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No. : INCOH/SAR-13/97

INFILTRATION AND ITS SIMULATION

V.N. Sharda
Sita Ram Singh

INDIAN NATIONAL COMMITTEE ON HYDROLOGY
(Committee Constituted by Ministry of Water Resources, Govt. of India)

INCOH SECRETARIAT
NATIONAL INSTITUTE OF HYDROLOGY
ROORKEE - 247 667, INDIA
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PREAMBLE

It has been estimated that the total world population will be around 6.5 billion by the year 2000, with the most rapid growth in the developing countries. By that time, the countries within the humid tropics and the other warm humid regions will represent almost one-third of the total world population. This proportion will continue to rise in the 21st century. The developing and under-developed countries thus quite clearly are the regions facing potentially serious water problems. Hence, it is urgent to question as to whether the fields of hydrology and water resources management have the appropriate methods in place to meet the rising demands that will be made on the water resources. Hence it becomes very important and expeditious to review and update the state-of-art in different facets of hydrology and component process. This calls for compiling and reporting present day technology in assessment of water resources and determining the quality of these water resources.

The Indian National Committee on Hydrology is the apex body on hydrology constituted by the Government of India with the responsibility of coordinating the various activities concerning hydrology in the country. The committee is also effectively participating in the actities of UNESCO and is the National Committee for International Hydrology Programme (IHP) of UNESCO. In pursuance of its objective of preparing and periodically updating the state-of-art in hydrology in the world in general and India in particular, the committee invites experts in the country to prepare these reports on important areas of hydrology.

Water moves continuously through the soil mass to remain in equilibrium with the prevailing environmental conditions. The rate at which water moves through the soil has been quantified in a number of measurable indices such as infiltration rate, hydraulic conductivity, soil water diffusivity and capillary rise. To make an economic and efficient use of our limited water resources available for irrigation, it becomes imperative to know in advance a general pattern of soil water distribution in response to a given quantity of irrigation under a given set of physico-chemical conditions of soil. However, to get a clear idea of soil moisture movement, it is important to know about developments made in the theory of infiltration. With this objective, the present report has been written. This report reviews the developments in the theory of infiltration and leads to its practical applications.

The Indian National Committee on Hydrology with the assistance of its erstwhile Panel on Ground Water has identified this important topic for preparation of this state-of-art report earstwhile and the report has been prepared by Dr. V.N.Sharda, Senior Scientist, CSWCR & TI, Dehradun and Dr. S.R.Singh, WTC, Bhubaneswar. The guidance, assistance and review provided by the Panel are worth mentioning. The report has been compiled and finalised by Dr. K.K.S.Bhatia, Member-Secretary and Sri R. Mehrotra, Scientist -in-charge, Indian National Committee on Hydrology.

It is hoped that this state-of-art report would serve as a useful reference material to practicing engineers, researchers, field engineers, planners and implementation authorities, who are involved in correct estimation and optimal utilization of the water resources of the country.

Roorkee

(S.M. Seth)
Executive Member, INCOH
& Director, NIH

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INTRODUCTION

Infiltration is the term applied to the process of water entry into the soil, generally by downward flow through all or part of the soil surface. Water may enter the soil through the entire surface uniformly as under ponding or rain or it may enter the soil through furrows or crevices. The rate of this process, relative to the rate of water supply, determines how much of water, if any, will run off. Infiltration not only affects the recharge of soil profile and ground water but, also the amount of surface runoff and subsequently soil erosion. For efficient soil and water management, knowledge of infiltration process, therefore, forms an essential prerequisite.

INFILTRATION CAPACITY OR INFILTRABILITY

Infiltration rate is defined as the volume flux of water entering the soil profile per unit of soil surface area and time. Horton (1940) defined infiltration capacity as the maximum rate at which a given soil in given condition can absorb rain as it falls. It is the infiltration capacity of the soil that determines for a given storm, the amount and time distribution of rainfall excess that is available for runoff and surface storage. More recently, Hillel (1971) defined the term infiltrability to designate infiltration flux when water at atmospheric pressure is made freely available at the soil surface. This single word replacement avoid the extensity-intensity contradiction in the term infiltration capacity and allows the use of the term infiltration rate in the ordinary literal sense under any set of circumstances, whatever the rate or pressure at which the water is supplied to the soil. For example, the infiltration rate can be expected to exceed infiltrability whenever water is ponded over the soil to a depth sufficient to cause the pressure at the surface, to be significantly greater than atmospheric pressure. On the other hand, if water is applied slowly or at a sub-atmospheric pressure, the infiltration rate may well be smaller than the infiltrability.

Infiltration rate is influenced by many factors such as the initial soil wetness and hence suction, the condition of surface crust, texture, structure and uniformity of the soil profile, temperature, rainfall intensity and extent of vegetative cover. Initially, when the soil is dry, the rate of infiltration is high; subsequently, it decreases monotonically and eventually approaches asymptotically a constant rate which is often termed as the final infiltration capacity, or basic infiltration rate, or steady state infiltrability. The decrease is primarily due to the reduction in the hydraulic gradients at the surface but is also affected by the gradual deterioration of the soil structure owing to the detachment and migration of soil particles and the consequent partial sealing of the profile by the formation of dense surface crust. The bulk compression of soil air, if prevented from escaping, also reduces the infiltration rate. The constant rate (f_c) is generally assumed to be equal to the saturated hydraulic conductivity (k_o) but will actually be less than k_0 due to entrapped air. In most cases, f_c is more accurately approximated by k_s, the hydraulic conductivity at residual air saturation.

Fig.1 shows the variations in infiltration rate over time for a ponded surface and under a constant application rate R (Skaggs, 1982). When R is less than infiltration capacity of the soil, the infiltration rate will be equal to R and is limited by the application rate rather than soil condition and properties. The variations in water content over the soil depth are depicted in Fig. 2 by curves 1,2 and 3. With continued infiltration, the infiltration capacity will decrease till it becomes equal to the application rate (point 4 in Fig.1 and curve 4 in Fig.2). Subsequently, the infiltration capacity is controlled by the Soil properties (points 5 and 6 in Fig.1 and curves 5 and 6 in Fig.2) and eventually reaches a constant value(f_c). If application rate is higher than f_c then surface ponding and runoff will result.

Bodman and Coleman (1943) demonstrated that soil profile during infiltration process can be divided into four zones, viz : Saturated zone extending to maximum depth of 1.5 cm from the surface, the transition zone, a region of rapid decrease of soil water content, extended from zone of saturation to the transmission zone, a zone of nearly constant water content and the wetting zone with nearly a constant shape and culminating in the wetting front which is the visible limit of water penetration into the soil. Except the transition zone, their results have been generally confirmed by other workers. McWhorter (1976) showed that an abrupt steepening of the profile near the surface would be predicted for rainfall infiltration if the resistance to air movement is considered.

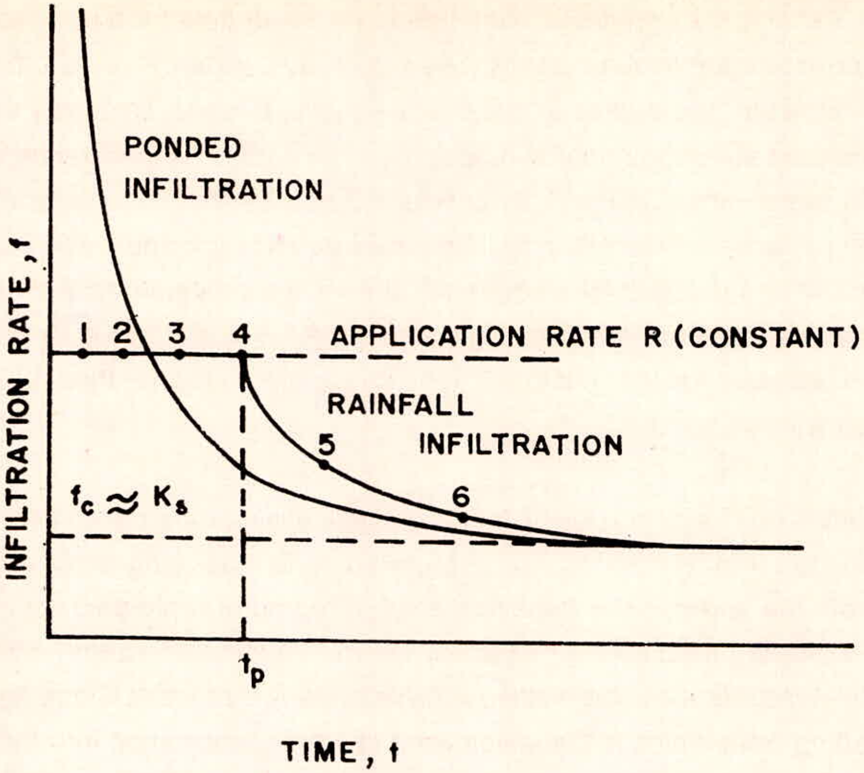

Fig. 1 : Variation of Infiltration rate over time for a ponded surface and for a constant application rate

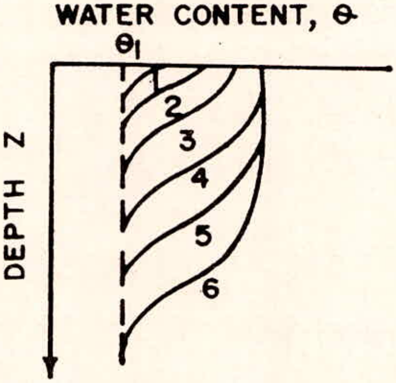

Fig 2 : Variations in soil water content over depth at different timings during infiltration

FACTORING AFFECTING INFILTRATION

Soil Propreties

One of the most important variables controlling infiltration is the hydraulic conductivity. However, during early stages of infiltration, soil structure or pore size distribution has a significant effect. As the soil behind the wetting front approaches saturation, the hydraulic gradient approaches unity and the hydraulic condutivity begins to control the flow rate. In general, the wider the range of pore sizes, the more gradual is the change in the infiltration rate. Fig.3 shows the infiltration rates of six different soils as predicted from numerical solution of Richards equation for vertical infiltration from a ponded surface into deep homogenous profiles.(Skaggs, 1982). Corresponding plots for cumulative infiltration are shown in Fig. 4.

Hanks and Bowers (1963) found that variation in the soil water diffusivity at low water contents has negligible effect on infiltration from a ponded water surface. However, variation in either the diffusivity or soil water characteristic at water contents near saturation have a strong influence on predicted infiltration.

Initial Water Content

Higher the initial water content, lower will be the infiltrability owing to smaller suction gradients. If infiltration continues indefinitely, the infiltration rate will eventually approaches k_s regardless of the initial water contents. Fig.5 shows the predicted influx curves for infiltration from a shallow ponded surface into a deep columbia silt loam at different initial water contants. Philip (1957) observed that for all times during infiltrtation, the wetting front advances more rapidly for higher initial water contents.

Rainfall Rates

Infiltration rate is a function of both rainfall rate and soil conditions. If the rainfall rate, R is less than K_s for a deep homogenous soil, infiltration may continue indefinitely at a rate equal to the rainfall rate without ponding at the surface. The water content of the soil in this case does not reach saturation at any point but approaches a limiting value which depends on rainfall intensity. However, for soils with restricting layers, infiltration will not always continue indefinitely without surface ponding when $R<K_s$ .When the

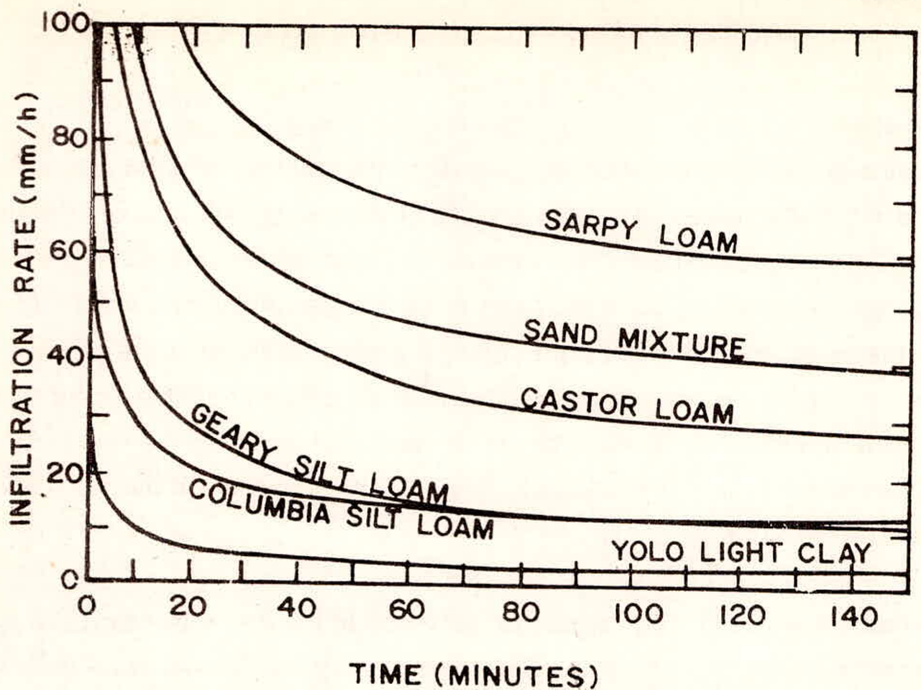

Fig.3 : Predicted infiltration rates for deep soils with a shallow ponded surface

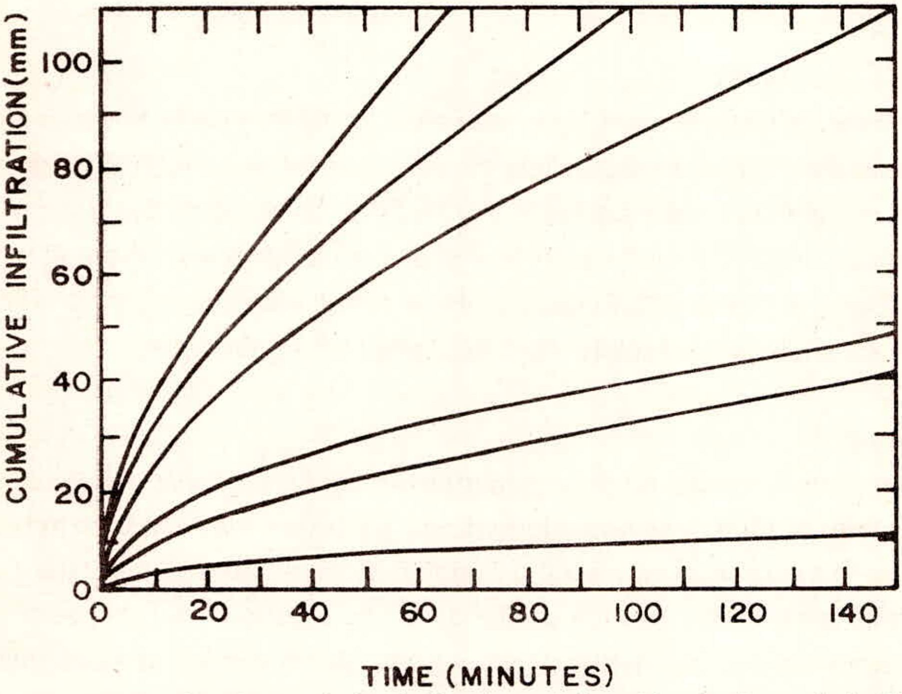

Fig.4 : Predicted cumulative infiltration relationships for the soils in Fig. 3

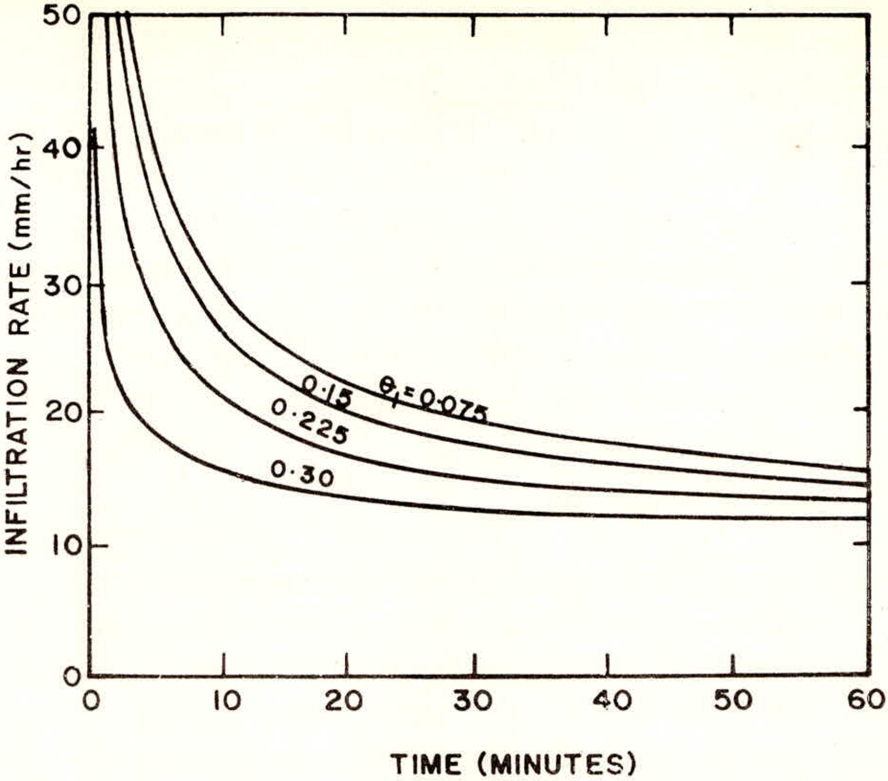

Fig.5 : Infiltration rate for different silty loamy soils for different initial soil moisture contents

wetting front reaches the restricting layer, water contents above the layer will increase and surface ponding may result eventhough the rainfall rate is less than K_s of the surface layer.

When $R>K_s$, the infiltration rate is initially controlled by the application rate till it falls below R. Subsequently, surface ponding begins and water becomes available for runoff. As obvious from Fig.4 (Skaggs, 1982), infiltration rate versus cumulative infiltration relationship can be assumed to be independent of R. Mein and Larson (1973) made use of this assumption while using Green and Ampt equation to stimulate infiltration under erratic rainfall conditions where the unsteady rainfall or application rate dropped below the infiltration capacity for period of time followed by a high intensity application.

Surface Sealing and Crusting

The changes in the hydraulic properties at the soil surface during the application of water strongly affect the infiltration rate. Horton (1939) attributed the exponential decay of infiltration rate with time to the slaking of aggregates and swelling of colloids which progressively sealed the soil. Edward and Larson (1969) applied the theory of soil water movement to investigate the influence of surface seal development on infiltration of water into a tilled soil. Hillel and Gardener (1969, 1970) while evaluating the effect of surface sealing on steady state and transient infiltration processes observed that infiltration into crusted profile may be approximated by assuming that water enters the soil layer below the crust at a nearly constant suction, the magnitude of which depends on the hydraulic properties of the underlying soil. Morin and Benyamini (1977) concluded that the crust formed by raindrop impact is the dominant factor influencing the infiltration capacity.

Fig.6 shows the effect of surface condition on infiltration rate for a Zanesville silt loam soil on cultivated plots subjected to simulated rainfall (Skaggs et. al., 1969). Mannering and Meyer (1963) showed that straw mulch applied at densities of greater than one ton per acre prevented surface sealing due to rainfall impact. Surface sealing effect is therefore, of great importance while predicting infiltration under rainfall conditions particularly for soils with only partial surface cover.

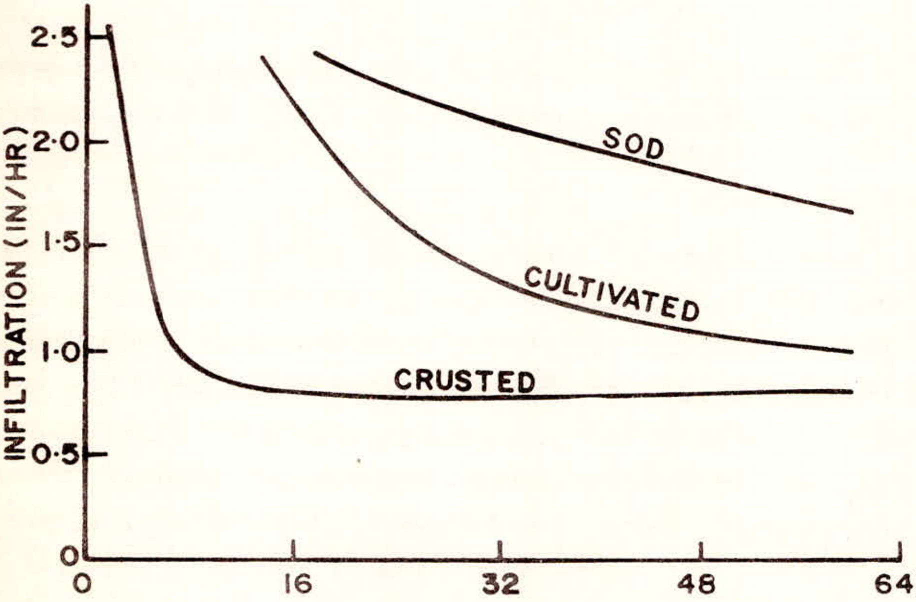

Fig. 6 : Effect of surface sealing and crusting due to rainfall impact on infiltration rate

Layered Soils

Normallly, infiltration processes occur in soils which are uniform neither in texture nor in initial wetness. Takagi (1960) analyse steady state downfall of water through a two layer profile and found that if the upper layer is less pervious than the lower, negative pressures develop in the lower layer and these can remain constant throughout a considerable depth range. Hanks and Bowers (1962) also solved Richards equation for infiltration from a ponded surface into a two layered soil. For a coarse soil over a fine one, infiltration proceeded exactly as for a coarse soil alone until the wetting front arrived at the boundary between the two layers. Thereafter, the progress of wetting front slowed and a positive pressure head developed in the top layer and over coarse soils were nearly the same as that predicted for a uniform fine textured soil except for a decrease in the infiltration rate when the wetting front reached the coarse layer. Similar solutions were obtained by Whisler and Klute (1966) for coarse textured soils over fine soils, fine textured lenses in coarse soil and coarse and textured lenses in fine soil.

Miller and Gandner (1962) through their experiments on the effects of thin layers of different texture sandwiched into otherwise uniform profiles showed that although in any soil the metric suction hydraulic head must be continuous throughout the profile regardless of layering sequence, the wetness and conductivity may exhibit abrupt discontinuities at interlayer boundaries. In the recent investigations, Hillel (1977) observed that dynamics of soil moisture storage is strongly dependent upon textural and structural composition of the soil profile.

Movement and Entrapment of Soil Air

The assumption of constant air pressure during derivation of Richards equation is rarely satisfied in actual practice. It is assumed that because of small viscosity of air relative to that of water, air can escape through large pores that remain partially open during infiltration. However, in many cases the trapped air causes air pressure build up thereby reducing the infiltration rate. Wilson and Luthin (1963) suggested that entrapment occurs primarily in the larger pores. Slack (1978) observed that a total air entrapment of 10 percent can bring 80 to 90 percent reduction in hydraulic conductivity. McWhorter (1971) presented a detailed study of this phenomenon with oil is as the infiltrating liquid. Analytical procedures were also developed for equations describing two phases (air-water) movement in unsaturated porous medium (Green et. al., 1970 ; McWhorter, 1971, 1976; Sonu and Morel-Seytoux, 1976).

MEASUREMENT OF INFILTRATION

The most common method of estimating the infiltration characteristic of the soil is through the use of cylinder or ring infiltrometers. It may be achieved in two days.

Single Ring

In this case infiltration characteristic of soil are determined by ponding water in a metal cylinder installed on the field surface. The infiltration rate is measured either by maintaining a constant head and estimating the amount of water being added into the cylinder or by observing, the rate at which the water level is lowered in the cylinder. It is argued that there is high degree of variability in the data collected by using single ring mainly due to uncontrolled lateral movement of water after the wetting front reached the bottom of the cylinder which otherwise is taken as insignificant.

Double Ring

The principle is the same as for the single ring except that one outer ring is provided to minimize lateral movement of water and thus serves as a buffer or border for the infiltrating water from the central ring. Presumably, this water moves only downwards, thereby providing a reliable estimate of the equilibrium infiltration rate.

Michael (1978) has given specifications for construction and installation of ring infiltrometers. Infiltration rates are influenced by the cylinder diameter, thickness of cylinder, bevelling of the cylinder bottom, the method of driving the cylinder into the soil and installation depth. The average depth of water maintained in the cylinder normally varies from 7 to 12 cm which is approximately equal to the water level expected in the irrigation systems. Water levels in the inner and outer cylinders are kept approximately the same. To arrive at an optimum value replicated trails are conducted at suitable locations in the field. The average values of the accumulated infiltration and average infiltration rate are then worked out and the values of the constants are determined through fitting procedure.

Soni and Singh (1988) conducted infiltration tests at different locations of a field through cylinder infiltrometers and found that during each elapsed time, the natural logarithm of cumulative infiltration were normally distributed . It was, therefore, concluded, that each time, geometric mean of the cumulative infiltration values should be taken to obtain average cumulative infiltration for the whole field.

INDICES OF INFILTRATION

The rational infiltration approach based upon infiltration curve is usually impracticable for the hydrological problems involving the prediction of runoff from a knowledge of storm characteristics and the infiltration characteristics of the area. Many infiltration indices have therefore, been devised by hydrologists, the use of which does not constitute a rational application of the infiltration theory. The use of such indices is considered to be superior to the use of runoff coefficient in the estimation of runoff from rainfall because the former takes into account the extent whereas the later are mere ratios of runoff to rainfall. Infiltration index is defined as the average rate or loss such that the volume of rainfall in excess of that rate will be equal to the direct runoff. The infiltration indices usually assume that infiltration occurs at some constant or average rate throughout a storm event. Consequently, initial infiltration rates tend to be under-estimated and final rates over-estimated. However, for long term storms, particularly when initial soil moisture levels are high, the infiltration indices work fairly well. Estimates of runoff volume from large areas, having hetrogeneous infiltration and rainfall characteristics can be made by use of these indices. The most commonly used indices are :

The θ Index

This is most common and simplest of all indices and is based on the assumption that for a specified storm with given initial conditions, the rate of basin recharge remains constant throughout the storm period. If a time intensity graph of rainfall is constructed, the θ-index is the average rainfall intensity above which the volume of rainfall equals the volume of observed runoff. To determine the θ-index of a given storm, the amount of observed runoff is determined from the hydrograph and the difference between this quantity and the total gauged precipitation is then calculated. The volume of loss (including the effects of interception, depression storage and infiltration) is distributed uniformly across the storm pattern excluding those periods when the rainfall intensity (less interception and depression storage inflow rates) is less than the capacity infiltration rates. The θ-index determined from a single storm usually is not applicable to other storms and unless it is corrected with basin parameters others than runoff, such as soil moisture, it is of little value.

The W-Index

The W-index excludes interception and surface storage and retention. It may be defined as the average rate of infiltration during the time rainfall intensity exceeds the infiltration capacity.

$$W = (P - R)/t \qquad (5.1)$$

where,

P = Total precipitation during time, t

R = Total surface runoff

t = Duration of rainfall

Essentially, the W-index is equivalent to θ-index minus the average rate of retention by depression storage. There is, however, little advantage of the W-index over the θ-index for multiple complex watersheds and for better results, the latter one may be used.

The Wmin-Index

Under very wet conditions, the infiltration capacity reaches a constant minimum rate, f_c and the W and θ indices become almost identical, the corresponding W-index is the Wmin-index. The infiltration index can be used to estimate the runoff coefficient, C, from the relation :

$$C = (P - W)/P \qquad (5.2)$$

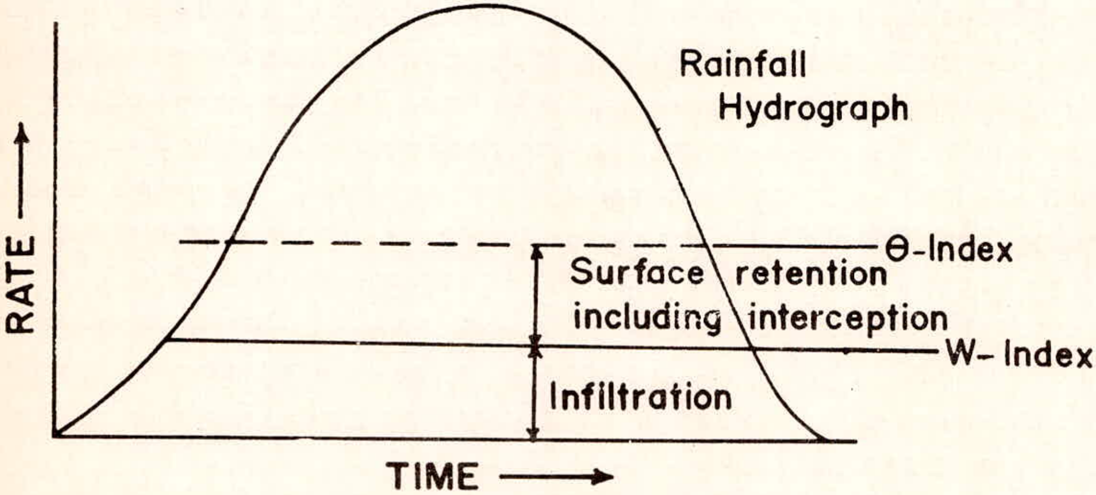

Fig.7 An illustrations of the θ and W abstraction indices.

SIMULATION OF INFILTRATION

Numerous formulations have been proposed over the years to express infiltrabilty as a function of time or of the total quantity of water infiltrated into the soil. Some of them are entirely empirical while others are theoretically explained. The theoretically based models normally employ numerical methods for the solution of governing differential equations and are extremely valuable in analyzing the effects of various factors on the infiltration process. However, computational requirements and difficulty of obtaining necessary soil property data restrict their use for production scale application in hydrology.

EMPIRICAL INFILTRATION MODELS

The approximate infiltration models have been developed by applying the principles governing soil water movement for simplified boundary and initial conditions. The parameters for such models are determined from a soil water properties. For models which are strictly empirical in nature, parameters must be obtained from measured infiltration data or estimated using more approximate procedures.

Kostiakov's Equation

Kostiakov (1932) proposed the simple form of infiltration equation given by:

$$f_p = Kt^{-n} \qquad (6.1)$$

where f_p = Infiltration capacity of the soil , mm/sec;
t = Time after infiltration started, sec; and
K&n = Constants which depend upon the soil type and initial moisture content of the soil.

This equation implies that infiltration rate approaches zero as time tends to infinity rather than a constant non-zero f_p which is not correct. Moreover, the parameters of this equation must be evaluated from experimental data and thus have no physical interpretation.

Horton's Equation

Horton (1939,1940) presented a three parameter infiltration equation which may be written as :

$$f_p = f_c + (f_0 - f_c)e^{-kt} \qquad (6.2)$$

where, f_c = Final constant rate of infiltration capacity;
f_0 = Initial rate of infiltration capacity;
f_p = Infiltration capacity at any time, t; and
K = A cosntant depending primarily upon soil and vegetation.

It represents the rate of decrease on infiltration capacity during storm event. At $t = 0$, the infiltrability is not infinite but takes on the finite value f_0. The constant K determines how quickly f_p will decrease from f_o to f_c. This equation is also integrable to give cumulative infiltration F at any time, t. Though this equation has the advantage of simplicity, the assumption that continuous ponding occurs at the surface or that the rainfall rate is always greater than the infiltration rate does not, of course, always exist during a storm. Moreover, the three constants must be evaluated experimentally.

In spite of the above disadvantages, the Horton's equation is widely used and the physical significance of its terms, as well as its limitation should be clearly evaluated by the hydrologist.

Smith's Equation

The limitation of both the Horton and Kostiakov equation is that they ignore the preponing infiltration and consider infiltration as single stage event. Smith (1972) modified the Israelson and Hansen form of Kostiakov equation for two stage infiltration events by adding an empirical parameter whose value is equal to zero for initially ponded infiltration as :

$$f_P = f_c + C(t - t_0)^d \qquad (6.3)$$

where, t_0 = An empirical constant which is equal to zero for initially ponded infiltration ; and

C & d = Constants determined as the intercept and slope respectively of a log-log plot of $(f_P - f_c)$ versus $(t - t_0)$.

Holtan's Equation

Holtan (1961) proposed an empirical equation for infiltration based on a storage concept as :

$$f_P = f_c + a(M - F)^n \qquad (6.4)$$

Where, f_c is the equilibrium infiltration rate associated with the gravity force at field capacity soil moisture content and F is the cumulative infiltration upto a given time period since the begining of infiltration . Holtan specified M as the water storage capacity of the soil but the meaning of M for a soil without an impend-ing stratum was not made clear. Moreover, it is only defined for the range $0 < F < M$ since $f_P = f_c$ can only occur at the single point $F = M$. When F exceeds M, then the quantity (M-F) becomes either positive and increasing, negative and decreasing or imaginary depending upon whether n is even, odd or fractional respectively. Thereafter, in addition to needing the condition $0 < F < M$ on equation (6.4) to be
complete, one must also state.

$$f_P = f_c \text{ for } F > M \qquad (6.5)$$

Hence, the Holtan expression must be recognised as the two form mathematical specification represented by Equations (6.4) and (6.5). 'a' and 'n' are the parameters determined experimentally from infiltrometers plot data. 'n' was found to be 1.4 and 'a' was found to vary between 0.2 and 0.8 for the soil cover complexes studied and for various soil moisture contents at time, t.

The advantage of Holtan's model over Horton's model is that only one parameter 'a' need to be estimated as compared to two, f_0 and K in the Horton's model.

Modified Holtan's Equation (1971)

Holtan and lopoz (1971) modified the original Holtan's equation in their USDAHL -74 watershed hydrology model which is given by

$$f_P = GI.a.SA^{1.4} = f_c \qquad (6.6)$$

Where, SA is available storage in the surface layer (inches), GI is the growth index of crop in percent of maturity, 'a' is an index of surface connected porosity which is a function of surface condition and the density of plants roots and f_c is the constant of steady state infiltration rate as estimated from the hydrologic soil group. Frere et. al. (1975) developed values for the parameter 'a' in terms of crop or surface cover conditions. GI curves have been developed for several crops by expressing experimental data on daily evapotransipiration as a percentage of the annual maximum daily rate.

Though, the Holtan's equation is simpler in its application, the main problem comes in deciding the control depth on which SA is based. Huggins and Monke (1966) observed that effective control depth was highly dependent on both the surface condition and cultural practices used in preparing the seed bed. Smith (1976) also found that Holtan's equation does not adequately describe the infiltration process as the infiltration curves are better related physically to gradients and hydraulic conductivity than to soil porosity.

Physically Based Infiltration Models

The models based upon soil physics approach are more complicated than the empirical models. They are derived by application of the conitnuity of mass and soil water movement with certain simplifications and assumptions.

The Green and Ampt Approach

Green and Ampt (1911) proposed an approximate model of infiltration utilizing Darcy's Law originally from a ponded surface into a deep homogenous soil with a uniform initial water content. The equation may be written as :

$$f_P = K_h \, (Z + S_e + D)/D \qquad (6.7)$$

where, f_P = Infiltration capacity, mm/day;

K_h = Hydraulic conductivity of the transmission zone, mm/sec;

Z = Depth of water ponded on the surface;

S_e = Effective suction at the wetting front, and

P = Distance from the surface to the wetting front.

Considering cumulative infiltration as F = MD and neglecting ponding at the surface (Z=0), Equation (6.7) may be written as :

$$f_P = K_n + K_n M S_e / F \qquad (6.8)$$

where, M denotes the initial soil water deficit which is the difference between initial and final volumetric water contents. The Green and Ampt's model is based upon the contents. The Green and Ampt's models is based upon the following assumptions:

(i) There exists a distinct and precisely definable wetting front.

(ii) Tension or suction at the wetting front remains essentially constant with time and depth.

(iii) Behind the wetting front, the soil is uniformly wet and has constant hydraulic conductivity.

(iv) The wetting front is viewed as separating a uniformly wetted infiltrated zone from the non-infilrated zone. This inturn supposes that k_n versus volumetric moisture content θ , relationship is discontinuous at the wetting front.

These assumption simplify the flow equation and make it amenable to analytical solution. In addition to uniform profiles for which it was originally derived, the Green and Ampt's equation has been satisfactorily used for profiles where hydraulic conductivity increases with depth (Bouwer, 1976), for soil with partially sealed surfaces (Hillel and Gardener, 1970) and for non-uniform initial water contents (Bouwer, 1969). Morel Seytoux and Khanji (1974) observed that equation (6.8) may be used for simultaneous movement of both water and air. Whisler and Bouwer (1970) compared the Green and Ampt and Philip equations with field data and concluded that Green and Ampt formula was best for practical reasons.

Agglides and Young (1978) studied the dependence of parameters in the Green and Ampt infiltration equation on the initial water content. They concluded that Green and Ampt approach is only a quasi-empirical method and does not give result of best fit due to the errors arising out in its derivation from the Richards flow equation. Rawls et.al. (1983) developed guidelines for estimating soil water retention properties and Green and Ampt parameters based on soil texture, organic matter and bulk density.

Skaggs et. al. (1969) experimentally tested the Hortan, Holtan, Philip and Green-Ampt equations. Though, all the equations were found to fit the data adequately, the Philip and Green Ampt equations were found to predict the infiltration rates that are too low for time greater than the duration of the experimental test for which the equations parameters were obtained. It highlights the need for accurately predicting the equations parameters in the field.

Mein and Larson (1971, 1973) applied the Green and Ampt model and developed a two stage model for infiltration under a constant intensity rainfall into a homogenous soil with uniform initial soil moisture content. The first stage predicts the volume of infiltration to the moment at which surface ponding begins. The second stage describes the post-surface ponding infiltration behaviour. The set of equations surface ponding infiltration behaviour. The set of equations developed are as under :

$$F = S_e.M/(I/K_h - 1) \qquad (6.9)$$

$$t_p = F_p/I$$

$$t - t_P + t_p^{'} = \frac{F_P}{K_h} - \ln\left(1 + \frac{F}{MS_e}\right) x \frac{MS_e}{K_h} \qquad (6.10)$$

where, F_p = Cumulative infiltration at the time of ponding,m;
S_e = Average suction at the wetting front,m;
M = Initial soil moisture deficit, m/m;
I = Rainfall/application rate, m/sec;
t_p = Time to surface ponding, sec
$t_p^{'}$ = Equivalent time to infltrate volume F under initially ponded surface conditions.

Then for steady rainfall, the infiltration rate, f_p, may be expressed as :

$$f_p = I,\ t < t_p \qquad (6.11)$$

$$f_p = K_h + K_h \cdot S_e \cdot M/F_p,\ t > t_p \qquad (6.12)$$

Where, $t_p = F_p/I$. If $I < K$, surface ponding will not occur provided the profile is deep and homogenous.

Since the relationship between infiltration capacity and cumulative infiltration is approximately independent of rainfall intensity, the Green and Ampt equation (6.8) can be applied directly for rainfall conditions. On the other hand, the time based equations like Kostiakov, Horton and Philip would be more difficult to apply because of the dependence of the equation parameters on rainfall intensity.

Determination of parameters in the Green-Ampt equation

Bouwer (1966) suggested that hydraulic conductivity parameter in Green and Ampt model may be taken as half of the saturated value because of the entrapped air. He further suggested that effective suction at the wetting front can be approximated as one half of the air entry value (Bouwer, 1969). Mein and Larson (1973) used the unsaturated hydraulic conductivity as a weighting factor to define the average suction. Neuman (1976) related average suction with the physical characteristics of the soil. Morel-Seytoux and Khanji (1974) observed that the value of average suction, Sav, as defined by Mein and larson (1973) is a reasonable approximation of effective matric drive. However, the main problem is to compute the unsaturated hydraulic conductivity function.

Brakensiek (1977) found that average suction can be related to the water entry suction which is approximately equal to one half of the air entry value (bubbling pressure). Brakensiek and Onstad (1977) utilized the infiltration data to test a fitting procedure for the Green and Ampt infiltration equation parameters. They concluded that variation in the fillable porosity and effective conductivity parameters has a major influence on infiltration and runoff amounts and rates whereas the effective capillary pressure is the least sensitive parameter. Though, the equation parameters have physical significance and can be computed from soil properties, it is more advantageous to determine these parameter from field measurement by fitting measured infiltration data. It will further enhance applicability of Green-Ampt equation for describing infiltration under varied initial, boundary and soil profile conditions.

Richards Equation

Richards (1931) derived the most theoritically based equation for unsaturated media by combining the Darcy's Law and the principle of conservation of mass for the soil which may be written as:

$$q_s = -K \ \partial H/\partial s \qquad (6.13)$$

$$\partial\theta/\partial t = -\nabla . \bar{q} \qquad (6.14)$$

where, q_s is the flux or volume of water moving through the soil in the S-direction per unit area per unit time and $\delta H/\delta s$ is the hydraulic gradient in the S-direction, K is the hydraulic conductivity which depends on both properties of fluid and the porous medium. H is the total potential head and may be considered equal to the hydraulic head which is the sum of the pressure head, h, and the distance above the datum plane or the elevation-head, Z. Taking datum plane at the soil surface.

$$H = h - Z \qquad (6.15)$$

where, Z is the distance measured positive downwards from the surface. For partially saturated soil condition where the water content varies with both time and position, the equation for flux may be written as,

$$q_s = -K(\theta)\frac{\partial H}{\partial s} \qquad (6.16)$$

Since the relationship $\theta = \theta(h)$ is a property of the soil, we may write $K = K(h)$ and Equation (6.13) becomes,

$$q_s = -K(h)\frac{\partial H}{\partial s} \qquad (6.17)$$

q is the flux vector, t is time and θ is the volumetric soil water content. For flux in the vertical Z direction only, equation (6.14) may be written as,

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q_z}{\partial_z} \qquad (6.18)$$

Combining Equations (6.17) and (6.18), the Richards equation in the vertical direction may be written as,

$$c(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}[K(h)\,\partial h/\partial z] - \frac{\partial K}{\partial z} \qquad (6.19)$$

where, C(H) is the soil water capacity and may be obtained from the soil water characteristic as,

$$c(h) = \frac{d\theta}{dh} \qquad (6.20)$$

The pressure head based equation (6.19) assumes that there is no resistance to soil air movement and the air pressure remains constant throughout the profile which is often not the case.

In terms of water content, θ, Richards equation may be written as,

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}[D(\theta)\frac{\partial \theta}{\partial z}] - \frac{\partial K}{\partial z} \qquad (6.21)$$

Where, D (θ) = K(h) dh/dθ and is known as soil water diffusivity.

Equations (6.19) and (6.21) are known as h-based and θ-based equations, respectively. The θ-based equation contains D(θ) and K(θ) and the h-based equation contains C(h) and K(h) as the parameter. For unsaturated soils, these parameters are related by D = K/C. The main problem in solving Richards equation subject to boundary conditions pertinent to infiltration is that for most of the soils, all these three parameters behave non-linearly with either water content or pressure head. Where both saturated and unsaturated flow conditions exist, h-based equation provides a valid solution, whereas under completely unsaturated condition, θ-based equation can be used with a dual advantage because changes in both, θ and D are typically an order of magnitude less than corresponding changes in h and C. Moreover, for homogenous soil, only θ-based equation can be used. Under saturated conditions, θ-based equation, however, does not hold good as D(θ) tends to infinity.

Solutions of Richards Equation

Analytical solution

Richarcs equation being non-linear in nature is difficult to solve analytically. In some cases, analytical solutions have been developed for idealized situations with specific boundary and initial conditions. The first mathematically rigorous solution of the flow equation applied to vertical infiltration was given by Philip (1957). He developed a series solution to Richards equation for infiltration from a ponded surface on a deep homogeneous soil with uniform initial moisture content. He suggested that first two terms of the series solution may be used to define the infiltration rate, f_p, as

$$f_p = \frac{S_n}{2} t^{-1/2} + A_h \tag{6.22}$$

Where, the parameters S_n and A_h are related to the initial soil moisture content and the hydraulic conductivity of the soil. After a long time, the infiltration rate approaches the value A_h which is related to the saturated soil conductivity. The sorptivity, S_n and A_h can be evaluated numerically-using the procedures given by Philip if the soil dissusivity and moisture characteristics are known. Young (1968) suggested that A_h may be approximated as 2 $KS_n/3$ and S_n as $(2MK_s S_e)^{1/2}$, where M is the fillable porosity, K_s is the saturated hydraulic conductivity and S_e is the effective suction at the wetting front.

Parlange (1971) developed an analytical solution for the infiltration equation which is valid for all times. Considering the effect of gravity and gradient of water pressure, the infiltration equation ;

$$\frac{\partial z}{\partial t} + \frac{\partial}{\partial z}[\frac{D}{\partial z/\partial \theta}] = \frac{dK}{d\theta} \tag{6.23}$$

where, D is the diffusivity, K is the hydraulic conductivity, $z(\theta,t)$ is the position or depth of a point in one dimensional field where moisture content is θ. He observed that Philip's equation is valid for short times only and diverges as $t \to \infty$. In case of Yolo clay, the series was found to converge for times upto 10^6 sec. For large times, Philip (1957) used as an asymptotic solution. The numerical solution of Equation (6.23) derived by him for all finite times was found to be in complete agreement with the Philip's solution.

Numerical solutions

Under non - uniform initial water contents, time dependent boundary conditions, heterogeneous and anisotropic porous media with hysteresis in soil properties, numerical solution of the governing equations provide the only answer. Staple (1966) used explicit scheme for solving Richards equation for infiltration and redistribution problems. Rubin (1967), Amerman (1976) and Freeze (1971) developed numerical procedures for solving Richards equation for two and three dimensional flow. Freeze (1969) summarized the finite difference solutions for the Richards equations. Whisler and Klute (1965) used an interactive numerical procedure to solve h-based equation subject to a non-uniform initial water content.The method is, however, time consuming and the nature of convergence or divergence of such a scheme appears to be dependent upon the type of the difference equation used, the finite grid dimensions and the local shape of the θ-h-K relationship (Smith and Woolhiser, 1971). Molz and Remson (1970) and Havercamp et. al. (197) developed, Implicit finite difference formulations and solutions of Richards equation using the Predictor- Corrector method.

The application of finite element technique to infiltration problems, especially for complex flow domains is of recent origin but is gaining recognition. Hayhoe (1978), while comparing the finite difference schemes and finite element technique concluded that Galerkin scheme with the linear elements or the finite difference scheme with the modified averaging procedure is preferable to the other schemes. Singh and Kumar (1985) solved Richards equation with a sink term using finite element technique for studying the water balance of an acquifer-soil system in the presence of crops. The Richards equation with a sink term has also been solved numerically by Nimah and Hanks (1973), Hillel (1977), Feddes et.al. (1976) and Slack et. al. (1977).

Haverkamp et. al. (1977) compared six different numerical schemes in terms of execution times and mass balance errors for constant flux infiltration into a uniform soil column. He concluded that explicit models consumed between 5 to 10 times more time than the implicit models. All the models had an excellent mass balance except the one where Kirchoff transformation integral was used which changed to drastically with time during infiltration.

Rainfall Infiltration

Rubin et. al. (1964 a, 1964 b) studied the process infiltration under rainfall conditions. They recognised three modes of infiltration due to rainfall: (1) non-ponding infiltration, involving rain not intense enough too produce ponding, (2) preponding infiltration, due to rain that can produce ponding but that has not done so and (3) rain pond infiltration, characterized by the presence of ponded water. The first two conditions are dictated by rain intensity and are therefore, supply controlled whereas the third one depends upon the transmission by the simple linearized solution.

The Green and Ampt model as modified by Mein and Larson (1973) is applicable only for steady rainfall conditions involving only one ponded time. In actual field conditions, the rain intensity may involve more than one ponding times depending upon rainfall intensity and saturated soil condutivity. Skaggs (1982) suggested that Green Ampt equation may also give good approximation of infiltration for steady rainfall provided the rainfall distribution does not include relatively long periods of low intensity or zero rainfall which may result in redistribution of the wetted profile.

Swartzendruber and Hillel (1975) combined theoretical and experimental study of rain infiltration to predict the time of appearance and the quantity of surface water excess for different rain intensities. The experimetal data was utilized to develop an infiltration equation which may determine the ultimate steady infiltration flux in the soil (near-saturated hydraulic conductivity).

Smith (1972) proposed that the assumption of infiltration rate versus cumulative infiltration relationship being independent of rainfall rate could be extended to the case of erratic rainfall where the unsteady rainfall or application rate dropped below the infiltration capacity for period of time followed by a high intensity application. Mein and Larson (1973) made use of this assumption to predict time of ponding. Reeves and Miller (1975) also supported the hypothesis that the maximum infiltration rate is simply a function of the maximum infiltration, regardless of the rainfall versus time history. They developed a method known as "Time compression approximation" to employ which the only soil characterization needed is the curve of cumulative infiltration under zero surface head versus time. They obtained numerical solutions to the Richards equation which considered hysteresis and surface crusting. Their finding reduced input requirements and made parameters of the approximate methods independent of rainfall rate and functions initial conditions.

Chu (1978) proposed that the assumption of cumulative infiltration being zero at the time when surface ponding starts does not usually hold good in practice. He modified the traditional Green and Ampt equation to describe infiltration during rainfall event by introducing the concept of surface indicators. The modifications is equivalent to a shift of the time scale by an amount which is referred to as the pseudotime. The value of the surface indicators prior to the occurence of each unit of rainfall event will decide whether the surface is ponded or not.

Morel-Seytoux (1978) included the effect of air viscous flow in deriving the equations for cumulative infiltration and ponding time under a condition of piecewise variable and even intermittent rainfall. He attributed the discrepancy between predicted and experimental observation of the previous studies to exclusion of the air viscous effect. Morel-Seytoux (1882) later derived a differential equation for the water content at the surface and obtained analytical procedures with the implicit numerical solutions to predict water content at the soil surface.

Smith and Parlange (1978) developed an infiltration model from the Richards equation based upon two extreme assumptions. Under the first assumption, the hydraulic conductivity varies slowly near saturation and result in equation for ponding time and infiltration decay similar to Green and Ampt expression. The second assumption in which hydraulic conductivity varies rapidly results in a model for both rainfall and ponded surface conditions. Only two parameters i.e. saturated soil conductivity and a parameter which is roughly related to sorptivity are required to be determined for each model and they are physically related to the measurable soil properties from infiltrometer tests. The basic equation for which solution were developed under the two assumption was as follows :

$$\int_{0}^{t} R\,dt = \int_{\theta i}^{\theta} (\theta - \theta_i) \frac{D(\theta)}{R - K(\theta)}\, d\theta \qquad (6.24)$$

Where, R = Time varying rainfall intensity,m/sec;
θ = Volumetric moisture content at time, t, cc/cc;
θ = Initial soil moisture content , cc/cc;
$D(\theta)$ = Soil water diffusivity, m^2/sec;
$k(\theta)$ = Hydraulic conductivity of the soil, m/sec.

Freyberg et. al. (1980) applied Green and Ampt-model to study the infiltration rates under time dependent depths of water above the ground surface. They concluded that for better results, the effective suction head parameter in the Green-Ampt model must be considered a function of time, surface water depth, initial soil moisture content and soil type. The best choice of the value of the effective suction head depends upon the particular problem to which the model is being applied.

Sharda (1990) developed finite element solution of the Richards equation to simulate soil moisture changes during and after infiltration under un-steady rainfall conditions. The Richards equation for one-dimensional flow in the soil in an acquifer-soil-plant continuum may be written as :

$$\frac{\partial}{\partial z}[(K(h)\frac{\partial h}{\partial z} - K(h))\,] - S(z,t) = C(h)\frac{\partial h}{\partial t} \qquad (6.25)$$

Where, S(Z,t) is the rate of water intake (sink term) per unit volume of the soil (cm^3/cm^3/hr) and the other terms have been defined previously in equation (6.19). The sink term takes into account the losses of water from the soil profile through plant transpiration. This, in turn, upgrades the soil moisture balance in different soil layers depending upon rooting depth and density during different stages of plants growth. The finite element solution of equation (6.25) was developed to stimulate infiltration and soil moisture balance upon the following initial and boundary conditions:

$$h(Z,0) = h_0(Z), \qquad 0 \le Z \le L \qquad (6.26)$$

$$-K(h)\left(\frac{\partial h}{\partial z} - 1\right)\Big|_{z=0} = R, \text{ at } t = t_1 \qquad (6.27a)$$

$$-K(h)\left(\frac{\partial h}{\partial z} - 1\right)\Big|_{z=0} = R, \; t \le t_f \qquad (6.27b)$$

$$h(0,t) = h_1(t) \qquad t_f < t \le t_a \qquad (6.28)$$

$$k(h)\left(\frac{\partial h}{\partial z} - 1\right)\Big|_{z=0} = EL, \; t_a < t \le t_p \qquad (6.29)$$

$$h(0,t) = h_d \qquad t_p < t < t_{nr} \qquad (6.30)$$

$$-K(h)\left(\frac{\partial h}{\partial z} - 1\right)\Big|_{z=L} = 0, \; t \ge 0 \qquad (6.31)$$

Where, t_1 is the time equivalent to first time step, t_f the time upto which the flux rate is either negative or more than the rainfall rate and the surface soil pressure head is less than or equal to air entry suction of the soil, t_a denotes the time upto which water ponded on the surface, t_p is the time upto which exfiltration from the land surface continues during first stage of drying , t_{nr} denotes the time at which next rainfall event occurs, h is the pressure head corresponding to the air dried moisture content of the land surface, L is the depth of impervious basis layer below the ground surface and R is the rainfall rate.

Numerical solution of equation (6.25) was obtained by assuming infiltration rate equal to the rainfall rate at the first time step of simulation. This assumption was employed till the time t_f at which the pressure head of the surface reached the air entry value of the soil. After this time, the infiltration rate was equal to Darcy's flux at the surface till time t_d at which the ponding vanished. The soil moisture simulation during evaporation phase assumed flux type boundary condition during first stage of drying whereas in the second stage of drying it was assumed that matric potential of the soil surface does not change with time. Also the entire evaporative energy was assumed to be utilized either in transpiration or evaporation as the water supply is considered not to be limiting. An impervious layer exists at some finite depth below the ground surface.

The sink term denotes the root water uptake from different soil layers under the prevailing soil moisture conditions. Modified Penman's method (Penman, 1948) was used to compute potential evapotranspiration (PET) from which potential plant transportation was calculated using Richie's (1972) model. The actual plant transpiration under prevailing moisture conditions has been computed by the methods as suggested by Feddes et al. (1978), Belmans et.al. (1983), Van Genuchten an Hoffman (1984) and VanGenuchten (1987). The total plant water uptake has been distributed in different soil layers of root zone as suggested by Van Genuchten (1983). Borg's (1988) model was used to compute root depth during period of palnt evapotranspiration were assumed (Singh and Kumar, 1983). Under bare soil conditions, the sink term may be taken as zero.

Sharda (1990) reported that numerical solution simulated the infiltration and soil moisture balance under unsteady rainfall conditions reasonably well. Fig.8 shows the simulated and oserved runoff hydrographs for a storm event which occured on 26.7.87 in Doon Valley under flat surface configuration on 2% slope. As evident from the figure, reasonably well under unsteady rainfall conditions. To obtain better results and to avoid divergence of the solution, the time step in the initial ten to fifteen minutes period may be kept infinitesimaly small and the element sizes near the ground surface may be kept smaller.

Though a considerable progress has been made in studying the infiltration process under rainfall conditions, efforts are still needed to establish the applicability of existing theories in the field conditions. Complications arise due to the discreteness of raindrops, variable nature of rainstorm intensities and raindrop energies and unstable nature of most soils. The air occlusion also causes problems when the soil exhibits profile or areal heterogenity. More over, a simple application of one dimensional infiltration theory can not by itself provide a complete understanding of phenomenon on a field scale due to heterogeneity of both rainfall and soil in the field.

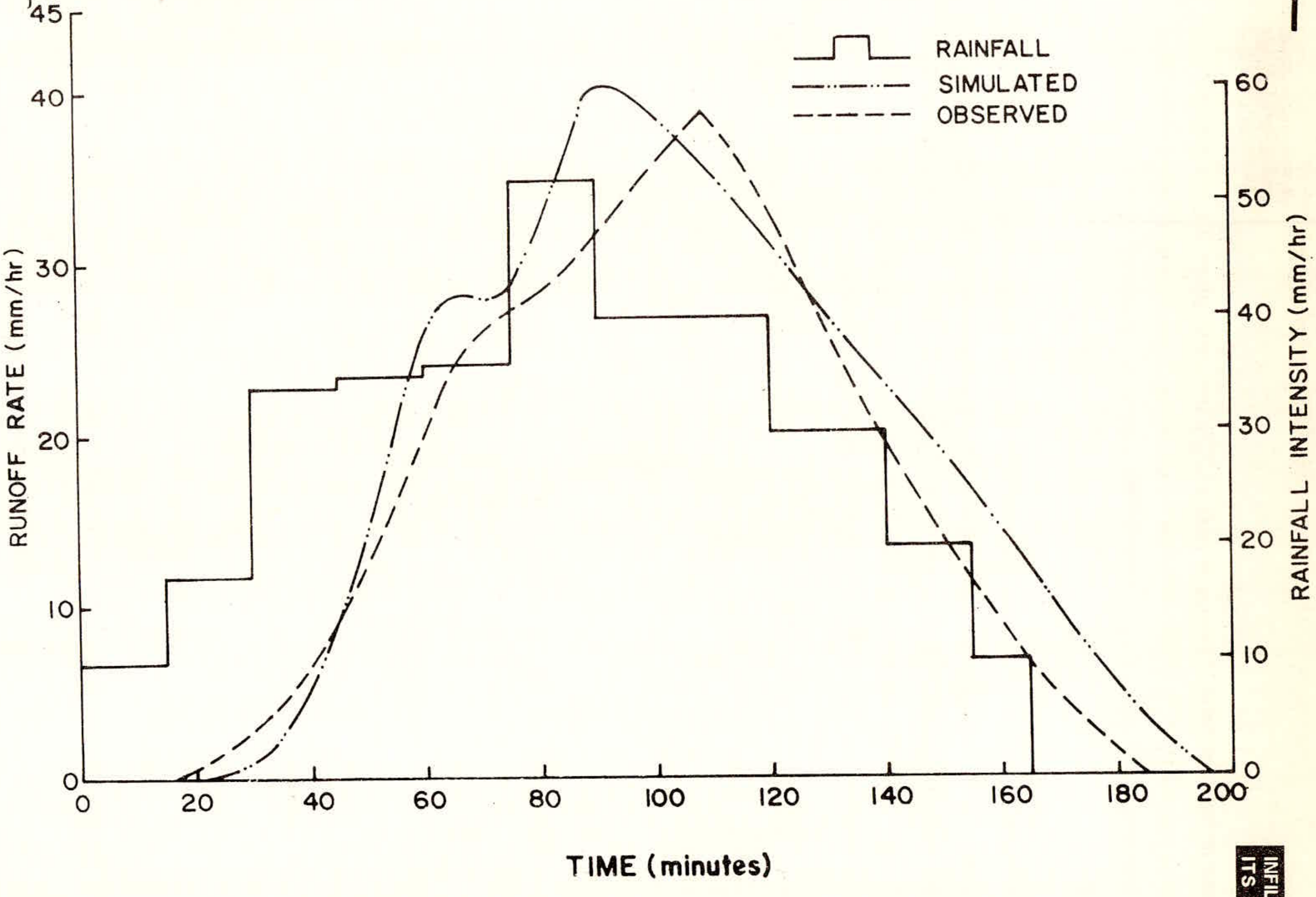

Fig 8 : Comparison of simulated and observed runoff hydrographs for the strom event on 26-7-87 (Flat surface configuration)

Another important topic of current research is the infiltration into swelling soils. Philip (1969) postulated that the total potential in a swelling soil includes a third component namely the overburden potential in addition to the two components of hydraulic potential in a rigid soil.

Smiles (1974, 1976) experimentally verified that during infiltration into a swelling soil the relative importance of gravity is reduced and the absorption phase is prolonged in comparison with infiltration into a rigid soil. Hysteresis is not nearly so significant in swelling soils as it is in coarse granular soil. Miller (1975) pointed out that a challenging problem in swelling soils is how to account for the role of cracks.

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