HYN-102

Lecture

Abstraction from Precipitation

Infiltration

- **PRECIPITATION LOSSES**

1. **INITIAL LOSSES**
2. **INFILTRATION LOSSES**

INITIAL LOSSES → **Interception loss**

INITIAL LOSSES → **Loss due to filling depression storage**

- **Interception**

Intercepted water may follow one of the three possible routes:

1) Retained by the vegetation as surface storage and returned to the atmosphere by evaporation; a process termed as interception loss.

2) It can drip off the plant leaves to join the ground surface or the surface flow; this is known as **throughfall**; and

3) The rainfall may run along the leaves and branches and down the stem to reach the ground surface. This part is called **stemflow**.

Interception loss is solely due to evaporation and does not include transpiration, through fall or stem flow.

Amount of water intercepted in a given area is difficult to measure.

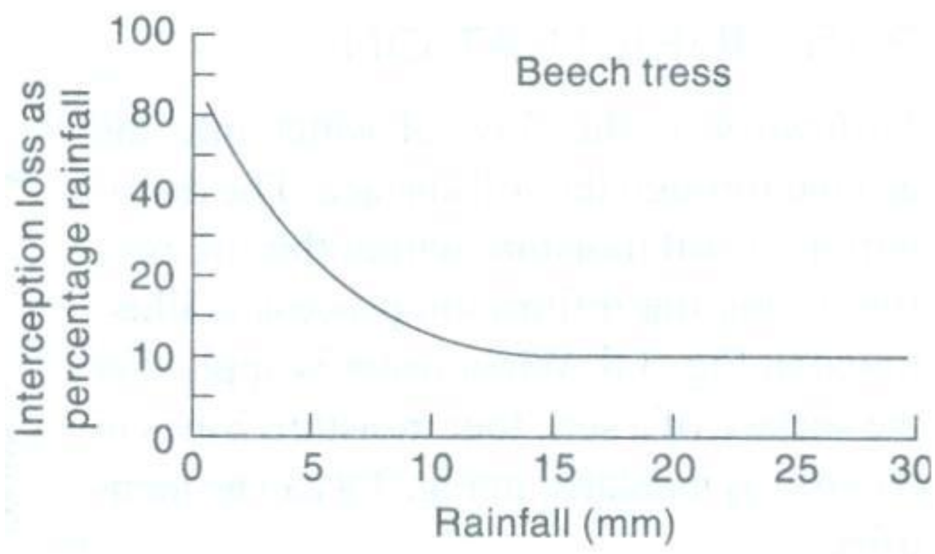
Depends on 1) Species composition of vegetation

2) its density, and also

3) Storm characteristics.

It is estimated that during a plant growing period the interception loss could be **10-20% of rainfall.**

If frequent rainfall occurs, the annual interception losses over forest regions could be high**, ≥ 25% of the annual precipitation**.



Typical Interception Loss Curve

- **Depression storage**

Factors influencing depression storage :

i. **The type of the soil**
ii. **The condition of the surface reflecting the amount and nature of depression.**
iii. **The slope of the catchment**
iv. **The antecedent precipitation.**

Qualitatively found that antecedent precipitation has a very pronounced effect on decreasing the loss to runoff in a storm due to depression.

During intensive storm 0.5 cm depression storage in sandy soil,

0.4 cm in loam,

0.25 cm in clay.

What is Infiltration?

- Important natural process,
- It is a major component of hydrological abstraction,
- How does it compare with other hydrological abstractions during a flood event?
  - Infiltration is a major process affecting timing and quantity of surface runoff during a storm,
  - Losses like interception, depression storage, evaporation during precipitation are small as compared to infiltration.

What is Infiltration?

- Initiated by creation of hydrogen bond between soil particles and water,
- The adhesive force of attraction between soil & water, surface tension, capillary and gravity forces help to move water between soil particles.
- **Definition:** Infiltration is the process of entry of water into soil through soil surface. *The rate at which water enters at soil surface is called* ***infiltration rate****.*
  – The infiltration rate as a function of time defines infiltration curve (*f* or *f(t)*).

How the process of Infiltration work?

- After reaching the ground, rainfall water moves downward through the surface of the earth.
- The earth surface may be permeable or impermeable,
  - but the most soils are permeable though their degree of permeability varies.
- Soil and rock strata that permit water flow are called porous media.
- A porous medium is an interconnected structure of tiny conduits of various shapes and sizes.
- It is made up of a matrix of particles and embedded voids, thus a portion of the soil cross-section is occupied by solid particles and the remainder by voids.

How the process of Infiltration work?

- Two important characteristics of a porous medium are **porosity (η)** and **moisture content (θ)**.

Porosity is defined as $$\eta = \frac{Volume\ of\ Voids}{Total\ Volume}$$

For soils, depending on the soil texture, the range of η varies approximately $0.25 < \eta < 0.75$.

A part of voids is occupied by water and the remainder by air, the volume occupied by water being measured by the *soil moisture content* θ defined as

Moisture Content $$\theta = \frac{Volume\ of\ Water\ in\ Voids}{Total\ Volume}$$

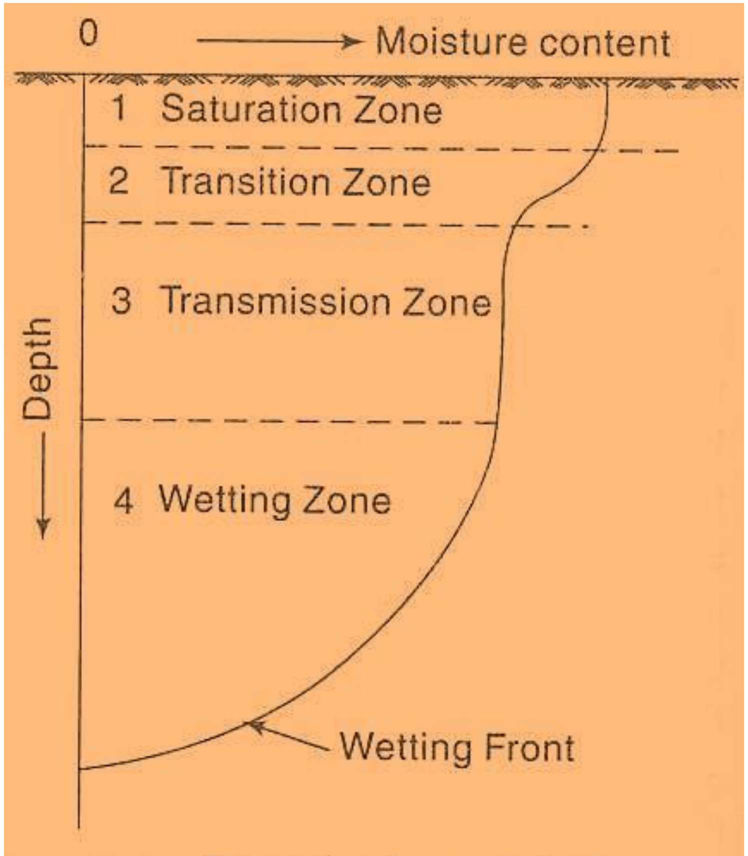
The range of θ is $0 < \theta \leq \eta$, that is, when the soil is saturated the soil moisture content is equal to the porosity.

How the process of Infiltration work?

- In the first few minutes of a rainstorm, water will accumulate on vegetation, and then it will reach the ground and start infiltrating into the soil.
- Subsurface flow is **unsaturated** when the porous medium still has some of its voids occupied by air ($\theta < \eta$) and
- **Saturated** when voids are filled with water ($\theta = \eta$).
- During severe storms, the upper soil layer will become saturated and water will start ponding and flowing on the surface.
- The distribution of soil moisture within the soil profile during the downward movement of water is illustrated in next slide.

Distribution of Soil Moisture

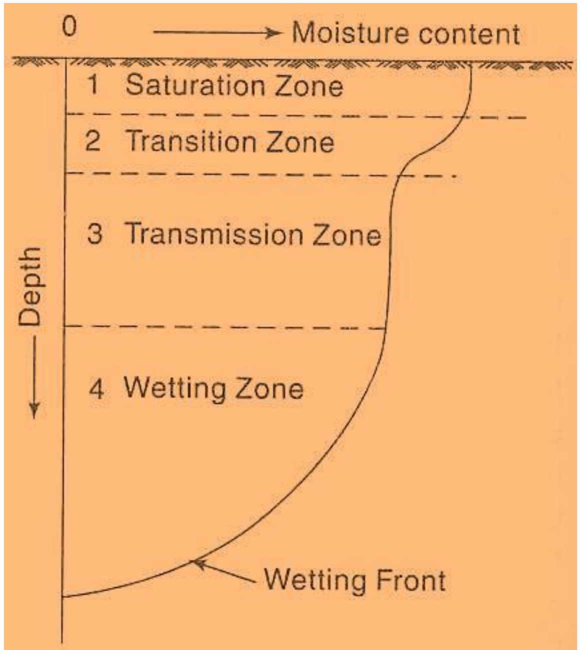
- The distribution of soil moisture within the soil profile during the infiltration process is illustrated in figure.
- Depending on amount of infiltration and physical soil properties, a wetting front may penetrate from few cm to several meters.



Distribution of Soil Moisture in the Infiltration Process

Distribution of Soil Moisture

- **Saturation zone:** Saturated layer just below the soil surface. Almost constant water content, only a few centimeters thick.
- **Transition zone:** Rapid decrease in water content with depth. Also only a few centimeters thick.
- **Transmission zone:** Partially saturated layer of almost constant water content, Much thicker, Gets thicker as wetting front moves down through soil column.
- **Wetting zone:** Steep decrease in water content with depth, soil wets as wetting zone moves down through the soil profile.
- **Wetting front:** Sharply defined leading edge of the wetting zone. Moves down as water passes through the transmission zone

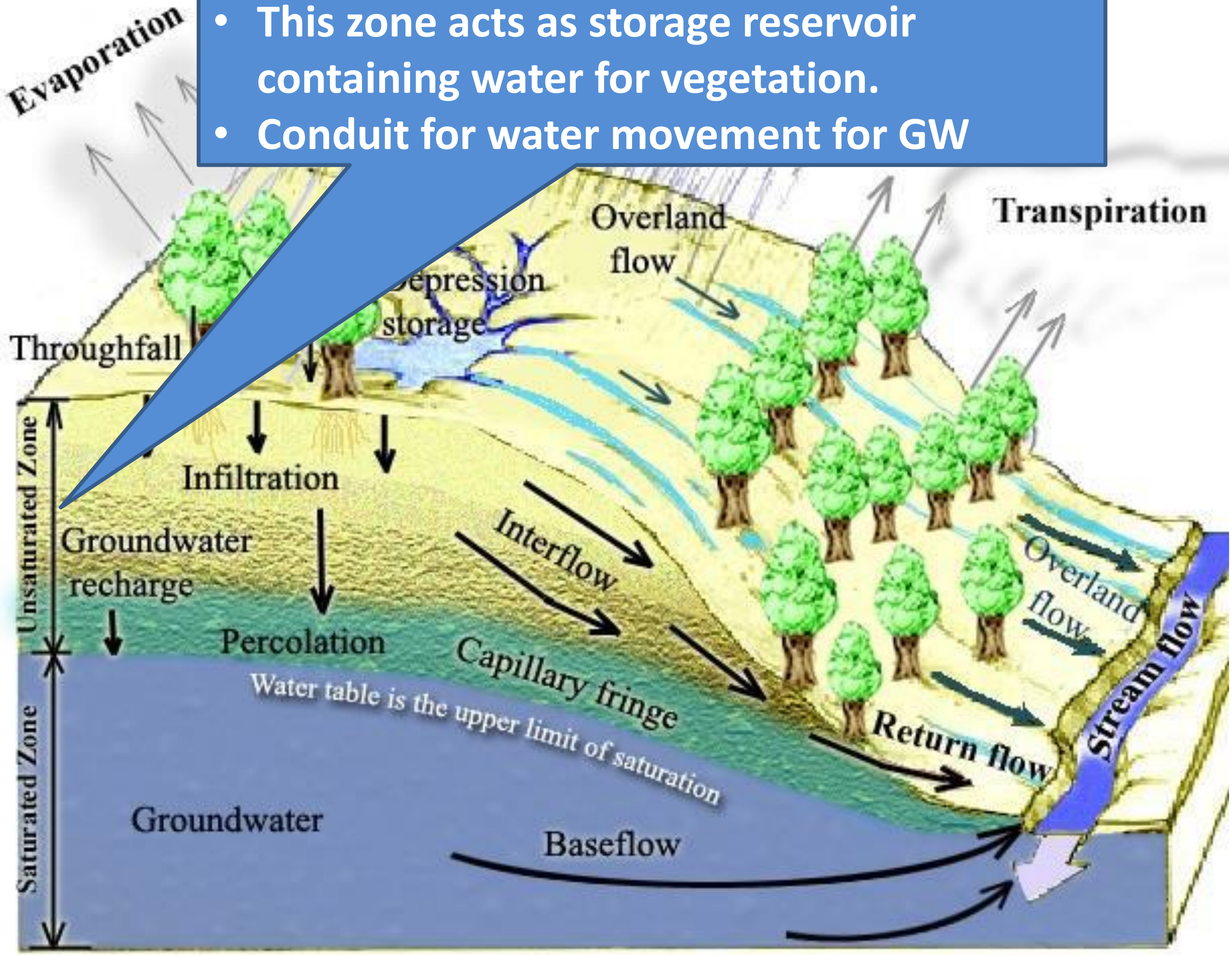


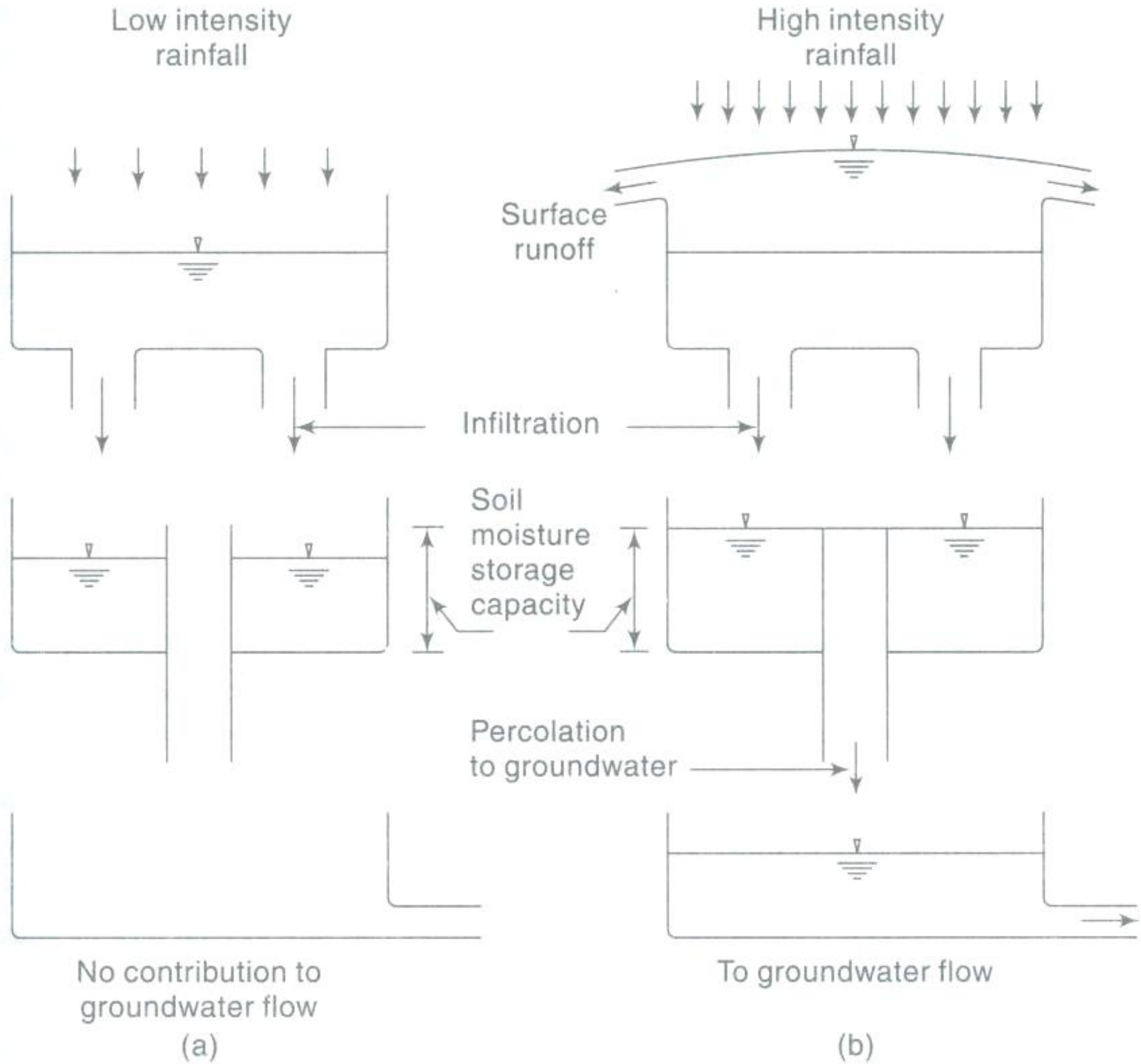
Distribution of Soil Moisture in the Infiltration Process

Zones of Sub-surface Water

- Water existing in soil is called sub-surface water. It is of two kind,
  - Soil water
  - Ground water
- The zone in which soil water occurs is called **unsaturated zone** (vadose zone or zone of aeration).
- The zone in which ground water occurs is called **ground water zone**.
- What are fundamental differences?

- Some soil pores contain water, some air.
- This zone acts as storage reservoir containing water for vegetation.
- Conduit for water movement for GW





An Infiltration Model

Infiltration Nomenclature

- **i** = intensity of rainfall (rate) (length/time)
- **f** = infiltration rate- measure of hydraulic conductivity (length/time)
- **F** = infiltrated volume (Length^3) or depth (L)

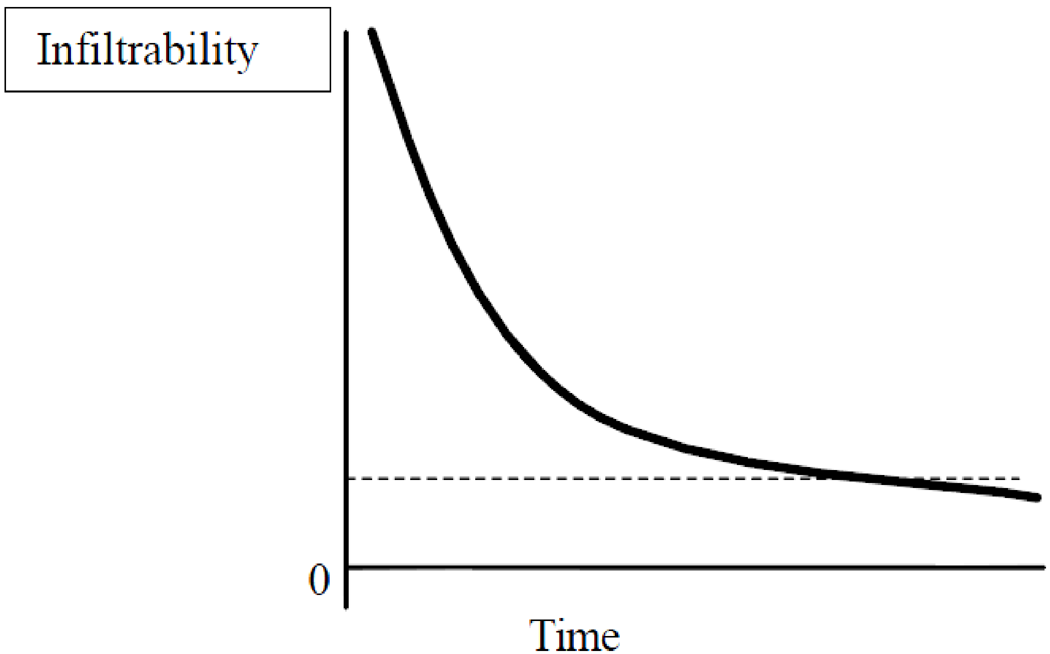
  - **If i < f what happens?**

  - **If i > f what happens?**

Infiltration Capacity

Infiltration vs. Time (vertical infiltration)

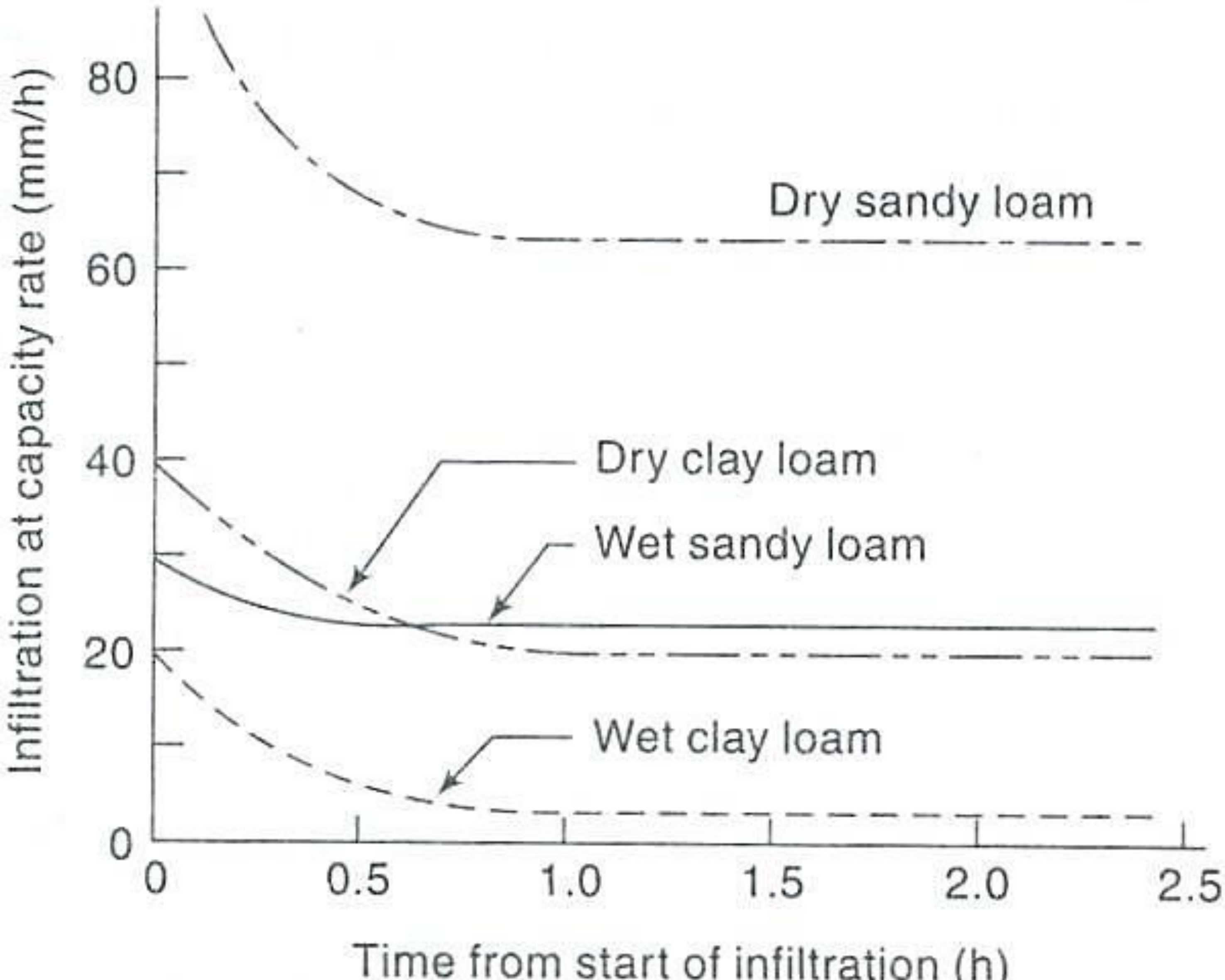
: Infiltration rate, when soil surface is ponded.



When the availability of water is not a limiting factor, maximum rate at which a given soil at a given time can absorb water is defined as the **Infiltration capacity (fp)**.

Infiltration Capacity

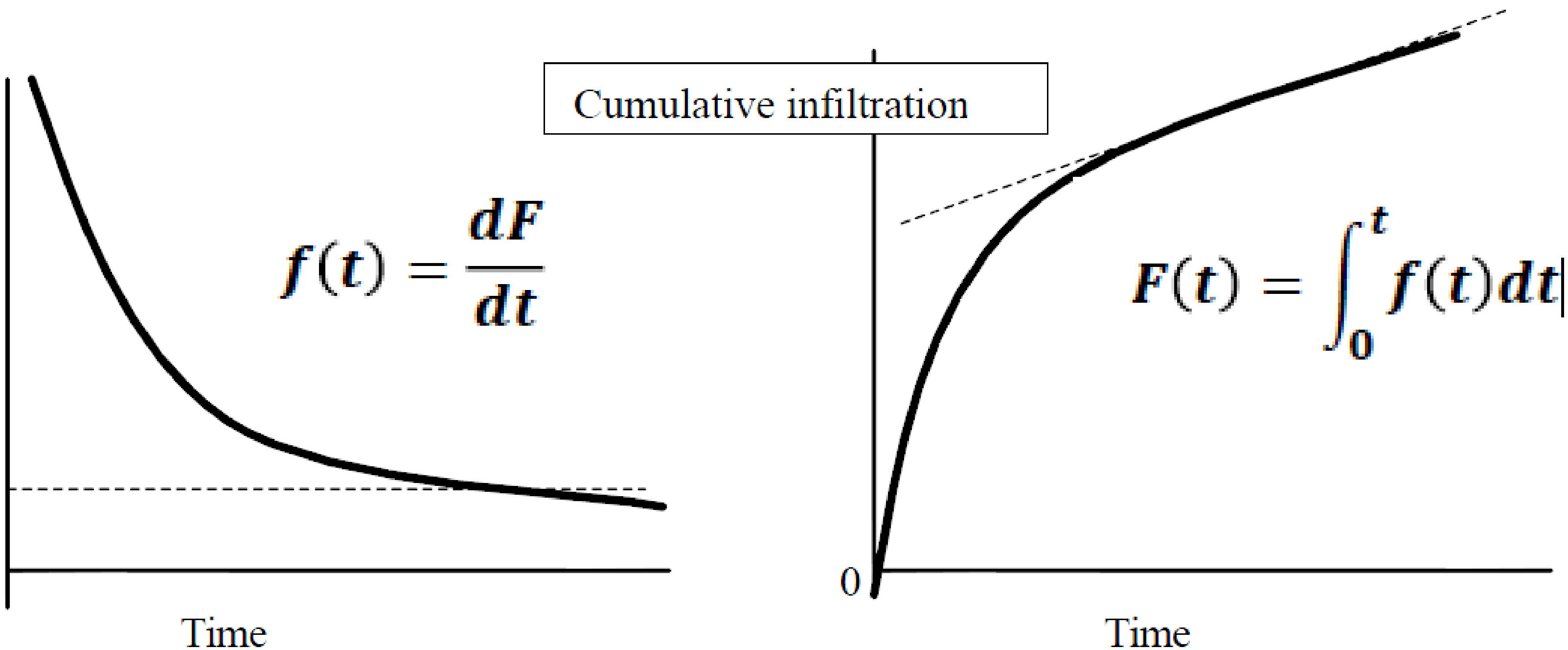
- It is designated as **fp**
- Expressed in units of cm/hr.
- The actual rate of infiltration f can be expressed as
  - f= fp when i ≥ fp
  - f=i when i< fp where, i= intensity of rainfall
  - In general 0 ≤ f ≤ fp
- The infiltration capacity of a soil is high at the beginning of a storm and has an exponential decay with time.



Variation of Infiltration Capacity

Cumulative Infiltration (F)

- This denotes volume of infiltration from beginning to time t.
- Expressed in units of length (depth).



$$f(t) = \frac{dF}{dt}$$

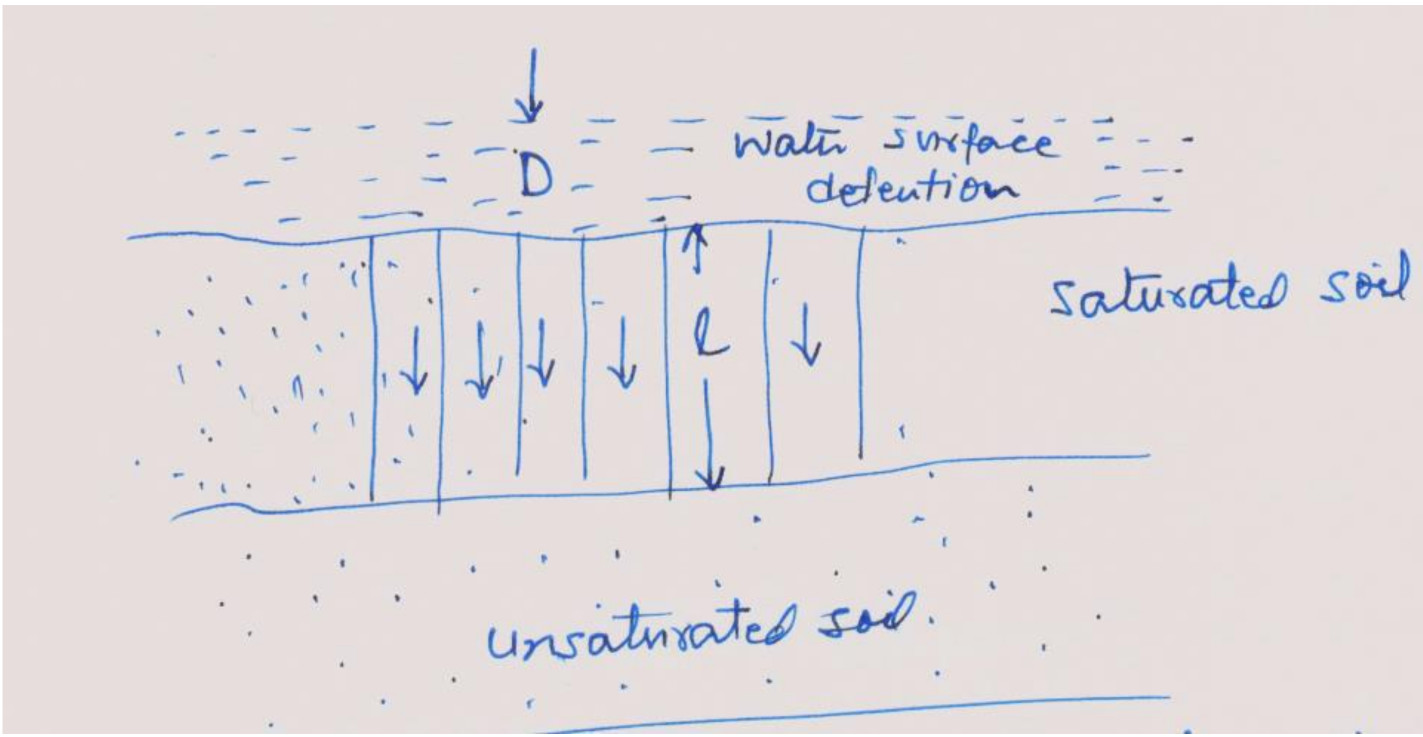
$$F(t) = \int_0^t f(t)\,dt$$

The infiltration capacity of an area is dependent on a large number of factors, chief of them are:

- Characteristics of the soil (texture, porosity and hydraulic conductivity)
- Condition of the soil surface
- Current moisture content
- Vegetative cover, and
- Soil temperature.

What factors affect infiltration?

- Depth of ponding and thickness of saturated layer



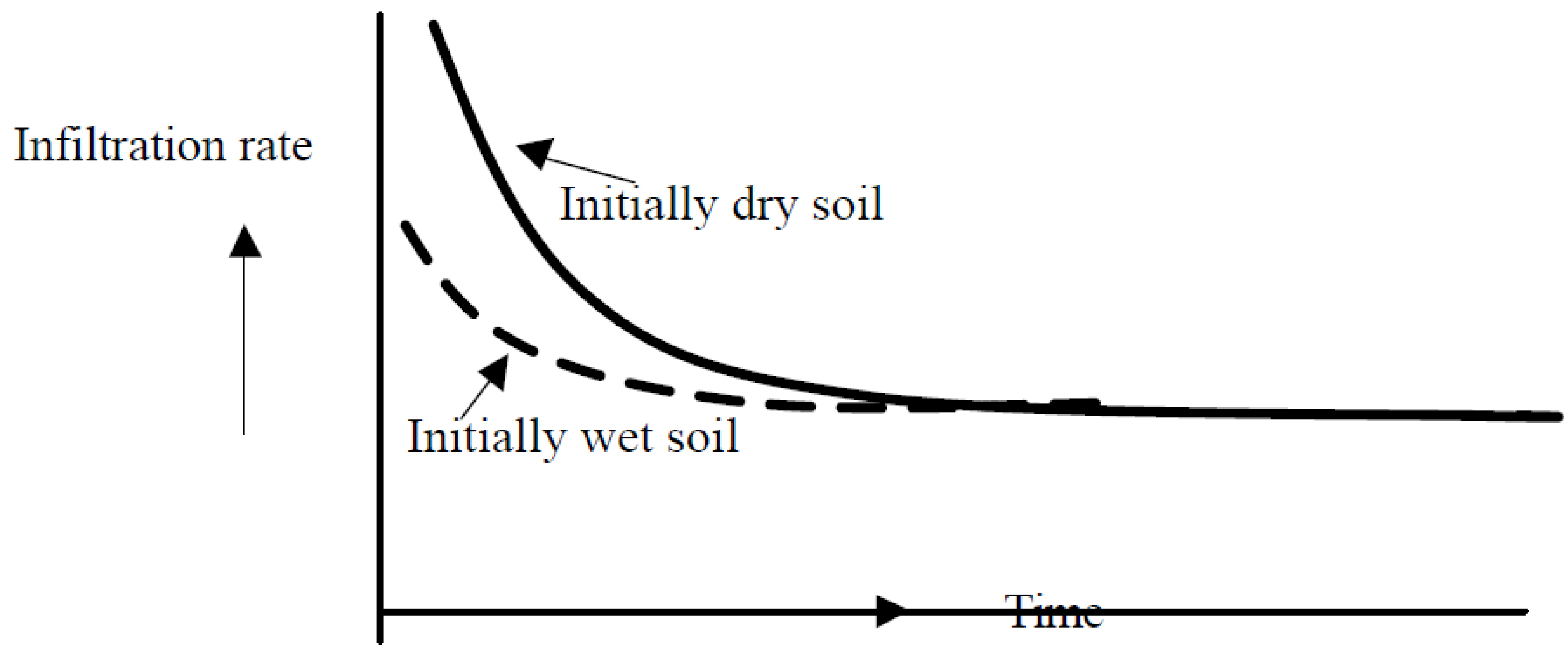
- Force causing downward movement is proportional to D + L
- Resistance to flow is proportional to L

What factors affect infiltration?

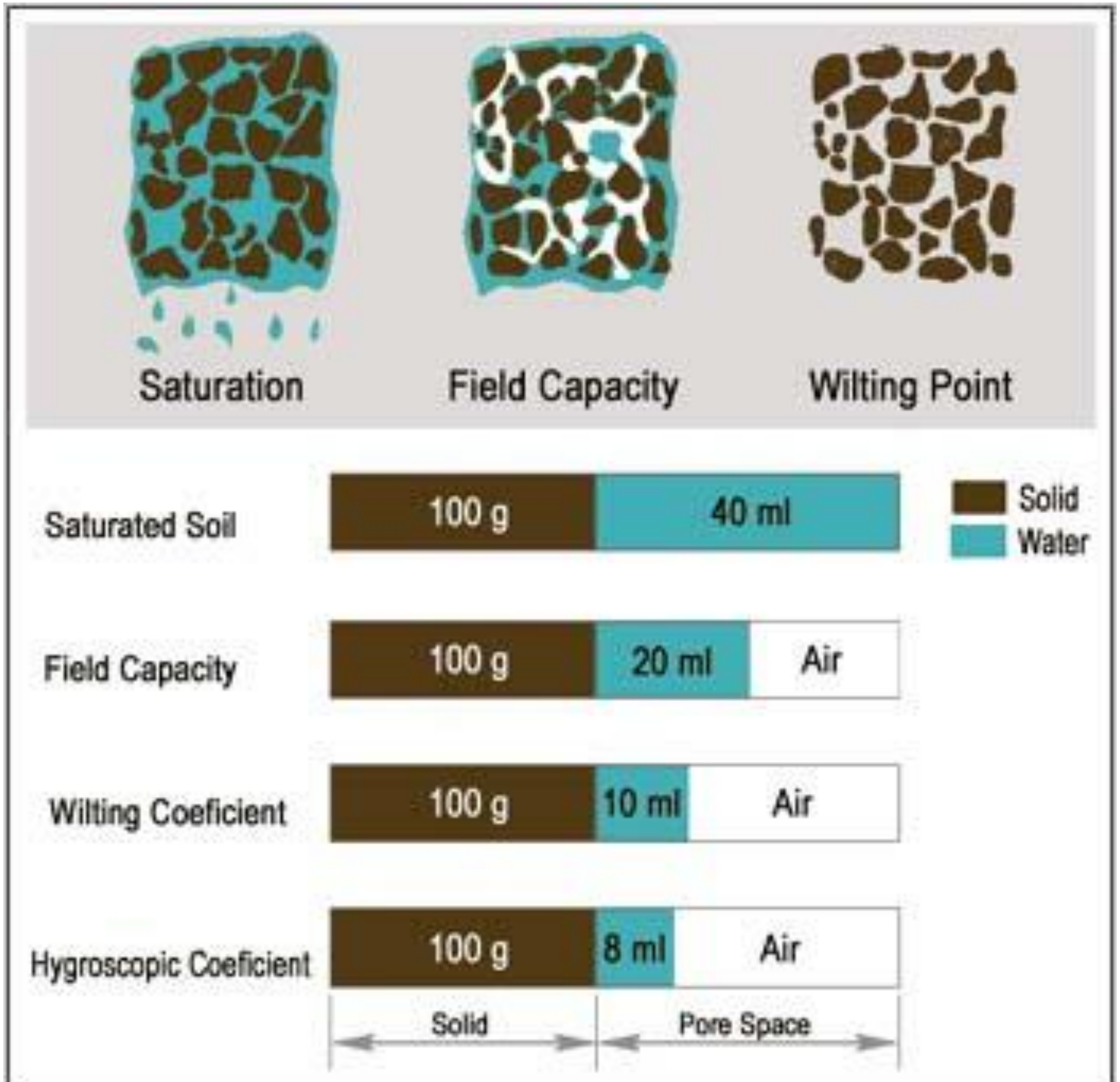
- Viscosity (function of temperature)
- Compaction due to rain
- Washing of fines
- Compaction due to man and animals

What factors affect infiltration?

Soil moisture:

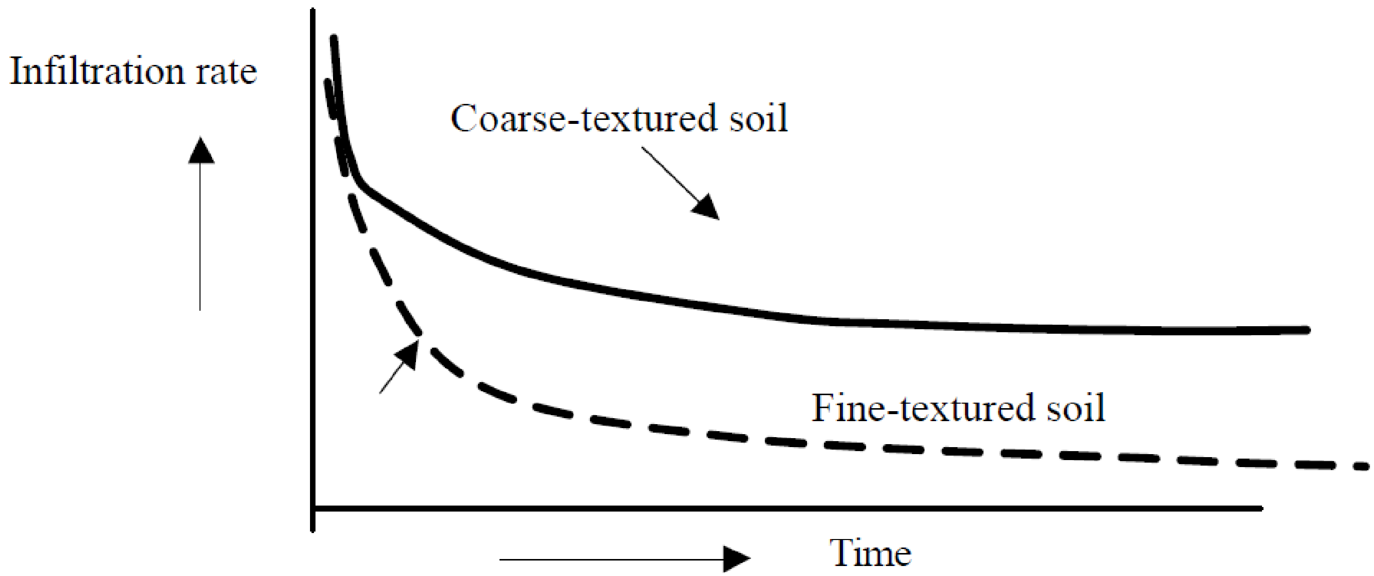


Moisture content



What factors affect infiltration?

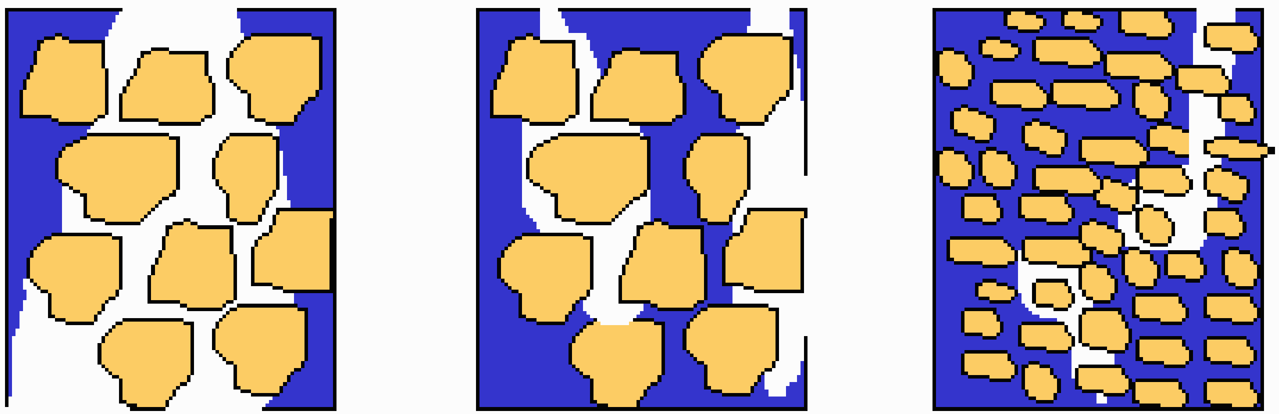
Soil texture:



Soil Type	Final infiltration rate (mm/hr)
Sands	> 20
Sandy/Silty soils	10-20
Loams	5-10
Clayey soils	1-5
Sodic clayey soils	< 1

Soil Texture

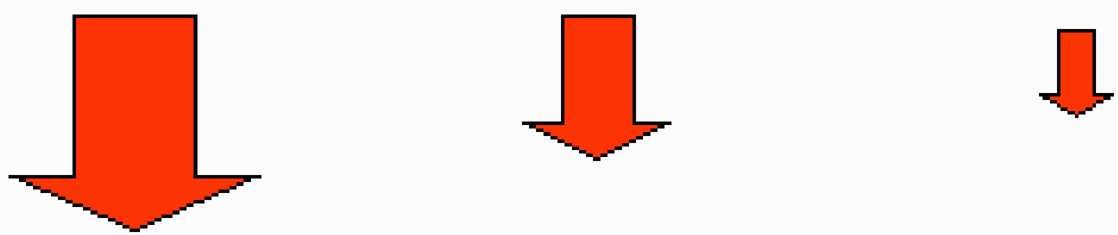
Soil texture:	Sand	Silt	Clay
Size [mm]:	0.05 - 2	0.002 - 0.05	< 0.002



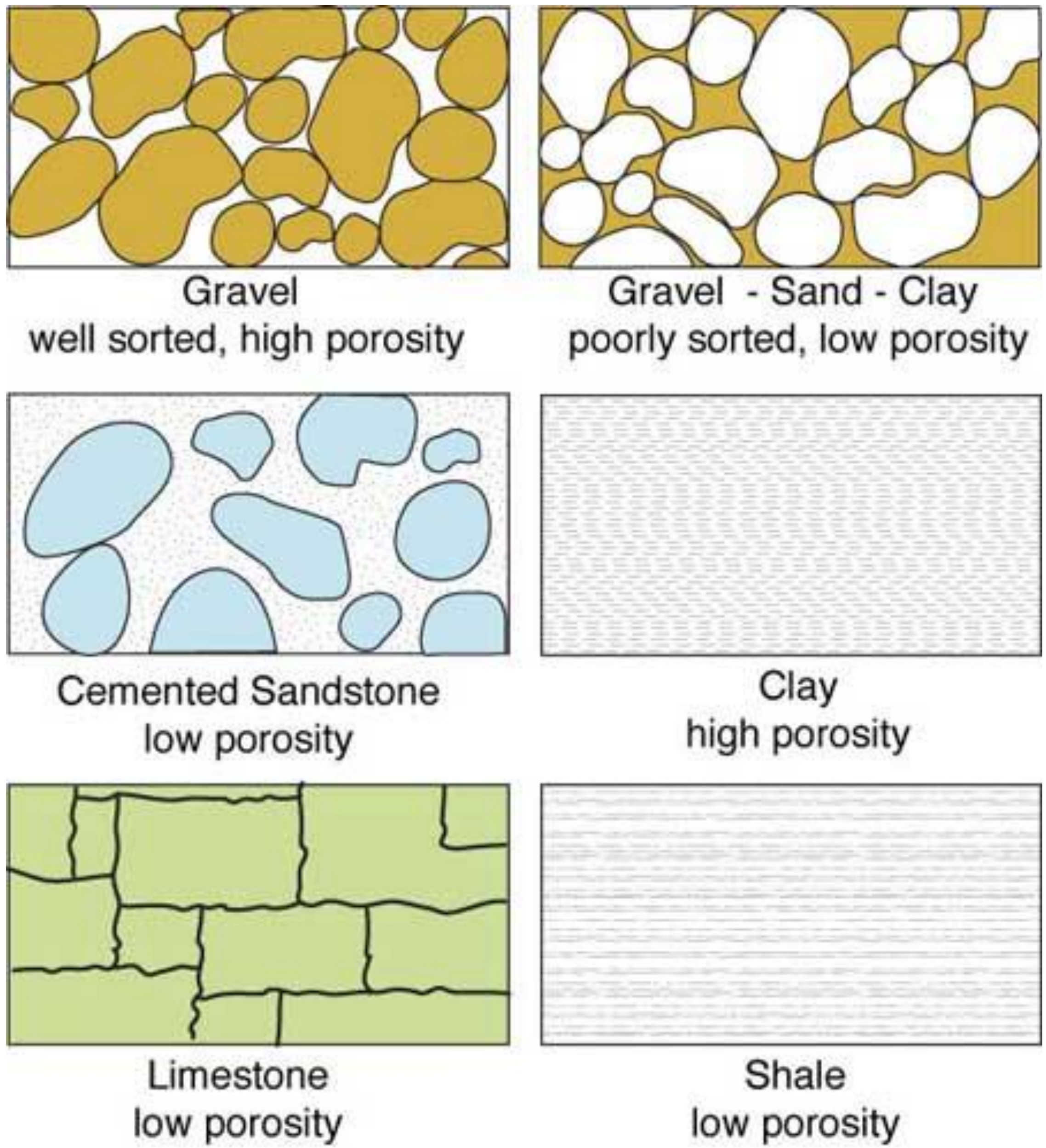
Macropores	+++	++	(+)
Medium-sized p.	++	++	++
Micropores	(+)	++	+++

Percolation:

Leaching:

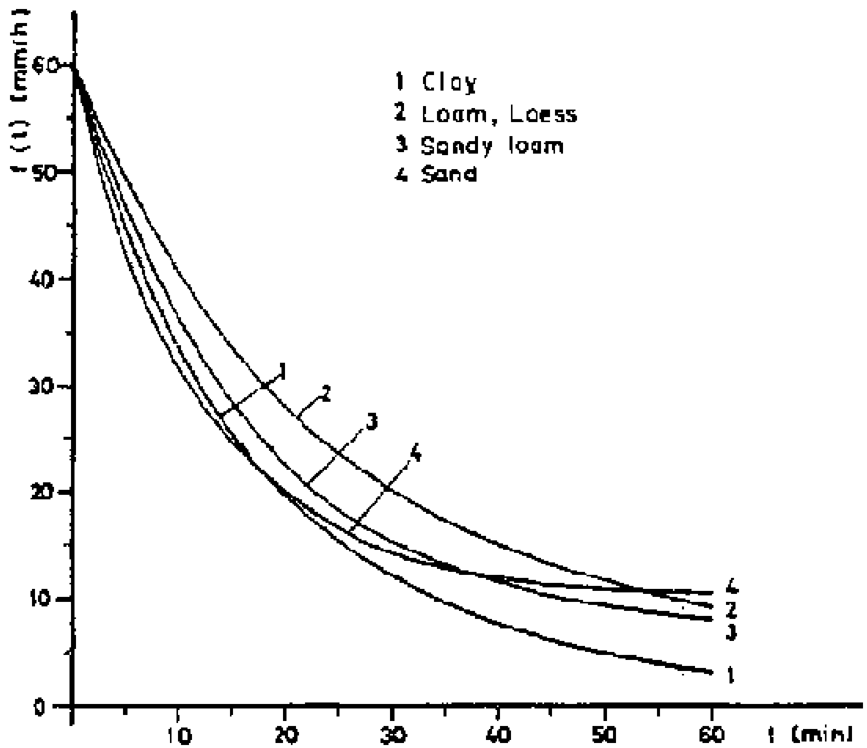


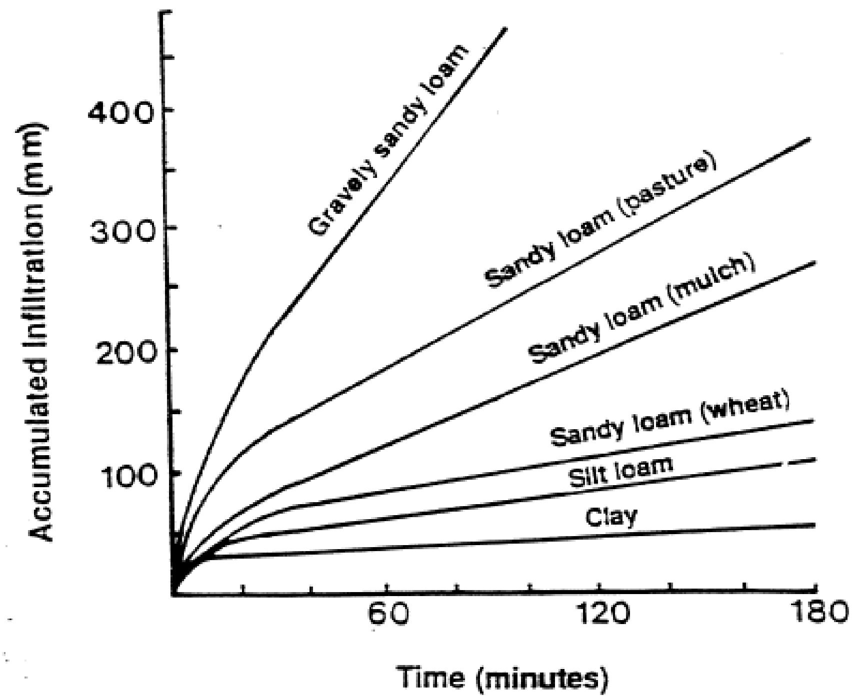
Soil porosity



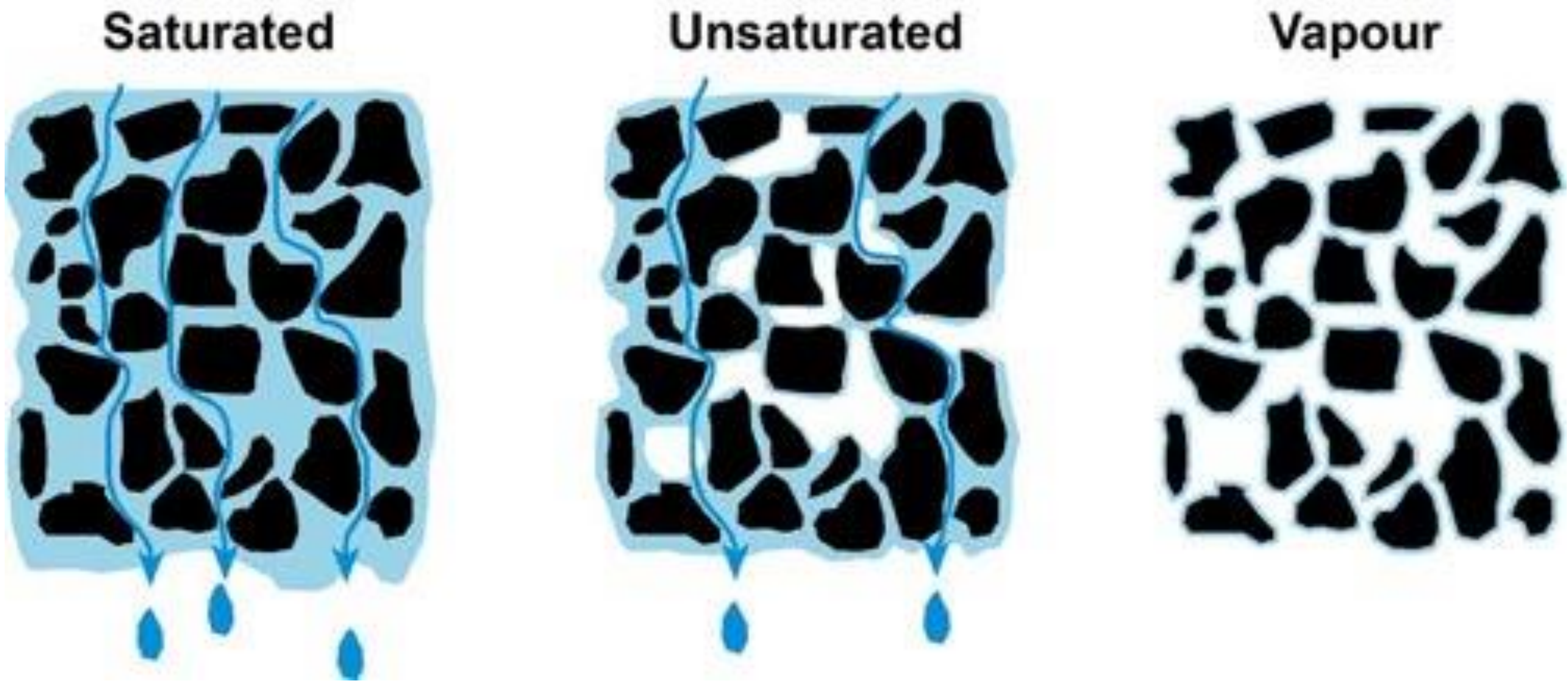
What factors affect infiltration?

- Sand soils have the highest infiltration rates
- Clay soils have the lowest infiltration rates.
- High organic matter improves infiltration





Hydraulic conductivity

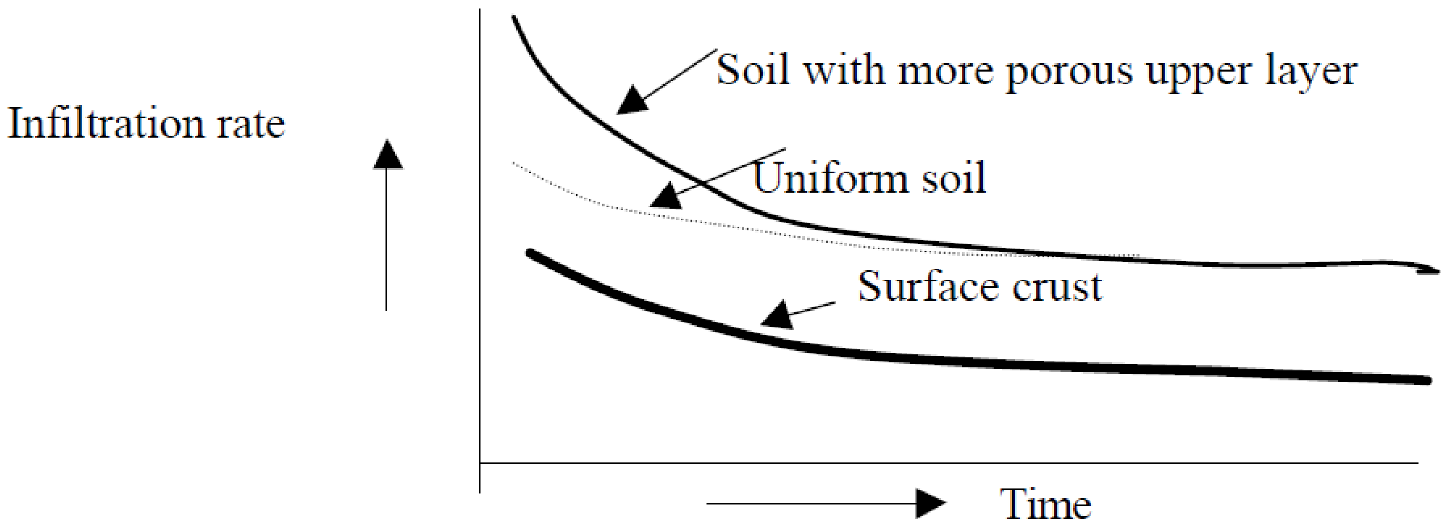


What factors affect infiltration?

Surface crusts:

Can develop by:

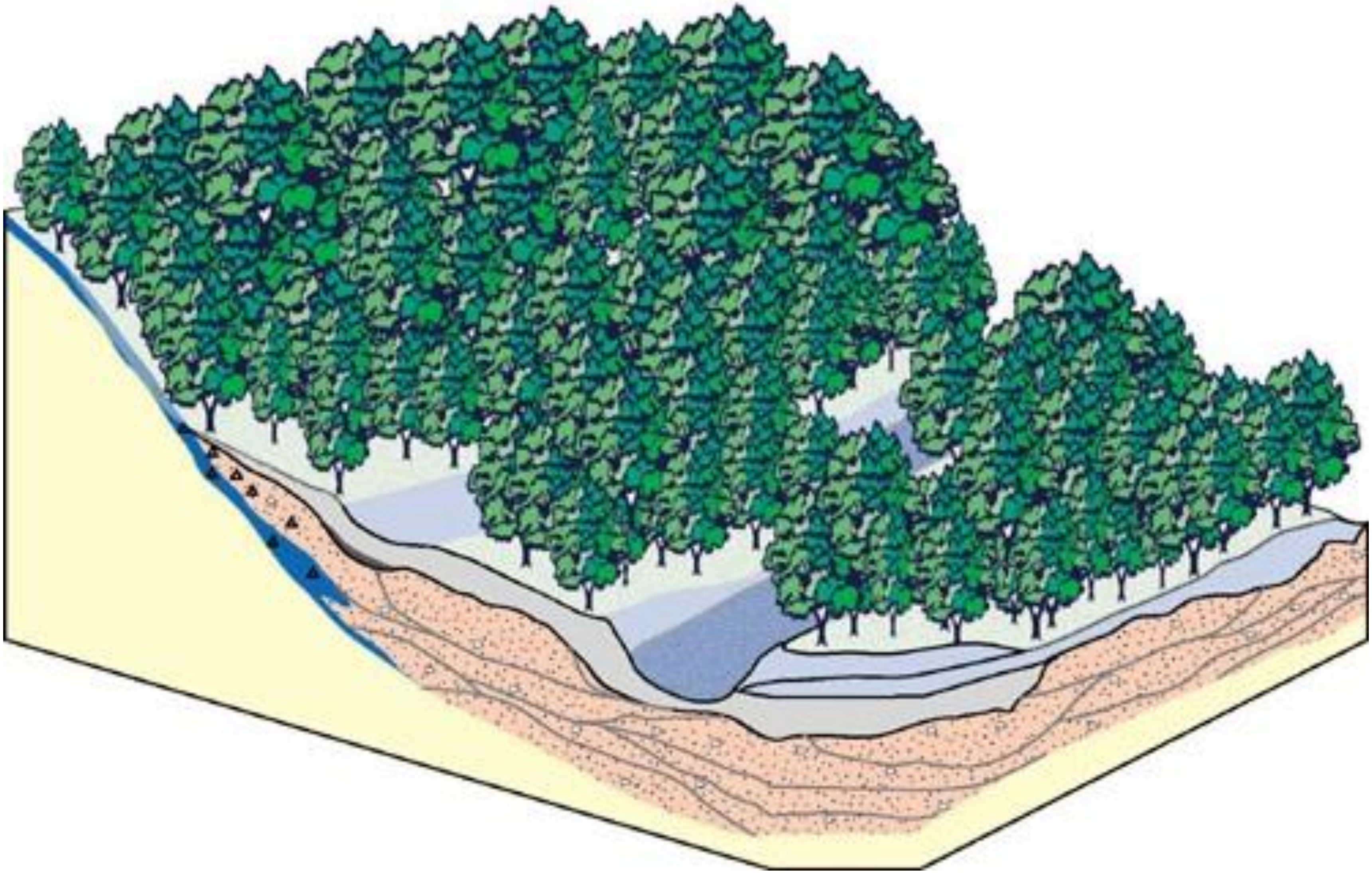
- Soil surface compaction
- Slaking of soil agggregates at soil surface by rainfall/irrigation



Soil surface condition

- **Good Condition** with good distribution of friable finer aggregates and no significant clodding.
- **Moderate Condition** soil contains significant proportions of both coarse firm clods andfriable fine aggregates.
- **Poor Condition** soil is dominated by extremely coarse very firm clods with very few finer aggregates.

Vegetative cover



What factors affect infiltration?

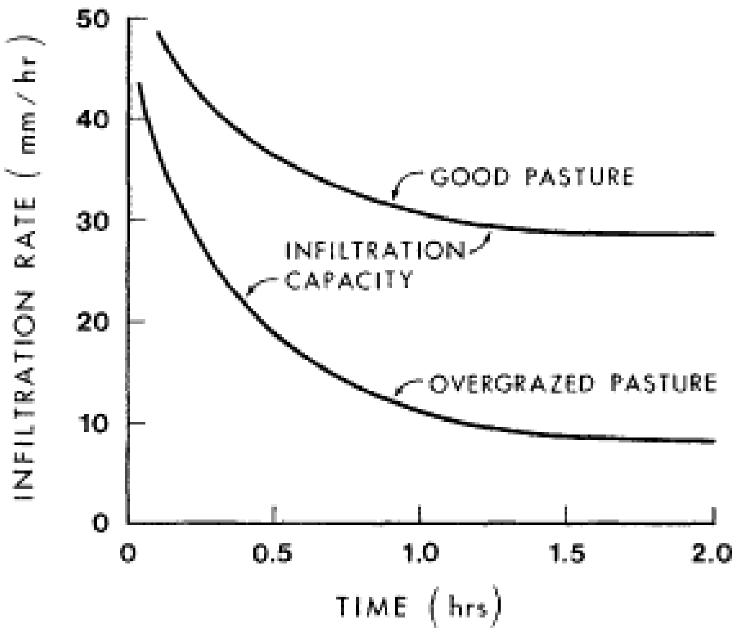


Figure 4.1.
Infiltration capacity curves for soils subjected to different levels of grazing.

- **Characteristics of the soil**

The type of soil. viz. , sand, silt or clay , its texture, structure, permeability and under drainage are the important characteristics. A loose, permeable sandy soil will have a larger infiltration capacity than a tight clayey soil. A soil with good under drainage would obviously have a higher infiltration capacity. When the soils occurs in layers, the transmission capacity of the layer determine the overall infiltration rate.

Also, a dry soil can absorb more water than the one whose pores are already full. The land use has a significant influence on fp. For eg., a forest rich in organic matter will have a much higher value of f_p under identical conditions than the same soil in an urban area where it is subject to compaction.

SURFACE OF ENTRY

At the soil surface, the impact of raindrops causes the fine soil at the soil surface to be replaced and there in turn clog the pore places in the upper layers of the soil. This is an important factor affecting the infiltration capacity. Thus a surface covered with grass and other vegetation which can reduce this process has a pronounced influence on the value of f_p.

FLUID CHARACTERISTICS

Water infiltration into the soil will have many impurities, both in solution and in suspension. The turbidity of the water, especially the clay and colloid content is an important factor and such suspended particles block the fine pores in the soil and reduces its infiltration capacity. The temperature of the water is a factor in the sense that it affects the viscosity of the water by which in turn affects the infiltration rate.

Contamination of the water by dissolved salts can affect the soil structure and in turn affects the infiltration rate.

Measurement of Infiltration

- Rate of infiltration could be measured in a variety of ways. Commonly used methods are:

1. Flooding type infiltrometer
2. Rainfall simulators
3. Hydrograph analysis

Flooding type Infiltrometers

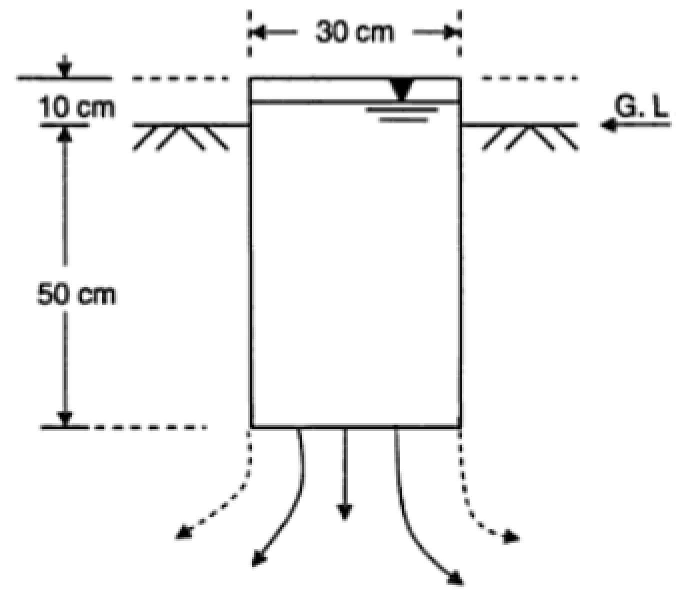
- These are experimental devices used to obtain data related to variation of **infiltration capacity with time.**
- Types of flooding type infiltrometers

a) Tube type or Single ring infiltrometer
b) Double ring infiltrometer

Water applied at Positive pressure

Flooding type Infiltrometers

- **Tube type or Single ring Infiltrometer**
  - Consists of metal cylinder 30 cm dia and 60 cm long, open at both ends
  - Cylinder driven in ground to a depth of 50 cm
  - Surface of soil inside of cylinder is protected with perforated disc
  - Water is poured to a depth of 5 cm and a pointer is set to mark water level

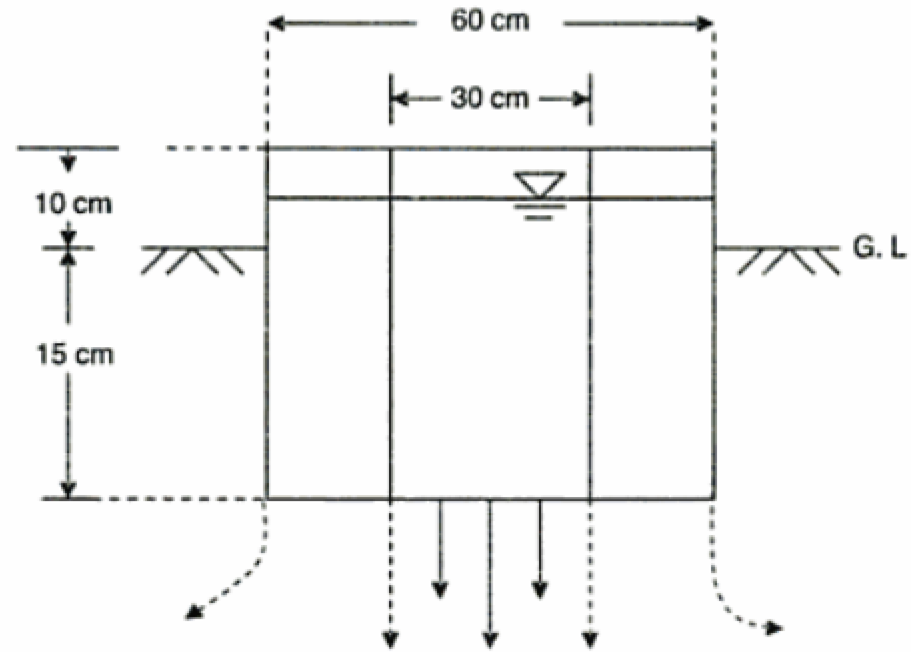


Flooding type Infiltrometers

- Tube type or Single ring infiltrometer
  - As infiltration proceeds, the volume of water is made up by adding water from a measuring burette to keep the level of water upto pointer at regular time intervals
  - Knowing the volume water added in different time periods, the plot of infiltration capacity with time is obtained.

Flooding type Infiltrometers

- **Double ring infiltrometer**
  - Two concentric rings are used
  - Water is poured in both outer and inner rings
  - Measurement is made in inner ring only



Flooding type Infiltrometers

Disadvantages of Flooding type infiltrometers

- The soil is disturbed to some extent when the tubes are driven into the soil.
- There may be lateral flow of infiltrated water. In double-tube infiltrometers, efforts are made to reduce it, but some lateral flow still occurs.
- Similarly, air entrapped in the soil may escape laterally. In a double-tube infiltrometer, this effect persists.
- Effect of the raindrop impact on soil is not accounted.
- Effect of the slope of ground is not accounted.
- Experiments cannot be conducted on soil with boulders etc.
- The infiltration is affected because of the ring size. Smaller the diameter of the ring, more will be the rate of infiltration.

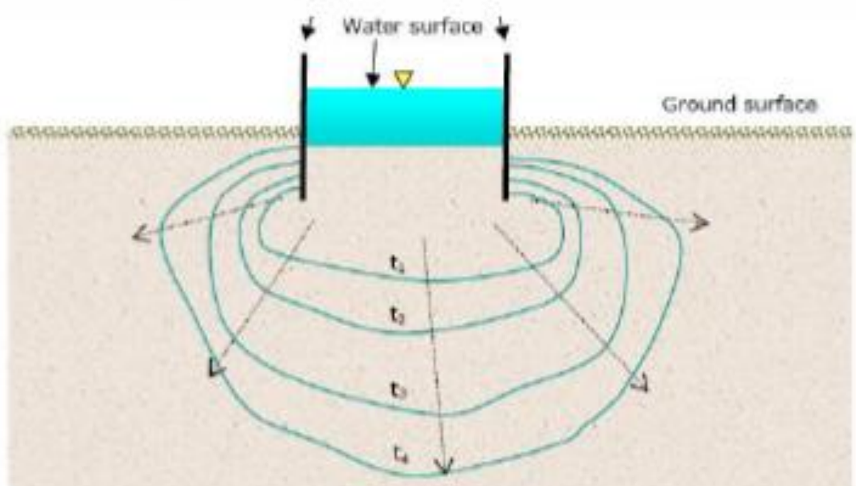


Figure: Infiltrometer diagram showing wetting-front

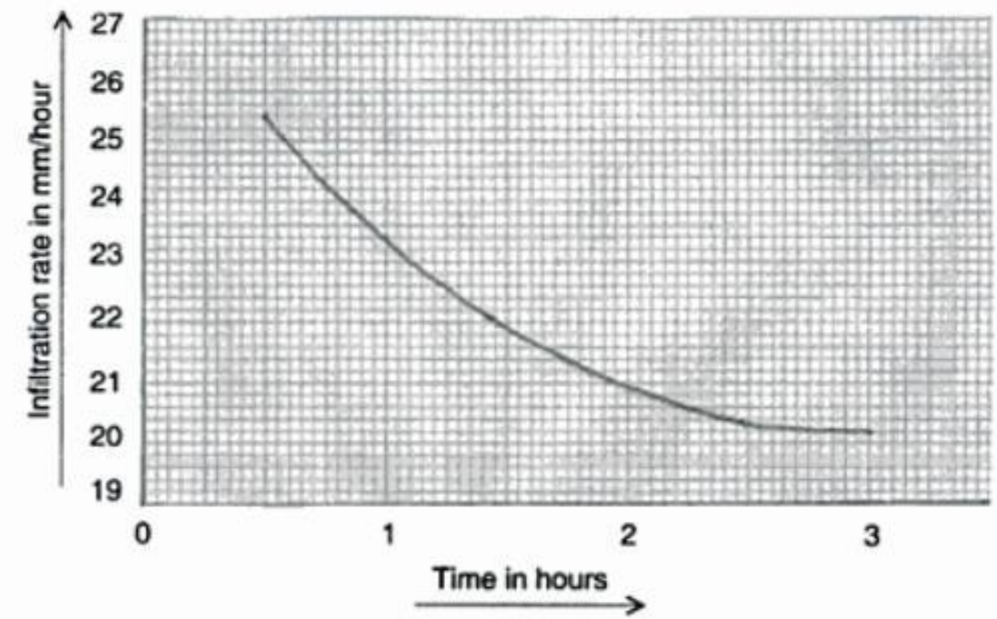
The quantity of water added to a double-ring infiltrometer of 1.0 m diameter at 30 min time interval to keep the water level constant is as follows:

Time (min)	0	30	60	90	120	150	180
Quantity of water added (lit)	0	10	9.2	8.6	8.2	8.0	8.0

Find: 1. Rate of infiltration at 30 min interval and plot the graph

2. compute average rate of infiltration

Solution:



$$\text{Area of ring} = \frac{\pi}{4} \times 1^2 = 0.786\ m^2$$

$$\text{Infiltration rate for 1st 30 min} = \frac{10 \times 10^{-3}}{0.786} \times 10^3 \times \frac{60}{30}$$

$$\text{Infiltration rate for next 30 min} = \frac{9.2 \times 10^{-3}}{0.786} \times 10^3 \times \frac{60}{30}$$

$$\text{Infiltration rate for next 30 min} = \frac{8.6 \times 10^{-3}}{0.786} \times 10^3 \times \frac{60}{30}$$

$$\text{Infiltration rate for next 30 min} = \frac{8.2 \times 10^{-3}}{0.786} \times 10^3 \times \frac{60}{30}$$

$$\text{Infiltration rate for next 30 min} = \frac{8 \times 10^{-3}}{0.786} \times 10^3 \times \frac{60}{30}$$

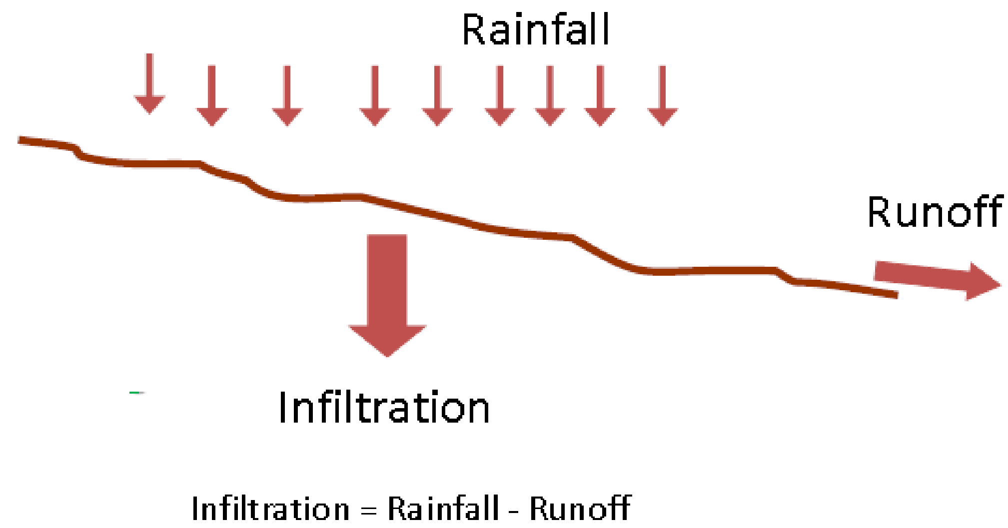
Total quantity of water added in 150 min till a steady state was achieved = 10.0 + 9.2 + 8.6 + 8.2 + 8.0 = 44.0 lit

$$\text{Therefore, average rate of infiltration} = \frac{44 \times 10^{-3} \times 10^3 \times 60}{150 \times 0.786} = 22.39\ mm/h/m^2$$

Measurement of infiltration Rainfall Simulators

Rainfall simulators

Needle drip systems
Stand pipes Sprinkler
nozzles Rotating boom



- Usually a small experimenta
area of about 5 sq.m. is selecte
and rainfall at a constant rate is simulated for sufficient time
- Accurate measurement of discharge is made

Measurement of input of water and output of water (runoff)

- difference is the amount infiltrated
- Plot scale
- Need lots of water, vehicles, plot boundaries

Measurement of infiltration Hydrograph Analysis

- **Average infiltration method**
  - Small basins or plots
  - Use storms with bursts of rain
  - Compute the amount of rain in the burst
  - Separate the runoff volume due to the burst
  - Difference is infiltrated volume

Modelling of Infiltration

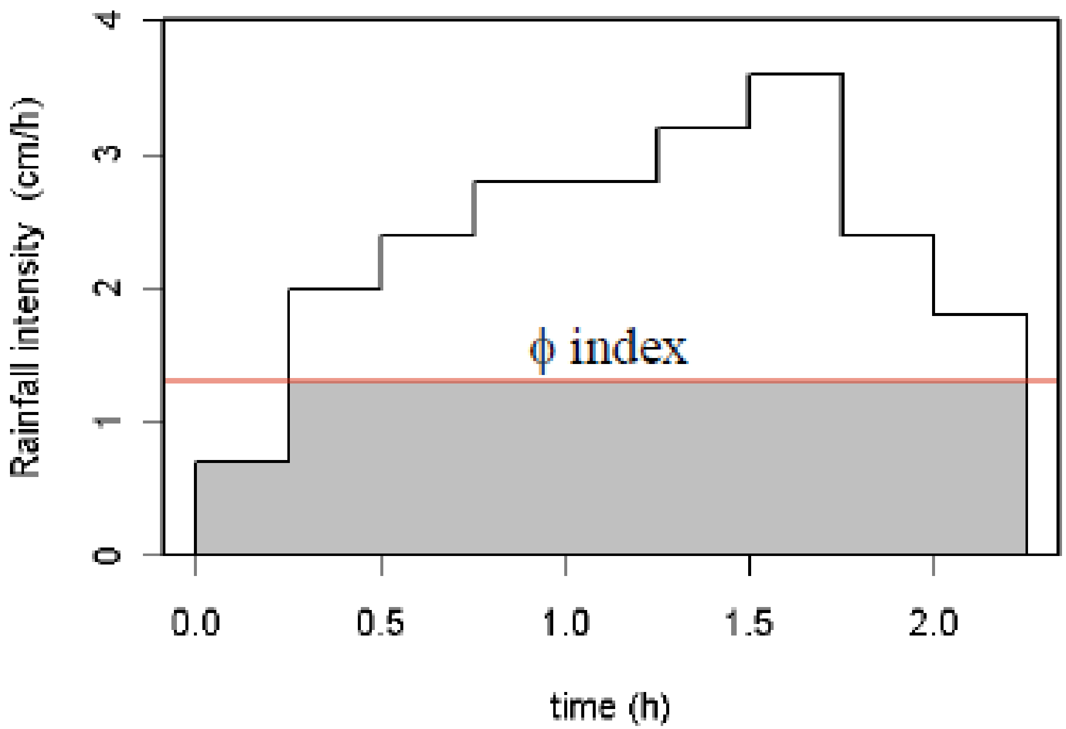
- Infiltration Indices
- Analytical/Conceptual Models of Infiltration

- **Infiltration Indices:**
  - For flood computation, it is found convenient to use a constant rate of infiltration for duration of storm.
  - Consequently the initial rates are underestimated and final rates are overestimated.
  - The defined average infiltration rate is called **infiltration index.**

Phi-index (ϕ-index)

- The ϕ-index is the mean infiltration rate occurring for the duration of storm
- At ϕ-index, rainfall volume = runoff volume
- The index is derived from rainfall hyetograph with knowledge of resulting runoff volume
- For a time interval if the rainfall intensity is less than ϕ, then infiltration is equal to rainfall intensity
- If rainfall intensity is larger than ϕ, the difference between rainfall and ϕ represent runoff in that time interval.
- The amount of rainfall in excess of ϕ index is called **rainfall excess or effective rainfall**.

Phi-index (ϕ-index)



Phi-index (ϕ-index) Computation procedure

- Consider a rainfall hyetograph of duration **D hour having N pulse of time interval Δt such that**
  - $N. \Delta t = D$
- Let **I_i be the intensity of rainfall in i^{th} pulse and Q_d = direct runoff**
  - Total rainfall = $P = \sum_{i=1}^{N} I_i \Delta t$
- If **ϕ is ϕ-index then** $P - \phi . t_e = Q_d$
  - where **t_e = duration of rainfall excess**
- **The ϕ-index can be determined by trial and error procedure.**

Phi-index (ϕ-index) Computation Steps

1. Assume that out of **N pulse**, **M number** of pulse have rainfall excess (note **M ≤ N**). Select **M** number of pulses in decreasing order of rainfall intensity $\mathbf{I_i}$.
2. Find the value of **ϕ** that satisfy the relation

$$Q_d = \sum_{i=1}^{M} (I_i - \phi)\Delta t$$

3. Using the value of **ϕ** in **step 2**, find the number of rainfall pulses $\mathbf{M_c}$ which give rainfall excess ($\mathbf{I_i \geq \phi}$).
4. If $\mathbf{M_c = M}$, step 2 gives correct value of **ϕ**. If not repeat procedure 1 onwards.

Compute ϕ-index for catchment area 430 km^2. volume of direct runoff observed at the catchment outlet = 10.75 M m^3. Observed mass rainfall is as follows.

Rainfall

Time from start	0	3	6	9	12	15
Cum. Depth of Rainfall (mm)	0	12	27	36	58	60

Solution:

Pulse No.	1	2	3	4	5
Time from start of rainfall (hr)	3	6	9	12	15
Cumulative rainfall (mm)	12	27	36	58	60
Incremental rainfall (mm)	12	15	9	22	2
Rainfall intensity (mm/hr)	4	5	3	7.33	0.67

Here, duration of rainfall N = 5 Δt = 3 h and D = N. Δt = 15 h

Depth of direct runoff $Q_d = \frac{10.75\ X\ 10^6\ X\ 1000}{430\ X\ 10^6} = 25\ mm$

Trial – 1: Assume M = 5 and hence $t_e = M.\Delta t = 15$ h

since M = N all pulses of rainfall are included

$$runoff \;\; Q_d = 25 = \sum_{i=1}^{5}(I_i - \phi)\Delta t = \sum_{i=1}^{5} I_i \Delta t - \phi(5X3)$$

$$= [(4X3) + (5X3) + (3X3) + (7.33X3) + (0.67X3)] - 15\phi$$

$$25 = 60 - 15\,\phi$$

$$\Phi = 2.33 \text{ mm/h}$$

By inspection of last row of table,

M_c = No. of pulses having $I_i \geq \phi$ (2.33 mm/h) are 4.

Thus M_c = 4 ≠ M. Hence assumed M is not correct

Try a new value of M < 5 in next trial.

Trial – 2: Assume M = 4 and hence $t_e = M.\Delta t = 12$ h

select 4 pulses in decreasing order, pulse 5 is omitted

$$runoff \;\; Q_d = 25 = \sum_{i=1}^{4}(I_i - \phi)\Delta t = \sum_{i=1}^{4} I_i \Delta t - \phi(4X3)$$

$$= [(4X3) + (5X3) + (3X3) + (7.33X3)] - 12\phi$$

$$25 = 58 - 12\,\phi$$

$$\Phi = 2.75 \text{ mm/h}$$

By inspection of last row of table,

M_c = No. of pulses having $I_i \geq \phi$ (2.75 mm/h) are 4.

Thus M_c = 4 = M. Hence assumed M is OK

Hence ϕ-index = **2.75 mm/h** .

Volume balance checking

Computed Excess rainfall + Total infiltration = Direct Runoff

Duration of rainfall excess = $M.\Delta t = 12$ h

Total Loss = $12 \times 2.75 + 2 = 35$ mm

Excess Rainfall = Total Rainfall − Total Loss

$= 60 - 35 = 25 \text{ mm} = Q_d$

Φ-index Problems

Prob. 1 Calculate **Φ** -index of a storm from the following data. Catchment area = 430 sq. km; Volume of direct runoff after separation of base flow = 10.75 $M.m^3$; Runoff started at 3:00 pm on 17/08/98 (CHECK THE DATA)

Time of rainfall (h)	15	18	21	24	03
Depth of rainfall (cm)	1.2	1.5	0.9	2.2	0.2

Prob. 2 Hourly rainfall of 2.5, 6 and 3 cm occurs over a 20 ha area consisting of 4 ha of **Φ** = 5 cm/hr; 10 ha of **Φ** = 3 cm/hr and 6 ha of **Φ** = 1 cm/hr. Derive hourly values of net rain

Φ-index for practical Purpose (CWC recommendation)

- The ϕ-index depends on soil type, vegetation cover, initial moisture condition, storm duration and intensity.
- For practical use, for estimation of flood magnitude due to large storms in wet season, initial losses are assumed negligible.
- Further only soil type and rainfall are found to be critical.
- On the basis of rainfall-runoff correlation CWC recommended following for Indian conditions:

$$R = \alpha I^{1/2}$$

$$\emptyset = \frac{I - R}{24}$$

Where **R** = runoff in cm from a 24-h rainfall of intensity **I** cm/hr

α = a coefficient depends on soil type

Φ-index for practical Purpose (CWC recommendation)

Variation of α with soil type

Soil type	α
Sandy, sandy loam	0.17 to 0.25
Coastal alluvial and silty loam	0.25 to 0.34
Red soils, clay loam, grey and brown alluvium	0.42
Black cotton soil and clay soil	0.42 to 0.46
Hilly soils	0.46 to 0.50

- **Rule of thumb**: in estimating maximum flood for design purpose, in absence of any other information or data, a **ϕ-index value of 0.10 cm/h** can be assumed.

W-Index

- W-index is considered an improvement over phi-index
- The initial losses are separated from total abstraction and an average value of infiltration, defined as W-index is computed as

$$W - index = \frac{P - Q - I_a}{t_e} = \phi - \frac{I_a}{t_e}$$

Where, P = total storm precipitation

Q = total storm runoff

I_a = Initial loss

t_e = duration of rainfall excess, i.e. total time in which the rainfall intensity is greater than W in (hrs) and

W = average rate of infiltration

- For computation, the initial losses are deducted from starting pulses of storm hyetograph, once initial losses are satisfied then same procedure as for ϕ-index is followed.

Try Prob 3.20 on page 119 (Subramanya)

Modelling Infiltration Capacity

Point infiltration models

Working with point infiltration models

- The **three infiltration models** presented are the most popular among a number of at a point infiltration models used in hydrology.
- Fundamentally there are no advantages of one over the other.
- **The Horton model** can be justified as a solution to Richard's equation under specific (and practically limiting) assumptions.
- **The Philip model** has less limiting assumptions (than Horton) but is a series approximation solution to Richard's equation.
- **The Green-Ampt model** provides a precise solution to a relatively crude approximation of infiltration in terms of a sharp wetting front.
- In many practical applications the parameters in the Horton model, Philip model and Green – Ampt model, are treated simply as empirical parameters whose values are those that <u>best fit infiltration data</u>, or as <u>fitting parameters in relating measured rainfall to measured runoff.</u>

Parameter Estimation

Horton's Model

$$\boxed{f_p(t) = f_c + (f_0 - f_c)e^{-kt}}$$

- f_0 initial infiltration rate, f_c is constant rate and **k** is decay constant
- Using the experimental data, parameters of Horton's model can be estimated

$$f_p - f_c = (f_0 - f_c)e^{-kt}$$

$$ln(f_p - f_c) = ln(f_0 - f_c) - kt$$

- Plot ***ln(f**$_p$** – f**$_c$**)*** against **t** and fit the best straight
- line through the plotted points
- The intercept gives ***ln(f**$_0$** – f**$_c$**)*** and the slope of the
- straight line is **k**.

Example: Horton's Model

Example 3.7 Infiltration capacity data obtained in a flooding-type infiltration test is given below:

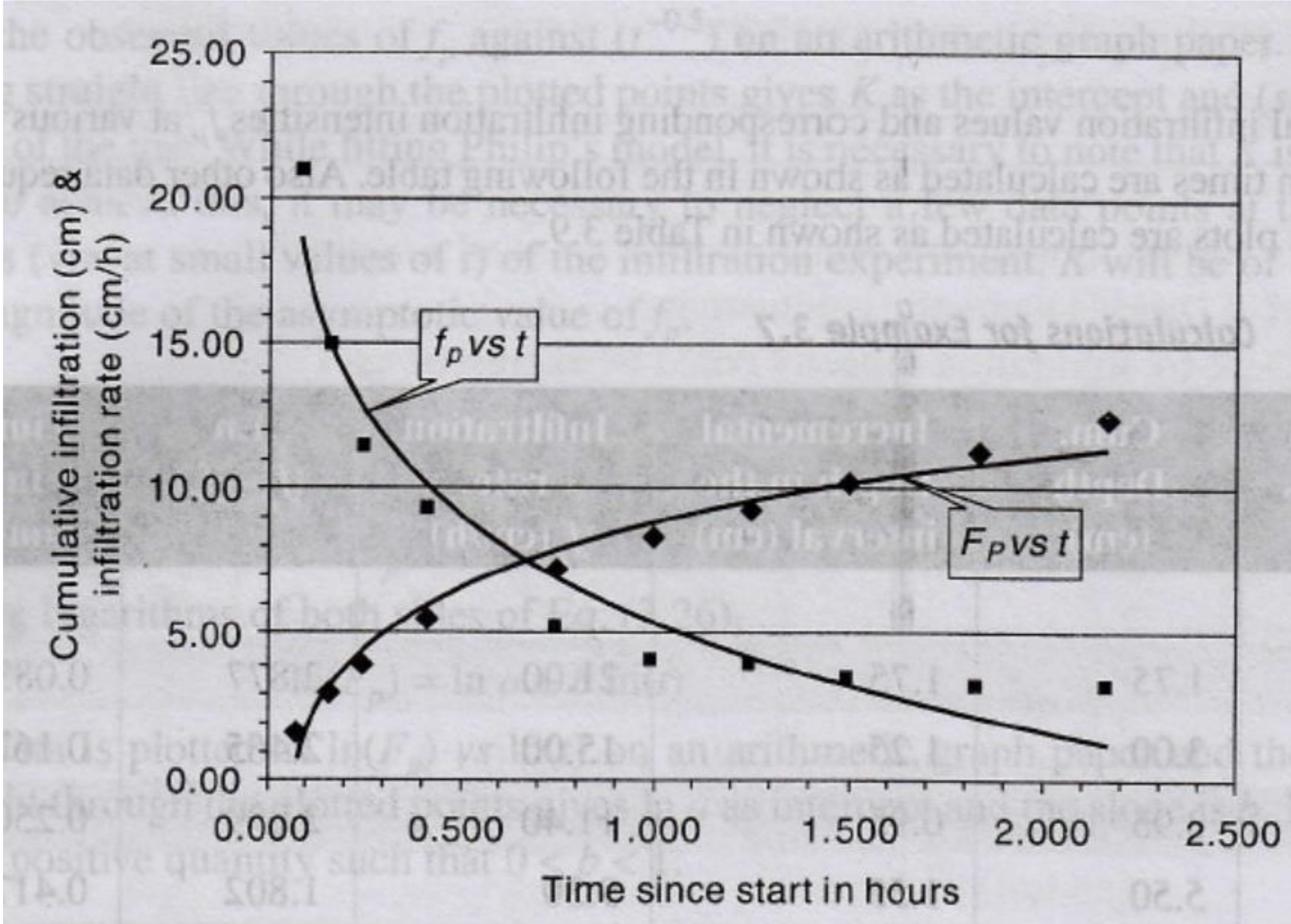
Time since start (minutes)	5	10	15	25	45	60	75	90	110	130
Cumulative infiltration depth (cm)	1.75	3.00	3.95	5.50	7.25	8.30	9.30	10.20	11.28	12.36

(a) For this data, plot the curves of (i) infiltration capacity vs time, (ii) infiltration capacity vs cumulative infiltration, and (iii) cumulative infiltration vs time.

(b) Obtain the best values of the parameters in Horton's infiltration capacity equation to represent this data set.

Table 3.9 *Calculations for Example 3.7*

Time in Minutes	Cum. Depth (cm)	Incremental Depth in the interval (cm)	Infiltration rate, f_p(cm/h)	Ln $(f_p - f_c)$	Time in hours
0					
5	1.75	1.75	21.00	2.877	0.083
10	3.00	1.25	15.00	2.465	0.167
15	3.95	0.95	11.40	2.099	0.250
25	5.50	1.55	9.30	1.802	0.417
45.	7.25	1.75	5.25	0.698	0.750
60	8.30	1.05	4.20	–0.041	1.000
75	9.30	1.00	4.00	–0.274	1.250
90	10.20	0.90	3.60	–1.022	1.500
110	11.28	1.08	3.24		1.833
130	12.36	1.08	3.24		2.167


25.00
20.00
15.00
10.00
5.00
0.00
Cumulative infiltration (cm) &
infiltration rate (cm/h)
f_p vs t
F_P vs t
0.000
0.500
1.000
1.500
2.000
2.500
Time since start in hours

By observation from Table 3.9, $f_c = 3.24$ cm/h

$\text{Ln}(f_p - f_c)$ is plotted against time t as shown in Fig. 3.14-c. The best-fit line through the plotted points is drawn and its equation is obtained as

$\ln(f_p - f_c) = 2.8868 - 2.6751\ t$

$-K_h$ = slope of the best fit line = -2.6751, thus $K_h = 2.6751\ \text{h}^{-1}$

$\ln(f - f_c)$ = intercept = 2.8868, thus $f_0 - f_c = 17.94$ and $f_0 = 21.18$ cm/h

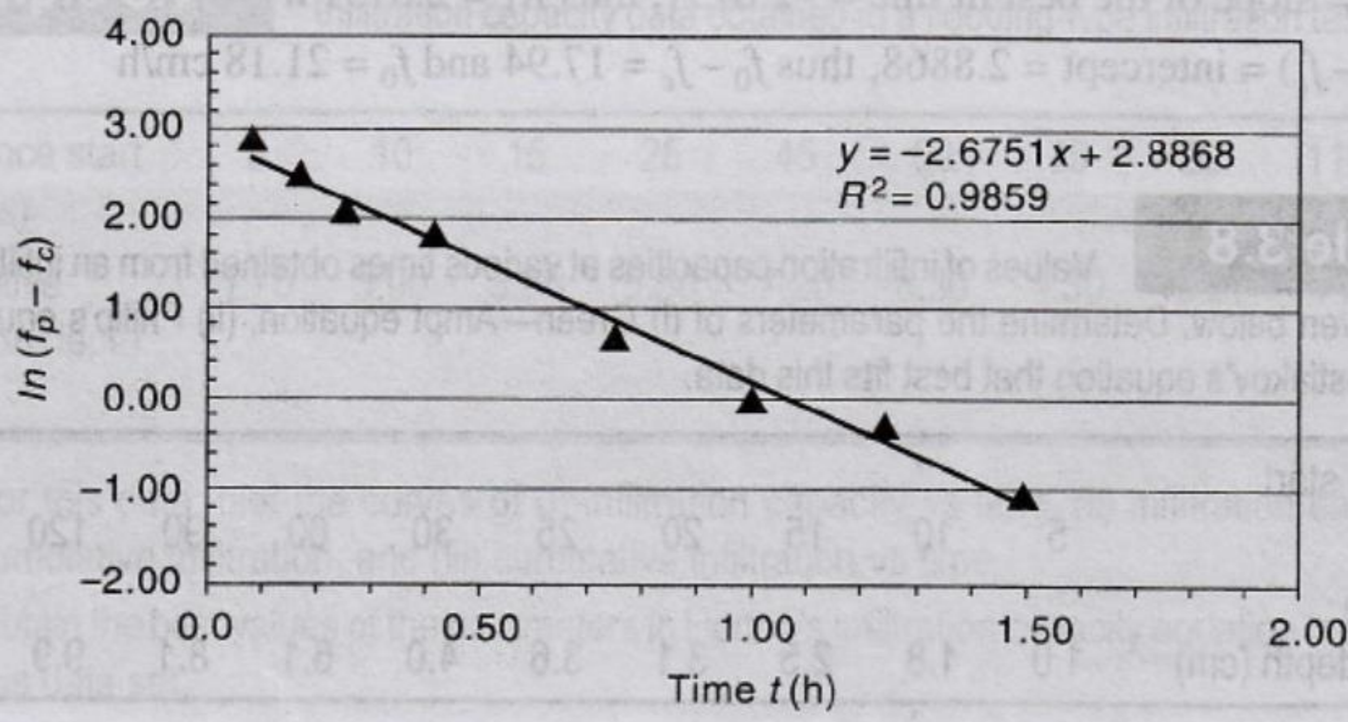


Fig. 3.14 (c) ***Horton's Equation. Plot of $\ln(f_p - f_c)$ vs Time***

Example 3.9

- The infiltration capacity in a basin is representred by Horton's equation as

$$f_p = 3.0 + e^{-2t}$$

Where *fp* is in cm/hr and t in hr. Assuming the infiltration to take place at capacity rates in a storm of 60 min duration, estimate the depth of infiltration in (i) first 30 min and (ii) the second 30 min of the storm.

Philip's Equation

- Philip's two-term model relates $F_p(t)$ *as*
- $F_p = st^{1/2} + Kt$
- Where s = a function of soil suction potential called *sorptivity*
- K = Darcy's hydraulic conductivity
- *Infiltration capacity* :

$$fp = \frac{1}{2} s t^{-\frac{1}{2}} + \mathrm{K}$$

Parameter Estimation

- Plot observed fp vs (t-0.5) on an arithmetic graph
- Best fitting straight line through the plotted points gives *K* as the intercept and (s/2) as the slope of the line
-

Green-Ampt Model $fp = m + \frac{n}{Fp}$

- f_p vs ($1/F_p$) on a simple arithmetic graph
- Best fit straight line
- Intercept and slope of the line are the coefficients *m* and *n respectively*

- **Kostiakov equation**

Cumulative Infiltration Capacity $$F_p = at^b \qquad a > 0 \; and \; 0 < b < 1$$

$$lnF_p = ln\, a + b\; ln(t)$$

- Data set is plotted as ln (F_p) vs ln(t) on a an arithmetic graph paper
- f_p is given by:

Infiltration Capacity

- $f_p = ab\; t^{b-1}$

Method of Least Square (MOLS)

- Suppose there are n pairs of x and y values plotted, and a straight line $y_e = a + b\,x$ can be fitted to the data points, where **a** and **b** are parameters.
- The value $\mathbf{y_e}$, obtained from the straight line, is the estimate of observed $\mathbf{y_o}$.
- The parameters must be determined such that the n points lie as close to the line as possible.
- In other words, the sum of errors between all values of $\mathbf{y_e}$ and $\mathbf{y_o}$, that is, $\sum|y_o - y_e|$ has the smallest possible value.
- One way to accomplish this objective is to determine **a** and **b** (or define the line) such that $\sum(y_o - y_e)^2$ has the smallest value.
- This procedure is called the method of least squares (MOLS), where the sum is computed for the given **n** pairs of **x** and **y** values

Method of Least Square (MOLS)

$$S = \sum_{i=1}^{n} d_i^2 = \sum_{i=1}^{n} [y_0(i) - y_e(i)]^2$$

$$= \sum_{i=1}^{n} [y_0(i) - f(x_i; a_1, a_2, \ldots, a_m)]^2$$

For a straight line $\boldsymbol{y_e = a + b\,x}$

$$a = \bar{y} - b\bar{x}$$

$$b = \frac{\Sigma x_i y_i - n\bar{x}\bar{y}}{\Sigma x_i^2 - n\bar{x}_i^2}$$

$$\bar{y} = \frac{1}{n}\Sigma y_i, \qquad \bar{x} = \frac{1}{n}\Sigma x_i$$

$$r = \frac{\Sigma xy - n\bar{x}\bar{y}}{[(\Sigma x^2 - n\bar{x}^2)(\Sigma y^2 - n\bar{y}^2)]^{0.5}}$$