Distr.
LIMITED
E/ESCWA/ENR/2002/WG.1/6
20 March 2002
ORIGINAL: ENGLISH

United Nations Economic and Social Commission for Western Asia

BGR Federal Institute for Geosciences and Natural Resources

Regional Training Workshop on the Application of Groundwater Rehabilitation Techniques to Different Hydrogeological Environments in the ESCWA Region
Beirut, 18-22 March 2002

INFILTRATION - RECHARGE MECHANISM

Note: This document has been reproduced in the form in which it was received, without formal editing.

02-0179

INFILTRATION - RECHARGE MECHANISM

Outline

Page

INFILTRATION - RECHARGE MECHANISM

I- INTRUDUCTION

Water from rainfall occurrence and all kinds of liquid can infiltrate across the ground surface into the underlying soil profile. If the supply continues at the surface, water may percolate through the soil profile until it reach the groundwater table aquifer. These processes are known as infiltration, percolatation, and recharge phenomena. A schematic diagrams simplified these processes are shown in figure (1).

II INFILTRATION PROCESS

Infiltration process: defined in a simple term represents the movement of cleaned or contaminated water or liquid across the ground surface into the underlying soil profile. The process is governed by the physical and chemical characteristic of the soil profile and infiltrated liquids.

Groundwater recharge: defined as percolation of water to the water table. It is coupling of the flow OF the soil profile and the underplaying groundwater flow. It involves complicated initial and boundary condition. Given the complexity of movement of water and pollutants, this lecture was prepared to provide an introduction and simplification of the physics of flow that include water and contaminates.

The physic of flow across the ground surface involves the movement of water or liquid into the void available between the soil particles or in other situation into the fractured rock. Thus during the infiltration process, the movement of water into the soil matrix pores displaces the air if the soil is dry or semi dry. The displaced air escapes across the land surface and sometimes is entrapped in the profile. As the water moves down the soil profile, it becomes saturated with a distinct front separating a saturated and unsaturated soil. This front is known for people of soil physics as the wetting front.

The transmitting zone, shown in figure 1, between the surface and the underlying aquifer is the unsaturated soil profile. If water application (flood or diverted waste) continues, the infiltrating wetting front propagates towards the water table, otherwise infiltration will cease, and previously infiltrated water may be redistributed in the unsaturated zone and move downward under the influence of gravity or upward by evaporation or by both until the soil moisture is depleted .

Once the wetting front reaches the water table, recharge begins. The merger of the infiltrated front with the water table causes the flow to change to a lateral direction. Once a hydraulic connection is established by the advancing wetting front and the water table, groundwater mound starts to build up under the active infiltration zones. The temporary hydraulic connection established between the source areas, wadi channel and spreading basin and the aquifer depends on flow duration, maximum stage, and depth to the water table. The flow mechanism as supplies moves from the ground surface to shallow aquifer is shown in figure 1.

III INFILTRATION ESTIMATION

The subject of infiltration has been researched since 1939 through empirical, analytical, and numerical solutions. The empirical infiltration equations suffer from serious limitations in predicting the movement of water in the soil profile as they were developed for specific conditions. There are many physically based infiltration equations but the most applied are the one developed by Philips and Green and the Amp. The Richard equation as well as others describe the dynamic of flow in an elaborate and realistic manner and have been solved through numerical solutions. During the last two decades, also many water and solute transport equations were developed and solved numerically.

As this lecture is intended to provide a basic understanding, the Green and Ampt infiltration equation is presented below for this purpose. It is based on Darcy law

$$Q=KA\,(h_2-h_1)/L \qquad (1)$$

Where

Q: the discharge rate as volume per time

A: the cross section where the flow take place

h_2-h_1: the hydraulic head difference that is forcing the flow

L: the length of the profile.

The Green and Ampt equation is represented by

$$I = dW / dt = K\,[\,S_t + W / W\,] \qquad (2)$$

Where:

I: infiltration rate, and can be in cm day^{-1}

W: cumulative infiltration depth of water, cm

t: time,

K: hydraulic conductivity of the wetted zone, cm /day

S_t: storage-suction factor, cm

The storage-suction factor can be estimated by the following equation:

$$St = (\theta_f - \theta_i)\,(H_t + H) \qquad (3)$$

Where:

θ_f : final water content behind the wetting front, fraction,

θ_i : initial water content for the soil profile, fraction

H_t: effective capillary drive or suction at the wetting front, cm, estimated from experienced analysis of soil sample and empirical equations

H: water depth at the surface, cm

The water content θ is defined as the volume of water in the soil per unit of bulk volume of soil. It represents the void between the soil particles that can be filled by the water or liquids as show in figure 2.

In water studies there is interest to estimate the volume of infiltrated water and then to relate it to the amount of recharge that reaches the groundwater table. To estimate the infiltrated volume W, Equation (2) can be integrated between the limits (t_{i-1}, W_{i-1}) and (t_i,W_i). After some simplification, the expression takes the form of:

$$K\,[t_j-t_{j-1}] = W_j - W_{j-1} - S_t \ln\,[\,S_{fj} + W_j / S_{fj} + W_{j-1}] \qquad (4)$$

Where:

t_j: time at the end of the jth period

t_{j-1}: time at the end of the j-1 period

W_j: cumulative infiltration depth up to time tj
W_{j-1}: cumulative infiltration depth up to time tj-1
The distance W_f, the wetting front advances to below the land surface can be estimated using the equation:

$$W_{fj} = W_j / \theta_f - \theta_i \qquad (5)$$

Where:

The average infiltration rate for the jth day can be evaluated from the following expressions:

$$I_j\ average = W_j - W_{j-1} / t_j - t_{j-1} \qquad (6)$$

The procedure is started by first estimating the parameters θ_f, θ_i, H_f and K. The initial water content θ_i was estimated by taking soil samples at the study site. The parameter θ_f represents the maximum water content (as a fraction) behind the wetting front after infiltration starts. It can be approximated by the average porosity of the soil below the reservoir.

- The K parameter is the hydraulic conductivity of the wetted zone. The value that should be used is the average hydraulic conductivity of the wetted zone.
- The effective capillary drive H_f is a measure or empirically estimated is expressed as equivalent depth of water. Almost all reported values in the literature for this parameter range between 5 and 40 cm. It can be neglected at later times in the infiltration process and its values becomes insignificant even at early times if the ponded head is large.

The parameters of equations 1 to 3 can be estimated from soil sample collected as well as other field measurement. The water content O, Hydraulic conductivity K, capillary head H can be determined in the laboratory analysis of soil samples collected from the field. The most difficult parameter to determine is the capillary head H. Variation of these parameters according to the soil types and their influence on the infiltration rate is shown in figures 3 and 4 .

IV-FACTORS AFFECTING THE INFILTRATION PROCESS

i- Physical characteristics:

The amount of water and waste infiltrated from ground surface, wadi channels or the dump sites depends on the physical characteristics of the surface, soil profile underneath bed material and hydraulic properties of the aquifer. Most important parameters are

a- Soil moisture (water content)
b- Hydraulic conductivity K,
c- Porosity,
d- Capillary head H
e- Chemical (soil)
f- Type of soil and geology at the surface and the profile
g- Depth to the water table

The physical and chemical properties of soil specially porosity, and hydraulic conductivity of the soil profile influence the infiltration rate across the surface and as well as during the percolation process .

- Dry soil, in addition to high hydraulic conductivity values may result in high abstraction volumes as shown in figure 4. High initial moisture content allows slow infiltration and faster movement at the surface, resulting in less contribution to groundwater recharge.

- clay, silt and biodegradable material. Gravel and sand allow high infiltration rates (high transmission losses) and lower field capacity. In wadi environments, the bed material along the entire length of the channel usually consists of a mixture of unsorted gravel, sand, silt, and clay. Coarse material is usually present in the upstream part of the basin due to the erosive power of flood flow.

- The position of the water table will influence the rate and magnitude of infiltration (abstraction). A water table close to the land surface will inhibit transmission loss due to poor storage availability and resistance to flow as a result of the groundwater mound build up. Theoretically, the infiltration rate decreases as the mound builds up to the soil surface.

- For a deep water table, the infiltration rate is initially high and may reach a steady state value equal to the hydraulic conductivity as shown in figure 4. A high value of hydraulic conductivity will result in the advancement of he wetting front to greater depths.

- In regard to the characteristics of groundwater formation, important parameters are; storativity, transmissivity and thickness as the represent the mechanisms controlling the dispersal of infiltrated water or waste both laterally and longitudinally. Aquifers with high values of specific yield and vertical and horizontal hydraulic conductivity can store significant amounts of water as well as dispose of water and contaminants in different directions. Aquifer parameters influence the growth of groundwater mound underneath the recharge channel.

Thus, many surface and subsurface factors, including the unsaturated and saturated soil profiles, have influence on infiltration, percolation, and recharge processes.

ii- Chemical Characteristics

The chemical characteristics of soil and contaminants also influences the flow process:

a- Absorption
b- Dispersion
c- Retardation

The availability of adequate soil profile depth provides a medium for accumulation or renovation of pollutants. The movement of water and liquid through the soil can result in physical, chemical and biological degradation and treatments.

- For sandy soil, the removal of suspended solids and some organic particulates and bacteria may be involved. Clay mixtures in the soil may form chemical reactions with dissolved ions and soil matrix.

- During the movement of wastes, chemical reactions may take place among dissolved ions, and interactions with the soil matrix.

  - Adsorption and precipitation can lead to retention of matter in the soil profile, especially in the presence of clay and humus particulates. Cation exchange is more predominant than ion exchange. These processes involve the status of dissolved ions and compounds especially for the sewage effluent, as well as electrical charges on the colloidal particles
  - The degree of adsorption depends on what is known as the cation exchange capacity, which represents a measure if the ability of the soil to retain cations. The greater the cation exchange capacity (CEC) of the soil, the greater is the removal of pollutants such as ammonia, calcium, magnesium, potassium, and sodium. Soil with high infiltration rates such as gravel, usually have poor removal rate.
  - The sodium Adsorption ratio (SAR) of the soil also indicates the degree of chemical reaction may take place. Fined textured soils, in general, have a greater capacity to retain phosphates in comparison to coarse soil. The form of phosphorous is determined by the pH and influences its degree of retention. In acidic soil, phosphate reacts with iron and aluminum oxides to from insoluble compounds. Field experimentation indicated that phosphate is removed as treated wastewater moves vertically through the soil profile and horizontally through aquifers.

- Another major area of concern in waste renovation involves the ability of the soil to remove contaminants by way of microorganism biological process. Organisms may include bacteria, worms, protozoa, insects and fungi, which may be active in the upper meter of the soil profile.

- For example in wastewater, organisms in this zone can alter waste content through matter decomposition, inorganic transformation, and nutrient assimilation. The availability of oxygen has a predominant effect on the decomposition process, resulting in either aerobic or anaerobic conditions. This process influences the level of nitrogen content in the soil profile and groundwater.

- The form and date of many elements in the soil profile is influenced by the oxygen status. Under aerobic conditions (presence of oxygen) up to 60 % or organic carbon is lost as carbon dioxide, and a small portion is incorporated into microbial cells. Other organic matter such as phosphorous, sulpher, and some trace elements can be converted into organic forms.

- Bacteria and viruses in the soil profile and underlying aquifer is determined by their survival characteristics and retention by the soil particles. Both survival and retention are influenced by the nature of the soil, prevailing climate, and the nature of the microorganism. At high temperatures, inactivation or die off is faster in comparison to low temperatures. High moisture prolongs the survival rates of bacteria and viruses. Particle size, cation exchange capacity, and clay content control the retention of bacteria and viruses in the soil (Gerba and Goyal 1985). Increased removal of bacteria from the soil profile in sandy soil conditions was reported to be inversely proportional to the decrease in soil particle size. The retention of viruses by the soil generally increases with lower pH levels. In addition, high concentrations of ionic

salts and cations enhance virus adsorption. In arid environments, sewage effluent usually has a high salt content.

- Soil profile and aquifer rock materials affect removal of bacteria and viruses. Fined textured soil is more effective in filtering out microorganisms in comparison to coarse soil. The level of bacterial contamination is estimated by counting the number of fecal coliforms. Bacteria are usually strained out of the water.

Adsorption of small viruses and bacteria is achieved at low pH, in the presence of high concentrations of salt, calcium and magnesium. Generally, absorption increases with clay content and surface area of the soil. Most bacteria and viruses die in a few weeks or months; however, longer survival periods have been occasionally reported. Fecal coliforms (bacteria) are usually removed when treated wastewater percolates a few meters through the soil profile. However, in coarse sand or gravel, a longer distance may be required. In addition, sufficient travel distance and detention time is required, especially in course of textured soil. The bacterial and viral removal efficiency of different media is shown in Table (1).

Table (1) Bacteria and Virus Removal Efficiency of Different Medium (after Gerba and Goyal 1985)

Type of Biological Pollutant	**Treatment Level**	**Organism**	**Media**	**Maximum distance traveled (m)**	**% Detected or removed**
Bacteria	Tertiary	Coliforms (b)	Fine to Medium sand	6.1	
	Secondary	Fecal Coliforms	Fine loamy sand to gravel	9.1	
	Primary	Fecal streptococci	Silty sand and gravel	183	
	Septic Tank Seepage	Bacillus coli	Sandy and sandy clay	10.7	
	Undisinfected	Coliforms	Sandy loam (Lodi, CA)	1.2-3.9	1 case Detected
	Primary oxidation	Fecal streptococci	Coarse gravel and sand (Santee, CA)	61-450 (L)	6.8-48 detected
	Secondary	Total colifroms	Sand and gravel (Flushing Meadows, AZ)	6	5 cases detected
	Secondary	Fecal coliiforms	Sand & gravel (Flushing Meadows, AZ)	60(L)	No detection
	Primary	Total coliforms	Gravelly sand over clay & silt	7-48	-
	Primary	Fecal coliforms	Gravelly sand over clay & silt	7-48	-
	Primary	Fecal coliforms	Sand (Vinelaw, NJ)	79	0-300
	Primary	Total coliforms	Sand & gravel (Ft. Deven, MA)	18.3	3500
	Primary	Fecal coliforms	Sand & gravel (Ft. Deven, MA)	60-100 (L)	<20
Viruses	Secondary	Poliovirus-2	Sandy gravel	60	100 %
	Secondary	F7	Sandy forest	0.02	99 %
	Secondary	Indigenous enteric	Loamy sand	3-9	100 %

(L) = lateral distance moved in the aquifer

V. GROUND WATER RECHARGE

A method for estimation of recharge under such conditions can be analyses by the analytical equations of by Abdulrazzak and Morel-Seytoux (1983) and others where the recharge rate per unit width of the channel q(t) shown in figure I can be estimated using the following analytical equation:

$$q(t) = IB \exp (IB)^2 kt / [T (D + H)2] \operatorname{erfc} IB (kt)^{½} / T (H + D) \qquad (7)$$

Where:

K: is the aquifer diffusivity T / Φ
T: is the transmissivity
Φ: is the effective porosity
B: is the half width of the channel
H: is the ponding depth
D: is the depth to the water table
erfc: is the error function complement.

In cases where there is superficial surface layer of the fine sediment, infiltration from the recharge basins or wadi bed is unsaturated. It has been indicated that a thin layer of fine sediment consisting of silt and clay usually occurs at the wadi bed. Consequently, the infiltration-recharge process under the conditions of a clogged surface layer seems to represent the actual conditions. Therefore, theoretical analysis of the infiltration recharge process with a clogging layer in relation to its influence is simplified.

The unsaturated infiltration – recharge process, resulting from clogged surface assumes that the infiltration rate I is less than the vertical conductivity Kv of the zone below the clogging layer. In the soil profile, below the clogged thin layer, the infiltration flux I is unsaturated and water content is less than the moisture content at natural saturation.

The analysis of the infiltration process before the wetting front reaches the water table, for the case of clogged surface layer, can be addressed by the application of an integral equation. The infiltration rate I for heterogeneous medium under a variable ponding depth (Morel-Seytoux 1983) is as follows:

$$I = [K_v (\tilde{O} - \theta_i) (H_c + Z_c + Y (t)) + K_{rw} (\theta) W] / (\tilde{O} - \theta_i) (K_v / K_c)Z_c + W \qquad (8)$$

Where:

K_v: is the hydraulic conductivity in the vertical direction
Y(t): is the stage ponded water depth time variation at the soil surface
K_c: is the hydraulic conductivity of the cogging layer
Z_c: is the thickness of the clogging layer
$K_{rw}(\theta)$: is the relative permeability

Other terms in the equation were defined previously. The infiltration rate can be estimated by equation 8 until the wetting front reaches the water table.

As soon as the unsaturated wetting front reaches the water table, a hydraulic connection between the infiltration basin and the aquifer is not immediately established. Since the arrival of the percolating flux is unsaturated, a fraction of it will be reflected as it hits the rising water table. The available pore spaces become saturated as a result of the reflected flux, and the increased weight of the water below the recharge zone will induce lateral movement of groundwater away from the developing mound. As a result, a fraction of the descending unsaturated flux is transmitted laterally to recharge the aquifer, and contributes to groundwater storage.

The groundwater configuration, as a result of this flow condition, is represented in Figure 1. The mound profile below the basin is approximated by the position of reflected front Z_{rf} above the initial water table level and by the profile h (x,t) in regions outside he recharge basin. The governing equations (Morel-Seytoux et al. 1988) for the reflected Z_{rf}, mound profile h (x,t) and lateral recharge rate q(t) are as follows:

$$Z_{rf} = It / (\tilde{O} - \theta_0) - 1 / (\tilde{O} - \theta_0)\, B \;{}_{o}\!\int^{1} q(t)\, d(t) \qquad (9)$$

$$h(t) = 2 / \sqrt{\O\, T\, \Pi}\;\; {}_{o}\!\int^{1} \sqrt{t_{-T}}\;\; dq(_T) / d_T - d_T \qquad (10)$$

$$q(t) = K\, [\, Z_{rf}(t) - h(t)] \qquad (11)$$

Where K is the effective conductivity related to the horizontal and vertical conductivities Kh and Kv, to the half width B of the basin and the saturated aquifer thickness e and I is the percolation flux at the water table, and θ_0 is the transmission zone moisture content less than Õ the moisture content at natural saturation:

$$K = K_h / [\, 1 + K_h e / K_v B] + K_v / [\, 1 + K_h B / K_v e\,] \qquad (12)$$

The characterized integro-differential equation for lateral recharge rate q(t) is as follows:

$$(\tilde{O} - \theta_0)\, Bq(n) + K \;{}_{v=1}\textstyle\sum^{n} q(v) + 2\, (\tilde{O} - \theta_0)\, KB / \quad T\, \O \sqrt{\Pi} \; + \;{}_{v=1}\textstyle\sum^{n} [\, q(v) - q(v\text{-}1)]\, \Delta\, (n\text{-}v\text{+}1) = K/Bn \qquad (13)$$

for n= 1,2,3 ….N

Where q(n) is the value of q(t) at discrete integer values of a selected period of time, and N is the total time horizon of interest. The discrete Δ (m) kernel is defined as:

$$\Delta\, (m) = 2/3\, [\, m^{3/2} - (m\text{-}1)^{3/2}] \qquad (14)$$

Where m = (n-v+1)

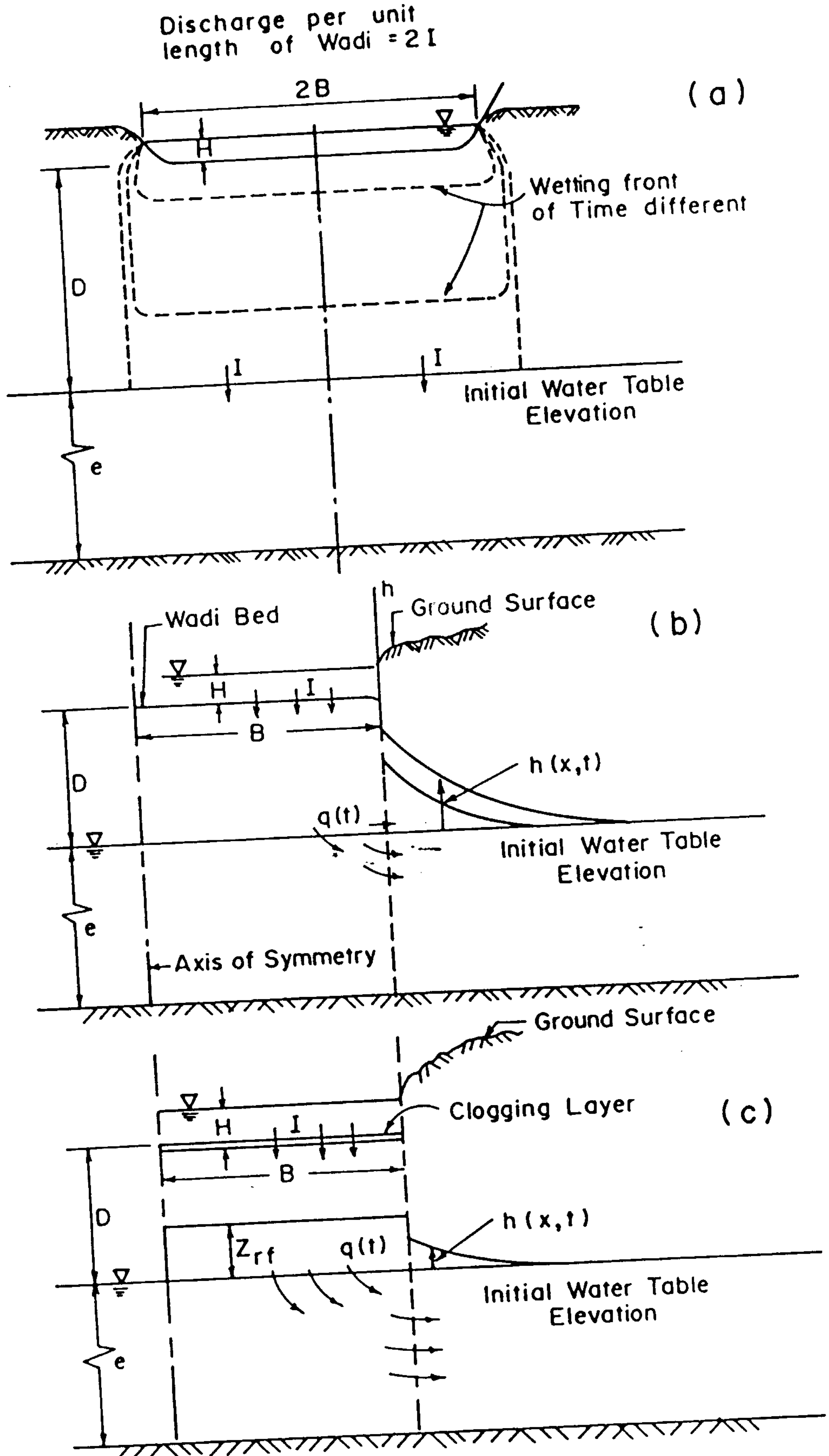


FIG. 4. Schematic View of Recharge From a Wadi Bed

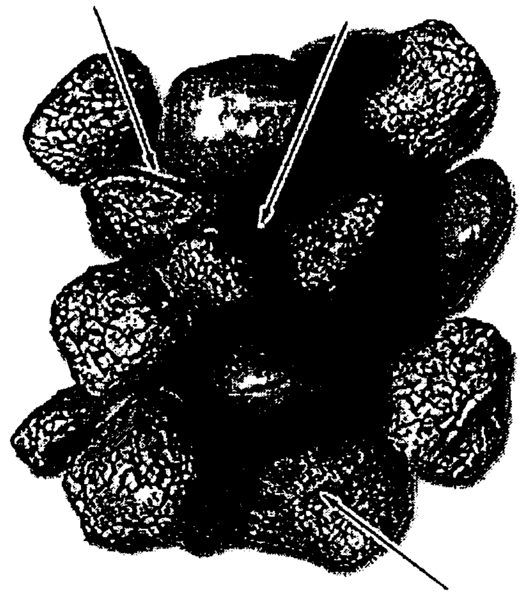
Saturation level

$$S_i = V_i/V_p$$

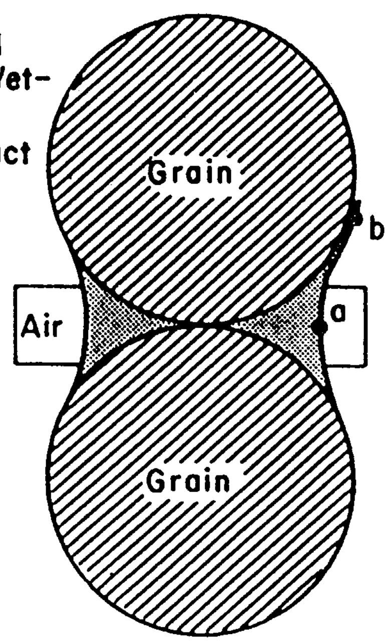
S_i = Saturation level

V_i = Volume of phase i

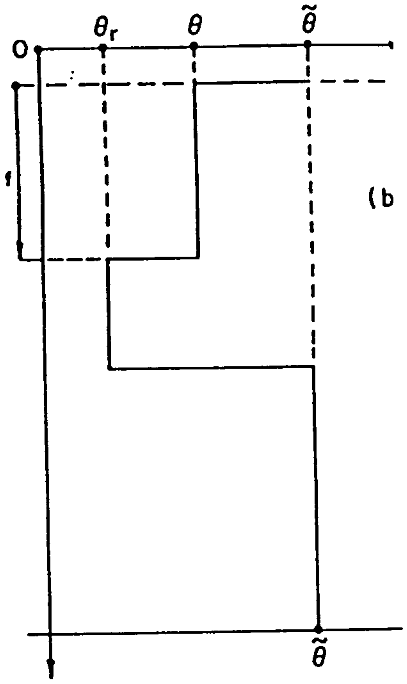
V_p = Volume of total pore space



Hydrostatical pressure



Enlarged View of Air-Water Interface Surrounding Grain Contact; Shows Curvature of Interface.



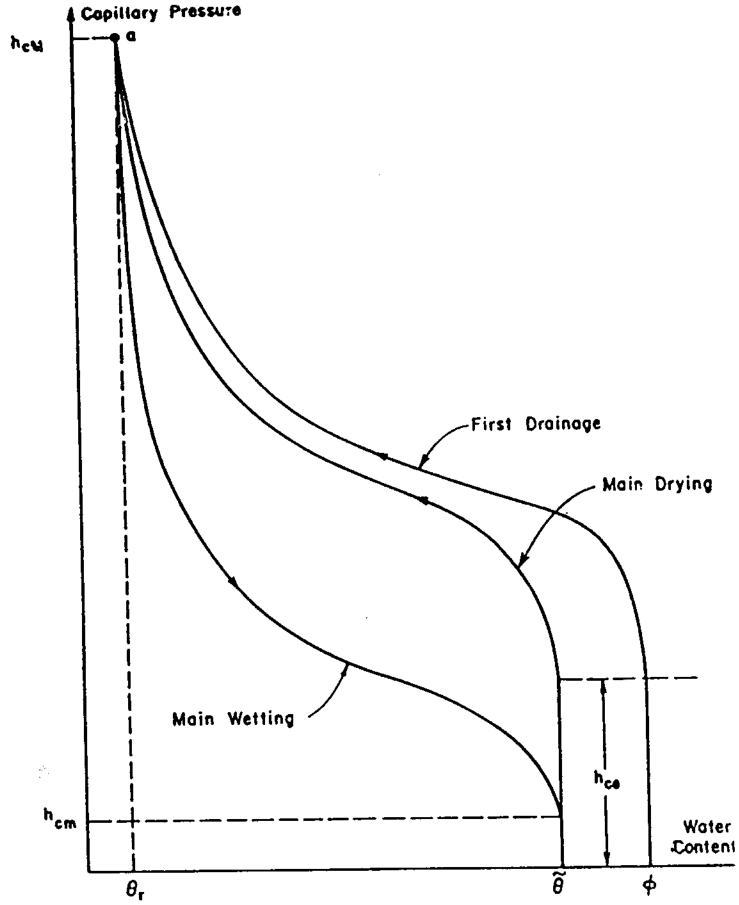


Figure 3 Typical hysteris of capillary pressure.

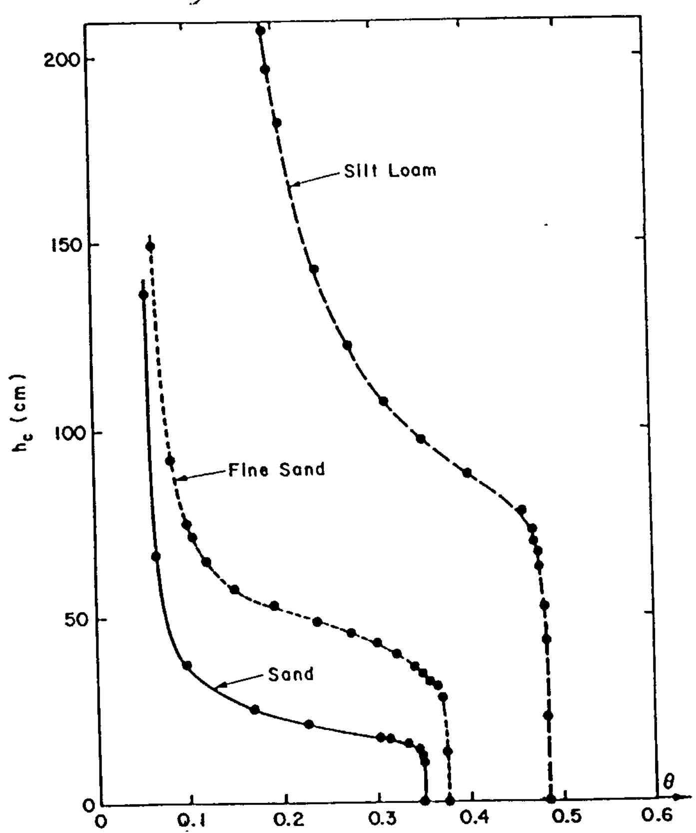


Figure 3. Drainage capillary pressure curves for sand, fine sand and silt loam (adapted from Brooks and Corey, 1966).

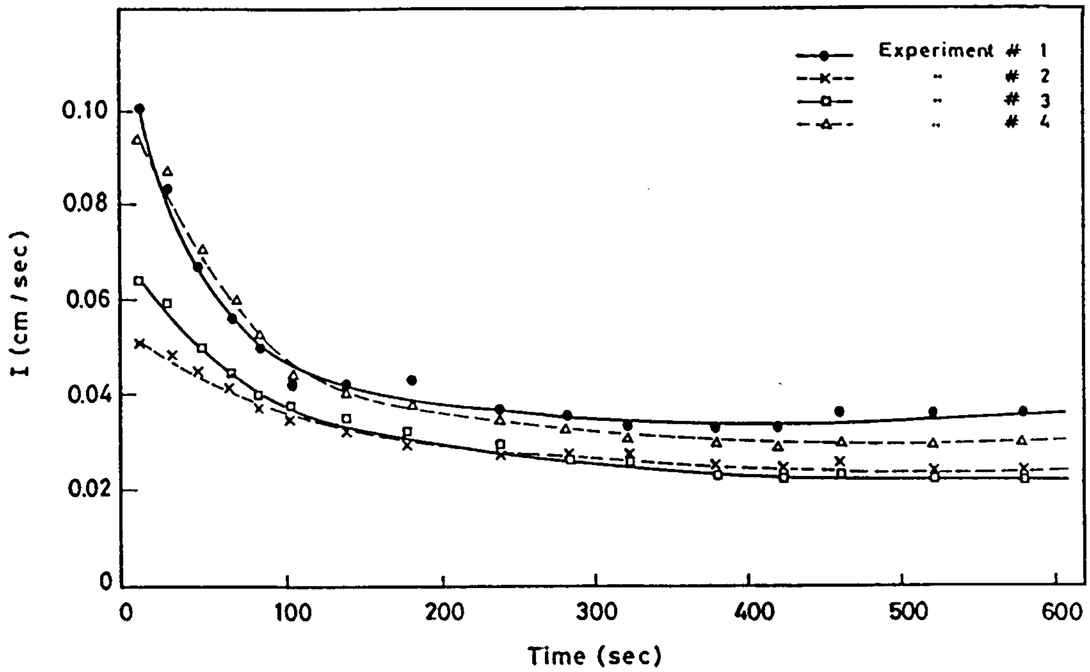


Figure 4 Variability of Infiltration Rate with Different Initial Moisture Contents.

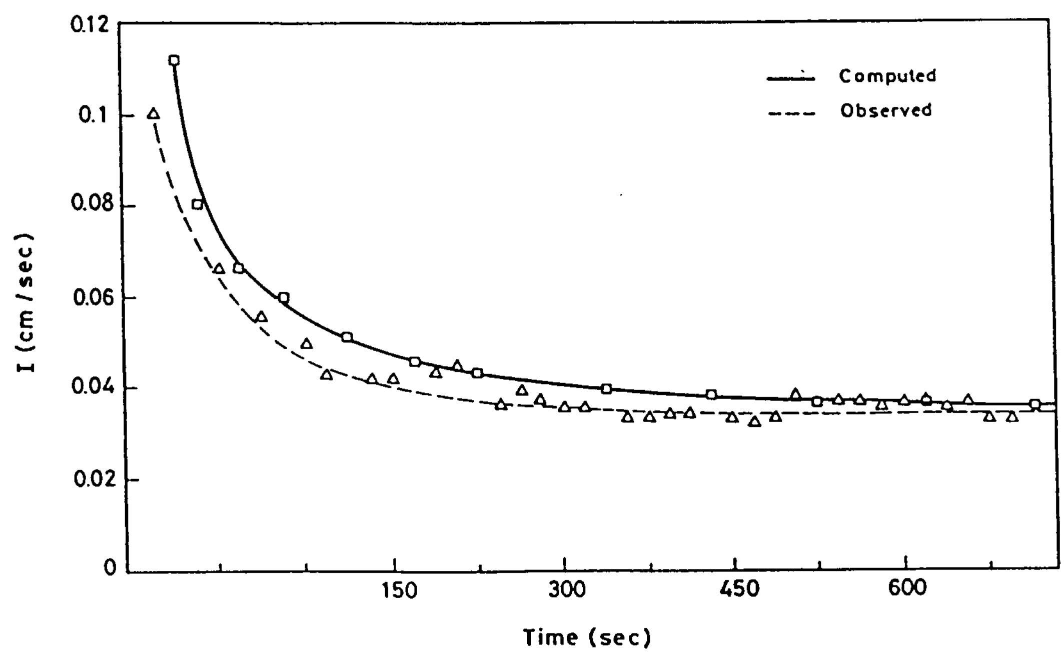


Figure 4. Comparison of Observed and Computed Infiltration Curves for Location 1.