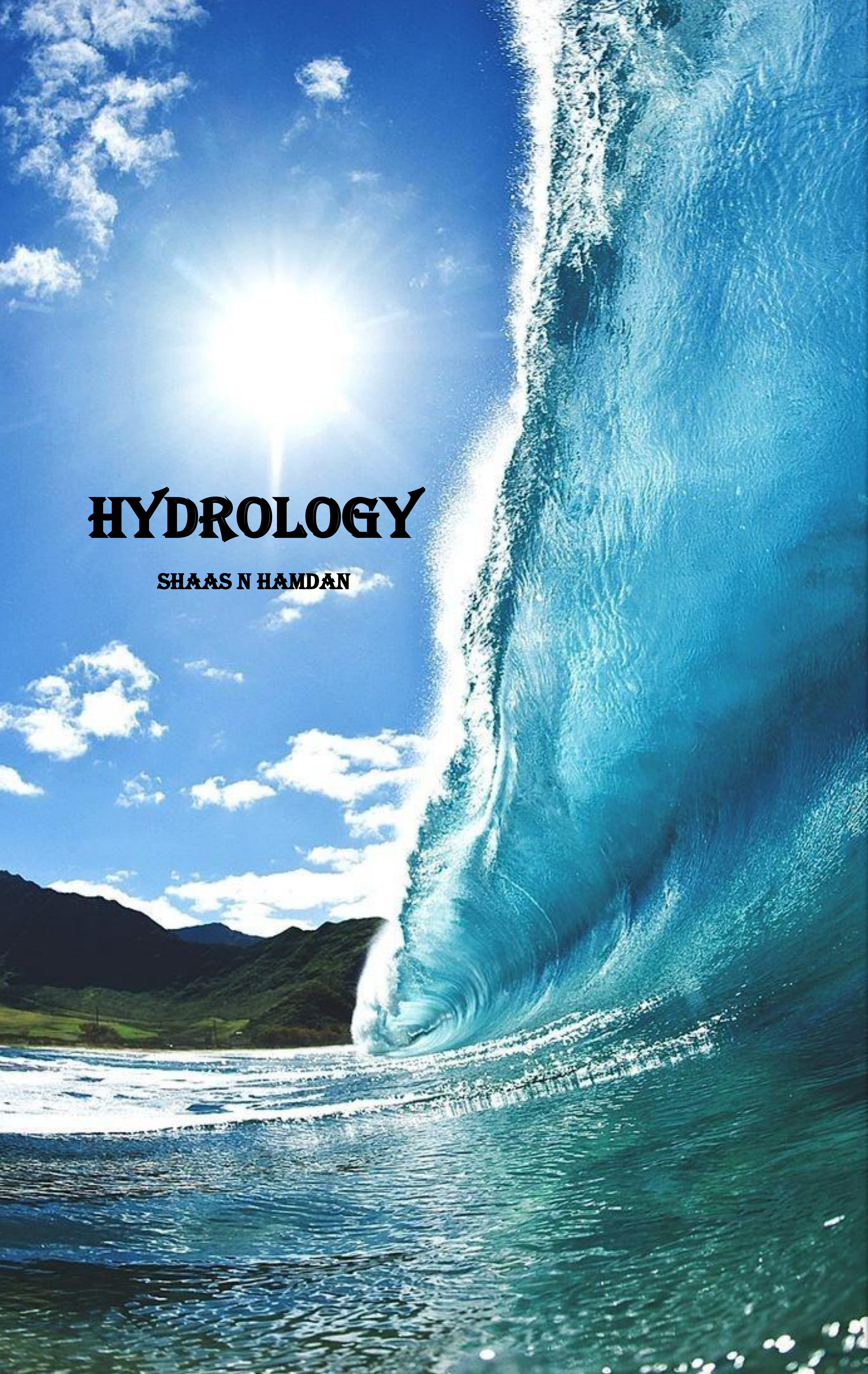
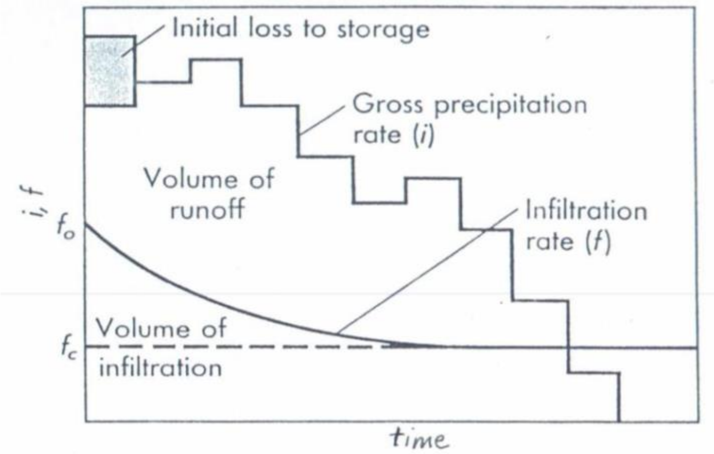


HYDROLOGY

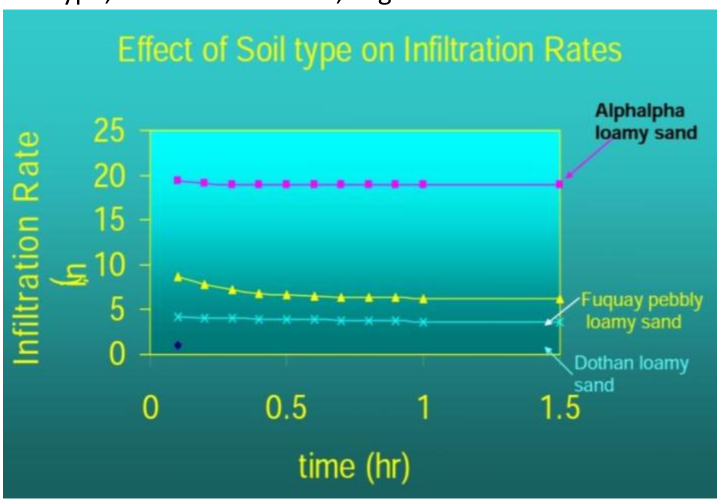
SHAAS N HAMDAN

INFILTRATION

- Rainfall: 3 Possibilities (Evaporation,Runoff,Infiltration)
- **Infiltration:** entrance of water into the ground surface
- **Infiltrated water affect**: replenishes soil moisture, & recharges groundwater
- evaporation can occur from soil & the water table
- **Motion of water is driven by** gravity & capillary action
- **capillary action**: Water attracted to soil surfaces causes water to move into the pores between soil particles
  - ➢ The smaller the pore, the greater the attraction & the greater the suction force
- When rainfall rate (i) > infiltration rate (f) → water infiltrates surface soil at a rate decreases with time, & usually reaches a constant value

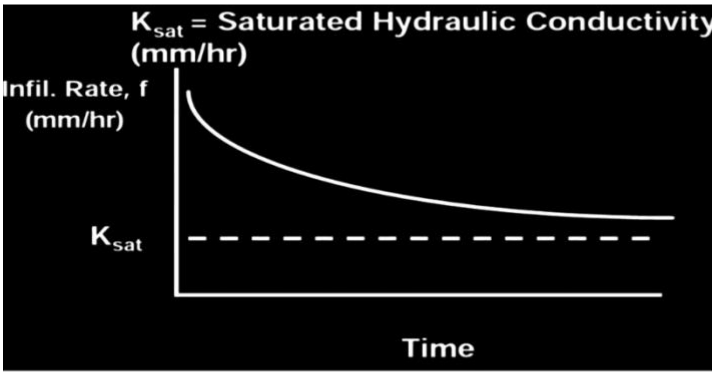


- Rate of infiltration is a function of rainfall intensity, soil type, surface conditions, vegetative cover

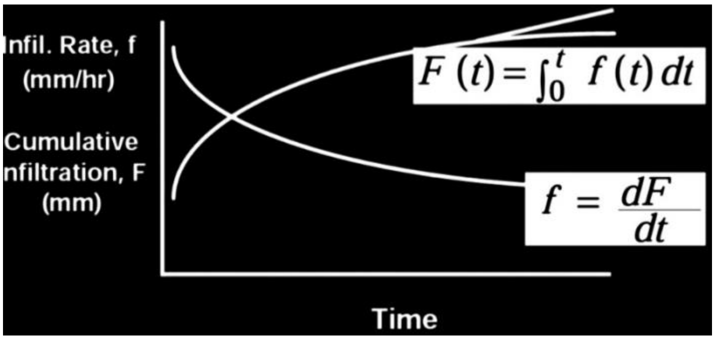


- **Infiltration Capacity**: maximum rate of infiltration
- Infiltration Rate: rate of actuall infiltration
- **Ideal case of Infiltration**: homogeneous soil with pores directly connected by capillary passage, & uniform distribution of rainfall over the surface

- The infiltration rate (capacity) is NOT constant over time
  - ➢ Starts out at a maximum, then drops off & approaches a constant with time
  - ➢ water which can not infiltrate is then free to run off
  - ➢ The land surface partitions flow in two directions



- *Saturated Hydraulic Conductivity K_{sat}* is a constant value
- *Unsaturated Hydraulic Conductivity* varies with moisture causing heaps of computational problems
- ***Infiltration rate = depth or volume*** of infiltrated water



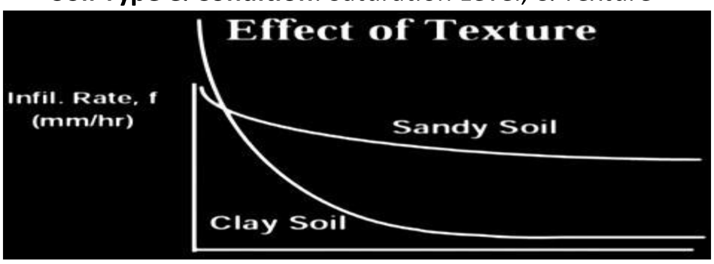
$$F(t) = {}_0\int^t f(t)\,dt$$

$$f = \frac{dF}{dt}$$

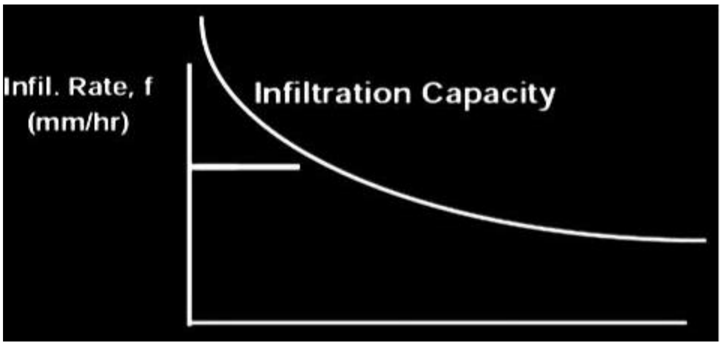
f: Infiltration rate (mm/hr), **F**: Cumulative infiltration (mm)

VARIABLES AFFECTING INFILTRATION

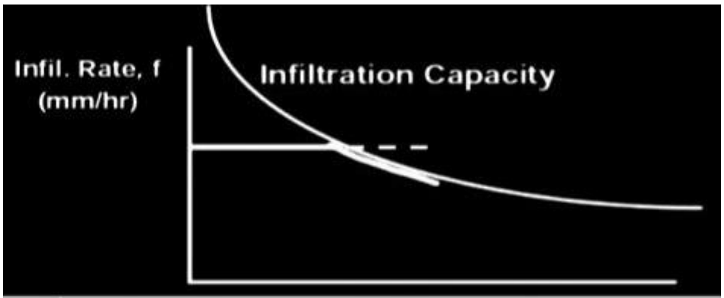
- **Factors affect the amount & the rate of Infiltration:**
  1. **Soil Type & Condition**: Saturation Level, & Texture
  2. **Surface Condition:** Sealed vs. Soil, & Surface Crust vs. Open Structure
  3. **Rainfall Intensities**
- **Soil Type & Condition**: Saturation Level, & Texture

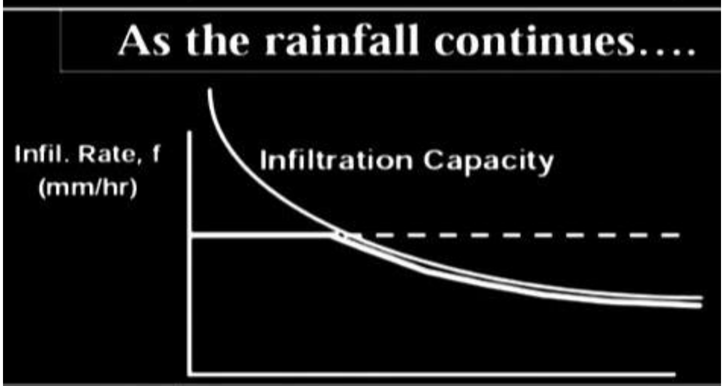


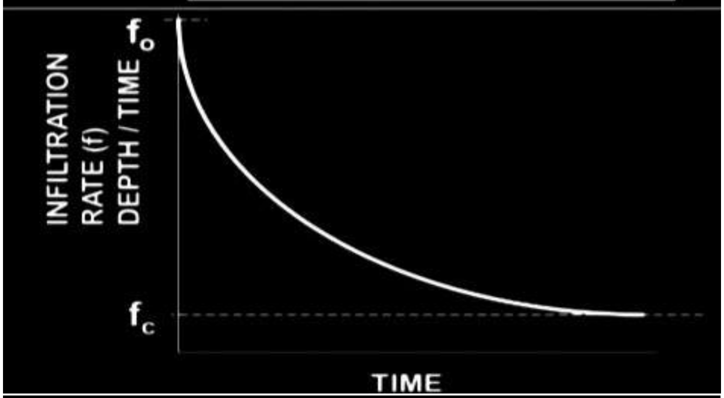
- **Effect of Rainfall Intensity:** Infiltration will occur at the rainfall intensity as long as the rainfall intensity is less than the infiltration capacity

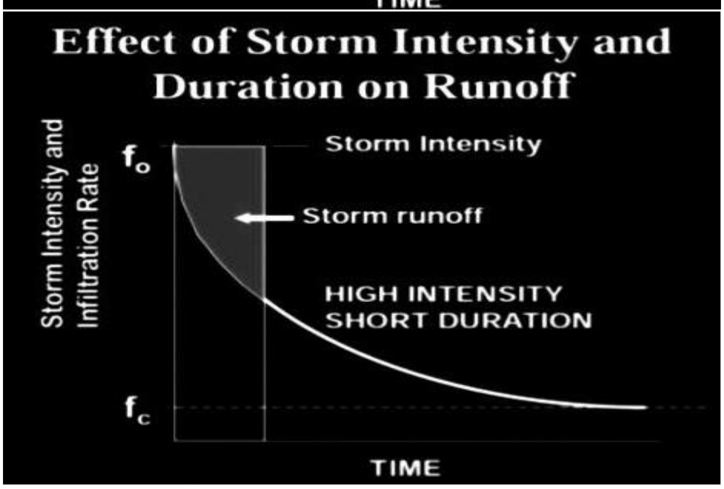


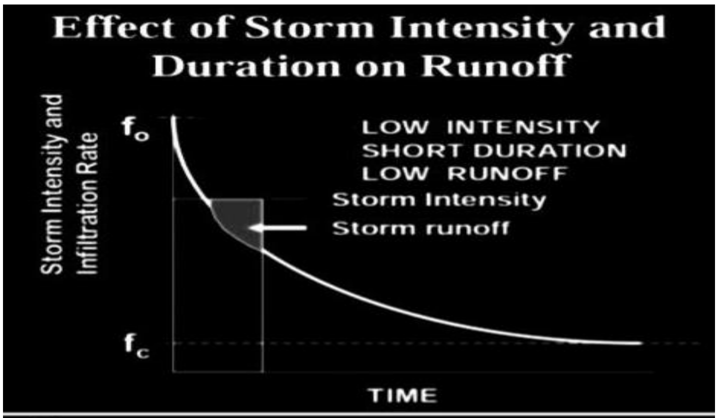
- If rainfall intensity > infiltration capacity: water enters the soil at the infiltration capacity

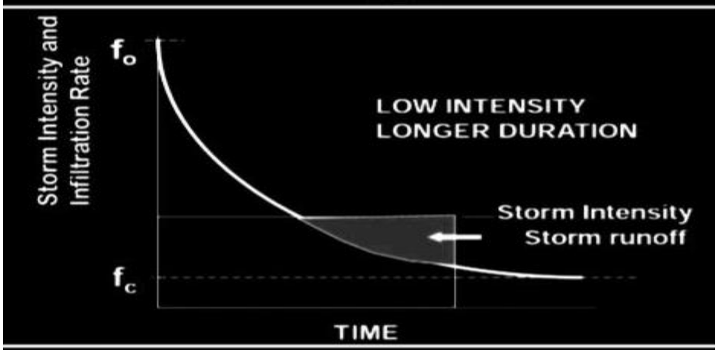


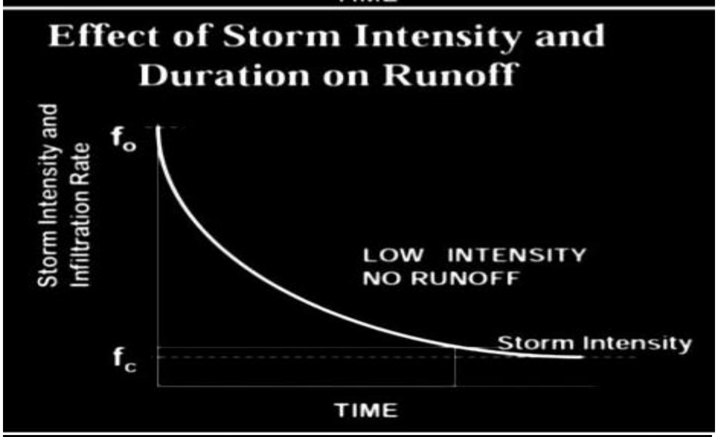


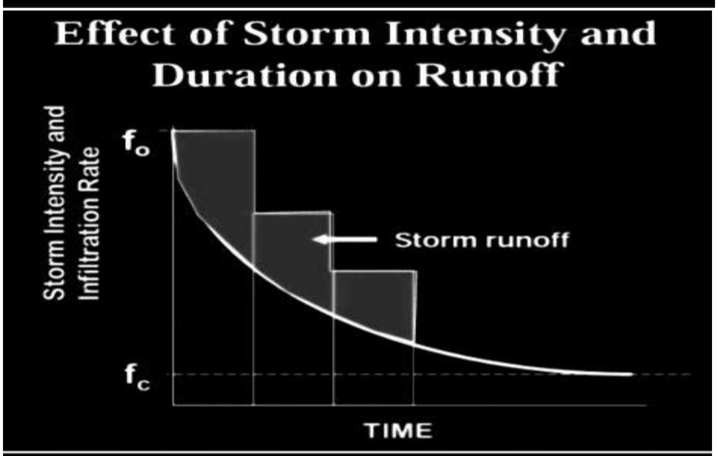


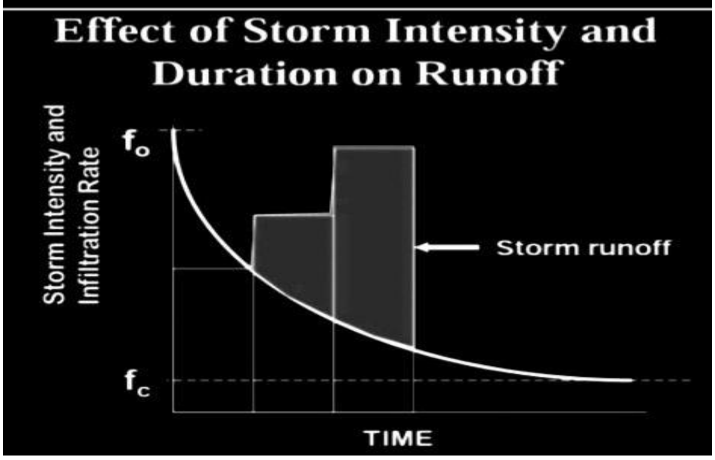












MODELLING INFILTRATION

- Models vary in sophistication from average rates for a different soils to the use of differential equations governing unsaturated flow in porous media
- Most efforts are of two approaches:
  1. Empirical equations based of observations
  2. Solution of equations based on mechanics

Horton's Infiltration Model rate is assumed to start at some rate f_0, & then falls exponentially to a constant rate fc

$$f(t) = f_c + (f_0 - f_c)e^{-kt}$$

f(t) = infiltration rate at time t (mm/hr), f_0 = Initial infiltration rate (mm/hr)
f_c = Equilibrium infiltration rate (mm/hr) (steady-state)
k = decay rate constant (hr^{-1})

When i > f: $f = f_c + (f_0 - f_c)e^{-kt}$

f = infiltration rate (in/hr), f_0 = Initial infiltration rate (in/hr)
f_c = Equilibrium infiltration rate (in/hr), ***k*** = decay rate constant (hr^{-1})

Soil Type	f_c	f_0	K
Alphalpha Loamy Sand	1.40	19.00	38.29
Carnegie Sandy Loam	1.77	14.77	19.64
Dothan Loamy Sand	2.63	3.47	1.400
Fuquay Pebbly Loamy Sand	2.42	6.24	4.700
Lee field Loamy Sand	1.73	11.34	7.700
Tooup Sand	1.80	23.01	33.71

Typical Values for the Horton Model in (in-hr units)

Example A soil has f_0 = 1.5, fc = 0.20, & k = 0.35, [In & hr]

1. Calculate the values of f at t (12 & 30 min; 1,2,&6hr)
2. Calculate total volume of infiltration over 6hr period

Solution

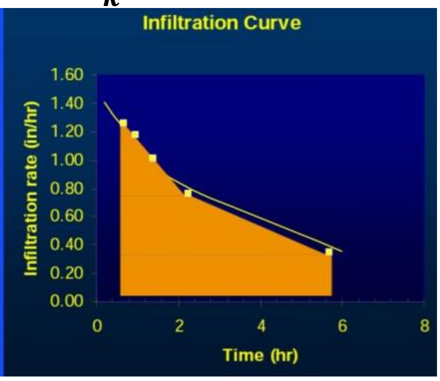
Can only use Horton's equation if i > f, so Assume i > f

Equation to calculate total volume

$$V = int_0^t f dt = int_0^t [f_c + (f_0 - f_c)e^{-kt}]dt$$

$$= f_c t + \frac{f_0 - f_c}{-k} e^{-kt}|_0^t$$

time (hr)	Infiltration rate (in/hr)
0.2	1.41
0.5	1.29
1	1.12
2	0.85
6	0.36



$$V = \left[\frac{(0.2x6) + (1.5x0.2)}{-0.35xe^{-6x0.35}}\right] - \left[\frac{(0.2x0) + (1.5 - 0.2)}{-0.35xe^{-0.35x0}}\right]$$

$$= 4.46in$$

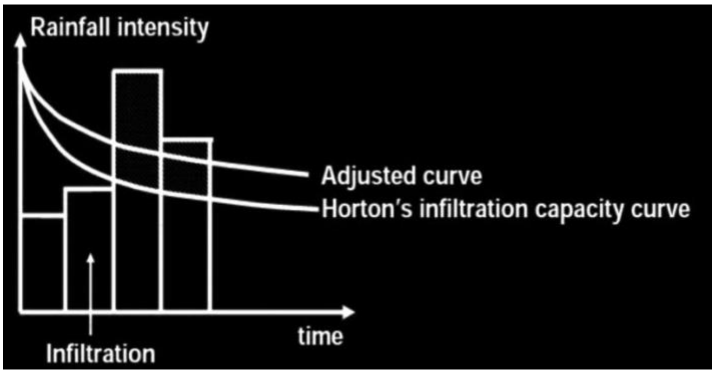
Infiltration capacity: f(t) = $0.2+1.3e^{-0.35t}$ [in/hr]

Cumulative depth: F(6)= 4.46 in

t	f
1/6	1.43
0.5	1.29
6	0.36

Mass infiltration Method

- Horton's infiltration curve is for continued ponding
- If rainfall intensity < infiltration capacity, curve adjusted

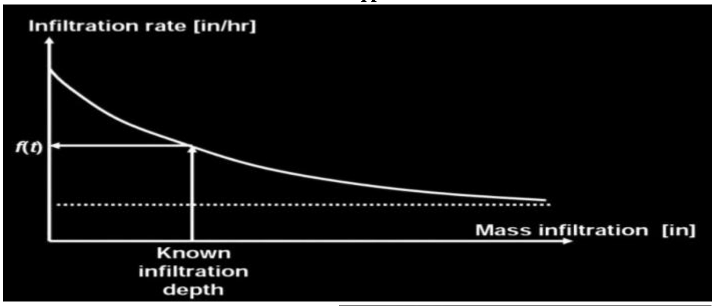


- **Assumption**: Infiltration capacity is a function of total mass of infiltrated water.

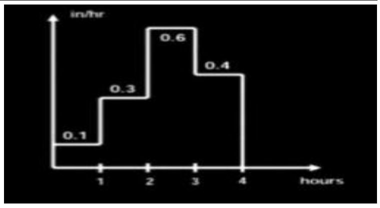
$$f(t) = f_c + (f_0 - f_c)e^{-kt}$$

Under ponding: mass curve data

$$F(t) = f_c t + \frac{f_0 - f_c}{K}(1 - e^{-kt})$$

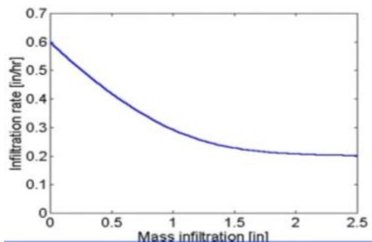


Example if f0 = 0.6 in/hr, fc = 0.2 in/hr, k = 0.6 1/hr, determine the depth of runoff associated with hyetograph



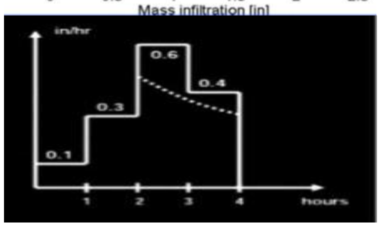
F(t) = $0.2+0.4e^{-0.6t}$

$$F(t) = 0.2t + \frac{0.4}{0.6}(1 - e^{-0.6t})$$



f(2) = 0.32

f(2) = 0.87



Assuming infiltration is limited by rain intensity:

f(2) = 0.40in/hr (rain in first 2hr)

f(2) = 0.45in/hr (from mass curve)

From t = 2 to 4

f(t) = fc + (f2-fc) $exp^{-0.k(t-2)}$ = $0.2+0.25exp^{-0.6(t-2)}$

At t = 2 → initial infiltration capacity = 0.45in/hr

The revised Horton model applies from t' = t-2

$$F(t') = f_c t' + \frac{f_2 - f_c}{k}[1 - e^{-kt'}] where\ t' = t - 2$$

= 0.2t' + 0.417[1-$e^{-0.6t'}$]

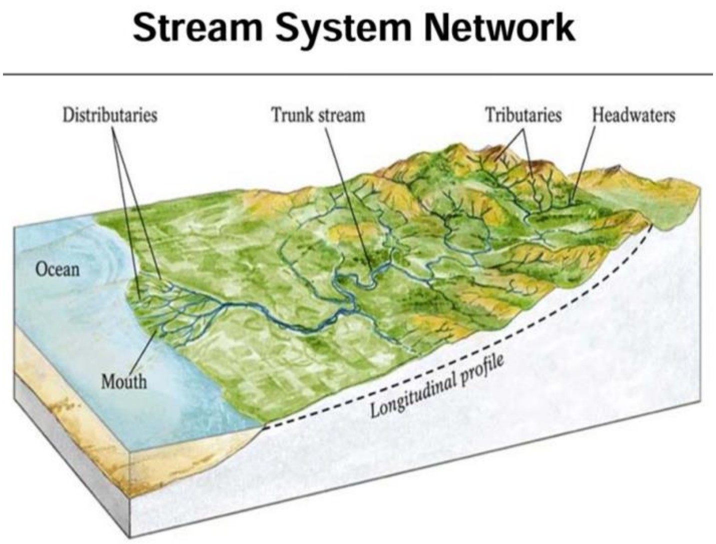
F(2) = 0.69in

Accumulated rainfall during period = 1in

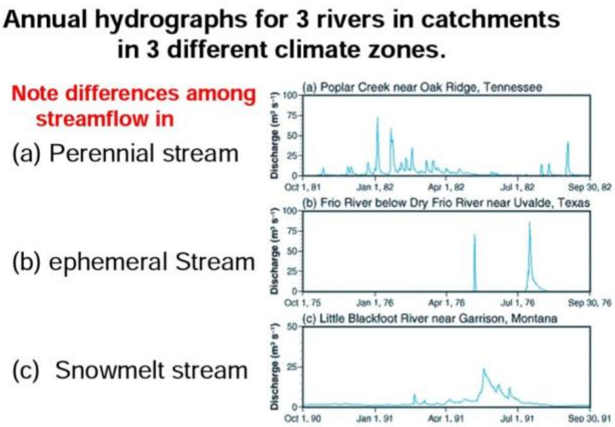
Depth of rainfall = 1-0.69 = 0.31in

STREAM FLOW MEASUREMENTS

- **Streamflow (SF)** is generated by snowmelt, rainfall, & groundwater entering a channel
- During dry period streamflow sustained by groundwater discharges, & where groundwater is below the channel level streamflow ceases until next storm or melt event

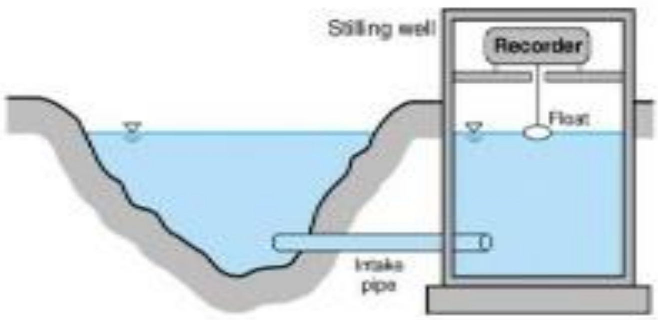


- **Flow Regime Classification:** based on continuity degree & reflects strong influence of climate factors
  1. **perennial**: never ceases to flow
  2. **intermittent:** flows only part of year
  3. **ephemeral:** flows only after rain event

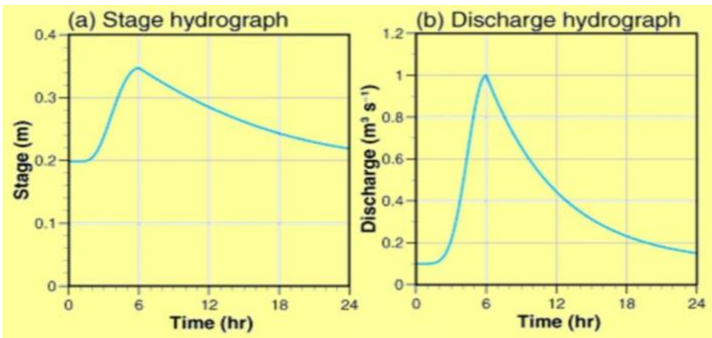


- **Knowledge of the quantity & quality are important for:**
  1. water supply, flood control, & reservoir design
  2. hydroelectric generation, navigation, & wildlife
- **Published SF are based on field measurements using:**
  1. flow-measuring devices such as weirs and flumes
  2. channel cross-sections along flow velocities
  3. measurement of water levels

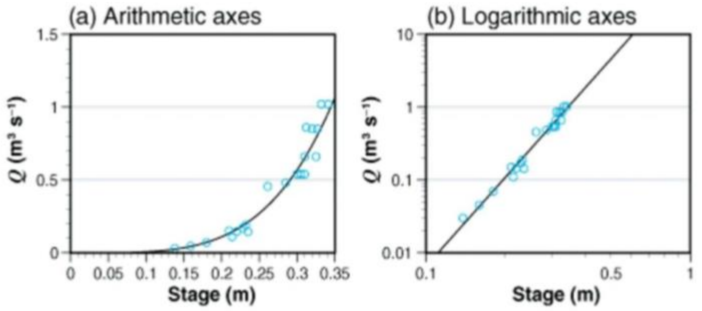
- Daily SF reported as discharge (flow rate): water volume passes a particular reference point / time [m^3 / s]
- **Stream gauging stations:** to record flow depth (stage) as a function of time, The result is a stage hydrograph

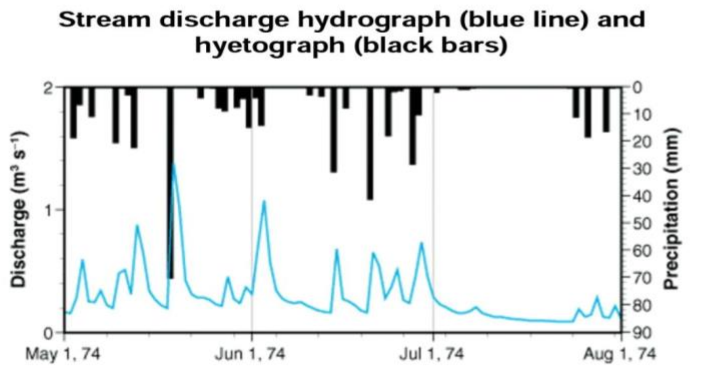


- **Hydrograph:** changes in the discharge of water as a function of time



- **Discharge-stage (Rating) curve**: stage hydrograph can be converted to a discharge curve using the rating curve





MEASUREMENT & RECORD

- For large stream systems discharge is estimated by measuring velocity & using cross-sectional area to translate measurement into discharge

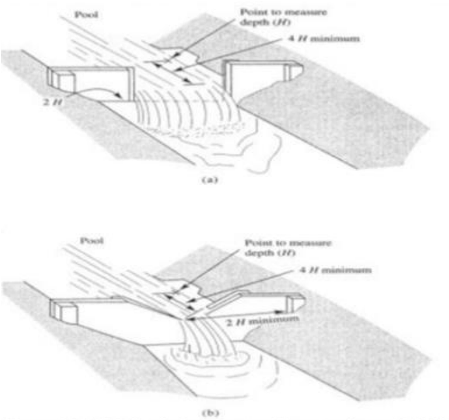
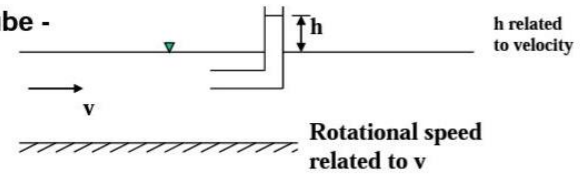


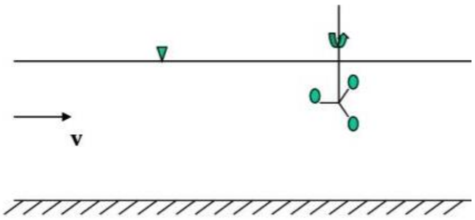
Figure 8.4 Field installation of weirs: (a) rectangular and (b) V-notch. USDA Cooperative Extension Service, Mountain States Area.

- Point flow velocities determined using several devices: Current meter (standard), Pitot tube, Dynamometer
- Channel velocities determined using: Chemical tracers

Pitot tube -



Current meter –

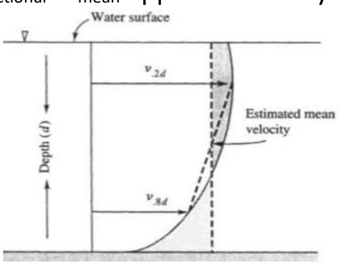


- Relating V_{point} to $V_{cross\text{-}Sectional}$: V_{mean} approximated by

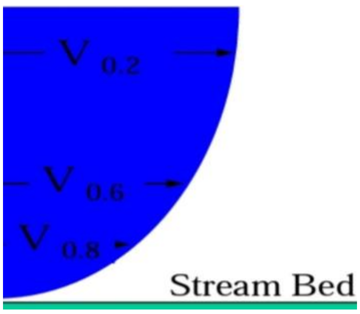
$$\overline{V} = \frac{v_{0.2d} + v_{0.8d}}{2}$$

order of 0.5 ft:

$$\overline{V} = v_{0.5d}$$



- **Velocity Profile**: Representative V obtained by the arithmetic mean of $V_{0.2}$ & $V_{0.8}$, For shallow depth-representative velocity can be approximated by $V_{0.6}$



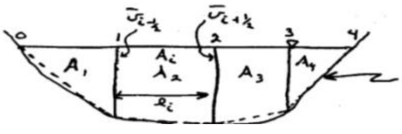
average velocity for each section: $V_i = \frac{\overline{V}_i + \overline{V}_{i+1}}{2}$

Area for section i is given by: $A_i = \frac{I_i(d_i + d_{i+1})}{2}$

discharge for section i: $Q_i = A_i v_i$

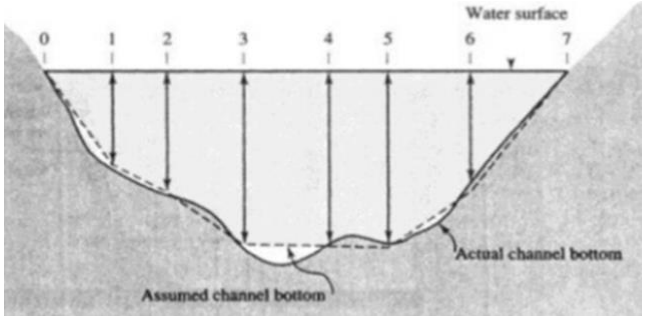
total discharge: $Q_{total} = \Sigma_{i=1}^{n} Q_i$

بعد حساب السرعات
نضربها بالمساحات المختلفة



- Average flow velocity when multiplied by the crosssectional area yields the discharge of the stream, A popular approach is the mean-section method
- **Mean-section method**: Divide stream cross-section into series of geometric shapes, & Estimate the mean velocity at each vertical location

EXAMPLE depending on the following mean-section, & the following data, calculate total discharge



Vertical section	Depth [ft]	$\overline{V}$ [ft/s]	Horizontal Segment	Segment width [ft]
0	0.0	0.0	0-1	4.2
1	4.0	2.1	1-2	3.3
2	5.0	2.3	2-3	4.8
3	7.2	2.7	3-4	5.2
4	7.4	2.8	4-5	3.7
5	7.1	2.5	5-6	5.1
6	4.7	2.2	6-7	5.9
7	0.0	0.0	0	0.0

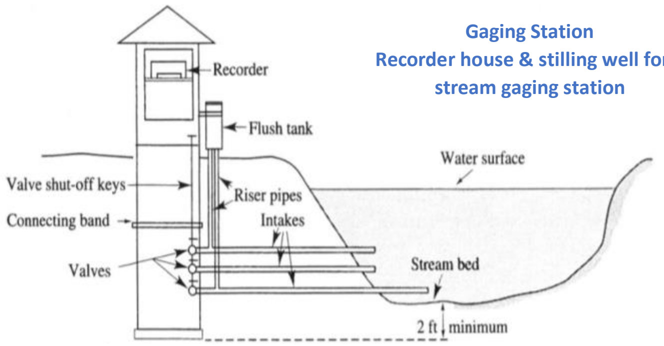
$$A_1 = 4.2x\frac{(4+0)}{2} = 4.8, A_2 = 3.3x\frac{5+4}{2} = 14.85 \ldots$$

$$V_1 = \frac{2.1+0}{2} = 1.05, V_2 = \frac{2.3+2.1}{2} = 2.2 \ldots$$

$$Q_1 = 8.4x1.05 = 8.82, Q_2 = 14.85x2.2 = 32.67 \ldots$$

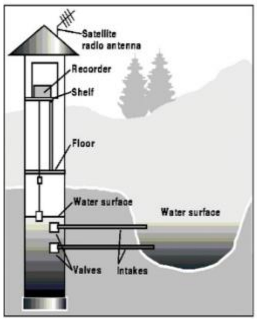
Section	A (ft²)	V (ft/s)	Flow (cfs)
A1	8.400	1.05	8.820
A2	14.85	2.20	32.67
A3	29.28	2.50	73.20
A4	37.96	2.75	104.4
A5	26.83	2.65	71.09
A6	30.09	2.35	70.71
A7	13.87	1.10	15.25
TOTAL DISCHARGE			376.13

- **Relating river stage to discharge** a water elevation (stage) surveyed during measurement of stream flow
  - with enough measurements one can construct a stage-discharge relationship for the site. using this relationship one need only to monitor river stage to obtain estimates of instantaneous discharge

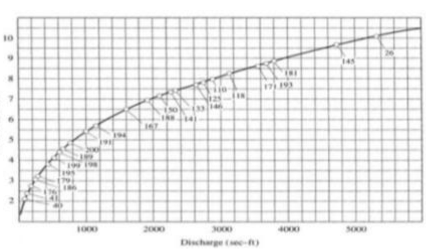


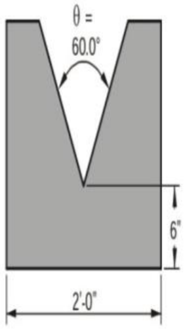
Gaging Station
Recorder house & stilling well for a stream gaging station

- **Measuring streamflow:** Measured at an observing station or elevation above a specific datum in a channel

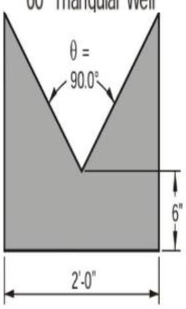


Stage-Discharge Relationship

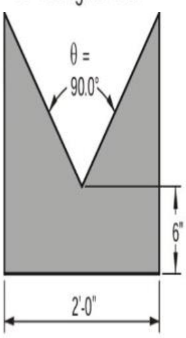




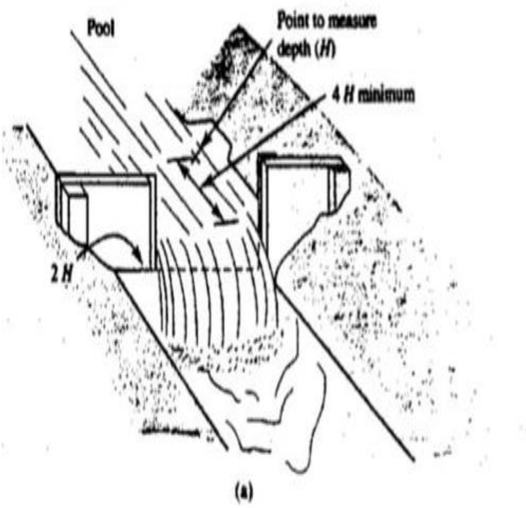
60° Triangular Weir



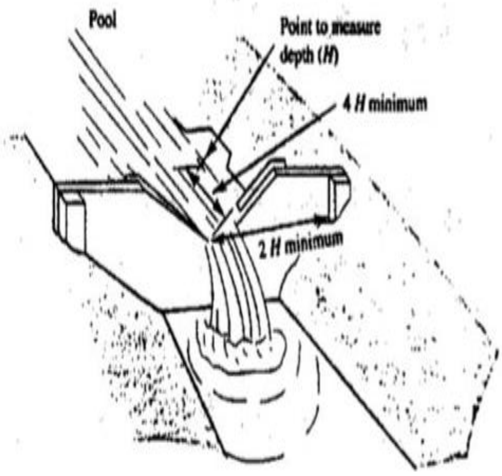
90° Triangular Weir



90° Triangular Weir



Rectangular Weir & V-notch

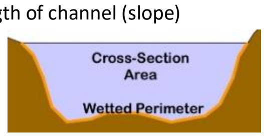


- Slope area method to determine discharge
  - ➢ Some cases difficult to make velocity measurements e.g., floods
  - ➢ Possible to take measurement of high-water lines, cross-sectional area, & channel slopes, then using Manning's equation to obtain estimate of discharge

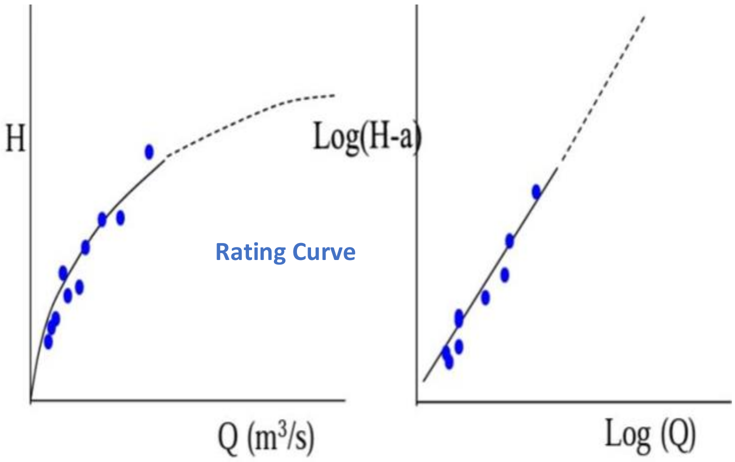
$$Q = \frac{1.49}{n} x A x R^{2/3} x S^{1/2} = AV$$

Q: discharge [m³/s], **n**: coefficient (empirical), **A**: Area [m²]
R: hydraulic radius [m], **S**: head loss per unit length of channel (slope)

$$\textit{Open Channel Flow}: V = \frac{C}{n} R^{2/3} S^{1/2}$$



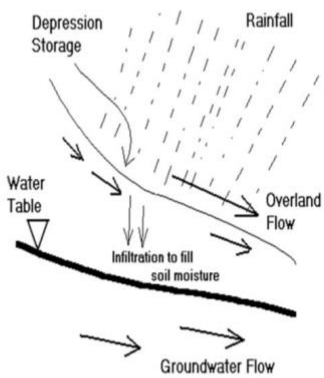
V: velocity, **S**: Slope [ft/ft], **n**: roughness coefficient
C = 1.49 (for ft unit) = 1 (for m unit)

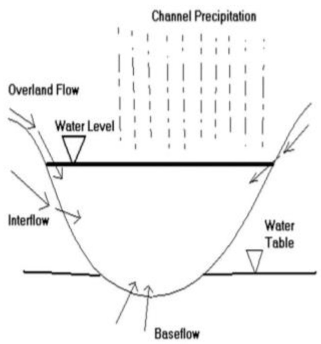


Minning Roughness Coefficient (n)			
Smooth concrete	0.012	Cultivated soil	0.040
Corrugated pipe	0.025	Sluggish weedy stream	0.150
Smooth soil	0.030	Shallow overland flow	0.300

STREAM FLOW ESTIMATION

- **Streamflow Estimation** for ungauged sites
  - ➢ correlation with data from gauged sites
  - ➢ relationship with climate/catchment characteristics
  - ➢ rainfall-runoff modelling
- **Baseflow index (BFI):** ratio of baseflow volume to total flow volume, indicates importance of g.w. contribution, & varies 0.1 - 0.7
- **Baseflow recession constant (K):** ratio of Q_t/Q_{t-1} indicates rate of depletion of g.w. storage, & depends on time interval used, varies from 0.95 - 0.995 (daily)
- **Interflow**: movement of water through a shallow soil horizon without reaching the zone of saturation
- **Overland flow**: surface runoff, movement of water over land, down-gradient to nearest channel (river, stream)
- **Baseflow**: portion of flow orginates from groundwater & soil, e.g., from a spring





- **Stream flow & Unit Hydrographs:** represent velocity & depths at particular cross-section of stream with time
  - ➢ Hydrograph magnitude, shape, & time depend on:

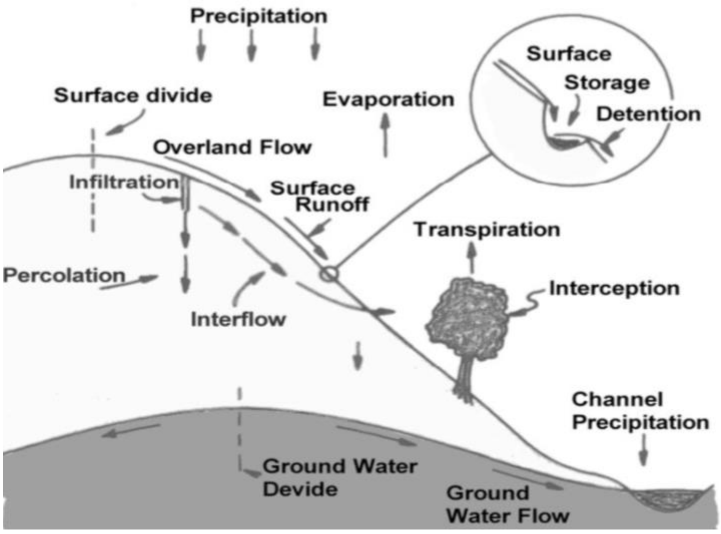
1. surface runoff, & interflow
2. groundwater or base flow, & channel precipitation
3. characteristics of the watershed: size, slope, shape, & storage
4. the rainfall event: intensity, & duration

RUNOFF

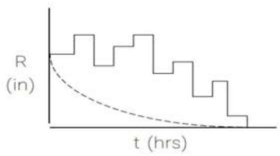
- **Runoff can occur if** precipitation rate > Infiltration rate, & when depression & Interception storage are filled

Runoff & Rainfall → Depression Storage → Overland Flow → Stream Flow

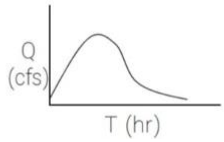
- **Runoff influenced by:** Soil properties, Soil water content, Climate, Topography, Vegetation, & Land cover
- **Abstraction:** Processes acting to reduce total ppt into effective ppt, & produce runoff, includ Interception, evapotranspiration, infiltration, evaporation, surface & depression storage



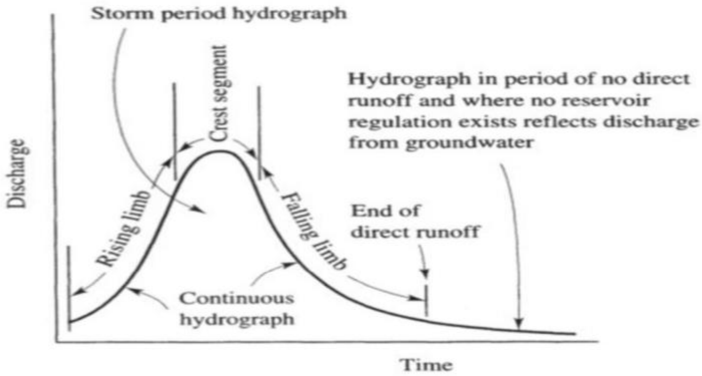
- **Interception**: Abstraction by surface cover (vegetation)
  - through fall, part of ppt that reaches the ground
  - amounts: light storms 25%, moderate 7-36% in sea, heavy & longer storms (small)
  - **Components:** evaporation loss, & Interception storage (retained by foliage)
- **Surface or depression storage:** Abstracted ppt retained in puddles, ditches , & other depressions in surface
  - milder the relief, greater the depression storage
  - sand 5mm, pervious urban 6.25mm, loam 3.75mm, paved areas 1.5mm, & clay 2.5mm
- **Infiltration**: seepage of rainfall into the ground (contribution to groundwater)



- **Runoff**: Volume or flow rate, varies with t express in flow/(drainage A, runoff depth)
- **components contribute to runoff:**
  - **Surface flow (runoff, or direct runoff):** Flows from channels that reach the catchment outlet
  - **Groundwater flow:** other route of infiltrated water to undergo deep percolation, & reach groundwater
  - **Interflow (through flow):** is a part of precipitation that infiltrate through soil & return to surface at some location away from the point of entry into soil
- **Surface runoff in catchments:**
  - **overland flow (sheet):** excess rainfall moves over land surface to reach small channels

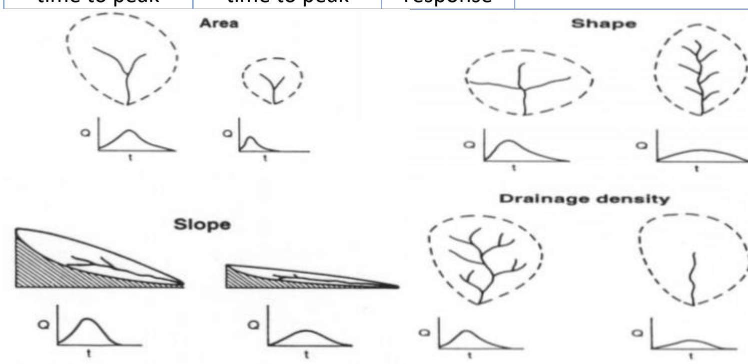


  - **gully flow:** runoff with erosive capability
  - **stream flow:** concentrated runoff
  - **river flow:** confluence of streams
- **Types of Inflows**
  - **Delayed interflow**
  - **Prompt interflow**: interflow with the least lag time
- **Types of ground water flow**
  - **Base inflow**: persistence over time
  - **Interflow**: for shorte periods of time
- **Hydrograph**: plot of flow rate (discharge) with time



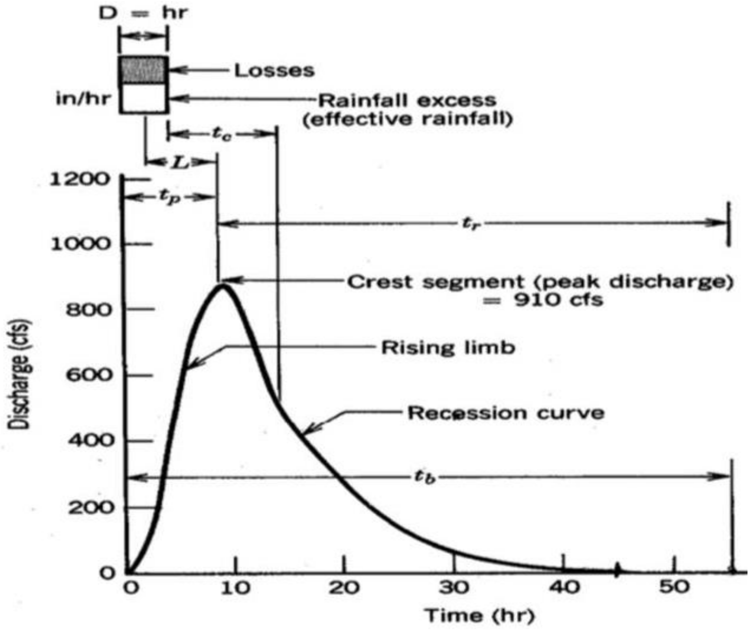
- **Hydrograph shape & peak flow are affected by watershed characteristics (α A, Slope, Elongation, ρ)**

Area	Slope	Shape	Drainage density
Larger basins larger response & more time to peak	**Steeper basins** Larger peak flow, & Faster time to peak	**Elongate** More diffuse response	**Higher Density** Larger peak flow, & Faster time to peak
Smaller basins Smaller response & less time to peak	**Gentler basins** Smaller peak flow, & Slower time to peak	**Spherical** Less diffuse response	**Lower Density** Smaller peak flow, & Slower time to peak

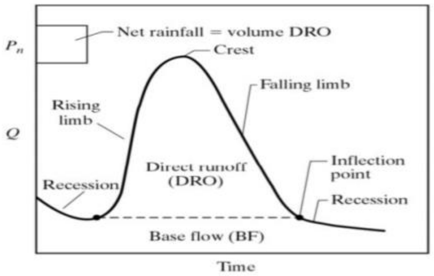


HYDROGRAPH PROPERTIES

- The hydrograph consists of 3 parts:
  1. Rising limb or concentration curve
  2. Crest segment or peak discharge
  3. Recession curve or falling limb



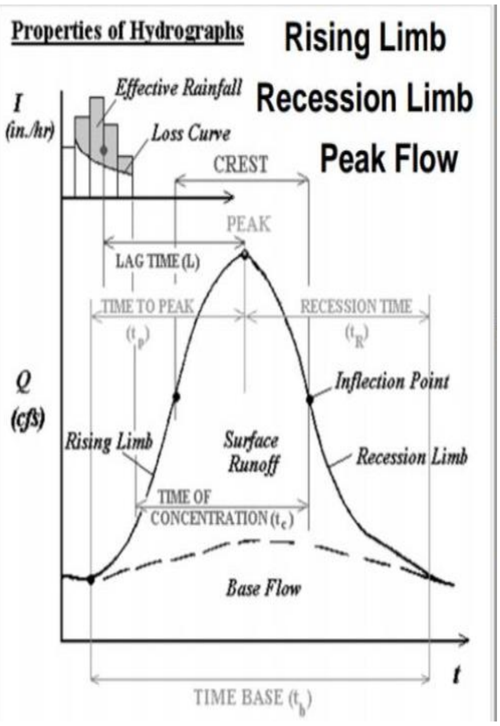
- rainfall excess or effective rainfall volume is the same as volume of runoff (area under runoff hydrograph)
- **Storm hydrograph include:** direct runoff & baseflow



Net rainfall = gross rainfall - infiltration

- **The runoff hydrograph properties**

Lag Time (L) Time interval from the center of mass of rainfall excess to the peak of the resulting hydrograph
Time Of Peak (p) Time interval from the start of runoff to the peak of the resulting hydrograph
(c) Time Of Concentration Time interval from the end of runoff excess to the inflection point on the recession curve
Recession time (r) Time from the peak to the end of surface runoff
Time base (tb) Time from the beginning to the end of surface runoff



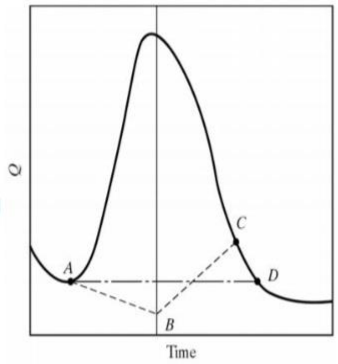
BASEFLOW (BF) SEPARATION

Method 1: BF = constant = lowest discharge before storm

Method 2/ Extend Base Flow recession to under peak then to inflection point on falling limb

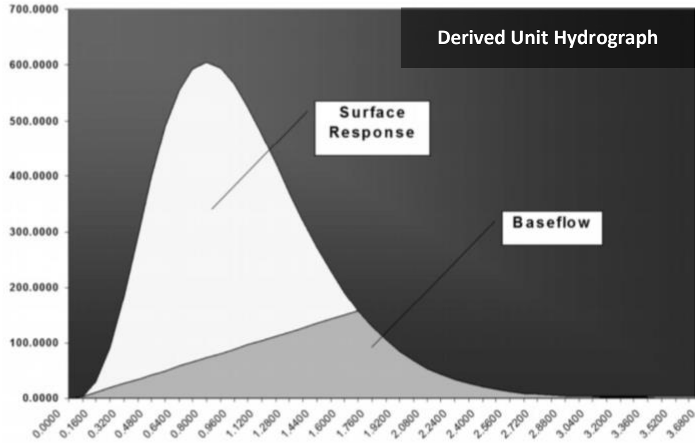
Method 3 : Empirical relationship: N = A0.2

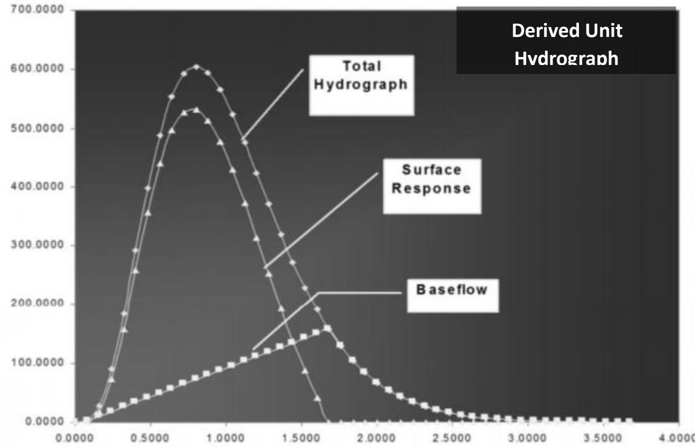
N: days from peak to end, A: area



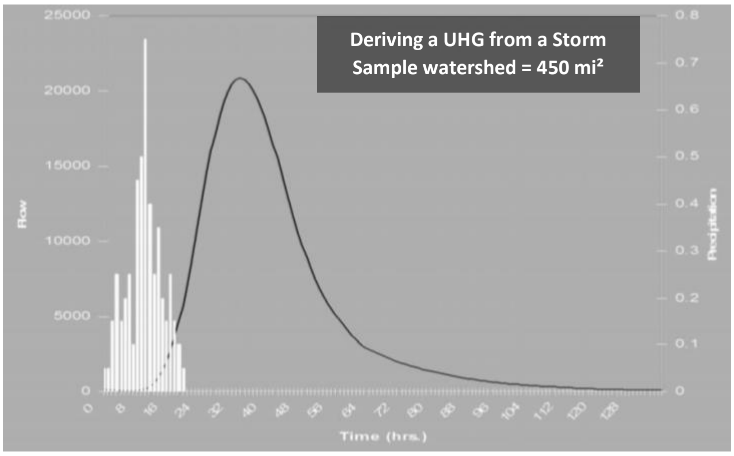
UNIT HYDROGRAPH

- The hydrograph that results from 1in or 1cm of excess precipitation (or runoff) spread uniformly in space & time over a watershed for a given duration
- **The key points:**
  - ➢ 1in of EXCESS precipitation
  - ➢ Spread uniformly over space (even over watershed)
  - ➢ Uniformly in time (excess rate is constant over time)
  - ➢ There is a given duration

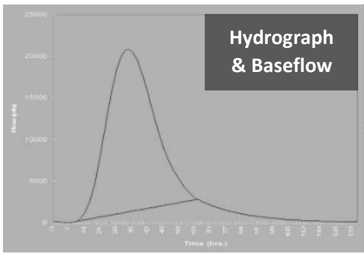


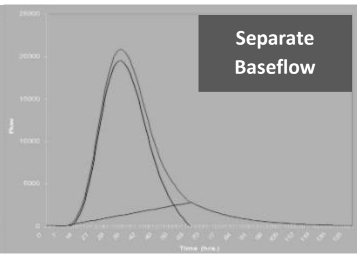


- **Rules of Thumb: to derived unit hydrograph**
  - ➢ the storm should be fairly uniform in nature & the excess precipitation should be equally as uniform throughout the basin. This require initial conditions throughout the basin to be spatially similar
  - ➢ the storm should be relatively constant in time (no breaks or periods of no precipitation)
  - ➢ the storm should produce at least an inch of excess precipitation (the area under the hydrograph after correcting for baseflow)



- **Separation of Baseflow:** the inflection point on the recession limb of a hydrograph is the result of a change in the controlling physical processes of the excess precipitation flowing to the basin outlet
  - ➢ In this example, baseflow is considered to be a straight line connecting point at which hydrograph begins to rise rapidly & the inflection point on the recession side of the hydrograph
  - ➢ the inflection point found by plotting hydrograph in semi-log fashion with flow being plotted on the log scale & noting the time at which the recession side fits a straight line

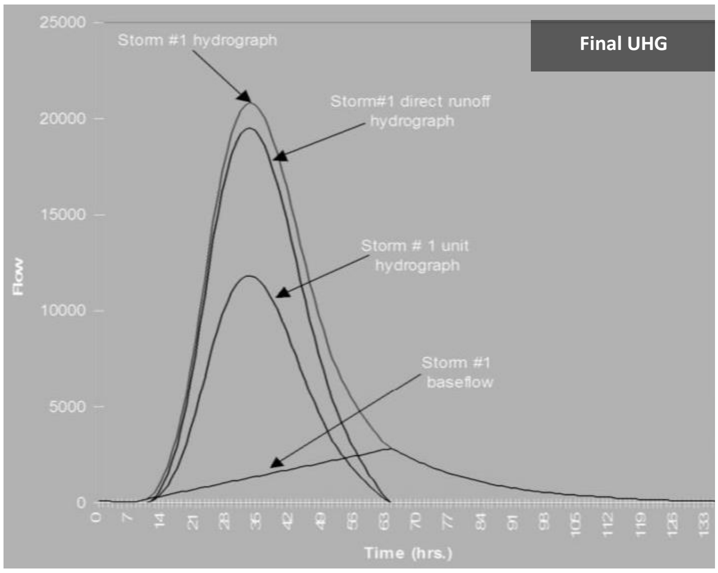




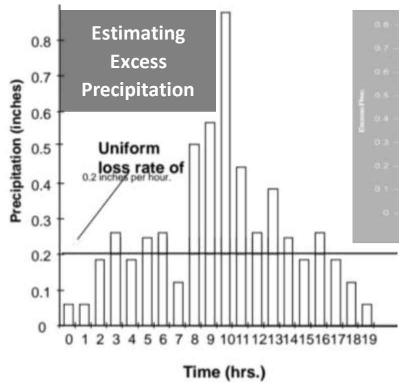
- Sample Calculations
  - ➢ In the present example (hourly time step), the flows are summed & then multiplied by 3600s to determine the volume of runoff in ft³ & converted to acre-feet by dividing by 43,560 ft² per acre
  - ➢ The depth of direct runoff in ft is found by dividing the total volume of excess precipitation (acre-ft) by watershed area (450 mi² converted to 288,000 acre)
  - ➢ the volume of excess precipitation or direct runoff for storm 1 was determined to be 39,692 acre-feet.
  - ➢ The depth of direct runoff is found to be 0.1378ft after dividing by the watershed area of 288,000 acre
  - ➢ the depth of direct runoff: 0.1378 x 12 = 1.65in

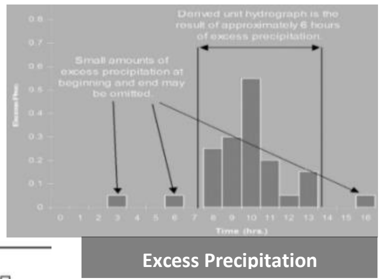
OBTAIN UHG ORDINATES

- The ordinates of the unit hydrograph are obtained by dividing each flow in the direct runoff hydrograph by the depth of excess precipitation
- In previous example, units of the unit hydrograph cfs/in



- **Determine Duration of UHG**
  - ➢ The duration of the derived unit hydrograph is found by examining the precipitation for the event & determining that precipitation which is in excess
  - ➢ This is accomplished by plotting the precipitation in hyetograph form & drawing a horizontal line such that the precipitation above this line = depth of excess precipitation as previously determined.
  - ➢ Horizontal line referred to Φ-index & is based on assumption of a constant or uniform infiltration rate
  - ➢ The uniform infiltration necessary to cause 1.65in of excess precipitation determined to be 0.2in/hr





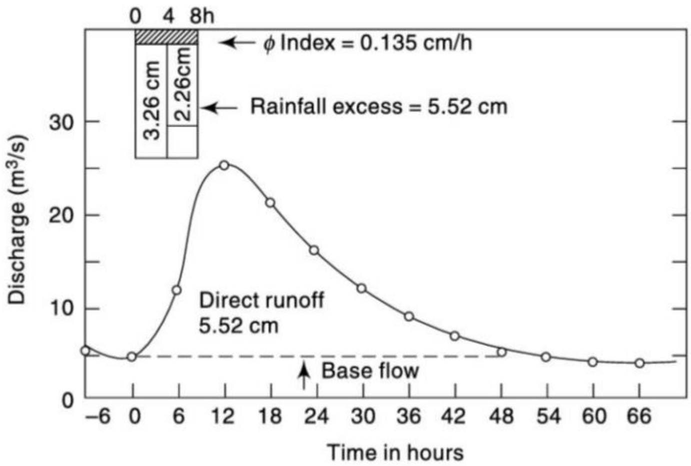
- **Changing the Duration of unit hydrograph** (necessary)
  - ➢ If unit hydrographs are to be averaged, then they must be of the same duration.
  - ➢ convolution of unit hydrograph with a precipitation event requires that the duration of unit hydrograph = the time step of the incremental precipitation
  - ➢ The most common method of altering the duration of a unit hydrograph is by the S-curve method
  - ➢ The S-curve method involves continually lagging a unit hydrograph by its duration & adding ordinates
  - ➢ For previous example, the 6hr unit hydrograph is continually lagged by 6hr & the ordinates are added

EXAMPLE

Rainfall magnitude 3.8cm & 2.8cm occurring on 2 consecutive 4h durations an a catchment of area 27km² produced the following hydrograph of flow on the outlet of the catchment.

t	-6	0	6	12	18	24	30	36	42	48	54	60	66
f	6	5	13	26	21	16	12	9	7	5	5	4.5	4.5

t: Time from start of rainfall in hr, f: Observed flow in m³/s



1. Calculate the *Base flow*
2. Estimate the *rainfall excess*
3. Calculate the *Φ-index*

Solution

1. Base flow is the area under the curve (from 0 – 48 hr, & from 0 to 5m³/s)

V = 5m³/s * 48 * 3600 s = 864000m³/s

2. rainfall excess = area under the curve

t [hr]	F [m³/s]	F-5 [m³/s]	
0	5	0	Direct runoff = ΔtxΣf = 6 x 3600 x (8+21+16+11+7+4+2) Rainfall excess = 1.4904x10⁶m³
6	13	8	
12	26	21	
18	21	16	
24	16	11	
30	12	7	runoff excess (Re) = Runoff depth = (direct Runoff/area) = 1.49x10⁶m³/27km² = 0.0552m = 5.52cm
36	9	4	
42	7	2	
48	5	0	
54	5	0	
60	4.5	0	
66	4.0	0	

3. Total rainfall (ΣR) = (3.8 + 2.8)cm = 6.6cm

Total durations (ΣD) = 2*4hr = 8hr

$$\Phi = \frac{\Sigma R - R_e}{\Sigma D} = \frac{(6.6 - 5.52)cm}{8hr} = 0.135cm/hr$$

1. احسب ال **flow** بطرح ال **Baseflow**
2. احسب ال **direct runoff** وهي المساحة تحت المنحنى
3. تكون قيمة ال **runoff excess** هي نفس ال **runoff depth** وهي ال **direct Rainfall** مقسومة على مساحة ال **catchment**
4. ولحساب ال **Φ-index** نقوم بحساب ال **total rainfall** (وهي مجموع ال **rainfall** المعطى في السؤال) وحساب ال **total duration** (عدد العوصف * فترة الزمن)

EXAMPLE

A storm over 5.0km² catchment had a duration of 14hr, if Φ index 0.4cm/hr, due to the storm, if the mass curve of rainfall as the following

t	0	2	4	6	8	10	12	14
R	0	0.6	2.8	5.2	6.6	7.5	9.2	9.6

t: Time from start of rainfall in hr, R: Rainfall in cm

1. Calculate the *effective rainfall*
2. Calculate the *intensity of effective rainfall*
3. Calculate the *volume of direct runoff*

Solution

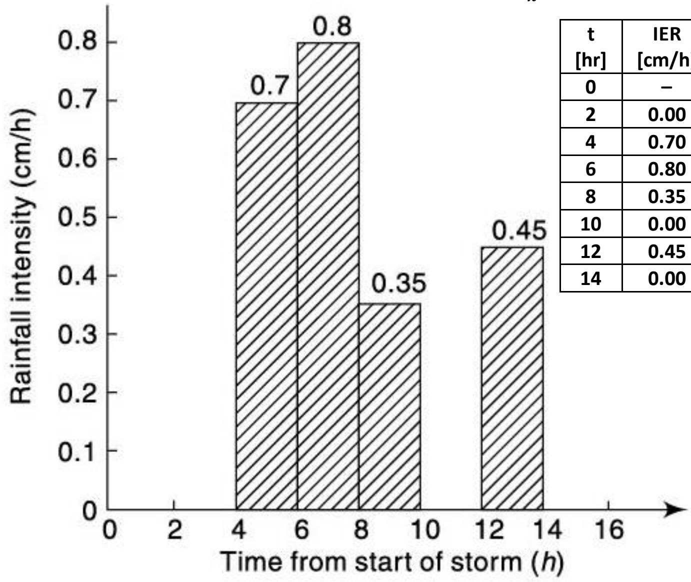
t [hr]	Δt [hr]	ΦΔt [cm]	R [cm]	Rd [cm]	ER [cm]	IER [cm/h]
0	–	–	0	0	–	–
2	2	0.8	0.6	0.6	0.0	0.00
4	2	0.8	2.8	2.2	1.4	0.70
6	2	0.8	5.2	2.4	1.6	0.80
8	2	0.8	6.6	1.5	0.7	0.35
10	2	0.8	7.5	0.8	0.0	0.00
12	2	0.8	9.2	1.7	0.9	0.45
14	2	0.8	9.6	0.4	0.0	0.00

R = Accumulated rainfall

Rd: depth of rainfall (excess runoff), $R_{d_x} = R_x - R_{x-1}$

ER: effective rainfall (direct Runoff), $ER_x = Rd - \Phi\Delta t$

IER: intensity of ER, $IER_x = \frac{ER_x}{\Delta t_x}$



t [hr]	IER [cm/h]
0	–
2	0.00
4	0.70
6	0.80
8	0.35
10	0.00
12	0.45
14	0.00

$$effective\ rainfall = direct\ runoff = \Sigma ER$$

$$\Sigma ER = \Sigma IER\ x\ \Delta t$$

$$effective\ rainfall = (0.7 + 0.8 + 0.35 + 0.45)x2$$

$$effective\ rainfall = 4.6cm$$

$$volume_{direct\ runoff} = effective\ rainfall\ x\ Area$$

$$volume_{direct\ runoff} = 4.6cm\ x\ 5km^2 = 23000m^3$$

1. نحسب ال **rainfall depth** من ال **accumulated rainfall**
2. نحسب ال **effective rainfall** من **Φ, Δt, rainfall depth**
3. ال **intensity of affective rainfall** من ال **effective**
4. نحسب حجم المياه المتدفقة بضرب ال **effective rainfall** في مساحة المنطقة

EXAMPLE

The data in the table represents the ordinates of 6-hr unit hydrograph, in 69hr, calculate the following:

1. Area of catchment
2. ordinates of the DRH due to a rainfall excess of 3.5cm occurring in 6hr

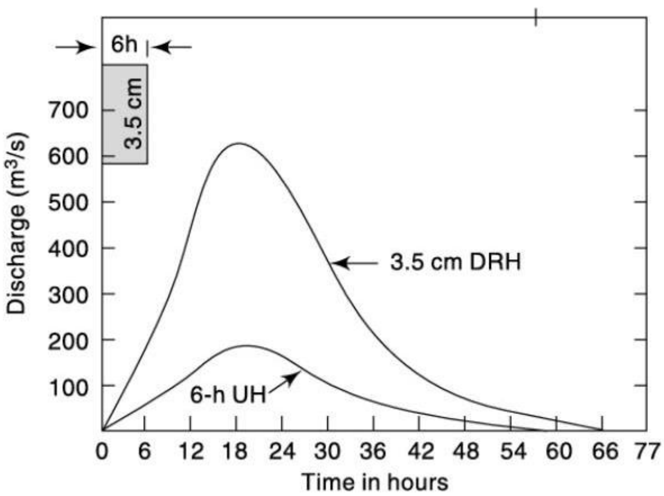
t [hr]	UH ordinates [m³/s]
0	0
6	50
12	125
18	185
24	160
30	110
36	60
42	36
48	25
54	16
60	8
66	0

Solution

A=6x3600x(50+125+185+160+110+60+36+25+16+8)/0.01

A = $1.674\times10^9 m^2$ = $1674 km^2$

t [hr]	UH ordinates [m³/s]	Ordination of 3.5cm DRH [m³/s]
0	0	00.00
6	50	175.0
12	125	437.5
18	185	647.5
24	160	560.0
30	110	385.0
36	60	210.0
42	36	126.0
48	25	87.50
54	16	56.0
60	8	28.00
66	0	00.00



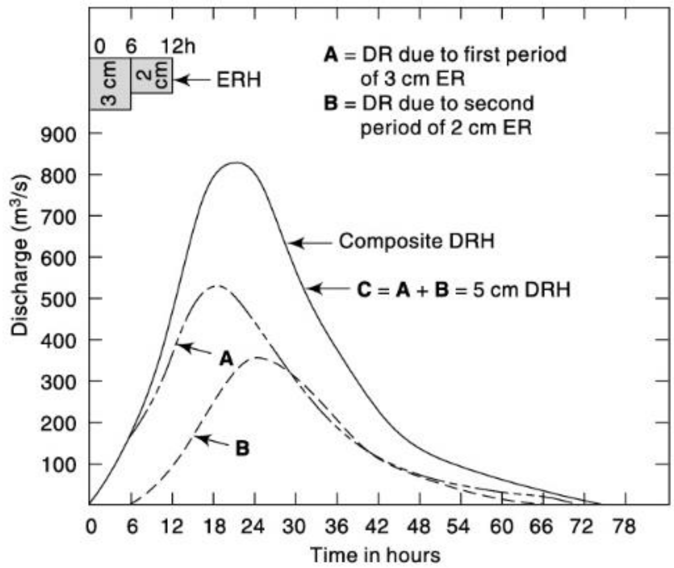
EXAMPLE

The 6hr hydrograph of the storms of 6hr duration having rainfall excess 3.0 & 2.0 respectively occur successively. The 2cm ER rain follows 3cm rain, Calculate the resulting DRH & area of catchment in each DHR

t [hr]	UH ordinates [m³/s]	t [hr]	UH ordinates [m³/s]
0	0	42	36
6	50	48	25
12	125	54	16
18	185	60	8
24	160	66	2.7
30	110	72	0
36	60	78	0

Solution

t [hr]	UH ordinates [m³/s]	3cm DHR [m³/s]	2cmDHR [m³/s]	DHR [m³/s]
0	0	0	Shift	0
6	50	150	0	150
12	125	375	100	475
18	185	555	250	805
24	160	480	370	850
30	110	330	320	650
36	60	180	220	400
42	36	108	120	228
48	25	75	72	147
54	16	48	50	98
60	8	24	32	56
66	2.7	8.1	16	24
72	0	0	5.4	5
78			0	0



$V = ½Y_1X_1 + ½(Y_1+Y_2)X_2 + ½(Y_2+Y_3)X_3 + … + ½(Y_n+Y_{n-1})X_n$

But. $\Delta t = X_1 = X_2 = X_3 = … = X_n$

So. $V = ½*2*\Delta t*\Sigma y \rightarrow A = V/UH$

A_{unit} = 6x3600x(777.7)/0.01 = $1.68\times10^9 m^2$ = $1680.0 km^2$

A_{3cm} = 6x3600x(2333.1)/0.03 = $1.68\times10^9 m^2$ = $1680.0 km^2$

A_{2cm} = 6x3600x(1555.4)/0.02 = $1.68\times10^9 m^2$ = $1680.0 km^2$

EXAMPLE

The ordinates of 6hr-unit hydrograph & storm are given below, calculate the flood hydrograph, & the area of catchment using the following information

1. the storm loss rate (Φ) = 0.25cm/hr
2. the base flow =15m³/s at the beginning
3. base flow increasingly by 2.0m³/s for every 12hr

t [hr]	UH ordinates [m³/s]	t [hr]	UH ordinates [m³/s]
0	0	42	36
6	50	48	25
12	125	54	16
18	185	60	8
24	160	66	2.7
30	110	72	0
36	60	78	0

t for start of storm [hr]	Accumulated rainfall (R), cm
0	0
6	3.5
12	11.0
18	16.5

SOLUTION

Effective rainfall calculations

	1st 6hr	2nd 6hr	3rd 6hr
R [cm]	3.5	11-3.5 = 7.5	16.5-11=5.5
ΦxΔt	1.5	1.5	1.5
R' [cm]	3.5-1.5= 2.0	7.5-1.5= 6.0	5.5-1.5= 4.0

T [hr]	UH [m³/s]	2cm [m³/s]	6cm [m³/s]	4cm [m³/s]	DHR [m³/s]	BF [m³/s]	FH [m³/s]
0	0	0	Shift	Shift	0	15	15
6	50	100	0		100	15	115
12	125	250	300	0	550	17	567
18	185	370	750	200	1320	17	1337
24	160	320	1110	500	1930	19	1949
30	110	220	960	740	1920	19	1939
36	60	120	660	640	1420	21	1441
42	36	72	360	440	872	21	893
48	25	50	216	240	506	23	529
54	16	32	150	144	326	23	349
60	8	16	96	100	212	25	237
66	2.7	5.4	48	64	117.4	25	142.4
72	0	0	16.2	32	48.2	27	75.2
78	0	0	0	10.8	10.8	27	37.8
84	0	0	0	0	0	30	30

B: base flow in m³/s (15, increase by 2m³/12hr)

FH: Ordinates of fluid hydrograph in m³/s

$A=6x3600(50+125+185+160+110+60+36+25+16+8)/0.01$

$= 1.674x10^9 m^2 = 1674 km^2$

EXAMPLE

Calculate UH (6cm with 6hr shift, & 4cm with 6hr shift)

T [hr]	UH [m³/s]	2cm [m³/s]	6cm [m³/s]	4cm [m³/s]	DHR [m³/s]
0					0
6					100
12					550
18					1320
24					1930

Solution

T [hr]	UH [m³/s]	2cm [m³/s]	6cm [m³/s]	4cm [m³/s]	DHR [m³/s]
0	X_1	$2X_1$	0	0	0
6	X_2	$2X_2$	$6X_1$	0	100
12	X_3	$2X_3$	$6X_2$	$4X_1$	550
18	X_4	$2X_4$	$6X_3$	$4X_2$	1320
24	X_5	$2X_5$	$6X_4$	$4X_3$	1930

$2X_1 + 0 + 0 = 0 \rightarrow X_1 = 0$

0	0	0	0	0	0
6	X_2	$2X_2$	0	0	100
12	X_3	$2X_3$	$6X_2$	0	550

$2X_2 + 6X_1 + 0 = 100 \rightarrow X_2 = 100/2 = 50$

0	0	0	0	0	0
6	50	100	0	0	100
12	X_3	$2X_3$	300	0	550
18	X_4	$2X_4$	$6X_3$	200	1320

$2X_3 + 300 + 0 = 550 \rightarrow X_3 = (550 - 300)/2 = 125$

0	0	0	0	0	0
6	50	100	0	0	100
12	125	250	300	0	550
18	X_4	$2X_4$	750	200	1320
24	X_5	$2X_5$	$6X_4$	500	1930

$2X_4 + 750 + 200 = 1320 \rightarrow X_4 = (1320-750-200)/2 = 185$

0	0	0	0	0	0
6	50	100	0	0	100
12	125	250	300	0	550
18	185	370	750	200	1320
24	X_5	$2X_5$	1110	500	1930

$2X_5 + 1110 + 500 = 1930 \rightarrow X_5 = 160$

0	0	0	0	0	0
6	50	100	0	0	100
12	125	250	300	0	550
18	185	370	750	200	1320
24	160	320	1110	500	1930

Calculation of the area under the curve

Assignments

Shaas Hamdan 0182778

T [hr]	UH [m³/s]	2cm [m³/s]	6cm [m³/s]	4cm [m³/s]	DHR [m³/s]	BF [m³/s]	FH [m³/s]
0	0	0	Shift	Shift	0	15	15
6	50	100	0		100	15	115
12	125	250	300	0	550	17	567
18	185	370	750	200	1320	17	1337
24	160	320	1110	500	1930	19	1949
30	110	220	960	740	1920	19	1939
36	60	120	660	640	1420	21	1441
42	36	72	360	440	872	21	893
48	25	50	216	240	506	23	529
54	16	32	150	144	326	23	349
60	8	16	96	100	212	25	237
66	2.7	5.4	48	64	117.4	25	142.4
72	0	0	16.2	32	48.2	27	75.2
78	0	0	0	10.8	10.8	27	37.8
84	0	0	0	0	0	30	30

$$V = ½Y_1X_1 + ½(Y_1 + Y_2)X_2 + ½(Y_2 + Y_3)X_3 + \cdots + ½(Y_{n-1} + Y_n)X_n + ½Y_nX_n$$

$$but\ \Delta t = X_1 = X_2 = X_{n-1} = X_n$$

$$So.V = ½x2x\Delta tx(Y_1 + Y_2 + Y_3 + \cdots + Y_{n-1} + Y_n)$$

$$So.V = \Delta t\ x\ \Sigma Y = \Delta t\ x\ \Sigma Discharge$$

$$Then.A = \frac{\Delta t\ x\ \Sigma Discharge}{UH}$$

$$in\ this\ Quastion\ .A = \frac{6x3600x\Sigma UH_x}{X - cm}$$

$$A_{UH} = \frac{6\ x\ 3600\ x\ (777.7)}{0.01} = 1.68x10^9m^2$$
$$= 1680km^2$$

$$A_{2cm} = \frac{6\ x\ 3600\ x\ (1555.4)}{0.02} = 1.68x10^9m^2$$
$$= 1680km^2$$

$$A_{6cm} = \frac{6\ x\ 3600\ x\ (4666.2)}{0.06} = 1.68x10^9m^2$$
$$= 1680km^2$$

$$A_{4cm} = \frac{6\ x\ 3600\ x\ (3110.8)}{0.04} = 1.68x10^9m^2$$
$$= 1680km^2$$

$$A_{DHR} = \frac{6\ x\ 3600\ x\ (9332.4)}{0.12} = 1.68x10^9m^2$$
$$= 1680km^2$$

2nd Exam

The following are the ordinates of 5hr duration flood hydrograph produced by total rainfall of 7.5cm/5hr, for a catchment characterized by Φ-index 0.5cm/hr

t [hr]	0	5	10	15	20	25	30	35	40
Flood [m³/s]	0	15	50	80	60	30	15	0	0

1. Calculate the area of the catchment
2. Calculate the 5hr ordinate unit hydrograph

If 3 successive rainfall storms occurred over the catchment each of 5hr duration & with the total rainfall 5.5, 8.5, & 4.5cm, calculate the following

3. Produced flood hydrograph from these 3 storms
4. The volume of flood water produced from 3 storms

SOLUTION

5hr duration flood hydrograph

total rainfall of 7.5cm/5hr

Φ-index (rate of losses) = 0.5cm/hr

Losses = t (duration) * Φ (losses rate)

= 5hr*0.5cm/hr = 2.5cm

Net rainfall (R) = total rainfall – losses = 7.5 – 2.5 = 5cm/hr

5.5 - 2.5 = 3cm

8.5 – 2.5 = 6cm

4.5 – 2.5 = 2cm

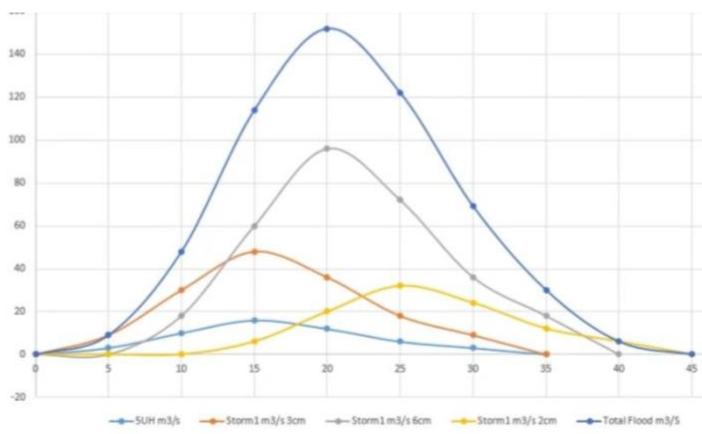
Time [hr]	Flood [m³/s]	5hrUH [m³/s]	3UH [m³/s]	6UH [m³/s]	2UH [m³/s]	Produced H [m³/s]
0	0	0	0			0
5	15	3	9	0		9
10	50	10	30	18	0	48
15	80	16	48	60	6	114
20	60	12	36	96	20	152
25	30	6	18	72	32	122
30	15	3	9	36	24	69
35	0	0	0	18	12	30
40	5hr UH = FH/R			0	6	6
45					0	0

V UH = 5x3600x(50) = 900,000m³

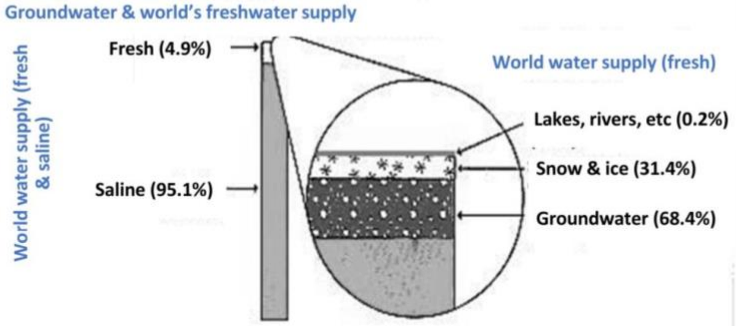
So. A = 900,000m³/0.01m = 90,000,000m² = 90Km²

V F = 5x3600x(550) = 9,900,000m³

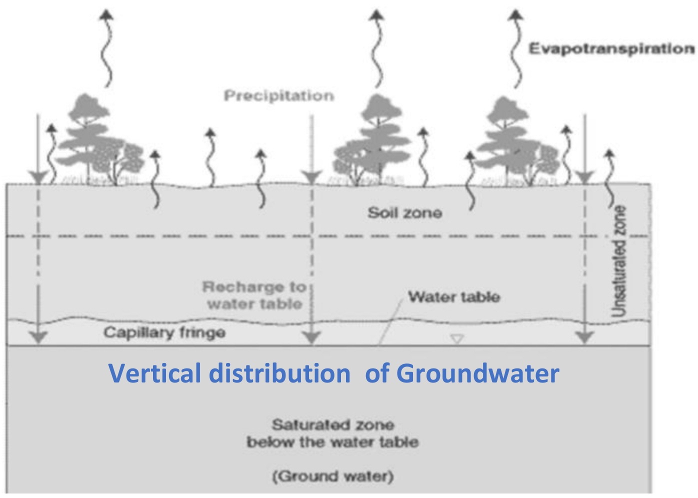
A = 9,900,000m³/0.11m = 90,000,000m² = 90Km²



GROUNDWATER

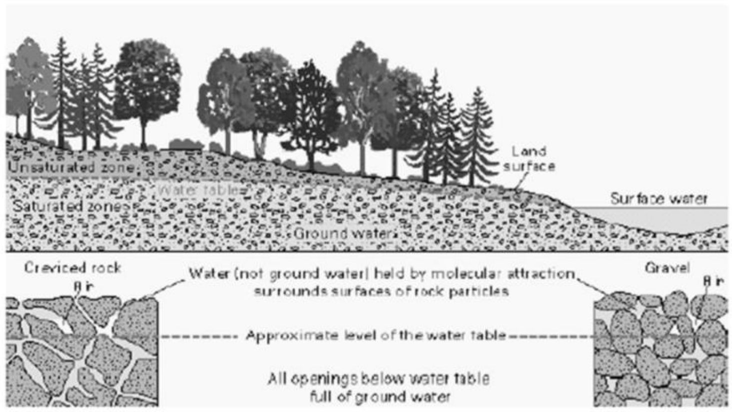


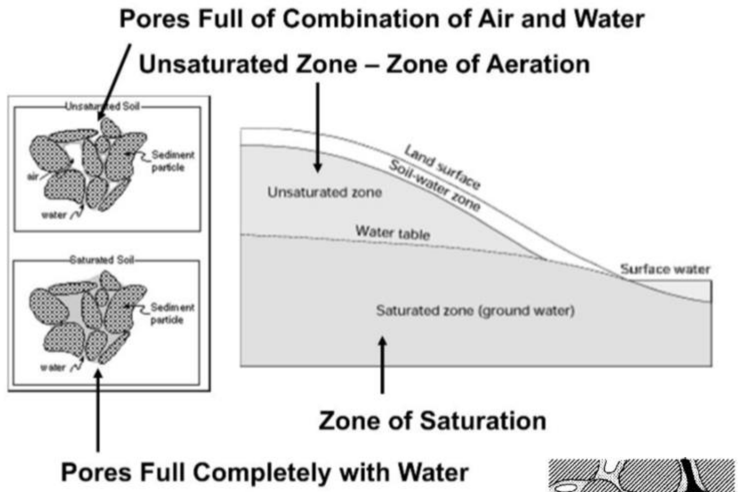
- **Groundwater:** all water found beneath the earth's surface, & **occurs in:**
  1. **saturated zones of soil or rock:** pores between soil or rock particles are totally filled with water
  2. **unsaturated zones of soil or rock:** pores are only partially filled with water
- **aquifer**: A water-bearing layer of soil, sand, gravel, or rock that will yield usable quantities of water to a well
  - ➢ many soil & rock contain water, but only those that produce useable quantities of water are aquifers
- **Aquifer Properties:**
  - ➢ confined & unconfirmed conditions
  - ➢ Aquifers & Aquitards
  - ➢ Water Tables & Piezometric Surfaces
- **Groundwater Flow**
  - ➢ Flow Lines & Flow Nets
  - ➢ Anisotropy
  - ➢ Refraction of Flow Lines
  - ➢ Confined Steady Flow
  - ➢ Unconfined Steady Flow
  - ➢ Transient Flow
- **Pumping tests:** عند عملية ضخ المياه من الابار يجب ان يتم ضخ اقل من ثلث المياه الموجودة فقط



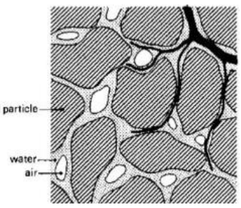
Vertical distribution of Groundwater

Regolith (soil mantle) - Unsaturated and Saturated Zones





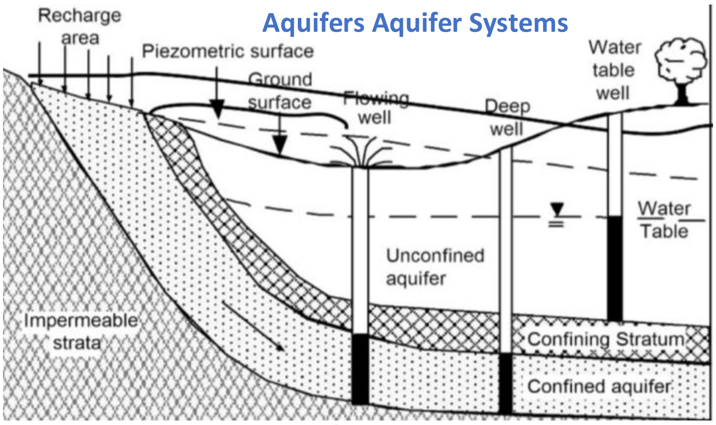
- **Unsaturated System**
  - ➢ **Zone of Aeration, Vadose Zone**
  - ➢ **This system have 3 phases:** air, water, & rock



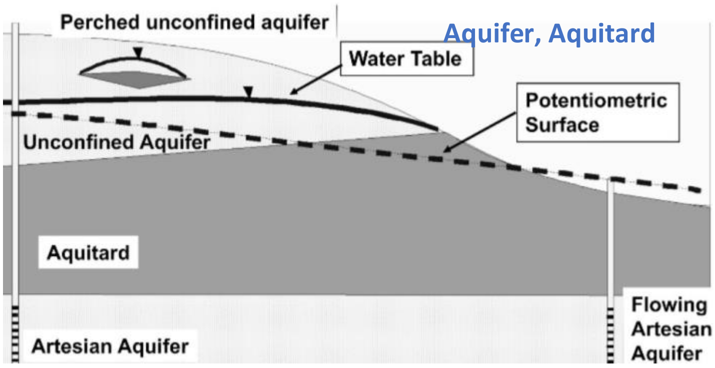
AQUIFER

- **Aquifer**: geologic unit that can store & transmit water at rates fast enough for supply
- **Confined (artesian) aquifer**: potentiometric surface above surface elevation of aquifer
- **Flowing artesian aquifer:** potentiometric surface above ground surface
- **Unconfined Aquifer (water-table aquifer):** free-surface within aquifer with no underlying unsaturated material
- **Perched aquifer**: free-surface aquifer above unsaturated material
- **Confining Layers:**

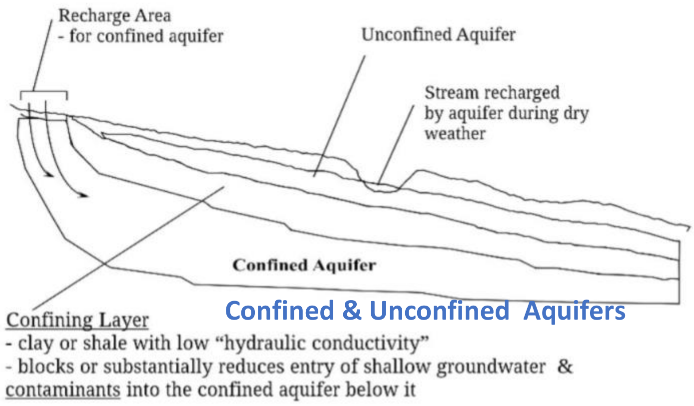
1. **Aquitard**: a geologic unit that may store but cannot transmit water at rates fast enough for supply
2. **Aquifuge**: cannot store or transmit water



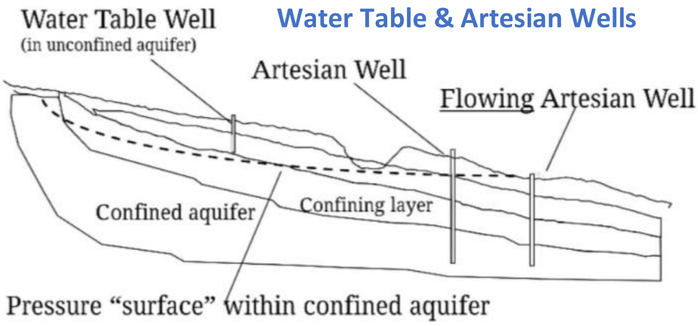
Aquifers Aquifer Systems



Aquifer, Aquitard



Confined & Unconfined Aquifers

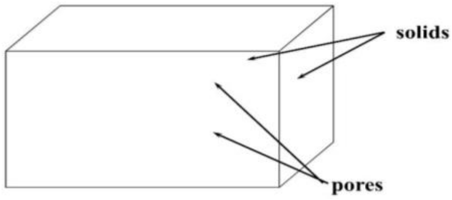


Water Table & Artesian Wells

- **Aquifer Materials:** Unconsolidated & Consolidated
- **Unconsolidated Aquifer Materials:** consist of individual grains of material (soil, loess, silt, clay, sand, & gravel)
  - **Porosity** is related to pore spaces between particles
- **Consolidated**: including fractured carbonate (limestone & dolomite) & some sandstone
  - Limestone & dolomite have little inherent pore space, & their porosity is derived from cracks, caused by shifting of earth's crust, & subsequent enlargement of cracks as water seeps through them & dissolves the calcium & magnesium

POROSITY

- All porous materials consist of solids surrounded by pore spaces



- Porosity expressed as a %Vol of the material

$$Porosity\ (n\%) = \frac{pore\ volume\ (V_v)}{total\ volume\ (V_T)} x100\%$$

EXAMPLE calculate the porosity if total aquifer volume = $1ft^3$ & pore volume = $0.3ft^3$

$$Porosity = \frac{0.3ft^3}{1ft^3} x100\% = 30\%$$

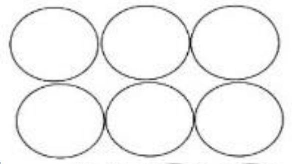
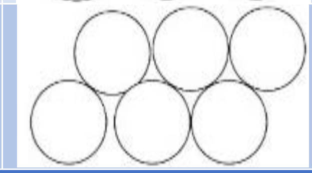
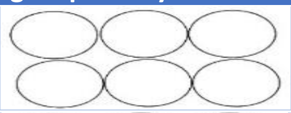
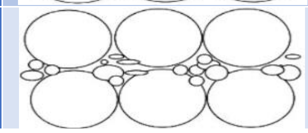
- The pore spaces within a geologic material are potential "storage space" for ground water (The more pore space, the greater its potential to hold ground water)
- **Fine-& coarse-grained materials have the same porosity because:** Fine-materials (e.g. clay or fine sand) have smaller individual pore spaces but have a much larger number of pores than coarse-grained materials
- **The materials that consist of mixture of fine-& coarse-grained particles have lower porosity because** smaller particles partially fill spaces between larger particles
- **Void ratio:** term in soil mechanics, Related to Porosity

$$Void\ ratio(e\%) = \frac{pore\ volume\ (V_v)}{soil\ volume\ (V_s)} x100\%$$

$$e\% = \frac{n\%}{1-n\%}\ OR\ n\% = \frac{e\%}{1+e\%}$$

Types of Porosity	
Primary (0-60%)	• **Water in pores between grains** • **measured in lab** • **Increases with decreasing grain size** for unconsolidated sediments (silts & clays more porous than sand) • Poorly sorted sediment are lower porous
Secondary	• **Groundwater in fractures, voids due to chemical weathering (karst)** • **measured by pumping test** • **Produced by** dissolution (carbonate-karst), precipitation (cementation) & deformation (fracturing) • **Increases with decreasing grain size for unconsolidated sediments**
Effective (<10%)	• **Connected pore for fluid flow (percentage of interconnected pore space)** • **biggest difference for fractured rock** • **Depending on:** 1. **n% = porosity (percentage)** 2. **ρ_b = bulk density of aquifer material** 3. **ρ_d = particle density of material** $n = \frac{V_v}{V_T} x100\% = \left(1 - \left(\frac{\rho_b}{\rho_d}\right)\right) 100\%$
Disconnected	• **Dead-end pores**

- **Factors Affecting Porosity**: Packing, Sorting, Shape of grains, Fabric or orientation of non-spherical particles

Effect of packing on porosity		
Packing	**n%**	**Shape**
Cubic	48%	
Rhombohedral	26%	
Effect of shape on porosity		
Structure		**Shape**
Clay Mineral		
Sand		
Effect of sorting on porosity		
Well Sorted		
Poorly Sorted		

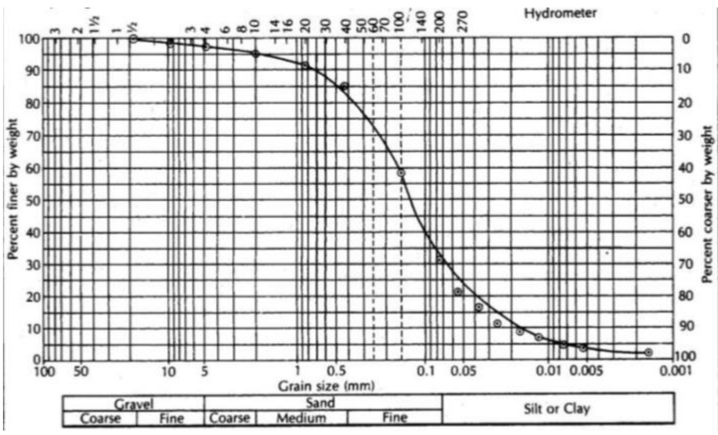
Total & Effective Porosities of some materials					
Material	**Total**	**Effective**	**Material**	**Total**	**Effective**
Anhydrite	0.5-5	0.05-0.5	**Shale**	1-10	0.5-5
Chalk	5-20	0.05-0.5	**Salt**	0.5	0.1
Lst	5-15	0.1-5	**Granite**	0.1	0.0005
dol	5-15	0.1-5	**Crystalline rock (fract)**	–	0.00005-0.01
Sandstone	5-15	0.5-10			

Porosity %			
Well-sorted sand	**25% – 50%**	**Till**	**10% – 30%**
Poorly-sorted sand	**20% – 35%**	**Rocks**	**0 – 2%**
Clay	**35% – 60%**	**Weathered rocks**	**0 – 60%**
Silt	**35% – 50%**	**Glacier**	**10%-20%**

- Sediments classified on basis of size of individual grains
- **Uniformity coefficient Cu:**

$$C_u = \frac{d_{60}\ (grain\ size\ that\ 60\%wt\ finer)}{d_{10}\ (grain\ size\ that\ 10\%wt\ finer)}$$

Grain size distribution curve

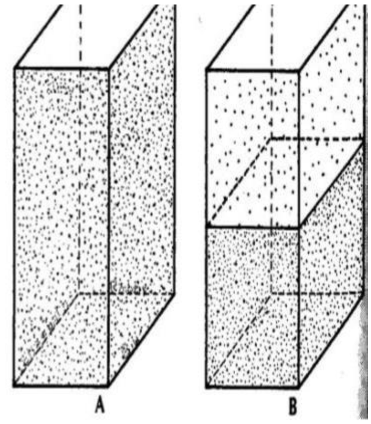


YIELD & RETENTION

- **Specific yield (Sy)**: ratio of volume of water that drains from a saturated rock owing to the attraction of gravity to the total volume of the rock
- **Specific retention (Sr)**: ratio of volume of water in a rock retain against gravity drainage to total volume of rock
  - ➢ Specific retention increase with decreases grain size

$$N = S_y + S_r$$

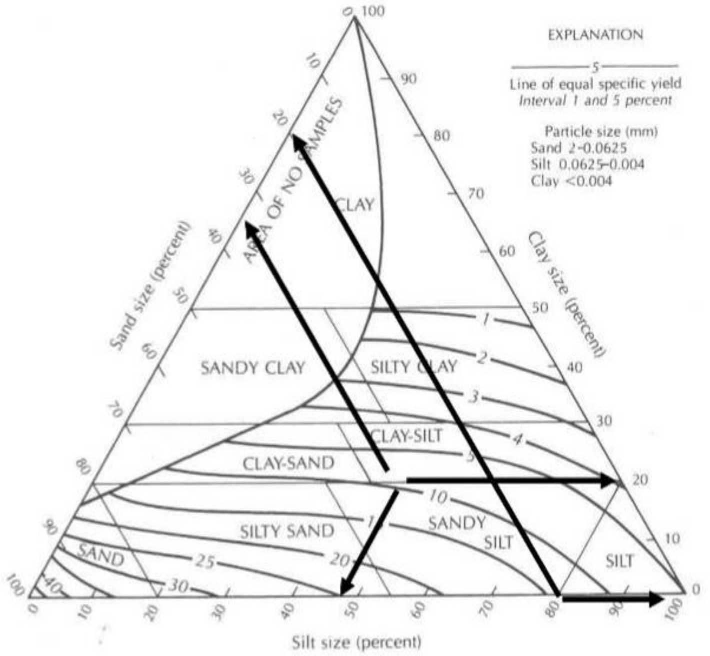
A. A volume of rock saturated with water.
B. After gravity drainage, 1 unit volume of the rock has been dewatered with a corresponding lowering of the level of saturation. Specific yield is the ratio of the volume of water that drained from the rock, owing to gravity, to the total rock volume.



% specific yields							
Materials	**Max**	**Min**	**Avg**	**Materials**	**Max**	**Min**	**Avg**
Clay	5	0	2	**Coarse sand**	35	20	27
Sandy clay	12	3	7	**Gravelly sand**	35	20	25
Silt	19	3	18	**Fine gravel**	35	21	25
Fine sand	28	10	21	**Medium gravel**	26	13	23
Medium sand	32	15	26	**Coarse gravel**	26	12	22

- When saturated aquifer material is drained by gravity, it will release only a portion of the total water stored in the pore spaces, the remaining water is held inside the pores spaces by molecular attraction & capillarity
- The amount of water released by gravity drainage of a porous materials is known as "specific yield" of material
- Like porosity, specific yield is expressed as a percentage of the total volume (pore space + solids) of the aquifer
- Specific yield is always less than porosity

$$water\ yielded\ by\ gravity = Volume_{aquifer} x S_y$$



HYDRAULIC CONDUCTIVITY (PERMEABILITY)

- **Hydraulic Conductivity or permeability**: the capacity of a porous medium to transmit water
  - ➢ Measure of how fast water can flow via the material
  - ➢ typical units are velocity units [distance]/[time]
- **highly conductive saturated materials** allow
  1. water to move via them rapidly
  2. contaminant carried by water to move via them
  3. yield water rapidly to a well or spring

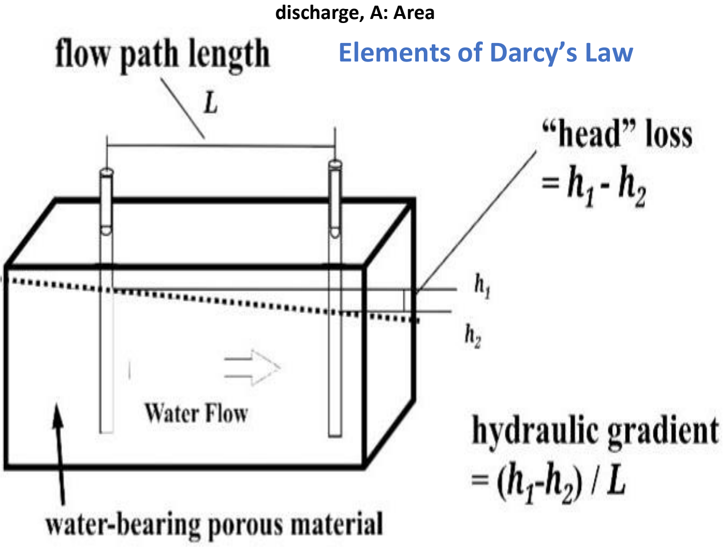
Conductivity in ft/day			
Clay soils	0.03 – 0.7	Sand + Gravel (mix)	16 - 328
Fine sand	3.0 - 16	Glacier till (clay, sand, gravel)	0.003 – 0.3
Medium sand	16 - 66	Sandstones	0.003 – 3
Coarse sand	66 - 238	Limestones	0.03 - 33
Gravel	328 - 3280	Shale	0.0000003

- **Darcy's Law predicts groundwater flow velocities based on 3 pieces of data:**
  1. **K**: the hydraulic conductivity of the porous media
  2. **L**: the length of the flow path that the water follows
  3. **(h1-h2)**: head loss as water move from starting to ending point along it's travel path
     - ▪ **Head**: water surface elevation level measured in a well, stream, tank, or other vessel
     - ▪ **head loss**: is the difference in water level measured at 2 points along the flow path

$$V_D = Kxi = K\left[\frac{h_1 - h_2}{L}\right]$$

$$V(apparant\ V) = Kxi = \frac{Q}{A}$$

V_D: Darcy velocity of water (ft/day), K: hydraulic conductivity of the porous media (ft/day), L: path length (ft), h2: final head, h1: initial head (ft), Q: discharge, A: Area



Elements of Darcy's Law

- **Head loss:** pressure or driving force that causes water to flow from one point to another (through a pipe, along a stream, or under ground)
  - ➢ Water flows from a point with high head, to a point with lower head if there is a difference in head
  - ➢ Greater difference in head → faster flow
  - ➢ The average steepness or slope of head difference [(h1 -h2)/L] controls how rapidly groundwater flow

- **Hydraulic gradient (dh/dL or Δh/ΔL)**: The value of the average slope of the head loss
- Darcy's law

$$V_D = K\ x\left[\frac{h_1 - h_2}{L}\right]$$

$$Q = -AK\left(\frac{dh}{dL}\right) = -AK\left(\frac{h_2 - h_1}{L_2 - L_1}\right) = K\left(\frac{dh}{dl}\right)$$

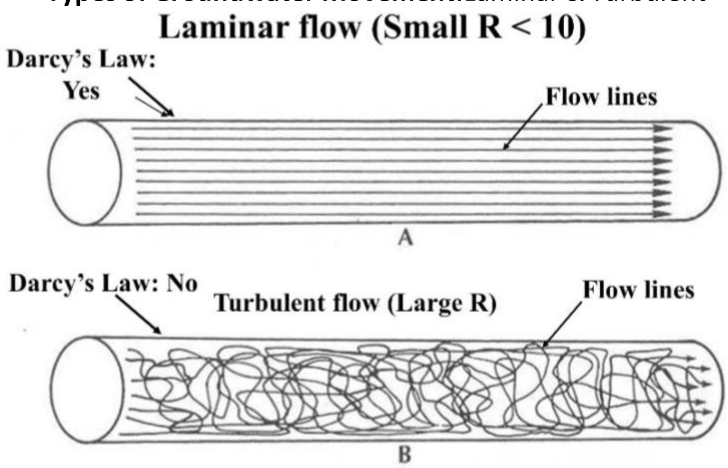
Q: specific discharge

- Groundwater moves very slowly in the aquifers under differential head, The flow is horizontal & uniformly distributed in a vertical section
- The velocity of flow is proportional to the (tan) of the instead of (sin) of the hydraulic gradient

$$l = \frac{dh}{dI} = tan(\alpha)$$

dh/dl (hydraulic gradient) is a dimensionless quantity & K has units of velocity

- **Types of Groundwater Movement:**Laminar & Turbulent



- **Reynolds number (R): dimensionless**

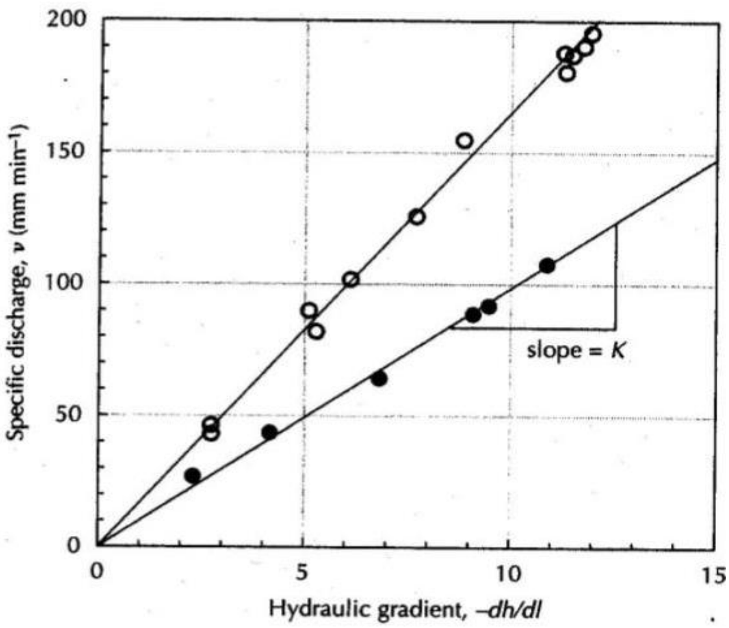
$$R = \frac{\rho q d}{\mu} = \frac{V d_a}{v}$$

ρ: fluid density (M/L, g/m³), μ: fluid viscosity (M/TL, kg/sm),q:discharge velocity (L/T, m/s), d: diameter of the passageway through which the fluid moves (L, m)

- **Hydraulic head**:

$$h = z + \psi$$

Z: is the elevation head (m), & ψ: is the pressure head (m)



- **Hazen method**:Estimate hydraulic conductivity in sands

$$K = C(d_x)^j$$

K: hydraulic conductivity, dx: effective grain size [mm]
C = coefficient, j = an exponent

PREDICTION OF HORIZONTAL GROUNDWATER VELOCITY

- head measurements are NOT made at the beginning & end of the flow path, instead head measurements are made in monitoring wells (or water supply wells) located along or near to the flow path, & average hydraulic gradient for the total flow path [(h1 -h2)/L] is estimated on the basis of these measurements
- For unconfined aquifers, hydraulic gradient between 2 points is the same as the slope on the water table

EXAMPLE In situation system, water level measurement made in the monitoring wells along the flow path of the groundwater indicate that the average head loss is 0.1ft in every 100ft of travel (i.e.hydraulic gradient = 0.001ft/ft), calculate the Darcy velocity (K = 15ft/day)

$$V_D = K\,x\left[\frac{h_1 - h_2}{L}\right] = \frac{15ft}{day}x\frac{1ft}{100ft} = 0.015ft/day$$

DARCY VELOCITY vs TRUE VELOCITY

- The velocity predicted by Darcy's law is not the true velocity of flow through the pores of the aquifer
- The velocity predicted by Darcy's law must be adjusted in order to estimate the true velocity of groundwater movement through pore spaces in aquifer
- The true velocity is important if you wish to accurately estimate groundwater travel time between 2 points

$$V_{true} = \frac{V_{darcy}}{n\ (Avg\ porosity)}$$

EXAMPLE for the situation where the Darcy velocity was calculated to be 0.015ft/day & the porosity is 30%, calculate the true velocity of water movement through the pores of the aquifer

$$V_{true} = \frac{0.015ft}{0.3day} = 0.05ft/day$$

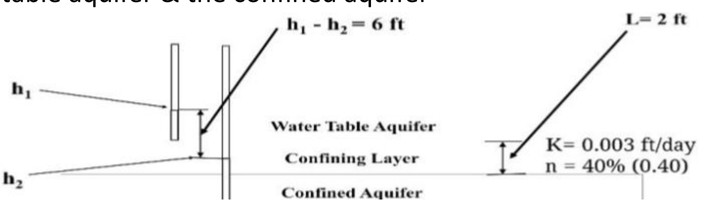
PREDICTION OF Vertical GROUNDWATER VELOCITY

- **Seepage (average linear) velocity**:

$$V_x = \frac{Q}{n_eA} = -\frac{K}{n_e}\left(\frac{dh}{dI}\right)$$

V: Avg linear velocity, **n**: effective porosity (dimensionless)

EXAMPLE calculate velocity of seepage between the water table aquifer & the confined aquifer



$$V_x = \frac{Q}{n_eA} = \frac{-K}{n_e}\left(\frac{dh}{dI}\right) = \frac{0.003ft}{0.40day}\left(\frac{6}{2}\right) = 0.009ft/day$$

$$V = \frac{V_x}{n} = \frac{0.009ft}{0.40day} = 0.023ft/day$$

CONDUCTIVITY PARAMETERS

- **Constant-head Permeameter**

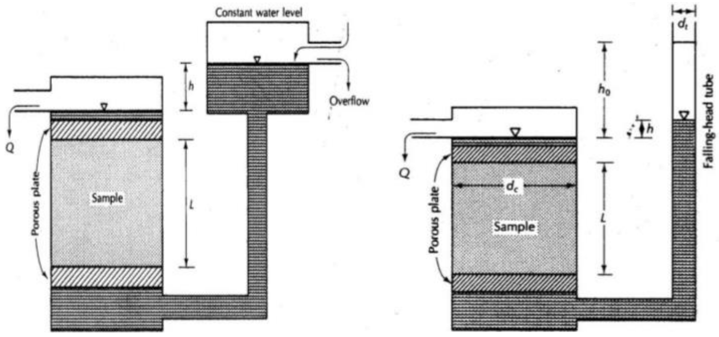
$$K = \frac{QxL}{Ax\Delta H} = \frac{VL}{A_th}\ where\ Q_t = -KA\left(\frac{h_a - h_b}{L}\right)$$

V: volume of water discharging in time, L: length of the sample, A: cross-sectional area of sample, h: hydraulic head, K: hydraulic conductivity

- **Falling head permeameter**

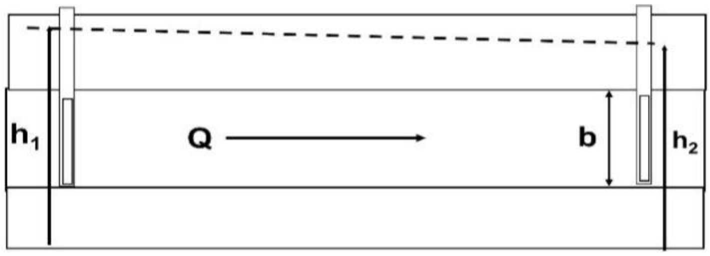
$$K = \frac{d_t^2L}{d_c^2t}ln\frac{h_0}{h}$$

K: Hydraulic conductivity, L: sample length, h: head in the falling tube
t: time that it takes for head to go from h0 to h, dt: diameter of falling head
dc= diameter of sample chamber



TRANSMISSIVITY

- **Transmissivity:** amount of water (per time) transmitted horizontally through a unit width by the full saturated thickness of the aquifer under a hydraulic gradient of 1



$$T = bK\ (saturated\ thickness * hydraulic\ conductivity)$$

$$for\ multilayers: T = T_1 + T_2 + \cdots + T_n$$

$$Darcy's\ law: Q = -KIA = -KIb = -TI$$

T: Transmissivity

$$T = \frac{discharge}{width\ of\ aquifer\ under\ gradient\ of\ 1}$$

COMPRESSIBILITY & STRESS

$$Q_T = \sigma_e + P$$

σT = total stress produced by weight of overlying rock & water,
P = fluid pressure. σe = effective stress (actual stress borne by aquifer skeleton)

- The chance in total stress result in changes of effective stress & pressure

$$dQ_T = d\sigma_e + dP$$

- **Confined aquifer**: change in pressure with very little change in thickness of saturated water column

$$dP = -d\sigma_e$$

- With reduction in pressure, effective stress will increase, & compaction of aquifer skeleton
- Consolidation depends on aquifer compressibility α

$$\alpha = \left[\frac{db}{b}\right]d\sigma_e = \frac{\left[\frac{db}{b}\right]}{dP}$$

b = original aquifer thickness, db = change in aquifer thickness