ESTIMATION OF GROUNDWATER RECHARGE FROM RAINFALL

1.0 INTRODUCTION

The major sources of recharge to aquifers in many areas are direct precipitation and stream runoff. Recharge from rainfall in an area is unevenly distributed in time and space and only a fraction of the annual precipitation percolates down to the water table depending upon the topography, vegetal cover soil moisture content, depth to water table, intensity and duration of rainfall, and other meteorological factors.

Assuming that the amount of water that escapes evaporation and transpiration moves down as deep percolation and eventually joins the ground water, the rate of ground water accretion can be calculated as the difference between infiltration and evapotranspiration over a long period.

Another technique for field evaluation of deep percolation is the water balance approach where deep percolation is indirectly evaluated as the difference between rainfall and runoff plus evapotranspiration. Runoff is found from stream flow measurements.

In addition to estimating the infiltration and evapotranspiration components, deep percolation can be directly measured in the field by lysimeters or tensiometers.

Morel-Seytoux (1985) has determined the recharge to an aquifer from a single rainfall event using the Green and Ampt infiltration equation. The time at which the wetting front reaches the water table, and subsequent recharge rate have been determined by him. Recharge due to several rainfall events can be estimated using the technique developed by Morel-Seytoux .

Recharge to an aquifer generally takes place through an unsaturated transition zone. The infiltration rate up to time of ponding is equal to the intensity of rainfall. The rate of infiltration decays with time after ponding and excess water contributes to depression storage and overland flow . During infiltration after ponding the soil is saturated upto some depth from ground surface and below the zone of complete saturation lies a zone of nearly saturated wetness known as transmission zone as shown in Fig.1.Beyond this zone is the wetting zone in which soil wetness decreases with depth at steepening gradient down to a wetting front where there appears to be a sharp boundary between the moistened soil above and dry soil beneath.The wetting zone moves downward continuously. No recharge takes place until the wetting front reaches the water table.

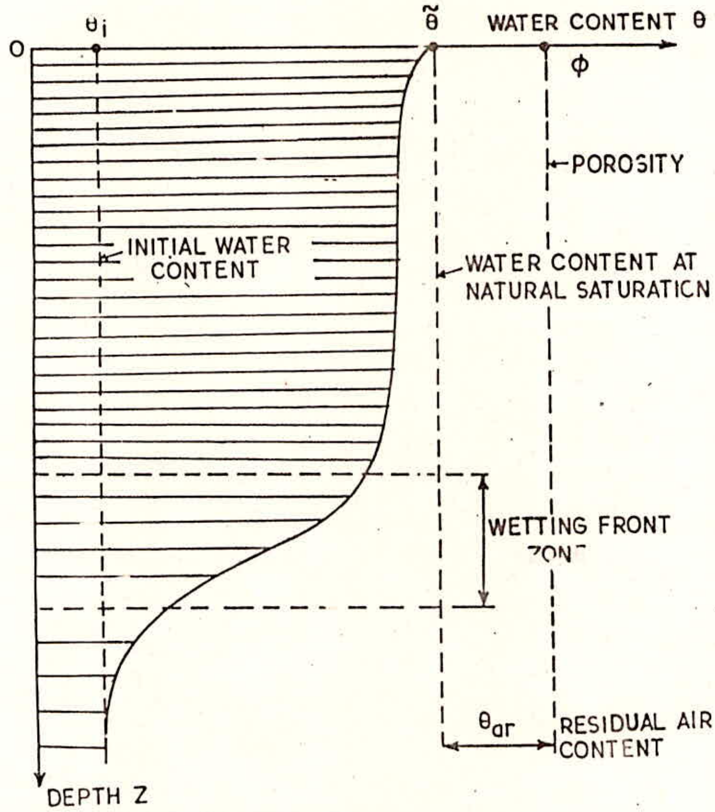
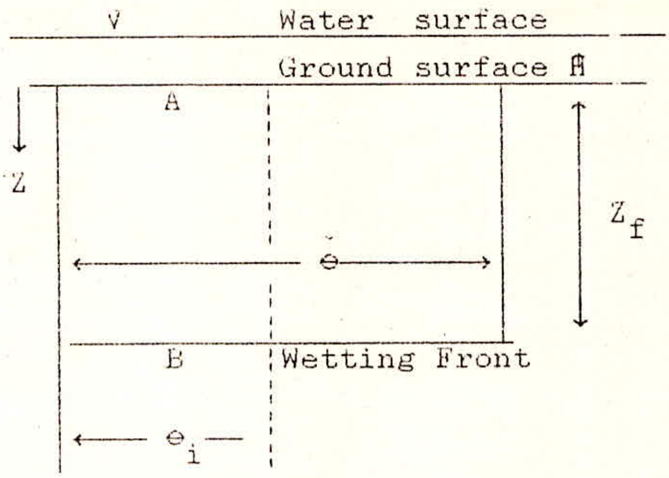


Fig.1: Variation of water content with distance from water source

Unsaturated flow in the vadose zone has been analysed on the basis of Darcy's law with added complication that the hydraulic conductivity, k , is dependent on water content, θ ,which also controls the pressure head. The hydraulic conductivity and soil moisture relationship and the capillary pressure and moisture content relationship are needed for the analysis .

2.0 THE GREEN AND AMPT INFILTRATION EQUATION

The derivation of Green and Ampt infiltration equation is based on the assumption that ponding occurs immediately after the rainfall.The soil behind the wetting front is completely saturated,and ahead of the front it has the initial moisture content that prevailed before the onset of rainfall.The depth of water on the surface during infiltration is constant.



$\tilde{\theta}$ =moisture content at natural saturation,

θ_i =initial soil moisture content at the time of rainfall,

H =depth of water on the soil surface during infiltration.

Fig.2-Soil moisture Profile Assumed for Derivation of Green and Ampt Infiltration Equation

The hydraulic head at point A $= p_a/\gamma_w + p_w/\gamma_w$ The hydraulic head at point B $= p_a/\gamma_w - p_c/\gamma_w - Z_f$. Let Z_f be the depth to saturation front at time t after the onset of rainfall. The hydraulic gradient at time t is thus given by $i = -(H_f + Z_f + H)/Z_f$,in which H_f = representative capillary pressure head, p_c/γ_w. The infiltration rate at time t, when the saturation front is at a depth Z_f, is given by:

$$I = \tilde{k}\ (H + H_f + Z_f)\ /\ Z_f \qquad \ldots(1)$$

The representative capillary pressure head H_f that appears in Green and Ampt infiltration equation is conveniently found from the available soil moisture and capillary pressure relationship in the following manner as suggested by Bouwer:

$$H_f = \int_0^{h_{ci}} k_{rw}(\theta)\ dh_c \qquad \ldots(2)$$

where $k_{rw}(\theta) = k(\theta)\ /\ \tilde{k}$, h_c= capillary pressure head, h_{ci} = capillary pressure head corresponding to the initial soil moisture θ_i ,prevailing at the onset of infiltration, and $\tilde{k}$ = hydraulic conductivity at natural saturation moisture content, $\tilde{\theta}$.

2.1 Infiltration Prior To Ponding:

Up to time of ponding, infiltration rate is equal to the intensity of rainfall. At the time of ponding the relationship between cumulative rainfall and rainfall rate is given by (Morel-Seytoux ,1982)

$$w_p = (\tilde{\theta} - \theta_i) H_f \,/\, (R^* - 1) \qquad \ldots(3)$$

and the expression for ponding time , t_p , for constant rainfall rate has been derived as:

$$t_p = \frac{(\tilde{\theta} - \theta_i) H_f}{R(R^* - 1)} \qquad \ldots(4)$$

where $R^* = R / \tilde{k}$. For variable rainfall pattern, the expression for ponding time is (Morel-Seytoux, 1982):

$$t_p = t_{J-1} + \frac{1}{R(J)} \left[\frac{(\tilde{\theta} - \theta_i) H_f}{R^*(J) - 1} - \sum_{\gamma=1}^{J-1} R(\gamma)\,(t_\gamma - t_{\gamma-1}) \right] \qquad \ldots(5)$$

where $R(J)$ is the rainfall at J^{th} time and $R^*(J) = R(J) / \tilde{k}$. The position of the wetting front, Z_f, at ponding time is

$$Z_f = w_p \,/\, (\tilde{\theta} - \theta_i) \qquad \ldots(6)$$

2.2 Soil Moisture Movement During Rainfall After Ponding:

The cumulative infiltration , w , after ponding at any time t is given by (Morel-Seytoux ,1982):

$$w - w_p = \tilde{k}(t - t_p) + (\tilde{\theta} - \theta_i)(H + H_f) \log_e \left[\frac{(H + H_f)(\tilde{\theta} - \theta_i) + w}{(H + H_f)(\tilde{\theta} - \theta_i) + w_p} \right] \qquad \ldots(7)$$

If at any time the rainfall is less than the infiltration capacity, the infiltration rate is equal to the rainfall intensity in case the depth of water on the surface is equal to zero. The position of wetting front Z_f at time t is given by the relation

$$Z_f = w \,/\, (\tilde{\theta} - \theta_i) \qquad \ldots(8)$$

2.3 Soil Moisture Movement After Cessation Of Rainfall:

For the analysis of soil moisture movement during the post rainfall period the time parameter has been counted from the instant the rain stops. The actual profile at $t = 0$, has been replaced by a simpler rectangular profile with a uniform value of water content equal to the limiting value θ_1. The value θ_1 is the water content necessary to transmit flux after capillary forces have become negligible as compared to those of gravity. At the end of rainfall the position of the wetting front has been given as:

$$Z_f^0 = \frac{w}{\theta_1 - \theta_i} = \frac{w}{(\tilde{\theta} - \theta_r)(\theta_1^* - \theta_i^*)} \qquad \text{... (9)}$$

where w = total infiltration at the end of rain, θ_r is the field capacity, and θ^* = is normalised water content defined as:

$$\theta^* = (\theta - \theta_r) / (\tilde{\theta} - \theta_r) \qquad \text{...(10)}$$

If saturation of soil surface has occurred at or before the end of rain, $\theta_1 = \tilde{\theta}$ or $\theta_1^* = 1$, and

$$Z_f^0 = w / \{(\tilde{\theta} - \theta_r)(1-\theta_i^*)\} \qquad \text{...(11)}$$

If Z_f is depth to the wetting front and θ the water content of the soil behind the front at any later time, then

$$Z_f = \frac{w}{\theta-\theta_i} = \frac{w}{(\tilde{\theta}-\theta_r)\left[\frac{\theta-\theta_r}{\tilde{\theta}-\theta_r} - \frac{\theta_i-\theta_r}{\tilde{\theta}-\theta_r}\right]} = \frac{w}{(\tilde{\theta}-\theta_r)(\theta^*-\theta_i^*)} \qquad \text{...(12)}$$

When the wetting front reaches water table, $Z_f = D$, where D is the depth to water table. Hence,

$$D = \frac{w}{(\tilde{\theta}-\theta_r)(\theta^*-\theta_i^*)} \qquad \text{...(13)}$$

Eq.(13) gives θ^* at the time wetting front reaches the watertable.

2.4 Recharge After Wetting Front Reaches Water Table:

Darcy's law for flow in unsaturated soil if capillary effects are neglected reduces to the form

$$q = \tilde{k}\, k_{rw}(\theta) \qquad \text{...(14)}$$

Expressing $k_{rw}(\theta)$ equal to $(\theta^*)^n$, eq.(14) becomes

$$q = \tilde{k}\, (\theta^*)^n \qquad \text{...(15)}$$

Eq.(15) gives the recharge rate when the wetting front reaches the water table.

Once the wetting front reaches the water table the recharge starts. The recharge rate is given by (Morel-Seytoux et al. 1984):

$$R = \frac{q}{\left[1+ \frac{(n-1)kt}{D(\theta-\theta_i)} \left(\frac{q}{k}\right)^{\frac{n-1}{n}}\right]^{\frac{n}{n-1}}} \qquad \ldots(16)$$

where D is the water table position, q is recharge rate when recharge starts, and the time, t, is measured from the beginning of recharge.

2.5 Time Taken By Wetting Front To Reach Water Table After Cessation Of Rainfall :

If q is the drainage rate from the soil column between ground surface and the wetting front, then according to Morel-Seytoux et.al (1984)

$$\frac{d\theta}{dt} = -q / Z_f$$

$$\text{or} \quad \frac{d\theta^*}{dt} = -q / \{Z_f (\tilde{\theta} - \theta_r)\} \qquad \ldots(17)$$

Eliminating Z_f from eq.(17) with the help of eq.(12) Morel-Seytoux et al have derived the following relation:

$$\frac{d\theta^*}{dt} = - \frac{q}{w} (\theta^* - \theta_i^*) \qquad \ldots(18)$$

or

$$\frac{d\theta^*}{dt} = - \frac{\tilde{k}}{w} (\theta^*)^n (\theta^* - \theta_i^*) \qquad \ldots(19)$$

For the first rainfall, $\theta_i = \theta_r$ and $\theta_i^* = 0$; hence, eq.(19) reduces to

$$\frac{d\theta^*}{dt} = - \frac{\tilde{k}}{w} (\theta^*)^{n+1} \qquad \ldots(20)$$

Integrating eqs.(19) and (20) from time t=0 when rain stops to time when wetting front reaches the water table, and taking $\theta^* = \theta_i^* = 1$ at time t=0, yields for n=4:

$$t = \frac{w}{\tilde{k}} \left[\frac{1}{(\theta_i^*)^4} \log_e \frac{\theta^*(1-\theta_i^*)}{\theta^* - \theta_i^*} + \frac{1}{(\theta_i^*)^3} \left(1 - \frac{1}{\theta^*}\right) + \frac{1}{2(\theta_i^*)^2} \left(1 - \frac{1}{(\theta^*)^2}\right) + \frac{1}{3\theta_i^*} \left(1 - \frac{1}{(\theta^*)^3}\right)\right] \text{, and} \qquad \ldots(21)$$

$$t = \frac{w}{4\tilde{k}} \left[\left(\frac{1}{\theta^*}\right)^4 - 1\right] \qquad \ldots(22)$$

respectively.From eqs.(22) and (21) the time a wetting front takes to reach the water table after cessation of each rainfall can be calculated for the first and for subsequent rainfall events after knowing θ^* from eq.(13).For sandy soil,n is equal to 4 .

Using eqs.(15), and (16) recharge to the water table can be calculated for each rainfall.

3 0 EXAMPLE OF CALCULATION:

The soil moisture characteristics required for estimation of infiltration rate have been taken from the experimental results of Sonu (1973).The variation of capillary pressure (h_c),with the volumetric soil moisture content,(θ),and relation of capillary pressure with relative permeability,$k_{rw}(\theta)$,for a silty loam soil are shown in Figs. 1(a) and 1(b) respectively.

i. The initial soil moisture content θ_r and saturation moisture content $\tilde{\theta}$ are taken to be 0.2425 and 0.485 respectively.

ii. k for the silt loam has been taken as 0.02088 m/hour.

iii. The value of H_f for θ_i = 0 2425 is found to be 0.7711 m.

iv. The rainfall data and depth to water table have been assumed.

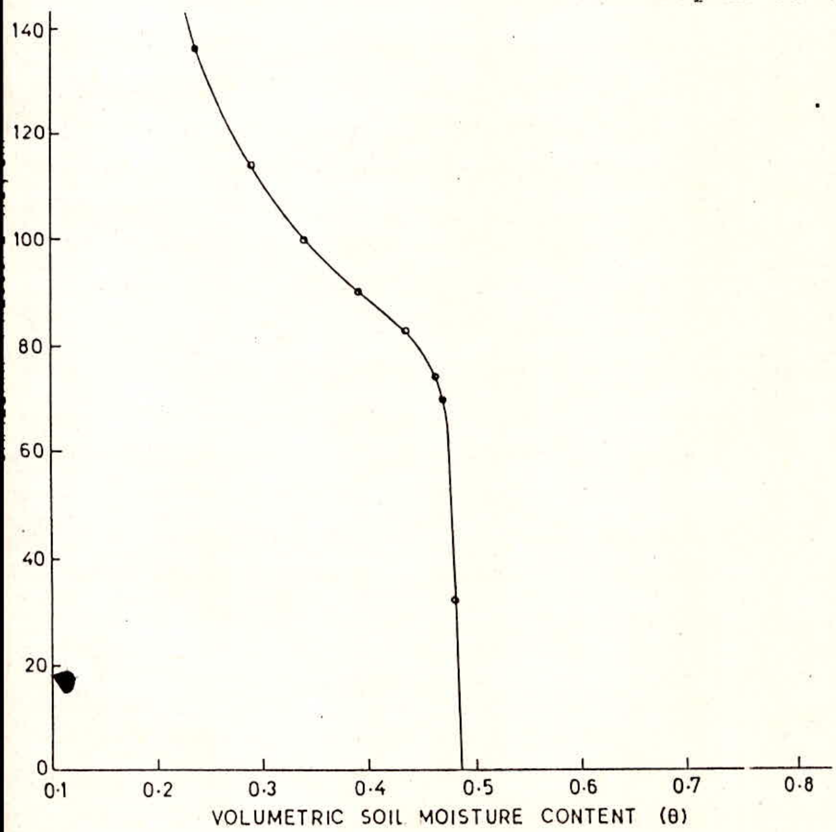


Fig.3(a)-Variation of h_c with θ for a silty loam soil.

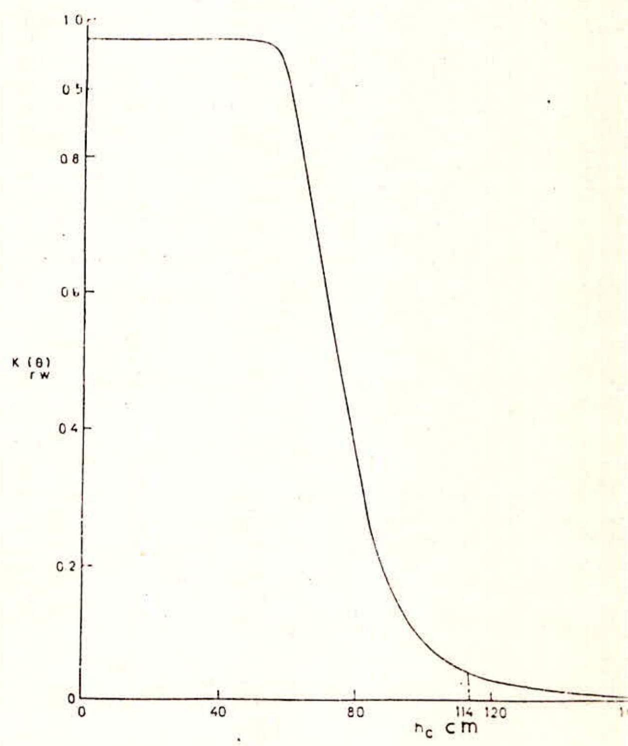


Fig.3(b)-Variation of $K_{rw}(\theta)$ with h_c for the silty loam soil.

Results have been obtained for three cases of different types of storms. The storms taken are arbitrary. In the first case, four different storms of variable rainfall rate have been taken.

In the second case, a single storm of variable rainfall rate has been repeated four times.

In the third case, a storm of constant rainfall rate has been repeated four times.

The quantity infiltrated, the percentage of rainfall recharged, and percentage of infiltrated quantity recharged for different successive rains have been presented in Table 1. From the table it is seen that for higher initial soil moisture content θ_i, the quantity of infiltration is less. But the percentage of infiltrated quantity that joins the water table is higher for higher value of θ_i. At some times the recharge is more than 100% of the current rainfall, meaning that part of infiltration due to previous rainfall is being recharged. The time taken by wetting front to reach the water table, which has been assumed to exist at a depth of 5 m, varies from about 10 hours to 24 days depending upon the rainfall intensity and initial soil moisture content. Thus the time lag between rainfall and water table rise would vary considerably depending on the initial soil moisture content.

Continuous variation of recharge with time during storm and inter storm periods is shown in Fig.3.

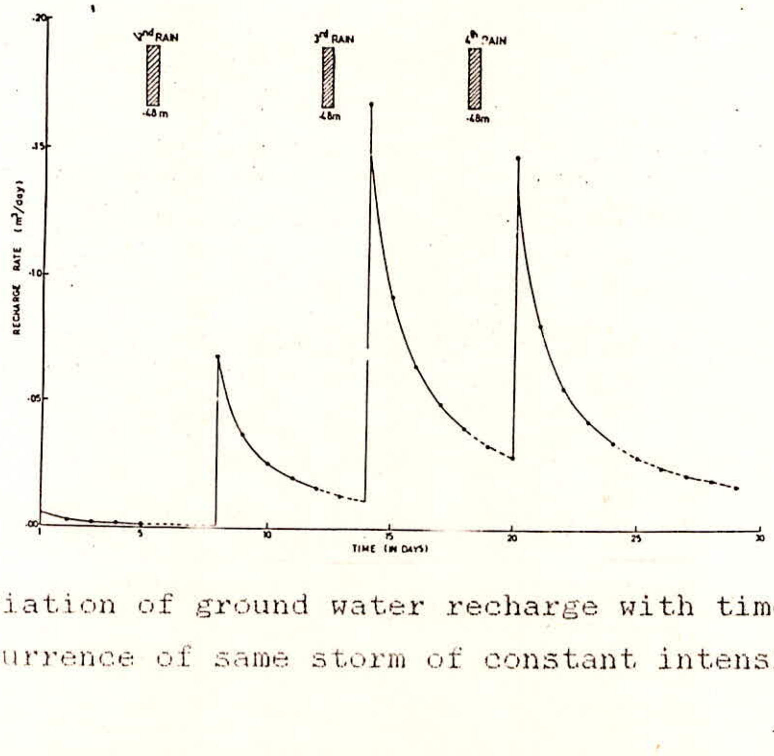


Fig.3 Variation of ground water recharge with time subsequent to occurrence of same storm of constant intensity.

Table 1- Percentage of total rainfall and cumulative infiltration that goes as recharge and time to reach water table

Case	Storm No.	Initial soil Moisture Content (θ_i)	Total Rain (m)	Quantity Infiltrated (m)	% of rainfall recharged	% of infiltration recharged	Time to reach water table (hrs.)
I	1	.2425	.42	.3528	1.36	1.62	585.31
	2	.3119	.43	.3326	18.14	23.45	64.27
	3	.3628	175	.1696	73.83	76.18	33.04
	4	.3015	.175	.1750	101.7	101.7	190.87
II	1	.2425	.42	.3528	1.36	1.62	585.31
	2	.3119	.42	.3253	17.79	22.96	66.44
	3	.3620	.42	.3030	57.21	79.31	20.54
	4	.3746	.42	.3015	74.52	103.61	14.79
III	1	.2425	.48	.4350	2.73	3.01	309.09
	2	.3269	.48	.4012	34.96	41.82	32.34
	3	.3736	.48	.3750	85.85	109.83	10.14
	4	.3661	.48	.3797	75.46	95.39	12.55

Case I - Different storms of varying rainfall rate
Case II - Same storm of varying rainfall rate repeated
Case III - Same storm of constant rainfall rate repeated

Table.2- Total recharge at the end of each day

Case	Storm No.	Recharge at the end of				
		1st day	2nd day	3rd day	4th day	5th day
I	1	.0023	.0013	.0009	.0007	.0006
	2	.0317	.0174	.0121	.0093	.0075
	3	.0525	.0289	.0200	.0153	.0124
	4	.0073	.0040	.0028	.0021	.0017
II	1	.0023	.0013	.0009	.0007	.0006
	2	.0304	.0167	.0116	.0089	.0072
	3	.0977	.0537	.0372	.0285	.0231
	4	.1273	.0699	.0485	.0372	.0302
III	1	.0053	.0029	.0020	.0016	.0013
	2	.0682	.0375	0260	.0199	.0162
	3	.1676	.0920	.0639	.0490	.0397
	4	.1473	.0809	.0561	.0430	.0349

4. CONCLUSION

It is possible to estimate groundwater recharge by Green and Ampt equation .

From the study it is found that the infiltration that occurs during the earlier rainfalls satisfies the soil moisture deficiencies and the rainfall contributions to groundwater recharge is less than 18% of the precipitation. The later rainfalls contribute more to the groundwater recharge, which is of the order of 57% of the precipitation. However these results are point recharge values predicted for a silty loam soil.

REFERENCE

1. Morel-Seytoux,H.J.,(1985)."Conjunctive Use of Surface and Ground Waters" ,Artificial Recharge of Ground Water, Edited by Asano Takashi, Butterworth Publisher.
2. Morel-Seytoux,H.J., Correia, F.N.,Hyre, J.H. and Lindell, L.A., (1984). "Some Recent Developments in Physically Based Rainfall-Runoff Modeling",Frontiers in Hydrology, Water Resources Publication, Edited by W.H.C. Maxwell and L.R. Beard.
3. Morel-Seytoux,H.J.,(1982).Physical Hydrology:Ensemble of Lecture Notes and Class Handouts Developed since 1977,HYDROPOWER Programme,Colorado State University,Fort Collins.
4. Sonu,D.(1973)."Water and Air Movement in Bounded Layered Soils", Ph.D. Thesis,Colorado State University,Fort Collins,USA.
5. Viswanathan,M.N.(1983). "The Rainfall - Water Table Level Relationship of an Unconfined Aquifer", Ground Water, Vol.21, No.1, January-February.