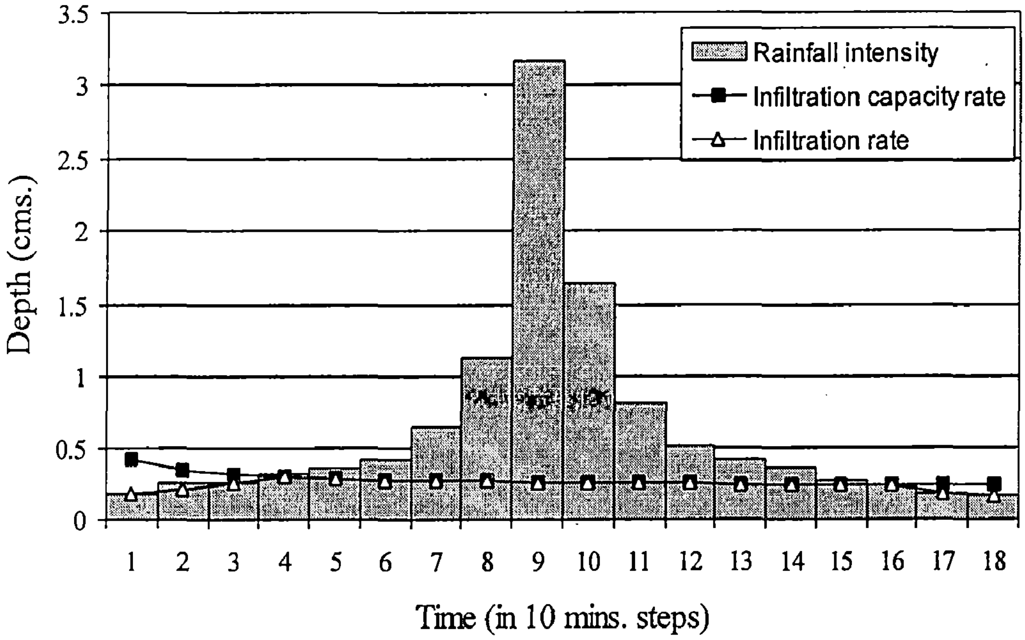

Fig.: 4.1 representation of relationship among rainfall intensity, infiltration capacity rate, infiltration rate curves and ponding time (without considering ponding height).

Table : 4.2 Infiltration after ponding time considering ponding height.

Infiltration after ponding time			
Time Step	Cumulative infiltration		Infiltration rate
3.480542	0.789512		
4	0.7899		0.3031
5	0.9473		0.2801
6	1.2274		0.2613
7	1.4887		0.2502
8	1.7389		0.2443
9	1.9832		0.2457
10	2.2289		0.248
11	2.477		0.2453
12	2.7223		0.2412
13	2.9635		0.2373
14	3.2008		0.2338
15	3.4346		0.2307
16	3.6652		0.2277
17	3.893		0.225
18	4.118		0.2227

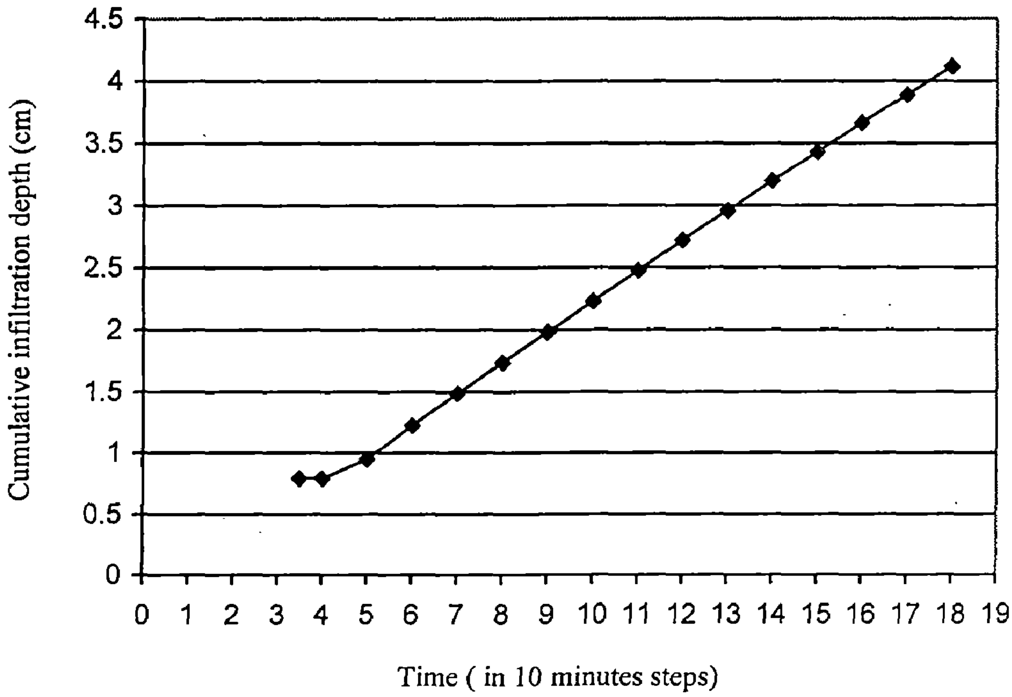

Fig: 4.2 Cumulative infiltration v_s time after ponding time considering ponding height.

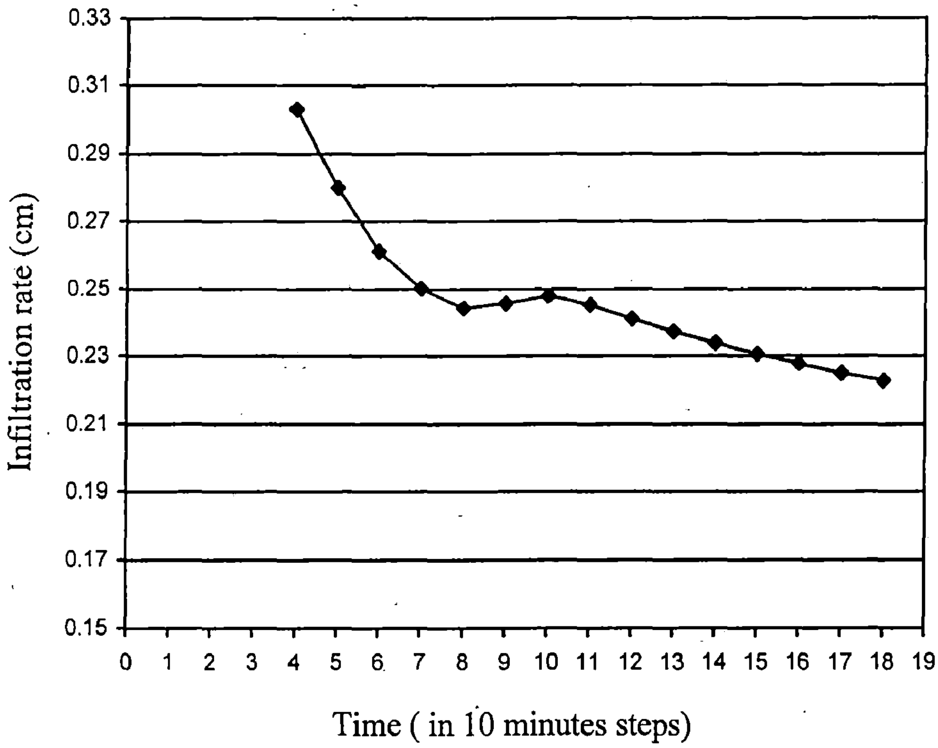

Fig: 4.3 Infiltration rate after ponding time v_s time considering ponding height.

4.4 DISCUSSIONS

While going through the result part of this chapter, we observe that potential evapo– transpiration is taken as a negative rainfall. This is used in all calculations. Green and Ampt's equation is used in the computer programme. As is evident from the result file and the graphs in figure: 4.1 that ponding starts after a lapse of 4.0 time units i.e. after 40.0 minutes since the onset of the rainfall event. This was an outcome achieved by means of comparison between the infiltration capacity rate and the rainfall intensity because at this point rainfall intensity becomes more than the infiltration capacity rate. Ponding time was also computed by Morel Seytoux approach which yielded a value of 3.481 time units i.e. 34.81 minutes. This is because the distribution of the rainfall intensity being considered uniform throughout inside any time step, infiltration capacity rate curve crosses it at a certain pont of time inside a time step only and thus the serial number of this time step is registered as ponding time which is an integer. But in the Morel Seytoux approach, ponding time formula for variable intensity rainfall has been derived by considering the fraction of time which has been passed by the ponding time since the start of the very time step in which it lies. This gives us a real number as ponding time since the on set of the rainfall.

Study on infiltration was conducted in three stages, namely pre ponding period after the start of the rainfall, post ponding period of the rainfall and post rainfall period. In the pre ponding phase all the rainfall enters into the soil. In post ponding period of rainfall, ponding height has been accounted for which has brought about a different picture of the infiltration scenario when compared to the case without considering the ponding height. This is given as under:

(1) Infiltration rate in post ponding phase varies from 0.2968 cm / 10 mins. To 0.1660 cm / 10 mins. in the time period 4,th time step to the 18'th time step. This was the result when ponding height was not taken into account.

(2) But in the second case when ponding height effect was considered, results were different. This time we see that the infiltration rate varied from 0.3031 cm / 10 mins. to 0.2227 cm / 10 mins. in a time period of 4'th time step to the 18' th time step

To calculate the infiltration volume in post ponding case, time area diagram was used which accounted for the slope aspects of the hilly catchment. Equation developed in this regard was used in the computer programme that yielded a value of 0.14 cm. as a unit of depth. This depth of water multiplied with the area of the catchment will provide the volume of the post rainfall infiltration..

So finally we accept the result shown in the table number.(4.1) for the pre ponding phase only and all the results contained in table number(4.2) for the post ponding phase because it has taken an account of the height of ponding also. Ponding time is accepted as 34.81 mins. from the onset of the rainfall and cumulative infiltration values from the table 4.2 are also accepted totally.

For the soil parameters, catchment topography and rainfall distribution 36.8 % of the rainfall infiltrates and 63.1 % appears as run off.

CHAPTER –V
CONCLUSION

An in depth study study has been conducted in this thesis on the rainfall infiltration which is of prime importance in computing water balance of a watershed. Infiltration studies help us to quantify the ground water recharge. This aspect of the study will be helpful in providing an alternate methodology in order to validate the estimations of water balance prepared on the basis of the recommendations of ' Ground Water Estimation Committee –97 '.

Computations of the infiltration were conducted in three phases, i.e. prior to ponding, after ponding, and post rainfall time up to the opportunity time of the catchment.

Ponding time for non uniform rainfall intensity over the total period is computed using two methods. One is the use of Green and Ampt's equation by Morel Seytoux approach, which provides ponding time even in fractional parts of a time step. But it was found that in certain cases, this approach showed no ponding even though it was really occuring there. This was because the fractional part by which the ponding time exceeded the lower limit of its own time step in which it was, did not lie between zero and one. In such cases another method of comparision between infiltration capacity rate and rainfall intensity was tried successfully and ponding time was fixed where rainfall intensity just exceeded the infiltration capacity rate.

An equation for infiltration rate and the cumulative infiltration for the period after ponding was developed using Green and Ampt's equation by considering the ponding height also. For post rainfall period up to the opportunity time of infiltration of the watershed, another equation was derived which takes into account of the slope characteristics of the hilly watershed.

It is very difficult to find authentic and complete data for the purpose of a water balance study in an area. For this detailed surveys, meteorological observations, investigations, laboratory and field tests in the area selected for water balance study are very necessary without which any estimate may become a misleading one.

APPENDIX - I

Unsaturated Flow

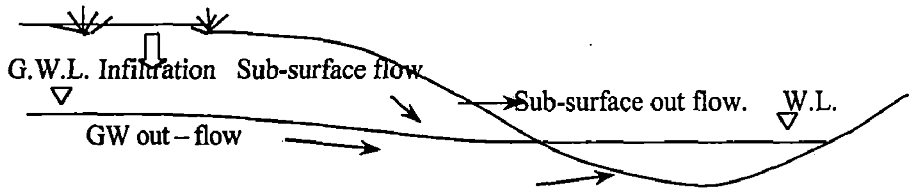

Fig : A . I. 1 Sub surface water flow processes

Sub-Surface Water Zones & Processes

Three important processes of sub surface flow are----

1- Infiltration of surface water into soil to become soil moisture

2- Sub-surface flow or Unsaturated flow through the soil

3- Ground Water Flow or Saturated Flow through soil or rock strata

Soil and rock strata that permit the water flow, are called porous media. Flow is unsaturated when the voids are not filled with water. Water table is the surface where water in a saturated porous medium is at atmospheric pressure. Below water table, porous medium is saturated and at a pressure greater than the atmospheric pressure. Above water table, capillary forces saturate the porous medium for a short height up to capillary fringe. Above this, the porous medium is unsaturated except for short time just after rainfall, when infiltration from land surface can produce saturated condition temporarily. Sub-surface and ground water flows occur when sub-surface water emerges out to become surface flow in a spring or stream. Soil moisture is extracted by evapo-transpiration as the soil dries out.

Continuity Equation For One Dimensional Unsteady Unsaturated Flow In Porous Medium

Consider a controlled volume in an unsaturated soil. A portion of this is occupied by the solid particles and remainder by the voids. A part of voids is occupied by water and rest by air.

We know that porosity η is defined as,

$$\eta = \frac{Volume\ \ of\ voids}{\text{Total volume}};$$

Also, soil moisture content is defined as,

$$\theta = \frac{\textit{volume}\text{ of water}}{\textit{total}\text{ volume}} \quad ; \text{ where } 0 \le \theta \le \eta$$

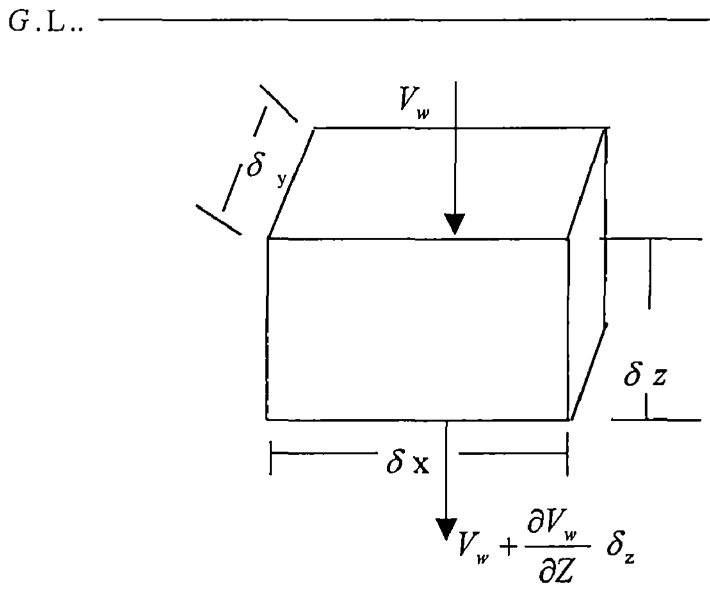

Fig : A . I . 2 Sketch of control volume

Here, δ_x, δ_y & δ_z are the dimensions of the controlled volume of the soil in X, Y & Z directions respectively, V_w =The inflow, ρ_w = specific weight of water

$$\textit{Inflow} = \rho_w . V_w . \delta_x . \delta_y . \delta_t$$

$$\textit{Initial}\text{ storage } = \rho_w . \theta . \delta_x . \delta y . \delta z$$

$$\textit{Final storage} = \left[\rho_w . \theta + \frac{\partial(\rho_w . \theta) . \delta_t}{\partial t} \right] . \delta_x . \delta_y . \delta_z$$

$$\textit{Outflow} = \left[\rho_w . V_W + \frac{\partial(\rho_w . V_w)}{\partial z} . \delta z \right] \delta_x \, \delta_y \, \delta t$$

We have (from the continuity):

(Initial storage) + (In flow) = (Final storage) + (Out flow)

$$\therefore \; [\rho_w . \theta . \delta_x . \delta_y . \delta_z] + [\rho_w . V_w . \delta_x . \delta_y . \delta_t] = \left[\rho_w . \theta + \frac{\partial(\rho_w . \theta)\delta_t}{\partial t} \right] \delta_x . \delta_y . \delta_z + \left[\rho_w . V_w + \frac{\partial(\rho_w . V_w)}{\partial z} \delta_z \right] \delta_x . \delta_y . \delta_t$$

$$\text{or} \quad 0 = \frac{\partial(\rho_w . V_w)}{\partial z} \delta_z . \delta_x . \delta_y . \delta_t + \frac{\partial(\rho_w . \theta)}{\partial t} \delta_t . \delta_x . \delta_y . \delta_z$$

$$\text{or} \quad \frac{\partial(\rho_w . V_w)}{\partial z} + \frac{\partial(\rho_w . \theta)}{\partial t} = 0$$

$$\text{or} \quad \frac{\partial V_W}{\partial z} + \frac{\partial \theta}{\partial t} = 0 \; ;$$

Richard's Equation

For unsaturated flow conditions, Darcy's Law (for saturated flow) was extended to relate the Darcy's velocity V_w to the rate of head loss per unit length of medium, S_f, unsaturated hydraulic conductivity of soil K(θ), at moisture content θ , z direction is taken +ve downwards.

$V_w = -K(\theta).\dfrac{\partial h}{\partial z}$; where ∂h is the head loss in Z - direction

$$h = \frac{p}{\gamma_w} - z = h_w - z = h_a - h_c - z$$

wehave;-- $\dfrac{\partial h}{\partial z} = \dfrac{\partial h_a}{\partial z} - \dfrac{\partial h_c}{\partial z} - 1$; h_a = *atmospheric* pressure

h_c = capillar suction head

$h_w = h_a - h_c$ = water pressure

$\therefore V_W = -K(\theta).\left[\dfrac{\partial h_a}{\partial z} - \dfrac{\partial h_c}{\partial z} - 1\right] = 0$; By Substituting V_w in the continuity equation -

$\dfrac{\partial}{\partial z}\left[-K(\theta).\dfrac{\partial h_c}{\partial z} + K(\theta)\right] + \dfrac{\partial \theta}{\partial t} = 0$; By neglecting the variation in air pressure

or $\dfrac{\partial}{\partial z}\left[-K(\theta).\dfrac{\partial h_c}{\partial \theta}.\dfrac{\partial \theta}{\partial z} + K(\theta)\right] + \dfrac{\partial \theta}{\partial t} = 0$

or $\dfrac{\partial}{\partial z}\left[D(\theta).\dfrac{\partial \theta}{\partial Z} + K(\theta)\right] + \dfrac{\partial \theta}{\partial t} = 0$; This is Richard's Equation

where $D(\theta) = -K(\theta).\dfrac{\partial h_c}{\partial \theta}$; here D(θ) is the Diffusivity which is a +ve quantity

Green & Ampt 's Infiltration Equation

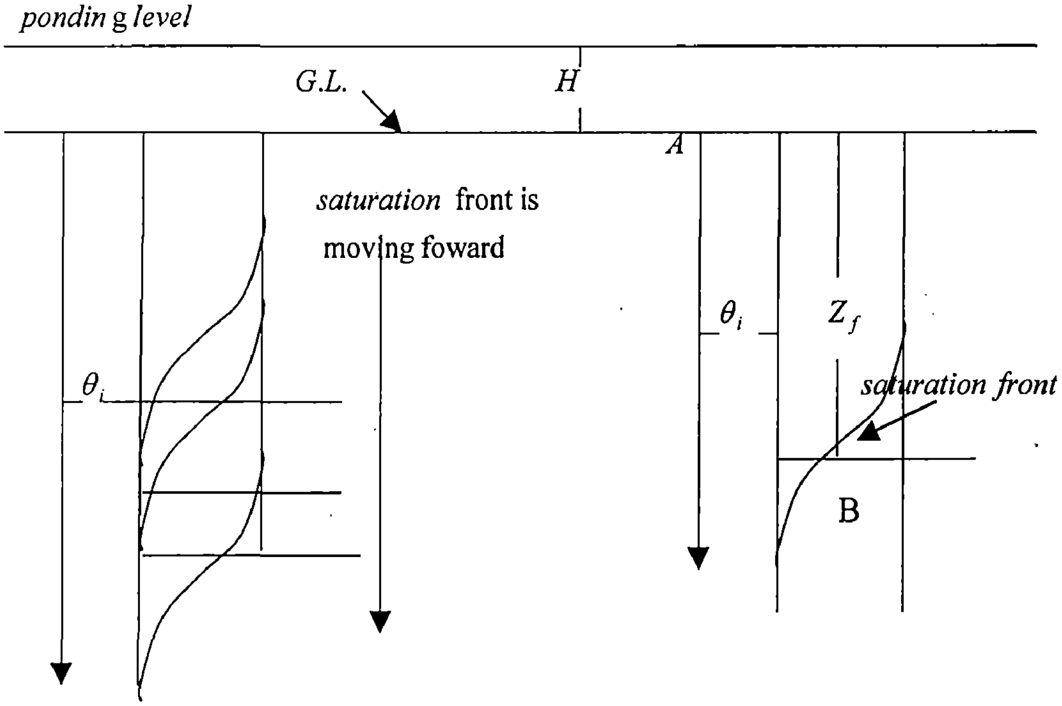

Fig : A . I . 3 Downward movement of the saturation front

As we already know that:

Total *head at* ground level $h_B = h_a + H$

Total Head at 'B', $h_B = h_w - Z_f$

$= (h_a - h_c) - Z_f$

$\therefore$ Hydraulic gradient causing flow $= \dfrac{(h_a - h_c - Z_f) - (h_a + H)}{Z_f}$;

Velocity $= -\overline{K}.\dfrac{h_a - h_c - Z_f - h_a - H}{Z_f}$; here $\overline{K}$ = saturated conductivity of soil

Darcy's velocity I $= \overline{K}.\dfrac{h_c + H + Z_f}{Z_f}$

Considering that the saturation front moves forward by a distance ΔZ_f in a time interval Δt and that the initial moisture content θ_i increases to θ_s in a unit c/s – area of soil; we have: -

The quantity of water infiltrating into the soil $= \mathbf{I}.\Delta t = (\theta_s - \theta_i).\Delta Z_f.\Delta_t$

$$\overline{K}.\frac{h_c + H + Z_f}{Z_f}.\Delta t = (\theta_s - \theta_i)\Delta Z_f.\Delta t$$

$$\frac{dZ_f}{dt} = \overline{K}.\frac{h_c + H + Z_f}{Z_f.(\theta_s - \theta_i)}$$

$$or\ \frac{Z_f.dZ_f}{h_c + H + Z_f} = \overline{K}.\frac{dt}{(\theta_s - \theta_i)} \qquad or\ \frac{\overline{K}.dt}{(\theta_s - \theta_i)} = \frac{Z_f + H + h_c - H - h_c}{h_c + H + Z_f}.dZ_f$$

Integrating both sides, we have: -

$$\frac{\overline{K}.t}{(\theta_s - \theta_i)} = Z_f - (H + h_c).l_n(h_c + H + Z_f) + A \qquad \ldots(1)$$

As per initial conditions, At t=0, Z_f =0 (i.e. the water has not infiltrated)

$0 = -(H + h_c).l_n(h_c + H) + A$

or $A = (H + h_c).l_n(h_c + H)$

Now, substituting the value of A in equation (1), we get –

$$\frac{\overline{K}.t}{(\theta_s - \theta_i)} = Z_f - (H + h_c)l_n(h_c + H + Z_f) + (H + h_c).l_n(h_c + H)$$

$$= Z_f - (H + h_c)l_n\frac{(h_c + H + Z_f)}{(h_c + H)}$$

Let up to time 't', w (t) be the volume of water that has infiltrated.

$$w(t) = z_f.(\theta_s - \theta_i) = \int_0^t I(\tau).d\tau\ ; \qquad \ldots(2)$$

From above, we have –

$$\overline{K}.t = (\theta_s - \theta_i)Z_f - (\theta_s - \theta_i)(H + h_c)l_n\frac{(\theta_s - \theta_i)(H + h_c) + Z_f.(\theta_s - \theta_i)}{(\theta_s - \theta_i)(H + h_c)}$$

$$= w - (\theta_s - \theta_i).(H + h_c).l_n\left[1 + \frac{w}{(\theta_s - \theta_i).(H + h_c)}\right]$$

$$= w - (\theta_s - \theta_i).(H + h_c).\left[\frac{w}{(\theta_s - \theta_i).(H + h_c)} - \frac{w^2}{2.(h_c + H)^2.(\theta_s - \theta_i)^2}\right]$$

$$= w - (\theta_s - \theta_i).(H + h_c)\frac{w}{(\theta_s - \theta_i).(H + h_c)} + \frac{w^2}{2.(h_c + H).(\theta_s - \theta_i)}.$$

$$or\ \overline{K}.t = \frac{w^2}{2.(h_c + H).(\theta_s - \theta_i)}$$

$$w^2 = 2.\overline{K}.t.(\theta_s - \theta_i).(H + h_c)$$

$$w = \sqrt{2.\overline{K}.(h_c + H)(\theta_s - \theta_i)}.\sqrt{t}$$

$$\frac{dw}{dt} = I(t)$$

$$= \sqrt{2.\overline{K}.(h_c + H)(\theta_s - \theta_i)}.\frac{1}{2.\sqrt{t}}$$

$$I(t) = \frac{1}{2}.\sqrt{2.\overline{K}.(h_c + H)(\theta_s - \theta_i)}.\frac{1}{\sqrt{t}}$$

$$or\ I(t) = \frac{1}{2}.S_{GA}.\frac{1}{\sqrt{t}} \quad ...(3)$$

where, S_{GA} = *Green & Ampt Sorptivity* = $\sqrt{2.\overline{K}.(h_c + H)(\theta_s - \theta_i)}$

Equation (3) is applicable in the beginning of the rain-fall during which capillary head is predominant

So far, we have dealt with the unsaturated flow with the help of Green & Ampt 's Method that provide us the infiltration capacity rate , I (t) in terms of sorptivity and time elapsed since the beginning rain-fall . But if we consider this time to be very large, we find the infiltration capacity rate to be very small or nearly equal to zero. This is unrealistic because as the time advances during rain – fall, the infiltration capacity decreases but never falls below $\overline{K}$ and remains stable there. This happens when the top most surface of soil just gets saturated and Saturated Flow begins.

In unsaturated flow conditions, capillary suction force is the governing force, where as, in case of saturated flow case, Gravity Force is the governing one.

Taking these factors into consideration, we modify equation number (3), in the following manner.

$$I(t) = \frac{1}{2}.\sqrt{2.\overline{K}.(h_c + H)(\theta_s - \theta_i)}.\frac{1}{\sqrt{t}} + \overline{K}$$

$$or\ I(t) = \frac{1}{2}.S_{GA}.\frac{1}{\sqrt{t}} + \overline{K} \quad ...(4)$$

Calculation of " Ponding Time " For Uniform Rainfall Event

We have the relationship:--

$$\text{inf}\,iltration\ I(t) = \overline{K}.\frac{h_c + H + Z_f}{Z_f}$$

Initially, we assume that when rains start, there is no ponding, H = 0; and all the rain water, that falls on the soil surface, is infiltrated.

Thus, $\dfrac{I(t)}{\overline{K}} = \dfrac{(Z_f + h_c)}{Z_f}$; $\quad I(t) = \overline{K}.\dfrac{h_c + Z_f}{Z_f}$; *here* $H = 0$

Before ponding I (t) = r (t)

$$Hence,\ \frac{r(t)}{\overline{K}} = \frac{(Z_f + h_c)}{Z_f};$$

$$= \frac{(Z_f + h_c)(\theta_s - \theta_i)}{Z_f.(\theta_s - \theta_i)};$$

$$= 1 + \frac{h_c.(\theta_s - \theta_i)}{Z_f.(\theta_s - \theta_i)}$$

$$= 1 + \frac{h_c.(\theta_s - \theta_i)}{w(t)}\ ;\ here\ w(t) = Z_f.(\theta_s - \theta_i)$$

$$or\ \frac{r(t)}{\overline{K}} - 1 = \frac{h_c.(\theta_s - \theta_i)}{w(t)}$$

$$or\ w(t) = \frac{h_c.(\theta_s - \theta_i)}{\frac{r}{\overline{K}} - 1}$$

For uniform rain-fall rate r, w (t) = r. t_p

$$Or\ r.t_p = \frac{h_c.(\theta_s - \theta_i)}{\frac{r}{\overline{K}} - 1}\ ;$$

Here w (t) = r(t_p) .t_p
Where t_p = Ponding Time

$$or\ t_p = \frac{h_c.(\theta_s - \theta_i)}{r.\left[\frac{r}{\overline{K}} - 1\right]}\ ;$$

Derivation of Equation of " Ponding time "For A Variable Intensity Rainfall Event (By Morel -- Seytoux Approach)

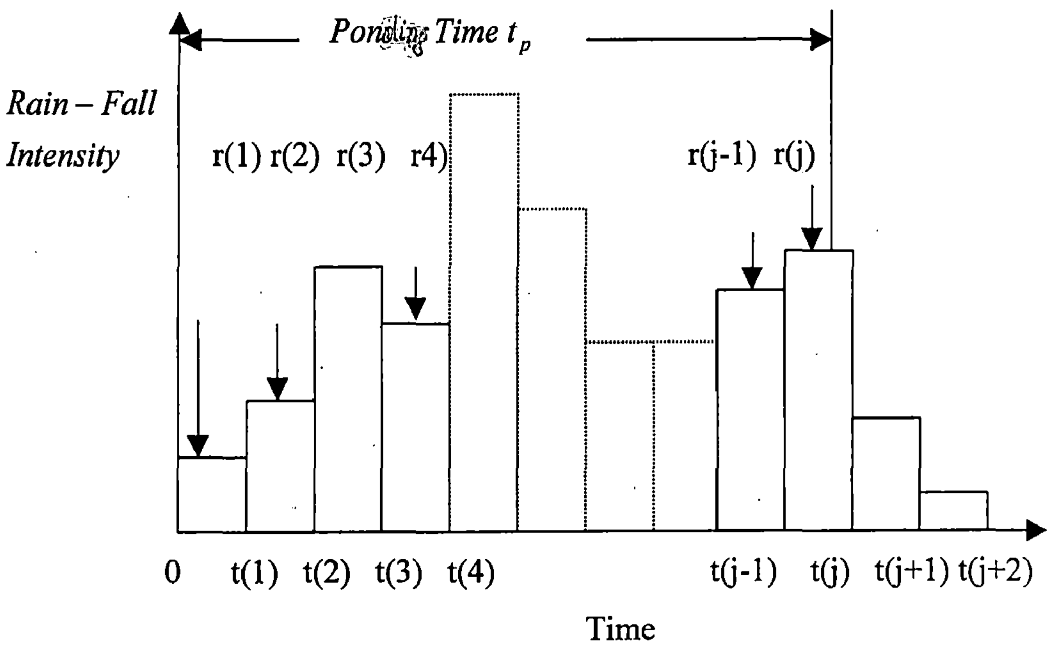

Fig : A . I . 4 Bar chart showing rainfall and ponding time

As from above , we have the following relationship :

$$w(t) = \frac{h_c \cdot (\theta_s - \theta_i)}{\frac{r(t)}{\overline{K}} - 1}$$

Also, we observe from the above figure that cumulative infiltration upto ponding time =

$$w(j) = \sum_{\gamma=1}^{j-1} r(\gamma) \cdot (t_\gamma - t_{\gamma-1}) + r(j) \cdot (t_p - t_{j-1})$$

$$or \quad r(j) \cdot (t_p - t_{j-1}) = \frac{h_c \cdot (\theta_s - \theta_i)}{\frac{r(j)}{\overline{K}} - 1} - \sum_{\gamma=1}^{j-1} r(\gamma) \cdot (t_\gamma - t_{\gamma-1})$$

$$or \quad t_p - t_{j-1} = \frac{1}{r(j)} \cdot \left[\frac{h_c \cdot (\theta_s - \theta_i)}{\frac{r(j)}{\overline{K}} - 1} - \sum_{\gamma=1}^{j-1} r(\gamma) \cdot (t_\gamma - t_{\gamma-1}) \right]$$

or Ponding time t_p *, for a variable intensity rain fall is given by* :

$$t_p = t_{j-1} + \frac{1}{r(j)} \cdot \left[\frac{h_c \cdot (\theta_s - \theta_i)}{\frac{r(j)}{\overline{K}} - 1} - \sum_{\gamma=1}^{j-1} r(\gamma) \cdot (t_\gamma - t_{\gamma-1}) \right]$$

Here the value of $\frac{1}{r(j)} \cdot \left[\frac{h_c \cdot (\theta_s - \theta_i)}{\frac{r(j)}{\overline{K}} - 1} - \sum_{\gamma=1}^{j-1} r(\gamma) \cdot (t_\gamma - t_{\gamma-1}) \right]$ should lie between zero and one.

APPENDIX -II

COMPUTER PROGRAMME FOR COMPUTING INFILTRATION

```
C     IN CVEDIF1.FOR
      DIMENSION RAIN(0:100),CAPINF(100),RINF(100)
      OPEN(1, FILE='cvf2.DAT',STATUS='OLD')
      OPEN(2, FILE='cvf2.OUT',STATUS='UNKNOWN')
      READ(1,*)CLENGTH,SLOPE,TIMEC,AN
      READ(1,*)HF,THETAS,THETAI,THETAF,HYDKS,PEVAP,RDEPTH
      READ(1,*)NDURA
      READ(1,*)(RAIN(I),I=1,NDURA)
      RAIN(0)=0.

      DO I=1,NDURA
      RAIN(I)=RAIN(I)-PEVAP
      END DO

      WRITE(2,200)
200   FORMAT(4X,'HF',9X,'THETAS',5X,'THETAI',5X,'HYDKS')

      WRITE(2,201)HF,THETAS,THETAI,HYDKS
201   FORMAT(4F10.3)
      WRITE(2,*)'PEVAP=',PEVAP
      WRITE(2,*)'COMPUTATION OF INFILTRATION CAPACITY'
      SORPT=SQRT(2.*HF*(THETAS-THETAI)*HYDKS)
      DO J=1,NDURA
      TIME=J
      CAPINF(J)=0.5*SORPT/SQRT(TIME)+HYDKS
      END DO
C
C     COMPUTATION OF INFILTRATION DURING RAIN FALL
C
      CUMINF=0.

      DO 100 J=1,NDURA
      TERM=RAIN(J)-CAPINF(J)
      IF(TERM)10,10,30
10    CONTINUE
      RINF(J)=RAIN(J)
      CUMINF=CUMINF+RINF(J)
      GO TO 100
30    CONTINUE
      RINF(J)=CAPINF(J)
      CUMINF=CUMINF+RINF(J)
100   CONTINUE


      WRITE(2,202)
202   FORMAT(4X,'J',7X,'RAIN(J)',4X,'CAPINF(J)',4X,'INF(J)')
      DO J=1,NDURA
      WRITE(2,203)J,RAIN(J),CAPINF(J),RINF(J)
```

```
203     FORMAT(I5,3F12.4)
        END DO
        WRITE(2,*)'CUMULATIVE INFILTRATION DURING RAINFALL=',CUMINF
        DO J=1,NDURA
        PONDT=J
        TERM=RAIN(J)-CAPINF(J)
C       WRITE(2,*)'TERM=',TERM
        IF(TERM.GT.0.0) GO TO 204
        END DO
        WRITE(2,*)'PONDING DOES NOT OCCUR AS PER  CAPACITY RATE'
        GO TO 104
204     CONTINUE
        WRITE(2,*)'PONDING OCCURRED AS PER CAPACITY RATE'
        WRITE(2,*)'PONDING TIME COMPUTED USING CAPACITY RATE=',PONDT

104     CONTINUE

        WRITE(2,*)'COMPUTATION OF PONDING TIME USING G. AMPT EQUATION'
        WRITE(2,*)'COMPUTATION IS MADE USING MOREL-SEYTOUX APPROACH'

        J=1
        TIMEJM1=0.
        SUMR=0.
        TERMR1=HF*(THETAS-THETAI)/(RAIN(1)/HYDKS-1.)
        TERM2=(TERMR1-SUMR)/RAIN(1)
        IF(TERM2.LT.0.0) GO TO 800
        IF(TERM2.GT.1.0) GO TO 800
C       WRITE(2,*)'TERM2=',TERM2,'J=',J
        GO TO 500
800     CONTINUE
21      FORMAT(E16.4,5F10.4)
        DO 60 J=2,NDURA
        SUMR=0.

        DO NGAMA=1,J-1
        SUMR=SUMR+RAIN(NGAMA)
        END DO

C       WRITE(2,*)SUMR
        TIME=J
        TIMEJM1=J-1
C       WRITE(2,*)'TIMEJM1=',TIMEJM1

        TERMR1=HF*(THETAS-THETAI)/(RAIN(J)/HYDKS-1.)
        TERM2=(TERMR1-SUMR)/RAIN(J)
C       WRITE(2,*)'TERM2=',TERM2,'TIMEJM1=',TIMEJM1
        PT=TIMEJM1+TERM2
        IF(TERM2.LT.0.0) GO TO 60
        IF(TERM2.GT.1.0)GO TO  60
        IF(TERM2.GT.0.) GO TO 500
60      CONTINUE
        WRITE(2,*)'PONDING DOES NOT OCCUR AS PER GREEN AND AMPT'
        WRITE(2,*)'J=',J,'TERM2=',TERM2
        WRITE(2,*)'FOR PONDING TO OCCUR TERM2 <1.0;AND >0.0'
        GO TO 600
```

```
500     CONTINUE
        WRITE(2,*)'PONDING TIME COULD BE COMPUTED AS PER G.& AMPT'
        WRITE(2,*)'PONDING TIME PT IN HOUR=',PT
        WRITE(2,*)'TERM2=',TERM2
        WRITE(2,*)'FOR PONDING TO OCCUR TERM2 <1.0;AND >0.0'
        RECHPT=SUMR+RAIN(J)*(PT-TIMEJM1)
        IPT=PT
        WRITE(2,*)'INFILTRATION UP TO PONDING TIME'
        WRITE(2,*)RECHPT
        GO TO 700

600     CONTINUE
        WRITE(2,*)'PONDING DOES NOT OCCUR AS PER GREEN AND AMPT'
        WRITE(2,*)'PONDING TIME IS ASSUMED AS PER CAPACITY RATE'
        IPT=PONDT
        PT=PONDT
        RECHPT=0.
        DO I=1,IPT
        RECHPT=RECHPT+RAIN(I)
        END DO

700     CONTINUE

        WRITE(2,*)'COMPUTATION OF INFILTRATION AFTER PONDING'
        WRITE(2,*)'AV. PONDING DEPTH  BETWEEN CONSECUTIVE TIME STEPS USED'

        TIME1=PT
        ITIME1=PT
        TIME2=ITIME1+1
        ITIME2=TIME2
        WRITE(2,*)'PT=',PT
        WRITE(2,*)'TIME1=',TIME1,'ITIME1=',ITIME1,'TIME2=',TIME2
        W1=RECHPT
        WRITE(2,23)
23      FORMAT(9X,'RES',9X,'TIME',7X,'AVCR',6X,'W1',9X,'w2',6x,'RINFR')
555     CONTINUE
        CALL TRIAL(W1,ITIME1,TIME1,TIME2,HF,THETAS,THETAI,
   1    HYDKS,RAIN, RES,W2,AVCR)
        DWP=W2-W1
        DWT=TIME2-TIME1
        RINFR=DWP/DWT
        WRITE(2,21)RES,TIME2,AVCR,w1,W2,RINFR
        TIME1=TIME2
        ITIME1=TIME1
        TIME2=TIME1+1.
        ITIME2=TIME2
        W1=W2
        IF(ITIME2.LE.NDURA) GO TO 555

        write(2,*)'post rainfall infiltrated depth'
        pdepth=hydks*timec**1/2
        write(2,*)'pdepth',pdepth
        STOP
        END
```

```
      SUBROUTINE TRIAL(W1,ITIME1,TIME1,TIME2,HF,THETAS,THETAI,
   1  HYDKS,RAIN, RES,W2,AVCR)
      DIMENSION RAIN(0:100)

      SUM1=0.
      DO I=1,ITIME1
      SUM1=SUM1+RAIN(I)
      END DO

      CRAVE=SUM1+0.5*RAIN(ITIME1+1)
      AVCR=CRAVE
C     write(*,*)avcr
      A=(THETAS-THETAI)/(1.-THETAS+THETAI)
      B=A*HF
      C=HYDKS*(1.-THETAS+THETAI)*(TIME2-TIME1)
      TERM1=A*CRAVE+B
      TERM2=W1+TERM1
      index=1
      DW2=0.1
      W2=W1+DW2
100   CONTINUE
      V1=W2-W1
      V2=TERM1*ALOG((W2+TERM1)/TERM2)
      RES=V1-V2-C
C     WRITE(*,*)'RES=',RES,'W2=',W2
      IF(ABS(RES).LT.0.0001) GO TO 200
      W2=W2+DW2
      IF(RES.LT.0.00) GO TO 100
      W21=W2-DW2
      W22=W21-DW2
300   W2=(W21+W22)/2.
      CONTINUE
      V1=W2-W1
      V2=TERM1*ALOG((W2+TERM1)/TERM2)
      RES=V1-V2-C
C     WRITE(2,*)'RES=',RES,'W2=',W2
      IF(ABS(RES).LT.0.0001) GO TO 200
      IF(RES.GT.0.0)GO TO 500
      IF(RES.LT.0.0)GO TO 600
500   W21=W2
      GO TO 300
600   W22=W2
      GO TO 300
200   CONTINUE
999   continue
      RETURN
      END

      SUBROUTINE RESIDUE(WP,PT,TIME,INDEX,HF,THETAS,THETAI,
   1  HYDKS,RAIN, RES,W,CR)
      DIMENSION RAIN(0:100)
      DW=0.01
      TERM1=(1.-THETAS+THETAI)
      TERM2=HYDKS*(TIME-PT)
```

```
      TERM3=TERM1*TERM2
      CR=0.
      DO I=1,INDEX
      CR=CR+RAIN(I)
      END DO
      TERM4=(THETAS-THETAI)*(HF+CR)
      TERM5=TERM1*WP+TERM4
      W=WP+DW
100   CONTINUE
      TERM6=TERM4+W*TERM1
      TERM7=ALOG(TERM6/TERM5)
      RES=W-WP-TERM3-TERM4*TERM7
C     WRITE(2,*)'RES=',RES,'W=',W
      IF(ABS(RES).LT.0.0001) GO TO 200
      W=W+DW
      IF(RES.LT.0.00) GO TO 100
      W1=W-DW
      W2=W1-DW
300   W=(W1+W2)/2.
      CONTINUE
      TERM6=TERM4+W*TERM1
      TERM7=ALOG(TERM6/TERM5)
      RES=W-WP-TERM3-TERM4*TERM7
C     WRITE(2,*)'RES=',RES,'W=',W
      IF(ABS(RES).LT.0.0001) GO TO 200
      IF(RES.GT.0.0)GO TO 500
      IF(RES.LT.0.0)GO TO 600
500   W1=W
      GO TO 300
600   W2=W
      GO TO 300
200   CONTINUE
      RETURN
      END

      SUBROUTINE RESID(WP,PT,TIME,INDEX,HF,THETAS,THETAI,
   1  HYDKS,RAIN, RES1,W,CR)
      DIMENSION RAIN(0:100)

      TERM1=(1.-THETAS+THETAI)
      TERM2=HYDKS*(TIME-PT)
      TERM3=TERM1*TERM2
      CR=0.
      DO I=1,INDEX
      CR=CR+RAIN(I)
      END DO

      TERM4=(THETAS-THETAI)*(HF+CR)
      TERM5=TERM1*WP+TERM4
      TERM6=TERM4+W*TERM1
      TERM7=ALOG(TERM6/TERM5)
      RES1=W-WP-TERM3-TERM4*TERM7
      RETURN
      END
```

APPENDIX – III

DATA FILE

100000. 0.36 1.5 0.03
11.02 0.453 0.40 0.412 0.181666 0.004 300.
30
0.18
0.21
0.26
0.32
0.37
0.43
0.64
1.14
3.18
1.65
0.81
0.52
0.42
0.36
0.28
0.24
0.19
0.17

APPENDIX – IV

RESULT FILE

HF	THETAS	THETAI	HYDKS
11.020	.453	.400	.182

PEVAP= 4.000000E-03

COMPUTATION OF INFILTRATION CAPACITY

J	RAIN(J)	CAPINF(J)	INF(J)
1	.1760	.4120	.1760
2	.2060	.3445	.2060
3	.2560	.3146	.2560
4	.3160	.2968	.2968
5	.3660	.2847	.2847
6	.4260	.2757	.2757
7	.6360	.2687	.2687
8	1.1360	.2631	.2631
9	3.1760	.2584	.2584
10	1.6460	.2545	.2545
11	.8060	.2511	.2511
12	.5160	.2482	.2482
13	.4160	.2455	.2455
14	.3560	.2432	.2432
15	.2760	.2411	.2411
16	.2360	.2392	.2360
17	.1860	.2375	.1860
18	.1660	.2360	.1660

CUMULATIVE INFILTRATION DURING RAINFALL= 4.357148

PONDING OCCURRED AS PER CAPACITY RATE

PONDING TIME COMPUTED USING CAPACITY RATE= 4.000000

COMPUTATION OF PONDING TIME USING G. AMPT EQUATION

COMPUTATION IS MADE USING MOREL-SEYTOUX APPROACH

PONDING TIME COULD BE COMPUTED AS PER G.& AMPT

PONDING TIME PT IN HOUR= 3.480542

TERM2= 4.805417E-01

FOR PONDING TO OCCUR TERM2 <1.0;AND >0.0

INFILTRATION UP TO PONDING TIME

7.898512E-01

COMPUTATION OF INFILTRATION AFTER PONDING

AV. PONDING DEPTH BETWEEN CONSECUTIVE TIME STEPS USED

PT= 3.480542

TIME1= 3.480542ITIME1= 3TIME2= 4.000000

RES	TIME	AVCR	W1	w2	RINFR
-.5177E-04	4.0000	.7960	.7899	.9473	.3031
.1264E-04	5.0000	1.1370	.9473	1.2274	.2801
.7139E-04	6.0000	1.5330	1.2274	1.4887	.2613
-.9231E-05	7.0000	2.0640	1.4887	1.7389	.2502
-.3546E-04	8.0000	2.9500	1.7389	1.9832	.2443
-.8165E-04	9.0000	5.1060	1.9832	2.2289	.2457

.7341E-04	10.0000	7.5170	2.2289	2.4770	.2480
.2754E-04	11.0000	8.7430	2.4770	2.7223	.2453
-.2085E-04	12.0000	9.4040	2.7223	2.9635	.2412
-.1115E-04	13.0000	9.8700	2.9635	3.2008	.2373
-.9786E-05	14.0000	10.2560	3.2008	3.4346	.2338
.3504E-04	15.0000	10.5720	3.4346	3.6652	.2307
.1476E-04	16.0000	10.8280	3.6652	3.8930	.2277
-.5645E-04	17.0000	11.0390	3.8930	4.1180	.2250
-.7775E-05	18.0000	11.2150	4.1180	4.3406	.2227

post rainfall infiltrated depth

pdepth 0.13624

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