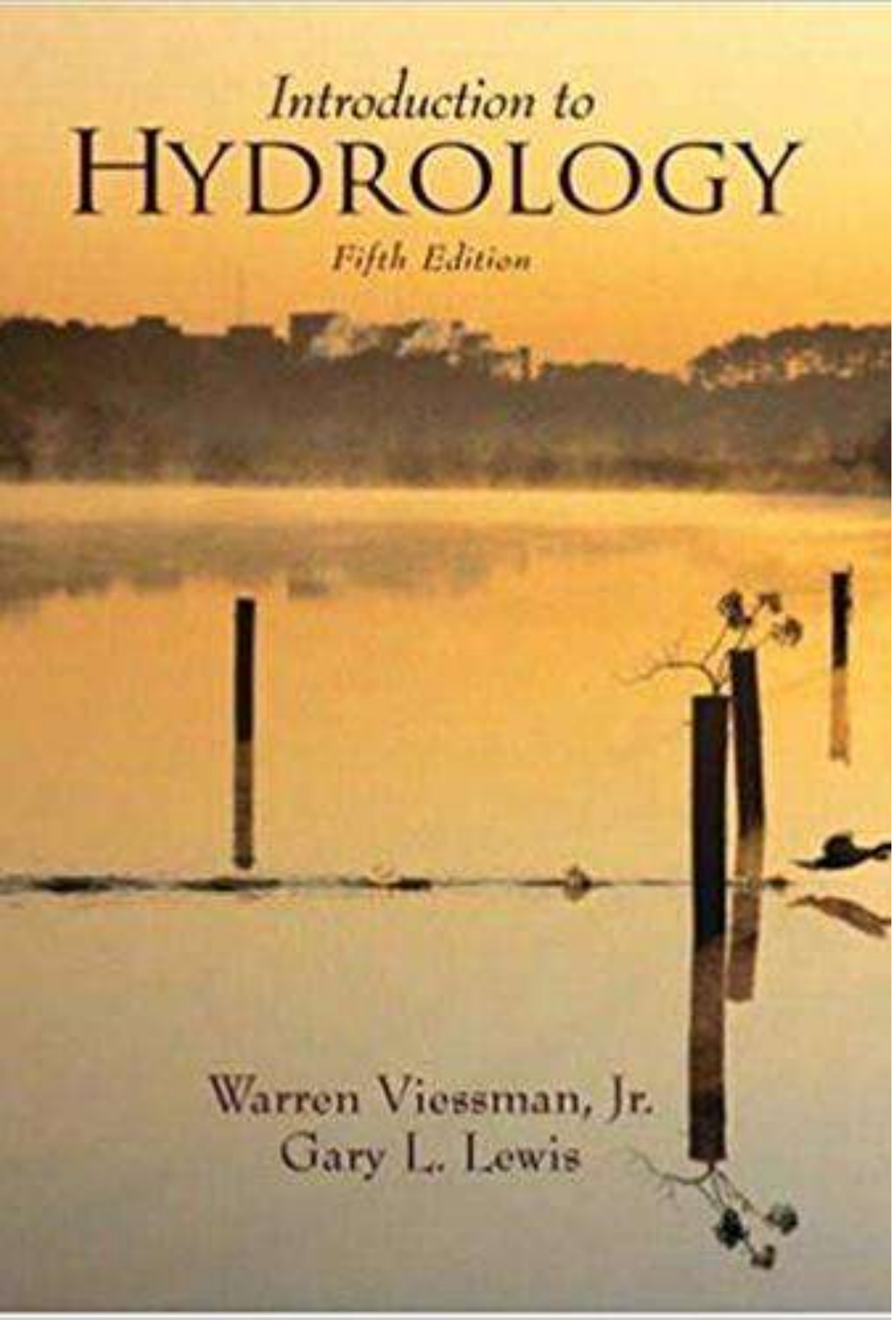
Engineering Hydrology
CE 454

Lectures 1+2 . Introduction, hydrologic cycle, hydrologic budget



Textbook

- Introduction to hydrology. Viessman W. (2002), 5th edition, Prentice Hall.

Course Description

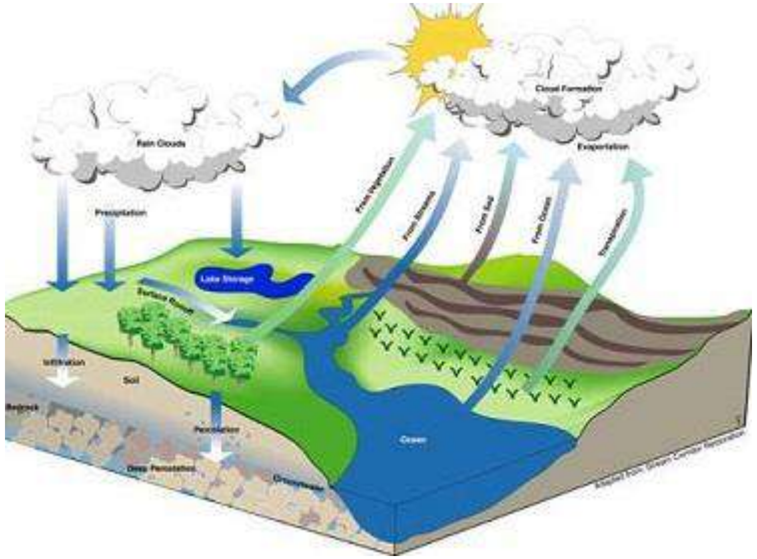
Hydrology is a basic civil engineering course that enables CE students to understand and perform engineering computations related to water quantities from rainfall or snow melt. In specific, topics related to hydrologic cycle and budget, statistical methods in hydrology, surface and groundwater flow computation will be addressed.

Course Learning Objective

Upon successful completion of the course you should be able to **use principles of engineering to compute the rain and groundwater flow**.

HYDROLOGY - definition

- **Hydrology** (from Greek: ὕδωρ, "hýdōr" meaning "water"; and λόγος, "lógos" meaning "study") is the scientific study of the movement, distribution, and quality of water on Earth and other planets, including the water cycle, water resources and environmental watershed sustainability.



Definitions- Cont.

- Hydrology, scientific discipline concerned with the waters of the Earth, including their occurrence, distribution, and circulation via the hydrologic cycle and interactions with living things.

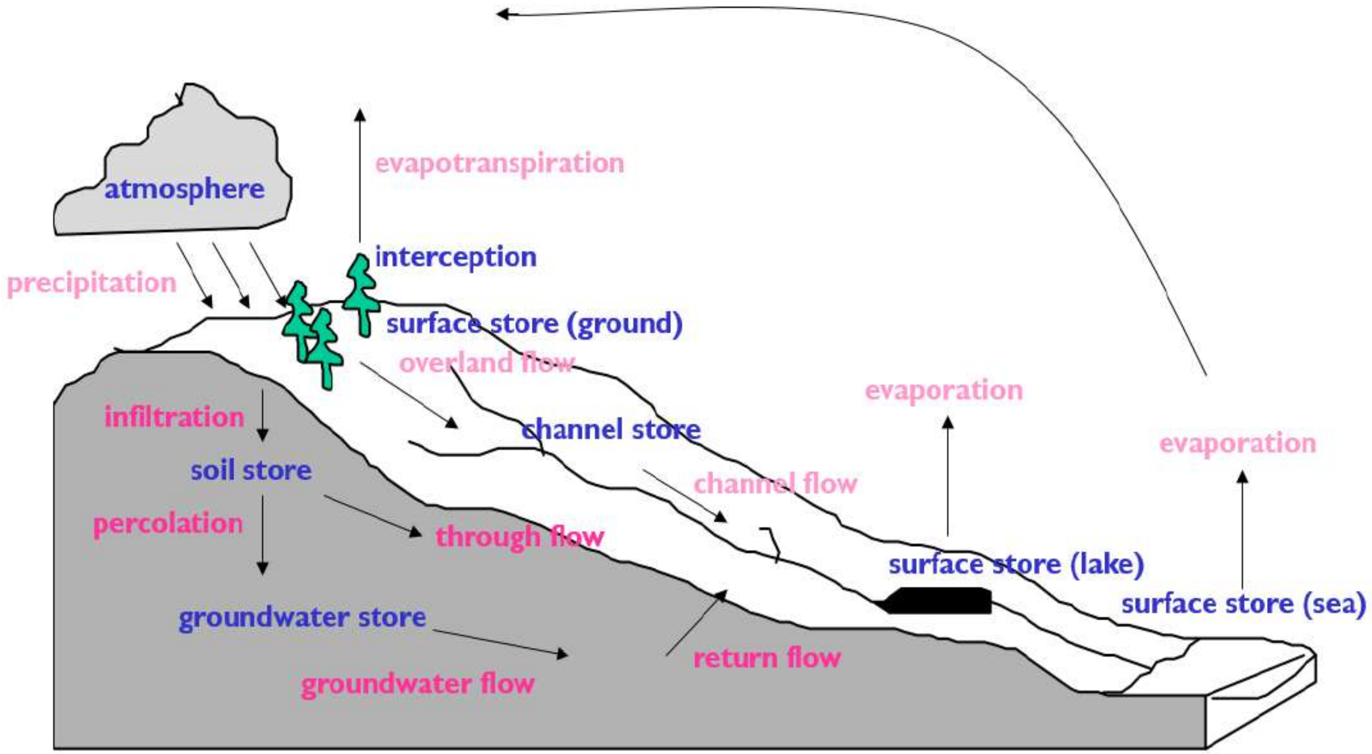
- Hydrology is an essential field of science since everything from tiny organisms to individuals to societies to the whole of civilization - depends so much on water.

The “Golden Rule” of hydrology.....

“water flows down hill”

under force of gravity
BUT, may move up through system via:

- Capillary action in soil.
- Hydraulic pressure in groundwater aquifers.
- Evapotranspiration.



HYDROLOGY | branches

Chemical Hydrology

Study of chemical characteristics of water

Water Quality

Chemistry of water in rivers and lakes, both of pollutants and natural solutes

Eco Hydrology

Study of interactions of living organisms and the hydrologic cycle

Hydrogeology

Study of the distribution and movement of groundwater in the soils and rocks of the Earth’s crust

Hydrometeorology

Study of the transfer of water and energy between land and water body surfaces and the lower atmosphere

Surface Hydrology

Study of hydrologic processes that operate at or near Earth's surface

Drainage Basin Management

Covers water-storage, in the form of reservoirs, and flood-protection

Problems in Hydrology

- Extreme weather and rainfall variation
- Streamflow and runoff considerations
- River routing and hydraulic conditions
- Overall water balances - local and global scales
- Flow and hydraulics in pipes, streams and channels
- Flood control and drought measures
- Watershed management for urban developmen

Water engineering problems and hydrologic variables

Water engineering problem	***Typical reference hydrologic variable***
Design of flood protection measures	*Peak flow discharge* *Flood volume and duration*
Design of storm drainage	*Extreme values of rainfall depth* *Peak flow discharge*
Design of a reservoir	*Annual water yield* *Seasonal/monthly water yield*
Design of an irrigation system	*Evapotranspiration* *Soil water content*
Landslide risk analysis	*Extreme values of rainfall depth and intensity*
River bed erosion	*River discharge*
Surface erosion	*Overland flow*
Water allocation to multiple users (hydropower, irrigation, water supply, …)	*Discharge time series*
…	…

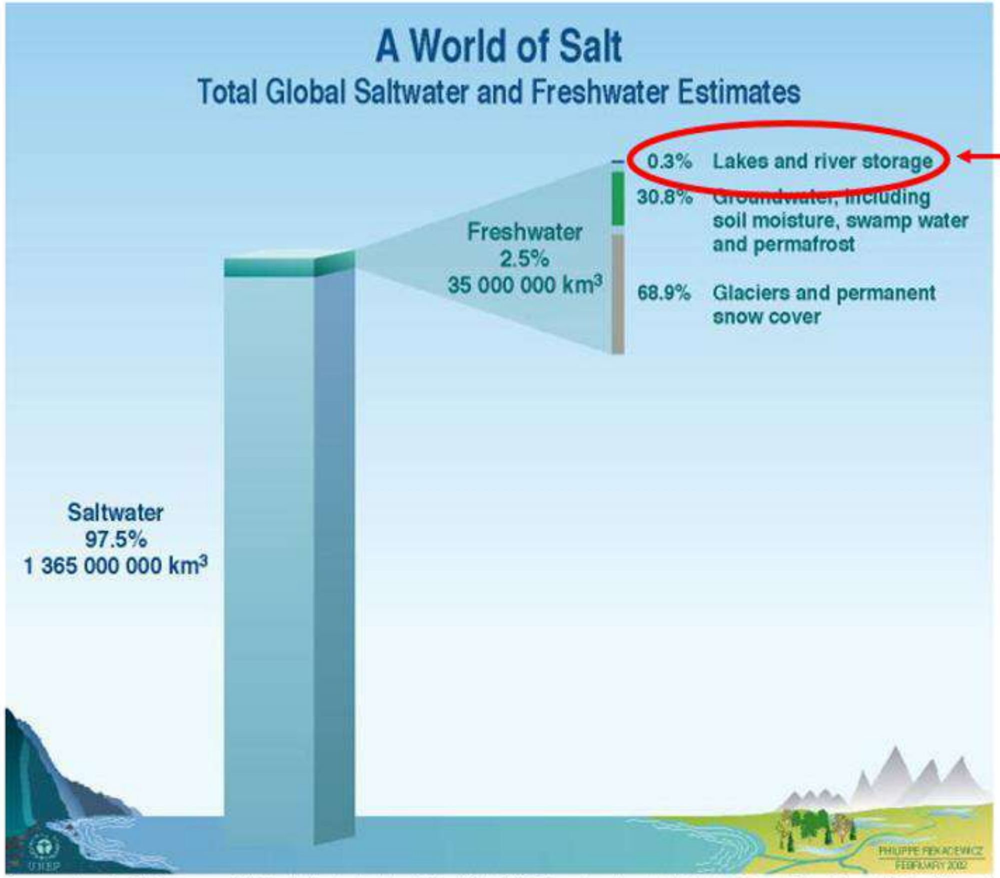
A school bus drives through floodwater in Houston, Texas.
September,20,2019

Arkansas River Flooding.
May, 2019

Hydrology Application

- Calculation of rainfall.
- Calculating surface runoff and precipitation.
- Determining the water balance of a region.
- Determining the agricultural water balance.
- Mitigating and predicting flood, landslide and drought risk.
- Real-time flood forecasting and flood warning.
- Designing irrigation schemes and managing agricultural productivity.
- Part of the hazard module in catastrophe modeling.
- Providing drinking water.
- Designing dams for water supply or hydroelectric power generation.
- Designing bridges.
- Designing sewers and urban drainage system.
- Assessing the impacts of natural and anthropogenic environmental change on water resources.
- Estimating the water resource potential of river basins.

Global water resources

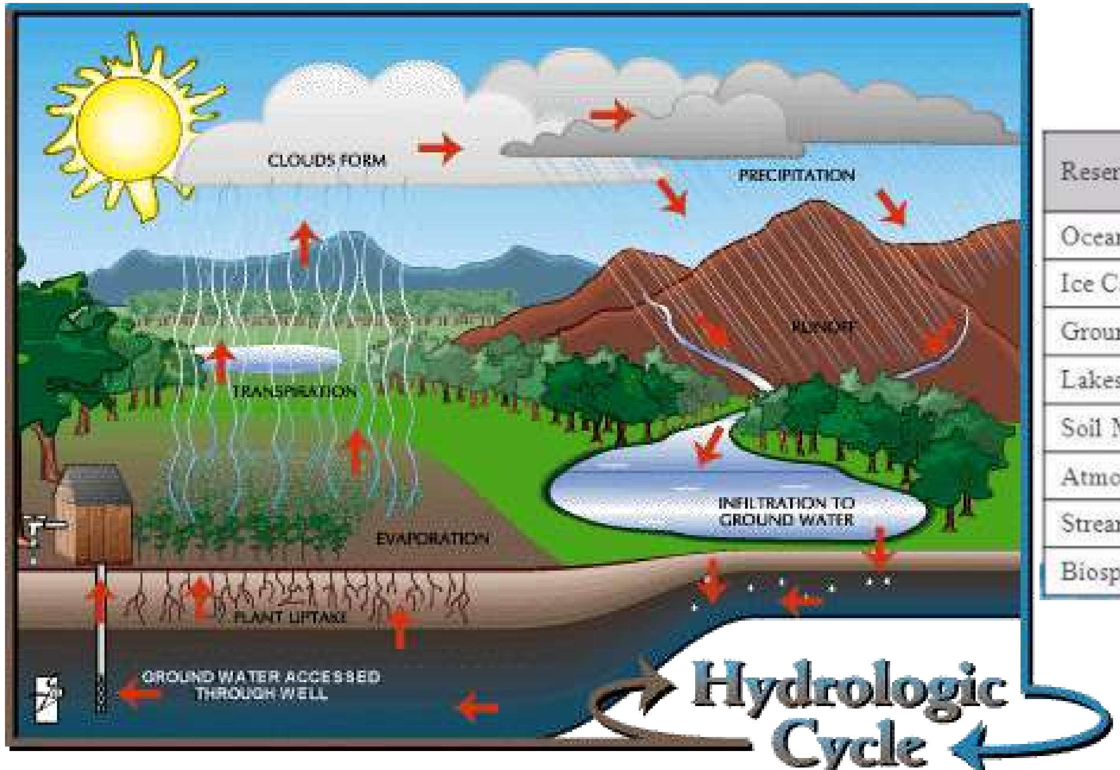


Source: Igor A. Shiklomanov, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational, Scientific and Cultural Organisation (UNESCO, Paris), 1999.

105,000 km^3 or **0.0076%** of total water

Hydrologic Cycle

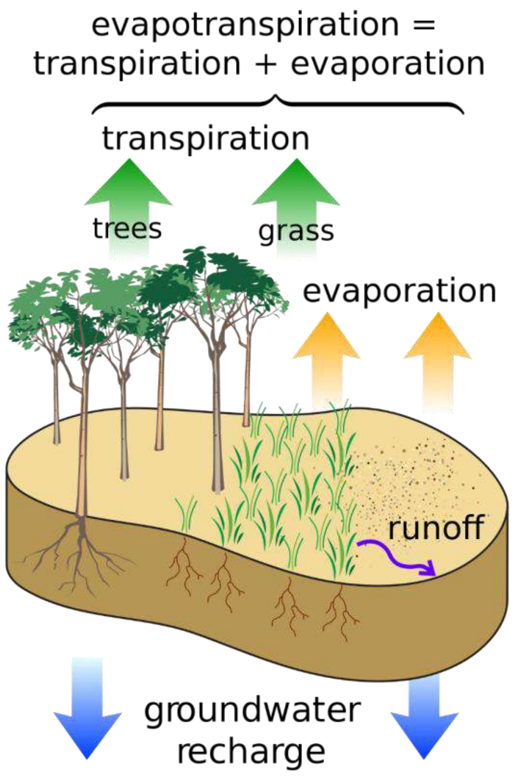
- Hydrologic cycle – A continuous process describes circulation of water in the environment.
- Through hydrologic cycle, water is transported from the oceans to the atmosphere to the land and back to the sea.

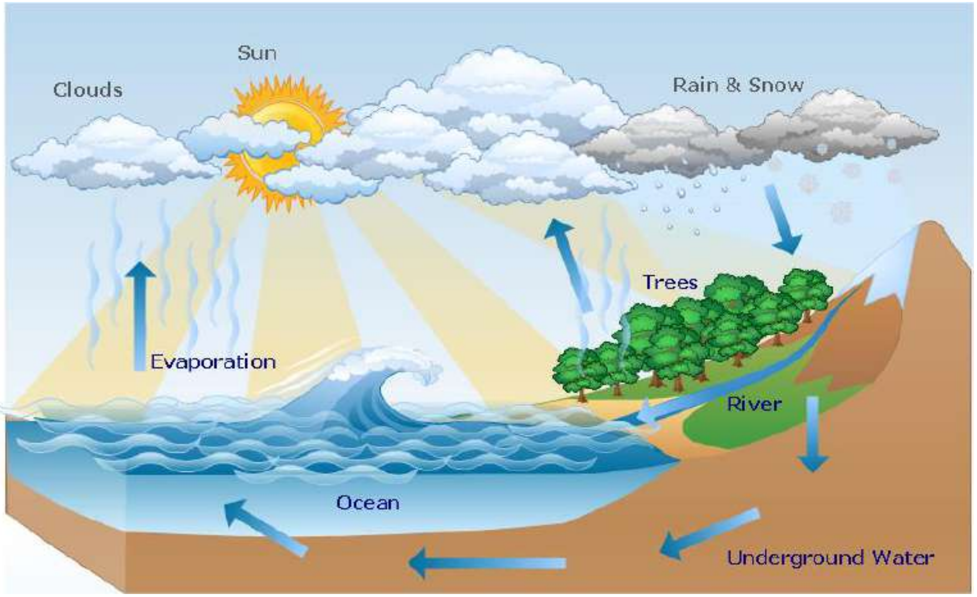


Reservoir	Volume (km^3 x10^6)	% of Total
Oceans	1370	97.25
Ice Caps & Glaciers	29	2.05
Groundwater	9.5	0.68
Lakes	0.125	0.01
Soil Moisture	0.065	0.005
Atmosphere	0.013	0.001
Streams & Rivers	0.0017	0.0001
Biosphere	0.0006	0.00004

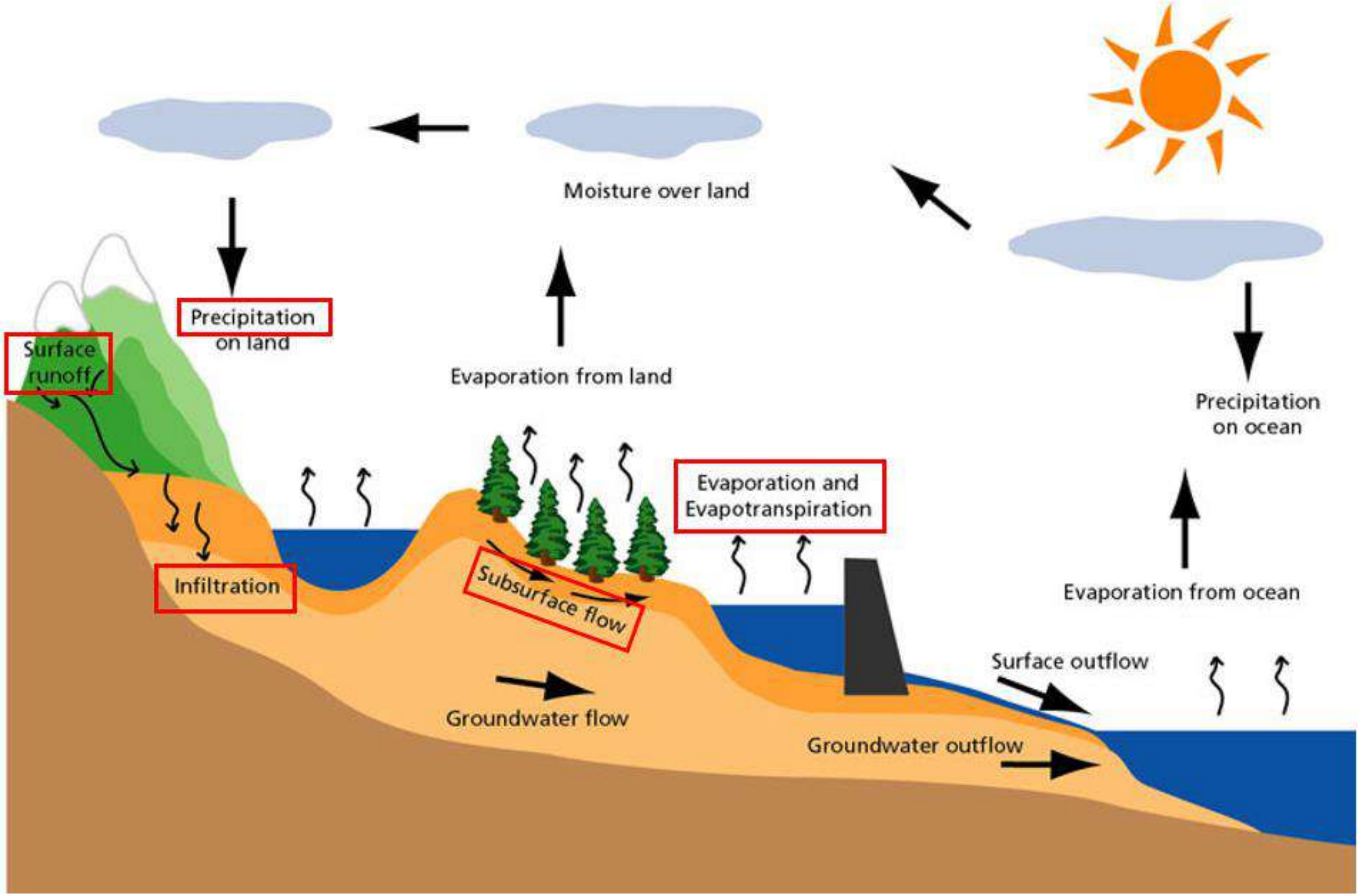
Components of hydrologic cycle

- Precipitation (P).
- Transpiration (T).
- Evaporation (E).
- Evapotranspiration (ET).
- Surface runoff (R).
- Groundwater flow (G).
- Infiltration (I)



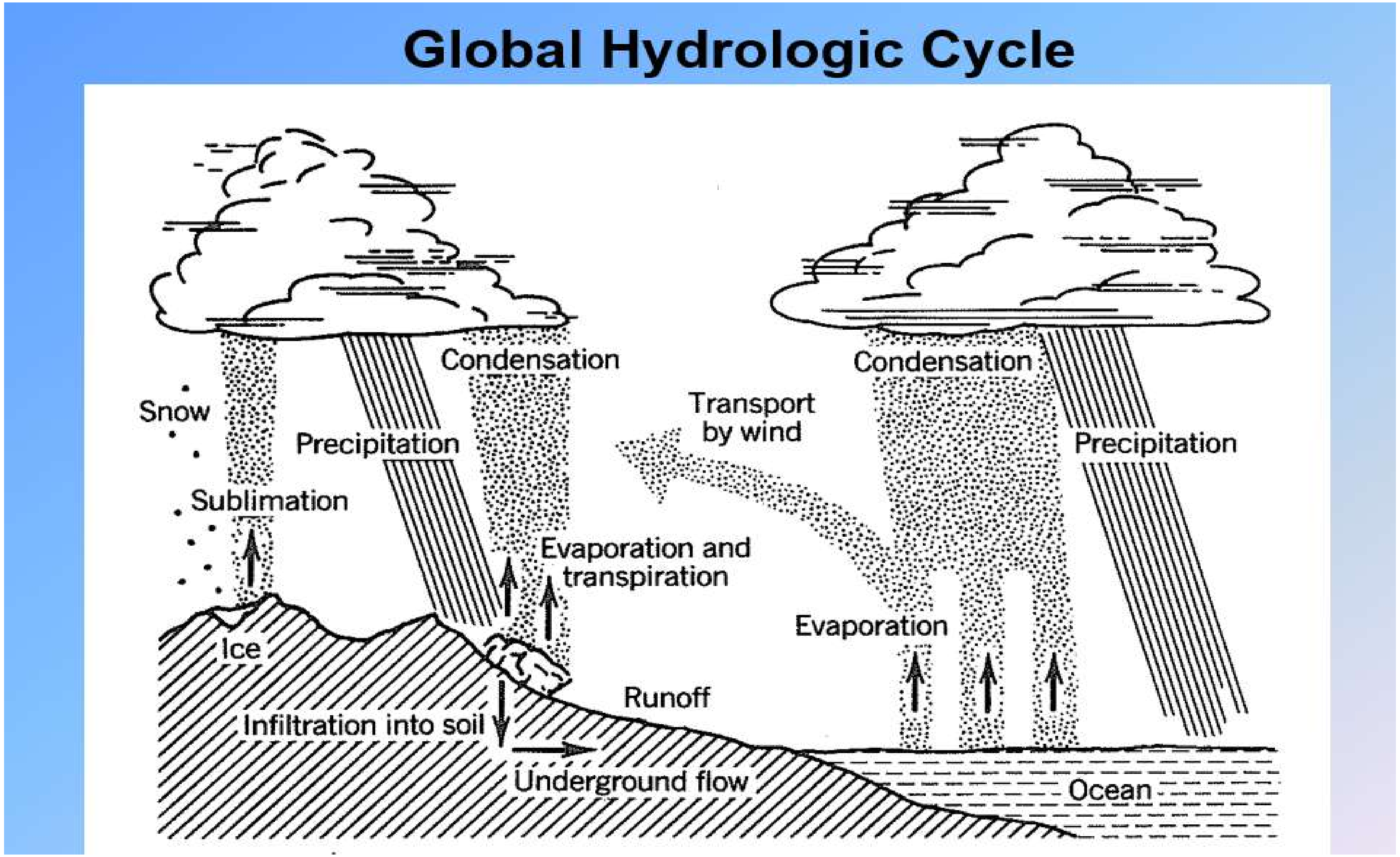


Hydrologic Cycle

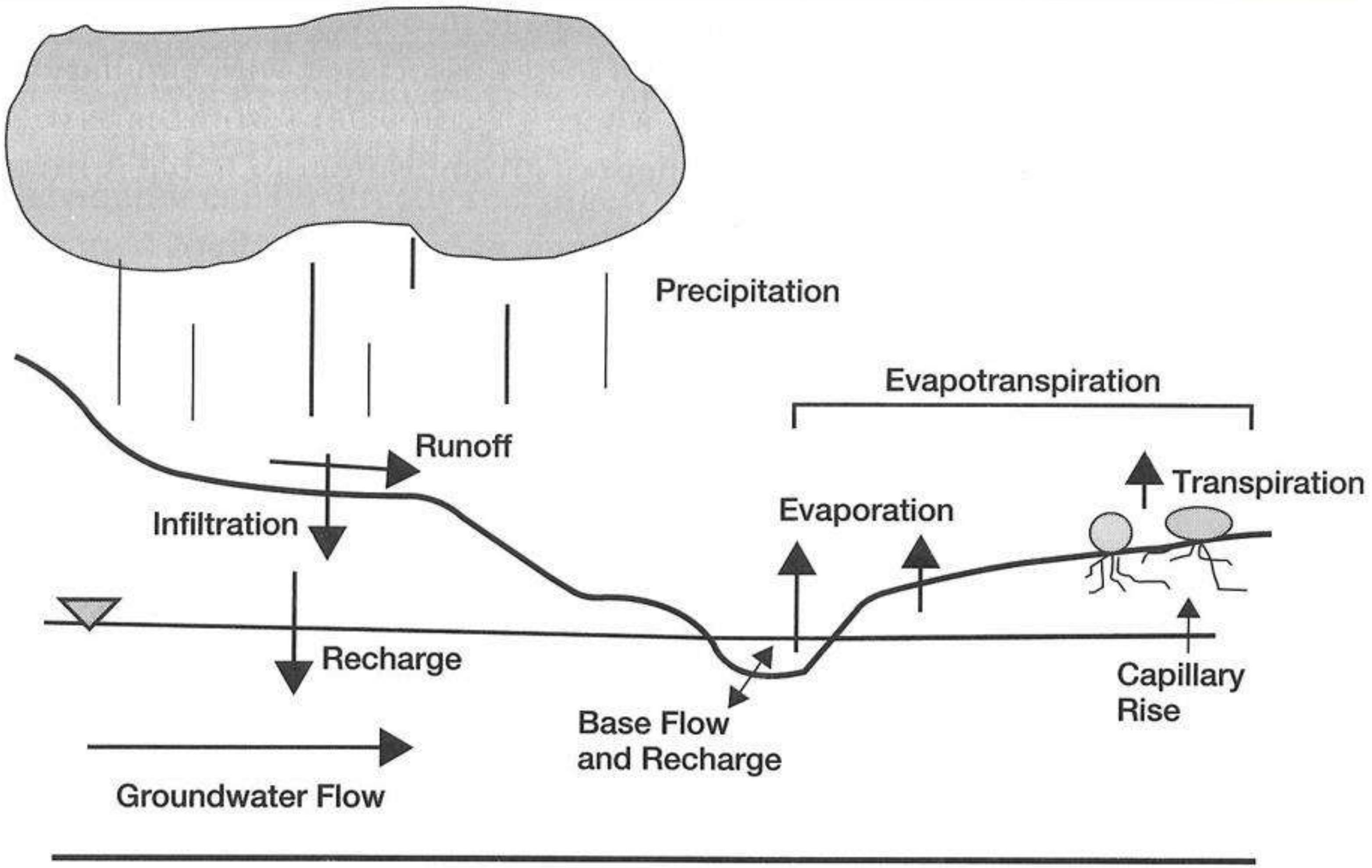


Hydrologic Cycle- Cont.

- World water problems require studies on regional, national, international, continental, and global scales.



Basin Hydrologic Cycle



Water Balance

- A water balance can be established for any area of earth's surface by calculating the total precipitation input and the total of various outputs.

- The water-balance approach allows an examination of the hydrologic cycle for any period of time.

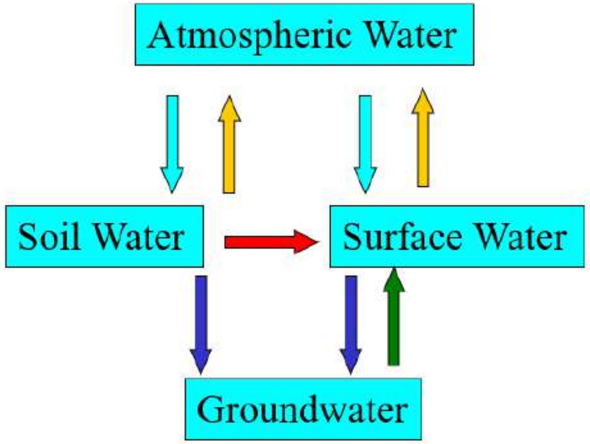
- The purpose of the water balance is to describe the various ways in which the water supply is expended.

Water Balance- Cont.

- The water balance is defined by the general hydrologic equation, which is basically a statement of the law of conservation of mass as applied to the hydrologic cycle. In its simplest form, this equation reads
- The water balance defines the conservation of mass across the different compartments of the hydrological cycle (atmosphere, water bodies, soil and ground, vegetation, snowpack and ice, …)

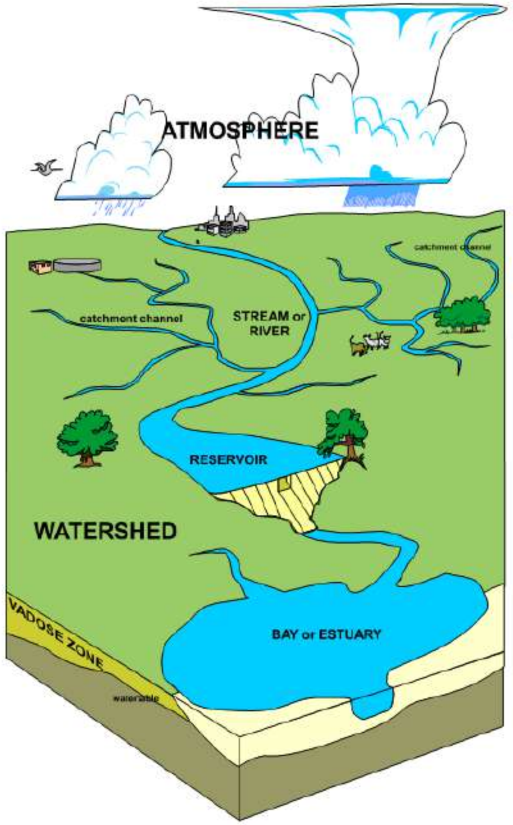
Inflow = Outflow + Change in Storage

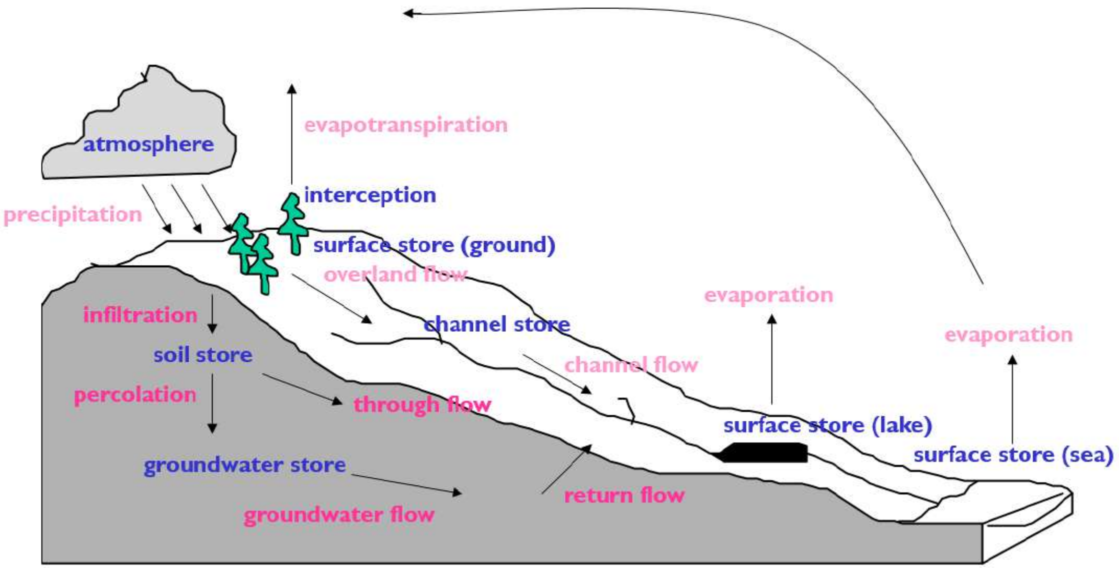
Water Balance



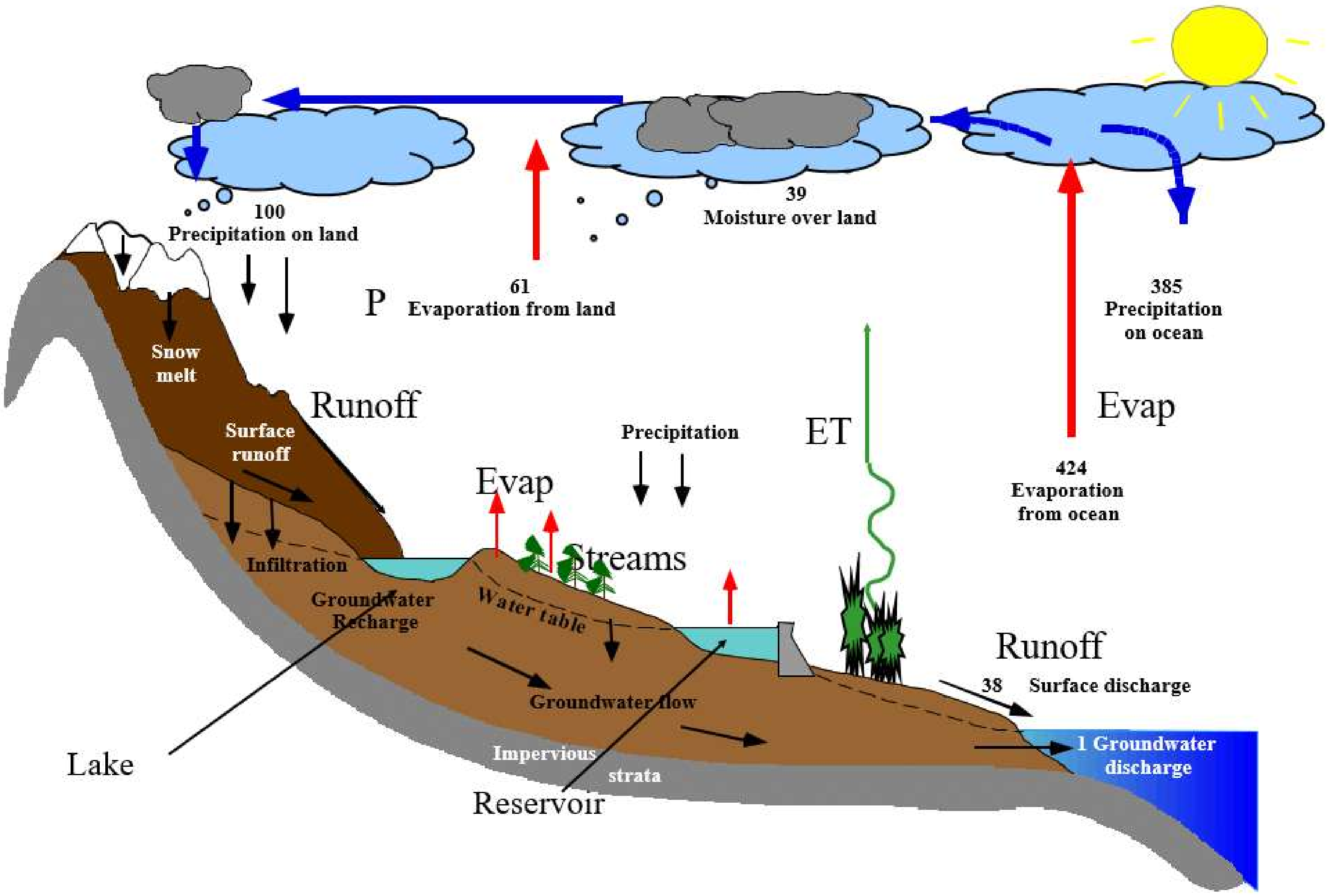
Inflow – Outflow = Change of Storage

$$I - Q = \frac{dS}{dt}$$

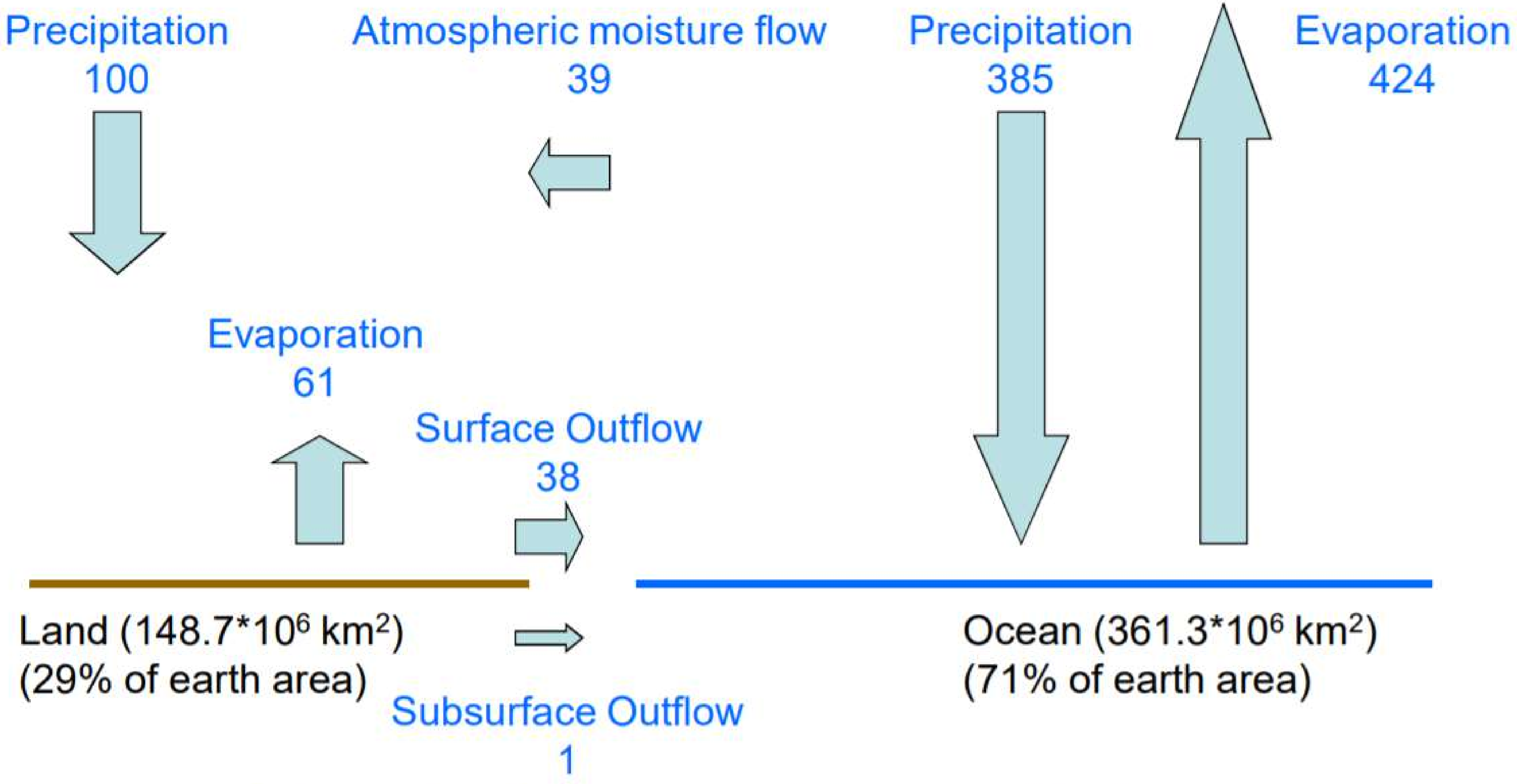




Water Balance



Global Water Balance (Volumetric)



Units are in volume per year relative to precipitation on land (119,000 km^3/yr) which is 100 units

Example

- If a vertical-walled reservoir having a surface area of 1 mi^2 receives an inflow of 12 cfs, how long will it take to raise the reservoir level by 6 inches?

1 mi = 5280 ft

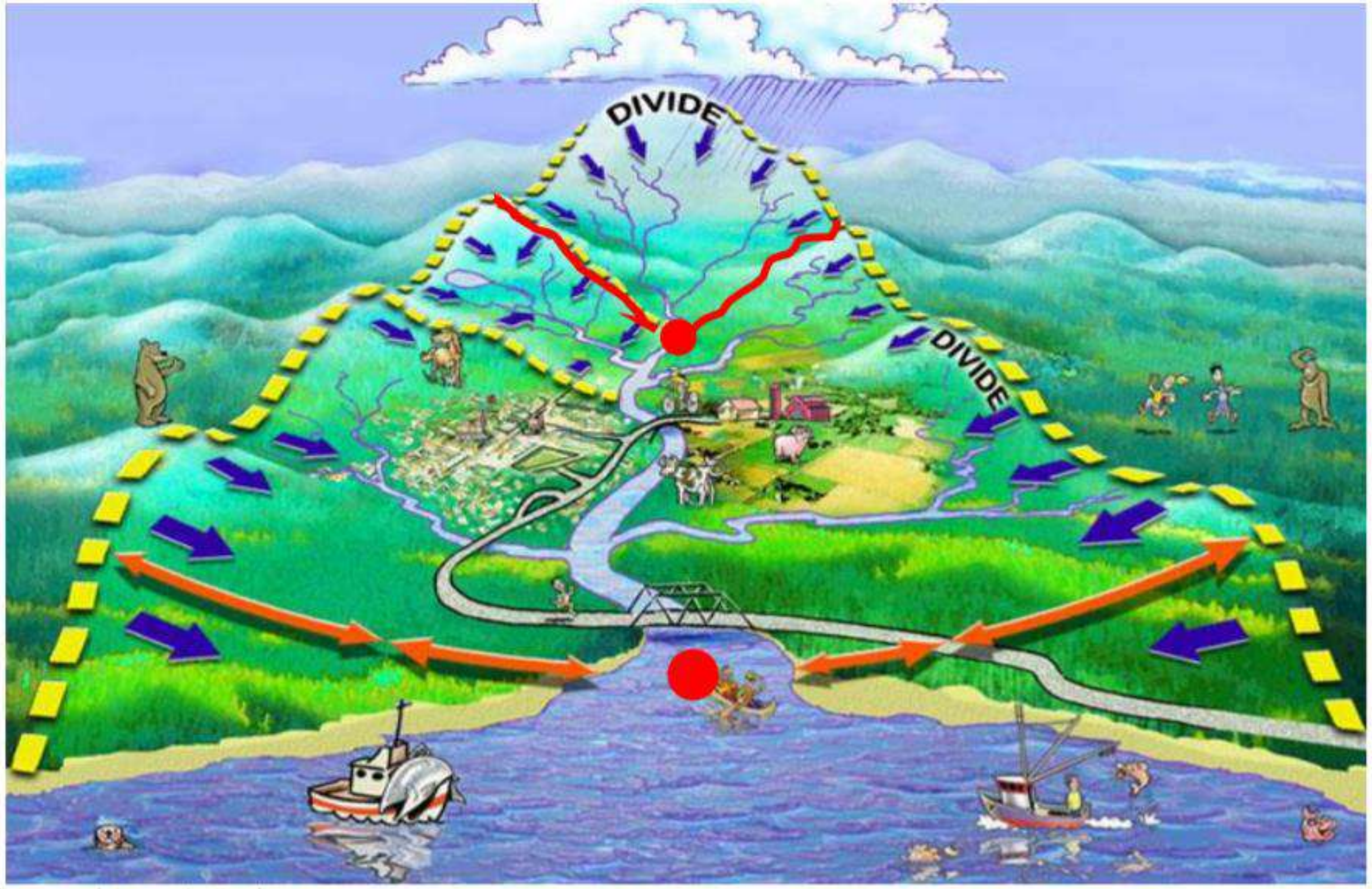
Example

- If the mean annual runoff of a drainage basin of 10000 km^2 is 140 m^3/sec, and the average annual precipitation is 105 cm, estimate the ET losses for the area in 1 year. What are your assumptions? How reliable do you think this estimate is?

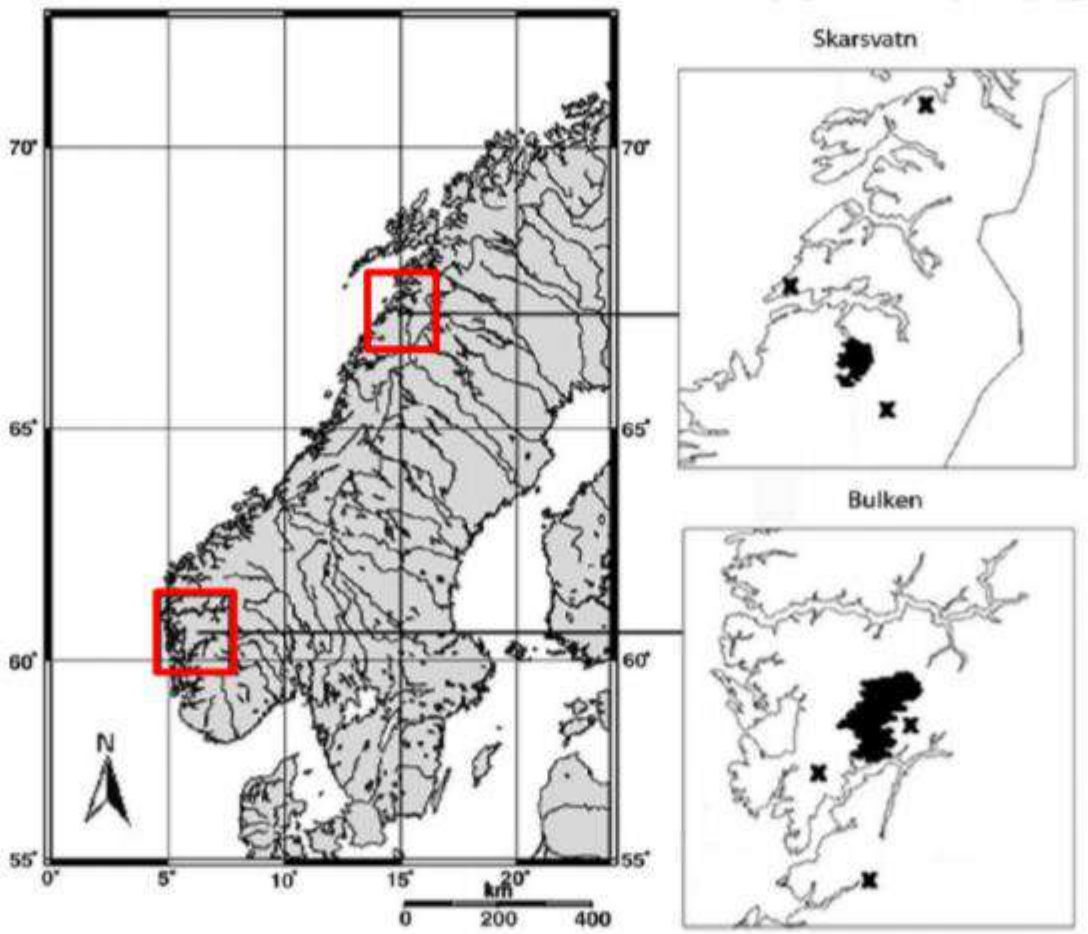
Catchment and watershed

The word Watershed is sometimes interchangeably used as Catchment Area. Are they the same!

A **catchment** is an **area** in which water falling on or flowing across the land surface drains into a particular stream or river and flows ultimately through a single point or outlet.



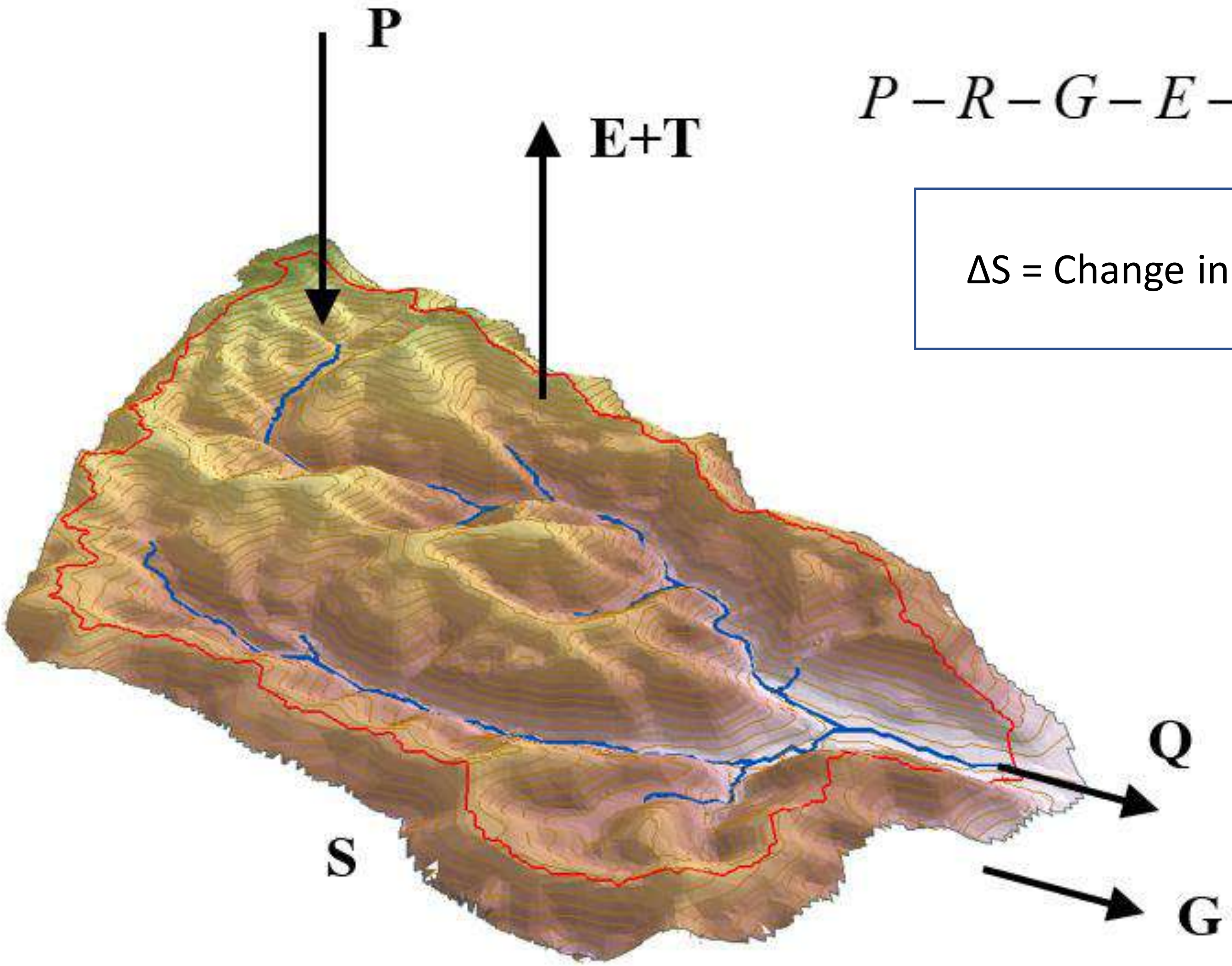
Catchment area is defined by topographical water divide.



Skarsvatn 86 km^2 – Bulken 1094 km^2

Amazon 7 x 10^6 km^2

Watershed water balance



$$P - R - G - E - T = \Delta S$$

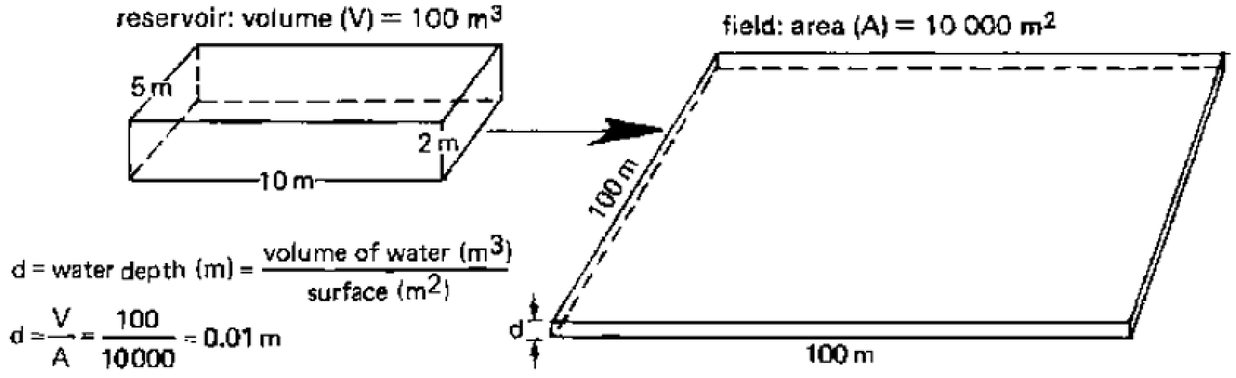
ΔS = Change in water storage

Example

- Suppose there is a reservoir, filled with water, with a length of 5 m, a width of 10 m and a depth of 2 m. All the water from the reservoir is spread over a field of 1 hectare. Calculate the water depth (which is the thickness of the water layer) on the field.

  - Surface of the field = 10 000 m^2
    Volume of water = 100 m^3
  - Formula:

$$d = V/A = 100 / 10{,}000 = 0.01 \text{ m} = 10 \text{ mm}$$



Example

- A water layer 1 mm thick is spread over a field of 1 ha. Calculate the volume of the water (in m^3).

<u>Given</u>

Surface of the field = 10 000 m^2
Water depth = 1 mm =1/1 000 = 0.001 m
Volume (m^3) = surface of the field (m^2) x water depth (m)

<u>Answer</u>

V = 10 000 m^2 x 0.001 m
V = 10 m^3 or 10 000 liters

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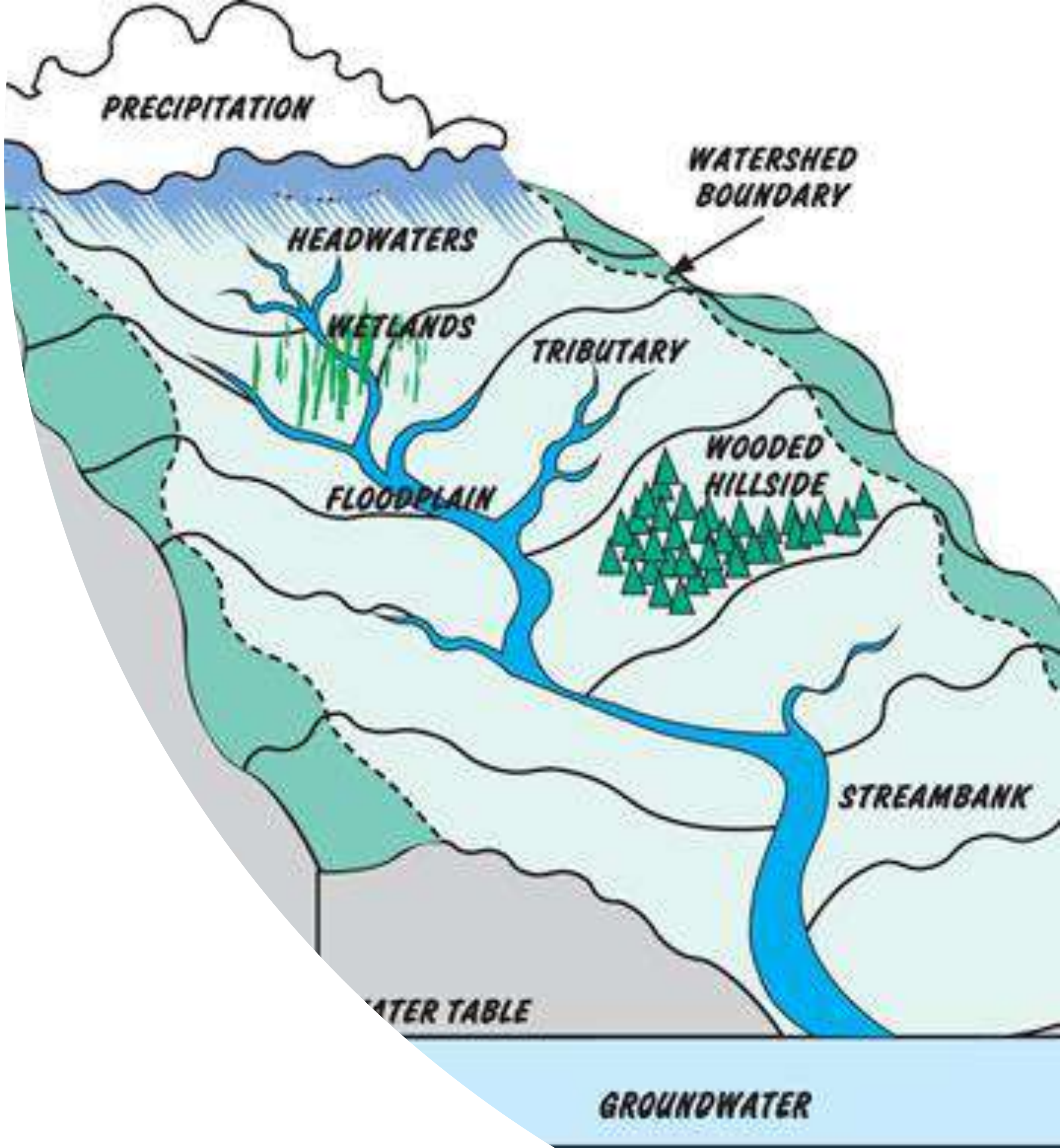
Lecture 3. Watershed

Cont. Watershed

- Watershed is the basic unit of all hydrologic analysis and designs.

- Usually a watershed is defined for a given drainage point. This point is usually the location at which the analysis is being made and is referred to as the watershed "outlet".

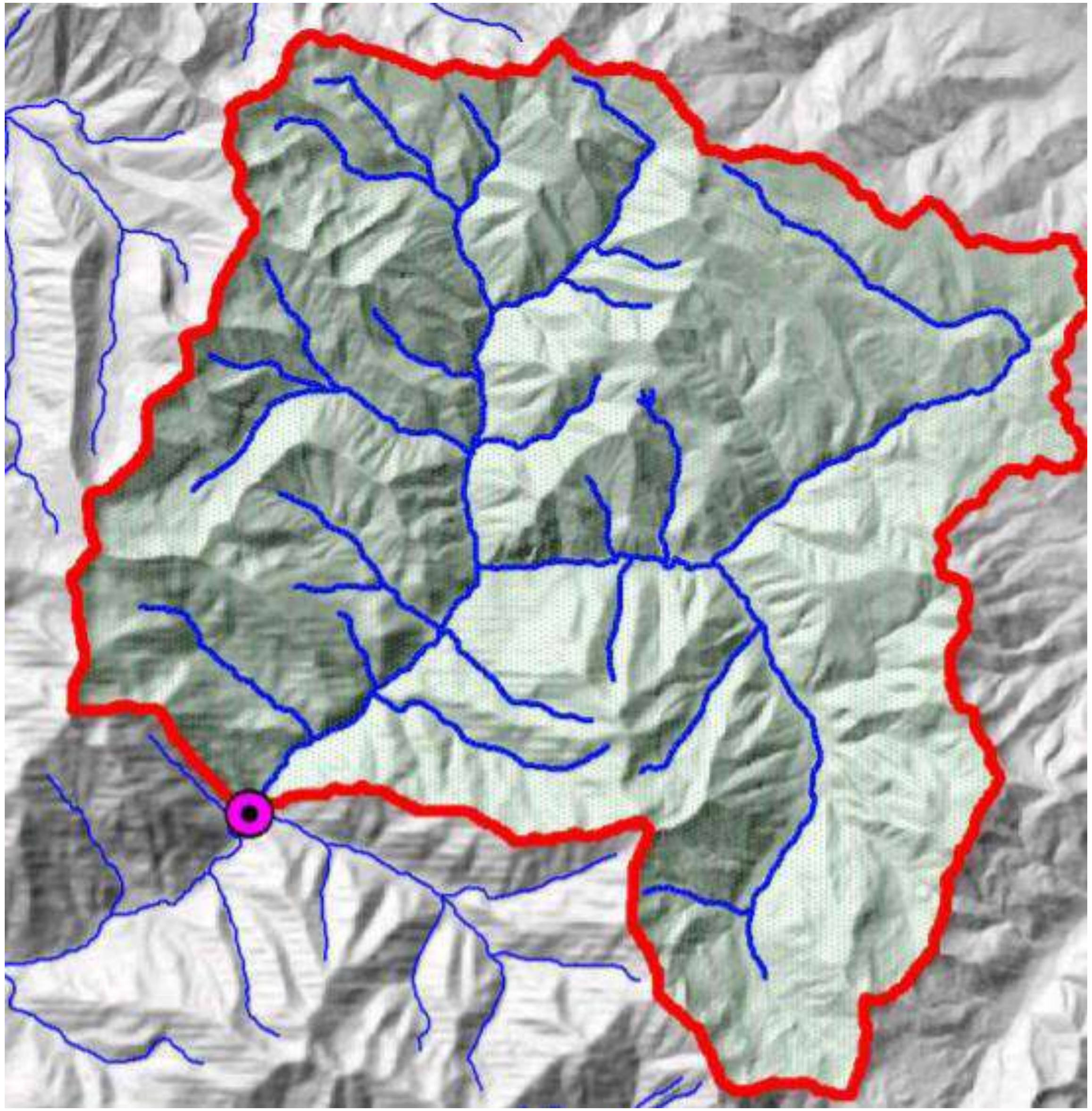
- The watershed, therefore, consists of all the land area that drains water to the outlet during a rainstorm.

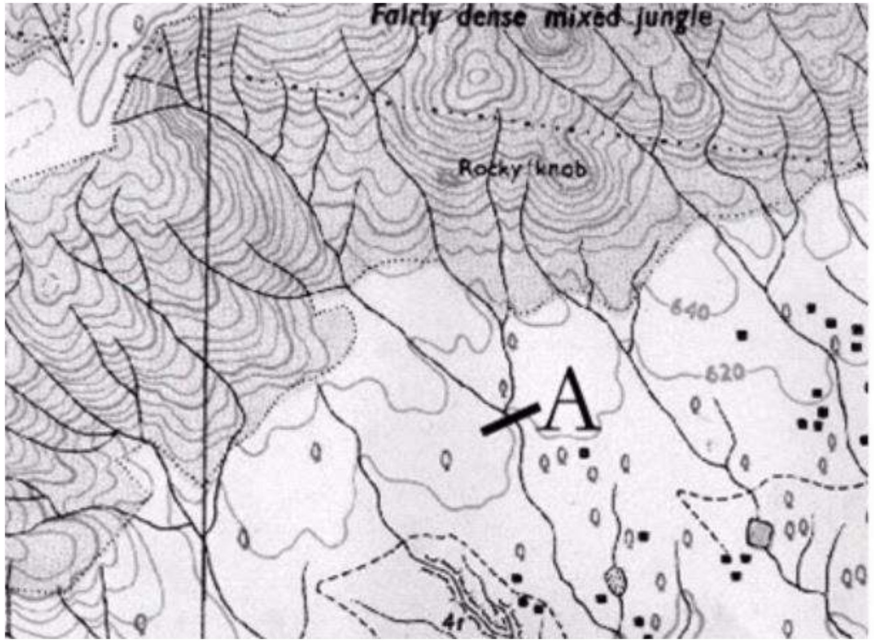


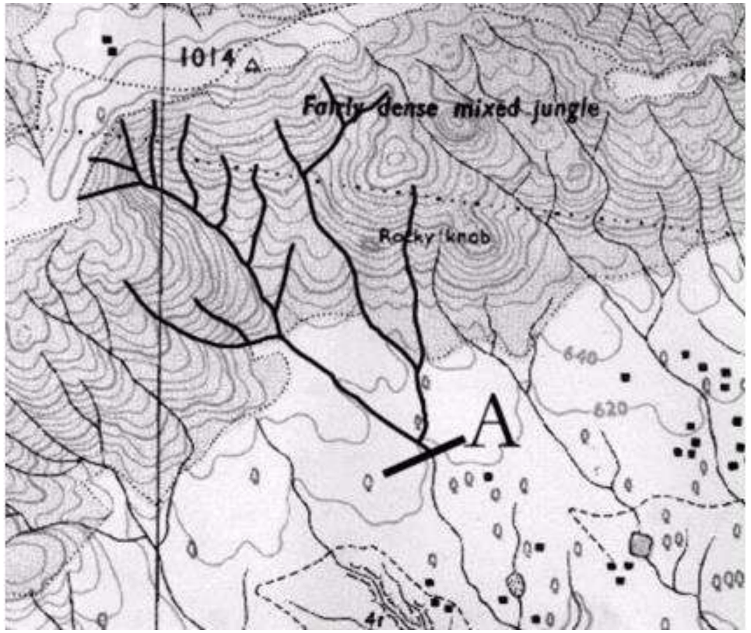
Watershed delineation

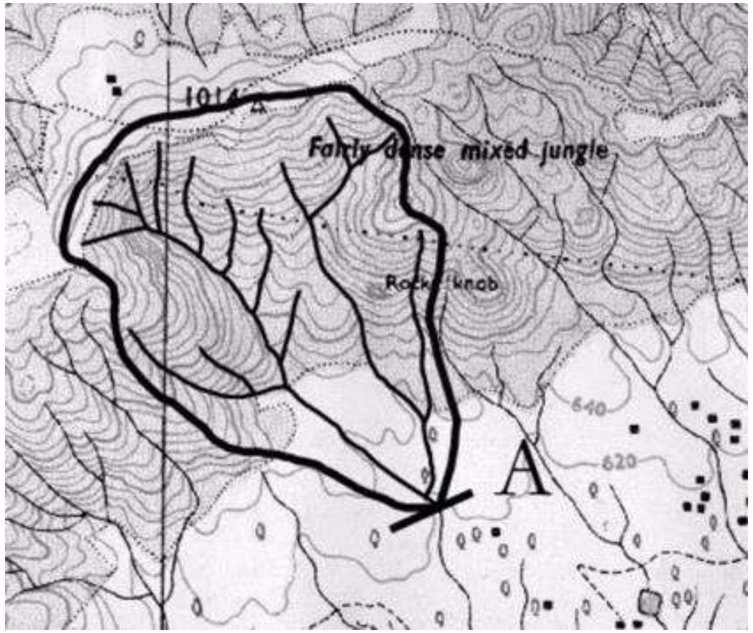
- Creating a boundary that represents the contributing area for a particular control point or outlet.

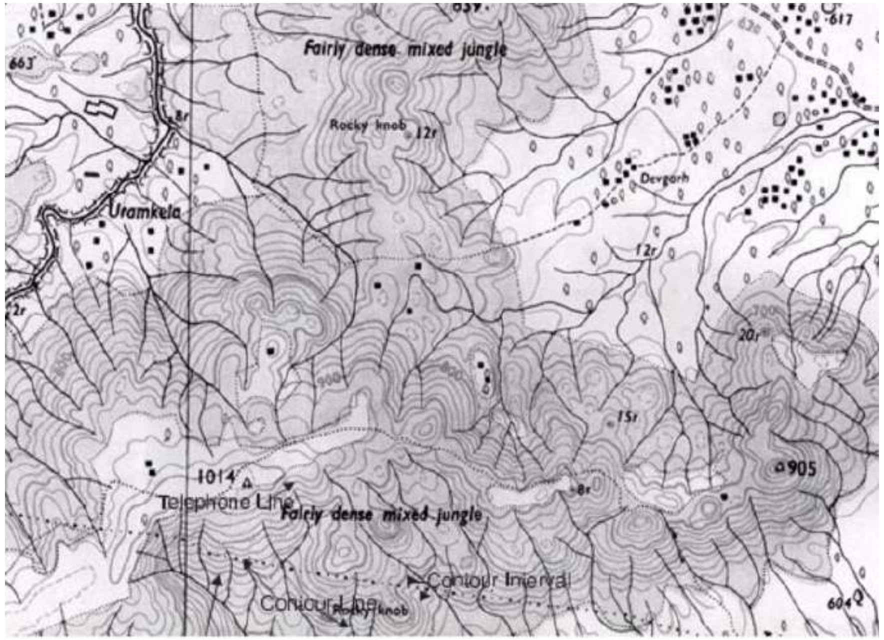
- Used to define boundaries of the study area, and/or to divide the study area into sub-areas.











Watershed delineation steps

Cont. Watershed delineation

- Use a topographic map(s) to locate the river, lake, stream, wetland, or other waterbodies of interest.

- Identify the point with respect to which the watershed is to be marked(the exit point or outlet).

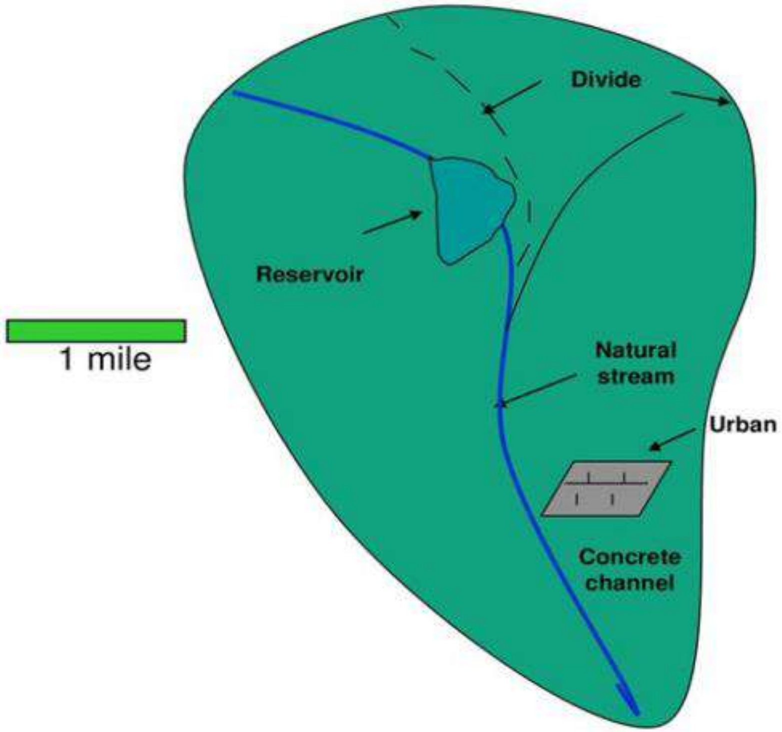
- Trace the watercourse from its source to its mouth, including the tributaries. Mark the drainage lines.

- Check the slope of the landscape by locating two adjacent contour lines and determine their respective elevations. The slope is calculated as the change in elevation, along a straight line, divided by the distance between the endpoints of that line.

- Watershed boundaries will be marked finally.

Watershed characteristics

- Size
- Slope
- Shape
- Soil type
- Storage capacity

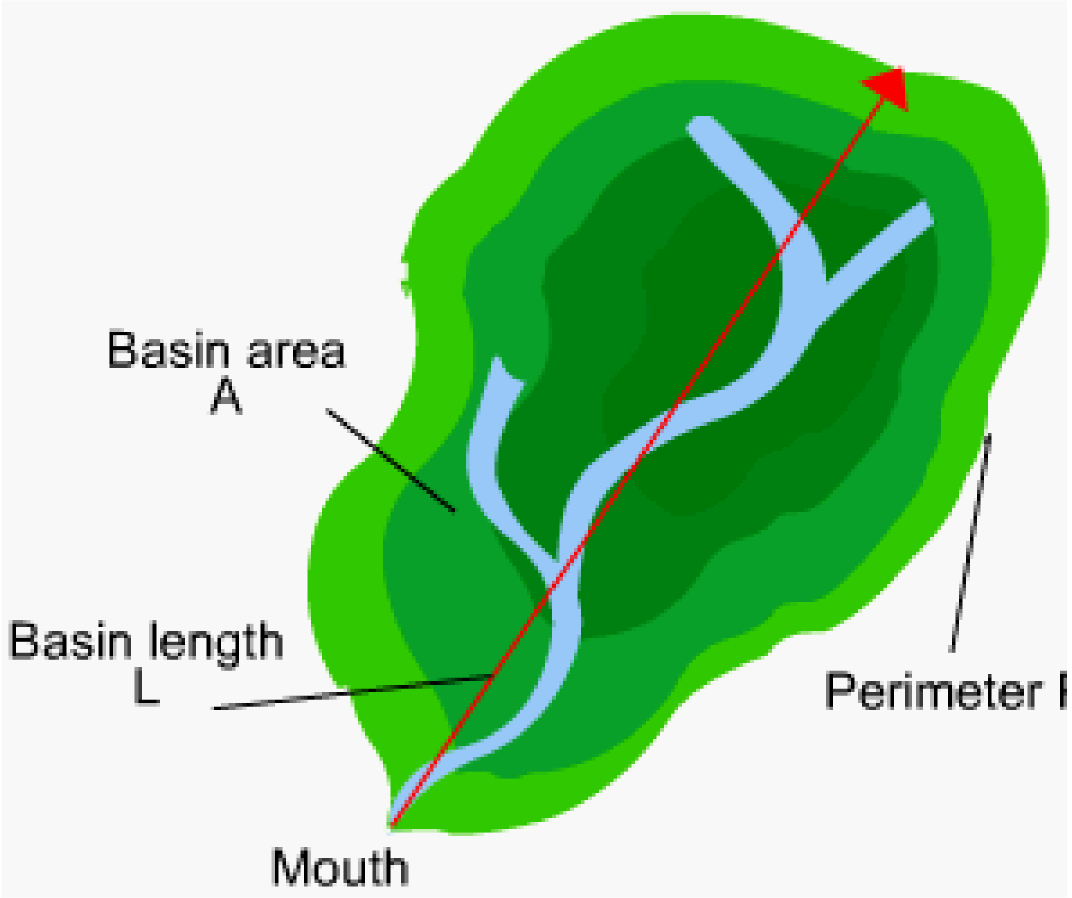


Watershed characteristics are referred to as watershed geomorphology, which are the physical properties of watersheds. It significantly affects the characteristics of runoff and hydrological responses such as the flow regime during floods and periods of drought.

Drainage Area

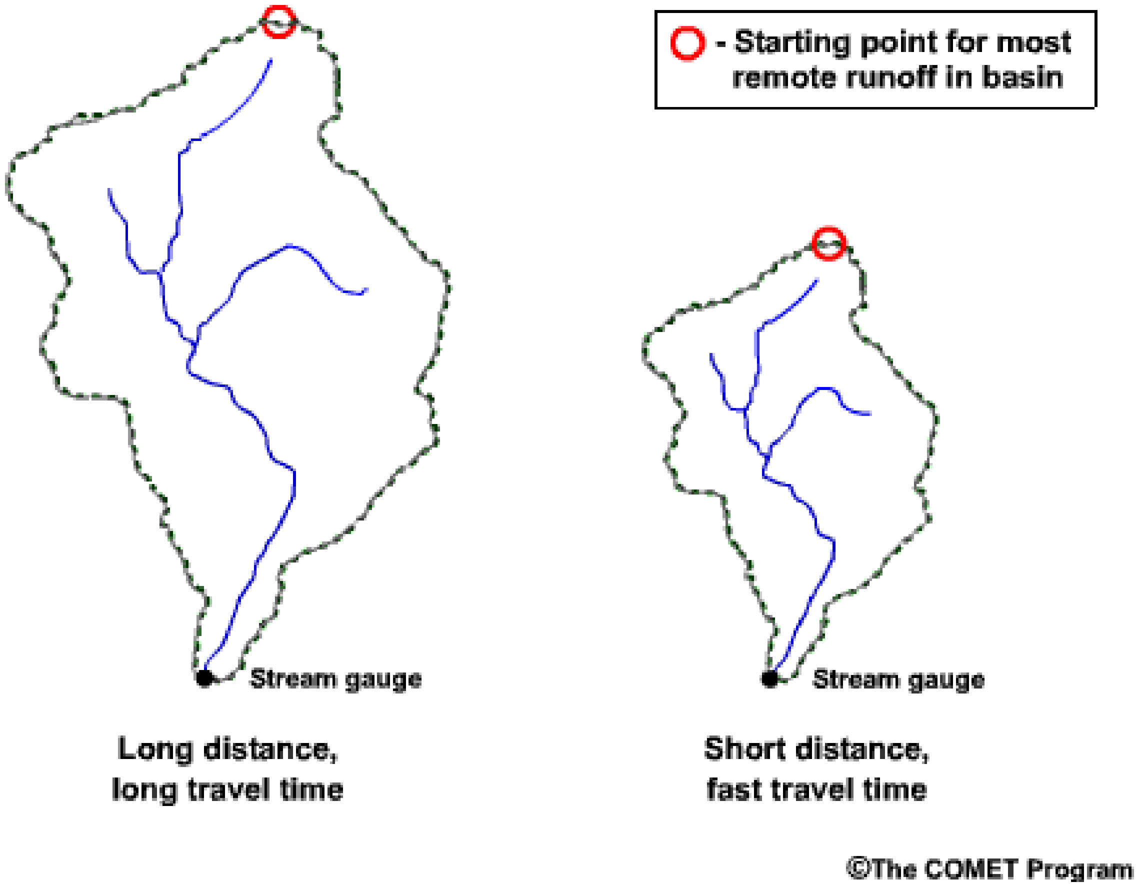
- The drainage area (A) is the probably the single most important watershed characteristic for hydrologic design. It reflects the volume of water that can be generated from rainfall.

- It is common in hydrologic design to assume a constant depth of rainfall occurring uniformly over the watershed. Under this assumption, the volume of water available for runoff would be the product of rainfall depth and the drainage area. Thus the drainage area is required as input to models ranging from simple linear prediction equations to complex computer models



Watershed length

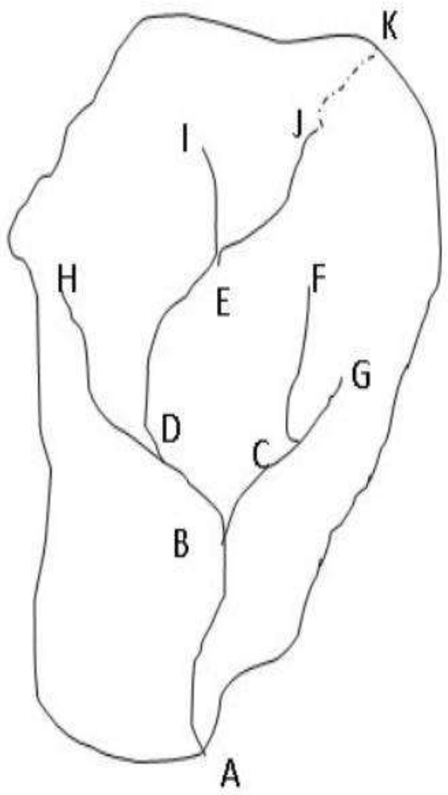
- The length (L) of a watershed is the second watershed characteristic of interest. While the length increases as the drainage increases, the length of a watershed is important in hydrologic computations. Watershed length is usually defined as the distance measured along the main channel from the watershed outlet to the basin divide.



Example

Main channel passes through points A, B, D, E and J. The length of AB is 1.8 km, BD is 1.3 km, DE is 1.7 km and EJ is 1.8 km. The remotest point of the watershed is K which is 0.8 km far from the start of main channel, i.e., point J. What will be the watershed length?

Solution:



The length of main channel is

AB+BD+DE+EJ = 1.8+1.3+1.7+1.8 = 6.6 km

The distance between the start of main channel and remotest point (shown by dotted line in the picture) is JK

Length of JK is 0.8

Hence total length of watershed is 6.6+0.8 = 7.4 km

Watershed Slope

- Watershed slope reflects the rate of change of elevation with respect to distance along the principal flow path. Typically, the principal flow path is delineated, and the watershed slope (S) is computed as the difference in elevation (ΔE) between the end points of the principal flow path divided by the hydrologic length of the flow path (L):

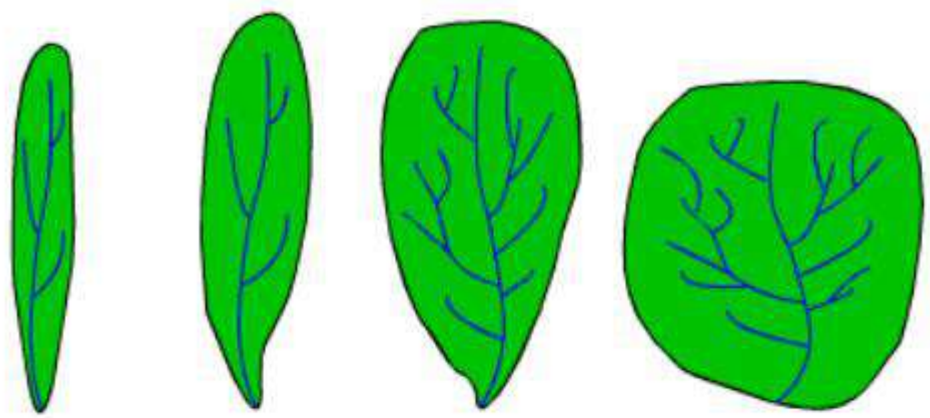
$$S = \Delta E / L$$

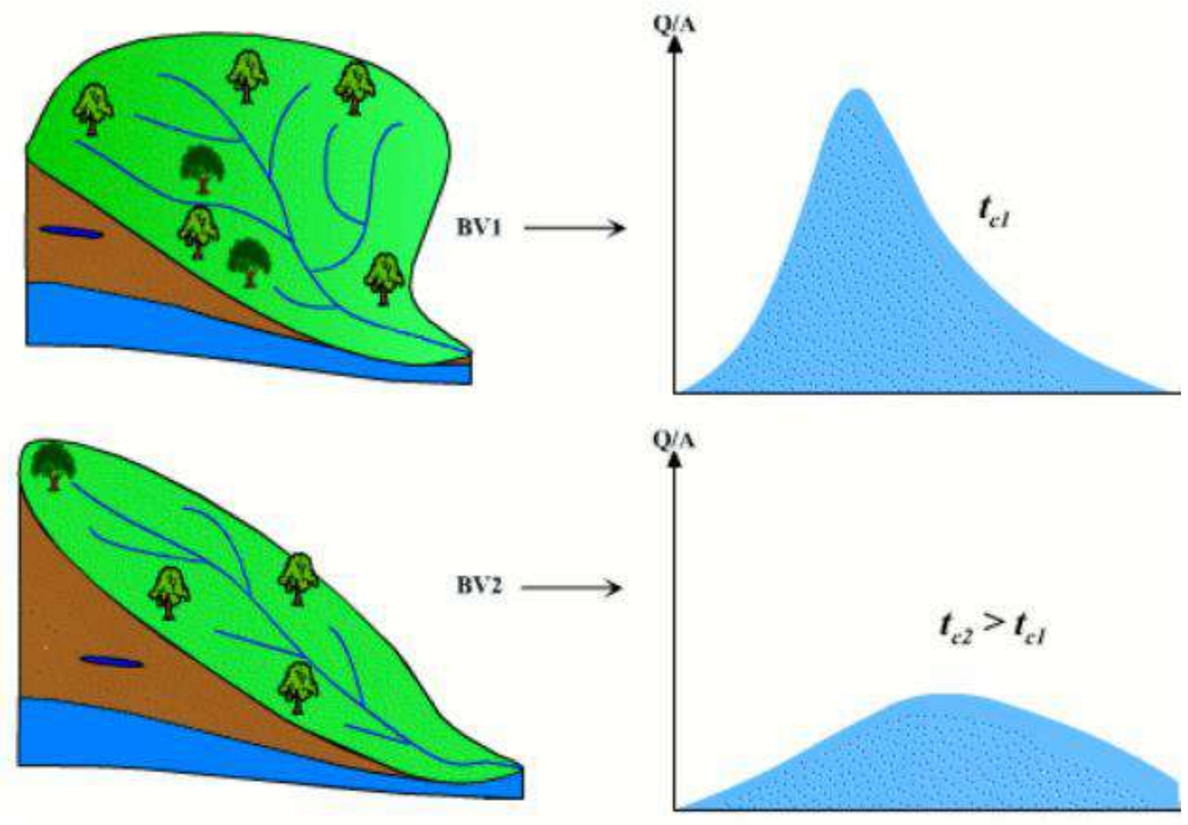
Example -2 . In continuation of example 1: K, A and J is having elevations of 578m, 316 m, 532 m respectively. Calculate the watershed slope.

Watershed slope = elevation difference between point K and A divided by watershed length i.e. (578-316)/7.4 = 262/7.4 = 35.4 m per km = 3.54%

Watershed shape

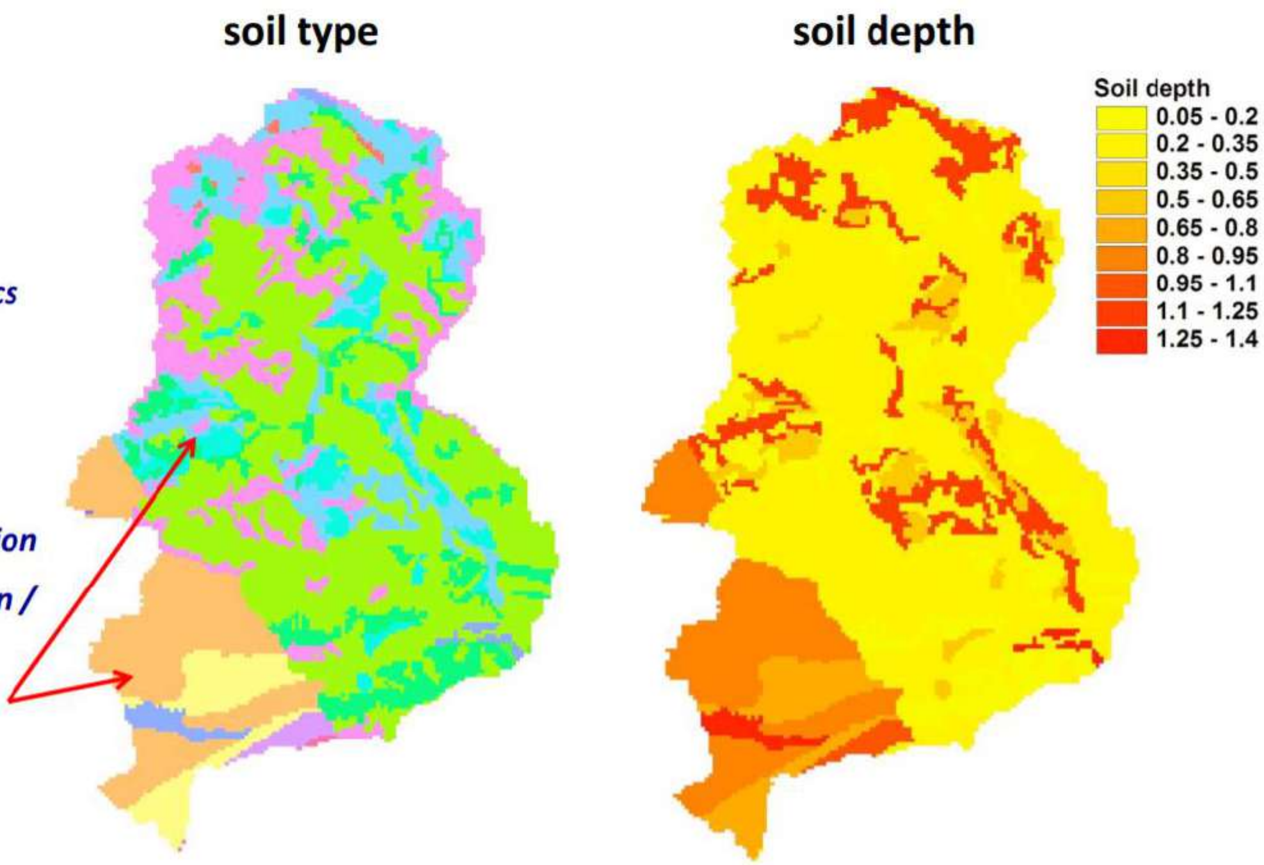
- The shape of a watershed influences the shape of its characteristic hydrograph. For example, a long shape watershed generates, for the same rainfall, a lower outlet flow, as the concentration time is higher. A watershed having a fan-shape presents a lower concentration time, and it generates higher flow.





Soil Type

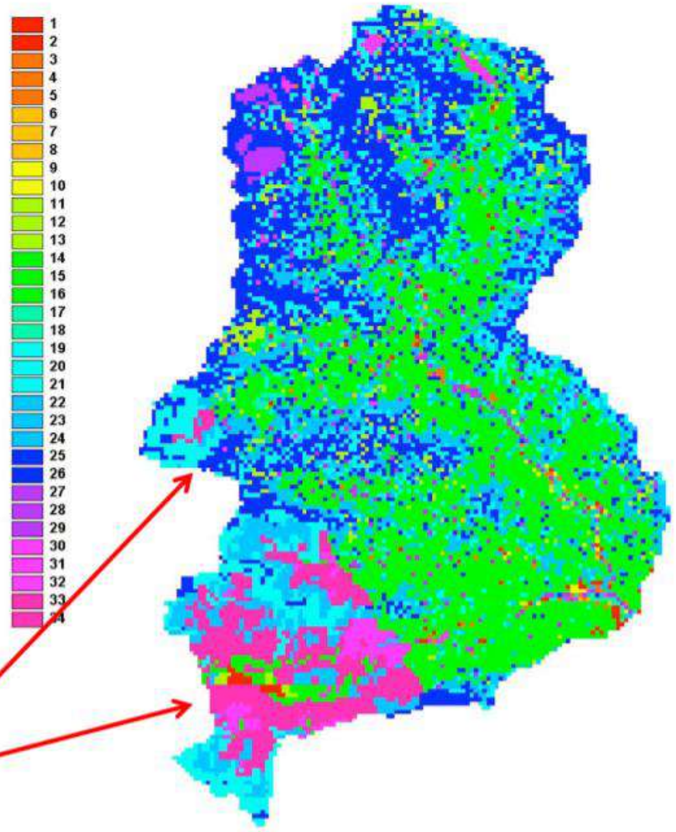
- use
  - ↳ *delineation of infiltration and soil storage characteristics*
  - ↳ *parameterisation of infiltration models*
- problems
  - ↳ *accuracy of information*
  - ↳ *different classification / resolution used by different countries*



(Maggia river basin, Tessin, CH)

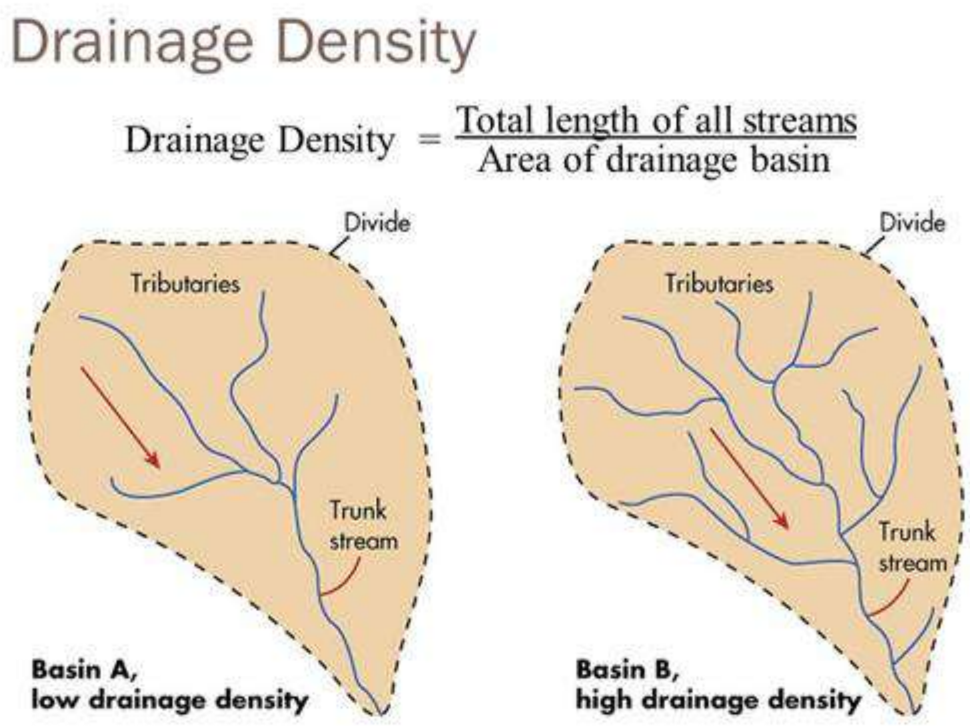
Land Use

- use
  - ↳ ***parameterisation of models***
    - – ***infiltration*** (e.g. SCS-CN)
    - – ***evapotranspiration***
- problems
  - ↳ ***representativeness of map depends on raster size***
  - ↳ ***different classification /resolution used by different countries***



1	Continuos urban fabric
2	Discontinuous urban fabric
3	Industrial or commercial units
4	Road and railway networks and associated land
5	Mineral extraction sites
6	Construction sites
7	Green urban areas
8	Sport & leisure facilities, Gras landingstrip
9	Non-irrigated arable
10	Vineyards
11	Fruit trees and berry plantations
12	Pastures
13	Complex cultivation pattern
14	Principals crops with significant natural vegetation
15	Forest
16	Open Forest
17	Meadows and agricultural land, good condition
18	Meadows and agricultural land, poor condition
19	Meadows in mountains
20	Natural grassland
21	Moors and heathland
22	Bushy sclerophillous vegetation
23	Transitional woodland-scrub
24	Sand plains
25	Bare rock
26	Sparsely vegetated areas
27	Glaciers and perpetual snow
28	Inland marshes (wet areas)
29	Water courses
30	Water bodies
31	Littoral zones
32	Broad Leaf
33	Coniferous Forest
34	Mixed Forest

Drainage density



- Drainage density is the total length of all the streams and rivers in a drainage basin divided by the total area of the drainage basin. It is a measure of how well or how poorly a watershed is drained by stream channels.

Cont. Drainage density

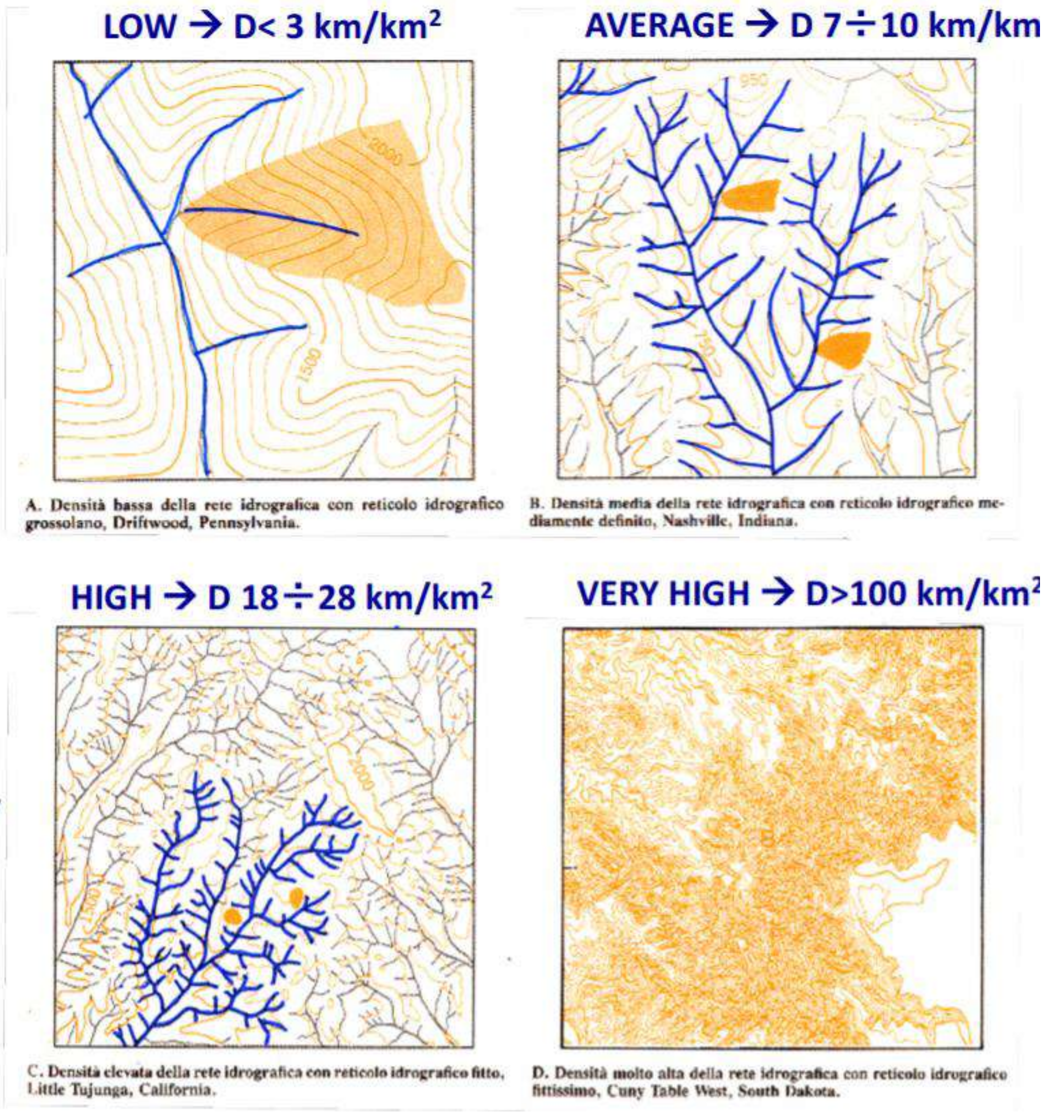
- It measures the efficiency of the basin drainage (i.e. of how well or how poorly a watershed is drained by rivers).

- It depends upon both climate (e.g. rainfall regime) and physical characteristics (e.g. geology, slope, soil, land cover) of the drainage basin.

- For equal climatic characteristics can be used as proxy information for permeability

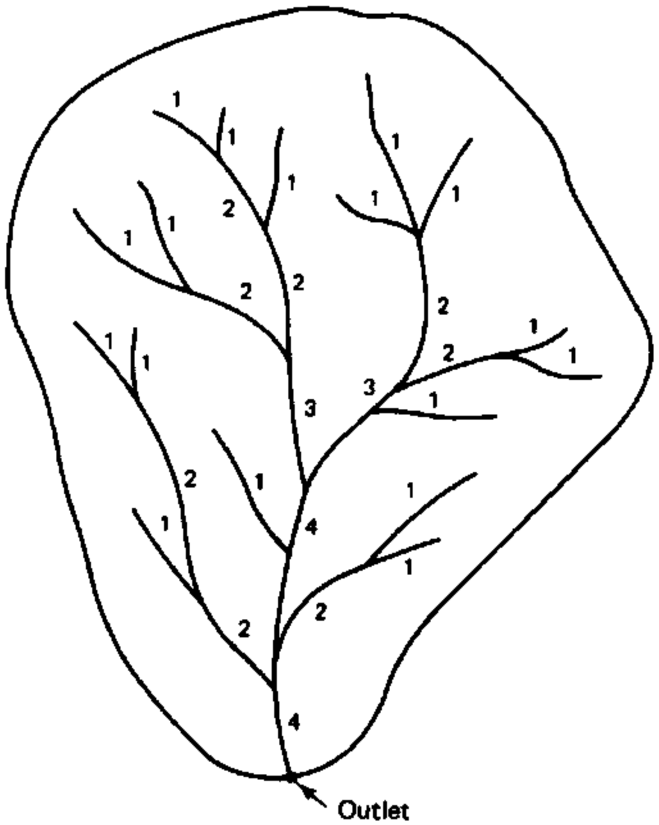
↳ *high D → low permeability*

↳ *low D → high permeability*



Stream order and Hortons Law

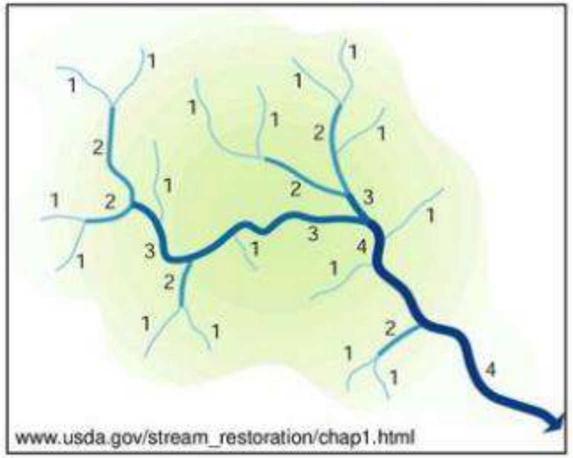
The stream order or waterbody order is a positive whole number used in geomorphology and hydrology to indicate the level of branching in a river system.



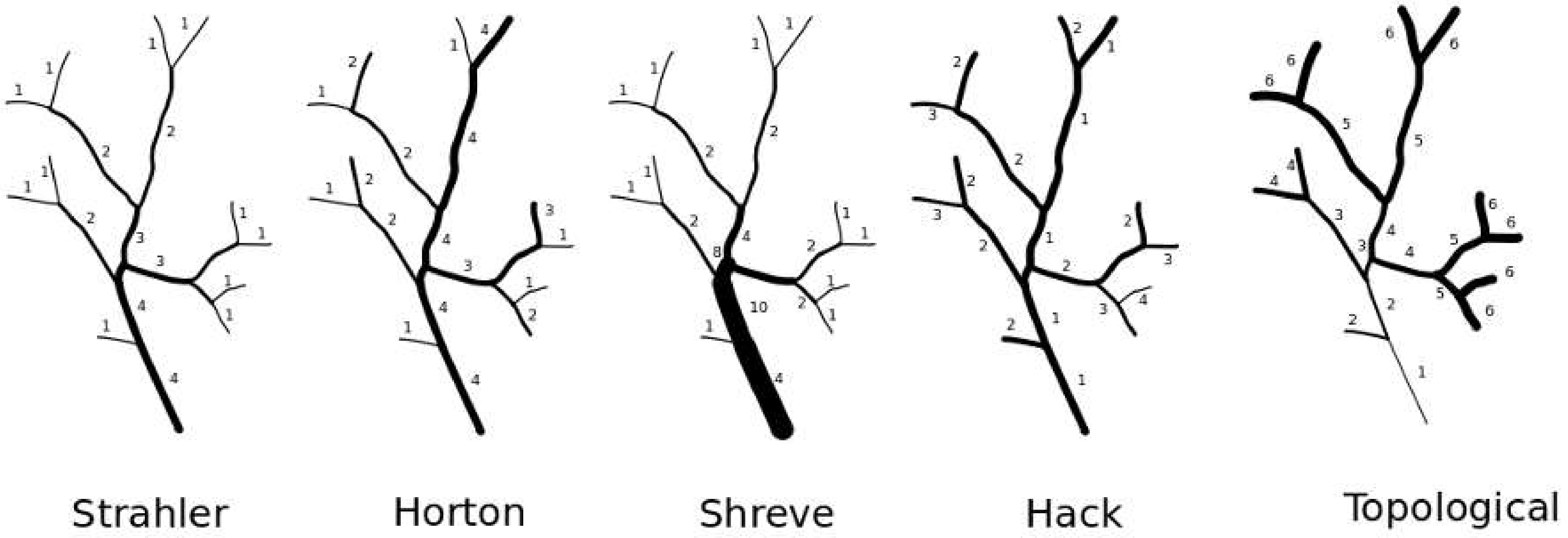
The **stream order** is a measure of the degree of stream branching within a watershed.

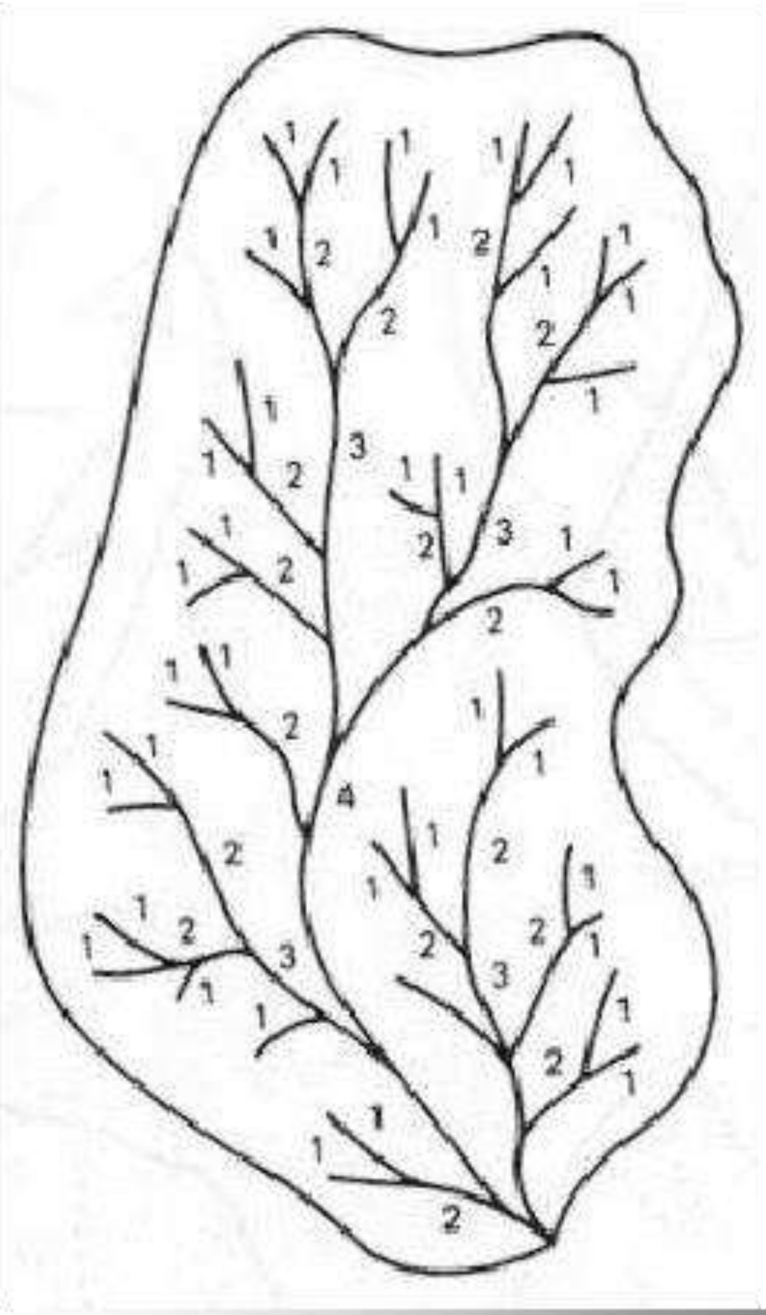
Cont. Stream order

- A method of classifying or ordering the hierarchy of natural channels.
- Strahler (1957) is the most widely used system.
- Stream order correlates well with drainage area, but is also regionally controlled by topography & geology.



Stream Order System

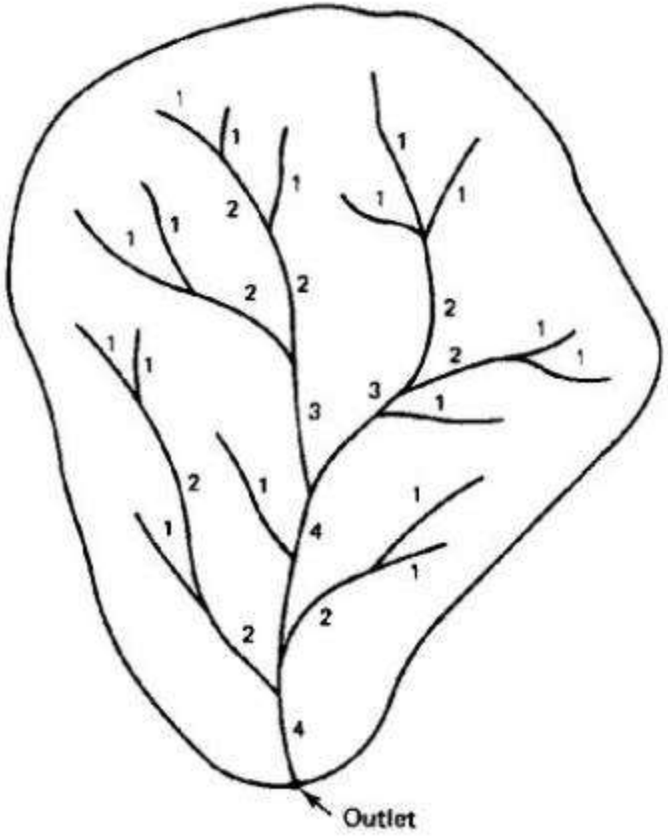




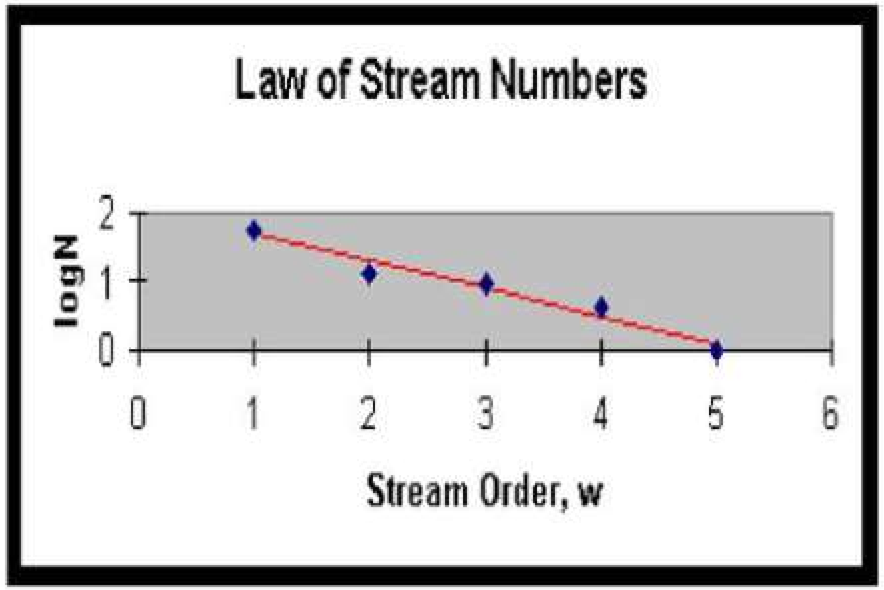
Cont. Stream order and Hortons Law

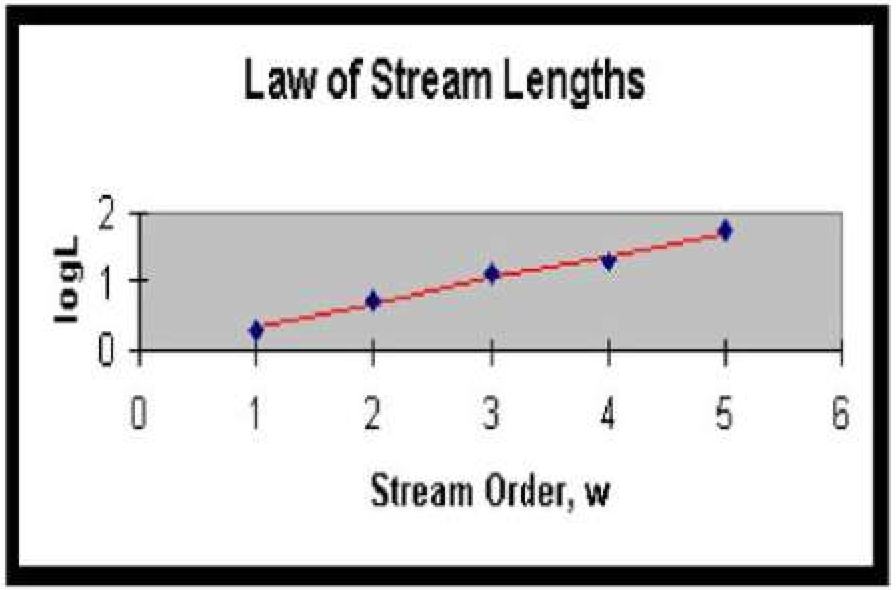
- Each length of stream is indicated by its order (for example, first-order, second-order, etc.). A first-order stream is an unbranched tributary, a second-order stream is a tributary formed by two or more first-order streams. A third-order stream is a tributary formed by two or more second-order streams and so on. In general, an nth order stream is a tributary formed by two or more streams of order (n-1) and streams of lower order.

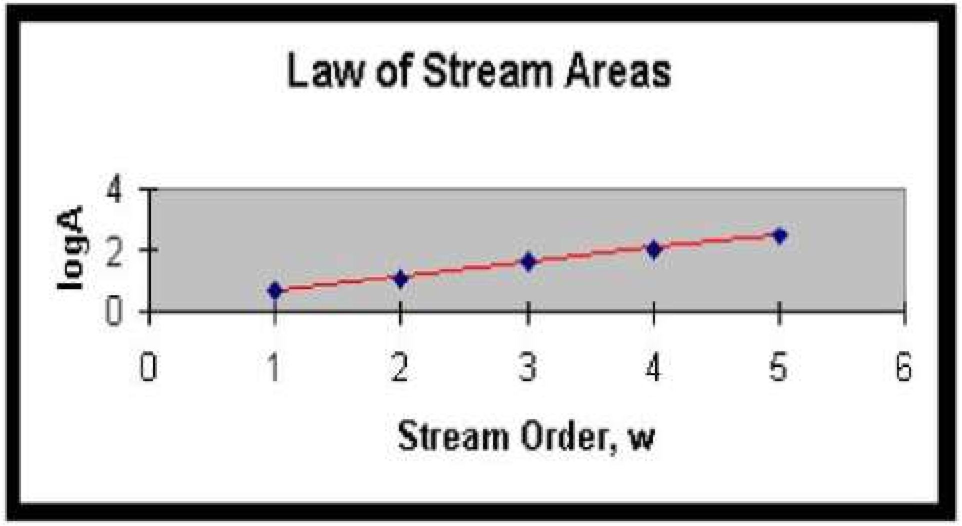
Horton's Law of Streams (modified by Strahler)



Law of Stream Lengths
Law of Stream Areas
Bifurcation Ratio


Law of Stream Numbers
logN
2
1
0
0
1
2
3
4
5
6
Stream Order, w


Law of Stream Lengths
logL
2
1
0
0
1
2
3
4
5
6
Stream Order, w


Law of Stream Areas
logA
4
2
0
0
1
2
3
4
5
6
Stream Order, w

Denoting by *m* the slopes of the corresponding fits

$$R_B = \frac{1}{anti\log(m)}$$

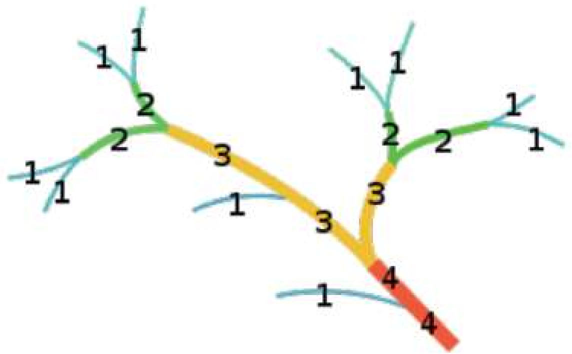
$$R_L = anti\log(m)$$

$$R_A = anti\log(m)$$

Bifurcation Ratio

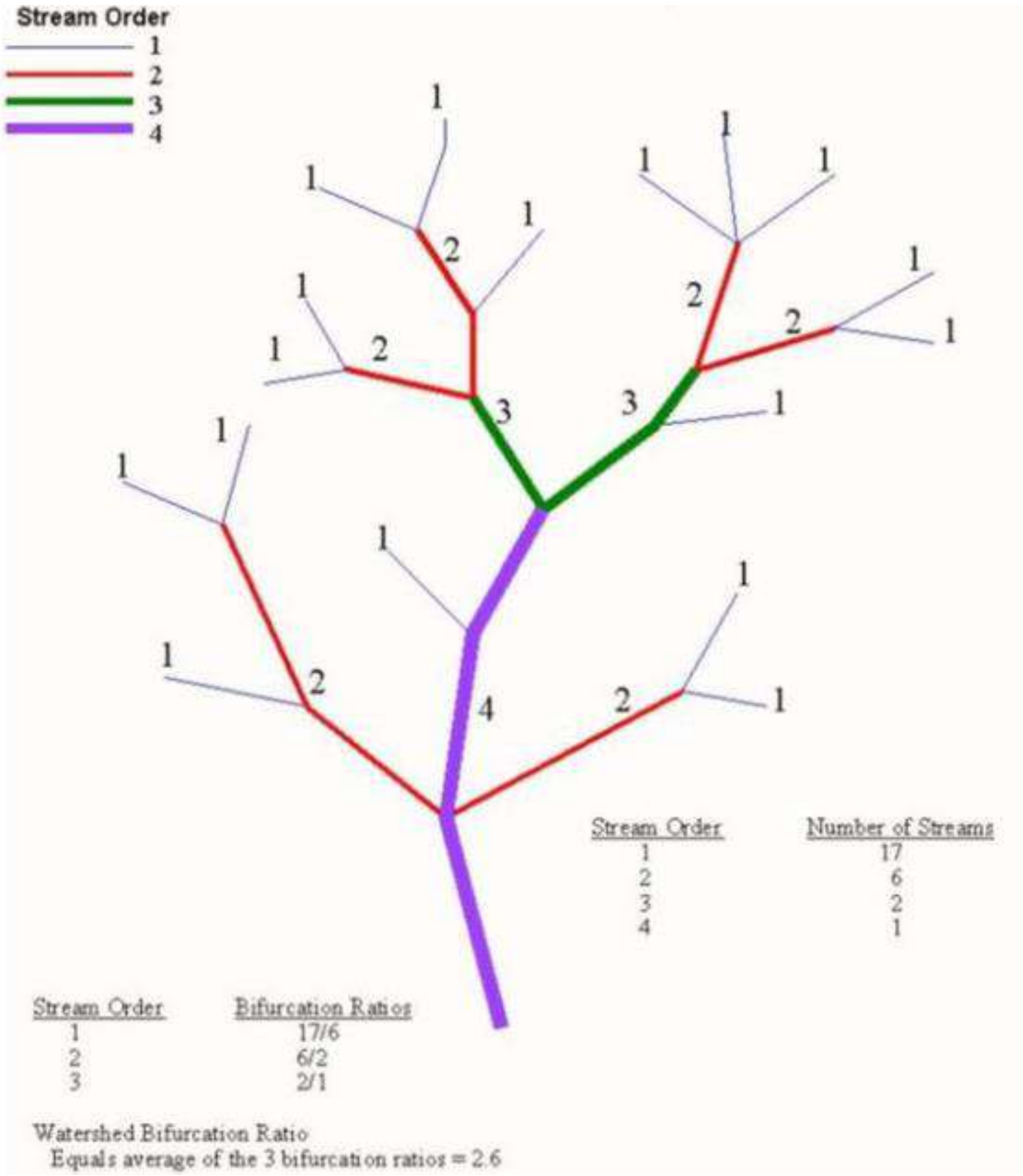
- Bifurcation Ratio is a dimensionless number denoting the ratio between the number of streams of one order and those of the next-higher order in a drainage network. The Bifurcation ratio looks at the relationship between streams of different orders.

Order	Number	$R_B(\omega)$
1.00	10.00	2.50
2.00	4.00	2.00
3.00	2.00	2.00
4.00	1.00	
Overall R_B		2.17



- Bifurcation ratio may be a useful measure of flood proneness – the higher the bifurcation ratio, the shorter will be the time taken for discharge to reach the outlet, and higher will be the peak discharge – leading to a greater probability of flooding. Bifurcation ratio correlates positively with drainage density i.e., a high bifurcation ratio indicates a high drainage density. Higher Bifurcation ratios also suggest that the area is tectonically active.

Bifurcation Example



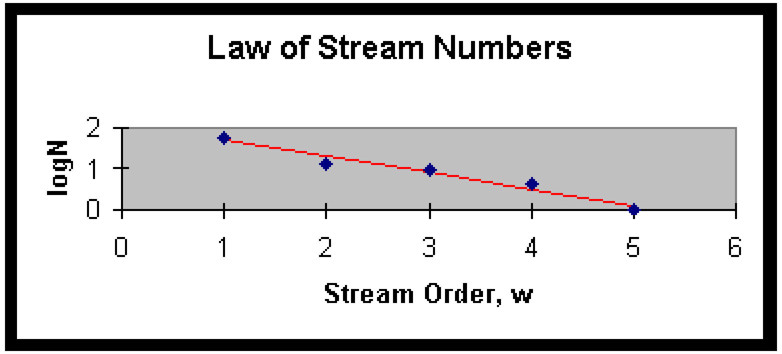
Hortons Law- Example

Obtain estimates of the Bifurcation Ratio, R_B, the Length Ratio, R_L, and the Area Ratio, R_A, using the data tabulated below.

Order, ω	Number of Streams	Average Length (km)	Average Area (km^2)
1	60	2	5
2	13	5	12
3	9	13	40
4	4	20	110
5	1	55	330

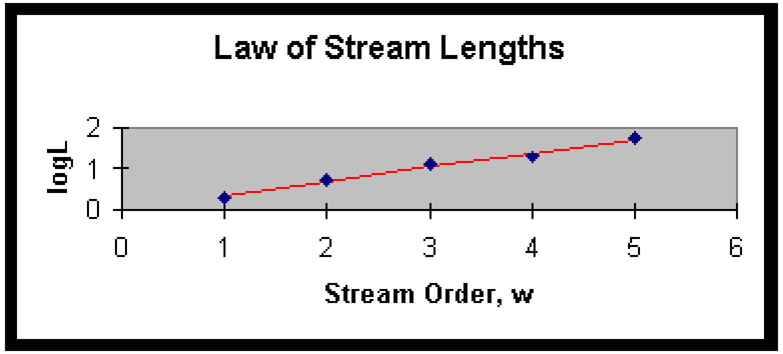
Order	Number of Streams	Average Length	Average Area	log(N)	log(L)	log(A)
1	60	2	5	1.778151	0.30103	0.69897
2	13	5	12	1.113943	0.69897	1.079181
3	9	13	40	0.954243	1.113943	1.60206
4	4	20	110	0.60206	1.30103	2.041393
5	1	55	330	0	1.740363	2.518514

A) Law of Stream Numbers and Bifurcation Ratio:



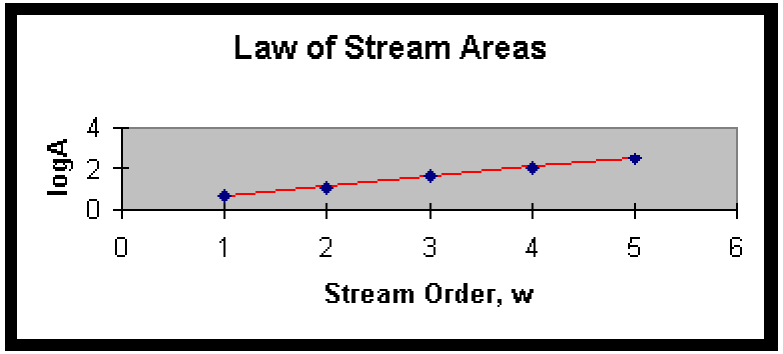
The linear regression analysis returns a slope *m* = -0.40682. Thus, R_B = 2.551635.

B) Law of Stream Lengths and Length Ratio:



The linear regression analysis returns a slope *m* = 0.348073. Thus, R_L = 2.228807.

C) Law of Stream Areas and Area Ratio:



The linear regression analysis returns a slope m = 0.46013. Thus, R_A = 2.884894.

D) The total length of streams can be calculated as:

$$L_T = \sum_{\omega=1}^{\Omega} N_\omega \bar{L}_\omega$$

Using the above equation leads to L_T = 437 *km*.

E) Drainage density:

$$D_d = \frac{L_T}{A_{\text{basin}}}$$

Thus, D_d = (437 *km*)/(330 km^2) = 1.3242 km^{-1}

F) Average length of overland flow:

$$L_o = \frac{1}{2D_d}$$

Thus, L_o = 0.377574 *km* = 377.74 *m*

Hydrology CE 454

Statistical methods in hydrology/ Flood frequency

Flood Frequency

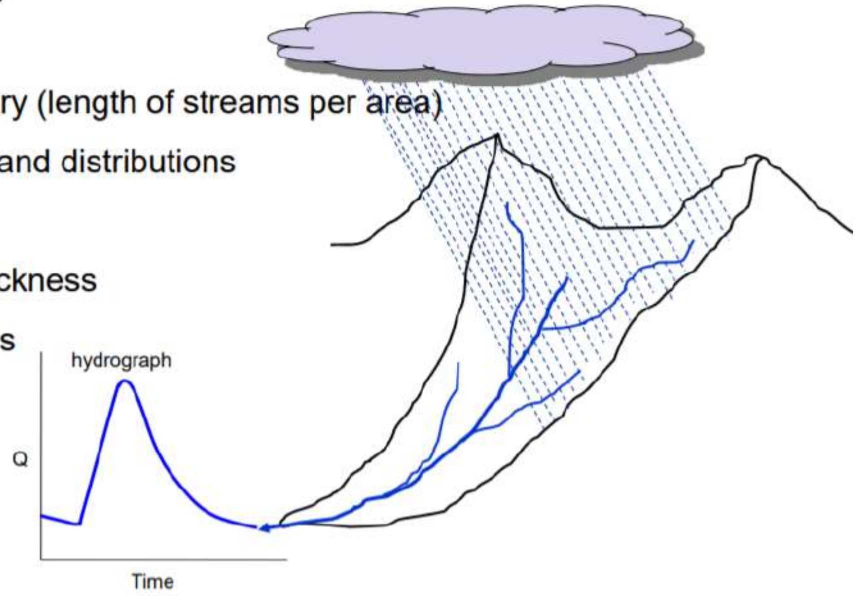
The frequency is the number of time that a given magnitude flood may occur in a given period.

Turkey2009

Japan 2017

FLOODS are usually caused by heavy rains and/or rapid snow melt—their severity is controlled by the watershed characteristics.

1. Basin size (area)
2. Topography
3. Drainage dentistry (length of streams per area)
4. Vegetation type and distributions
5. Geology
6. Soil type and thickness
7. Runoff processes



Flooding effects about 75 million people per year

An aerial view of the flooded I-5 overpass looking south Flooding in Chehalis (December 04, 2007)

The Chehalis River has flooded 18 times in the last 20 years. "Major" floods occurred in 1990, 1996, 2007, and 2009.

Floods are the #1 weather-related killer in the U.S.

Cowlitz River near Packwood, Washington

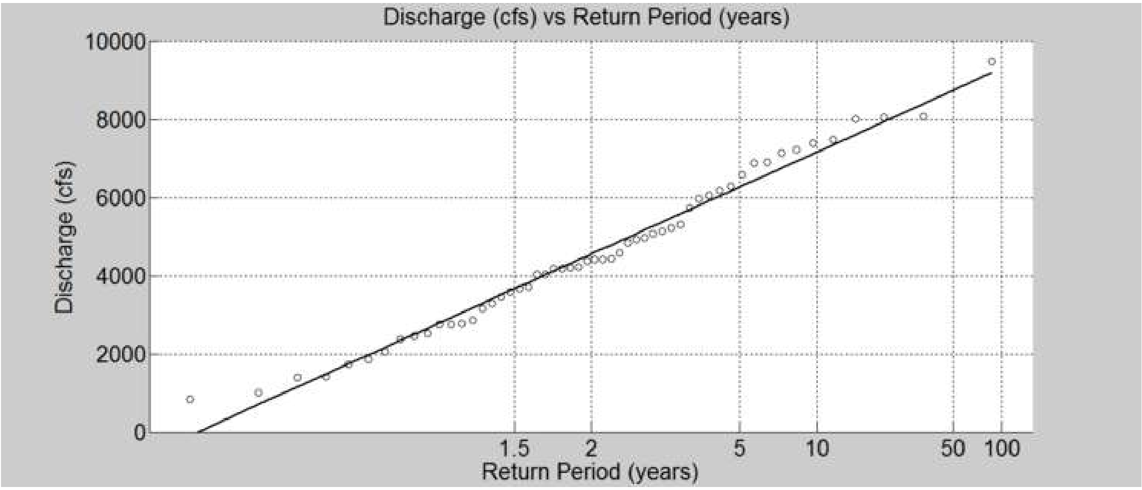
Cont. Flood frequency

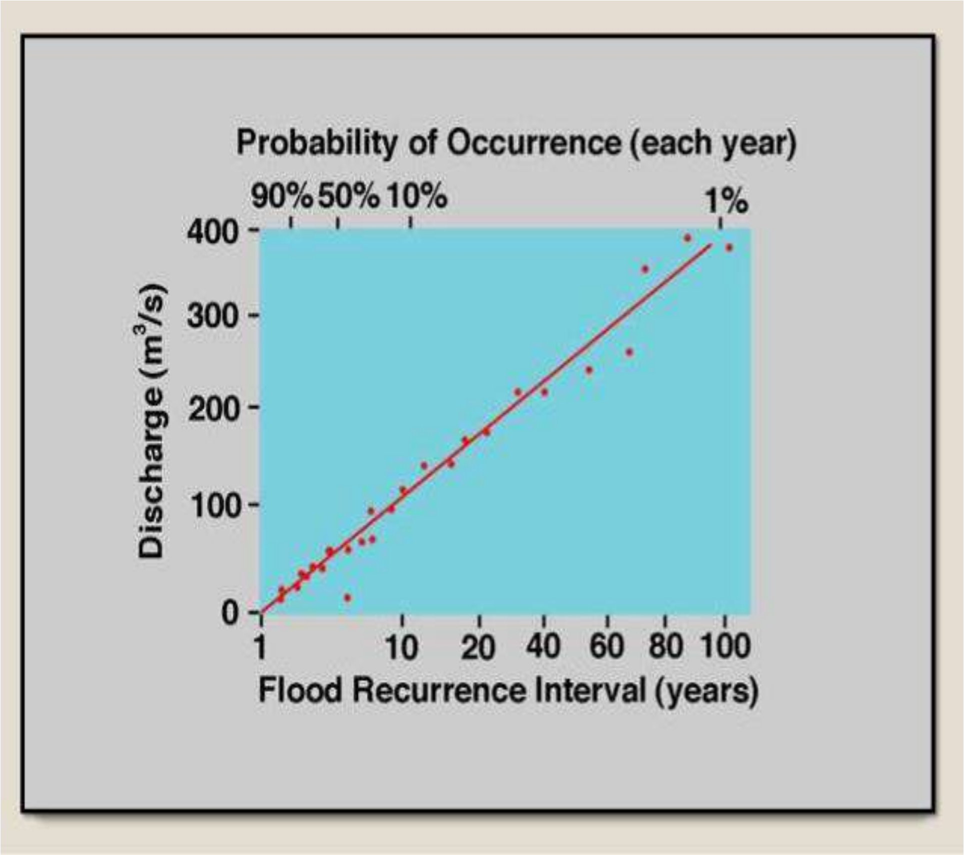
Flood frequency is the concept of the probable frequency of occurrence of a given flood. For the design of engineering works, for example, it is not sufficient to say that the maximum observed flood was, say, 900 m^3/s; it is also necessary to say what is the frequency of occurrence of this flood.

There are several ways of describing flood frequency, all using statistical probability.

1. Assigning *return periods* to particular floods was traditionally used, but is an unhelpful term when trying to explain its meaning to the public and others. An example of a return period is when a flood has a 1 % probability of occurring in a given year (i.e. 1 chance in 100) and is thus described as a 100-year flood event. This term suggests the common but mistaken notion that there should be an interval of 100 years between such events. In fact, the probability of having two 100-year floods within 10 years is almost 10 %.
2. The *annual exceedence probability* (AEP) is also used. This is simply the probability that a particular flood size will occur in any given year. As for the example above, the 100-year flood will have an AEP of 1 % (or 1 chance in 100). Explaining the probability to the public in this way is usually better.
3. The *probable maximum flood* (PMF) concept is sometimes used for engineering applications. Again, this is similar to the above two methods, and often uses the 100-year / 1 % probability, as many designs are based on this. However PMF also implies a lower probability than 1 %, and values as low as 0.1 % will be used for some applications. Trying to derive a PMF is usually very risky unless there is a very long record.

- For the evaluation of **flood frequency** can be classified into **two approaches:**
  - (1) **Statistical approach** estimates flood quantiles by applying **probability** models.
  - (2) The design storm method uses the **rainfall-runoff model.**
- In **statistical** Method:
  - 1) Probability plotting method
  - 2) Weibull formula
  - 3) Hazen method
  - 4) Califomia method
  - 5) Gumbel's method
- From this all method **Weibull** formula is most commonly used.





A "100-year flood" is a flood that has a 1% chance of occurring in any given year

Nooksack River in Whatcom County, Jan 9, 2009

How to determine the discharge of a "100-year flood"

Frequency analysis

- Probability of exceedance (P): the probability in which a certain event (rainfall) is equaled or exceeded.

- Return period (recurrence interval) , Tr: the average interval in years within which a given event will be equaled or exceeded

Exceedance obability(P), %	Return Period (Tr) Years	Rainfall equalled or exceeded
100	1	Every Year
80	1.25	Once in 1.25 years (4 times in 5 years)
75	1.33	Once in 1.33 years (3 times in 4 years)
67	1.5	Once in 1.5 years (2 times in 3 years)
1	100	Once in 100 years

Frequency analysis steps

- Step 1 : Obtain annual rainfall totals for the cropping season from the area of concern.
- Step 2 : Arrange the rainfall data in the descending order of magnitude.
- Step 3 : Give ranks (m) to each ordered data. Rank of 1 for the largest value and n for the smallest value, where n is the number of data points.
- Step 4 : Determine the recurrence interval Tr of each rainfall value using formula: $T_r = (N+1)/m$, or any other position formulae.

Frequency analysis steps

- Step 5 : Compute the probability of exceedance P,

  $$P = 1 / Tr = (m) / (n + 1)$$

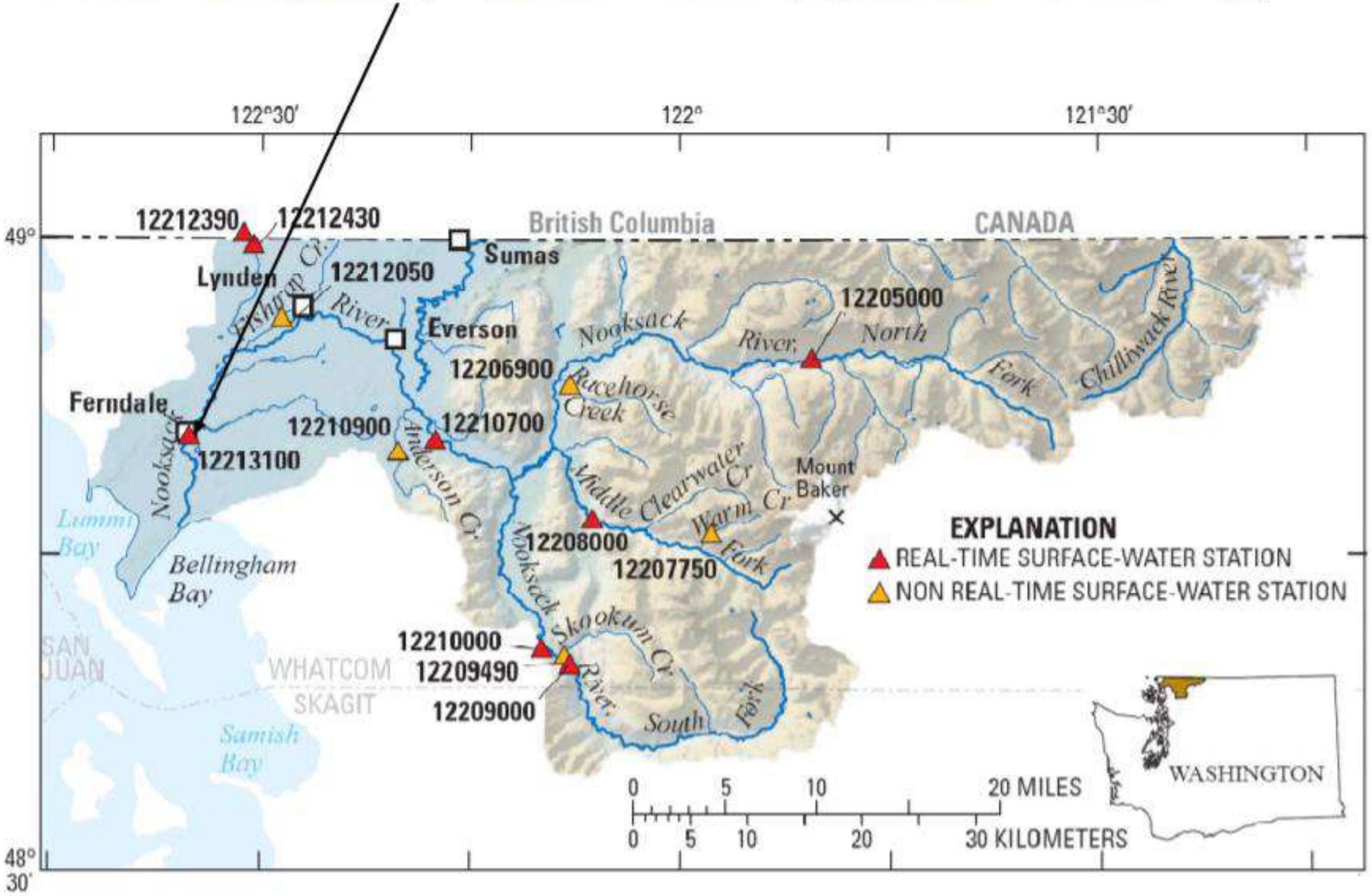
- Step 6 : Plot the value of P or Tr against the corresponding magnitude of rainfall data, on probability paper , & fit a line for the plotted data.

- Step 7 : To determine the design rainfall look the corresponding value of rainfall for the exceedance probability used.

Plotting position formulae

Name of formula	*Year in which introduced*	$T = \dfrac{1}{P(X \geq x)}$
California	1923	N/m
Hazen	1930	$2N/(2m - 1)$
Weibull	1939	$(N + 1)/m$
Chegodayev	1955	$(N + 0.4)/(m - 0.3)$
Blom	1958	$(N + 0.25)/(m - 0.375)$
Tukey	1962	$(3N + 1)/(3m - 1)$
Gringorten	1963	$(N + 0.12)/(m - 0.44)$
Cunnane	1989	$(N + 0.2)/(m - 0.4)$

1. Collect the historical peak flows for a river (e.g., Nooksack at Ferndale).



Example

1. Collect the historical peak flows for a river (e.g., Nooksack at Ferndale).

Year	cfs	Year	cfs	Year	cfs	Year	cfs
10/26/1945	41600	12/14/1966	21400	4/27/1985	16300	1/26/2003	20100
11/27/1949	27500	12/26/1967	23900	2/25/1986	29900	10/21/2003	39900
2/10/1951	55000	1/5/1969	28100	11/24/1986	36000	11/25/2004	42300
1/31/1952	18300	11/5/1969	17300	4/6/1988	17700	1/10/2006	19500
2/1/1953	19300	1/31/1971	38100	10/16/1988	21000	11/7/2006	38100
10/31/1953	18500	3/6/1972	24800	11/11/1989	47800	12/4/2007	21100
11/19/1954	20700	12/26/1972	24800	11/10/1990	57000	1/8/2009	51700
11/4/1955	35000	1/17/1974	21800	1/24/1992	18100		
12/10/1956	23000	12/21/1974	20800	1/25/1993	19000		
1/17/1958	18300	12/3/1975	46700	3/2/1994	18500		
4/30/1959	30200	1/18/1977	20600	12/20/1994	21700		
11/23/1959	22000	12/3/1977	23900	11/30/1995	47200		
1/16/1961	30800	11/8/1978	18800	3/20/1997	38100		
1/8/1962	18800	12/15/1979	36400	10/30/1997	17600		
11/20/1962	26000	12/27/1980	29700	12/14/1998	24600		
11/27/1963	23300	2/15/1982	27200	12/16/1999	22200		
1/31/1965	20000	1/11/1983	34200	10/21/2000	14300		
12/4/1965	17500	1/5/1984	41500	2/23/2002	30300		

Note : This example is solved using Weibull formula

2. “Rank” the peak flow discharges from highest to lowest.

Rank	cfs
1	57000
2	55000
3	51700
4	47800
5	47200
6	46700
7	42300
8	41600
9	41500
10	39900
11	38100
12	38100
13	38100
14	36400
15	36000
16	35000
17	34200
18	30800
19	30300
20	30200
21	29900

1	57000
2	55000
3	51700
4	47800
5	47200
6	46700
7	42300
8	41600
9	41500
10	39900
11	38100
12	38100
13	38100
14	36400
15	36000
16	35000
17	34200
18	30800
19	30300
20	30200
21	29900
22	29700
23	28100
24	27500
25	27200
26	26000
27	24800
28	24800
29	24600
30	23900
31	23900
32	23300
33	23000
34	22200
35	22000
36	21800
37	21700
38	21400
39	21100
40	21000
41	20800
42	20700
43	20600
44	20100
45	20000
46	19500
47	19300
48	19000
49	18800
50	18800
51	18500
52	18500
53	18300
54	18300
55	18100
56	17700
57	17600
58	17500
59	17300
60	16300
61	14300

3. Estimate the **exceedance probability** using the ranked values and the Weibull position formula.

$$P = \frac{m}{n + 1}$$

m = rank

n = total number of values

in this case “n = 61”

2. "Rank" the peak flow discharges from highest to lowest.

Rank	cfs
1	57000
2	55000
3	51700
4	47800
5	47200
6	46700
7	42300
8	41600
9	41500
10	39900
11	38100
12	38100
13	38100
14	36400
15	36000
16	35000
17	34200
18	30800
19	30300
20	30200
21	29900

1	57000
2	55000
3	51700
4	47800
5	47200
6	46700
7	42300
8	41600
9	41500
10	39900
11	38100
12	38100
13	38100
14	36400
15	36000
16	35000
17	34200
18	30800
19	30300
20	30200
21	29900
22	29700
23	28100
24	27500
25	27200
26	26000
27	24800
28	24800
29	24600
30	23900
31	23900
32	23300
33	23000
34	22200
35	22000
36	21800
37	21700
38	21400
39	21100
40	21000
41	20800
42	20700
43	20600
44	20100
45	20000
46	19500
47	19300
48	19000
49	18800
50	18800
51	18500
52	18500
53	18300
54	18300
55	18100
56	17700
57	17600
58	17500
59	17300
60	16300
61	14300

Example: for m = 15

$$P = \frac{m}{n + 1}$$

m = rank

n = total number of values

$$P = \frac{15}{61+ 1} = 0.24$$

The discharge for “m = 15” is 36,000 cfs. This means that in any given year there is a 0.24 probability or a 24% chance of a “peak flow” occurring that will equal or exceed a Q of 36,000 cfs.

4. The exceedance probability can be used to estimate the **return period** of a certain peak flow (i.e., how often can we expect a certain magnitude flood?)

$$\text{Return Period} = \frac{1}{P}$$

Example: for $m = 15$ where $P = 0.24$

$$\text{Return Period} = \frac{1}{0.24} = 4.13 \text{ years}$$

The means that one can expect a flood with a peak flow of about 36,000 cfs every 4.13 years.

A 100-year flood is a flood that has a return period of 100 years

OR a probability of 0.01 of occurring in any given year

OR a 1% chance of occurring in any given year

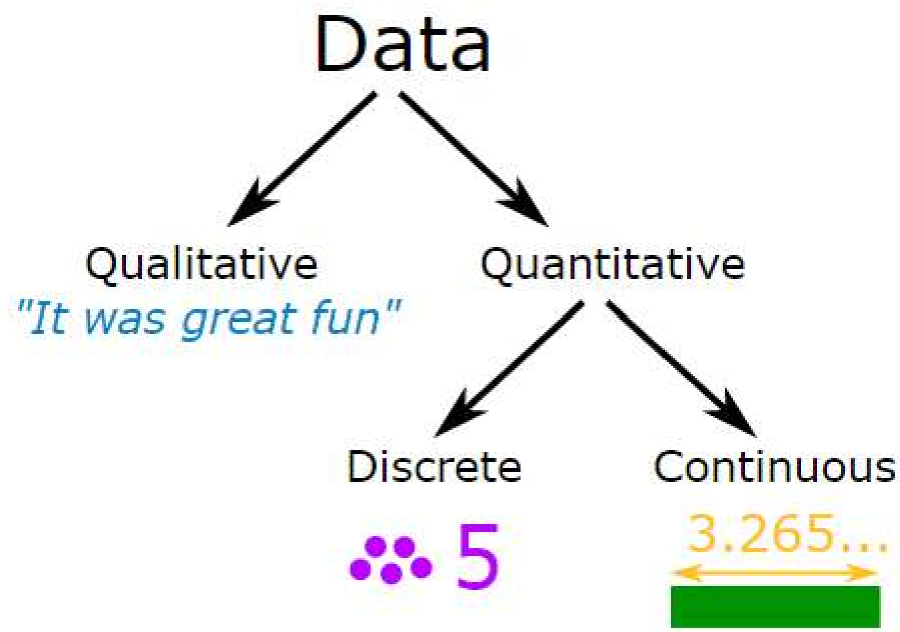
How Can We Have two “100-year floods” in less than two years?

- This question points out the importance of proper terminology. The term “100-year flood” is used in an attempt to simplify the definition of a flood that statistically has a 1-percent chance of occurring in any given year. Likewise, the term “100-year storm” is used to define a rainfall event that statistically has this same 1-percent chance of occurring. In other words, over the course of 1 million years, these events would be expected to occur 10,000 times. But, just because it rained 10 inches in one day last year doesn’t mean it can’t rain 10 inches in one day again this year.

Recurrence intervals and probabilities of occurrences

Recurrance interval, in years	Probability of occurrence in any given year	Percent chance of occurrence in any given year
100	1 in 100	1
50	1 in 50	2
25	1 in 25	4
10	1 in 10	10
5	1 in 5	20
2	1 in 2	50

Continuous and discrete Data



Examples

Discrete

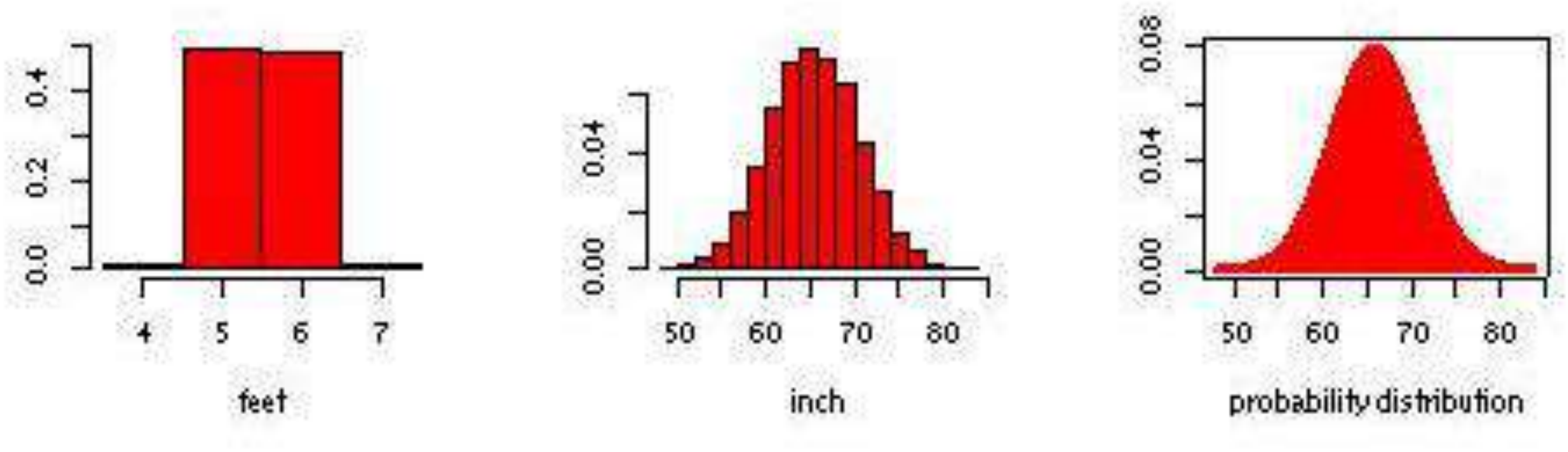
- # of eggs in a basket
- # of kids in a class
- # of Facebook likes
- # of diaper changes in a day
- # of wins in a season
- # of votes in an election

Continuous

- Weight difference to 8 decimals before and after cookie binge.
- Wind speed
- Water temperature
- Volts of electricity

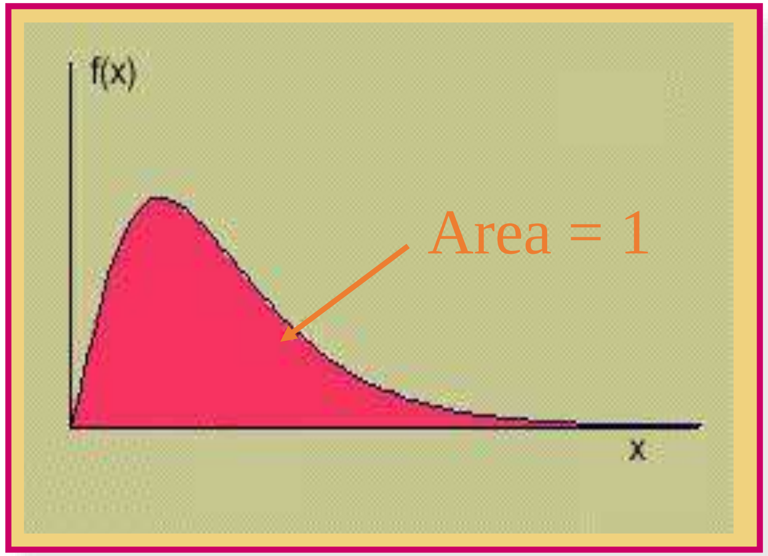
Continuous Probability Distribution

- Suppose we measure height of students in this class. If we “discretize” by rounding to the nearest feet, the discrete probability histogram is shown on the left. Now if height is measured to the nearest inch, a possible probability histogram is shown in the middle. We get more bins and much smoother appearance. Imagine we continue in this way to measure height more and more finely, the resulting probability histograms approach a smooth curve shown on the right.



Cont. Continuous Probability Distribution

- **Probability distribution** describes how the probabilities are distributed over all possible values. A **probability distribution** for a **continuous random variable *x*** is specified by a mathematical function denoted by *f(x)* which is called the **probability density function (PDF).** The graph of a density function is a smooth curve.



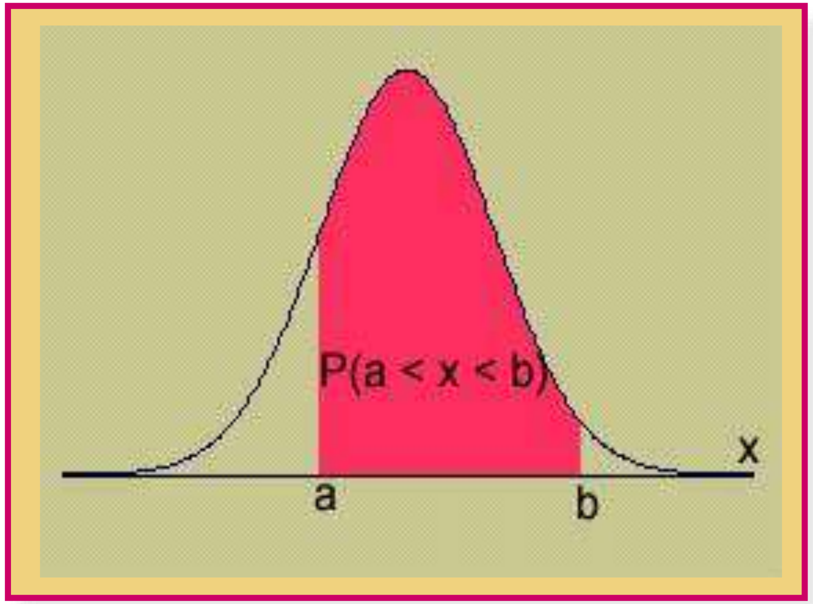
Probability distributions

$$F(x) = P(X \le x) = \sum_i P(x_i)$$

$$F(x_1) = P(-\infty \le x \le x_1) = \int_{-\infty}^{x1} f(x)dx$$

$$P(x_1 \le x \le x_2) = F(x_2) - F(x_1)$$

Properties of PDFs



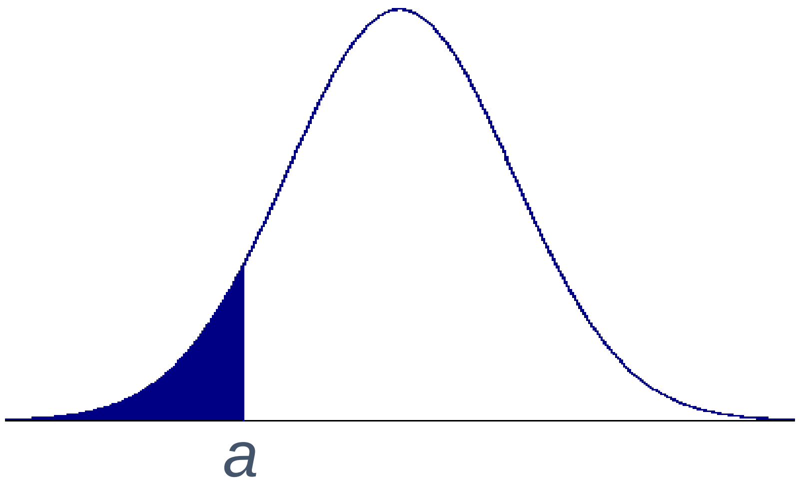
1) $f(x) \geq 0$

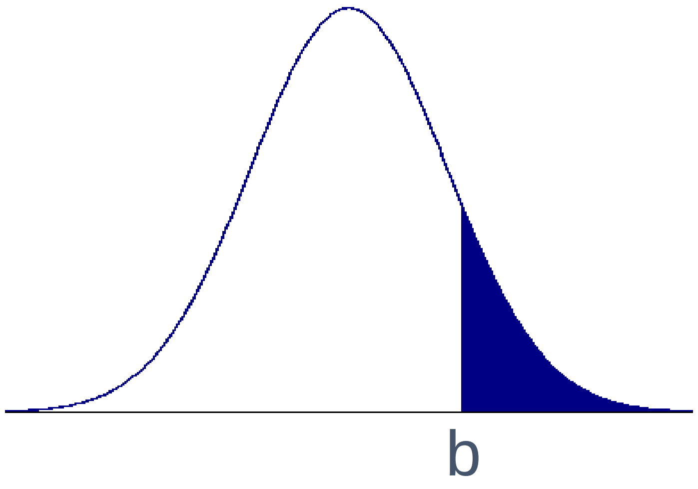
2) $\int_{-\infty}^{\infty} f(x)\,dx = 1$

3) $\text{Prob}(x < b) = \text{Prob}(x \leq b) = \int_{-\infty}^{b} f(x)\,dx$

4) $\text{Prob}(a < x < b) = \text{Prob}(a \leq x \leq b) = \int_{a}^{b} f(x)\,dx$

5) $\text{Prob}(x = a) = 0$





Notice that for a continuous random variable x,

$$P(x = a) = 0$$

for any specific value a because the "area above a point" under the curve is a line segment and hence has 0 area. Specifically this means

$$P(x<a) = P(x \leq a)$$

$$P(a<x<b) = P(a \leq x<b) = P(a<x \leq b) = P(a \leq x \leq b)$$

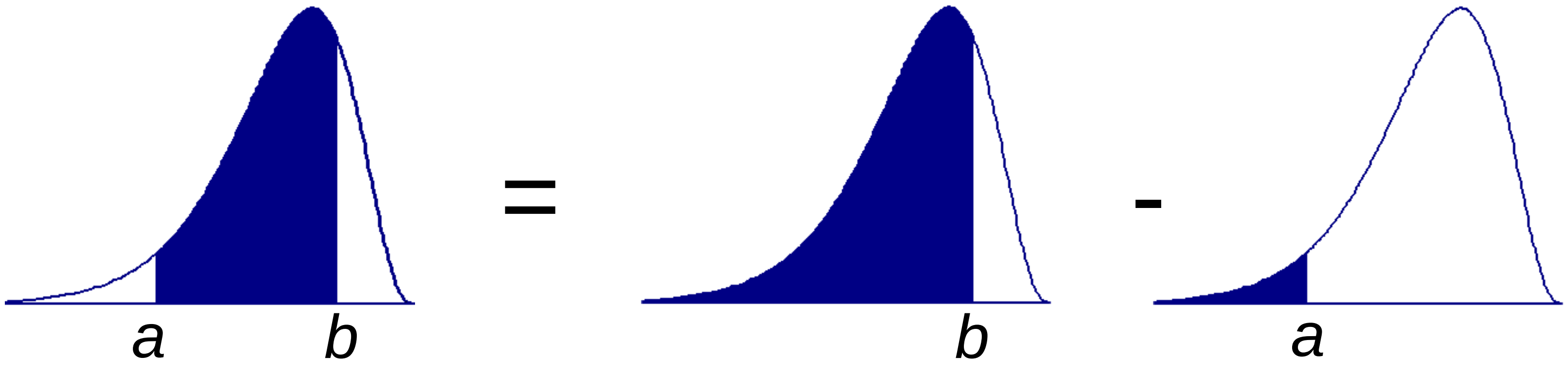
Method of Probability Calculation

The probability that a continuous random variable *x* lies between a lower limit *a* and an upper limit *b* is

P($a<x<b$) = (cumulative area to the left of b) –

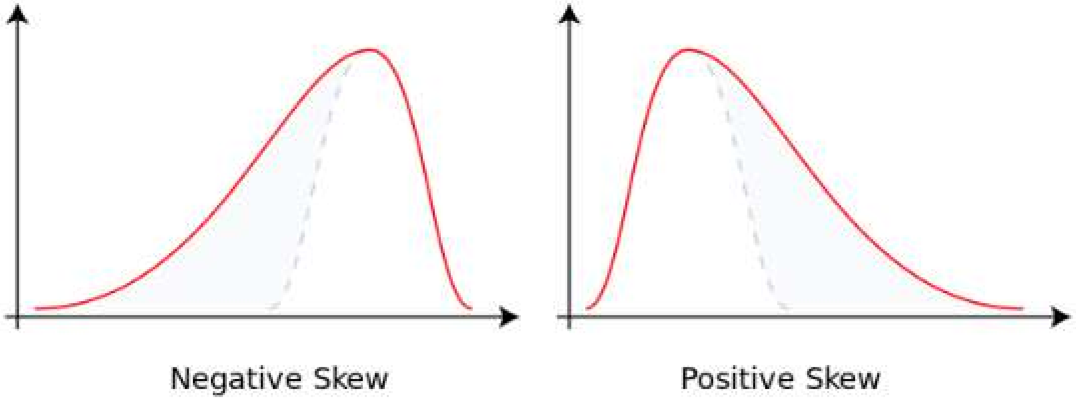
(cumulative area to the left of a)

= P($x < b$) – P($x < a$)



Skewness

- **skewness** is a measure of the asymmetry of the probability distribution of a real-valued random variable about its mean. The skewness value can be positive or negative, or undefined.



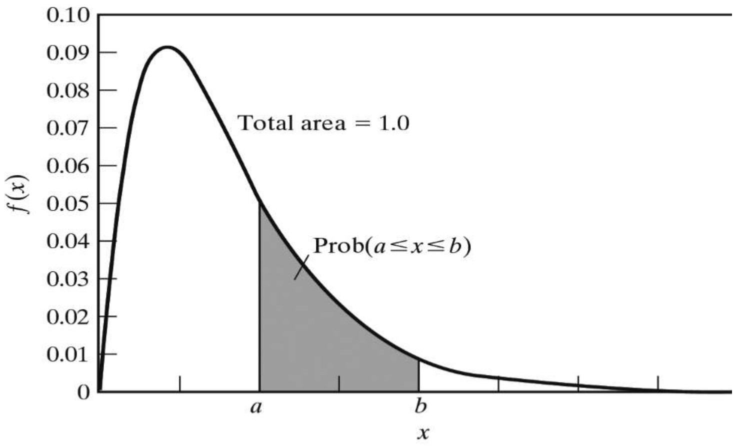


Figure 3.7

Continuous probability density function.

Skewness coefficient

- Used to evaluate high or low data points - flood or drought data

$$\text{Skewness} \rightarrow \frac{\mu_3}{\sigma^3} \rightarrow \text{third central moment}$$

$$C_s = \frac{n}{(n-1)(n-2)} \frac{\sum (x_i - \bar{x})^3}{s_x^3}$$

$$\text{Coeff of Var} = \frac{\sigma}{\mu}$$

Skewed data-Long right tail

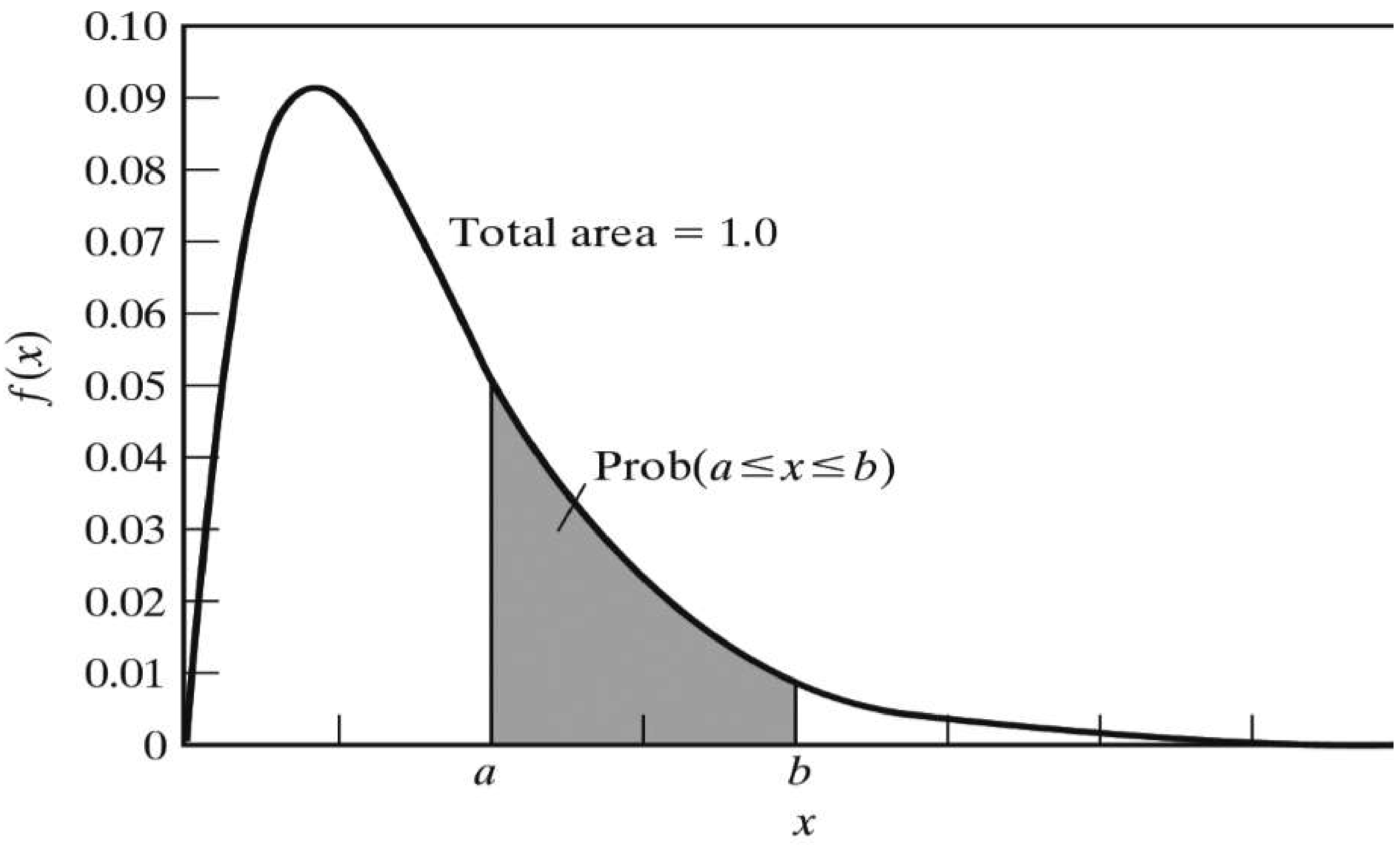


Figure 3.7

Continuous probability density function.

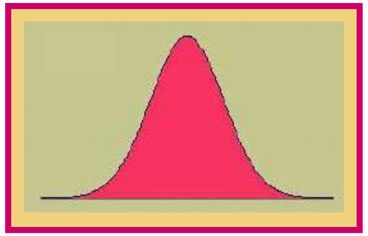
Continuous Probability Distributions

- There are many different types of continuous random variables
- We try to pick a model that
  - **Fits the data well**
  - **Allows us to make the best possible inferences using the data.**
- One important continuous random variable is the **normal random variable**.

Major distributions

- Binomial - P (x successes in n trials)
- Exponential - decays rapidly to low probability
- Normal - Symmetric based on μ and σ
- Lognormal - Log data are normally distributed
- Gamma - skewed distribution
- Log Pearson III - skewed and recommended by the IAC on water data - most used

The Normal Distribution



The formula that generates the normal probability distribution is:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad \text{for } -\infty < x < \infty$$

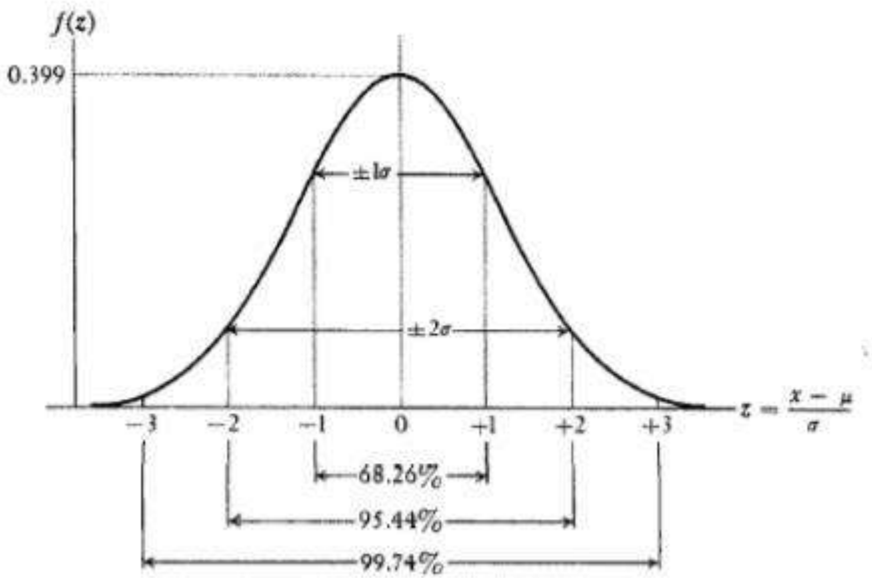
$$e = 2.7183 \qquad \pi = 3.1416$$

μ and σ are the population mean and standard deviation.

Two parameters, mean and standard deviation, completely determine the Normal distribution. The shape and location of the normal curve changes as the mean and standard deviation change.

Why normal distribution!

- The normal distribution is the most widely known and used of all distributions. Because the normal distribution approximates many natural phenomena so well, it has developed into a standard of reference for many probability problems.



Why is the normal distribution useful?

- Many things actually are normally distributed, or very close to it. For example, height and intelligence are approximately normally distributed; measurement errors also often have a normal distribution

- The normal distribution is easy to work with mathematically. In many practical cases, the methods developed using normal theory work quite well even when the distribution is not normal.

- There is a very strong connection between the size of a sample N and the extent to which a sampling distribution approaches the normal form. Many sampling distributions based on large N can be approximated by the normal distribution even though the population distribution itself is definitely not normal.

Mean and Variance

- The mean or expected value:

$$\mu = E(X) = \int_{-\infty}^{\infty} x f(x)\,dx$$

- The variance and standard deviation:

$$\sigma^2 = Var(X) = \int_{-\infty}^{\infty} (x-\mu)^2 f(x)\,dx = \int_{-\infty}^{\infty} x^2 f(x)\,dx - \mu^2 = E(X^2) - \left[E(X)\right]^2$$

The standard deviation: $\sigma = \sqrt{\sigma^2}$

Estimate of moment from data

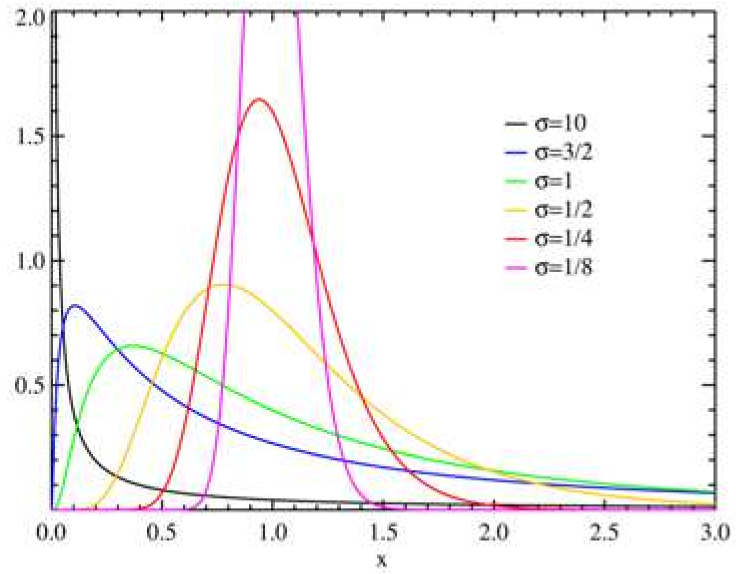
$$\bar{x} = \frac{1}{n}\sum_{i}^{n} x_i \Rightarrow \text{Mean of Data}$$

$$s_x^2 = \frac{1}{n-1}\sum (x_i - \bar{x})^2 \Rightarrow \text{Variance}$$

Std Dev. $S_x = (S_x^{2})^{1/2}$

Lognormal distribution

- If the pdf of X is skewed, it's not normally distributed
- If the pdf of Y = log (X) is normally distributed, then X is said to be lognormally distributed.



$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left(-\frac{(y-\mu_y)^2}{2\sigma_y^2}\right) \qquad x > 0, and\ y = log\ x$$

Hydraulic conductivity, distribution of raindrop sizes in storm follow lognormal distribution.

Example

The annual rainfall totals from a station, Mogadishu (Somalia), for a period of 32 years are given. Compute the annual rainfall total corresponding to 67 % & 33 % probabilities of exceedance.

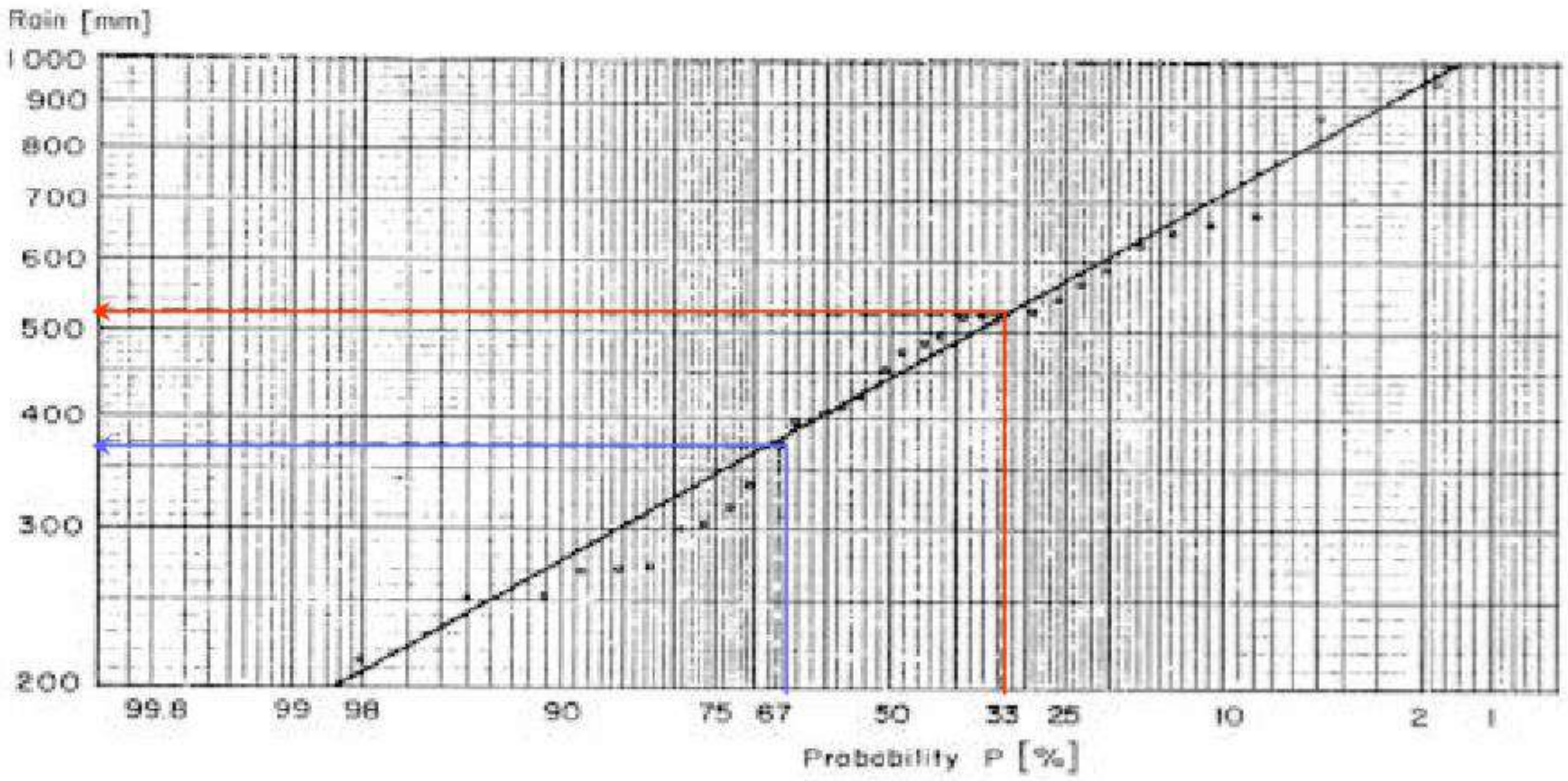
Year	1957	1958	1959	1960	1961	1962	1963	1964
Rainfall	484	529	302	403	960	453	633	489
Year	1965	1966	1967	1968	1969	1970	1971	1972
Rainfall	498	395	890	680	317	300	271	655
Year	1973	1974	1975	1976	1977	1978	1979	1980
Rainfall	371	255	411	339	660	216	594	544
Year	1981	1982	1983	1984	1985	1986	1987	1988
Rainfall	563	526	273	270	423	251	533	531

Solution

Arrange values in decreasing order

Year	R mm	m	p %	Year	R mm	m	p %	Year	R mm	m	p %
1961	960	1	1.9	1958	529	12	36.0	1976	339	23	70.2
1967	890	2	5.0	1982	526	13	39.1	1969	317	24	73.3
1968	680	3	8.1	1965	498	14	42.2	1959	302	25	76.4
1977	660	4	11.2	1964	489	15	45.3	1970	300	26	79.5
1972	655	5	14.3	1957	484	16	48.4	1983	273	27	82.6
1963	633	6	17.4	1962	453	17	51.6	1971	271	28	85.7
1979	594	7	20.5	1985	423	18	54.7	1984	270	29	88.8
1981	563	8	23.6	1975	411	19	57.8	1974	255	30	91.1
1980	544	9	26.7	1960	403	20	60.9	1986	251	31	95.0
1987	533	10	29.8	1966	395	21	64.0	1978	216	32	98.1
1988	531	11	32.9	1973	371	22	67.1				

Note: Blom formula is used in this example plot p against R on a probability paper and draw the best fit line



p = 67 % , Tr = 1.5 years , R = 371 mm

p = 33 % , Tr = 3 years , R = 531 m

Extreme value (EV) distributions

- Extreme values – maximum or minimum values of sets of data.

- Annual maximum discharge, annual minimum discharge.

- When the number of selected extreme values is large, the distribution converges to one of the three forms of EV distributions called Type I, II and III.

Frequency analysis for extreme events

Q. Find a flow (or any other event) that has a return period of T years

$$f(x) = \frac{1}{\alpha}\exp\left[-\frac{x-u}{\alpha} - \exp\left(-\frac{x-u}{\alpha}\right)\right] \qquad F(x) = \exp\left[-\exp\left(-\frac{x-u}{\alpha}\right)\right]$$

EV1 pdf and cdf

$$\alpha = \frac{\sqrt{6}s_x}{\pi} \qquad u = \bar{x} - 0.5772\alpha$$

Define a reduced variable y $\quad y = \frac{x-u}{\alpha}$

$$F(x) = \exp[-\exp(-y)]$$

$$y = -\ln[-\ln(F(x))] = -\ln[-\ln(1-p)] \quad where\ p = P(x \geq x_T)$$

$$y_T = -\ln\left[-\ln\left(1-\frac{1}{T}\right)\right]$$

If you know T, you can find y_T, and once y_T is know, x_T can be computed by

$$x_T = u + \alpha y_T$$

Example

- Given annual maxima for 10-minute storms
- Find 5- & 50-year return period 10-minute storms

$$\bar{x} = 0.649\,in$$
$$s = 0.177\,in$$
$$\alpha = \frac{\sqrt{6}s}{\pi} = \frac{\sqrt{6}*0.177}{\pi} = 0.138 \qquad u = \bar{x} - 0.5772\alpha = 0.649 - 0.5772*0.138 = 0.569$$
$$y_5 = -\ln\left[\ln\left(\frac{T}{T-1}\right)\right] = -\ln\left[\ln\left(\frac{5}{5-1}\right)\right] = 1.5$$
$$x_5 = u + \alpha y_5 = 0.569 + 0.138*1.5 = 0.78\,in$$
$$x_{50} = 1.11\,in$$

Example

- Given annual maximum rainfall, calculate 5-yr storm using frequency factor

$$K_T = -\frac{\sqrt{6}}{\pi}\left\{0.5772 + \ln\left[\ln\left(\frac{T}{T-1}\right)\right]\right\}$$

$$K_T = -\frac{\sqrt{6}}{\pi}\left\{0.5772 + \ln\left[\ln\left(\frac{5}{5-1}\right)\right]\right\} = 0.719$$

$$\begin{aligned} x_T &= \bar{x} + K_T s \\ &= 0.649 + 0.719 \times 0.177 \\ &= 0.78\ in \end{aligned}$$

Hydrology CE 454

Precipitation

Precipitation

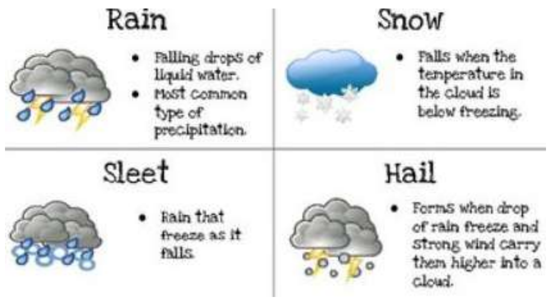
Precipitation

Liquid (Rainfall)

Solid (Ice)

Snow (vapor condensed to ice)

Hail (water condensed to ice)



Uses of precipitation data

- Runoff estimation analysis.
- Groundwater recharge analysis.
- Water balance studies of catchments.
- Flood analysis for design of hydraulic structures.
- Real-time flood forecasting.
- low flow studies.

Formation of Precipitation

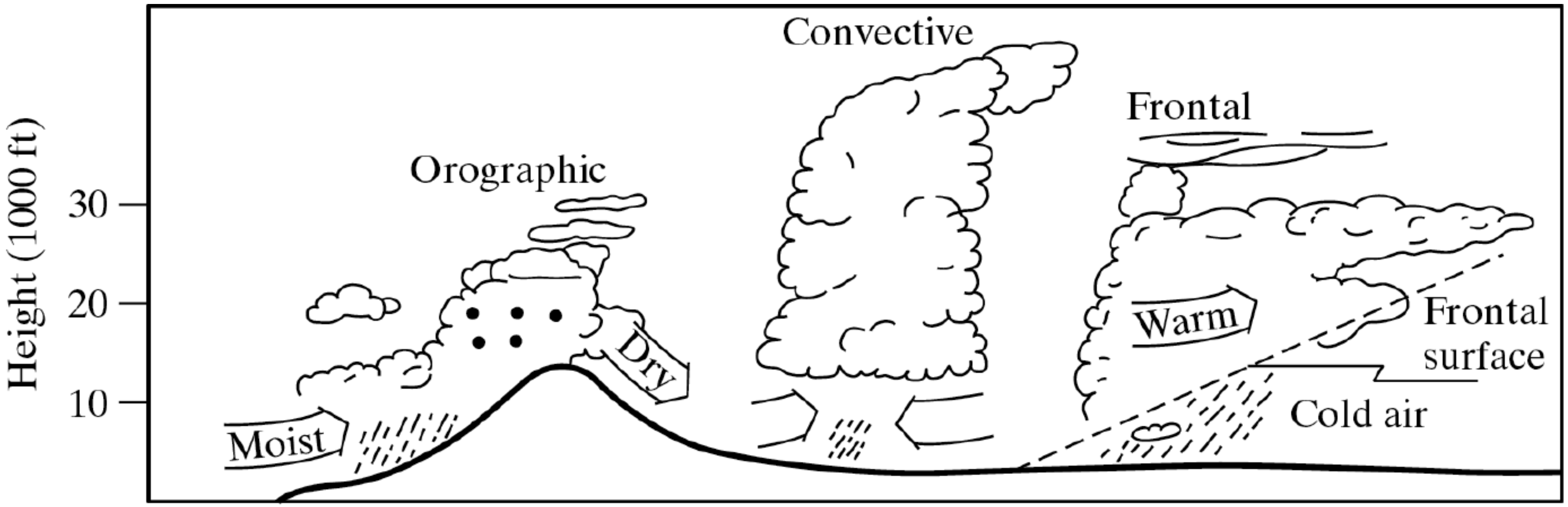
Three mechanisms are needed for formation of precipitation

1. **Lifting and Cooling** - Lifting of air mass to higher altitudes causes cooling of air.

2. **Condensation** - conversion of water vapor into liquid droplets.

3. **Droplet Formation** - Growth of droplets is required if the liquid water present in a cloud is to reach ground against the lifting mechanism of air.

Types of rainfall



- Depending upon the way in which the air is lifted and cooled so as to cause precipitation, we have four types of precipitation, as given below

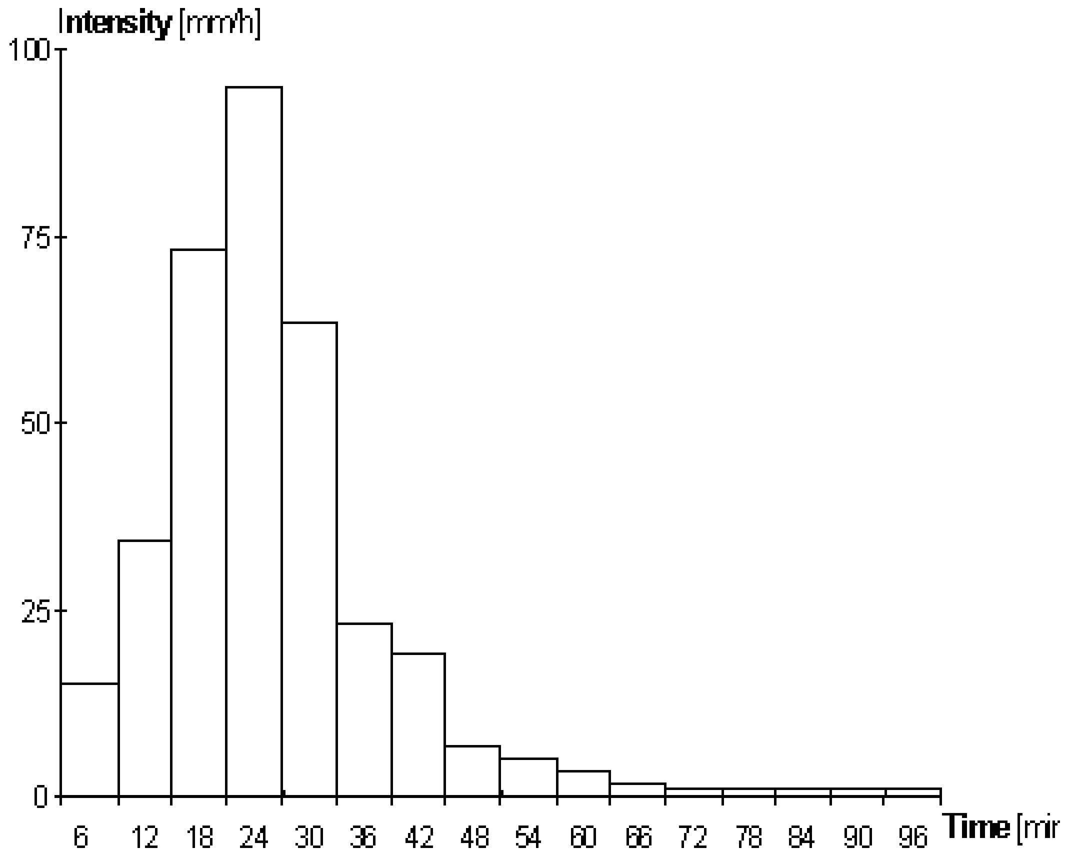
  - Cyclonic/ Frontal Precipitation.
  - Convective Precipitation.
  - Orographic Precipitation.

Probabilistic
Rainfall Characteristics

- Intensity
- Duration
- Frequency
- Amount
- Time Distribution
- Spatial Variability

Definitions

- **Depth:** depth of rainfall at a point or over an area (mm)
- **Duration**: the period of time during which rain fell (hours)
- **Intensity**: Depth of rainfall per unit time i.e. depth/duration (mm/hr)
- **Time distribution**: Rainfall **hyetographs** are plots of rainfall depth or intensity as a function of time. Cumulative rainfall hyetographs are also called rainfall mass curve.
- **Isohyets** (contours of constant rainfall) can be drawn to develop isohyetal maps of rainfall depth.
- **Normal Annual Precipitation** (mean of 30 years annual ppt)



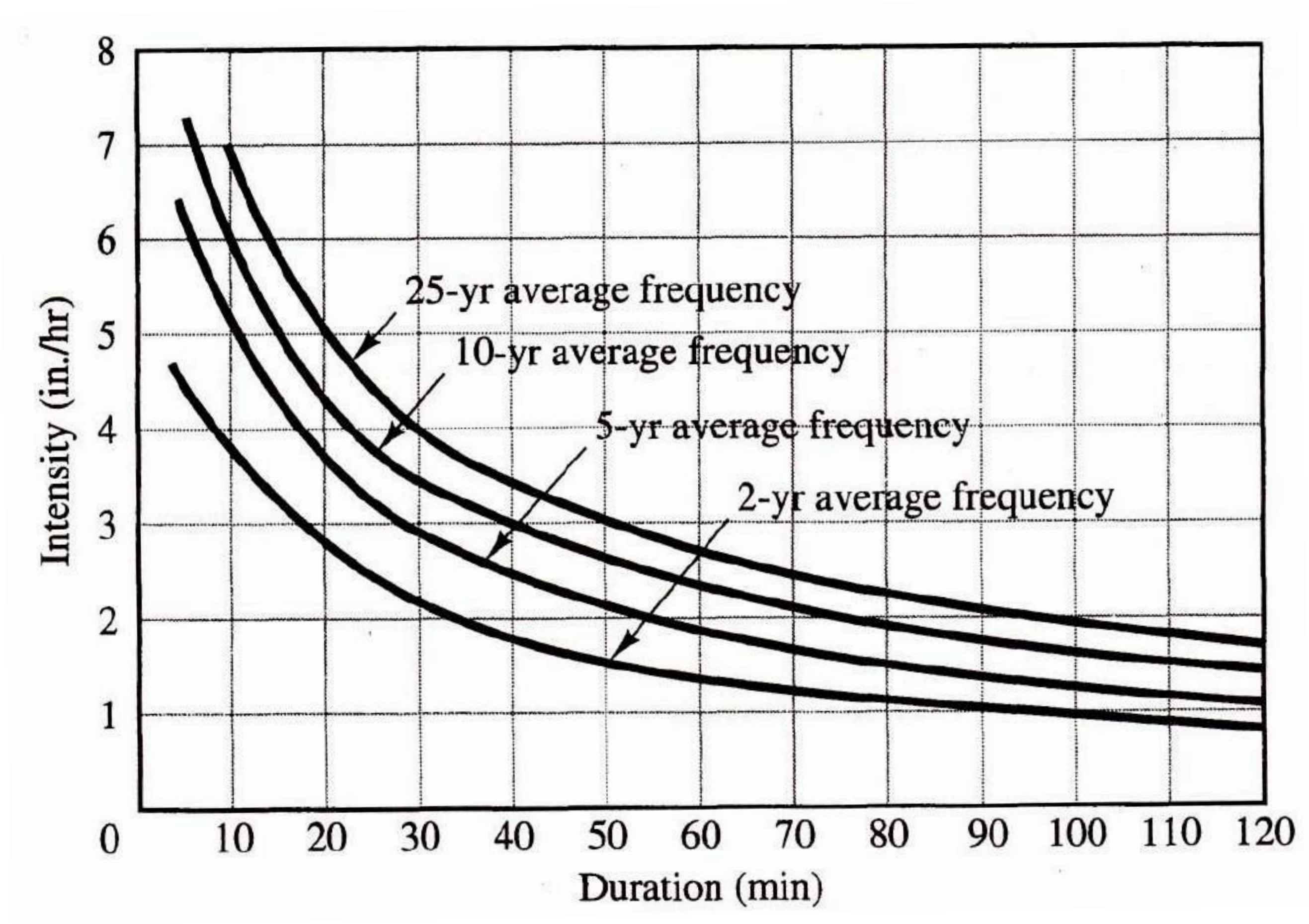
Frequency

- The frequency of occurrence of a storm of given magnitude and duration is important to establish a measure of risk.

- For a given storm duration, the probability that an event of certain magnitude has of being equaled or exceeded in any one year is termed the probability of exceedance.

- In general, for the same return period, short storms are more intense than long storms. Similarly, for a given intensity, longer storms are associated with greater return periods.

Intensity-Duration- Frequency Curves



IDF curves show frequency of storms of *at least* the given intensity over the given duration.

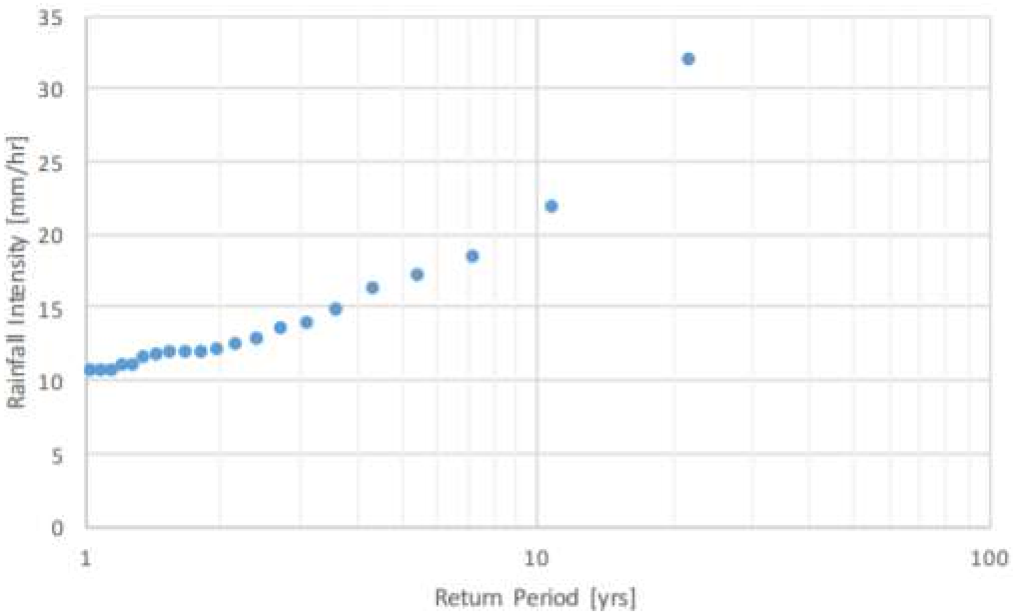
Example

Establish the IDF curves for the following data

Mean Annual Rainfall Volume for the Shown Duration [mm]									
	5 min 0.08 hr	10 min 0.17 hr	15 min 0.25 hr	30 min 0.50 hr	1 hr 1 hr	2 hr 2 hr	6 hr 6 hr	12 hr 12 hr	24 hr 24 hr
1985	2.8	5.3	8.1	10.9	13.7	14.4	24.2	28	30.4
1986	2.5	3.9	4.4	5.9	8.6	14.6	36.8	56.3	84.7
1987	1.5	2.5	3.2	5.5	9.9	17.7	33.8	43.2	65.3
1988	2	3.2	4.2	5.3	6.8	11.1	27.7	45	51.8
1989	3	4.3	5.2	6.9	9.3	15.2	30	45.6	50.9
1990	2.4	2.9	3.5	6.2	10.5	17.7	41.4	52.1	78.6
1991	2.6	3.6	4.8	6.4	10.7	17.4	36	66.4	100.9
1992	1.7	2	3.1	5.3	9.1	15.3	26.1	43.9	54.4
1993	2.8	4	4.5	7.4	10.8	15.8	27.2	38.2	64.9
1994	1.8	2.7	3.6	5.8	10.1	15	30.9	40.1	60.6
1995	2.5	3.2	4.1	5.9	9.4	14.4	33.7	50.7	82.6
1996	4.4	6.9	9.9	15.9	21.2	24	46.7	50.3	60.9
1997	3.1	3.6	4.3	6.7	10.5	15.9	38.8	54.8	65.2
1998	1.9	2.3	2.9	5.3	8.8	14.4	33.5	44.3	48.5
1999	2	2.5	3.5	6	10.8	17.4	35.9	48	59.4
2000	2	3.5	4	5.9	8.7	15	30.1	45.2	47.6
2001	2.9	4	4.2	5.5	7.8	13.2	23.2	36.2	45.6
2002	4.4	4.8	4.8	5.7	9.3	14.5	30	38	64.9
2003	2.3	4.2	5.6	8.1	8.7	11.8	29.1	45.5	72.6
2004	3.9	6.3	7.6	9.2	10.2	15.2	27.7	33	41
2005	3.2	5	6.5	8.5	9.8	13.9	24.1	34.5	43.7
Mean	2.65	3.84	4.86	7.06	10.22	15.42	31.76	44.73	60.69
St. Dev.	0.82	1.28	1.80	2.50	2.87	2.61	6.04	8.79	16.69

1. Rainfall frequency analysis for each duration
30 minutes analysis

1	2	3	4	5	6
		30 min			
Rank	**Year**	**0.50 hr**	**p**	**T**	**Intensity [mm/hr]**
1	1996	15.9	0.05	22.00	31.8
2	1985	10.9	0.09	11.00	21.8
3	2004	9.2	0.14	7.33	18.4
4	2005	8.5	0.18	5.50	17
5	2003	8.1	0.23	4.40	16.2
6	1993	7.4	0.27	3.67	14.8
7	1989	6.9	0.32	3.14	13.8
8	1997	6.7	0.36	2.75	13.4
9	1991	6.4	0.41	2.44	12.8
10	1990	6.2	0.45	2.20	12.4
11	1999	6	0.50	2.00	12
12	1986	5.9	0.55	1.83	11.8
13	1995	5.9	0.59	1.69	11.8
14	2000	5.9	0.64	1.57	11.8
15	1994	5.8	0.68	1.47	11.6
16	2002	5.7	0.73	1.38	11.4
17	1987	5.5	0.77	1.29	11
18	2001	5.5	0.82	1.22	11
19	1988	5.3	0.86	1.16	10.6
20	1992	5.3	0.91	1.10	10.6
21	1998	5.3	0.95	1.05	10.6



2- Calculate frequency factors

$$K_T = -\frac{\sqrt{6}}{\pi}[0.5772 + \ln(\ln(\frac{T}{T-1}))]$$

T	2	5	10	25	50	100	1000
K_T	-0.164272	0.7194574	1.3045632	2.0438459	2.5922880	3.1366806	4.9355236

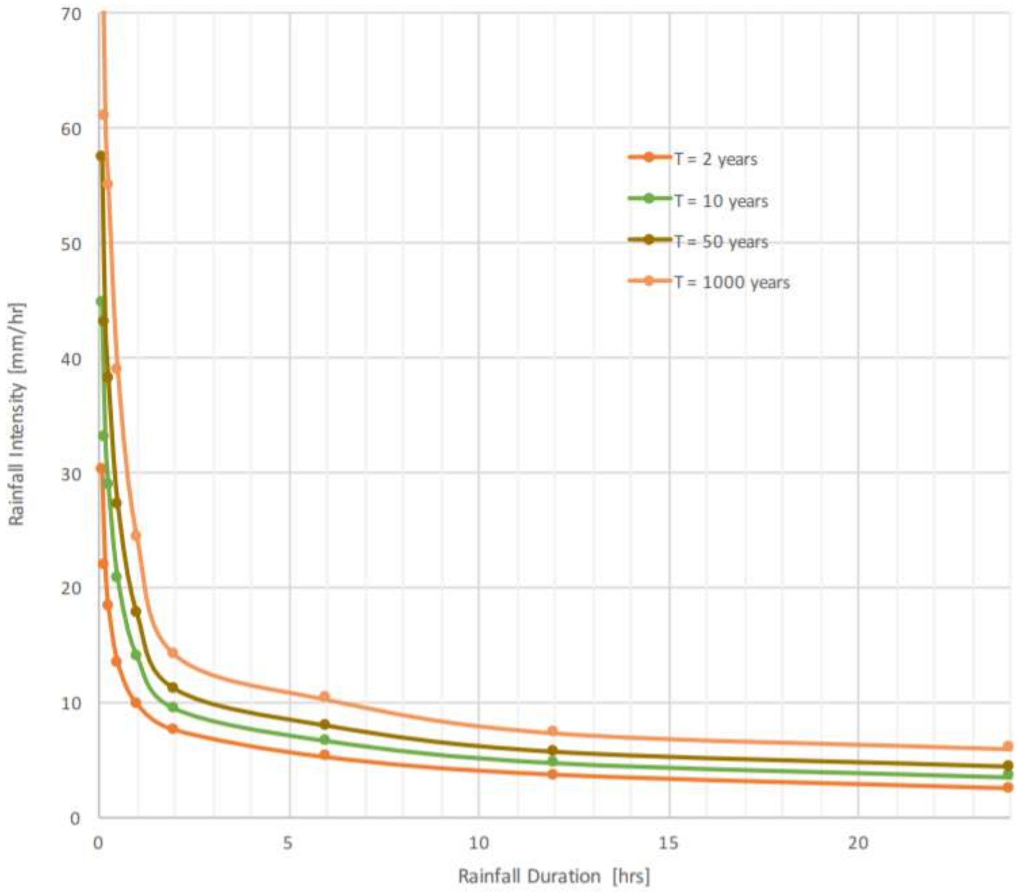
$$\bar{X} = \frac{1}{m}\sum_{i=1}^{m} x_i \quad \text{and} \quad S = \frac{1}{m-1}\sum_{i=1}^{m}(x_i - \bar{X})^2$$

$$X_T = \bar{X} + K_T S$$

3. Compute the precipitation intensity associated with each return period.

	Return Period *T*						
	2	**5**	**10**	**25**	**50**	**100**	**1000**
Duration	30.213	38.904	44.658	51.928	57.322	62.676	80.366
5 min	30.213	38.904	44.658	51.928	57.322	62.676	80.366
10 min	21.795	28.585	33.080	38.759	42.973	47.155	60.976
15 min	18.248	24.600	28.806	34.121	38.063	41.976	54.907
30 min	13.303	17.719	20.642	24.336	27.076	29.797	38.785
1 hr	9.753	12.287	13.965	16.085	17.657	19.218	24.377
2 hr	7.497	8.651	9.415	10.380	11.096	11.807	14.155
6 hr	5.128	6.017	6.605	7.349	7.901	8.449	10.259
12 hr	3.607	4.254	4.683	5.225	5.626	6.025	7.343
24 hr	2.415	3.029	3.436	3.950	4.331	4.710	5.961

4. Plot the results



Example

Establish the IDF curves for the following data

Max. rainfall (mm) for different durations.

Year	1H	2H	6H	12H	24H	Year	1H	2H	6H	12H	24H
1969	44.5	61.6	104.1	112.3	115.9	1986	65.2	73.7	97.9	103.9	104.2
1970	37	48.2	62.5	69.6	92.7	1987	47	55.9	64.8	65.6	67.5
1971	41	52.9	81.4	86.9	98.7	1988	148.8	210.8	377.6	432.8	448.7
1972	30	40	53.9	57.8	65.2	1989	41.7	47	51.7	53.7	78.1
1973	40.5	53.9	55.5	72.4	89.8	1990	40.9	71.9	79.7	81.5	81.6
1974	52.4	62.4	83.2	93.4	152.5	1991	41.1	49.3	63.6	93.2	147
1975	59.6	94	95.1	95.1	95.3	1992	31.4	56.4	76	81.6	83.1
1976	22.1	42.9	61.6	64.5	71.7	1993	34.3	36.7	52.8	68.8	70.5
1977	42.2	44.5	47.5	60	61.9	1994	23.2	38.7	41.9	43.4	50.8
1978	35.5	36.8	52.1	54.2	57.5	1995	44.2	62.2	72	72.2	72.4
1979	59.5	117	132.5	135.6	135.6	1996	57	74.8	85.8	86.5	90.4
1980	48.2	57	82	86.8	89.1	1997	50	71.1	145.9	182.3	191.3
1981	41.7	58.6	64.5	65.1	68.5	1998	72.1	94.6	111.9	120.5	120.5
1982	37.3	43.8	50.5	76.2	77.2	1999	59.3	62.9	82.3	90.7	90.9
1983	37	60.4	70.5	72	75.2	2000	62.3	78.3	84.3	84.3	97.2
1984	60.2	74.1	76.6	121.9	122.4	2001	46.8	70	95.9	95.9	100.8
						2003	53.2	86.5	106.1	106.2	106.8

Example

- Calculate rainfall intensity

The rainfall intensity (mm/hr) for different durations.

Year	1H	2H	6H	12H	24H	Year	1H	2H	6H	12H	24H
1969	44.50	30.80	17.35	9.36	4.83	1986	65.20	36.85	16.32	8.66	4.34
1970	37.00	24.10	10.42	5.80	3.86	1987	47.00	27.95	10.80	5.47	2.81
1971	41.00	26.45	13.57	7.24	4.11	1988	148.80	105.40	62.93	36.07	18.70
1972	30.00	20.00	8.98	4.82	2.72	1989	41.70	23.50	8.62	4.48	3.25
1973	40.50	26.95	9.25	6.03	3.74	1990	40.90	35.95	13.28	6.79	3.40
1974	52.40	31.20	13.87	7.78	6.35	1991	41.10	24.65	10.60	7.77	6.13
1975	59.60	47.00	15.85	7.93	3.97	1992	31.40	28.20	12.67	6.80	3.46
1976	22.10	21.45	10.27	5.38	2.99	1993	34.30	18.35	8.80	5.73	2.94
1977	42.20	22.25	7.92	5.00	2.58	1994	23.20	19.35	6.98	3.62	2.12
1978	35.50	18.40	8.68	4.52	2.40	1995	44.20	31.10	12.00	6.02	3.02
1979	59.50	58.50	22.08	11.30	5.65	1996	57.00	37.40	14.30	7.21	3.77
1980	48.20	28.50	13.67	7.23	3.71	1997	50.00	35.55	24.32	15.19	7.97
1981	41.70	29.30	10.75	5.43	2.85	1998	72.10	47.30	18.65	10.04	5.02
1982	37.30	21.90	8.42	6.35	3.22	1999	59.30	31.45	13.72	7.56	3.79
1983	37.00	30.20	11.75	6.00	3.13	2000	62.30	39.15	14.05	7.03	4.05
1984	60.20	37.05	12.77	10.16	5.10	2001	46.80	35.00	15.98	7.99	4.20
						2003	53.20	43.25	17.68	8.85	4.45

- Calculate the mean and standard deviation for different duration

Duration	1H	2H	6H	12H	24H
Mean	48.70	33.17	14.46	8.05	4.38
Std. Dev.	21.53	15.9	9.59	5.52	2.86

- Calculate KT values at given return periods

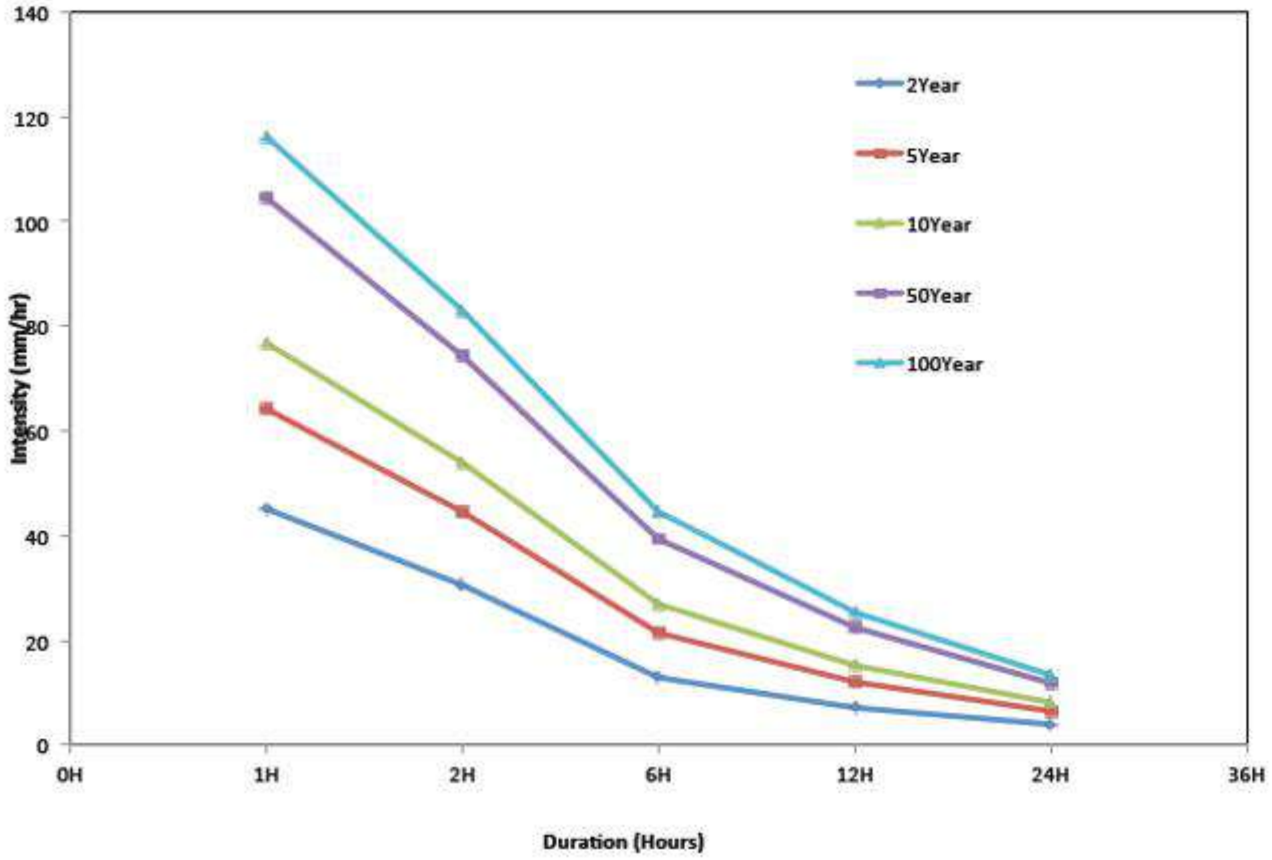
$$K_T = -\frac{\sqrt{6}}{\pi}\left\{0.5772 + \ln\left[\ln\left(\frac{T}{T-1}\right)\right]\right\}$$

T (years)	2	5	10	50	100
K_T	-0.164	0.719	1.305	2.592	3.137

- Calculate rainfall intensity using

$$x_T = \bar{x} + K_T s$$

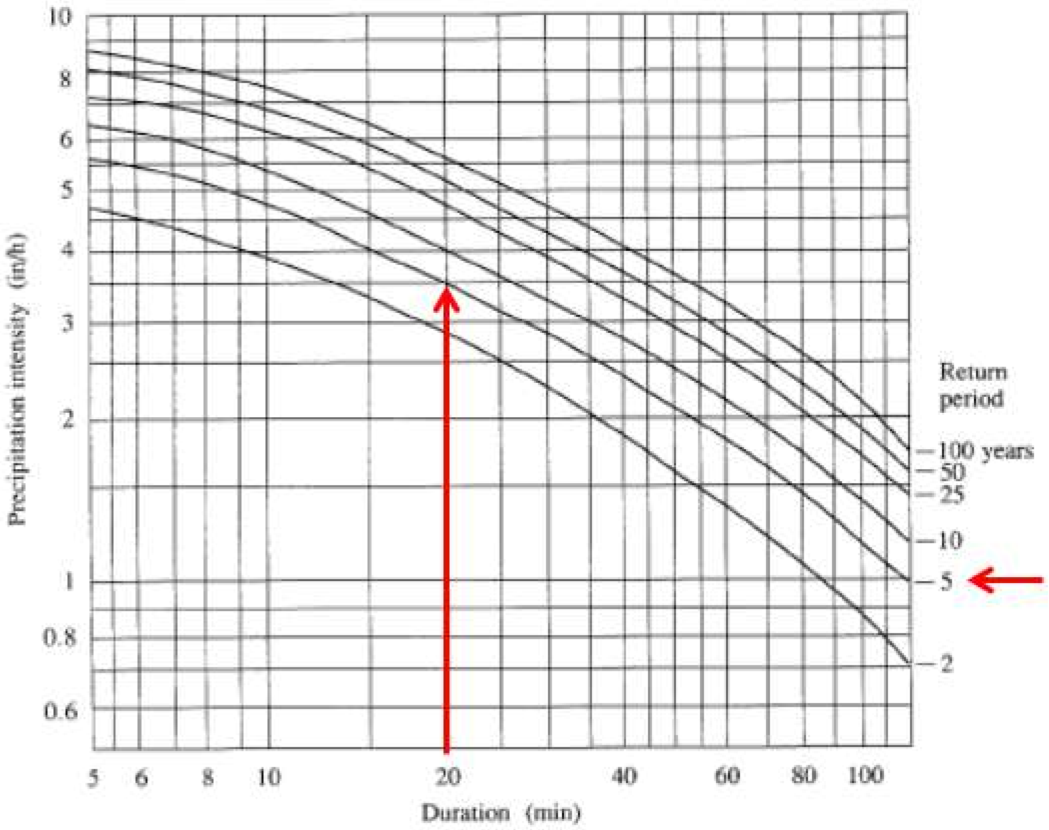
Duration (hours)	Return Period T (Years)				
	2	5	10	50	100
1H	45.17	64.19	76.79	104.51	116.23
2H	30.55	44.60	53.90	74.36	83.02
6H	12.89	21.36	26.97	39.31	44.53
12H	7.14	12.02	15.25	22.36	25.37
24H	3.91	6.44	8.11	11.79	13.35



140
120
100
80
60
40
20
0
Intensity (mm/hr)
0H
1H
2H
6H
12H
24H
36H
Duration (Hours)
2Year
5Year
10Year
50Year
100Year

Example

Determine i and P for a 20-min duration storm with 5-yr return period in Chicago



From the IDF curve

i = 3.5 in/hr for T_d = 20 min and T = 5yr

P = $i \times T_d$ = 3.5 x 20/60 = **1.17 in**

Equations for IDF curves

IDF curves can also be expressed as equations to avoid reading from graphs

$$i = \frac{c}{T_d^e + f}$$

i is precipitation intensity, T_d is the duration, and *c, e, f* are coefficients that vary for locations and different return periods

$$i = \frac{cT^m}{T_d^e + f}$$

This equation includes return period (T) and has an extra coefficient (m)

TP-40

TECHNICAL PAPER NO. 40

RAINFALL FREQUENCY ATLAS OF THE UNITED STATES

for Durations from 30 Minutes to 24 Hours and Return Periods from 1 to 100 Years

Prepared by
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Example

Using IDF curve equation, determine 10-yr 20-min design rainfall intensities for Denver

$$i = \frac{c}{T_d^e + f}$$

From Tables, c = 96.6, e = 0.97, and f = 13.9

$$i = \frac{96.6}{20^{0.97} + 13.9} = 3.002 \ \ in/hr$$

Similarly, i = 4.158 and 2.357 in/hr for T_d = 10 and 30 min, respectively

24-hour Design Rainfall Totals Data

p24lkup [Read-Only] [Compatibility Mode]

24-Hour Rainfall Depth versus Frequency for Texas Counties

	Rainfall depth in inches for given Return Interval						
County	1-year	2-year	5-year	10-year	25-year	50-year	100-year
Terrell		2.88	4.04	4.76	5.68	6.19	7.12

Tarrant
Taylor
Terrell
Terry
Throckmorton
Titus
Tom Green

Rainfall depth in mm for given Return Interval						
1-year	2-year	5-year	10-year	25-year	50-year	100-year
56	74	99	122	142	165	185

TP-40 | reference | English | eb&d

Rainfall Frequency Analysis from **TP-40**

$$I = \frac{b}{(t_c + d)^e}$$

t_c = time of concentration in minutes (not less than 10 minutes)
I = rainfall intensity (inches/hour)
e, d : From tables.

p24lkup [Read-Only] [Compatibility Mode]

	2-year			5-year			10-year			25-year			50-year			100-year	
County name	e	b	d	e	b	d	e	b	d	e	b	d	e	b	d	e	b
Anderson	0.799	1575	8.6	0.792	1956	8.8	0.763	1981	8.8	0.772	2337	8.8	0.744	2362	8.8	0.740	2515
Andrews	0.812	1016	9.8	0.827	1448	10.2	0.809	1600	10.2	0.793	1753	10.2	0.807	2134	10.2	0.804	2337
Angelina	0.785	1575	8.8	0.762	1753	7.6	0.746	1854	7.6	0.726	1956	7.6	0.727	2184	7.6	0.716	2286
Aransas	0.821	1854	9.2	0.787	1956	8.5	0.753	2007	8.5	0.745	2235	8.5	0.739	2413	8.5	0.725	2489
Archer	0.798	1245	9.2	0.783	1549	8.5	0.794	1880	8.5	0.789	2184	8.5	0.792	2540	8.5	0.784	2819
Armstrong	0.846	1321	10.8	0.819	1600	10.4	0.820	1905	10.4	0.835	2413	10.4	0.831	2667	10.4	0.840	2870
Atascosa	0.808	1524	9.2	0.791	1880	9.0	0.780	2032	9.0	0.770	2286	9.0	0.757	2413	9.0	0.761	2743

TP-40 | reference | English | eb&d

Rainfall Frequency Analysis from **TP-40**

p24lkup [Compatibility Mode]

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1			2-year		5-year			10-year			25-year			50-year				100-year	
2	County name	e	b	d	e	b	d	e	b	d	e	b	d	e	b	d	e	b	d
230	Terrell	0.808	1092	8.8	0.793	1372	9.0	0.800	1702	9.0	0.793	1930	9.0	0.806	2311	9.0	0.805	2642	8.8
231	Terry	0.828	1143	10.0	0.828	1499	10.0	0.806	1651	10.0	0.809	1956	10.0	0.806	2184	10.0	0.812	2464	10.0
232	Throckmorton	0.791	1194	9.1	0.779	1499	8.6	0.792	1880	8.6	0.783	2134	8.6	0.795	2489	8.6	0.783	2718	9.1
233	Titus	0.779	1321	8.0	0.780	1753	8.6	0.759	1829	8.6	0.758	2083	8.6	0.744	2210	8.6	0.741	2388	8.4
234	Tom Green	0.768	940	7.9	0.769	1295	9.0	0.777	1626	9.0	0.771	1905	9.0	0.782	2235	9.0	0.770	2413	7.9
235	Travis	0.796	1422	8.1	0.780	1753	8.6	0.775	1956	8.6	0.766	2210	8.6	0.751	2311	8.6	0.752	2616	8.1
236	Trinity	0.791	1600	7.8	0.764	1803	7.7	0.750	1930	7.7	0.729	2032	7.7	0.734	2286	7.7	0.716	2311	7.8

TP-40 | reference | English | eb&d

$$I = \frac{b}{(t_c + d)^e} \qquad I = \frac{2642}{(t_c + 8.8)^{0.805}} \qquad I = \frac{2642}{(1440 + 8.8)^{0.805}}$$

For t_c = 24 hours = 24*60 = 1440 min, I = 7.53 inches/hour

IDF curves for Austin

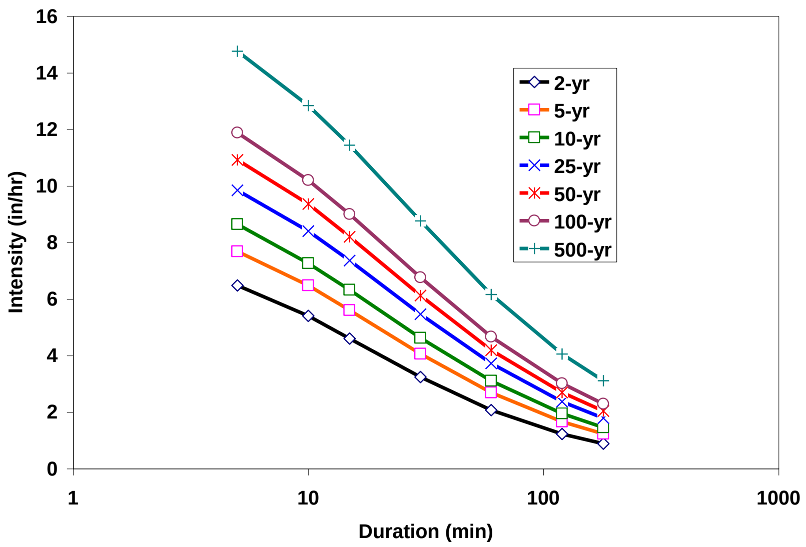
$$i = \frac{a}{(t+b)^c}$$

$i =$ design rainfall intensity

$t =$ Duration of storm

$a, b, c =$ coefficients

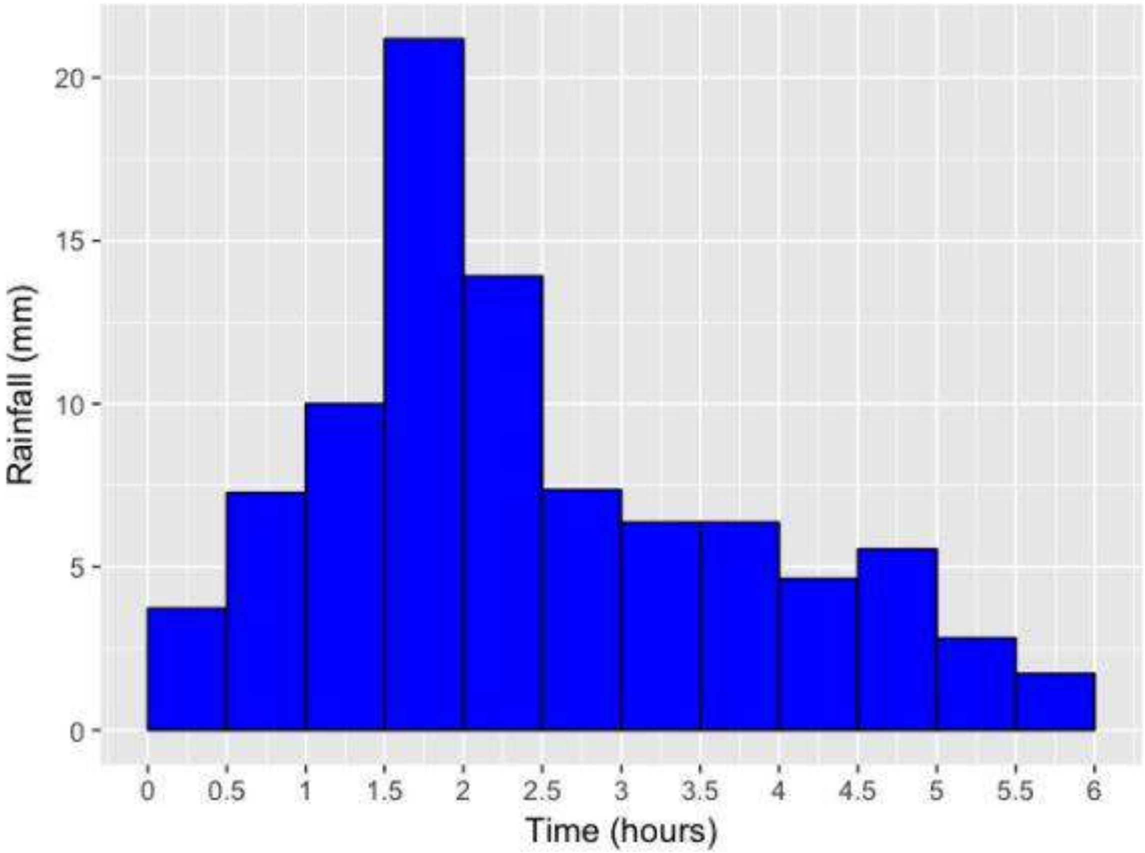
Storm Frequency	a	b	c
2-year	106.29	16.81	0.9076
5-year	99.75	16.74	0.8327
10-year	96.84	15.88	0.7952
25-year	111.07	17.23	0.7815
50-year	119.51	17.32	0.7705
100-year	129.03	17.83	0.7625
500-year	160.57	19.64	0.7449



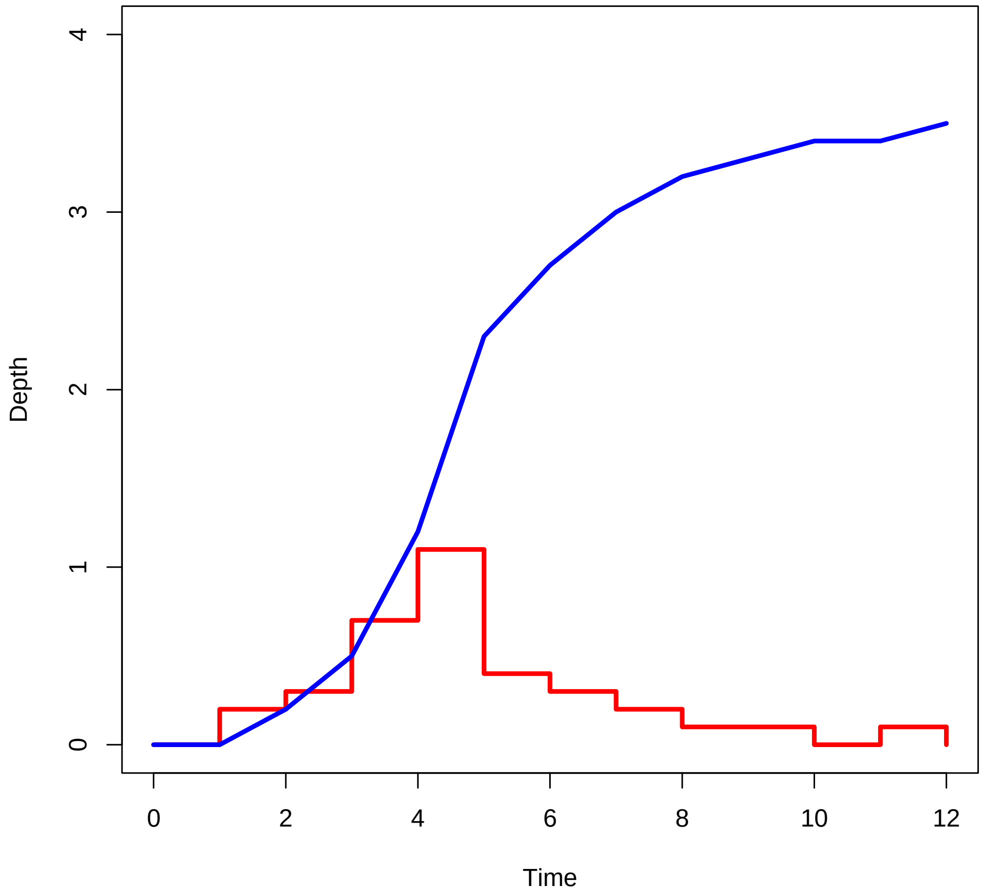
Source: City of Austin, Watershed Management Division

Design Precipitation Hyetographs

- A **hyetograph** is a graphical representation of the distribution of rainfall intensity over time.



Rainfall distributions



- Each “block” represents the amount of rainfall for the time interval
- The diagram is called “incremental” rainfall
- The running sum of the blocks is the cumulative distribution

Design Precipitation Hyetographs

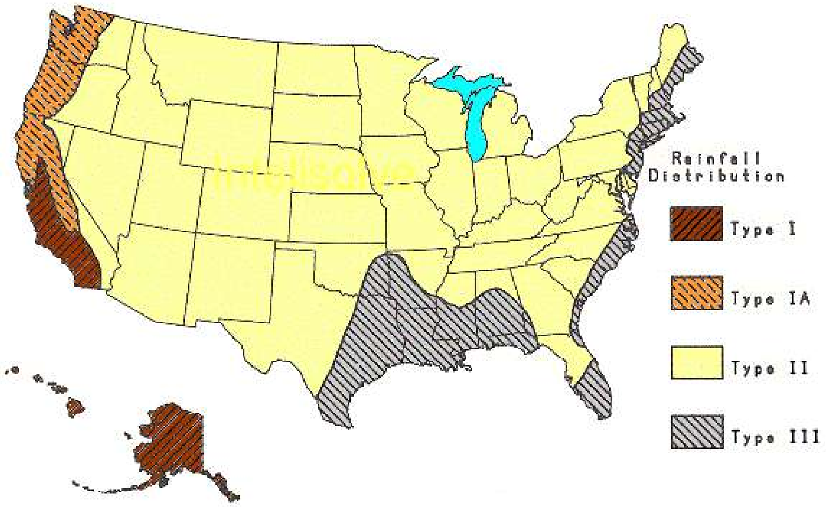
- Most often hydrologists are interested in precipitation hyetographs and not just the peak estimates.

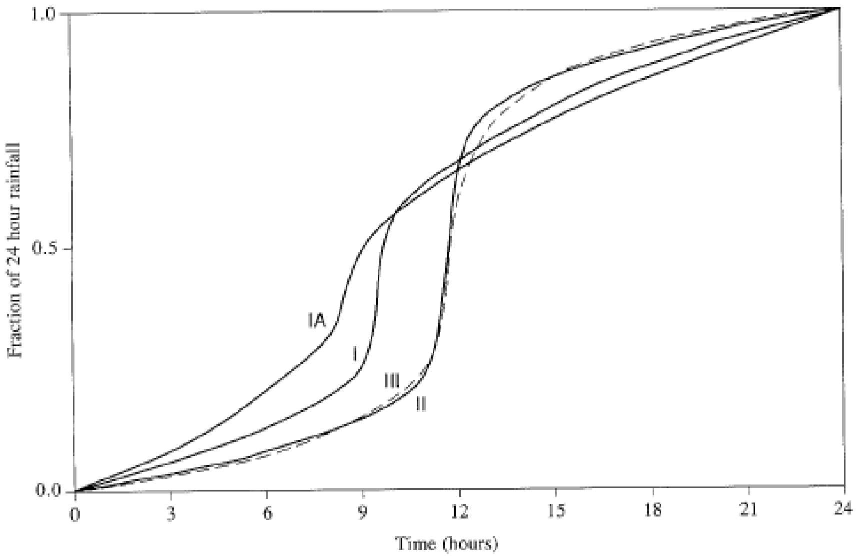
- Techniques for developing design precipitation hyetographs

1. SCS method
2. Triangular hyetograph method
3. Using IDF relationships (Alternating block method)

SCS Method

- SCS (1973) adopted method similar to DDF to develop dimensionless rainfall temporal patterns called type curves for four different regions in the US.
- SCS type curves are in the form of percentage mass (cumulative) curves based on 24-hr rainfall of the desired frequency.
- If a single precipitation depth of desired frequency is known, the SCS type curve is rescaled (multiplied by the known number) to get the time distribution.
- For durations less than 24 hr, the steepest part of the type curve for required duration is used





Example

Find - rainfall hyetograph for a 25-year, 24-hour duration SCS Type-III storm in Harris County using a one-hour time increment

SCS 24-Hour Rainfall Distributions		
T (hrs)	Fraction of 24-hr rainfall	
	Type II	Type III
0.0	0.000	0.000
1.0	0.011	0.010
2.0	0.022	0.020
3.0	0.034	0.031
4.0	0.048	0.043
5.0	0.063	0.057
6.0	0.080	0.072
7.0	0.098	0.089
8.0	0.120	0.115
8.5	0.133	0.130
9.0	0.147	0.148
9.5	0.163	0.167
9.8	0.172	0.178
10.0	0.181	0.189
10.5	0.204	0.216
11.0	0.235	0.250

SCS 24-Hour Rainfall Distributions		
T (hrs)	Fraction of 24-hr rainfall	
	Type II	Type III
11.5	0.283	0.298
11.8	0.357	0.339
12.0	0.663	0.500
12.5	0.735	0.702
13.0	0.772	0.751
13.5	0.799	0.785
14.0	0.820	0.811
15.0	0.854	0.854
16.0	0.880	0.886
17.0	0.903	0.910
18.0	0.922	0.928
19.0	0.938	0.943
20.0	0.952	0.957
21.0	0.964	0.969
22.0	0.976	0.981
23.0	0.988	0.991
24.0	1.000	1.000

SCS Method Steps

- Given T_d and frequency/T, find the design hyetograph
  1. Compute P/i (from DDF/IDF curves or equations)
  2. Pick a SCS type curve based on the location
  3. If T_d = 24 hour, multiply (rescale) the type curve with P to get the design mass curve
     1. If T_d is less than 24 hr, pick the steepest part of the type curve for rescaling
  4. Get the incremental precipitation from the rescaled mass curve to develop the design hyetograph

Example

- Find - rainfall hyetograph for a 25-year, 24-hour duration SCS Type-III storm in Harris County using a one-hour time increment
- a = 81, b = 7.7, c = 0.724

$$i = \frac{a}{(t+b)^c} = \frac{81}{(24*60+7.7)^{0.724}} = 0.417\, in/hr \qquad P = i * T_d = 0.417\, in/hr * 24\, hr = 10.01\, in$$

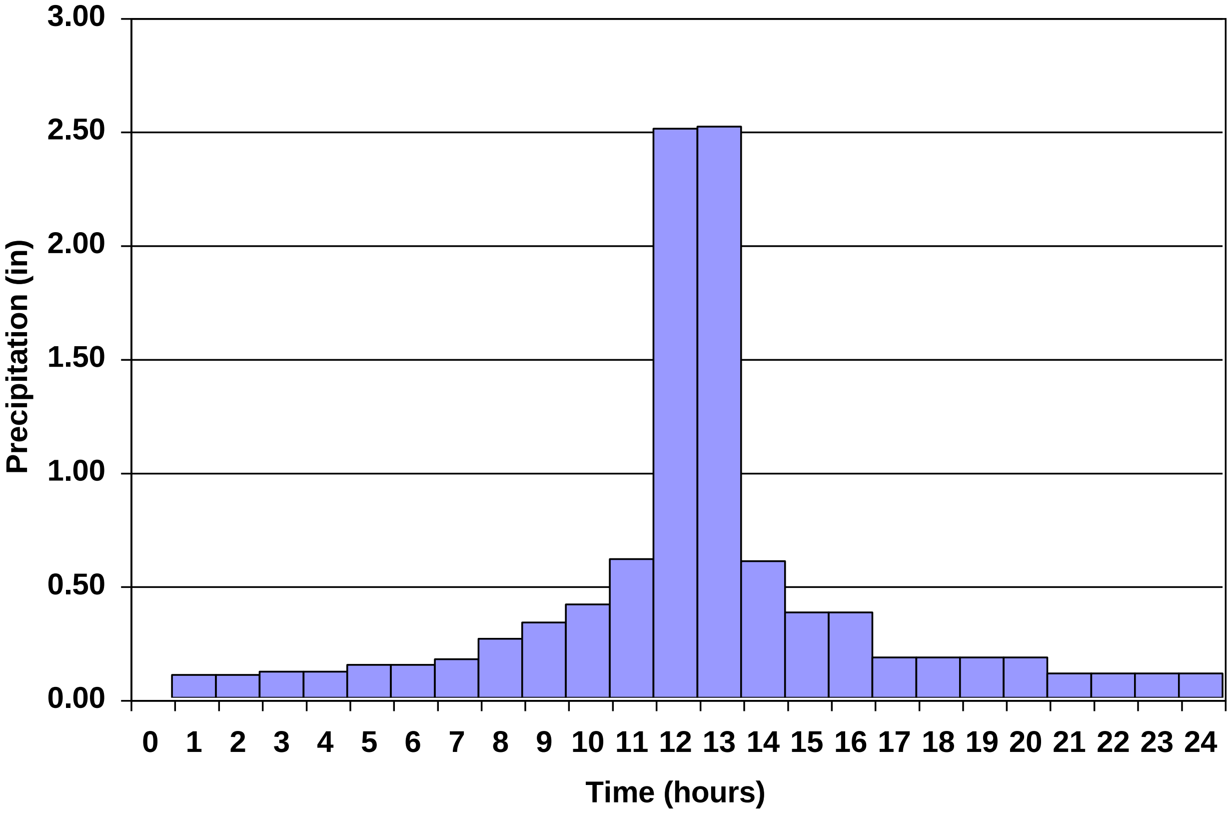
- Find
  - Cumulative fraction - interpolate SCS table
  - Cumulative rainfall = product of cumulative fraction * total 24-hour rainfall (10.01 *in*)
  - Incremental rainfall = difference between current and preceding cumulative rainfall

Example

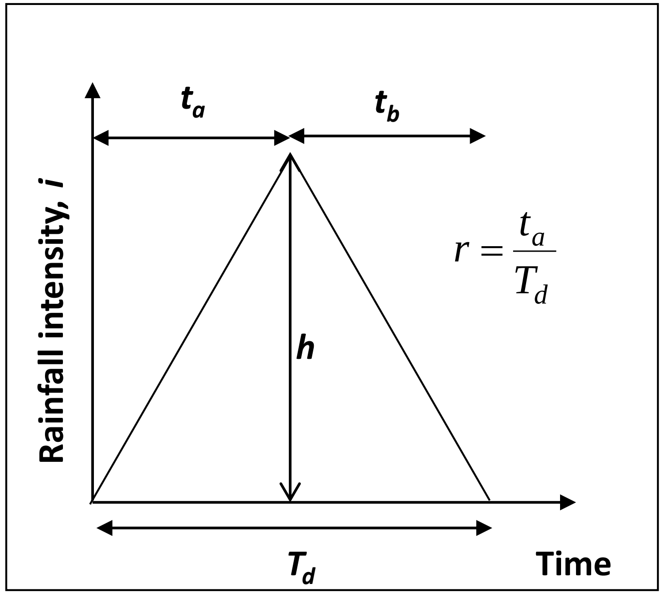
SCS Tabulation

Time	Cumulative Fraction	Cumulative Precipitation	Incremental Precipitation
(hours)	Pt/P24	Pt (in)	(in)
0	0.000	0.00	0.00
1	0.010	0.10	0.10
2	0.020	0.20	0.10
3	0.032	0.32	0.12
4	0.043	0.43	0.12
5	0.058	0.58	0.15
6	0.072	0.72	0.15
7	0.089	0.89	0.17
8	0.115	1.15	0.26
9	0.148	1.48	0.33
10	0.189	1.89	0.41
11	0.250	2.50	0.61
12	0.500	5.01	2.50
13	0.751	7.52	2.51
14	0.811	8.12	0.60
15	0.849	8.49	0.38
16	0.886	8.87	0.38
17	0.904	9.05	0.18
18	0.922	9.22	0.18
19	0.939	9.40	0.18
20	0.957	9.58	0.18
21	0.968	9.69	0.11
22	0.979	9.79	0.11
23	0.989	9.90	0.11
24	1.000	10.00	0.11

$$p(t) = \frac{P_t}{P_{24}} \times P$$



Triangular Hyetograph Method



T_d: hyetograph base length = precipitation duration

t_a: time before the peak

r: storm advancement coefficient = t_a/T_d

t_b: recession time = $T_d - t_a = (1\text{-}r)T_d$

$$P = \frac{1}{2} T_d h$$

$$h = \frac{2P}{T_d}$$

- Given T_d and frequency/T, find the design hyetograph
  1. Compute P/i (from DDF/IDF curves or equations)
  2. Use above equations to get t_a, t_b, T_d and h (*r* is available for various locations)

Triangular hyetograph - example

- Find - rainfall hyetograph for a 25-year, 6-hour duration in Harris County. Use storm advancement coefficient of 0.5.
- a = 81, b = 7.7, c = 0.724 (from Tx-DOT hydraulic manual)

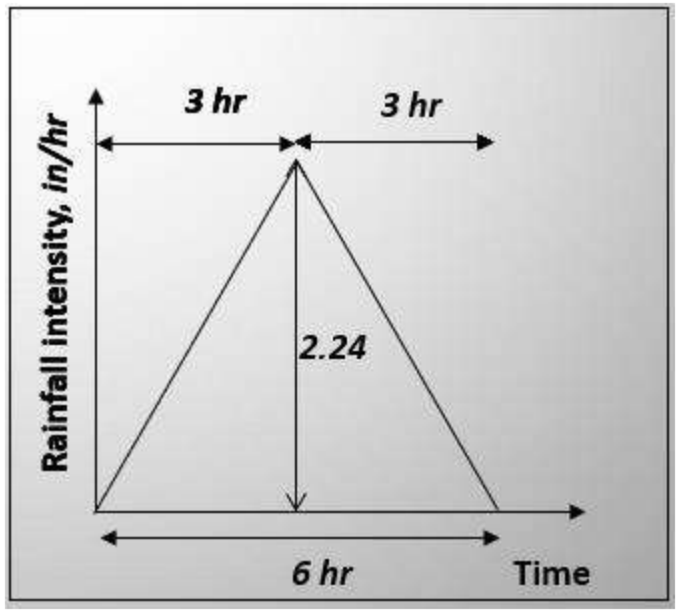
$$i = \frac{a}{(t+b)^c} = \frac{81}{(6*60+7.7)^{0.724}} = 1.12\, in/hr$$

$$P = i*6 = 1.12\, in/hr * 6\, hr = 6.72\ \ in$$

$$h = \frac{2P}{T_d} = \frac{2\times 6.72}{6} = \frac{13.44}{6} = 2.24\ \ in/hr$$

$$t_a = rT_d = 0.5\times 6 = 3\ \ hr$$

$$t_b = T_d - t_a = 6-3 = 3\ \ hr$$



Alternating block method

- Given T_d and T/frequency, develop a hyetograph in Dt increments

  1. Using T, find i for Dt, 2Dt, 3Dt,…nDt using the IDF curve for the specified location
  2. Using i compute P for Dt, 2Dt, 3Dt,…nDt. This gives cumulative P.
  3. Compute incremental precipitation from cumulative P.
  4. Pick the highest incremental precipitation (maximum block) and place it in the middle of the hyetograph. Pick the second highest block and place it to the right of the maximum block, pick the third highest block and place it to the left of the maximum block, pick the fourth highest block and place it to the right of the maximum block (after second block), and so on until the last block.

Example: Alternating Block Method

Find: Design precipitation hyetograph for a 2-hour storm (in 10 minute increments) in Denver with a 10-year return period 10-minute

$$i = \frac{c}{(T_d)^e + f} = \frac{96.6}{(T_d)^{0.97} + 13.90}$$

i = design rainfall intensity

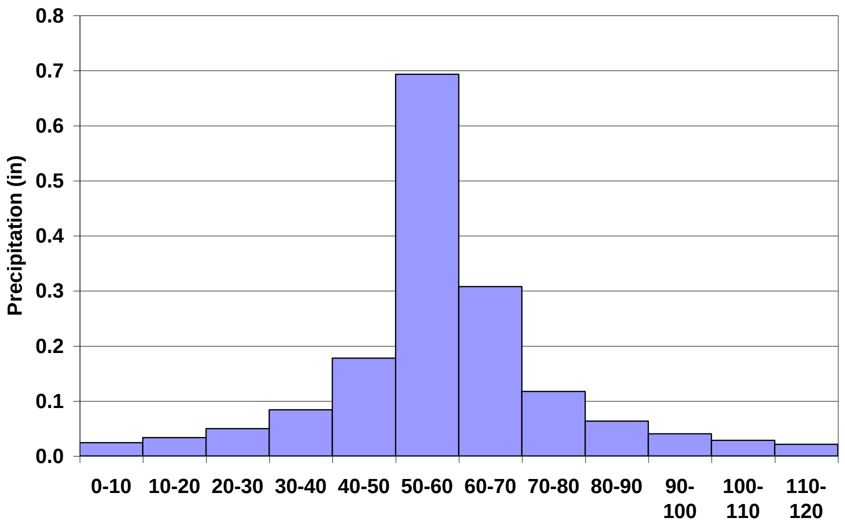
T_d = Duration of storm

c, e, f = coefficients

$$i = \frac{c}{(T_d)^e + f} = \frac{96.6}{(T_d)^{0.97} + 13.90}$$

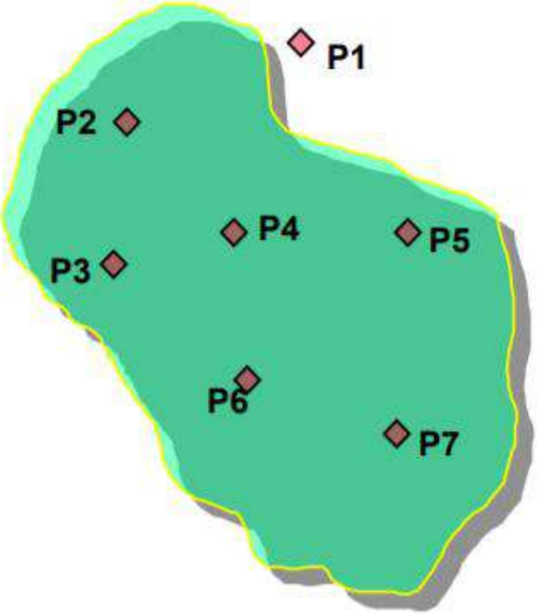
Duration (min)	Intensity (in/hr)
10	4.158
20	3.002
30	2.357
40	1.943
50	1.655
60	1.443
70	1.279
80	1.149
90	1.044
100	0.956
110	0.883
120	0.82

Duration (min)	Intensity (in/hr)	Cumulative Depth (in)	Incremental Depth (in)	Time (min)	Precip (in)
10	4.158	0.693	0.693	0-10	0.024
20	3.002	1.001	0.308	10-20	0.033
30	2.357	1.178	0.178	20-30	0.050
40	1.943	1.296	0.117	30-40	0.084
50	1.655	1.379	0.084	40-50	0.178
60	1.443	1.443	0.063	50-60	0.693
70	1.279	1.492	0.050	60-70	0.308
80	1.149	1.533	0.040	70-80	0.117
90	1.044	1.566	0.033	80-90	0.063
100	0.956	1.594	0.028	90-100	0.040
110	0.883	1.618	0.024	100-110	0.028
120	0.820	1.639	0.021	110-120	0.021

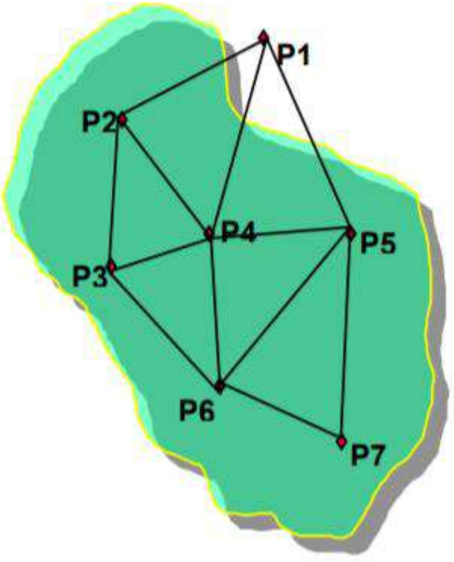


No.	Time (min)	Precip. (in)	No.
1	0-10	0.024	11
2	10-20	0.033	9
3	20-30	0.050	7
4	30-40	0.084	5
5	40-50	0.178	3
6	50-60	0.693	1
7	60-70	0.308	2
8	70-80	0.117	4
9	80-90	0.063	6
19	90-100	0.040	8
11	100-110	0.028	10
12	110-120	0.021	12

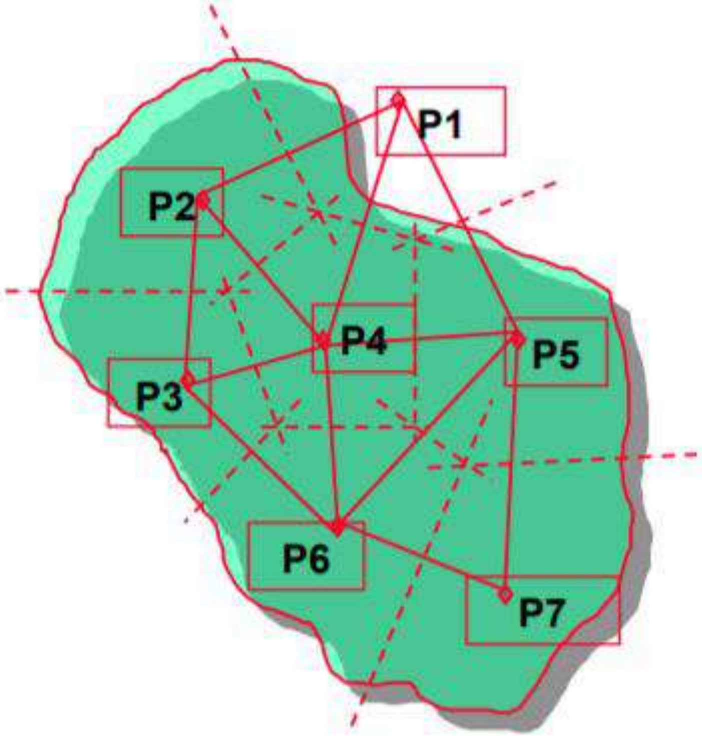
Computation of average rainfall over a watershed - Thiessen Polygon Method



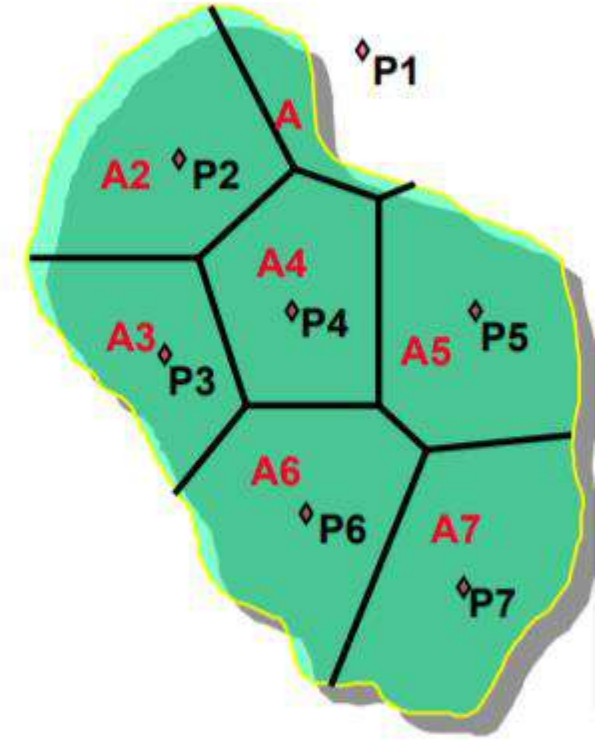
Step 1: Draw the area concerned to a suitable scale, showing its *boundary*, *locations of the raingauges* in the area and outside but close to the boundary



Step 2: Join location of the raingauges to form a network of triangles



Step 3: Draw perpendicular bisectors to the triangle sides. These bisectors form polygons around the stations



Step 4: Delineate the formed polygons and measure their areas using a planimeter or by converting them into smaller regular geometric shapes (i.e. triangles, squares, rectangles, etc.)

Step 5: Compute the average rainfall using the following formula

$$P_{av} = \frac{P_1 x A_1 + P_2\ x A_2 + \ldots + P_n x A_n}{A_1\ A_1 + A_2 + \ldots. + A_n}$$

Example

Given : Bi-sectional areas (A) of Theissen polygon, and the measured precipitation (P) for stations

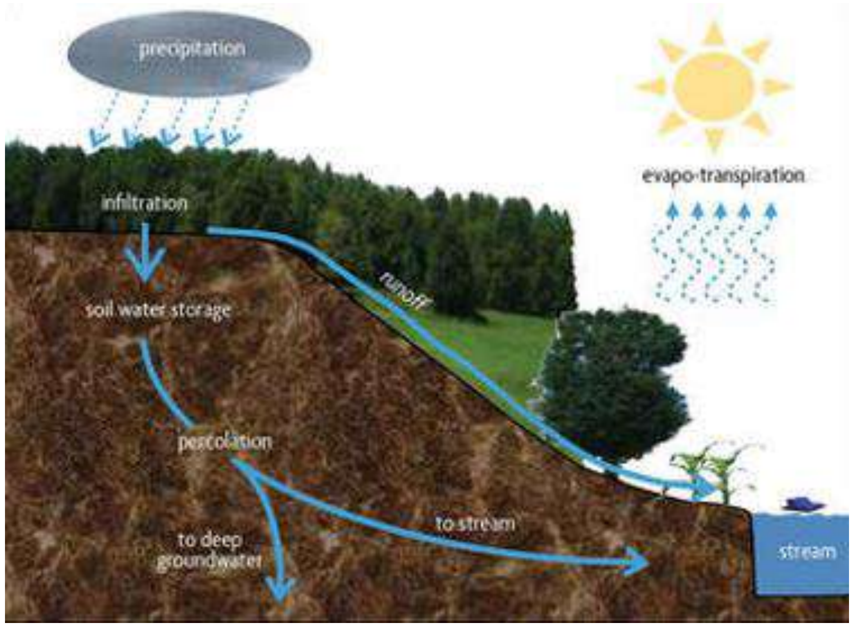
Station No.	Bi-sectional areas (Ai) [km^2]	Measured precipitation (Pi) [mm]	(Col. 2 * Col. 3) (Ai *Pi)
P1	25	10	250
P2	125	15	1875
P3	80	20	1600
P4	90	17	1530
P5	120	25	3000
P6	115	40	4600
P7	130	12	1560
Total	**685**		**14415**

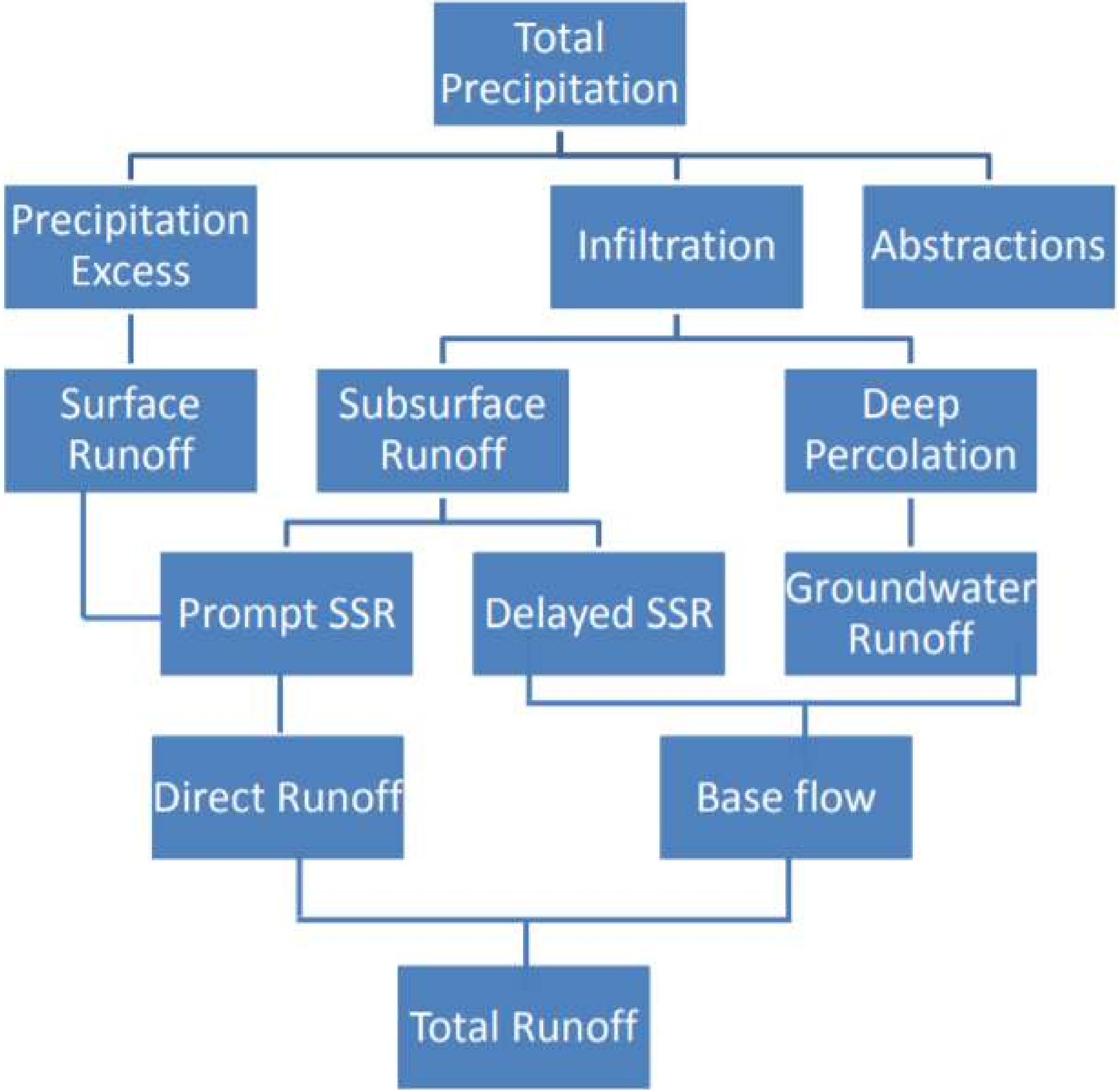
Then the average precipitation over the catchment will be computed by the total of the column 4 to the total area in column 2. The result will be found as: 21.04 mm.

Hydrologic Parameters

- Runoff

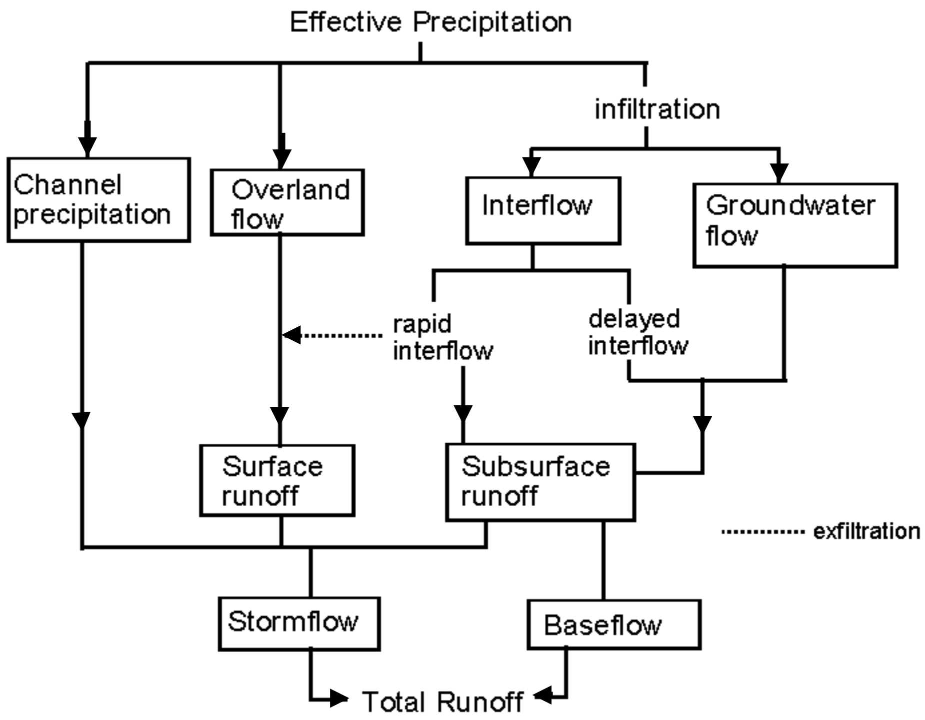
- Runoff is the portion of rainfall which flows through the rivers, streams etc.





Types of runoff

- Surface runoff – Portion of rainfall (after all losses such as interception, infiltration, depression storage etc. are met) that enters streams immediately after occurring rainfall – After laps of few time, overland flow joins streams – Sometime termed prompt runoff (as very quickly enters streams)
- Subsurface runoff – Amount of rainfall first enter into soil and then flows laterally towards stream without joining water table – Also take little time to reach stream



Runoff Computation
- Rational Method

$$Q = CiA$$

Where:

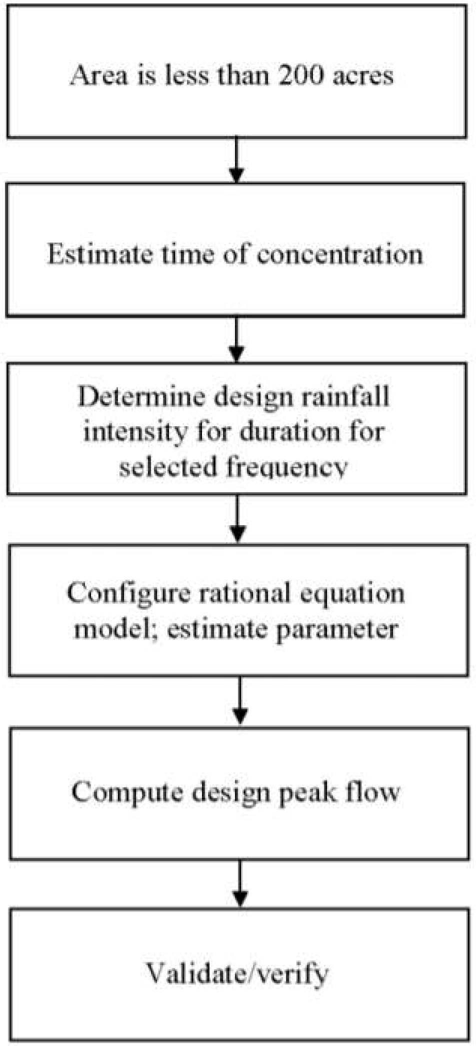
Q = Maximum Rate of Runoff (cfs)
C = Runoff Coefficient
i = Average Rainfall Intensity (in/hr)
A = Drainage Area (in acres)

An urban area consisting of sub-areas with different surface characteristics

$$Q = i\sum_{j=1}^{m} C_j A_j$$ **Composite rational equation**

j = number of sub-catchments drained by a sewer

Rational Method



Assumptions and Limitations:

- Watershed area < 200 acres
- The method is applicable if time of concentration (t_c) for the drainage area is less than the duration of peak rainfall intensity.
- The time of concentration (t_c) is the time required for water to travel from the hydraulically most remote point of the basin to the point of interest.

Rational Method

Assumptions and Limitations:

- The calculated runoff is directly proportional to the rainfall intensity.
- Rainfall intensity is uniform throughout the duration of the storm.
- Rainfall is distributed uniformly over the drainage area.
- The minimum duration to be used for computation of rainfall intensity is 10 minutes.

Runoff Coefficient (C)

Definition: Dimensionless ratio intended to indicate the amount of runoff generated by a watershed given a average intensity of precipitation for a storm.

$$C = \frac{R}{P}$$

Where: R = Total depth of runoff P = Total depth of precipitation

Runoff Coefficient (C)

Table 1 Runoff Coefficients for the Rational Method

	FLAT	ROLLING	HILLY
Pavement & Roofs	**0.90**	**0.90**	**0.90**
Earth Shoulders	0.50	0.50	0.50
Drives & Walks	0.75	0.80	**0.85**
Gravel Pavement	**0.85**	**0.85**	**0.85**
City Business Areas	0.80	**0.85**	**0.85**
Apartment Dwelling Areas	0.50	0.60	0.70
Light Residential: 1 to 3 units/acre	0.35	0.40	0.45
Normal Residential: 3 to 6 units/acre	0.50	0.55	0.60
Dense Residential: 6 to 15 units/acre	0.70	0.75	0.80
Lawns	0.17	0.22	0.35
Grass Shoulders	0.25	0.25	0.25
Side Slopes, Earth	0.60	0.60	0.60
Side Slopes, Turf	0.30	0.30	0.30
Median Areas, Turf	0.25	0.30	0.30
Cultivated Land, Clay & Loam	0.50	0.55	0.60
Cultivated Land, Sand & Gravel	0.25	0.30	0.35
Industrial Areas, Light	0.50	0.70	0.80
Industrial Areas, Heavy	0.60	0.80	**0.90**
Parks & Cemeteries	0.10	0.15	0.25
Playgrounds	0.20	0.25	0.30
Woodland & Forests	0.10	0.15	0.20
Meadows & Pasture Land	0.25	0.30	0.35
Unimproved Areas	0.10	0.20	0.30

Rainfall intensity (i)

- The determination of rainfall intensity (i) for use in the Rational Formula involves consideration of three factors:

- Average frequency of occurrence.
- Intensity-duration characteristics for a selected rainfall frequency.
- The time of concentration (t_c).

Time of Concentration (t_c)

- Definition: The time required for a parcel of runoff to travel from the most hydraulically distant part of a watershed to the outlet.

- tc represents the time at which all areas of the watershed that will contribute runoff are just contributing runoff to the outlet.

Time of Concentration (t_c)

Morgali and Linsley Method (1965)

$$t_c = \frac{0.94(nL)^{0.6}}{i^{0.4} S^{0.3}}$$

t_c = time of concentration (min),
i = design rainfall intensity (in/hr),
n = Manning surface roughness (dimensionless),
L = length of flow (ft), and
S = slope of flow (dimensionless).

Table 3-2. Manning's Roughness Coefficient (n) for Overland Sheet Flow[8].

Surface Description	n
Smooth asphalt	0.011
Smooth concrete	0.012
Ordinary concrete lining	0.013
Good wood	0.014
Brick with cement mortar	0.014
Vitrified clay	0.015
Cast iron	0.015
Corrugated metal pipe	0.024
Cement rubble surface	0.024
Fallow (no residue)	0.05
Cultivated soils	
Residue cover ≤ 20%	0.06
Residue cover > 20%	0.17
Range (natural)	0.13
Grass	
Short grass prairie	0.15
Dense grasses	0.24
Bermuda grass	0.41
Woods*	
Light underbrush	0.40
Dense underbrush	0.80

*When selecting n, consider cover to a height of about 30 mm. This is only part of the plant cover that will obstruct sheet flow.

Time of Concentration (t_c)

Kirpich Method (1940)

$$t_c = 0.0078(L^3/h)^{0.385}$$

t_c = time of concentration (min),

L = length of main channel (ft), and

h = relief along main channel (ft).

Assumptions and Limitations:

- For small drainage basins dominated by channel flow.

Time of Concentration (t_c)

Kerby-Hatheway Method (1959)

$$t_c = \left[\frac{0.67NL}{\sqrt{S}}\right]^{0.467}$$

t_c = time of concentration (min),
N = Kerby roughness parameter (dimensionl
S = overland flow slope (dimensionless).

Assumptions and Limitations:

- Primarily used for overland flow.

Table 3: Kerby's roughness parameter.

Description	N
Pavement	0.02
Smooth, bare packed soil	0.10
Poor grass, cultivated row crops or moderately rough bare surfaces	0.20
Pasture, average grass	0.40
Deciduous forest	0.60
Dense grass, coniferous forest, or deciduous forest with deep litter	0.80

Time of Concentration (t_c)

TIME OF CONCENTRATION (t_c)

Numerous Flow Segments

$$t_c = t_{t1} + t_{t2} + \ldots + t_{tn}$$

Where:

t_c = Time of Concentration
t_{t1} = Travel time of Segment 1
n = Number of segments

Example

Given T_d =10 min (Duration), C = 0.6, ground elevations at the pipe ends (498.43 and 495.55 ft), length = 450 ft, Manning n = 0.015, i=120$T^{0.175}$/(T_d + 27), compute flow, pipe diameter and flow time in the pipe. Knowing that area of drainage is 4 acre,and the return period is 5 years.

$$i = \frac{120(5)^{0.175}}{(10+27)} = 4.30 \ \ in/hr$$

$$Q = CiA = 0.6 \times 4.30 \times 4 = 10.3 \ \ cfs$$

$$D = \left(\frac{2.16Qn}{\sqrt{S_0}}\right)^{3/8} = \left(\frac{2.16 \times 10.3 \times 0.015}{\sqrt{0.0064}}\right)^{3/8} = 1.71 \ \ ft = 1.75 \ \ ft$$

$$Flow\ time = length\ of\ \ pipe\ /\ velocity$$

$$= \frac{450}{Q} \times A_{pipe} = \frac{450}{10.3} \times \frac{\pi \times 1.75^2}{4}$$

$$= 105\ sec = 1.75\ min$$

Manning's equation

$$Q = \frac{1.49}{n} A R^{2/3} S_f^{1/2} \qquad D = \left(\frac{2.16 Q n}{\sqrt{S_0}} \right)^{3/8}$$

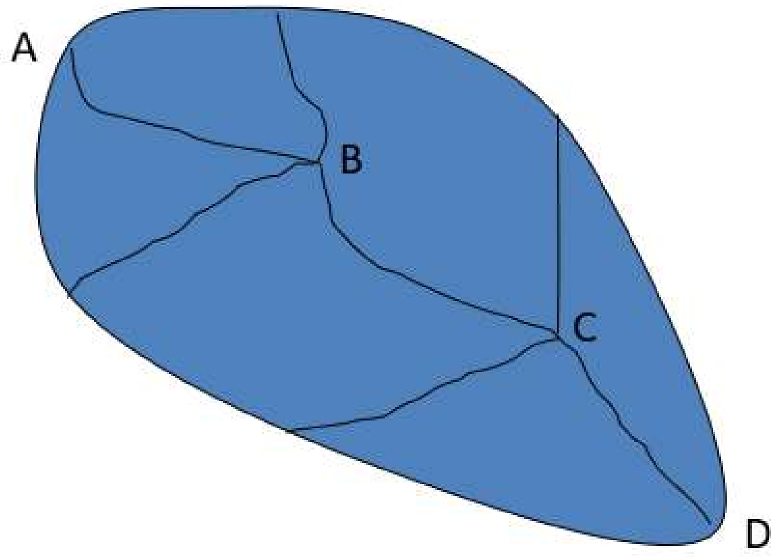
Valid for Q in cfs and D in feet. For SI units (Q in m^3/s and D in m), replace 2.16 with 3.21.

Darcy-Weisbach equation

$$Q = A \left(\frac{8g}{f} R S_f \right)^{1/2} \qquad D = \left(\frac{0.811 f Q^2}{g S_o} \right)^{1/5}$$

Equation is valid for both SI and English system as long as the units are consistent

Example



Compute t_c and peak flow at D for *I* = 3.2 in/hr

Reach	Description of flow	C	Slope (%)	Length (ft)	Area (acre)
A-B	Natural channel	0.41	4.5	300	8
B-C	Natural channel	0.85	3	540	20
C-D	Storm drain (n = 0.015, D = 3 ft)	0.81	1.2	500	10

Solution

Compute t_c for AB and BC using Kirpich formula

$$t_c(AB) = 0.0078L^{0.77}S^{-0.385} = 0.0078 \times 300^{0.77} \times (0.045)^{-0.385} = 2.8 \ \text{min}$$

$$t_c(BC) = 0.0078L^{0.77}S^{-0.385} = 0.0078 \times 540^{0.77} \times (0.03)^{-0.385} = 3.8 \ \text{min}$$

For CD, compute velocity by Manning's equation and t_c = length/velocity

$$V_{CD} = \frac{1.49}{n} R^{2/3} S^{1/2} = \frac{1.49}{0.015} \times (3)^{2/3} \times (0.012)^{1/2} = 9 \ ft/s$$

$$t_c(CD) = 500/9 = 55 \ s = 1 \ \text{min}$$

$$t_c(AD) = 2.8 + 3.8 + 1 = 7.6 \ \text{min}$$

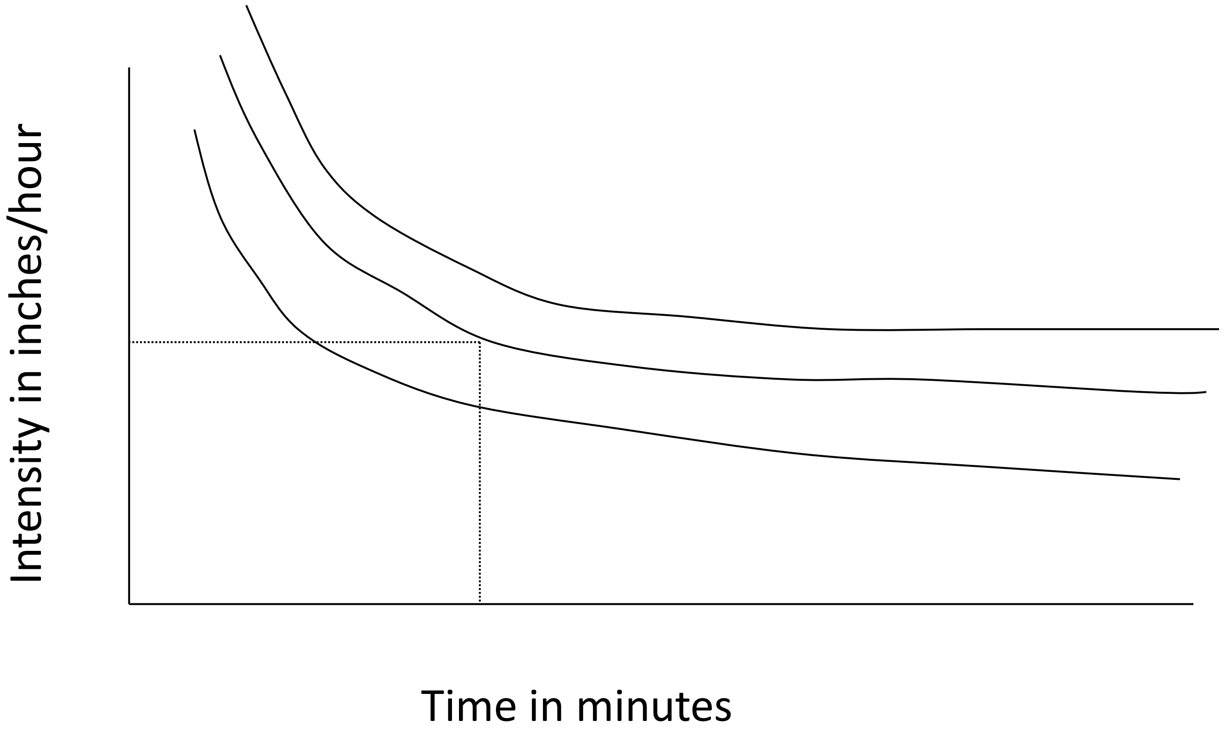
$$Q_p = i \sum c_j A_j = 3.2 \times (0.41 \times 8 + 0.85 \times 20 + 0.81 \times 10) = 90.8 \ cfs$$

Probabilistic
Rainfall Characteristics

- Intensity
- Duration
- Frequency
- Amount
- Time Distribution
- Spatial Variability

Rainfall Patterns

Typically characterized by *intensity-duration-frequency (IDF) curves*



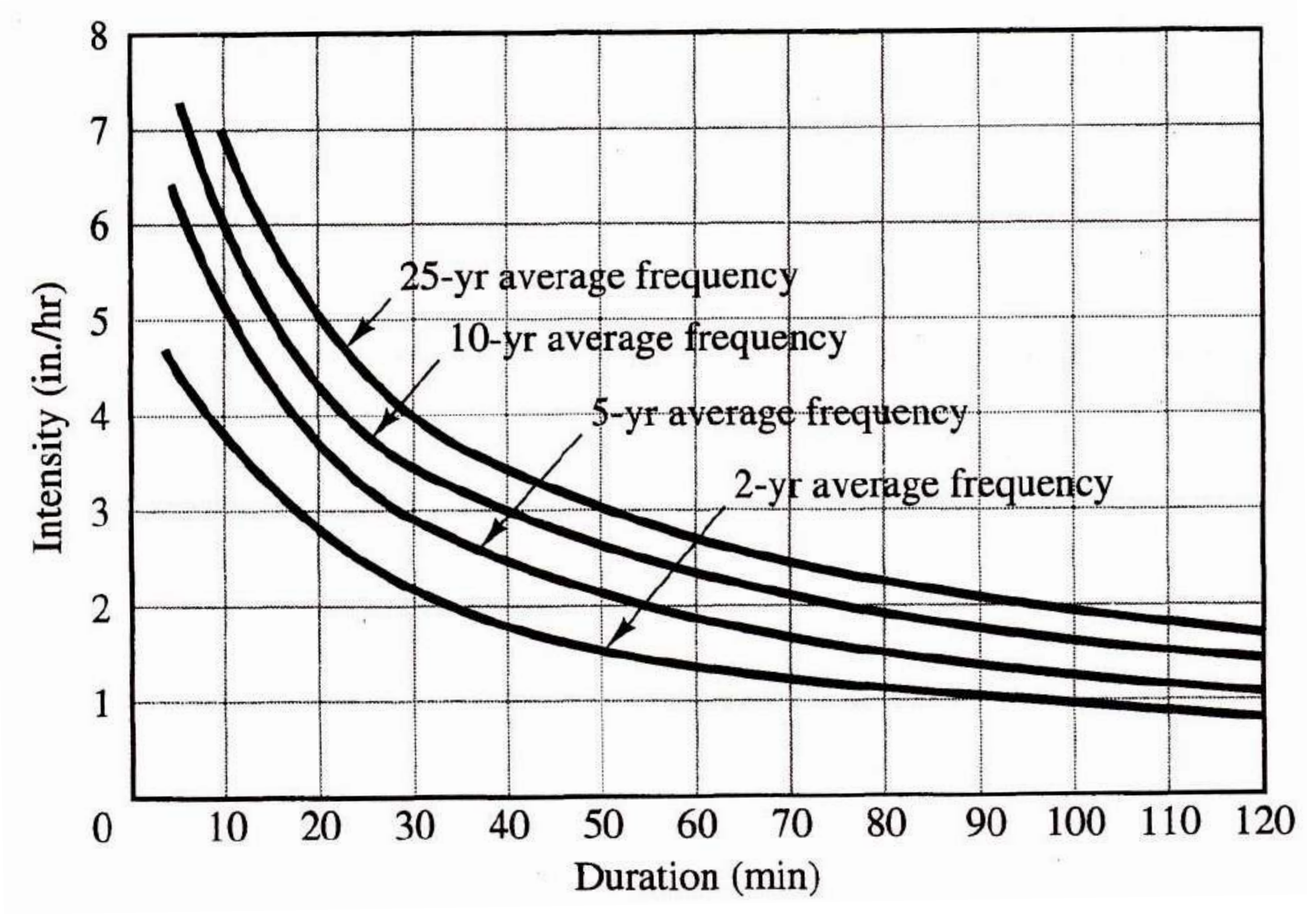
Duration

- The duration of the storm is directly related to the volume of surface runoff.
- High intensities are generally associated with short duration storms. Large water volumes are generally associated with long duration storms.

Frequency

- The frequency of occurrence of a storm of given magnitude and duration is important to establish a measure of risk.
- For a given storm duration, the probability that an event of certain magnitude has of being equaled or exceeded in any one year is termed the probability of exceedance.
- In general, for the same return period, short storms are more intense than long storms. Similarly, for a given intensity, longer storms are associated with greater return periods.

IDF Curves



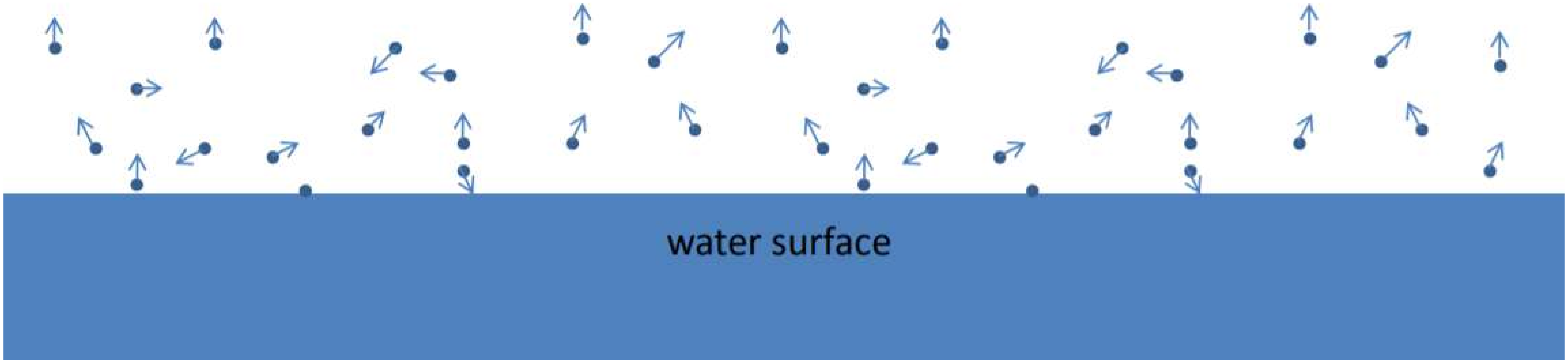
IDF curves show frequency of storms of *at least* the given intensity over the given duration.

Hydrology CE 454

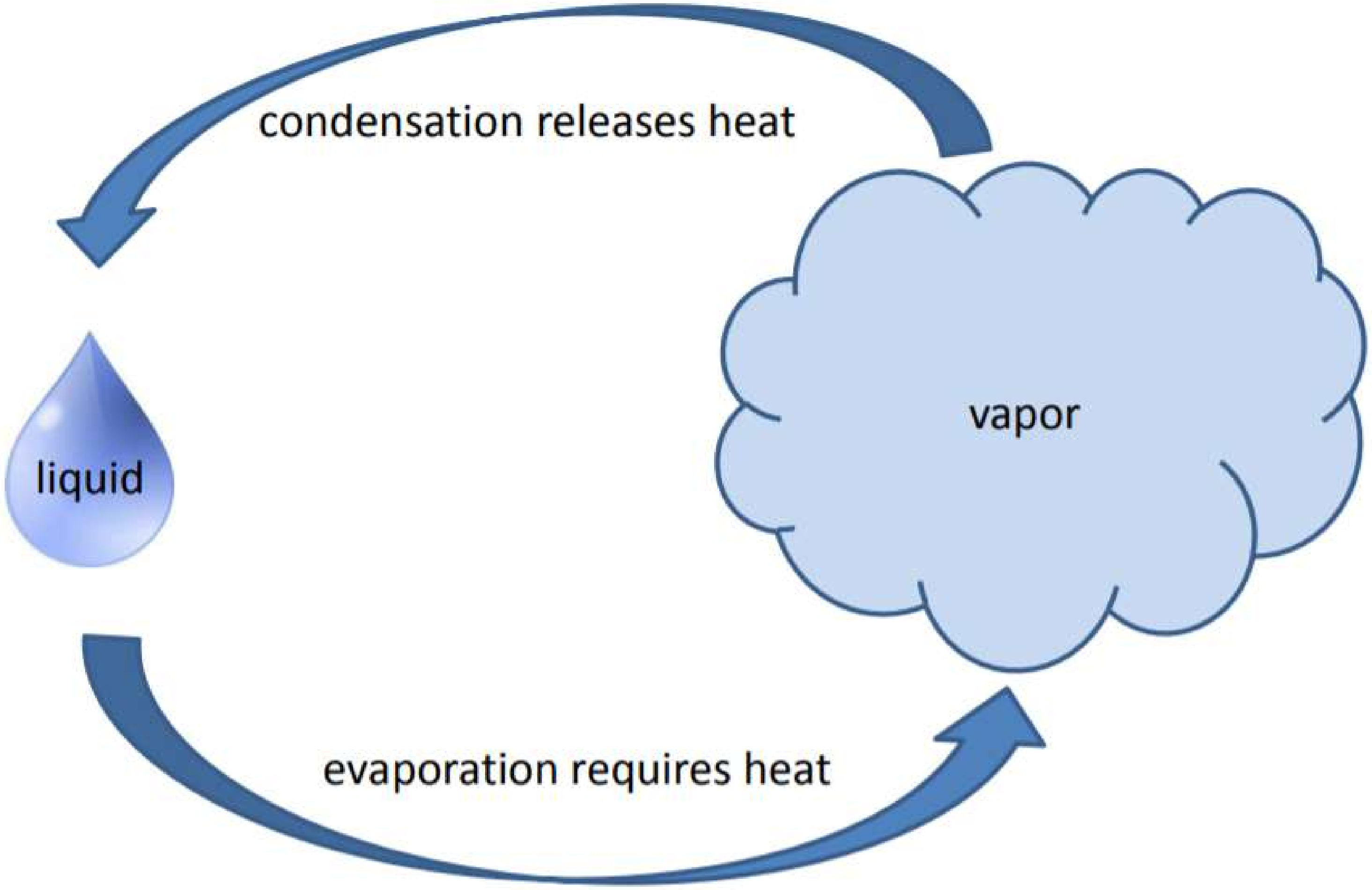
Hydrological parameters

Evaporation

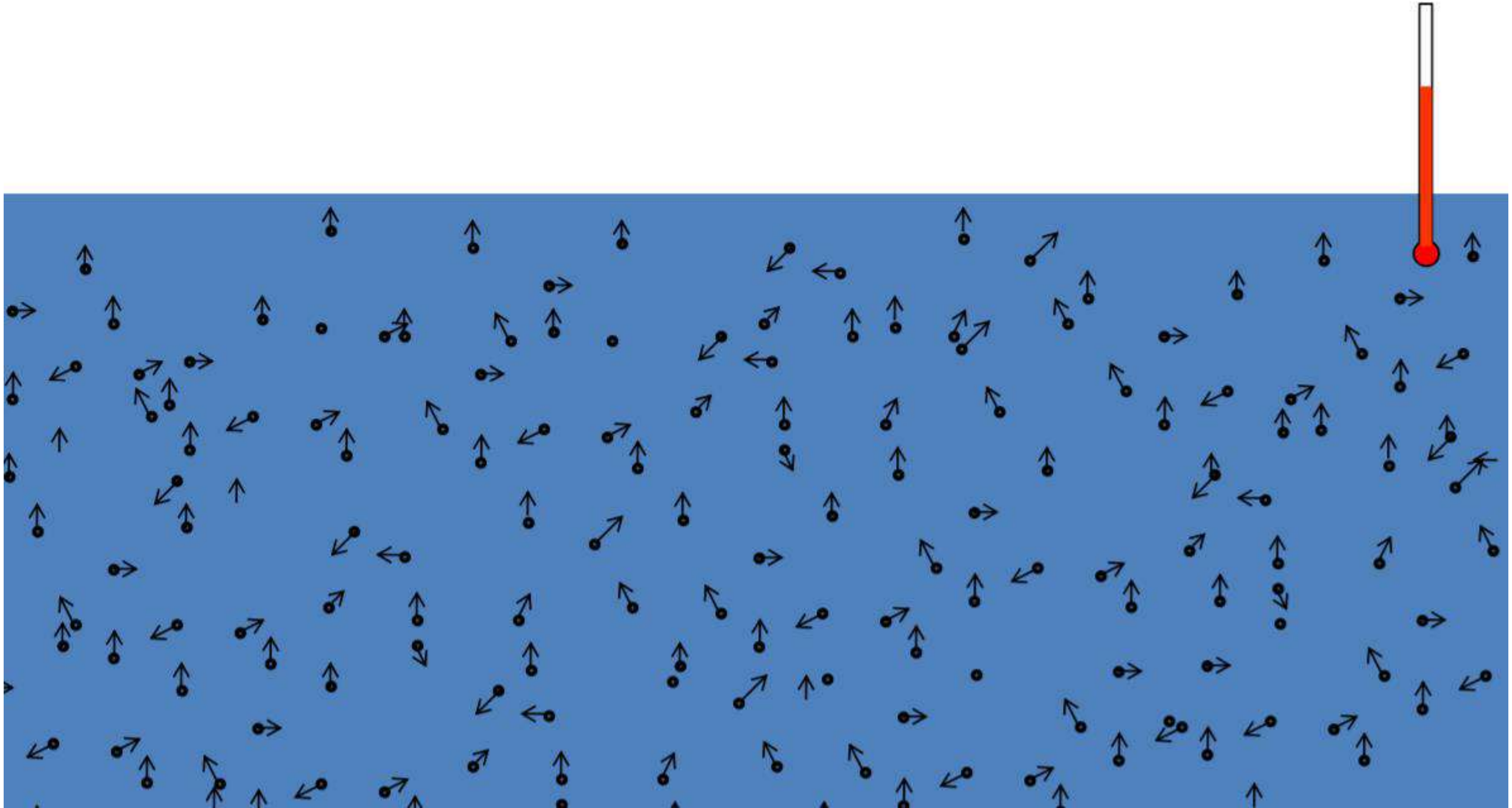
- Evaporation is the net loss of water from a liquid surface that results from a phase change from a liquid to a vapor.
- It is a net process because water vapor is constantly moving back and forth from the water surface.
- Evaporation occurs when there are more molecules leaving the water surface then entering.



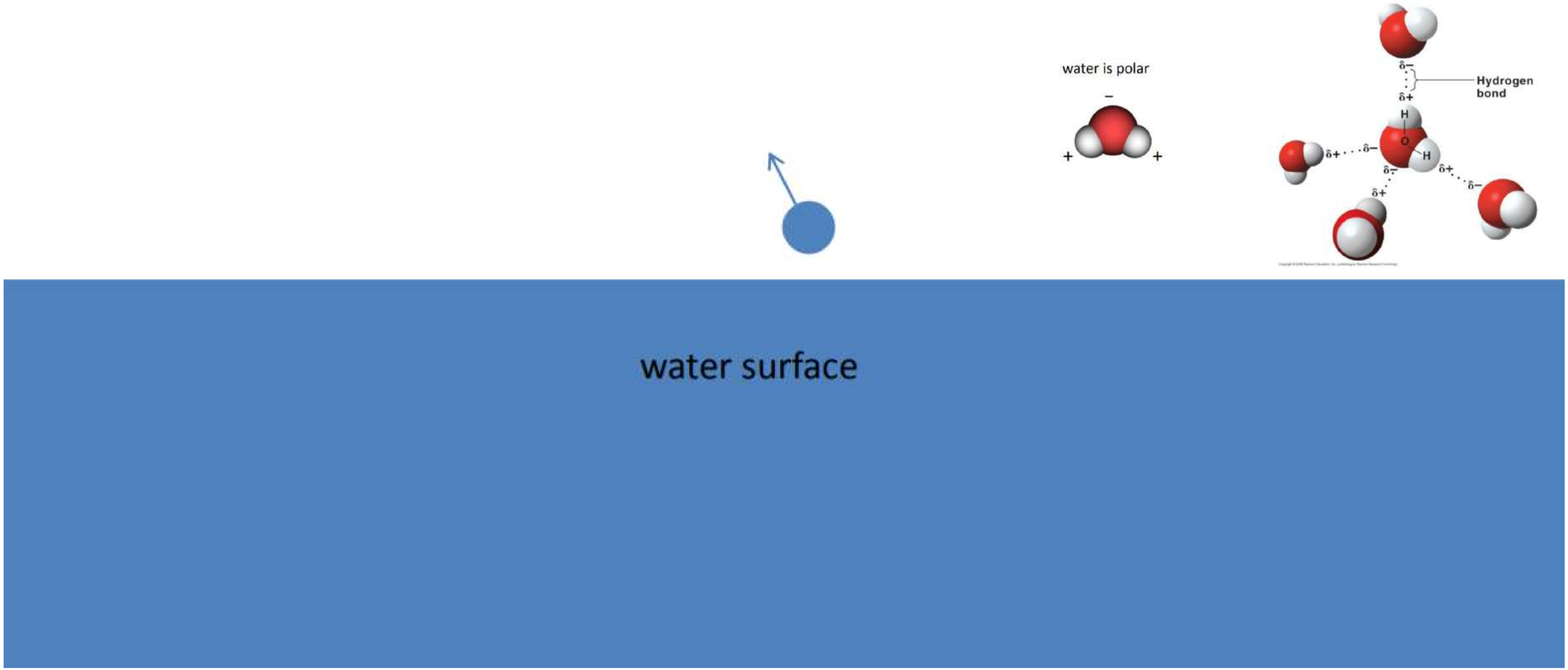
Phase changes involve heat (energy) exchanges (latent heat)



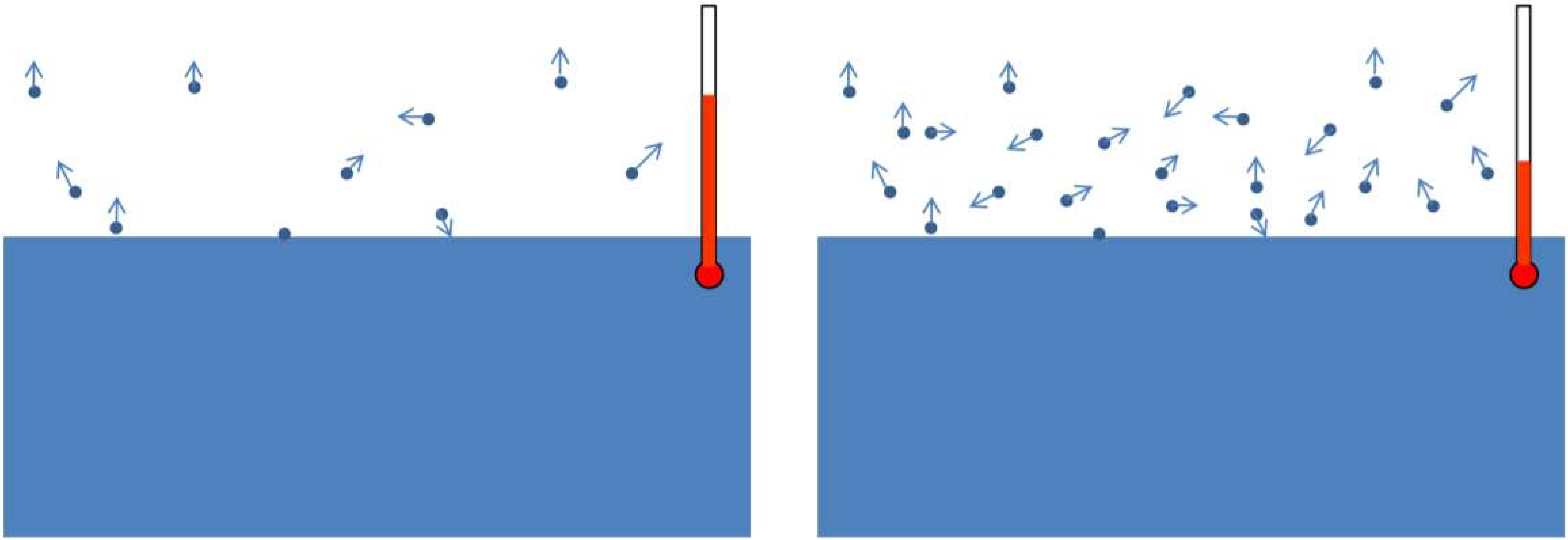
The collective motion of water molecules in the water is called kinetic energy. The average kinetic energy of the molecules quantifies the water temperature.



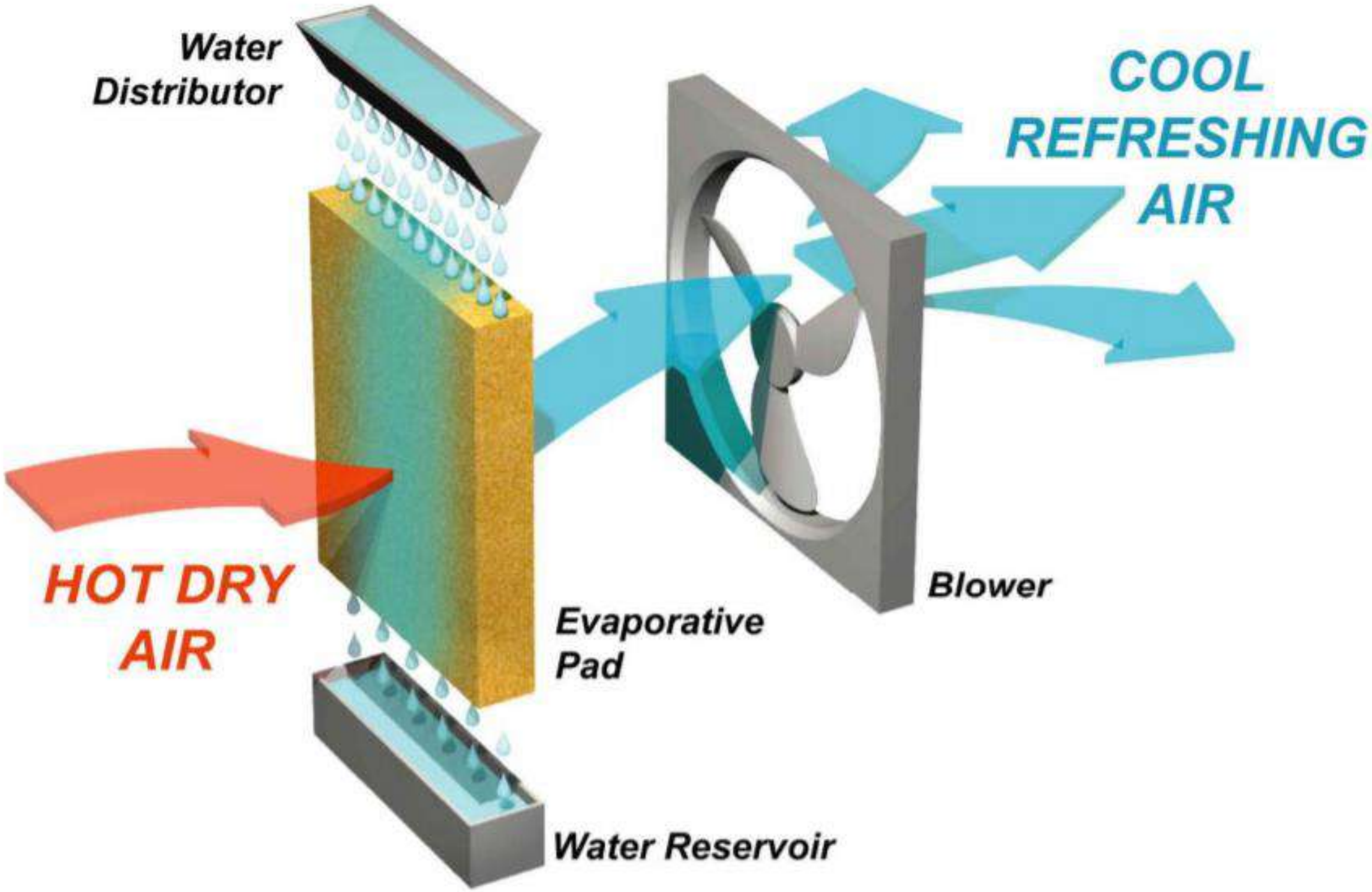
Molecules with the highest kinetic energy can break the hydrogen bonds and escape the water surface. Thus, reducing the water temperature because the average kinetic energy is reduced (heat is removed).



Evaporation cools off the water!



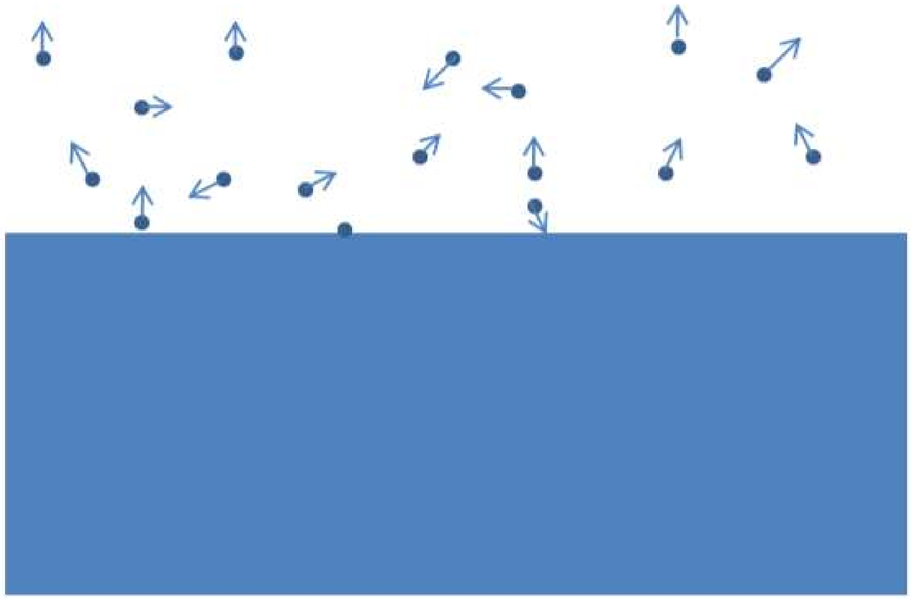
Swamp Cooler (evaporation cools)



http://www.pinnacleint.com/evap.html

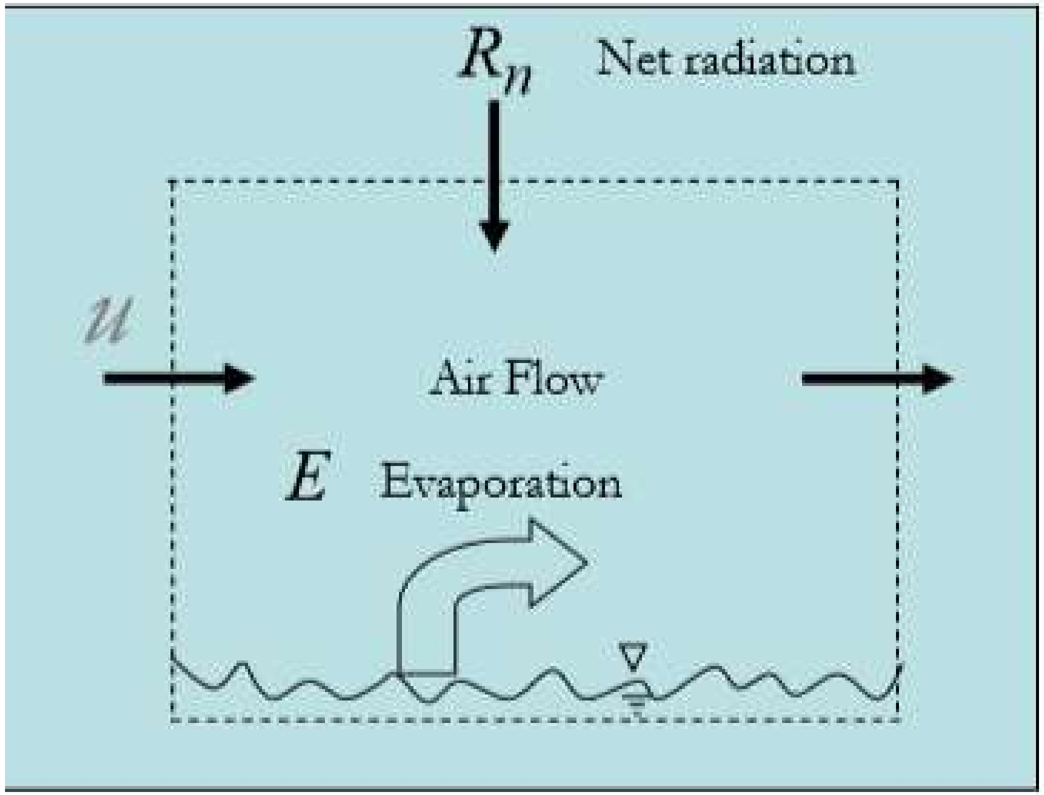
What drives evaporation?

- 1) Energy input to the water to supply heat (i.e., increase the kinetic energy so molecules can escape).
- 2) Diffusion of water vapor molecules from the water surface to the atmosphere.
- 3) Transport of water vapor molecules away from the water surface.



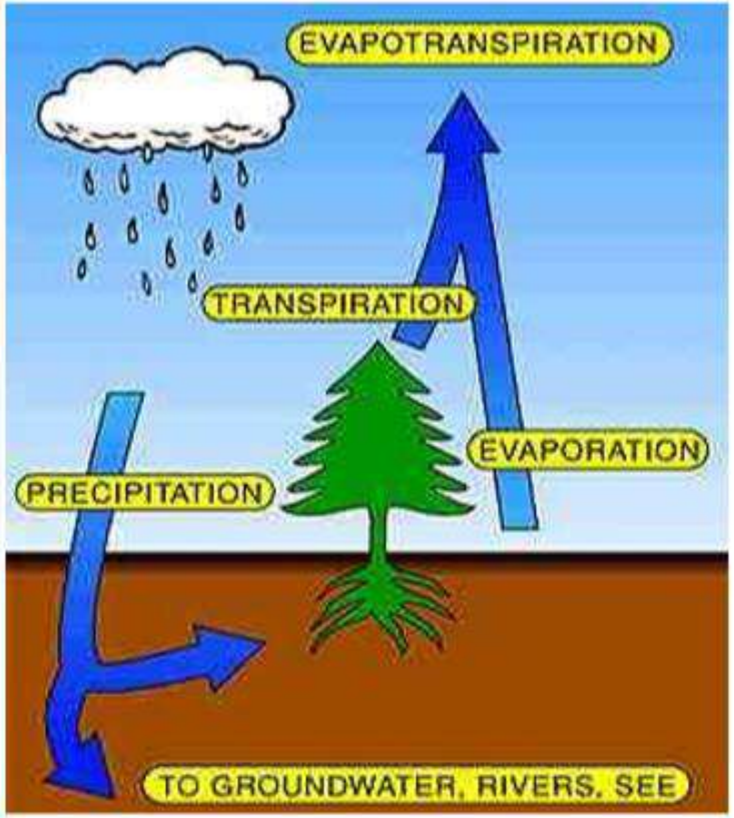
Factors Influencing Evaporation

- Energy supply for vaporization (latent heat) – Solar radiation
- Transport of vapor away from evaporative surface – Wind velocity over surface – Specific humidity gradient above surface
- Vegetated surfaces – Supply of moisture to the surface – Evapotranspiration (ET)



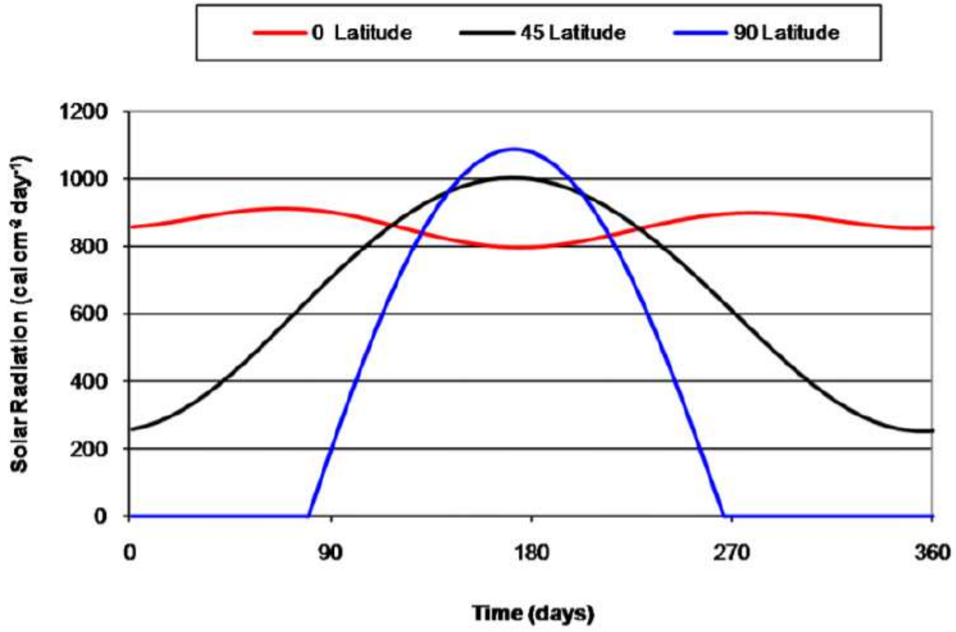
Evapotranspiration (ET)

- Over land surfaces, we cannot distinguish between water vapor that evaporated from the soil and water vapor that was transpired through plants.



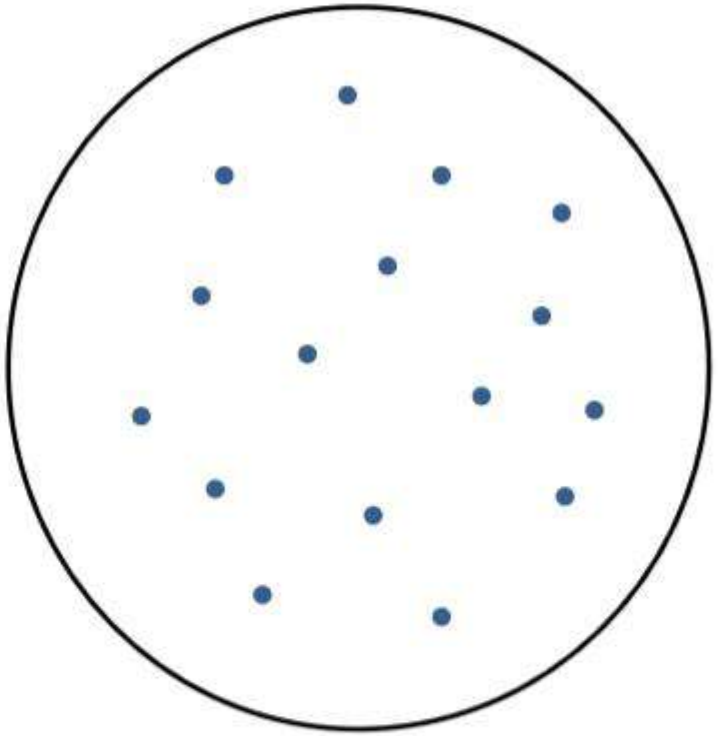
Heat Inputs

Solar radiation is the main source of heat to a lake. The amount of solar radiation depends on the time of year and latitude.

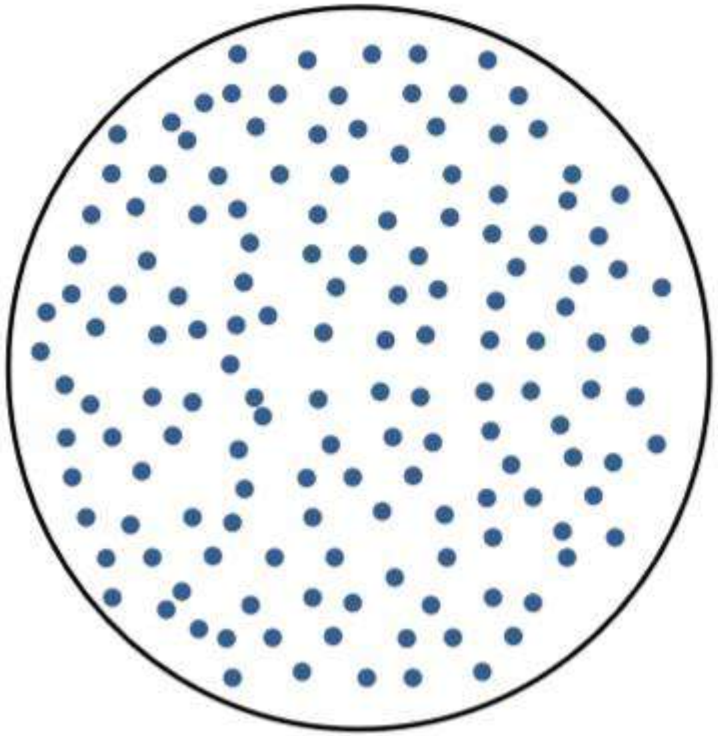


Actual vapor pressure is a measure of the amount of water vapor molecules present in a given parcel of air.

e_a = actual vapor pressure.

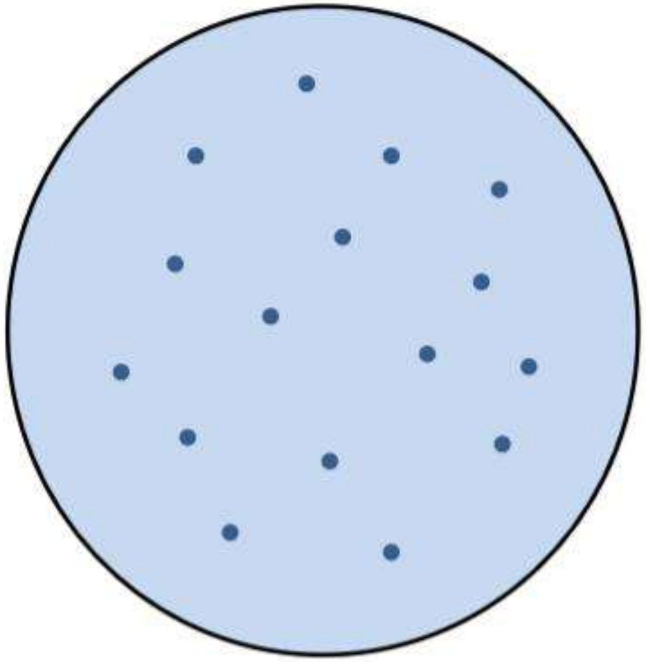


Low vapor pressure

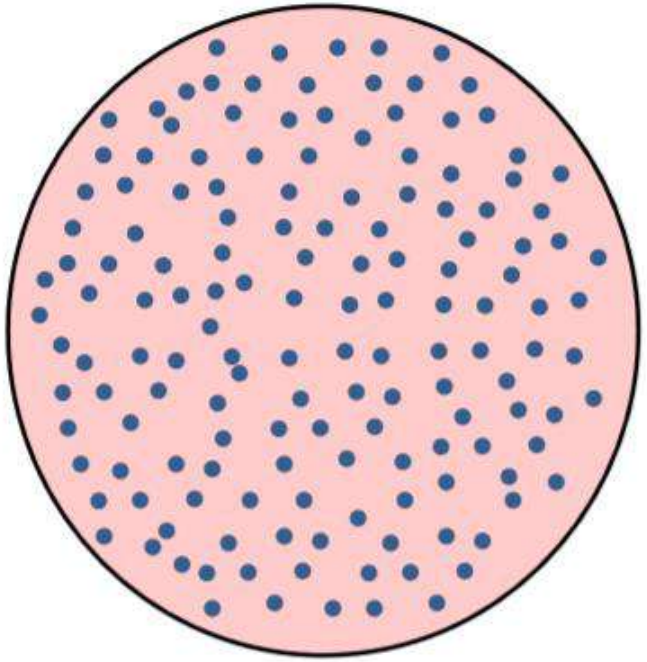


High vapor pressure

Saturation vapor pressure is the maximum amount of water vapor a parcel of air could hold at a specific temperature (which decreases with temperature).
e_{sat} = saturation vapor pressure

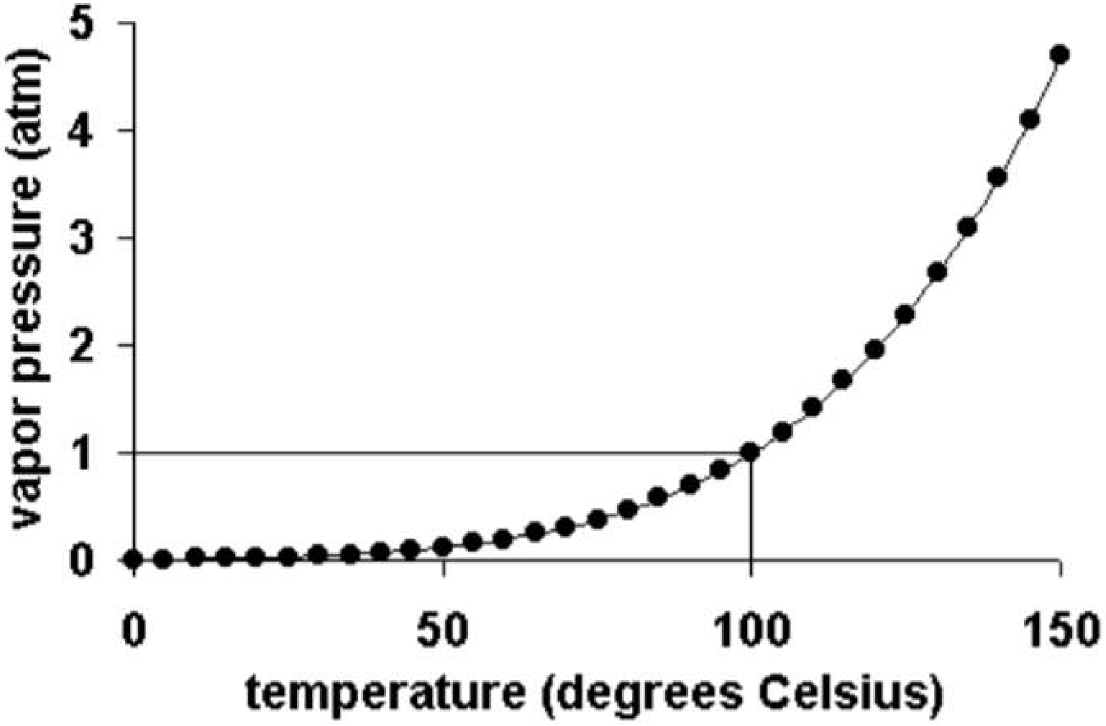


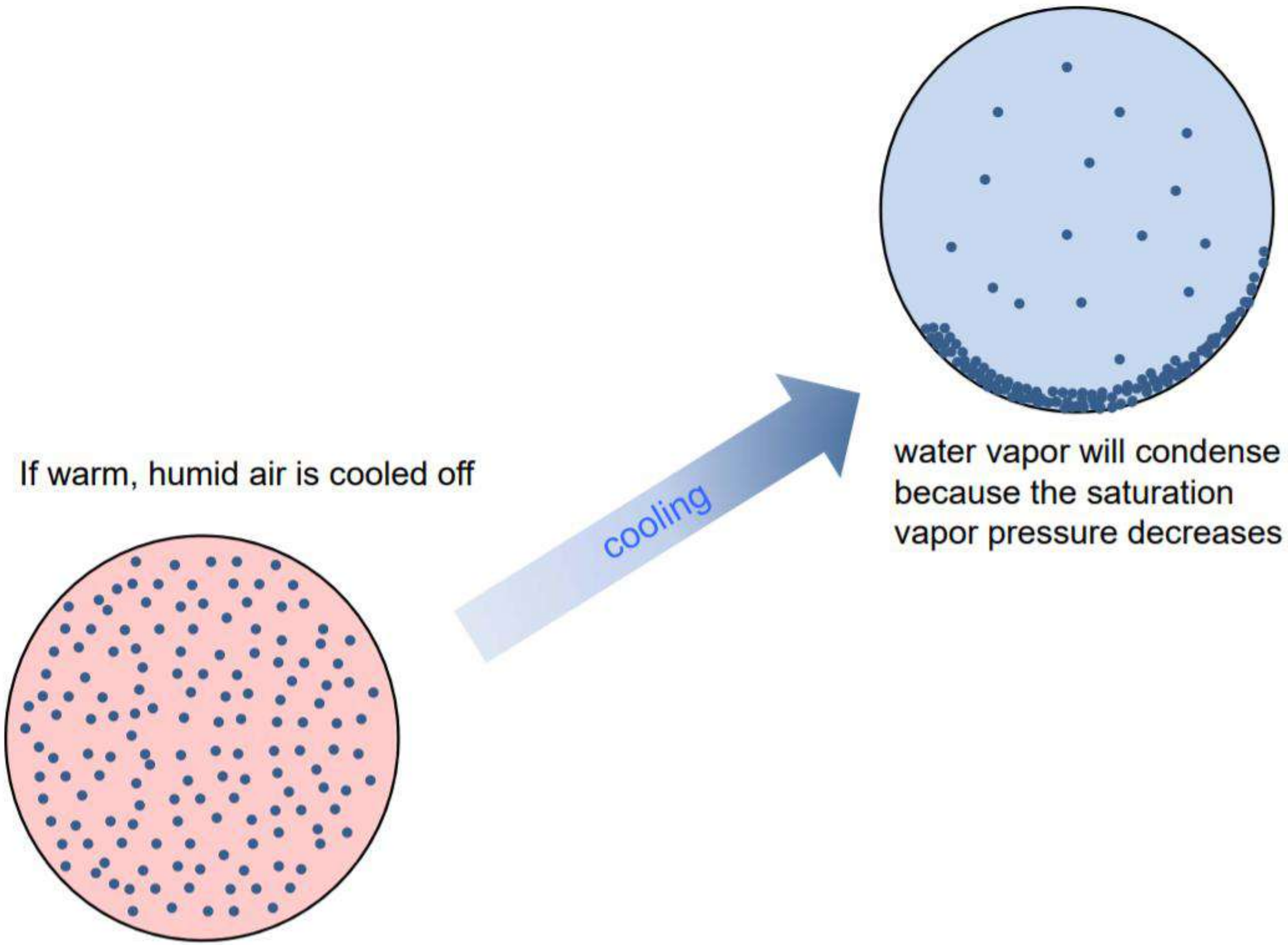
cool air has a low saturation vapor pressure



warm air has a higher saturation vapor pressure (more water molecules)

Saturation vapor pressure is the maximum amount of water vapor a parcel of air could hold at a specific temperature (which decreases with temperature).




If warm, humid air is cooled off
cooling
water vapor will condense
because the saturation
vapor pressure decreases

Relative humidity is the ratio of the amount of water vapor in a parcel of air (absolute vapor pressure) to how much water vapor the parcel could hold at a given temperature (saturation vapor pressure).

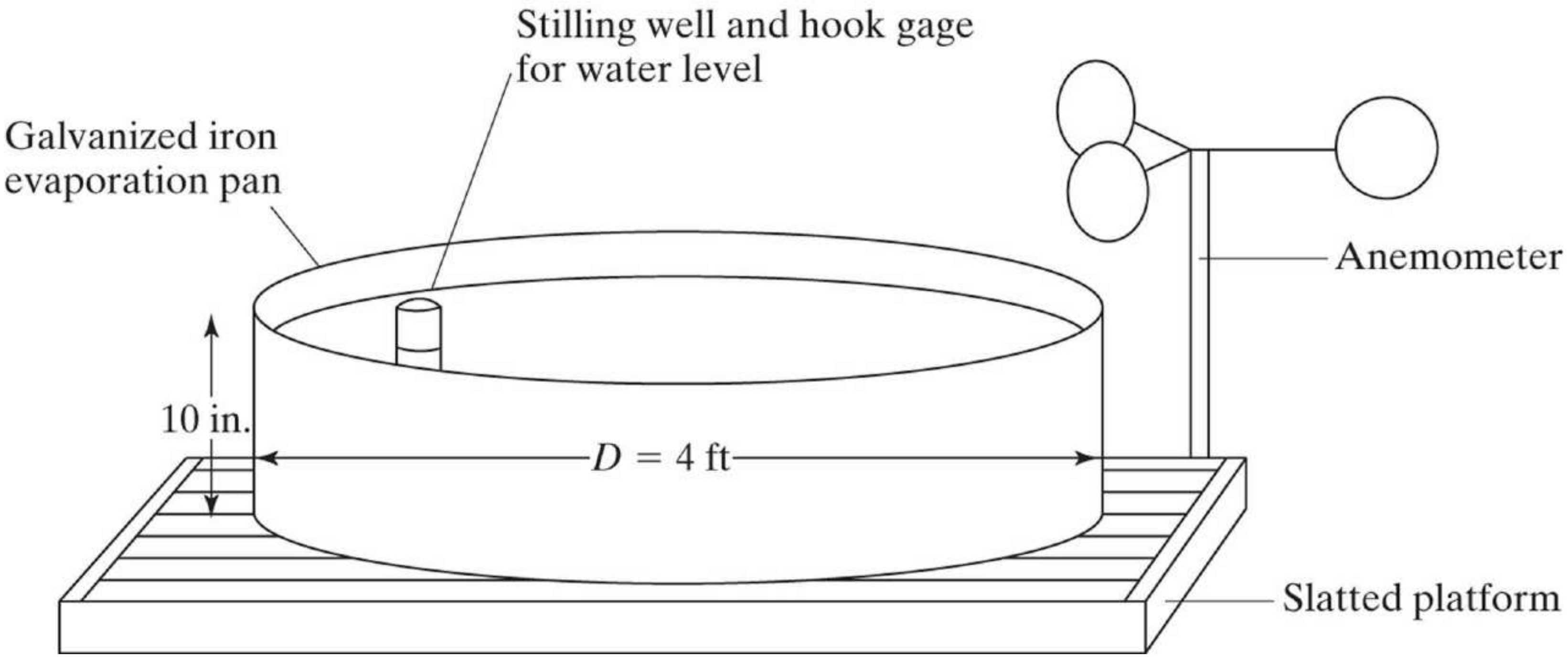
$$\text{relative humidity} = \frac{\text{actual vapor pressure}}{\text{saturation vapor pressure}} \times 100$$

Dew point temperature is the temperature at which a parcel of air reaches saturation.

Estimating Evaporation

Class A Evaporation Pan

Filled to 8 inches and observed daily. Plus a rain gage, thermometer for water temp, and a psychrometer for air temperature and wet bulb temperature (calculations reveal dewpoint T_d)



Keep animals from drinking

Pan Evaporation

Class A Pan, 4’x10”

- We estimate how much water evaporates from an area with a pan of water.
- Measure how much water leaves the pan in a day.
- Out in the open, so you need a rain gauge.

Pan evaporation is used to estimate the evaporation from lakes. Evaporation from a natural body of water is usually at a lower rate because the body of water does not have metal sides that get hot with the sun. Most hydrologists suggest multiplying the pan evaporation by 0.75 to correct for lakes.

Evapotranspiration E + T

- The pan actually measures evaporation, not evapo-transpiration.
- You have to multiply the pan evaporation by a different pan coefficient to estimate the E+T over plants

http://www.eijkelkamp.com/Portals/2/Eijkelkamp/Files/Manuals/M4-1689e%20Evaporation%20pan.pdf

Table 1–5. Pan Coefficients for Evapotranspiration Estimates

Type of Cover	Pan Coefficient		Reference
St. Augustine grass	0.77		Weaver and Stephens (1963)
Bell peppers	0.85–1.04		
Grass and clover	0.80	pasture	Brutsaert (1982, p. 253)
Oak–pine flatwoods (east Texas)	1.20	coastal plain	Englund (1977)
Well-watered grass turf			Shih et al. (1983)
Light wind, high relative humidity	0.85	golf course	
Strong wind, low relative humidity	0.35		
Everglades agricultural areas	0.65		
Irrigated grass pasture (central California)	0.76	pasture	Hargreaves and Samani (1982)

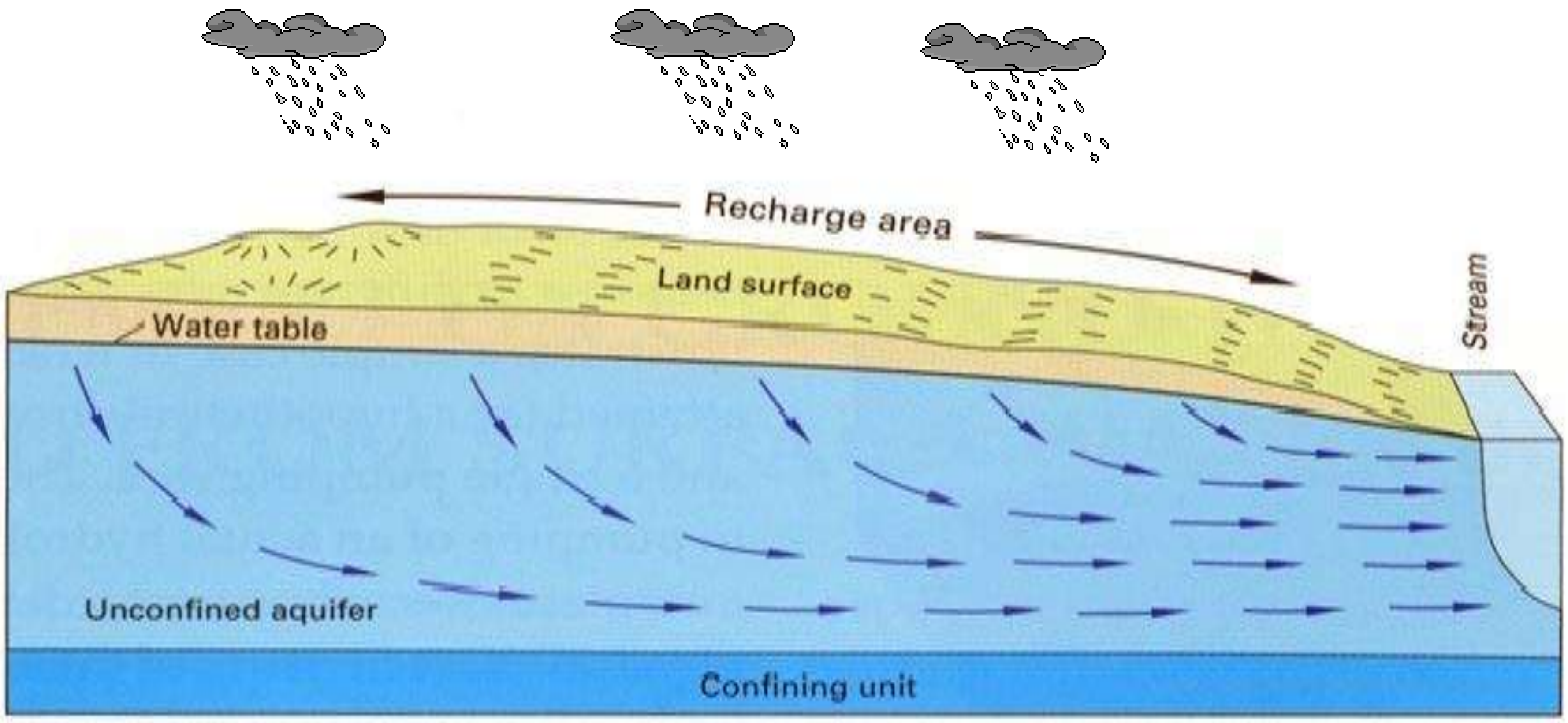
Notice some vegetation has high transpiration, pan coefficient > 1

Example

- Type of pan: Class A evaporation pan
- Water depth in pan on day 1 = 150 mm
- Rainfall (during 24 hours) = 1 mm
- Water depth in pan on day 2 = 144 mm (after 24 hours)
- Formula: $E = K_{pan} \times E_{pan}$
- $K_{pan} = 0.75$, E_{pan} = start + rain - finish
- Calculation: $E_{pan} = (150 + 1 – 144) = 7$ mm/day
- $E = 0.75 \times 7 = 5.2$ mm/day

Infiltration

Rainwater that soaks into the ground and may reach the groundwater table.



Field Tests

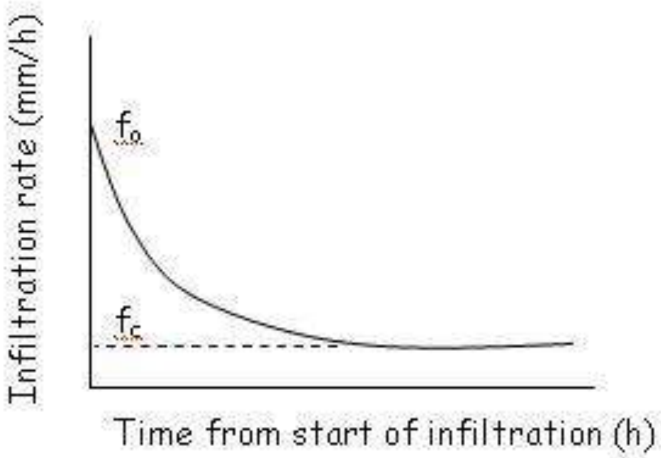
Single Ring

Double Ring

24 inch double ring infiltrometer with Mariotte Tubes http://www.hilbec.com/STORMWATER.htm

Horton's Equation

- Horton: The infiltration capacity decreases exponentially with time and ultimately reaches a constant rate
- Infiltration capacity $$f_t = f_c + (f_0 - f_c)e^{-kt}$$
- *Where* f_t is the infiltration rate at time t;
- f_0 is the initial infiltration rate or maximum infiltration rate;
- f_c is the constant or equilibrium infiltration rate after the soil has been saturated or minimum infiltration rate; NOTE e is a number, ~ 2.718
- k is the decay constant specific to the soil.
- the f's have units in/hr and k is a time constant hr $^{-1}$

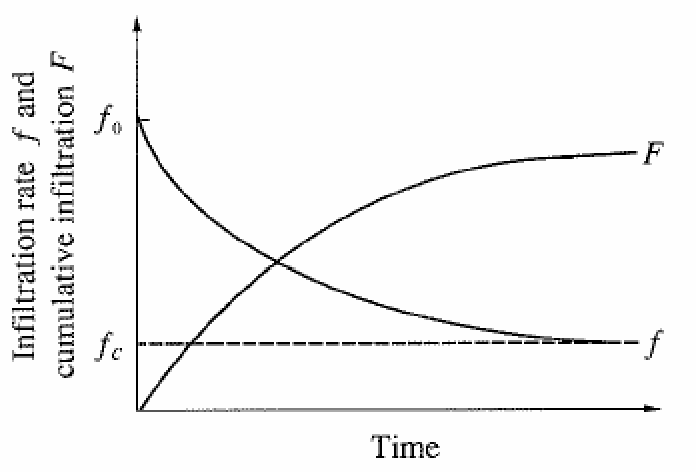


Infiltration

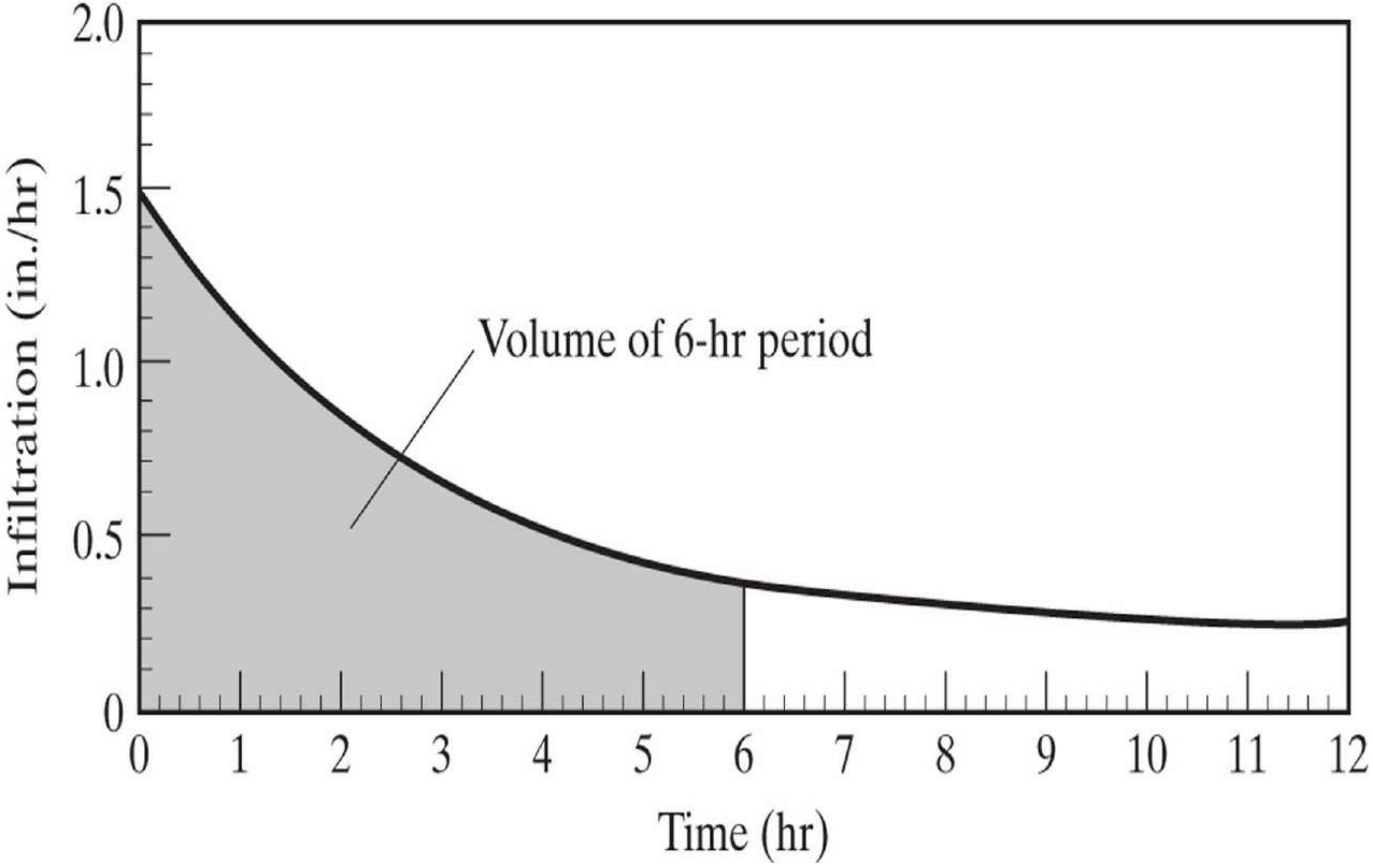
- Infiltration rate $f(t)$
  - Rate at which water enters the soil at the surface (in/hr or cm/hr)
- Cumulative infiltration
  - Accumulated depth of water infiltrating during given time period

$$F(t) = \int_0^t f(\tau)d\tau$$

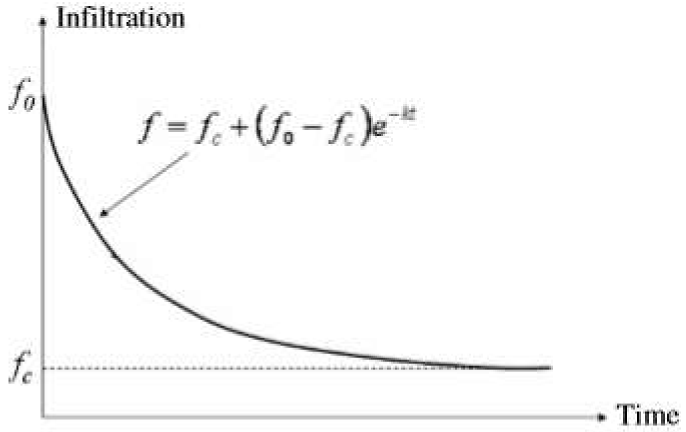
$$f(t) = \frac{dF(t)}{dt}$$



Infiltration rate and cumulative infiltration.



2.0
1.5
1.0
0.5
0
Infiltration (in./hr)
Volume of 6-hr period
0 1 2 3 4 5 6 7 8 9 10 11 12
Time (hr)



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

Example

For a soil, the asymptotic or final equilibrium infiltration capacity is f_c = 1.25 cm/h; and the initial infiltration capacity is f_o = 8 cm/h. The rate of decay of infiltration capacity parameter is k = 3 h^{-1}

Compute the infiltration capacity rate for 2 hrs (10 min. interval)

Time (*min*)	Infiltration Capacity, f_p (*cm/h*)
0	8
10	5.344082
20	3.733186
30	2.756129
40	2.163513
50	1.804074
60	1.586063
70	1.453832
80	1.373631
90	1.324986
100	1.295481
110	1.277586
120	1.266732

Depression Storage

Precipitation that reaches the ground may infiltrate, flow over the surface or become trapped in numerous small depressions from which the only escape is evaporation or infiltration

The nature of depression as well as their size is largely a function of the original land form and local land use practices.

Hydrology

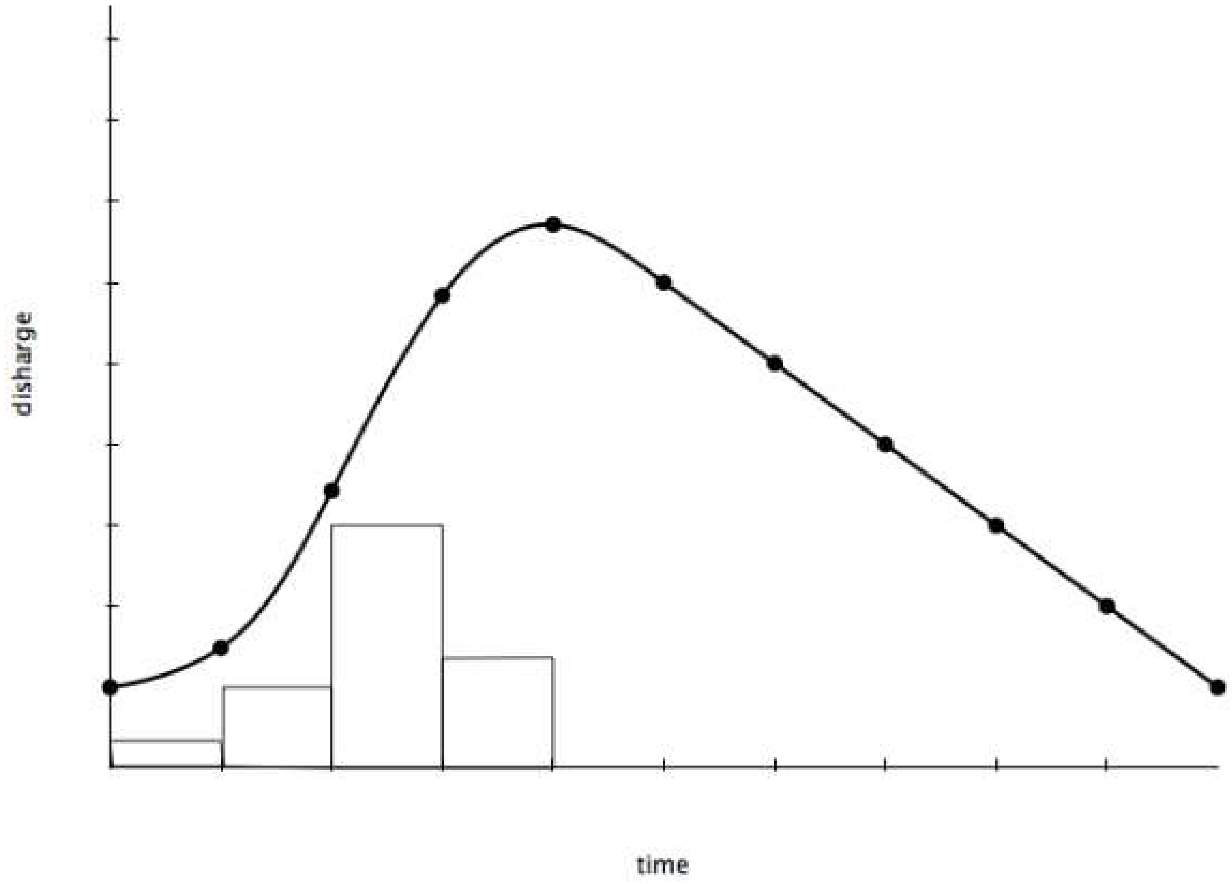
CE 454

Hydrograph

Hydrograph

- A hydrograph is a graph showing the rate of flow (discharge) versus time past a specific point in a river, channel, or conduit carrying flow. The rate of flow is typically expressed in cubic meters or cubic feet per second (cms or cfs).

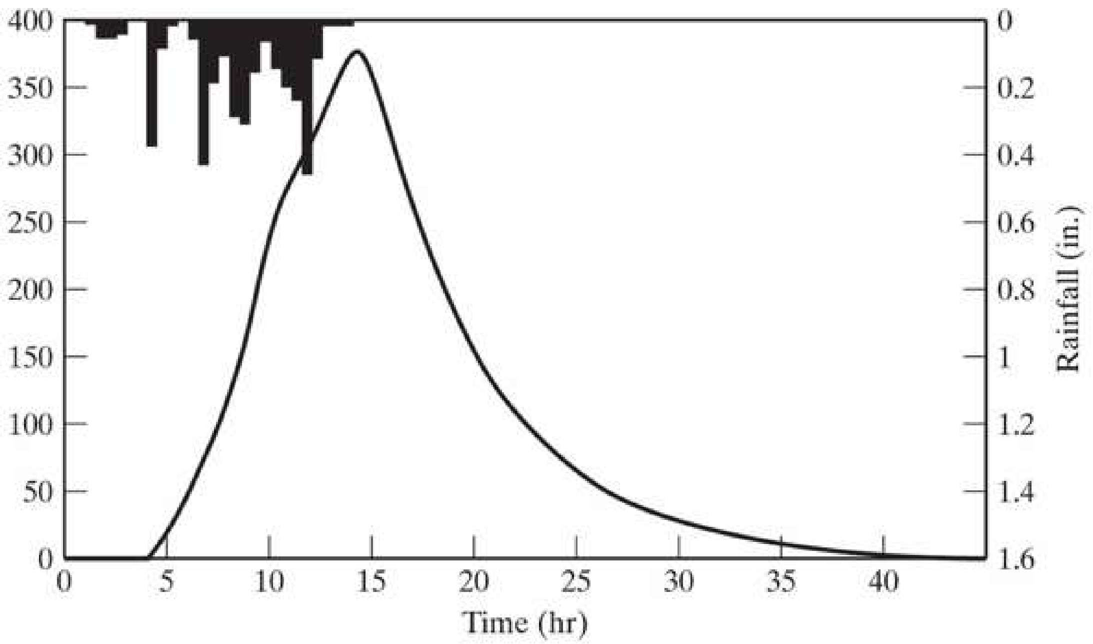
- Hydrograph has three regions: rising limb, crest segment and falling limb.

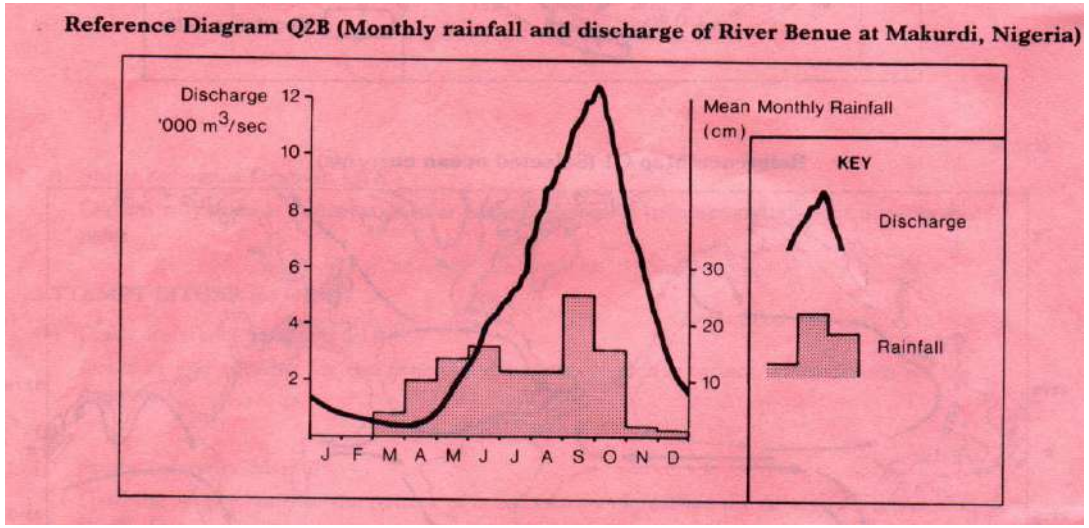


Hydrograph

- For a watershed It is a plot of discharge vs. time at any point of interest in a watershed, **usually its outlet**. Hydrographs are the ultimate measure of a watershed’s **response to precipitation events**

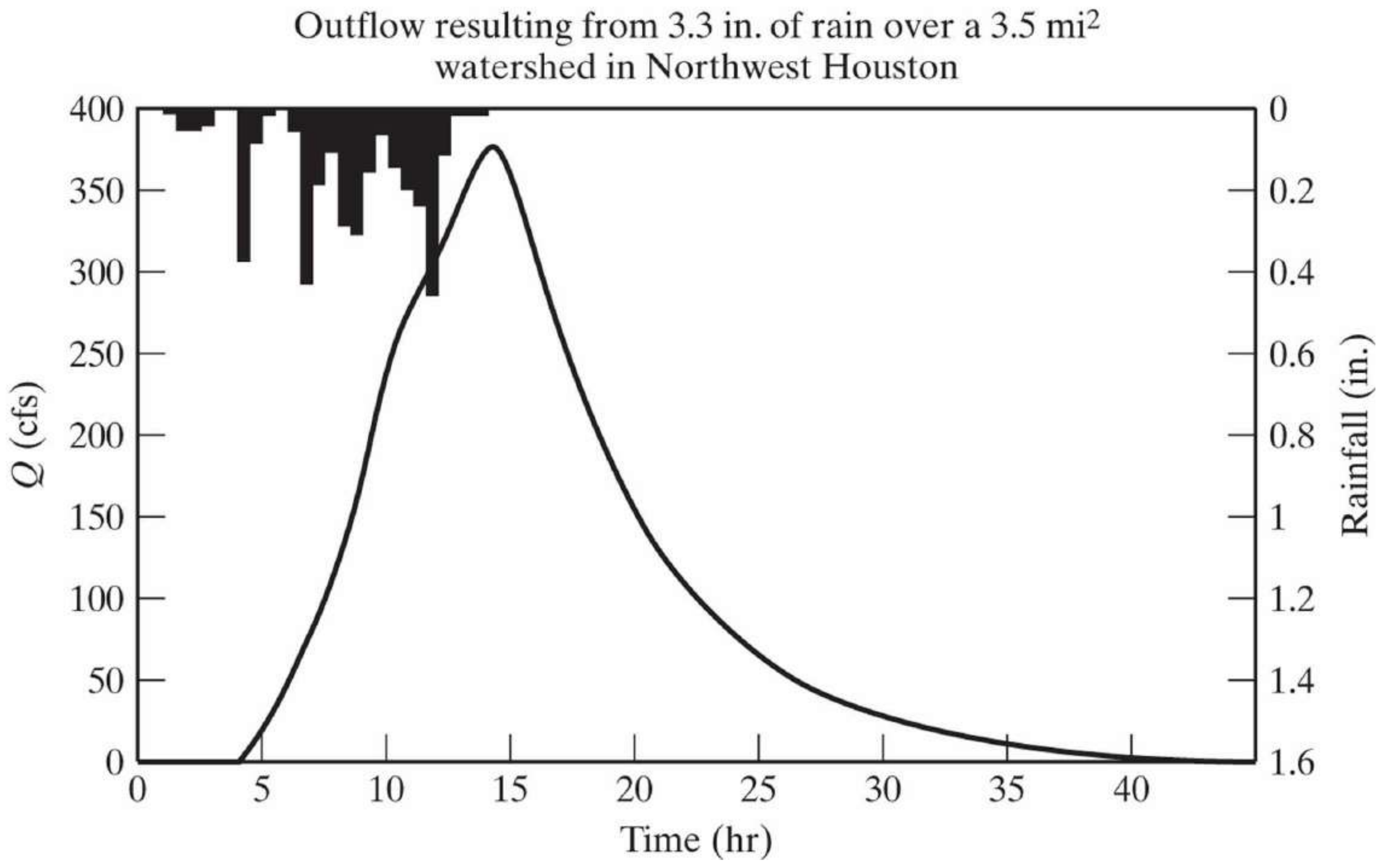
- Nature of hydrograph depend on rainfall and watershed characters.





Plot of discharge against time.

Hydrograph



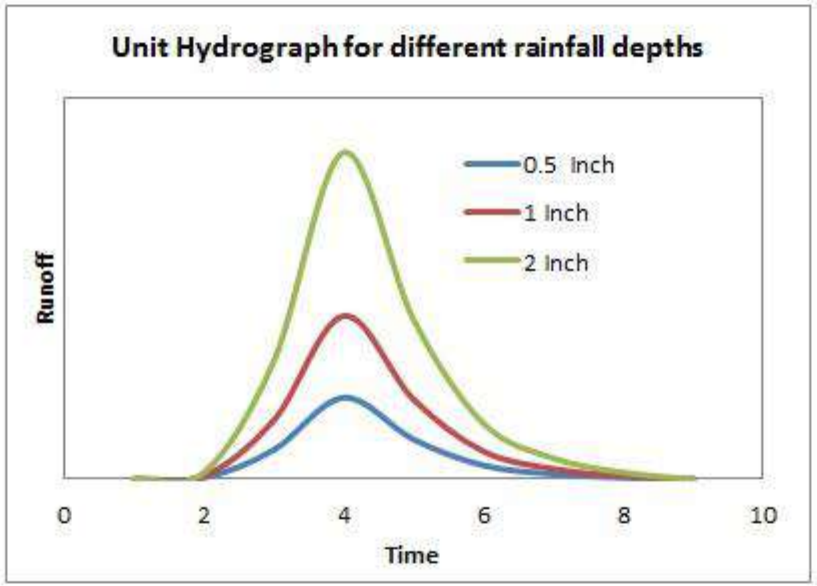
- When rainfall starts, some gets caught in retention storage depressions where it will be evaporated again, but some enters the ground (infiltration, including some from detention storage) where it will contribute to the channel flow at some later time.

- The remainder, however, begins to make its way down to the channel, causing that sharply defined rising limb.

- At the time of the flood crest, maximum flow reaches our outlet gauge. Flow then tails off gradually with time, and eventually, all direct runoff stops. At this point groundwater takes over again—because groundwater flow is much slower than surface water, the rate of decrease abruptly slows. This marks an inflection point in the flow.

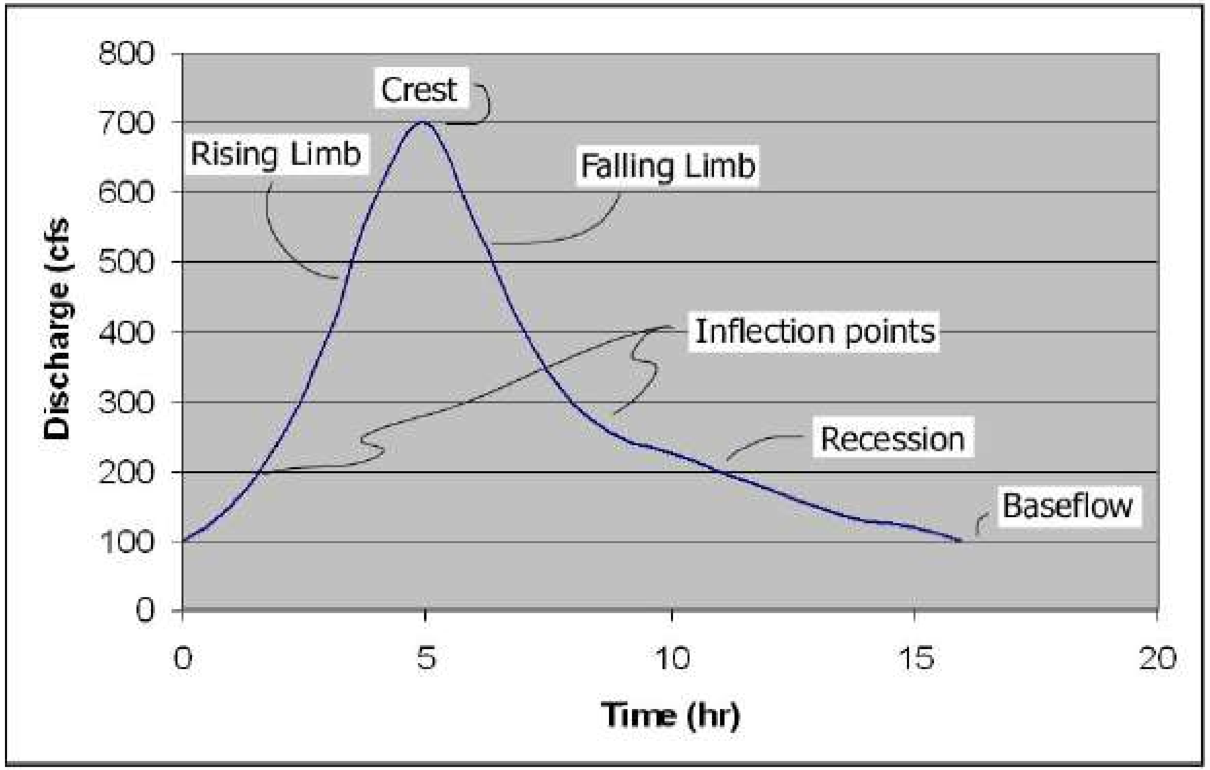
Why to construct/analyze hydrograph?

- To find out the discharge pattern of a particular watershed.
- Predicting flood events.
- Hydrograph analysis is the most widely used method of analyzing surface runoff.



Hydrograph Vocabulary

- Rising limb – Ascending portion representing rising discharge due to gradual increase in flow in stream Slope depend on storm and basin characteristics.
- Crest Segment – Inflection point on rising limb to falling limb – Indicate the peak flow – Controlled by storm and watershed characteristics – Multiple peaks – due to occurrence of two or more storms of different intensities in a closer interval.
- Falling limb (recession limb) – From point of inflection at the end of crest segment to base flow.



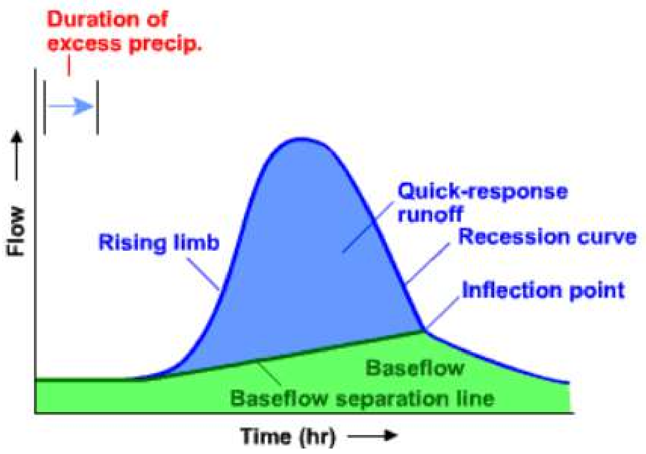
Hydrograph Vocabulary

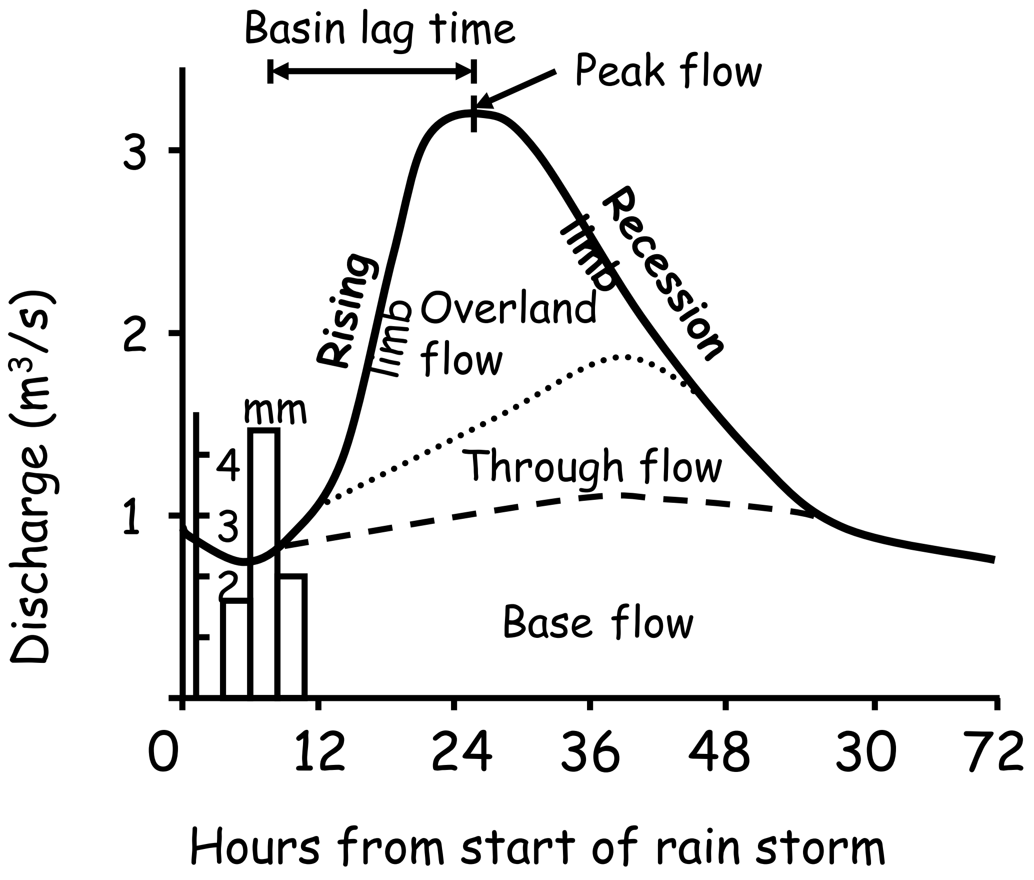
Run off: the sum of all the rainwater that flows over the surface of the river basin (stream flow and overland flow)

Through flow: the downslope movement of water through soil towards streams and rivers.

Baseflow: groundwater movement, which often lags behind precipitation by weeks, months or even years.

Stormflow: discharge that is not baseflow.





Parts of A Storm Hydrograph

Overland flow

Volume of water reaching the river from surface run off

Inter flow

Volume of water reaching the river through the soil and underlying rock layers

GW

The Base flow

Parts of A Storm Hydrograph

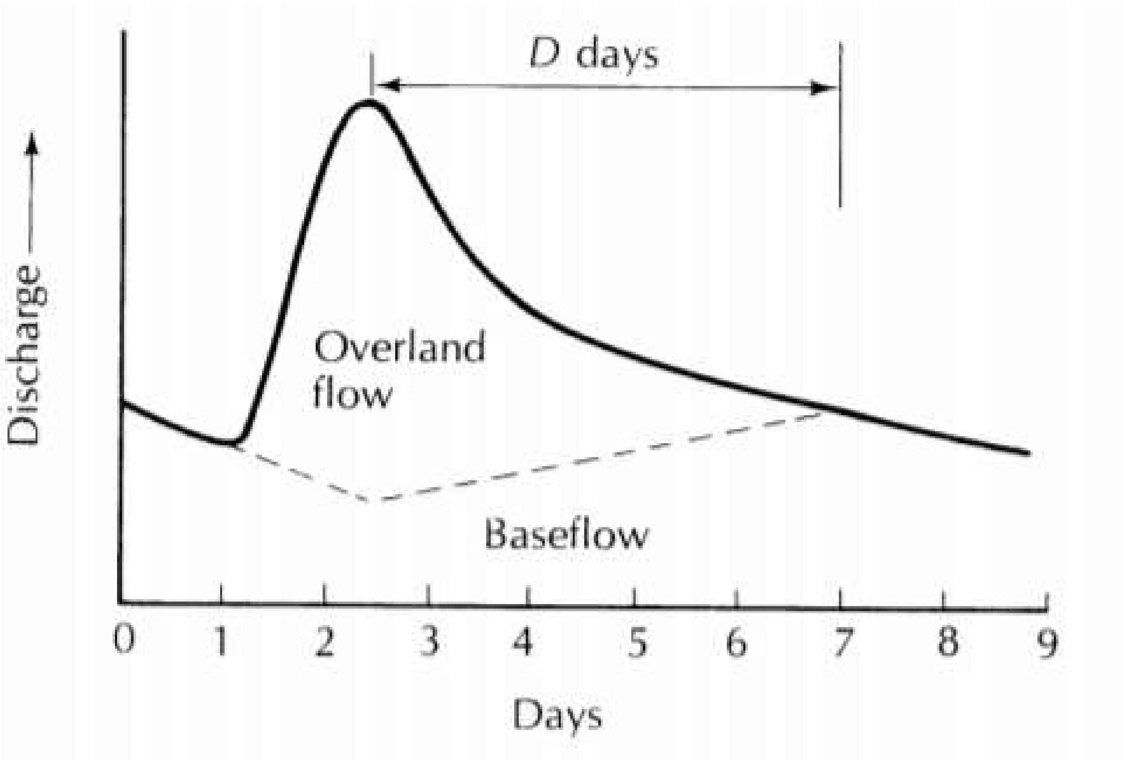


Fig.1 Storm and baseflow contribution to storm hydrograph

- Discharge not associated with the storm (i.e. from groundwater) is termed **baseflow.**
- Baseflow separation is performed to determine the portion of the hydrograph attributable to baseflow
- Surface runoff hydrograph derived by separating base flow from hydrograph
- **Straight line method** is used for baseflow separation

– Join the starting and end points of surface runoff by straight line (**Fig.1)**

– Area under the straight line is base flow **(Fig.1)**

Factors affecting shape of hydrograph

- Area
- Shape
- Slope
- Rock Type
- Soil
- Land Use
- Drainage Density
- Precipitation / Temp
- Tidal Conditions

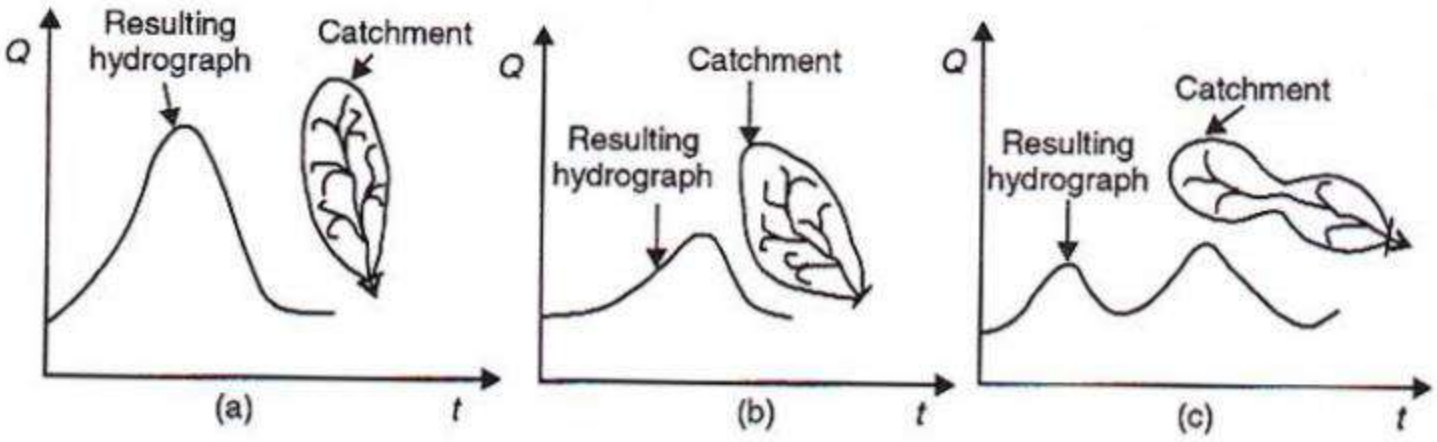
Area

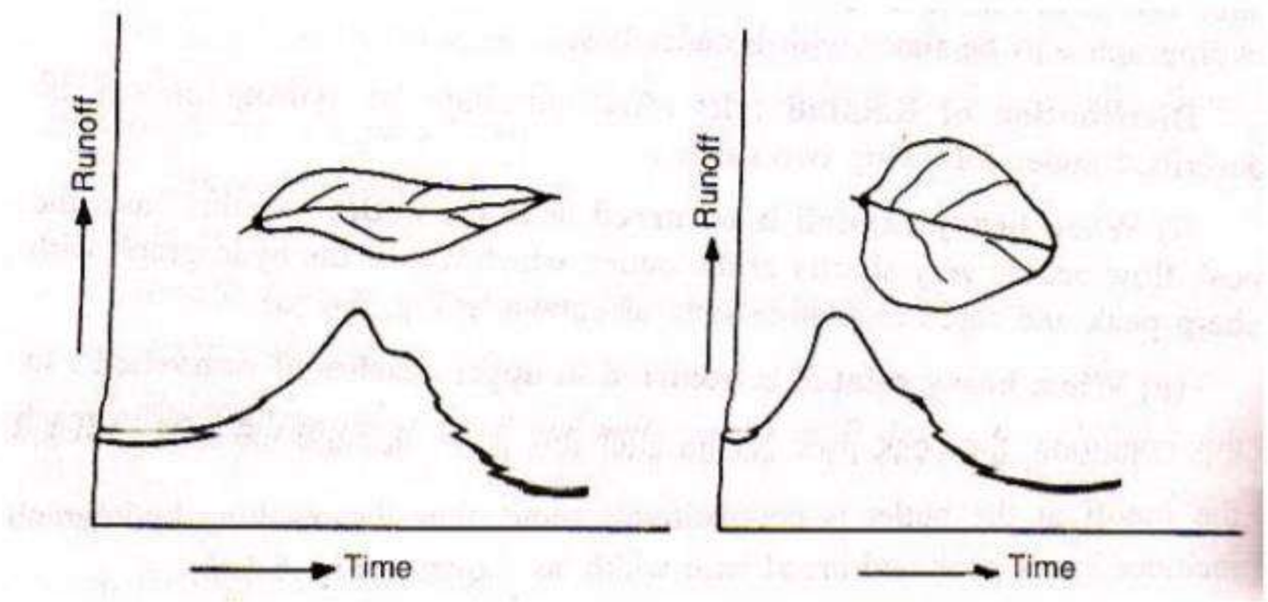
- Large basins receive more precipitation than small therefore have larger runoff.

- Larger size means longer lag time as water has a longer distance to travel to reach the trunk river.

Shape

- Elongated basin will produce a lower peak flow and longer lag time than a circular one of the same size





Effect on Hydrograph by Shape of catchment

Slope

- Channel flow can be faster down a steep slope therefore steeper rising limb and shorter lag time

Rock Type

- Permeable rocks mean rapid infiltration and little overland flow therefore shallow rising limb

Soil

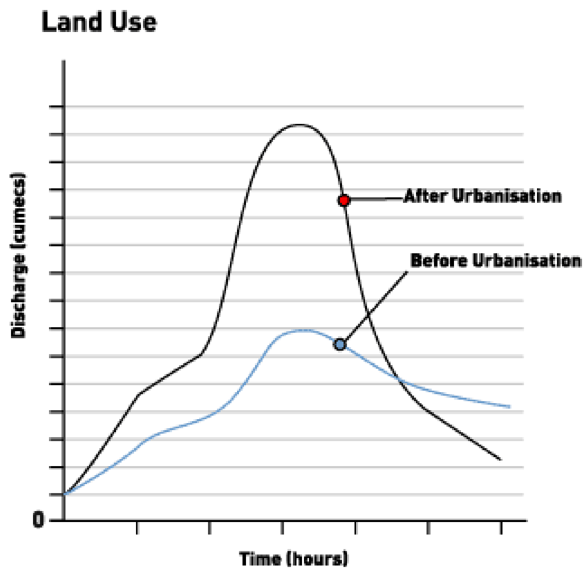
- Infiltration is generally greater on thick soil, although less porous soils eg. clay act as impermeable layers

- The more infiltration occurs the longer the lag time and shallower the rising limb

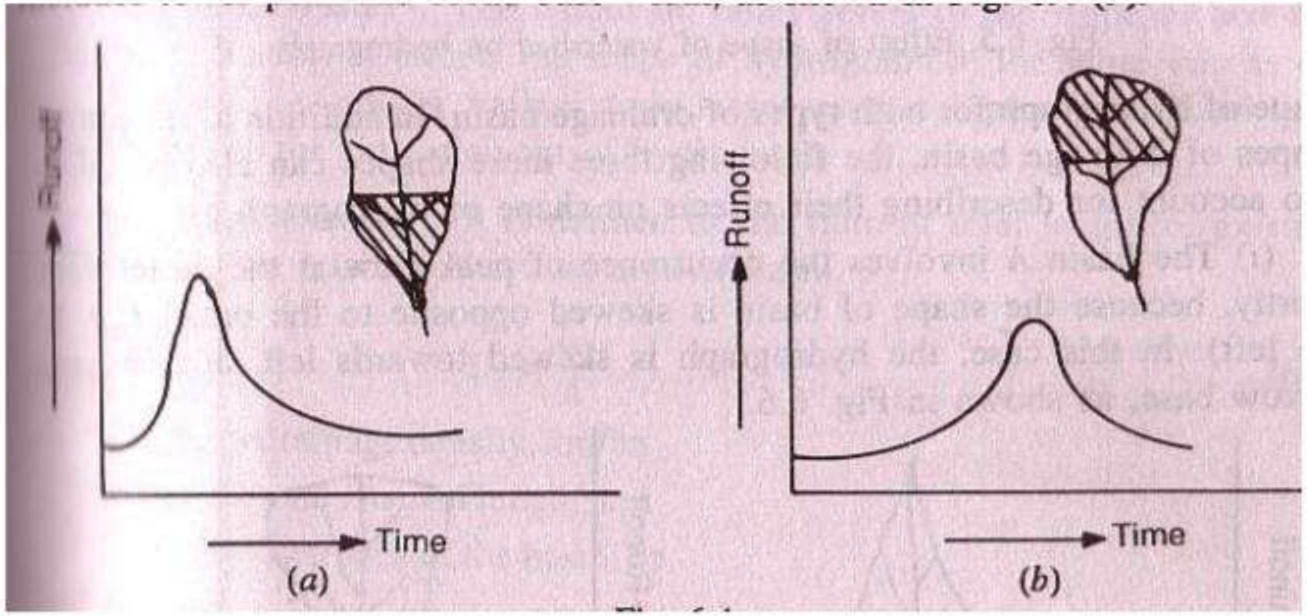
Land Use

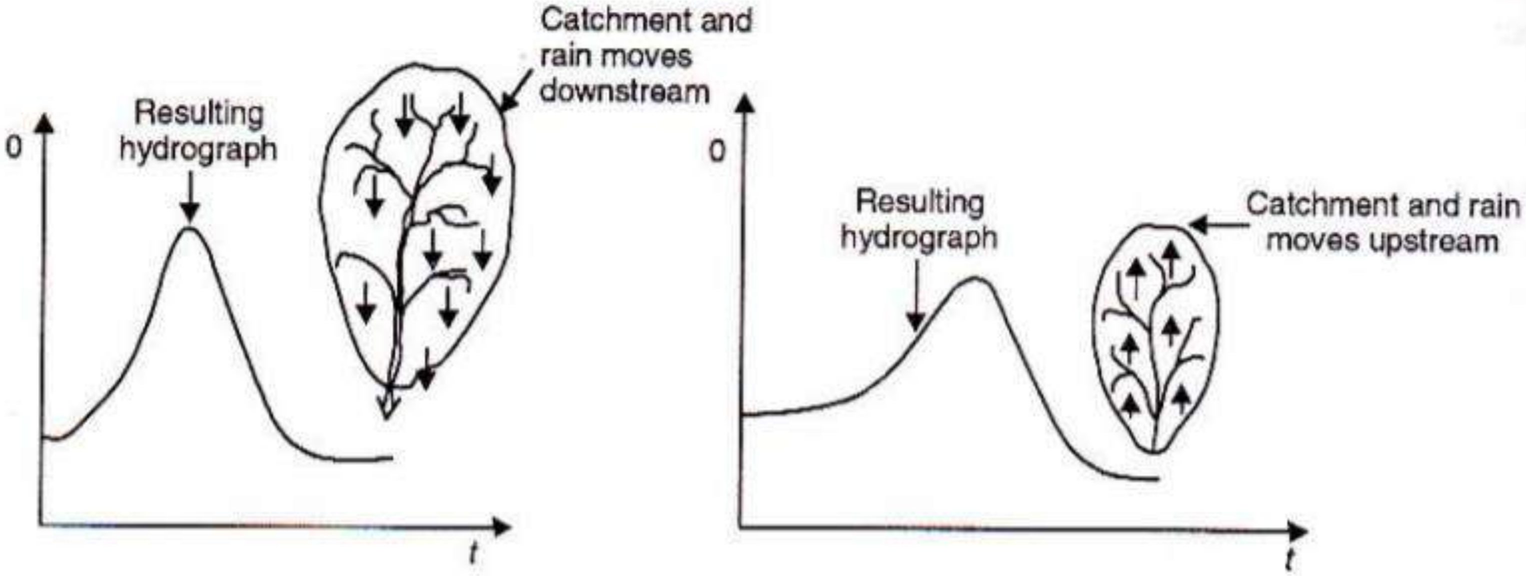
- Urbanization - concrete and tarmac form impermeable surfaces, creating a steep rising limb and shortening the time lag.

- Afforestation - intercepts the precipitation, creating a shallow rising limb and lengthening the time lag.



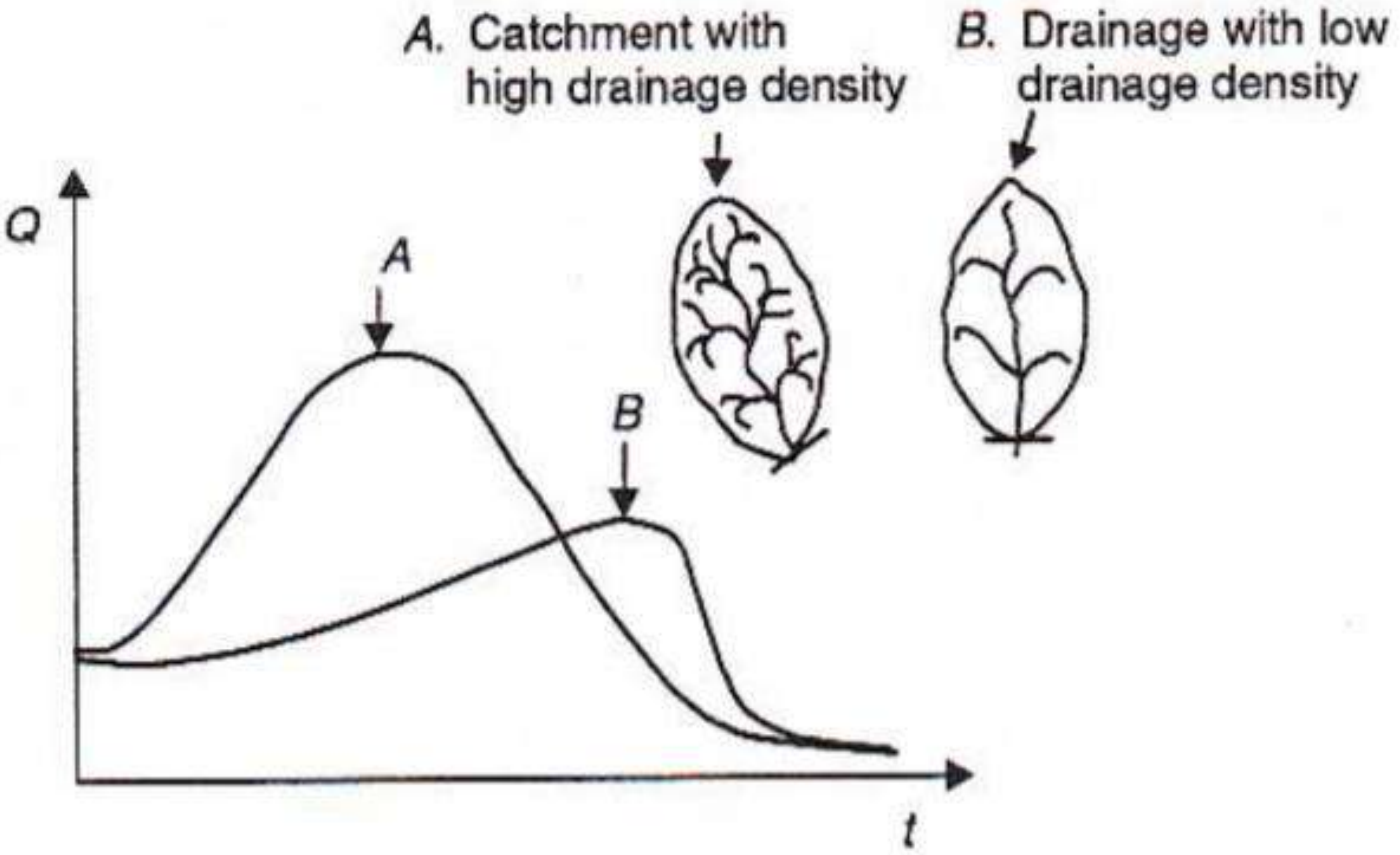
Distribution of rainfall and hydrograph





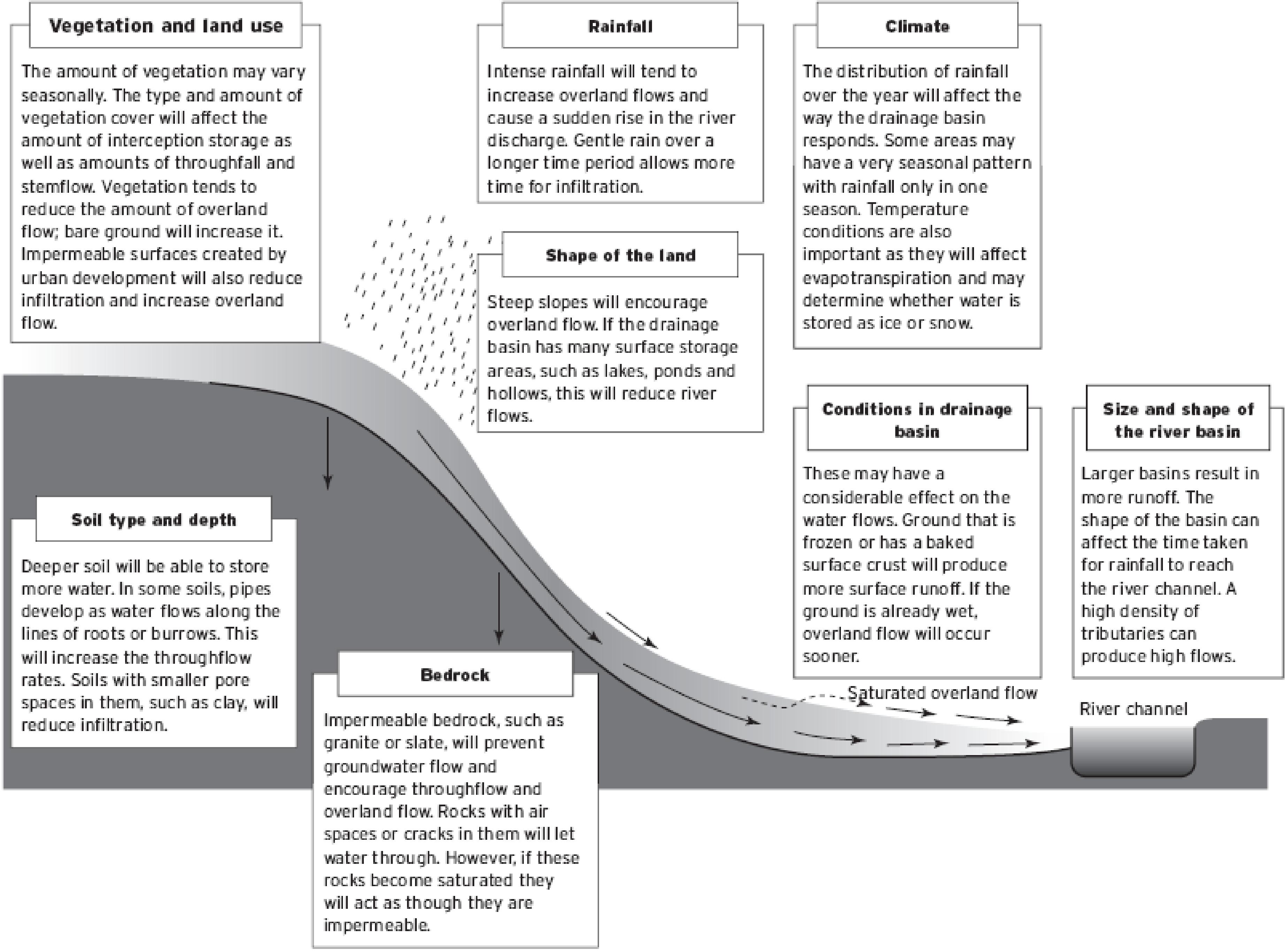
Hydrograph affected by movement of rainfall

Drainage density

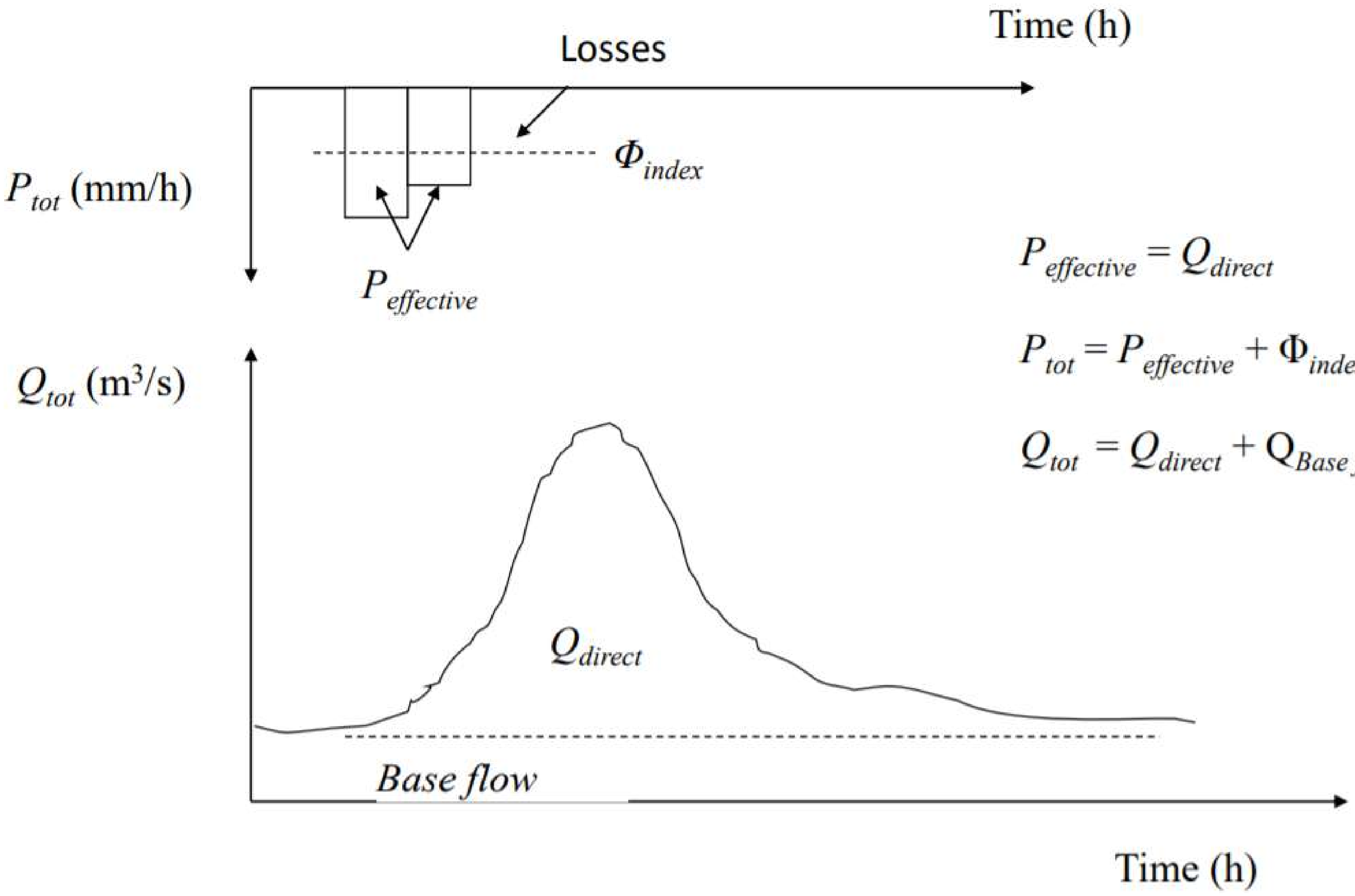


- A higher density will allow rapid overland flow

Factors influencing hydrographs



Hydrograph theory



$$P_{effective} = Q_{direct}$$

$$P_{tot} = P_{effective} + \Phi_{index}$$

$$Q_{tot} = Q_{direct} + Q_{Base\ flow}$$

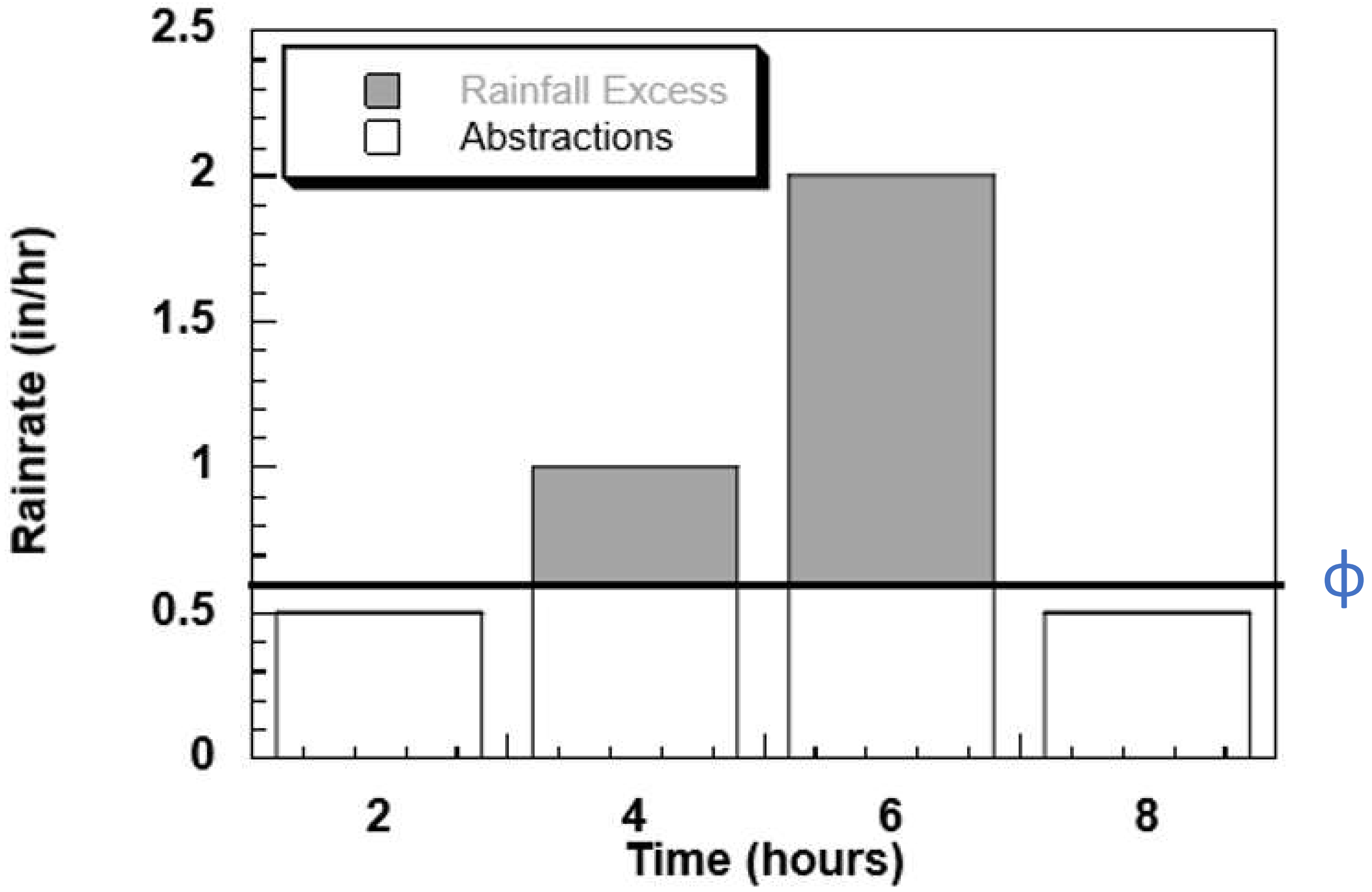
Excess rainfall

- Rainfall that is neither retained on the land surface nor infiltrated into the soil → The volume of rainfall available for direct surface runoff.
- Direct runoff = observed streamflow - baseflow
- Excess rainfall = observed rainfall - abstractions
- Abstractions/losses – difference between total rainfall hyetograph and excess rainfall hyetograph

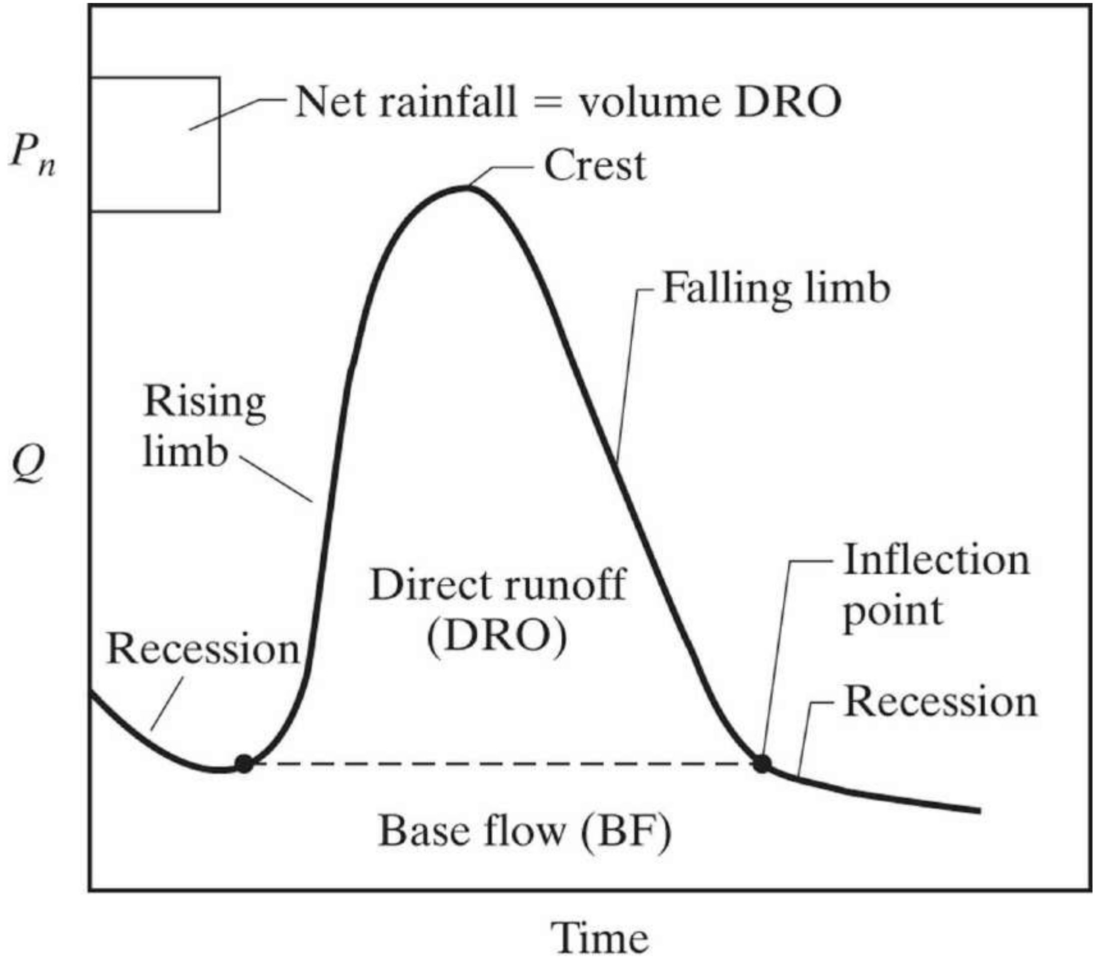
ϕ index

Constant rate of loss yielding excess rainfall hyetograph with depth equal to depth of direct runoff.

Phi (ϕ) index Method



Convert the gross hyetograph to net rainfall by subtracting infiltration, ϕ, and totaling for the storm.



Notice the hyetograph and hydrograph areas are in different scales

$$r_d = \sum_{m=1}^{M} (R_m - \phi \Delta t)$$

r_d = depth of direct runoff

R_m = observed rainfall

ϕ = Phi index

M = # intervals of rainfall contributing to driect runoff

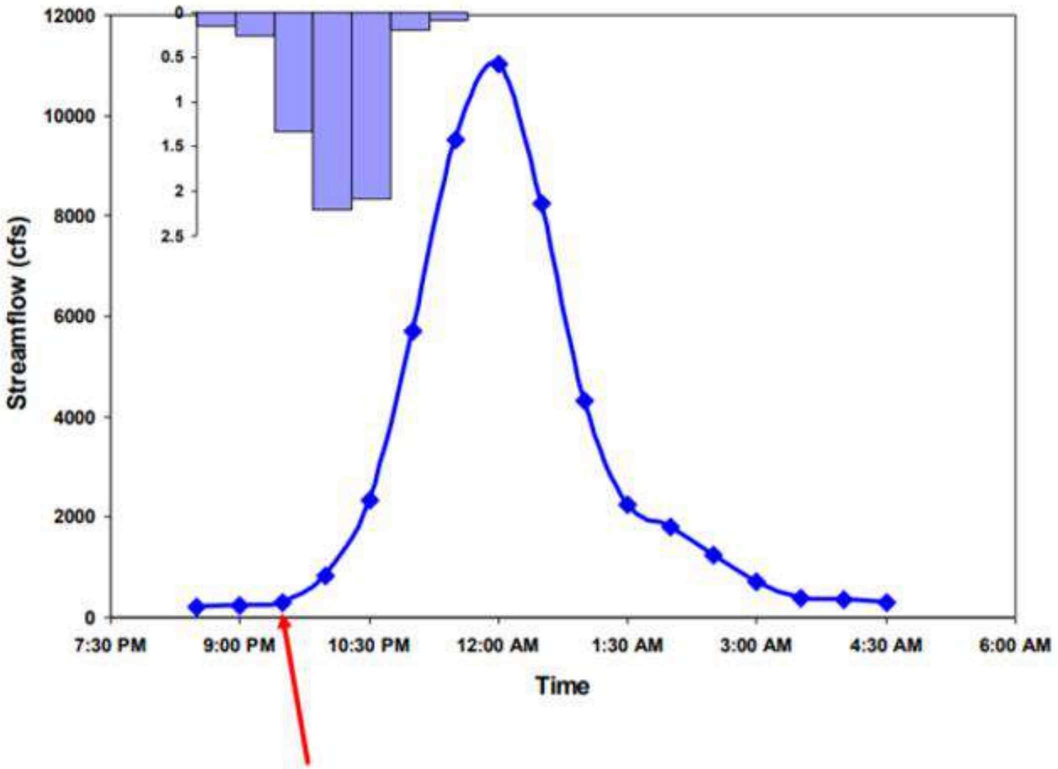
Δt = time interval

Example - Loss estimation : Phi index Method (ϕ index)

Compute volume and depth of direct runoff, ϕ index.

Time	Observed Rain (in)	Observed Flow (cfs)
8:30	0.15	203
9:00	0.26	246
9:30	1.33	283
10:00	2.2	828
10:30	2.08	2323
11:00	0.2	5697
11:30	0.09	9531
12:00		11025
12:30		8234
1:00		4321
1:30		2246
2:00		1802
2:30		1230
3:00		713
3:30		394
4:00		354
4:30		303

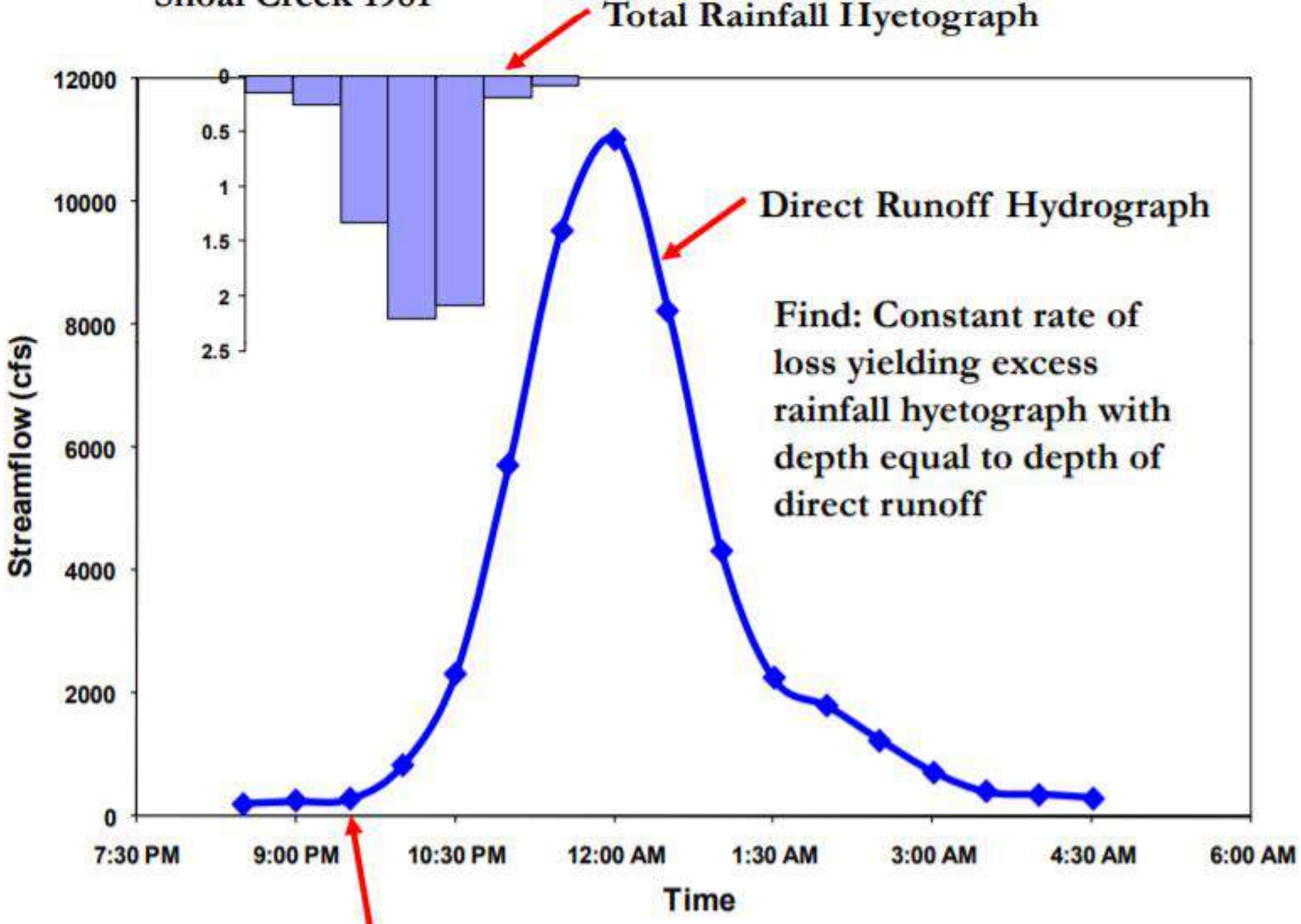
Have precipitation and streamflow data, need to estimate losses



No direct runoff until after 9:30
And little precip after 11:00

Basin area A = 7.03 mi2

Shoal Creek 1981

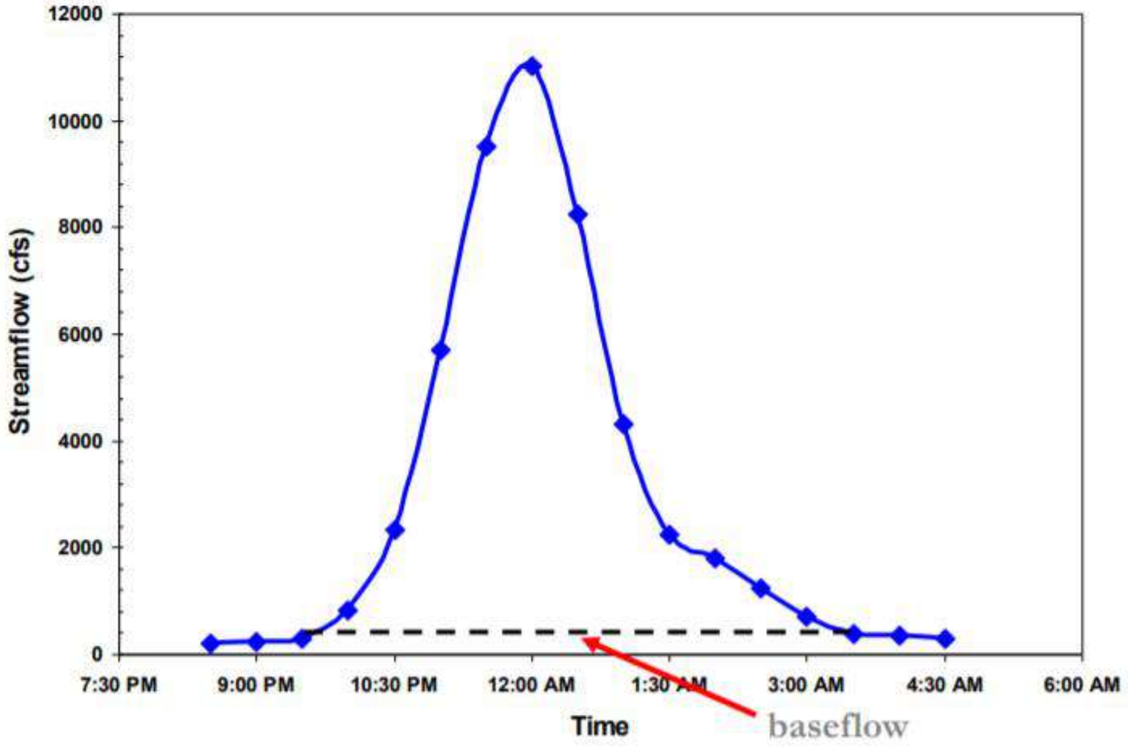


Find: Constant rate of loss yielding excess rainfall hyetograph with depth equal to depth of direct runoff

No direct runoff until after 9:30
And little precip after 11:00

Basin area A = 7.03 mi2

- Estimate baseflow (straight line method)
  - Constant = 400 cfs



- Calculate Direct Runoff Hydrograph
  - Subtract 400 cfs

Time	Observed Rain	Observed Flow	Direct Runoff
	in	cfs	cfs
8:30	0.15	203	
9:00	0.26	246	
9:30	1.33	283	
10:00	2.2	828	428
10:30	2.08	2323	1923
11:00	0.2	5697	5297
11:30	0.09	9531	9131
12:00		11025	10625
12:30		8234	7834
1:00		4321	3921
1:30		2246	1846
2:00		1802	1402
2:30		1230	830
3:00		713	313
3:30		394	
4:00		354	43550
4:30		303	

Total = 43,550 cfs

- Compute volume of direct runoff

$$V_d = \sum_{n=1}^{11} Q_n \Delta t = \Delta t \sum_{n=1}^{11} Q_n$$

$$= 3600\,\text{s/hr} * 0.5\,\text{hr} * 43{,}550\,\text{ft}^3/\text{s}$$

$$= 7.839 * 10^7\ \text{ft}^3$$

- Compute depth of direct runoff

$$r_d = \frac{V_d}{A}$$

$$= \frac{7.839 * 10^7\ \text{ft}^3}{7.03\,\text{mi} * 5280^2\ \text{ft}^2}$$

$$= 0.4\,\text{ft}$$

$$= 4.80\,\text{in}$$

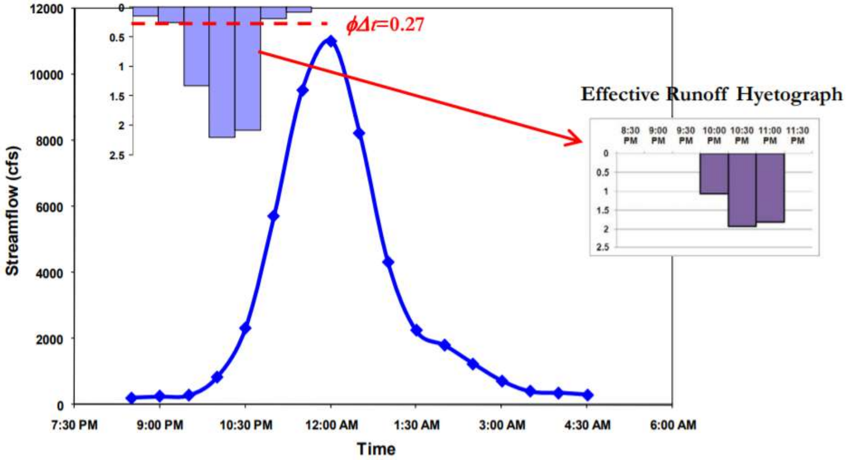
- Neglect all precipitation intervals that occur before the onset of direct runoff (before 9:30)
- Select Rm as the precipitation values in the 1.5 hour period from 10:00 – 11:30

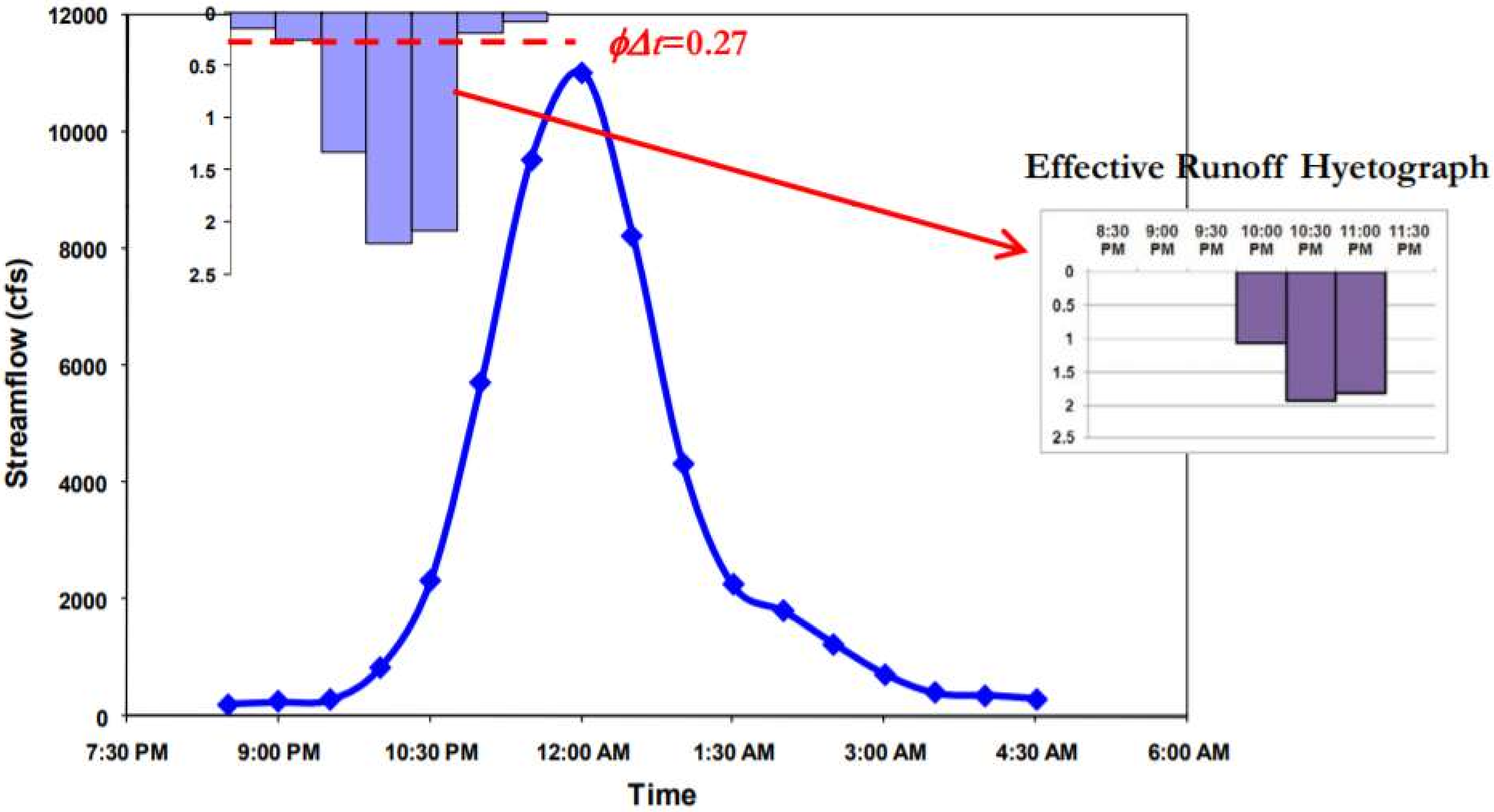
$$r_d = \sum_{m=1}^{M} (R_m - \phi \Delta t)$$

$$r_d = 4.80 \, \text{in}$$

$$4.80 = (1.33 + 2.20 + 2.08 - \phi * 3 * 0.5)$$

$$\phi = 0.54 \, \text{in}$$



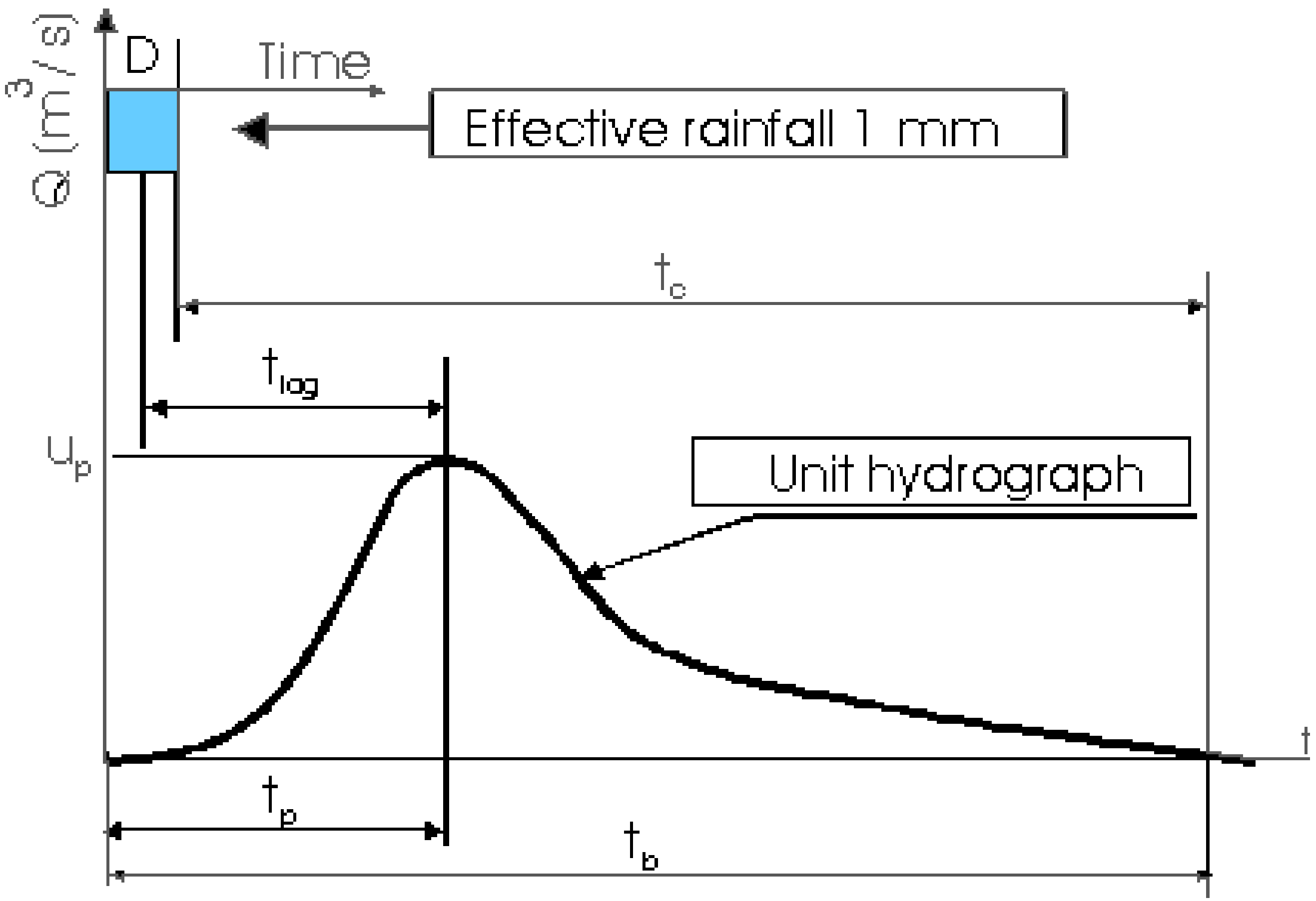


φΔt=0.27
Effective Runoff Hyetograph
8:30 PM
9:00 PM
9:30 PM
10:00 PM
10:30 PM
11:00 PM
11:30 PM
0
0.5
1
1.5
2
2.5
12000
10000
8000
6000
4000
2000
0
Streamflow (cfs)
7:30 PM
9:00 PM
10:30 PM
12:00 AM
1:30 AM
3:00 AM
4:30 AM
6:00 AM
Time

Unit Hydrograph (UH)

- A unit hydrograph (UH) is the hypothetical unit response of a watershed (in terms of runoff volume and timing) to a unit input of rainfall. It can be defined as the direct runoff hydrograph (DRH) resulting from one unit (e.g., one cm or one inch) of effective rainfall occurring uniformly over that watershed at a uniform rate over a unit period of time.

- The unit hydrograph (UH) of a catchment is defined as the hydrograph resulting from an effective rainfall of 1mm evenly distributed over the basin during the time *D.*



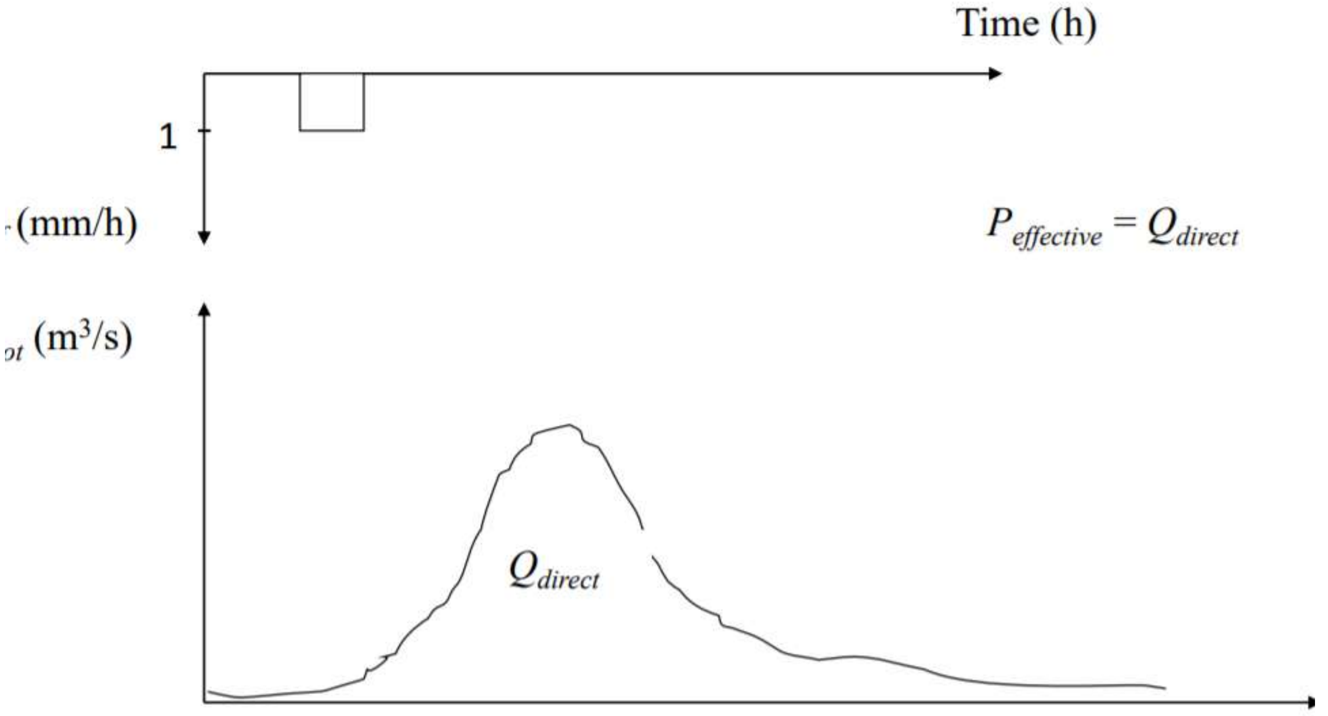
Unit Hydrograph (UH)

- **The hydrograph (direct runoff)resulting from 1-inch (or 1cm) of excess precipitation spread uniformly in space and time over a watershed for a given duration.**

- **The key points :**

  - **1-inch (1cm) of EXCESS precipitation**
  - **Spread uniformly over space - evenly over the watershed**
  - **Uniformly in time - the excess rate is constant over the time interval**
  - **There is a given duration. t-UH (ex. 2hr-UH)**

- The runoff hydrograph for $P_{effective}$ = 1mm



Time

Uses of unit hydrograph

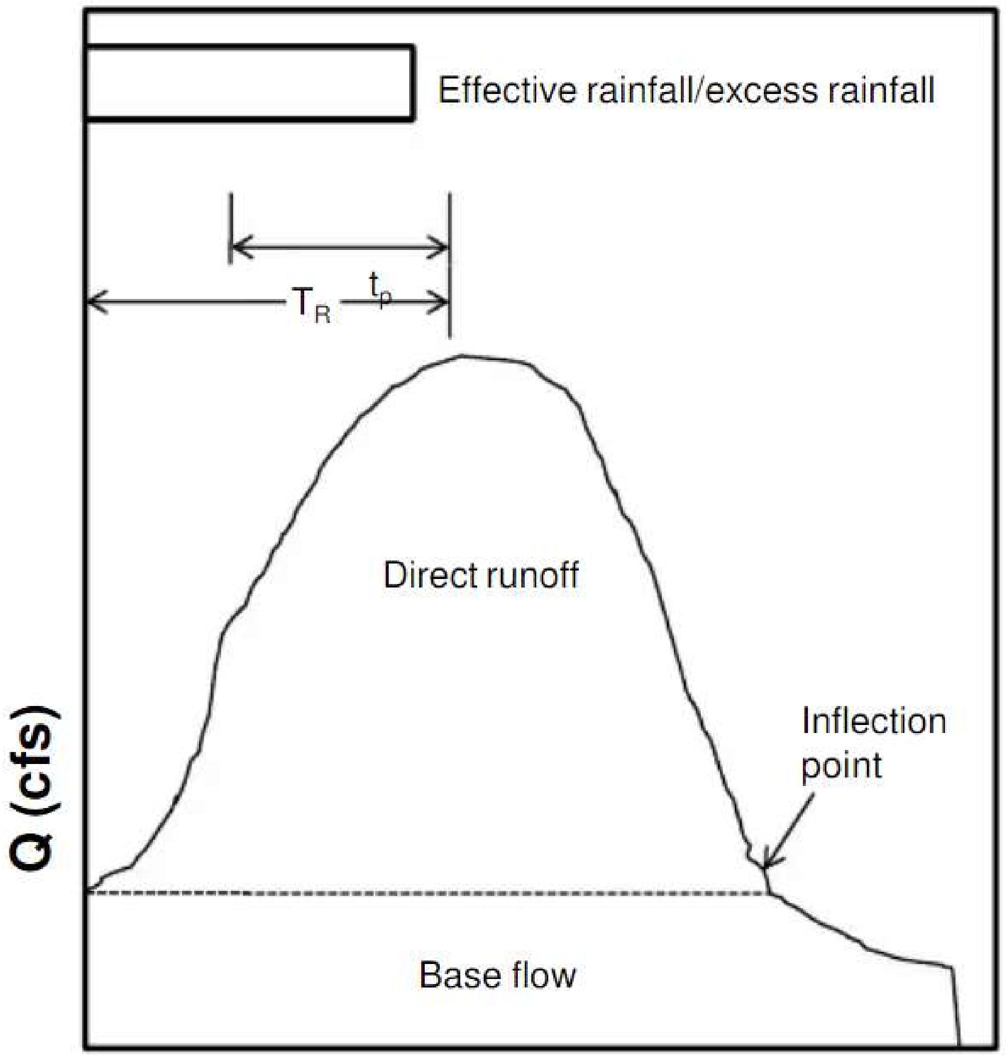
- Can be used to determine volume of direct runoff of any storm occurring in the catchment
- Unit hydrograph can be used to get the hydrographs for other rainfall events. – Example : If 1 hour unit hydrograph is known, it can be used to compute hydrograph of a three hour event.
- Development of flood hydrographs for extreme rainfall events that can be used to design hydraulic structures such as bridges, culverts etc. – Flood forecasting and warning – To extend flood flow records based on rainfall

- Engineering Hydrology
- Hydrograph (2)

Unit Hydrograph

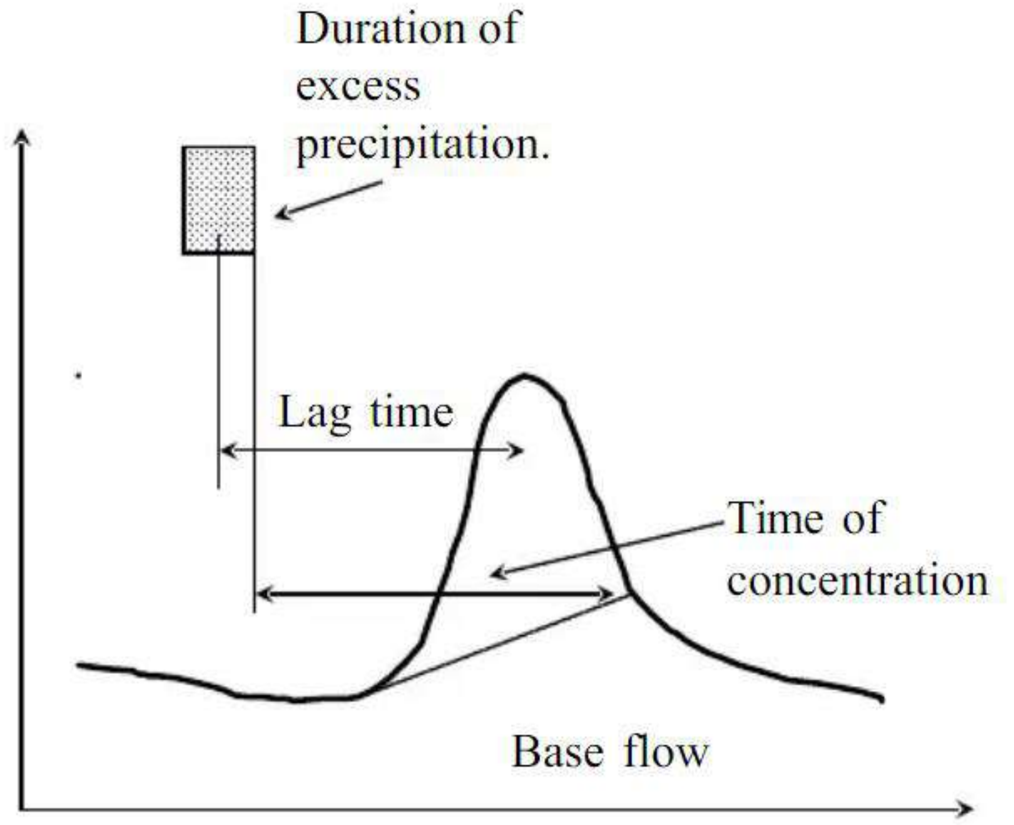
Terminologies

1. **Duration** of effective rainfall : the time from start to finish of effective rainfall
2. **Lag time** (L or t_p): the time from the center of mass of rainfall excess to the peak of the hydrograph
3. **Time of rise** (T_R): the time from the start of rainfall excess to the peak of the hydrograph
4. **Time base** (T_b): the total duration of the DRO hydrograph



Method of developing unit hydrograph

- From streamflow – Runoff data
- Synthetically : Snyder, SCS method.



Essential steps for developing UH from single storm hydrograph

- 1. Analyze the hydrograph and separate base flow.
- 2. Measure the total volume of DRO under the hydrograph and convert time to inches (mm) over the watershed.
- 3. Convert total rainfall to rainfall excess through infiltration methods, such that rainfall excess = DRO, and evaluate duration D of the rainfall excess that produced the DRO hydrograph.
- 4. Divide the ordinates of the DRO hydrograph by the volume in inches (mm)and plot these results as the UH for the basin. Time base Tb is assumed constant for storms of equal duration and thus it will not change5. Check the volume of the UH to make sure it is 1.0 in.(1.0mm), and graphically adjust ordinates as required

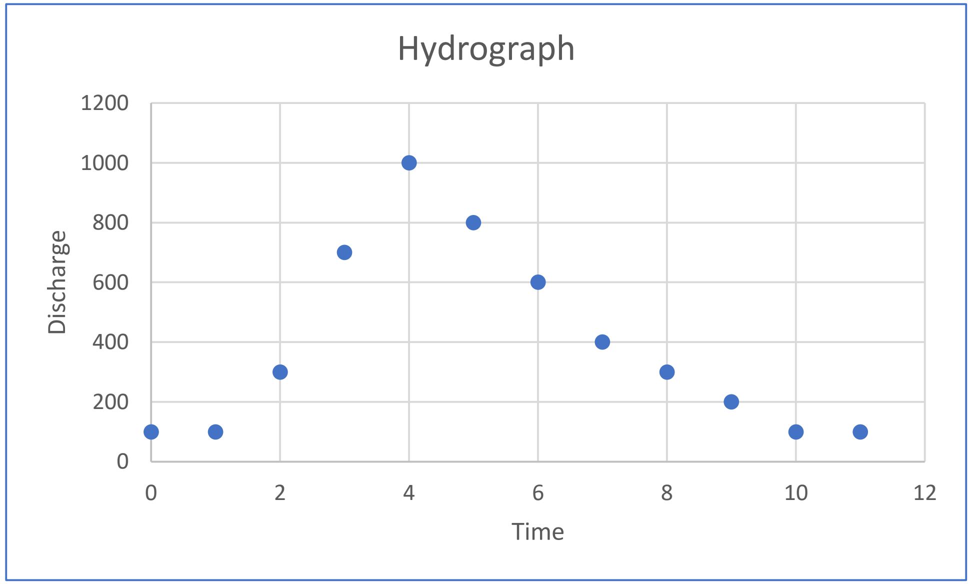
Example

A. **Obtain a Unit Hydrograph** for a basin of 315 km2 of area using the rainfall and stream flow data tabulated below.

B. Predict the total streamflow that would be observed as a result of specific ERH

Time (hr)	Observed Hydrograph (m^3/s)
0	100
1	100
2	300
3	700
4	1000
5	800
6	600
7	400
8	300
9	200
10	100
11	100

Time	Rainfall (cm/hr)
0_1	0.5
1_2	2.5
2_3	2.5
3_4	0.5



Example - Solution

Empirical unit hydrograph derivation separates the base flow from the observed stream flow hydrograph in order to obtain the direct runoff hydrograph (DRH). For this example, use the horizontal line method to separate the base flow. From observation of the hydrograph data, the stream flow at the start of the rising limb of the hydrograph is 100 m^3/s

Compute the volume of direct runoff. This volume must be equal to the volume of the effective rainfall hyetograph (ERH)

$$V_{DRH} = (200+600+900+700+500+300+200+100)\ m^3/s\ (3600)\ s = 12'600{,}000\ m^3$$

Express V_{DRH} in equivalent units of depth:

V_{DRH} in equivalent units of depth = V_{DRH}/A_{basin} = 12'600,000 m^3/(315000000 m^2) = 0.04 m = 4 cm

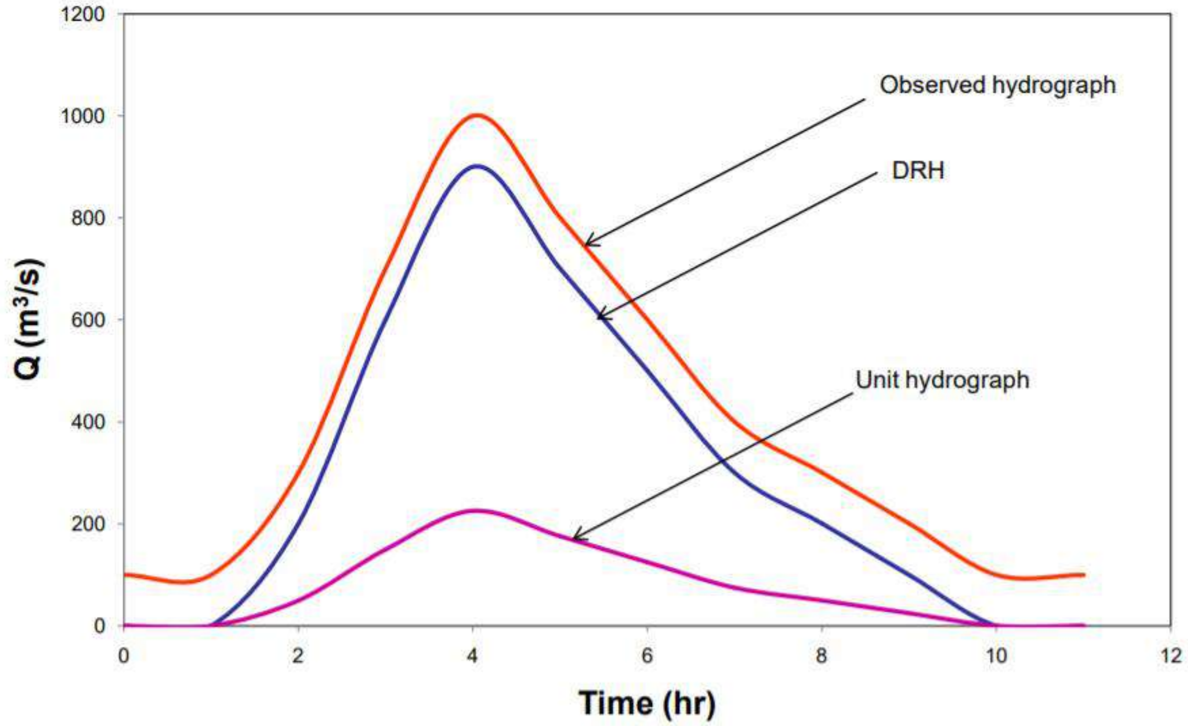
Time (hr)	Observed Hydrograph (m3/s)	Direct RunoffHydrograph (m3/s)
0	100	0
1	100	0
2	300	200
3	700	600
4	1000	900
5	800	700
6	600	500
7	400	300
8	300	200
9	200	100
10	100	0
11	100	0

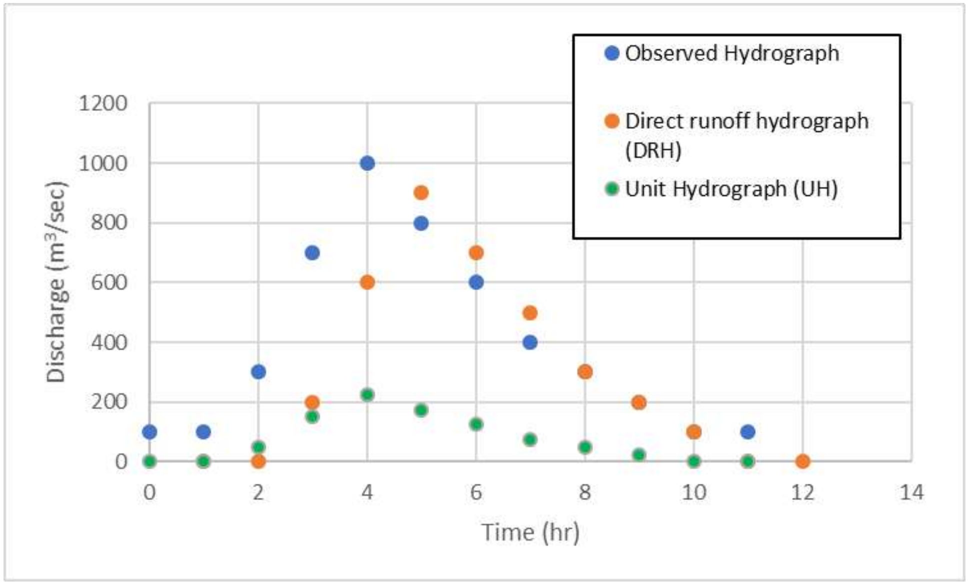
Example - Solution

Obtain a Unit Hydrograph by normalizing the DRH. Normalizing implies dividing the ordinates of the DRH by the VDRH in equivalent units of depth

Time (hr)	Observed hydrograph(m^3/s)	Direct Runoff Hydrograph (DRH) (m^3/s)	Unit Hydrograph ($m^3/s/cm$)
0	100	0	0
1	100	0	0
2	300	200	50
3	700	600	150
4	1000	900	225
5	800	700	175
6	600	500	125
7	400	300	75
8	300	200	50
9	200	100	25
10	100	0	0
11	100	0	0

Example - Solution





Example - Solution

Determine the duration D of the ERH associated with the UH obtained in the example

1. Determine the volume of losses, V_{Losses} which is equal to the difference between the volume of gross rainfall, V_{GRH}, and the volume of the direct runoff hydrograph, V_{DRH}.
   $\boldsymbol{V_{Losses} = V_{GRH} - V_{DRH}}$ **= (0.5 + 2.5 + 2.5 +0.5) cm/h 1 h - 4 cm = 2 cm**

2. Compute the *f*-index equal to the ratio of the volume of losses to the rainfall duration, t_r. Thus,
   ø-index = $\boldsymbol{V_{Losses}/t_r}$ **= 2 cm / 4 h = 0.5 cm/h**

3. Determine the ERH by subtracting the infiltration (*e.g.*, ø-index) from the GRH:

Example - Solution

Time (hr)	Effective precipitation (ERH) (cm/hr)
0-1	0
1-2	2
2-3	2
3-4	0

As observed in the table, the duration of the effective rainfall hyetograph is 2 hours. Thus, D = 2 hours, and the Unit Hydrograph obtained above is a 2-hour Unit Hydrograph.

Example - Solution

B. Predict the total streamflow that would be observed as a result of the following ERH.

Time (h)	Effective Precipitation (ERH) (cm/h)
0 - 2	0.5
2 - 4	1.5
4 - 6	2.0
6 - 8	1.0

As observed in the table, the ERH can be decomposed into a sequence of rectangular pulses, each of 2 hours duration. Thus, we can use the 2-hour UH obtained in **A**.

Example - Solution

- As observed in the table, the duration of the effective rainfall hyetograph is 2 hours. Thus, D = 2 hours, and the Unit Hydrograph obtained above is a 2-hour Unit Hydrograph. Therefore, it can be used to predict runoff from precipitation events whose effective rainfall hyetographs can be represented as a sequence of uniform **intensity (rectangular) pulses** each of duration D. This is accomplished by using the principles of superposition and proportionality, encoded in the discrete convolution equation:

$$Q_n = \sum_{m=1}^{n} P_m U_{n-m+1}$$

Example - Solution

Time (h)	Effective Precipitation (ERH) (cm/h)
0 - 2	0.5
2 - 4	1.5
4 - 6	2.0
6 - 8	1.0

→

Time (h)	P_m (cm)
0 - 2	1.0
2 - 4	3.0
4 - 6	4.0
6 - 8	2.0

Example - Solution

	1	2	3	4	5	6	7
Time(h)	UH (m^3/s/cm)	P_1*UH (m^3/s)	P_2*UH (m^3/s)	P_3*UH (m^3/s)	P_4*UH (m^3/s)	DRH (m^3/s)	Total (m^3/s)
1	0	0				0	100
2	50	50				50	150
3	150	150	0			150	250
4	225	225	150			375	475
5	175	175	450	0		625	725
6	125	125	675	200		1000	1100
7	75	75	525	600	0	1200	1300
8	50	50	375	900	100	1425	1525
9	25	25	225	700	300	1250	1350
10	0	0	150	500	450	1100	1200
11			75	300	350	725	825
12			0	200	250	450	550
13				100	150	250	350
14				0	100	100	200
15					50	50	150
16					0	0	100

Unit Hydrograph (m^3/s/cm)
0
0
50
150
225
175
125
75
50
25
0
0

Time (h)	P_m (cm)
0 - 2	1.0
2 - 4	3.0
4 - 6	4.0
6 - 8	2.0

Changing the duration of unit hydrograph

- Very often, it is necessary to change duration of the unit hydrograph.
- 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 and adding the ordinates.
- Shortcut method for changing the duration of the unit hydrograph is used if the two durations are multiples of one another.

Example

Obtain a four hour unit hydrograph using the two hour unit hydrograph data given below

Time (hr)	Q
0	0
1	2
2	4
3	6
4	10
5	6
6	4
7	3
8	2
9	1
10	0

Time (hr)	Q	Displaced UHG
0	0	
1	2	
2	4	0
3	6	2
4	10	4
5	6	6
6	4	10
7	3	6
8	2	4
9	1	3
10	0	2
11		1
12		0

- The 2 hr-UH is displaced by 2 hours.

Time (hr)	Q	Displaced UHG	Sum
0	0		0
1	2		2
2	4	0	4
3	6	2	8
4	10	4	14
5	6	6	12
6	4	10	14
7	3	6	9
8	2	4	6
9	1	3	4
10	0	2	2
11		1	1
12		0	0

- Finally the summed hydrograph is divided by two.
- This is done because when two unit hydrographs are added, the area under the curve is two units. This has to be reduced back to one unit of runoff.

Time (hr)	Q	Displaced UHG	Sum	4 hour UHG
0	0		0	0
1	2		2	1
2	4	0	4	2
3	6	2	8	4
4	10	4	14	7
5	6	6	12	6
6	4	10	14	7
7	3	6	9	4.5
8	2	4	6	3
9	1	3	4	2
10	0	2	2	1
11		1	1	0.5
12		0	0	0

Synthetic unit hydrograph- Snyder's method

$$t_p = C_t(LL_C)^{0.3}$$

where

t_p= basin lag (hr)

L= length of the main stream from the outlet to the divide (mi)

L_c = length along the main stream to a point nearest the watershed centroid (mi)

C_t= Coefficient usually ranging from 1.8 to 2.2

Synthetic unit hydrograph- Snyder's method

$$Q_p = 640\ C_pA/t_p$$

where

Qp = peak discharge of the UH (cfs)

A = Drainage area (mi2)

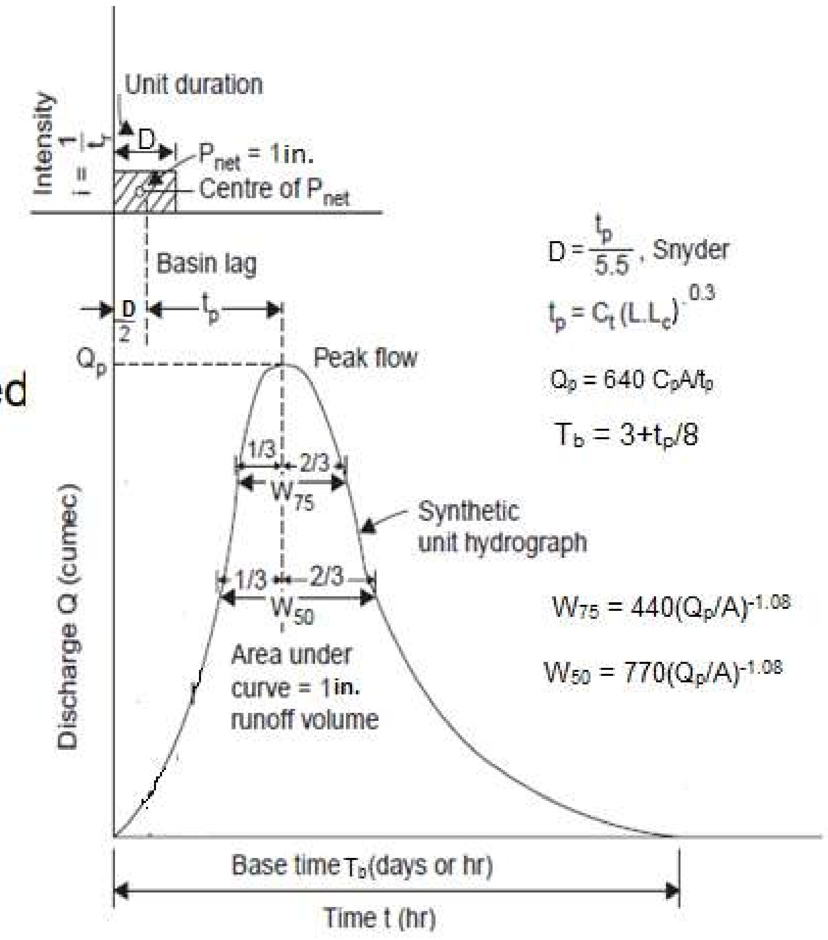
C_p = storage coefficient ranging from 0.4 to 0.8, where larger values of cp are associated with smaller values of Ct

$$T_b = 3+t_p/8$$

where Tb is the time base of hydrograph

Note: For small watershed the above eq. should be replaced by multiplying t_p by the value varies from 3-5

- The above 3 equations define points for a UH produced by an excess rainfall of duration $D= t_p/5.5$



Snyder's hydrograph parameter

Example- Solution

Use Snyder's method to develop a UH for the area of 100mi2 described below. Sketch the appropriate shape. What duration rainfall does this correspond to?

$C_t = 1.8$, $L = 18mi$,

$C_p = 0.6$, $L_c = 10mi$

Calculate t_p

$t_p = C_t(LL_C)^{0.3}$

$= 1.8(18 \cdot 10)^{0.3}$ hr,

= 8.6 hr

Calculate Qp

$Q_p = 640(c_p)(A)/t_p$

$= 640(0.6)(100)/8.6$

= 4465 cfs

Since this is a small watershed,

$Tb \approx 4tp = 4(8.6)$

= 34.4 hr

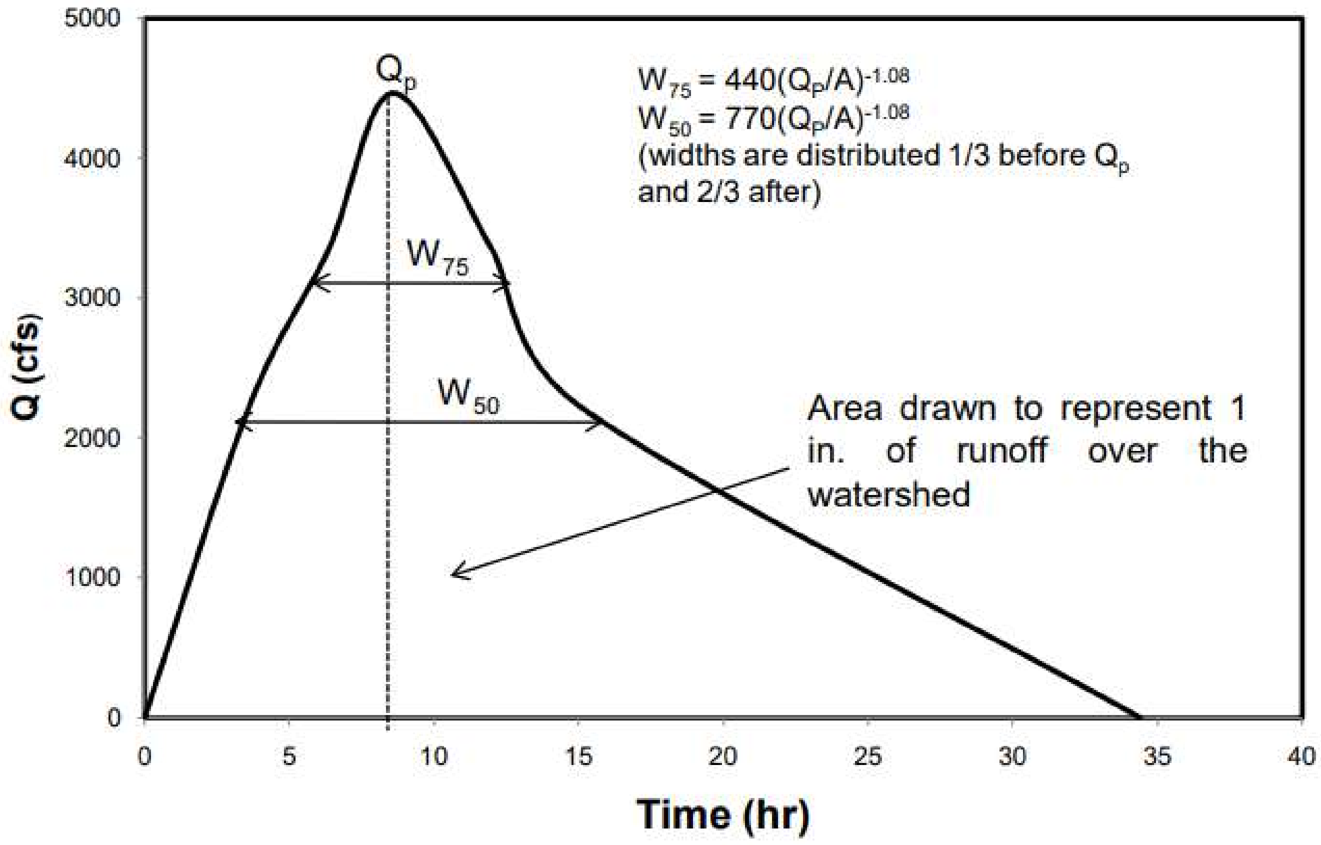
Duration of rainfall

$D = t_p/5.5$ hr

$= 8.6/5.5$ hr

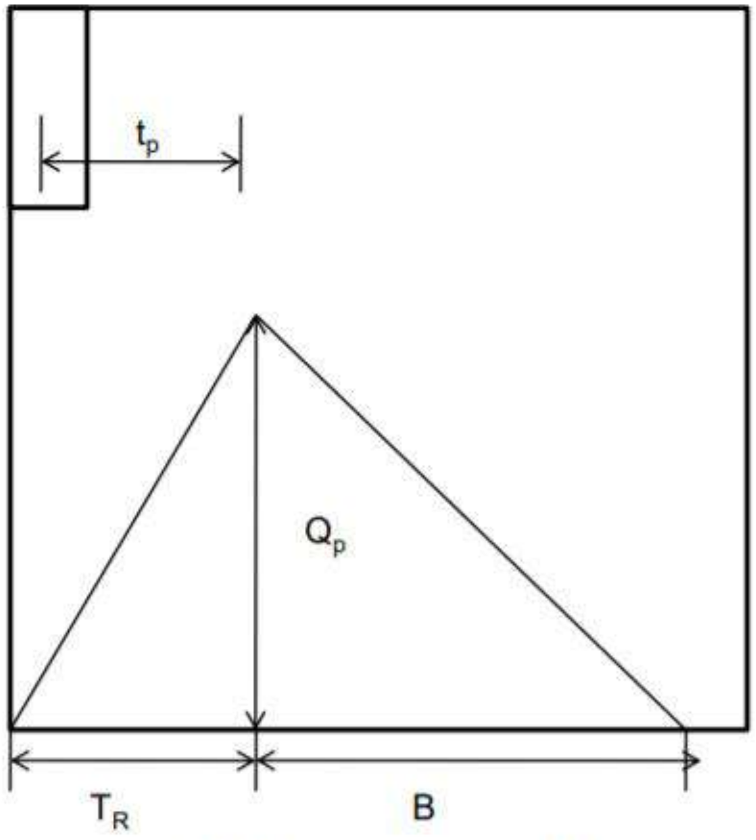
= 1.6 hr

Example - Solution



Synthetic unit hydrograph- SCS method

• SCS method assumed a hydrograph as a simple triangle, with rainfall duration D, time of rise TR (hr), time of fall B. and peak flow Q_p (cfs).



SCS triangular UH

- The volume of direct runoff is

$$Vol = \frac{Q_p T_R}{2} + \frac{Q_p B}{2} \quad \text{or} \quad Q_p = \frac{2vol}{T_R + B}$$

where B is given by

$$B = 1.67 T_R$$

Therefore runoff eq. becomes, for 1 in. of rainfall excess,

$$Q_p = \frac{0.75vol}{T_R} = Q_p = \frac{0.75(640)A(1.008)}{T_R}$$

$$Q_p = \frac{484A}{T_R}$$

where
A= area of basin (sq mi)
T_R = time of rise (hr)

- Time of rise TR is given by

$$T_R = \frac{D}{2} + t_p$$

where

D= rainfall duration (hr)

t_p= lag time from centroid of rainfall to Q_P

Lag time is given by

$$t_p = \frac{L^{0.8}\left(\frac{1000}{CN} - 9\right)^{0.7}}{19000y^{0.5}}$$

where

L= length to divide (ft)

Y= average watershed slope (in present)

CN= curve number for various soil/land use

Runoff curve number for different land use (source: Woo-Sung et al.,1998)

Land Use Descrition	Treatment	Hydrologic condition	Hydrologic Soil Group A	B	C	D
Fallow	Straight row	-	77	86	91	94
Row crop	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Contoured	Poor	70	79	84	88
	Contoured	Good	65	75	82	86
	Cont.& terraced	Poor	66	74	80	82
	Cont.& terraced	Good	62	71	78	81
Small grains	Straight row	Poor	65	76	84	88
	Straight row	Good	63	75	83	87
	Contoured	Poor	63	74	82	85
	Contoured	Good	61	73	81	84
	Cont.& terraced	Poor	61	72	83	82
	Cont.& terraced	Good	59	70	78	81
Close-seeded Legumes or rotation meadow	Straight row	Poor	66	77	85	89
	Straight row	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	Contoured	Good	55	69	78	81
	Cont.& terraced	Poor	63	73	80	83
	Cont.& terraced	Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	Contoured	Fair	25	59	75	83
	Contoured	Good	26	35	70	79
Meadow		Good	30	58	71	78
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Forests		-	56	75	86	91
Farmsteads		-	59	74	82	86
Roads (dirt)		-	72	82	87	89
(hard surface)			74	84	90	92
Commercial & business Area		-	89	92	94	95
		-	81	88	91	93
Industrial Area		-	77	85	90	92
Residental Area		-	57	71	86	86

Example

Use the SCS method to develop a UH for the area of 10 mi^2 described below.
Use rainfall duration of D = 2 hr

$C_t = 1.8, \quad L = 5mi,$

$C_p = 0.6, \quad L_c = 2mi$

The watershed consist CN = 78 and the average slope in the watershed is 100 ft/mi. Sketch the resulting SCS triangular hydrograph .

Solution

Find t_p by the eq.

$$t_p = \frac{L^{0.8}\left(\frac{1000}{CN} - 9\right)^{0.7}}{19000y^{0.5}}$$

Convert L= 5mi, or (5*5280 ft/mi) = 26400 ft.

Slope is 100 ft/mi, so y = (100ft/mi) (1mi/5280 ft)(100%) = 1.9%

Substituting these values in eq. of t_p, we get t_p = 3.36 hr

Find T_R using eq.

$$T_R = \frac{D}{2} + t_p$$

Given rainfall duration is 2 hr, T_R = 4.36 hr, the rise of the hydrograph

Then find Q_p using the eq, given A= 10 mi^2

$$Q_p = \frac{484A}{T_R}$$. Hence Q_p = 1.110 cfs

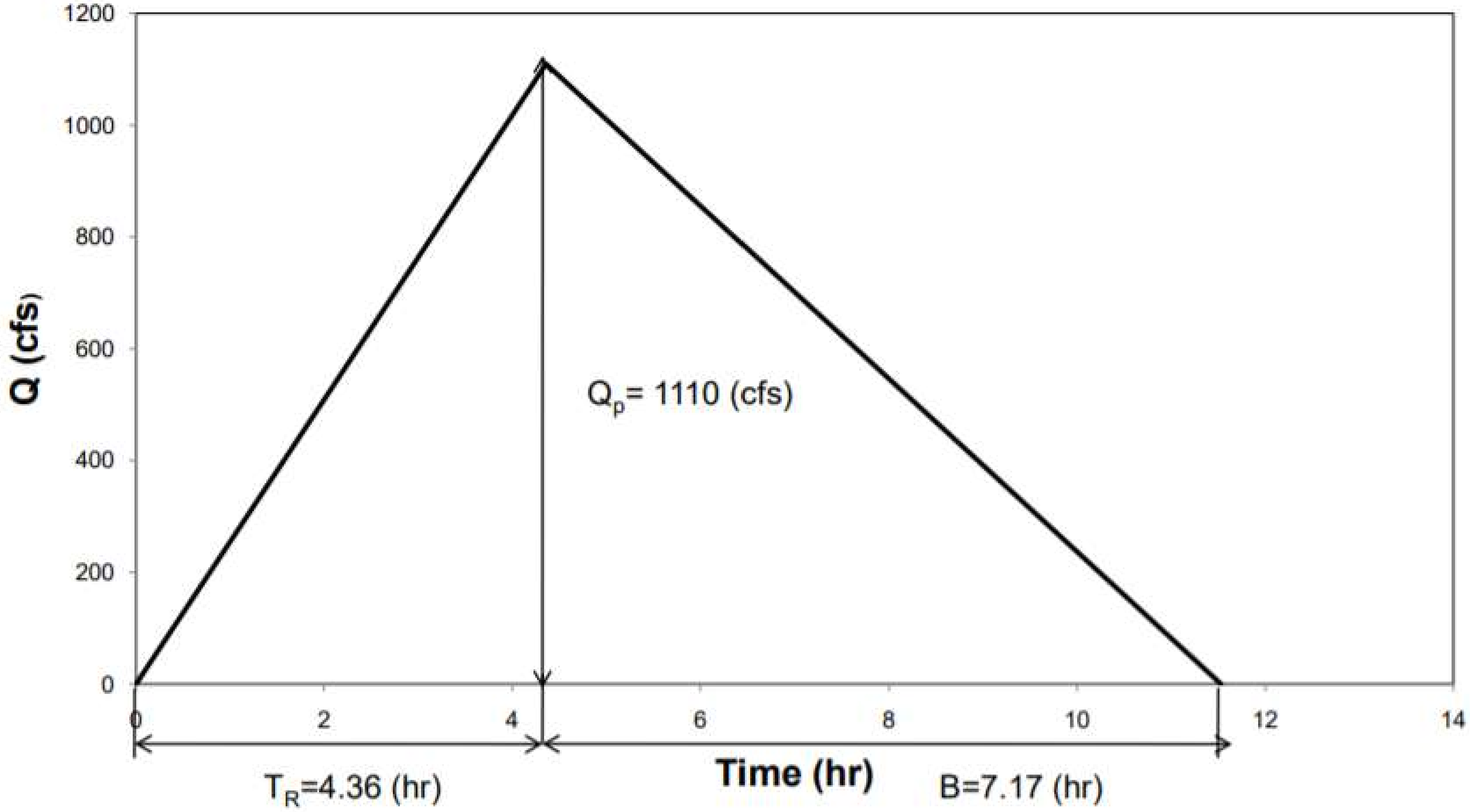
To complete the graph, it is also necessary to know the time of fall B. The volume is known to be 1 in. of direct runoff over the watershed.

So, Vol. = ($10mi^2$) $(5280ft/mi)^2$ ($ac/43560ft^2$) (1 in.) = 6400 ac-in

Hence from eq.

$$Vol = \frac{Q_p T_R}{2} + \frac{Q_p B}{2}$$

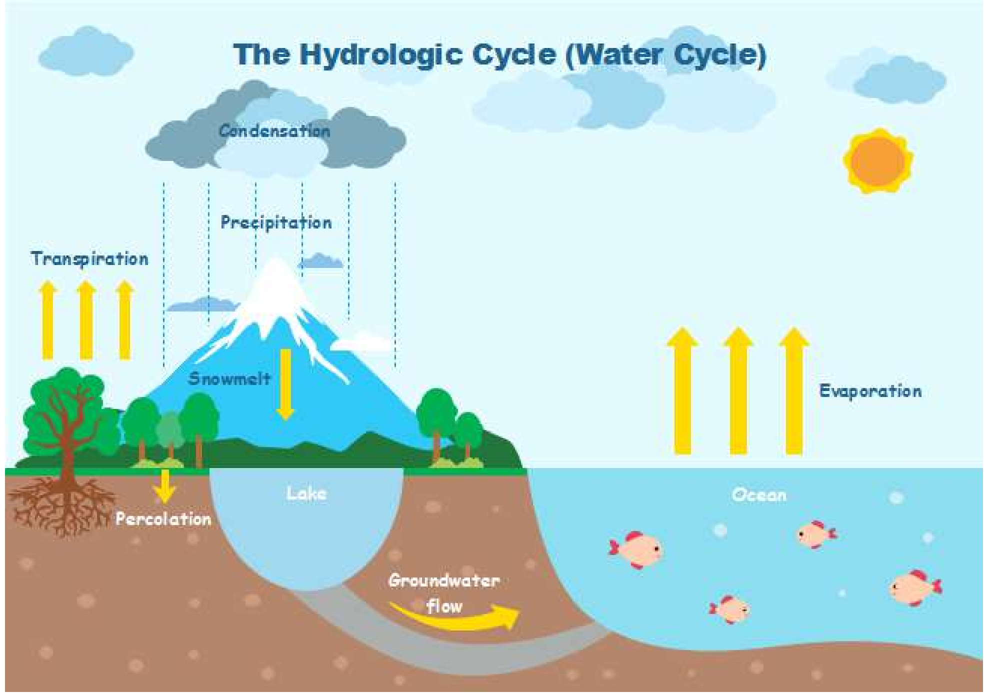
B = 7.17 hr

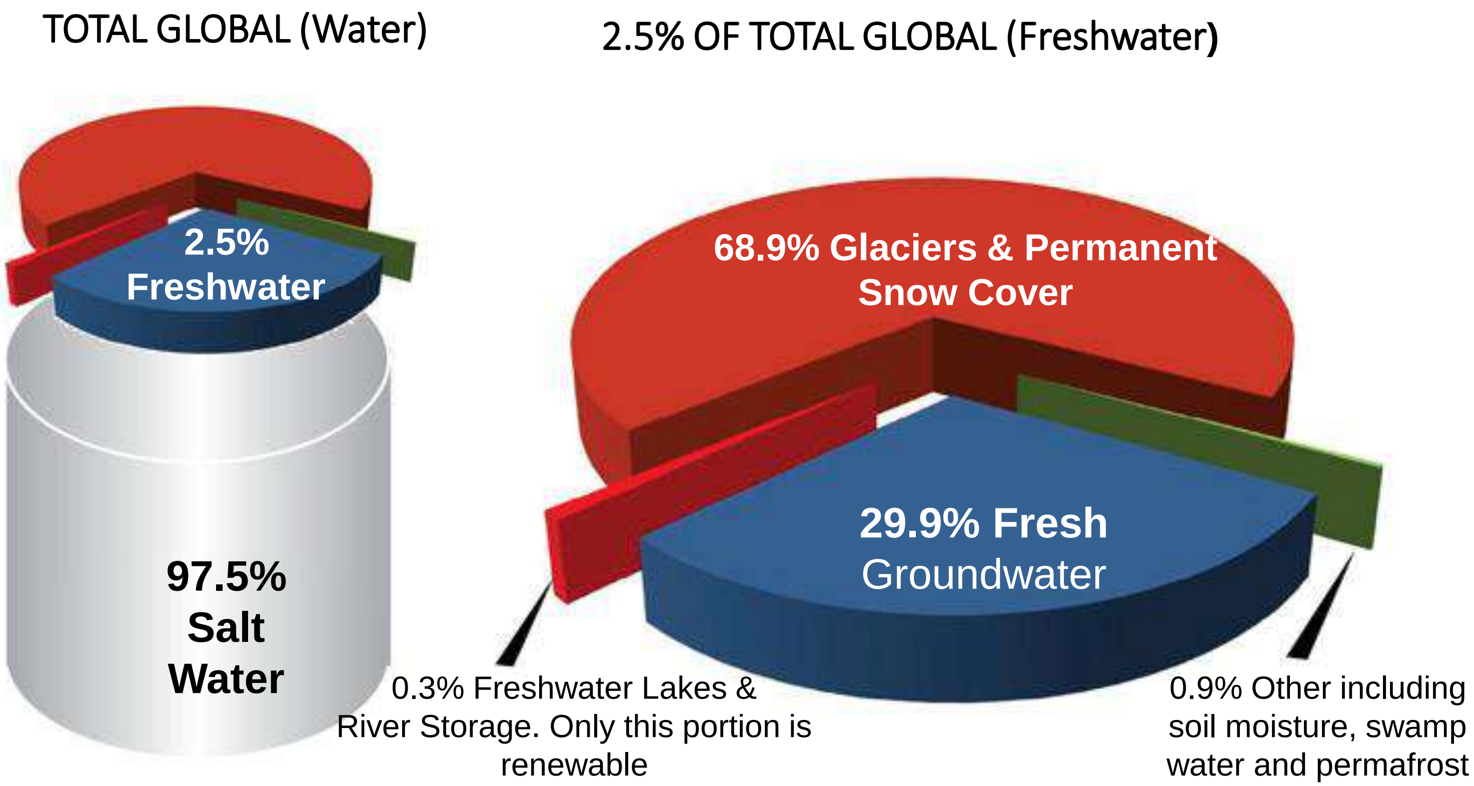


1200
1000
800
600
400
200
0
Q (cfs)
Qp= 1110 (cfs)
0
2
4
6
8
10
12
14
TR=4.36 (hr)
Time (hr)
B=7.17 (hr)

- Groundwater Hydrology

Global Water Resources and water cycle

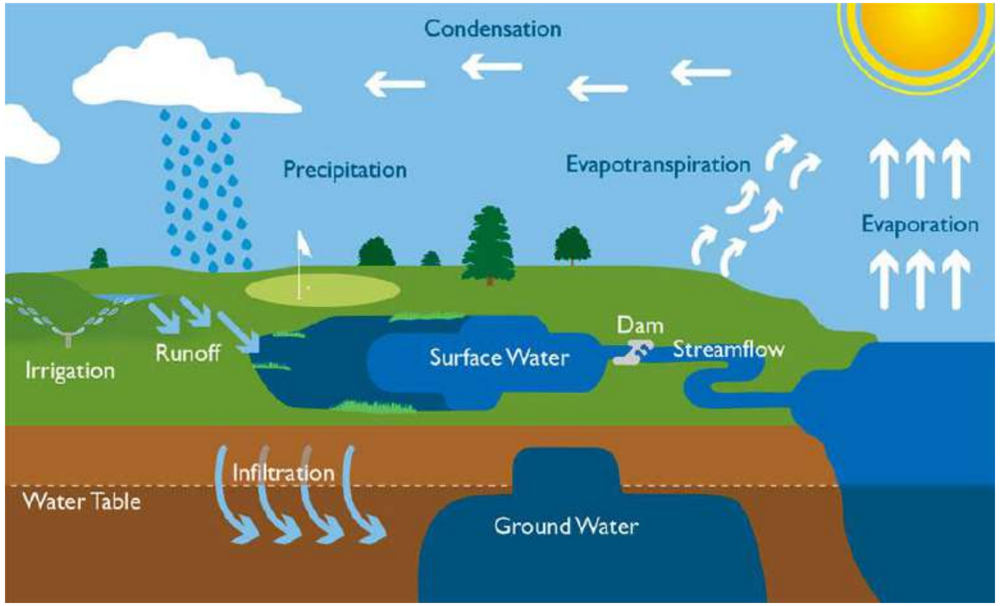




Distribution of the Earth's Water

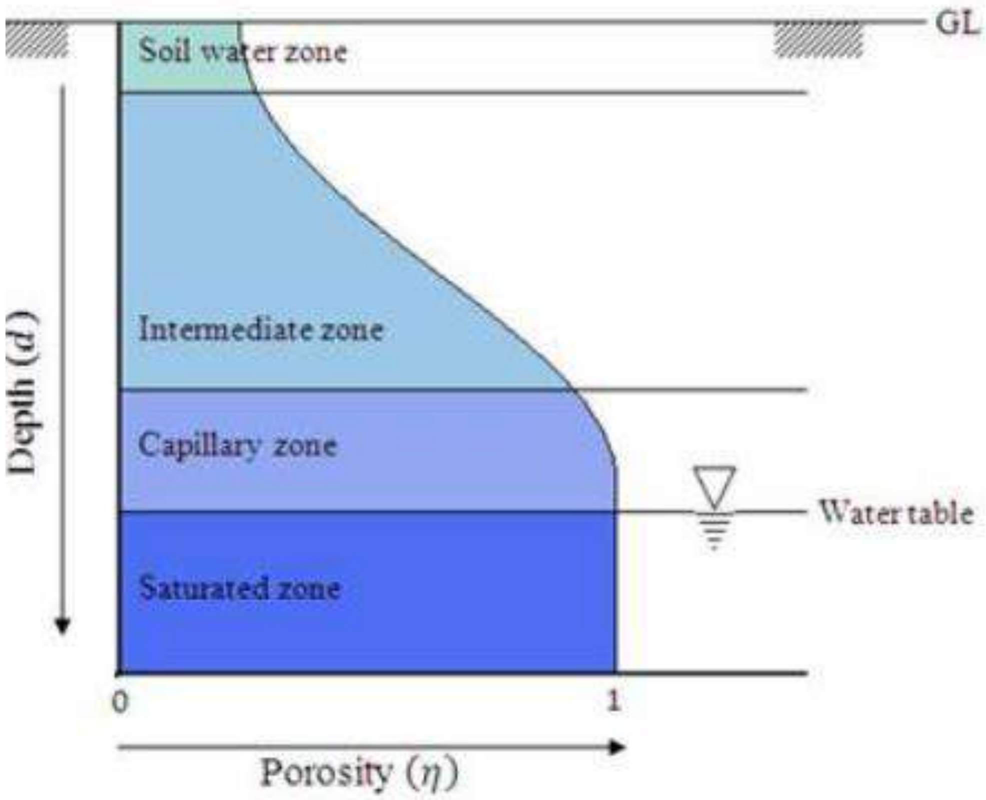
Groundwater Hydrology

- A major component of precipitation that falls on the earth surface eventually enters into the ground by the process of infiltration. The infiltrated water is stored in the pores of the underground soil strata.
- The water which is stored in the pores of the soil strata is known as groundwater. Therefore, the groundwater may be defined as all the water present below the earth surface and the groundwater hydrology is defined as the science of occurrence, distribution and movement of water below the earth surface.



Groundwater Table

- The water table acts as a boundary between saturated zone and unsaturated zone. The soil matrix is fully saturated below the water table. At the same time, the soil just above the water table is also saturated due to the capillary effect.

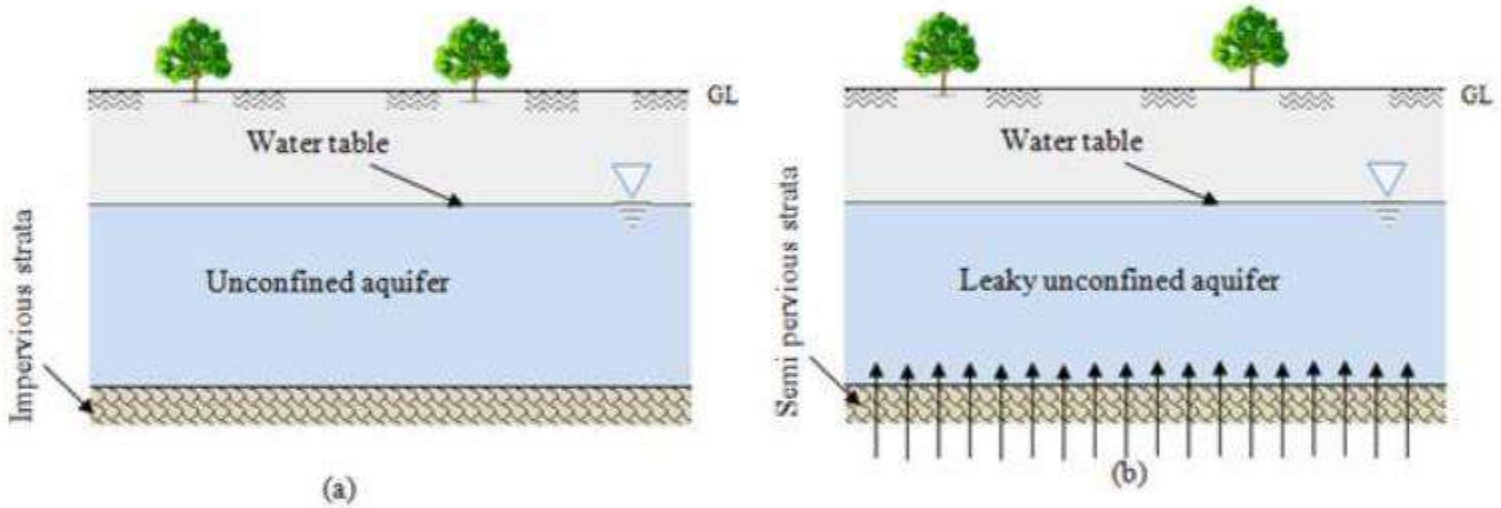


Geological formations and their classification

Aquifer

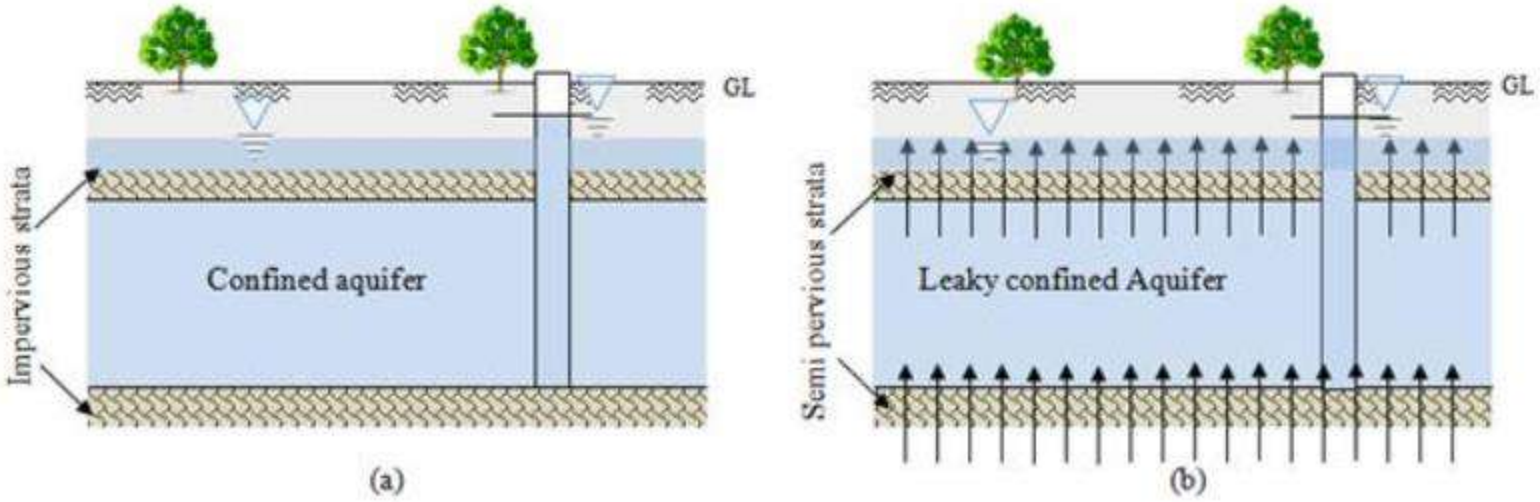
An aquifer is an underground geological formation which contains water and sufficient amount of water can be extracted economically using water wells. Aquifers comprise generally layers of sand and gravel and fracture bedrock.

When water table serves as the upper boundary of the aquifer, the aquifer is known as unconfined aquifer.



(a) Unconfined aquifer, (b) Leaky unconfined aquifer

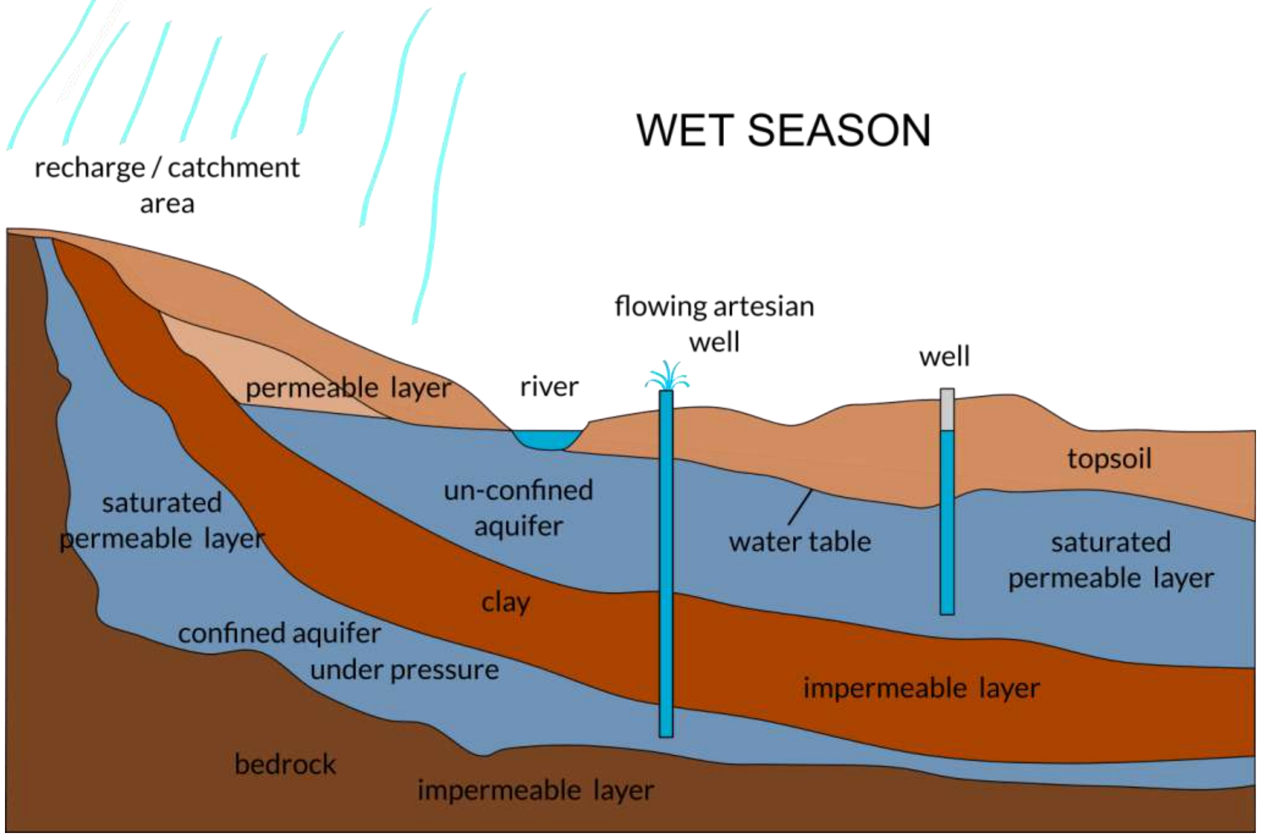
Confined aquifers

- An aquifer which is bounded by two impervious layers at top and bottom of the aquifer is called confined aquifer.
- 

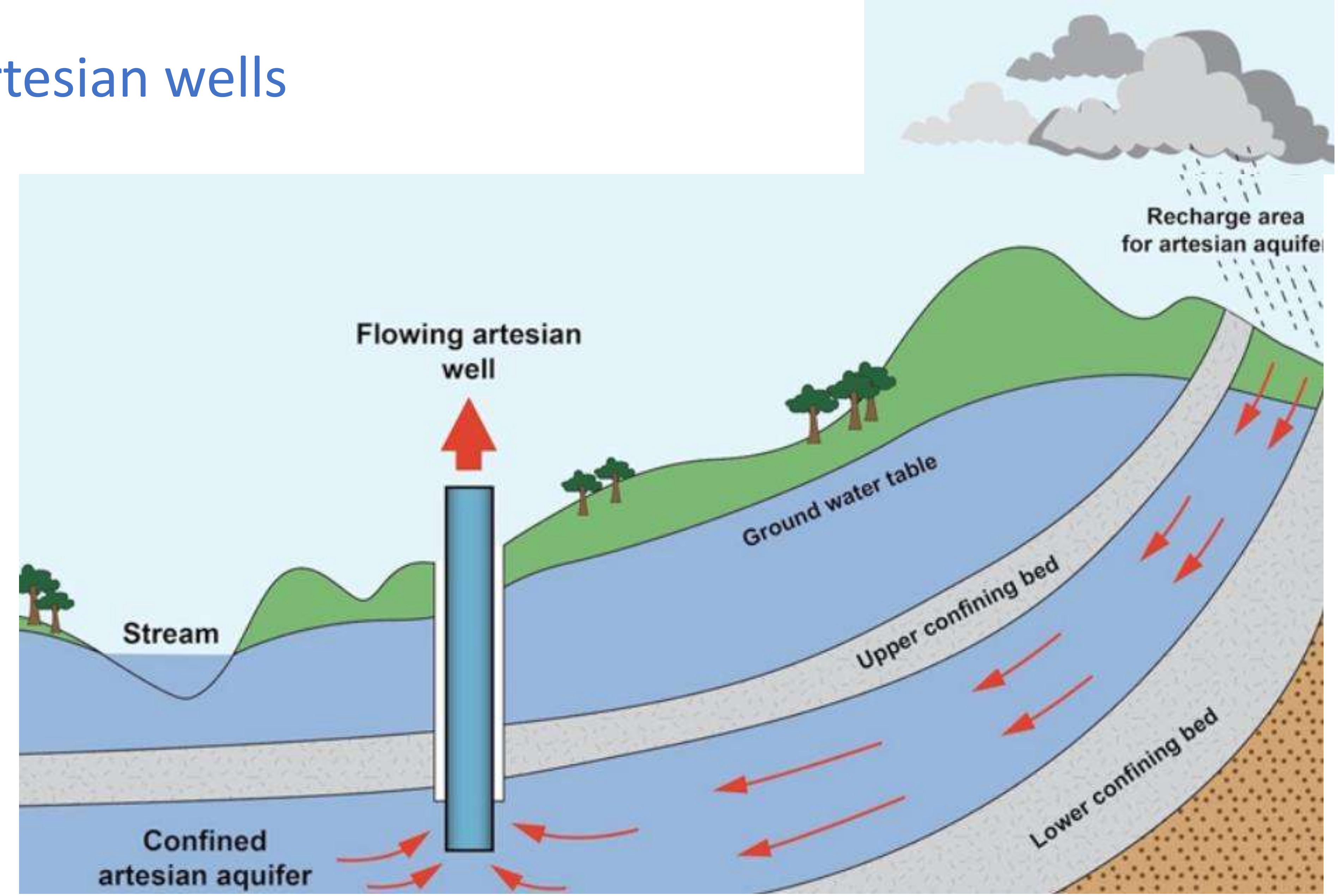
(a) Confined aquifer (b) Leaky confined aquifer

Aquifers

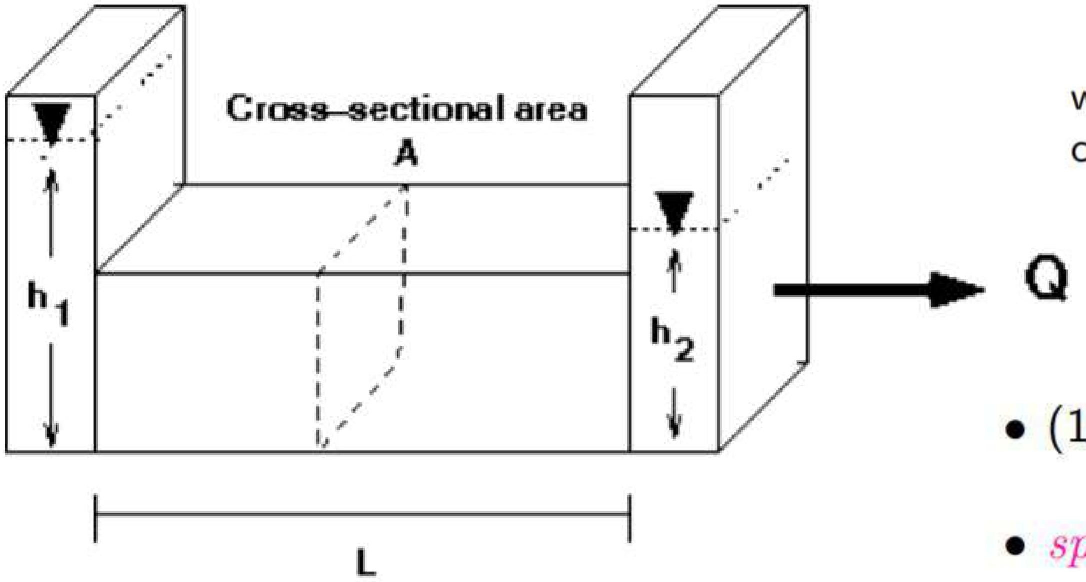
- In case of confined aquifer, if we insert a piezometer into the aquifer, the water level will rise above the top impervious layer as the pressure in the aquifer is more than the atmospheric pressure. As such, the confined aquifer is also known as pressure aquifer. Top and bottom layer of a confined aquifer is generally impervious.



Artesian wells



Groundwater flow



- Darcy found the following relationship

$$Q \propto \frac{A(h_1 - h_2)}{L}$$

or

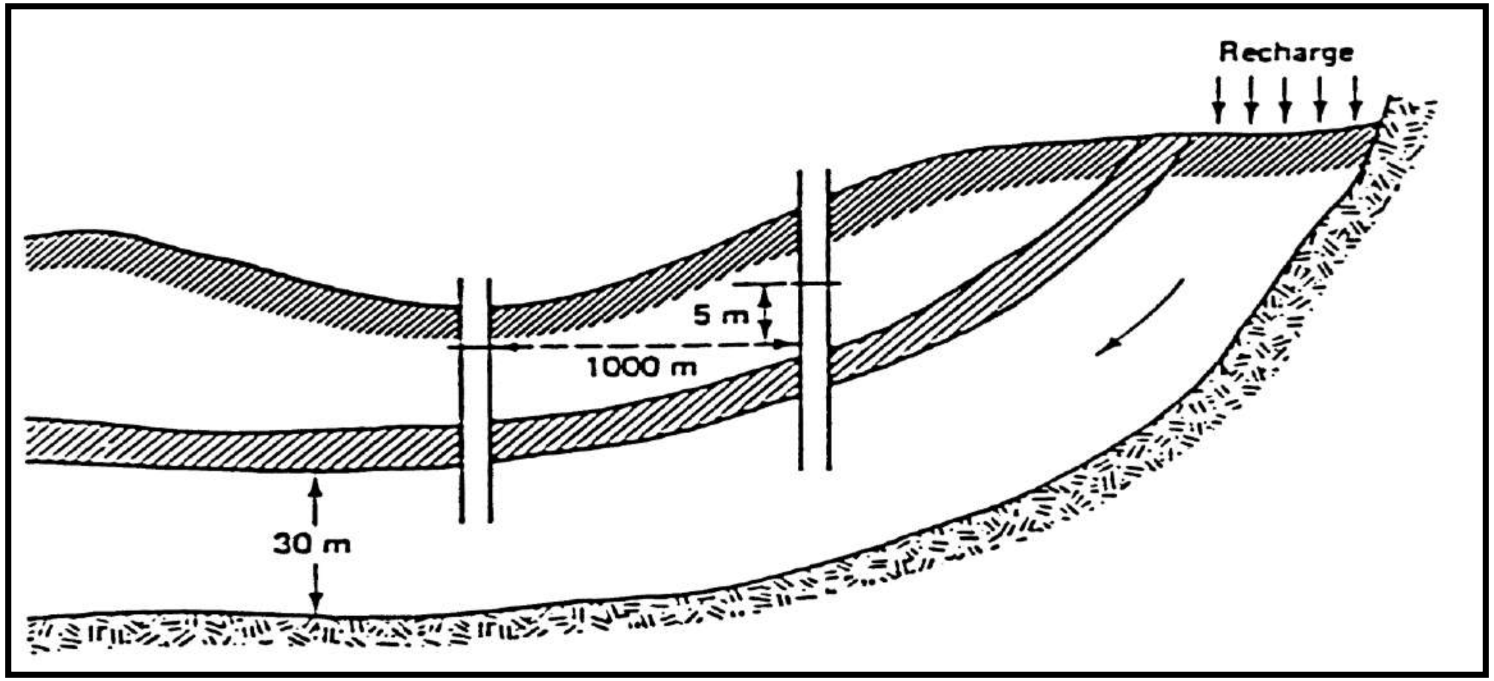
$$Q = KA\frac{h_1 - h_2}{L} \qquad (1)$$

where K is a proportionality constant termed hydraulic conductivity $\frac{\mathrm{L}}{\mathrm{T}}$

- (1) gives total discharge through the cross-sectional area A
- *specific discharge* (q traditionally, v in the text) is the flux per unit area $q = \frac{Q}{A}$

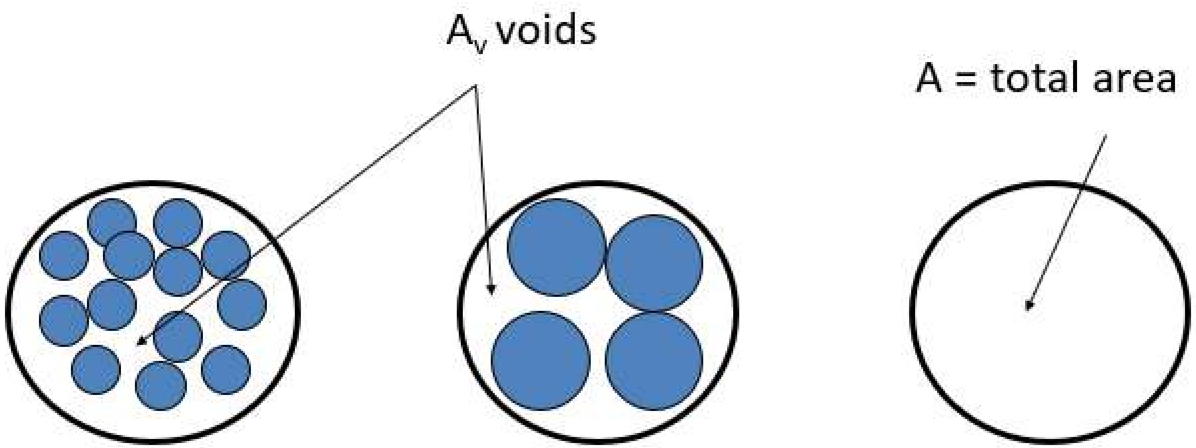
Darcy’s allows an estimate of:

- The velocity or flow rate moving within the aquifer
- The average time of travel from the head of the aquifer to a point located downstream
- Very important for prediction of contaminant plume arrival

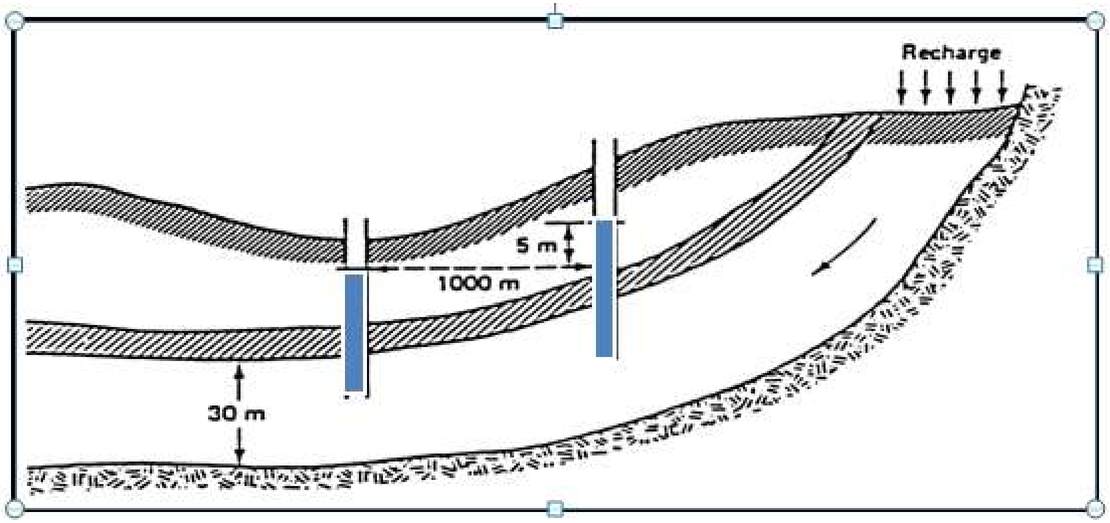


Darcy and Seepage Velocity

- Darcy velocity V_D is a fictitious velocity since it assumes that flow occurs across the entire cross-section of the sediment sample. Flow actually takes place only through interconnected pore channels (voids), at the seepage velocity V_S.



Example

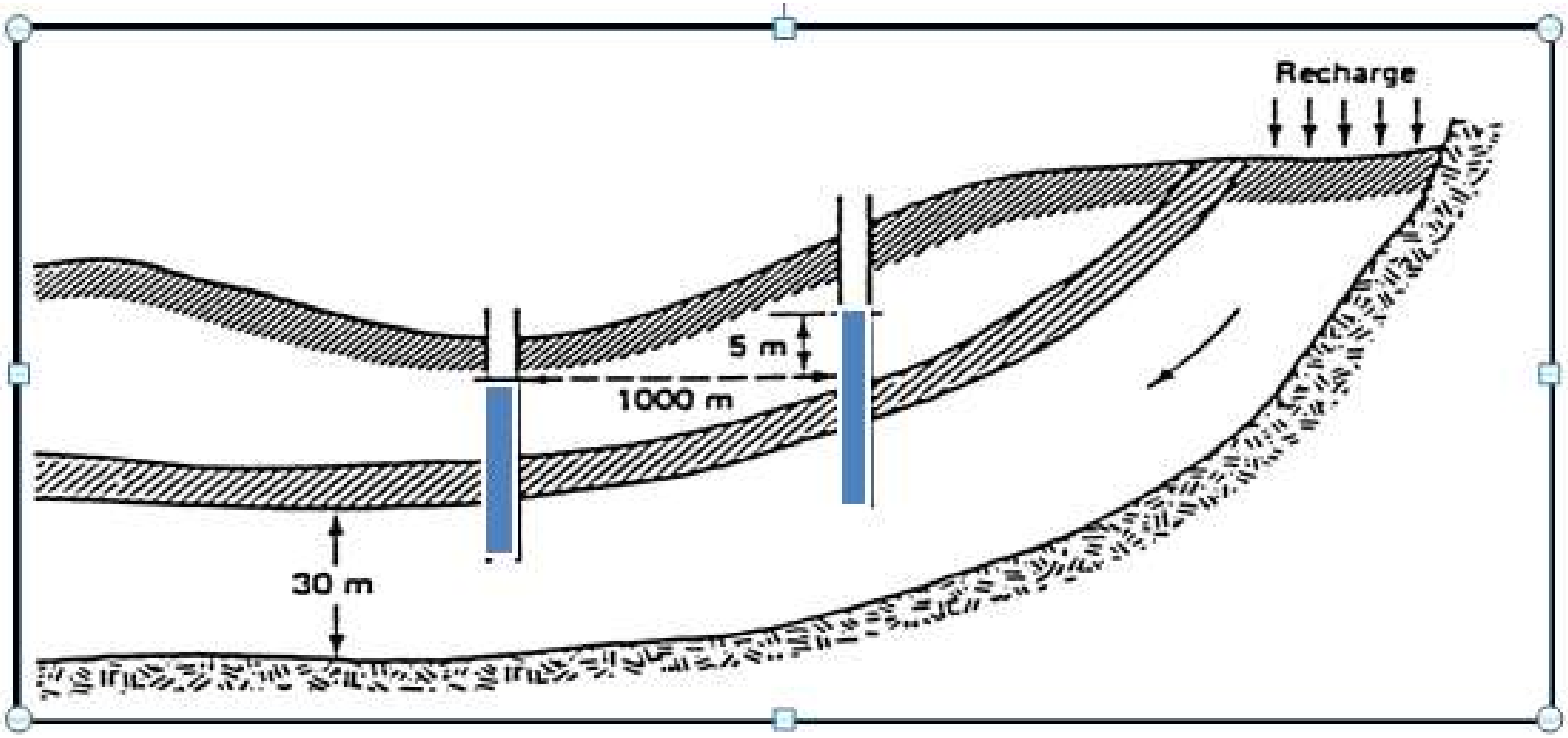


- A confined aquifer has a source of recharge.
- K for the aquifer is 50 m/day, and porosity n is 0.2.
- The piezometric head in two wells 1000 m apart is 55 m and 50 m respectively, from a common datum.
- The average thickness of the aquifer is 30 m, and the average width of the aquifer is 5 km = 5000m.

Example

Compute

- a) The rate of flow through the aquifer.
- b) The average time of travel from the head of the aquifer to a point 4 km downstream.



Solution

$$Q = KA\ (dh/dL)$$

- Cross-Sectional area= 30(5000) = $1.5 \times 10^5\ m^2$
- Hydraulic gradient dh/dL= (55-50)/1000 = 5×10^{-3}
- Find Rate of Flow for K = 50 m/day

$Q = (50\ m/day)\ (1.5 \times 10^5\ m^2)\ (5 \times 10^{-3})$

$Q = 37{,}500\ m^3/day$

- Darcy Velocity: V = Q/A
- = $(37{,}500 m^3/day) / (1.5 \times 10^5\ m^2)$ = <u>0.25m/day</u>

Solution

- Seepage Velocity:

  $V_s = V_D/n = (0.25) / (0.2) =$

  1.25 m/day (about 4.1 ft/day)

- Time to travel 4 km downstream:

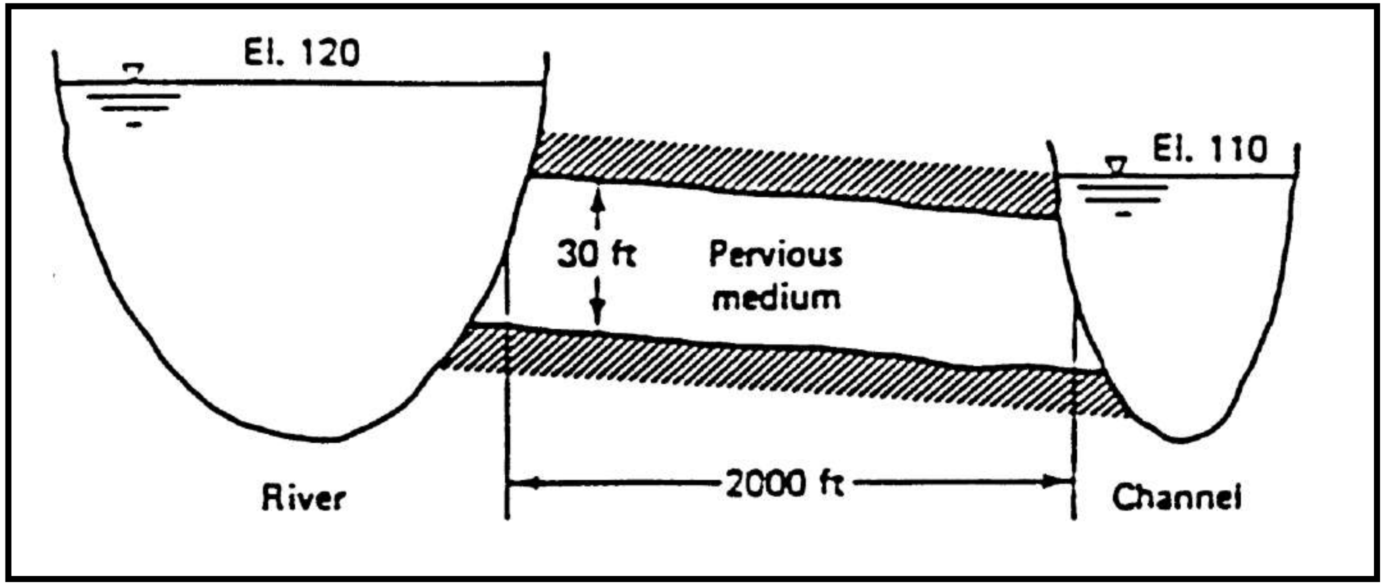
  T = (4000m) / (1.25m/day) =

  3200 days or 8.77 years

Lesson: Groundwater moves very slowly

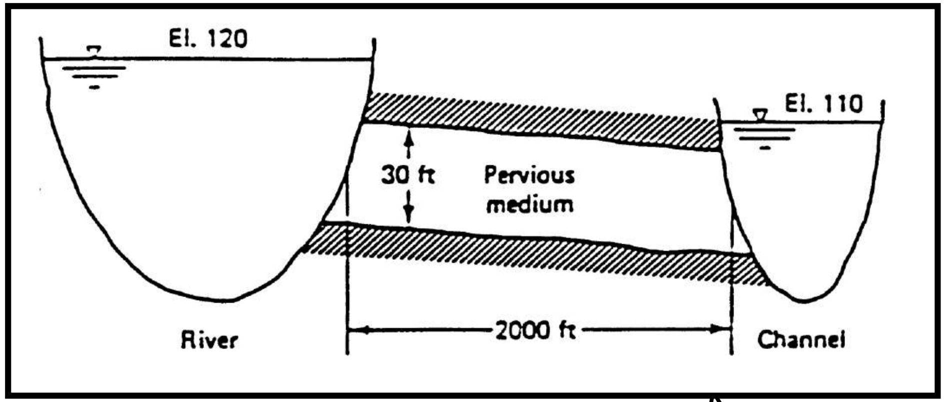
Example

- A channel runs almost parallel to a river, and they are 2000 ft apart.
- The water level in the river is at an elevation of 120 ft . The channel is at an elevation of 110ft.
- A pervious formation averaging 30 ft thick and with hydraulic conductivity *K* of 0.25 ft/hr joins them.
- Determine the flow rate Q of seepage from the river to the channel.



Solution

- Consider 1-ft (i.e. unit) lengths of the river and small channel.
- $Q = KA\,[(h_1 - h_2) / L]$



- Where:

  $A = (30 \times 1) = 30\ ft^2$ K

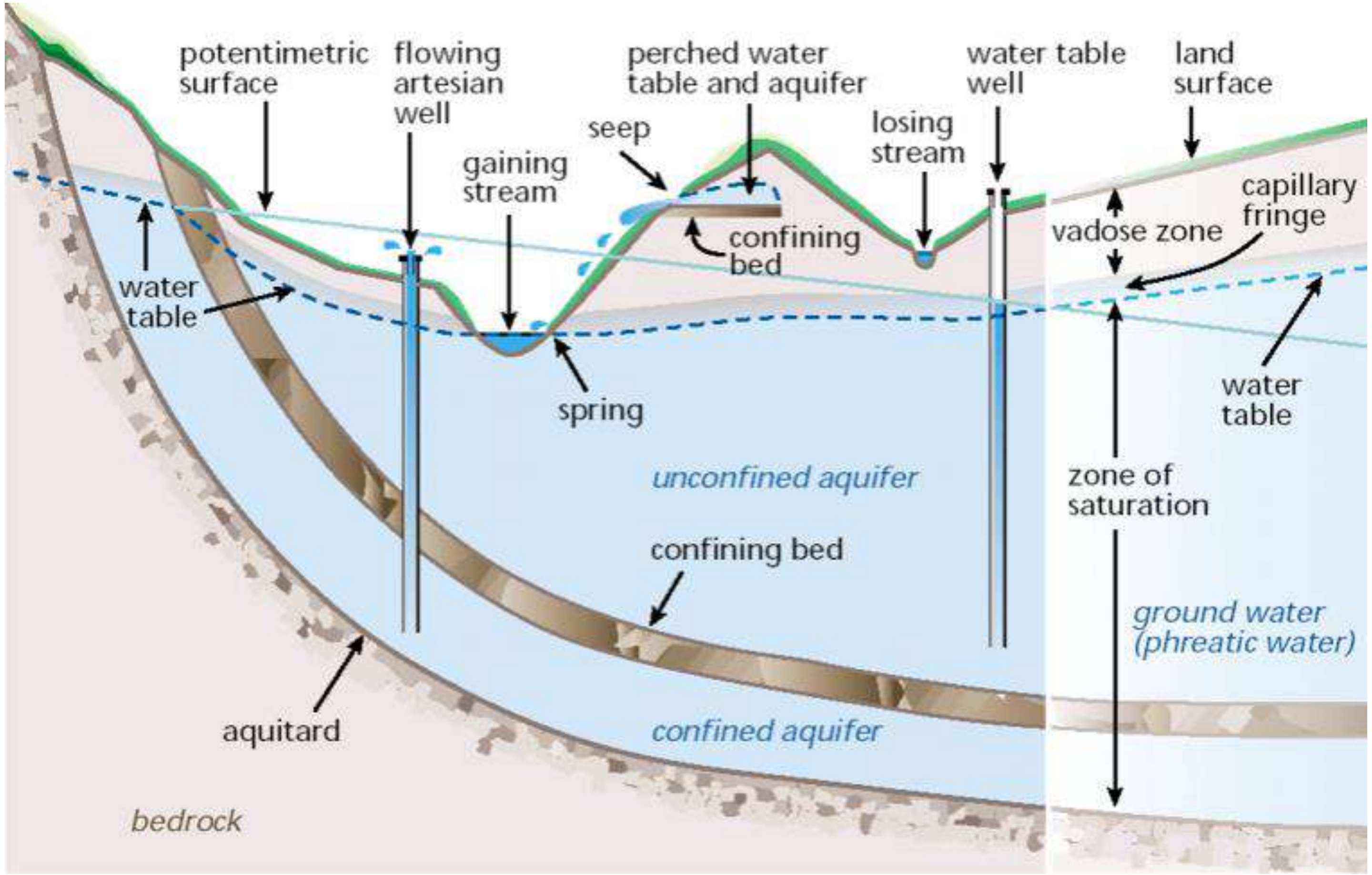
  = (0.25 ft/hr) (24 hr/day) = 6 ft/day

- Therefore,

  $Q = [6ft/day\ (30ft^2)\ (120 - 110ft)] / 2000ft$ Q

  = 0.9 ft^3/day **for each 1-foot length**

Pumping wells



Pumping Rate

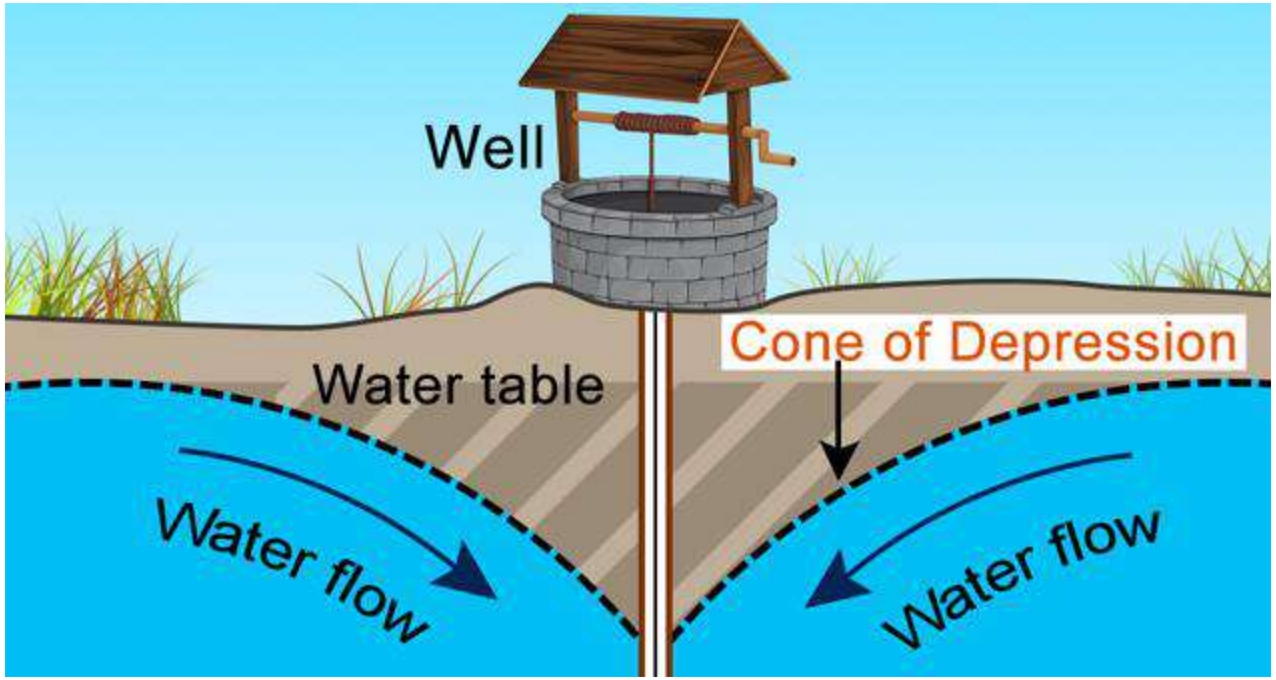
- The rate of which water is extracted from the pumping well.
- Usually written as Q.

Drawdown

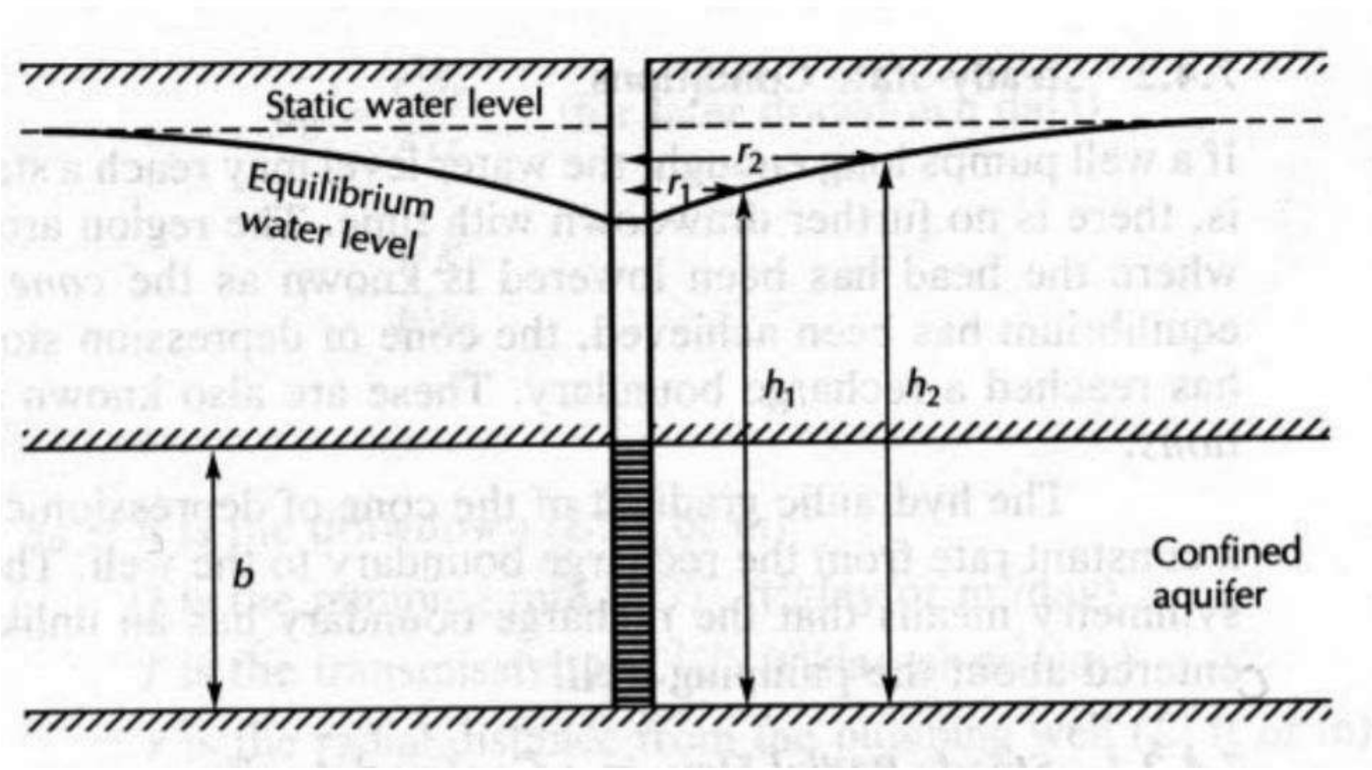
- Lowering of water table caused by pumping of wells.
- Defined as the difference between elevations of the current water table and water table before pumping began

Cone of depression

Cone of depression will form in the aquifer around a pumping well as the water level declines.



Steady-State Conditions

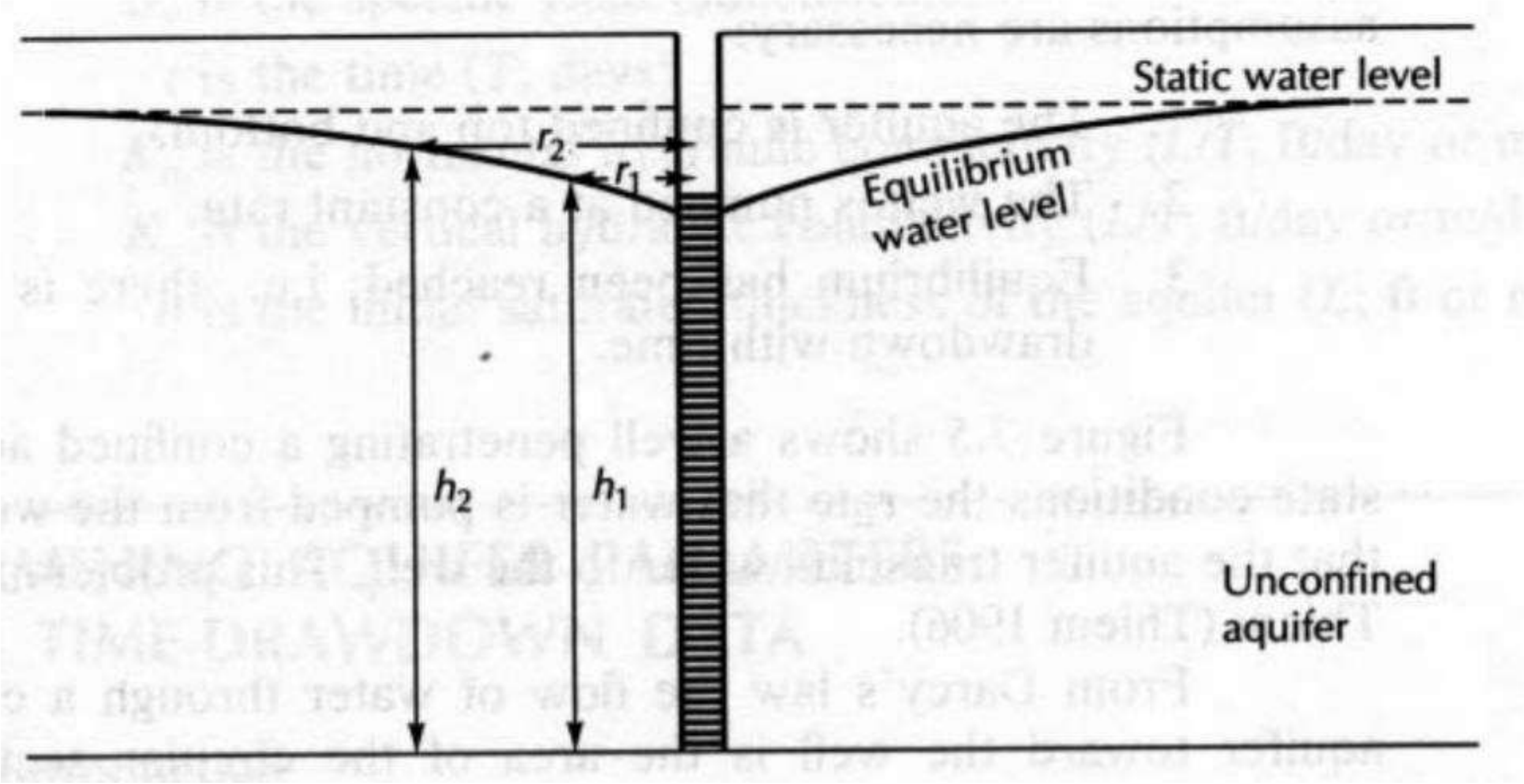


Equilibrium drawdown: A. confined aquifer

- Steady-state : No further drawdown with time.
- The cone of depression stops growing because it has reached a recharge boundary
- The hydraulic gradient of the cone of depression causes water to flow at a constant rate from the recharge boundary to the well

Steady Radial Flow in a Confined Aquifer

- Assumptions:
- The aquifer is confined at the top and bottom
- The well is pumped at a constant rate.
- Equilibrium has been reached; i.e., there is no further change in drawdown with time



Equilibrium drawdown: B. unconfined aquifer

From Darcy’s law:

$$Q = (2\pi rb)K(\frac{dh}{dr})$$

$$Q = 2\pi rT(\frac{dh}{dr})$$

$$dh = \frac{Q}{2\pi T}\frac{dr}{r}$$

$$\int_{h_1}^{h_2} dh = \frac{Q}{2\pi T}\int_{r_1}^{r_2} \frac{dr}{r}$$

$$h_2 - h_1 = \frac{Q}{2\pi T}\ln\left(\frac{r_2}{r_1}\right)$$

$$T = \frac{Q}{2\pi(h_2 - h_1)}\ln\left(\frac{r_2}{r_1}\right)$$

T- Transmissivity

Steady Radial Flow in an Unconfined Aquifer

$$Q = (2\pi r h) K (\frac{dh}{dr})$$

$$h dh = \frac{Q}{2\pi K} \frac{dr}{r}$$

Steady Radial Flow in an Unconfined Aquifer

$$\int_{h_1}^{h_2} h\,dh = \frac{Q}{2\pi K}\int_{r_1}^{r_2}\frac{dr}{r}$$

$$h_2^2 - h_1^2 = \frac{Q}{\pi K}\ln\left(\frac{r_2}{r_1}\right)$$

$$K = \frac{Q}{\pi(h_2^2 - h_1^2)}\ln\left(\frac{r_2}{r_1}\right)$$

Example

A 2-ft diameter well penetrates vertically through a confined aquifer 50 ft thick. When the well is pumped at 500 gpm, the drawdown in a well 50 ft away is 10 ft and in another well is 100 ft away is 3 ft. Take the initial piezometeric level as 100 ft above the datum. calculate the transmissivity

$$K = \frac{Q \ln(r_2/r_1)}{2\pi b\,(h_2 - h_1)} = \frac{500 \ln(100/50)}{2\pi\,(50)(97 - 90)} = 0.158 \text{ gpm/ft}^2$$

Then compute the transmissivity:

$$T = Kb = 0.158 \times 50 = 7.90 \text{ gpm/ft}$$

Example 1

A well fully penetrates a 25-m thick confined aquifer. After a long period of pumping at a constant rate of 0.05 m^3/s, the drawdowns at distances of 50 and 150 m from the well were observed to be 3 and 1.2 m, respectively. Determine the hydraulic conductivity and the transmissivity?

Example 1

$$K = \frac{Q}{2\pi b(h_2 - h_1)} \ln\left(\frac{r_2}{r_1}\right)$$

$$Q = 0.05 \frac{m^3}{sec} \cdot \frac{24 \times 60 \times 60 \text{ sec}}{day} = 4320 \; m^3/day$$

$b = 25$ m

$$\Rightarrow \quad K = \frac{4320}{2\pi(25)(1.8)} \ln\left(\frac{150}{50}\right)$$

$$K = 16.8 \; m/day$$

Transmissivity (T)

$$T = Kb$$
$$= 16.8\,(25)$$
$$\Rightarrow \quad T = 420 \; m^2/day$$

Example 2

A well fully penetrates an unconfined aquifer. Prior to pumping the water level (head) is h_o = 25 m After a long period of pumping at a constant rate of 0.05 m^3/s, the drawdowns at distances of 50 and 150 m from the well were observed to be 3 and 1.2 m, respectively. Compute the hydraulic conductivity of aquifer?

Example 2

$$K = \frac{Q}{\pi(h_2^2 - h_1^2)} \ln\left(\frac{r_2}{r_1}\right)$$

$$= \frac{4320}{\pi(238^2 - 22^2)} \ln\left(\frac{150}{50}\right)$$

$$K = 18.3 \text{ m/day}$$

Example 3

A well 0.5 m in diameter penetrates 33 m below the static water table. After a long period of pumping at a rate of 80 m^3/hr., the drawdowns in wells 18 and 45 m from the pumped well were found to be 1.8 and 1.1 m respectively. What is hydraulic conductivity of the aquifers?

Example 3

$$K = \frac{Q}{\pi(h_2^2 - h_1^2)} \ln\left(\frac{r_2}{r_1}\right)$$

$$h_1 = 33 - 1.8 = 31.2 \text{ m}$$

$$h_2 = 33 - 1.1 \doteq 31.9 \text{ m}$$

$$K = \frac{1920 \text{ m}^3/\text{day}}{\pi(31.9^2 - 31.2)^2} \ln\left(\frac{45}{18}\right)$$

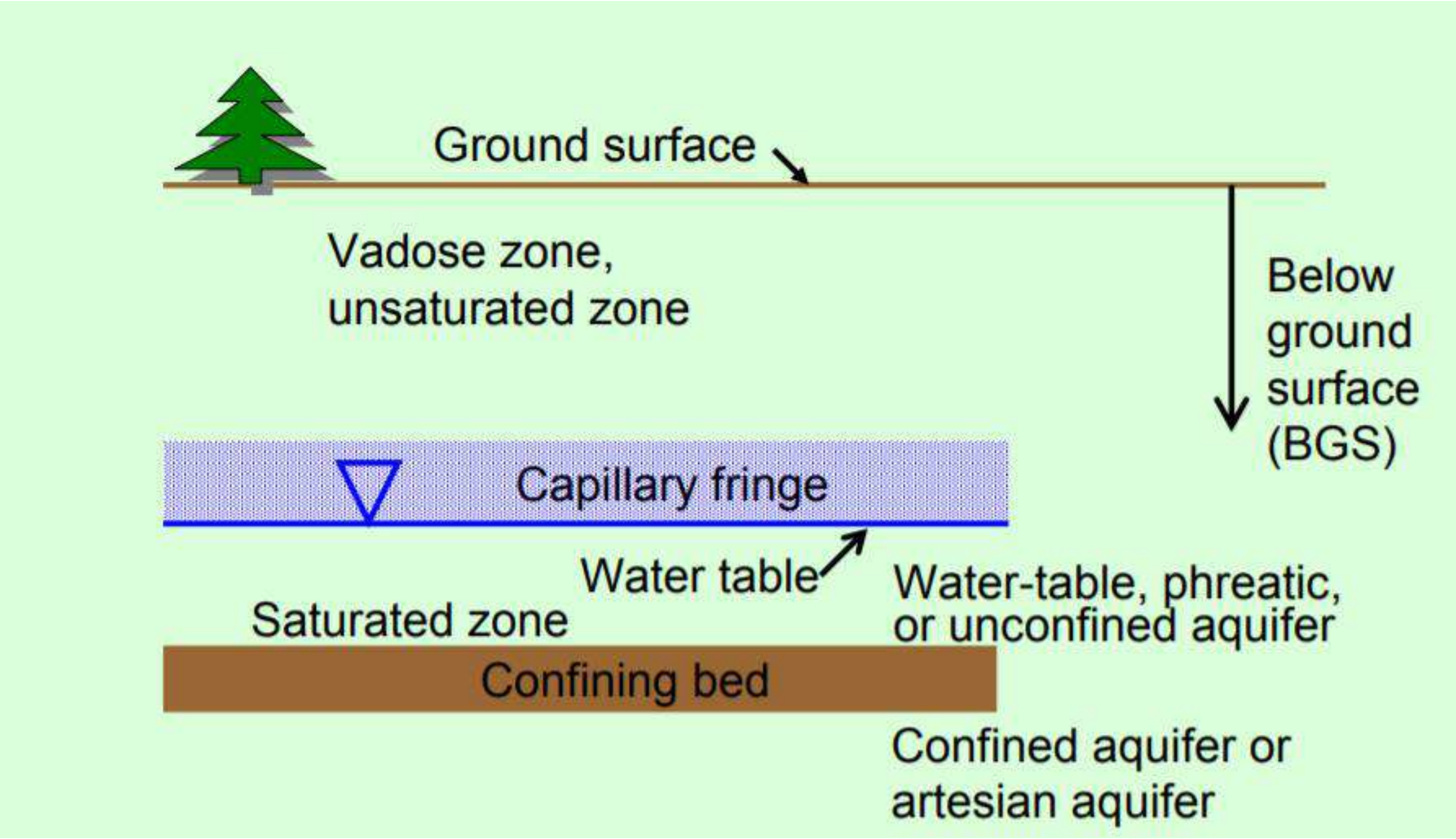
$$\Rightarrow K = 12.7 \text{ m/day}$$

Contaminant Transport in Groundwater Mechanisms and Principles

* Nearly all GW originates as rain or snow that infiltrates to the saturated zone

*Infiltration through soil zone / vadose zone & flow in saturated zone influences chemistry of water

***Contaminant transport & fate** refers to the physical, chemical, and biological processes that impact the movement of the contaminants from point A to point B and how these contaminants may be altered while they are transported.



Controls on Contaminant Distribution

*Physical & chemical characteristics of earth materials

– Porosity

– Permeability

– Organic carbon content

– Cation exchange capacity

*Hydraulics of the flow system

– Groundwater velocity (Advection)

- Hydraulic conductivity

– Permeability (property of the aquifer)

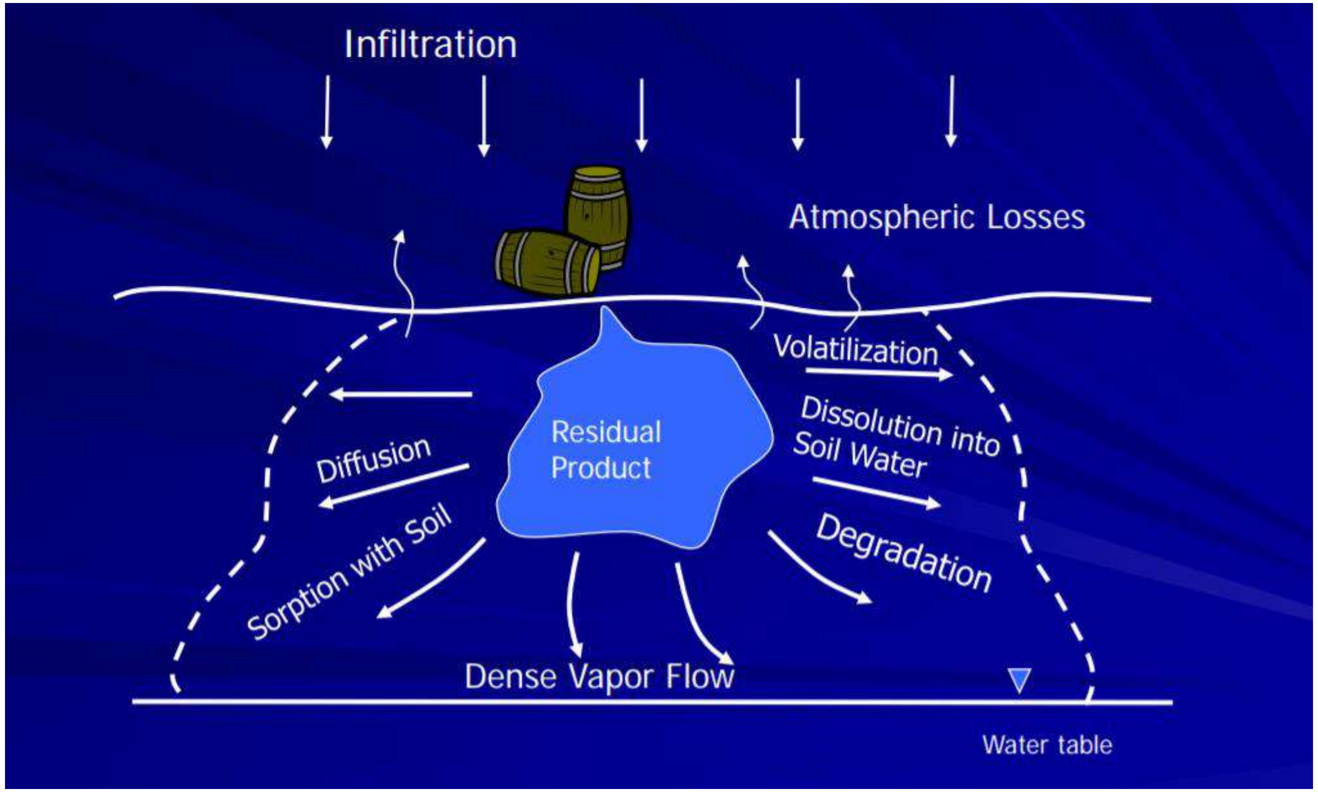
– Fluid density, specific gravity, dynamic viscosity Hydraulic gradient

Natural processes that tend to remove or degrade :

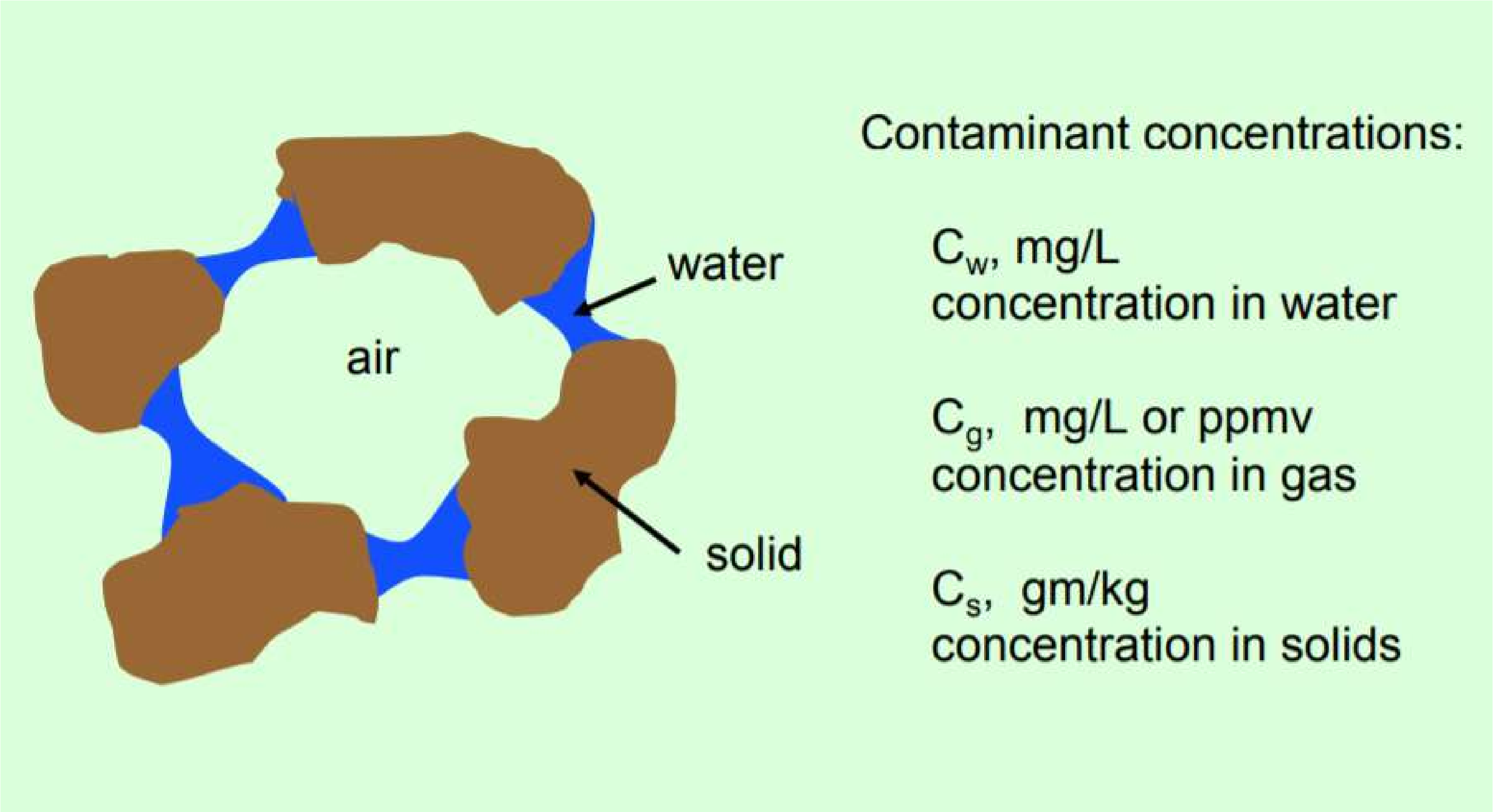
– Advection
– Dispersion
– Partitioning
  Sorption
  Dissolution/Precipitation
  Volatilization

– Biological transformation

– Abiotic transformation
Complexation
Acid-base reactions
Redox reactions



Micro View Of Unsaturated Zone



How to convert mg/ L to ppmV!

Partitioning Relationships

A **partition coefficient** (***P***) or **distribution coefficient** (***D***) is the ratio of concentrations of a compound in a mixture of two immiscible solvents at equilibrium

Solid ↔ water

$$\frac{C_s}{C_w} = K_d = \frac{\text{mg/kg solid}}{\text{mg/L water}}$$

K_d = partition coefficient

Water ↔ vapor

$$\frac{C_g}{C_w} = H = \frac{\text{mol/m}^3\text{ air}}{\text{mg/m}^3\text{ water}}$$

H = Henry's Law constant

Henry's law is a gas law that states that the amount of dissolved gas in a liquid is proportional to its partial pressure above the liquid. The proportionality factor is called Henry's law constant

Henry’s Law Constant

H has dimensions: atm m^3 / mol

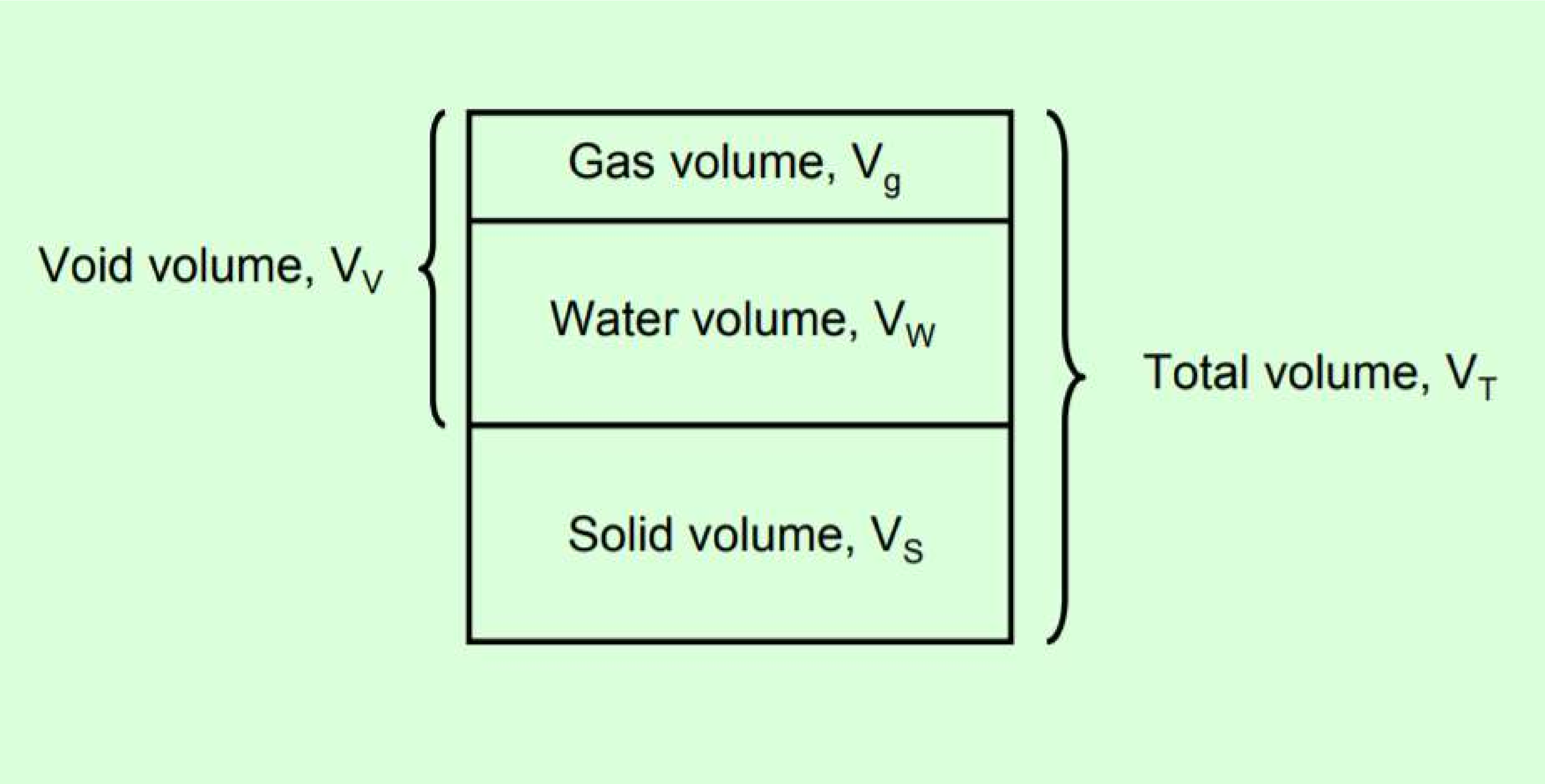
H’ is dimensionless

H’ = H/RT

R = gas constant = 8.20575×10^{-5} atm m^3/mol °K

T = temperature in °K

Volume Representation



Volume-related Properties

$$\text{Bulk density} = \rho_b = \frac{\text{mass of solids}}{\text{total volume}}$$

$$\text{Porosity} = n = \theta = V_V/V_T$$

Volumetric water content or

$$\text{water-filled porosity} = \theta_W = V_W/V_T$$

$$\text{Saturation} = S = V_W/V_V$$

$$\text{Gas-filled porosity} = \theta_g \ (\text{or } \theta_a) = V_g/V_T$$

$$\theta_W + \theta_g = n$$

Contaminant Concentration In Soil

Total mass in unit volume of soil:

$$C_T = \rho_b C_s + \theta_w C_W + \theta_g C_g$$

If soil is saturated, $\theta_g = 0$ and $\theta_W = n$

$$C_T = \rho_b C_s + n C_W$$

Nomenclature For Darcy's Law

$Q = K\,i\,A$

K = hydraulic conductivity

i = hydraulic gradient = dh/dL

A = cross-sectional area

Velocity of ground-water movement

$u = Q / nA = q / n = K\,i / n$ = average linear velocity

nA = area through which ground water flows

$q = Q / A$ = Darcy seepage velocity = Specific discharge

For transport, n is n_e, effective porosity

Advective Flux

Advection is mechanical transport of solutes along with the bulk flux of the water.
Transport with pore water.

Advective fluxes are simply the product of the water flux from Darcy's law with the solute concentration:

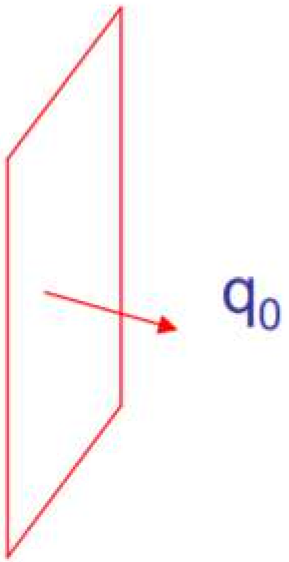
$$\bar{J}_{\mathrm{a}} = C\bar{\bar{K}}\nabla h = C\bar{q}$$

where J¯a is the advective solute flux, *C* the volume concentration, K= the hydraulic conductivity tensor, ∇h the hydraulic head gradient, and q¯ the specific discharge. Advection transports all solutes at the same rate.

Diffusive Flux

Diffusion is the net movement of anything from a region of higher concentration to a region of lower concentration.
Spreading due to gradient in concentrations

Brownian motion is the random motion of particles suspended in a fluid resulting from their collision with the fast-moving molecules in the fluid.



Movement of mass by molecular diffusion (Brownian motion) – proportional to concentration gradient

$$q_0 = -D_o \frac{\partial C}{\partial x}$$

← Concentration gradient

D_O is molecular diffusion coefficient [L^2/T]

Diffusive Flux

– Process by which molecules move under the influence of their kinetic activity in the direction of their (decreasing) concentration gradient.

– Occurs whether or not there is bulk flow of groundwater.

– Ceases only when concentration gradients become nonexistent.

Diffusive Flux

In porous medium, geometry imposes constraints:

$$J_D = -\tau \, D_O \, n \frac{\partial C}{\partial x} = -D^* n \frac{\partial C}{\partial x}$$

τ = tortuosity factor

D^* = effective diffusion coefficient

Factor n must be included since diffusion is only in pores

Tortuosity

Solute must travel a tortuous path, winding through pores and around solid grains

Common empirical expression: $$\tau = \left(\frac{L}{L_e}\right)^2$$

L = straight-line distance

L_e = actual (effective) path

$\tau \approx 0.7$ for sand

Dispersion Flux

Mixing that occurs as a consequence of pore-scale variations in groundwater velocity.

- Spreading due to:
  - pore to pore variation in velocity
  - velocity variation within the pores

$$q_M = -D_M \frac{\partial c}{\partial x}$$

Concentration gradient

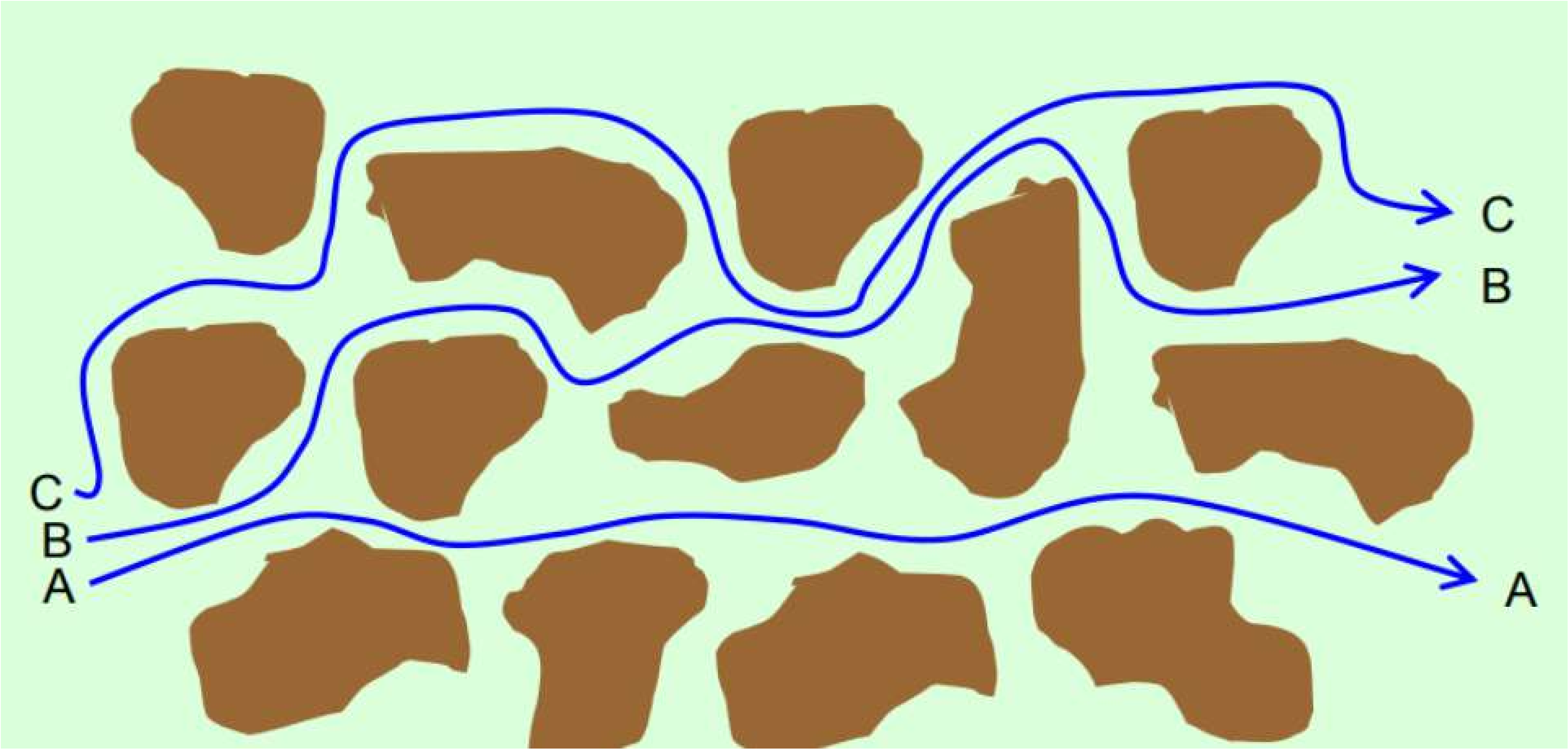
Mechanical dispersion coefficient

$$D_M = \alpha \cdot v_a$$

Pore velocity

Dispersivity

Mechanical Dispersion



A arrives first, then B, then C → mechanical dispersion

Mechanical Dispersion

Viewed at micro-scale (i.e., pore scale) arrival times A, B, and C can be predicted

Averaging travel paths A, B, and C leads to apparent spreading of contaminant about the mean

Spatial averaging → dispersion

Mechanical Dispersion

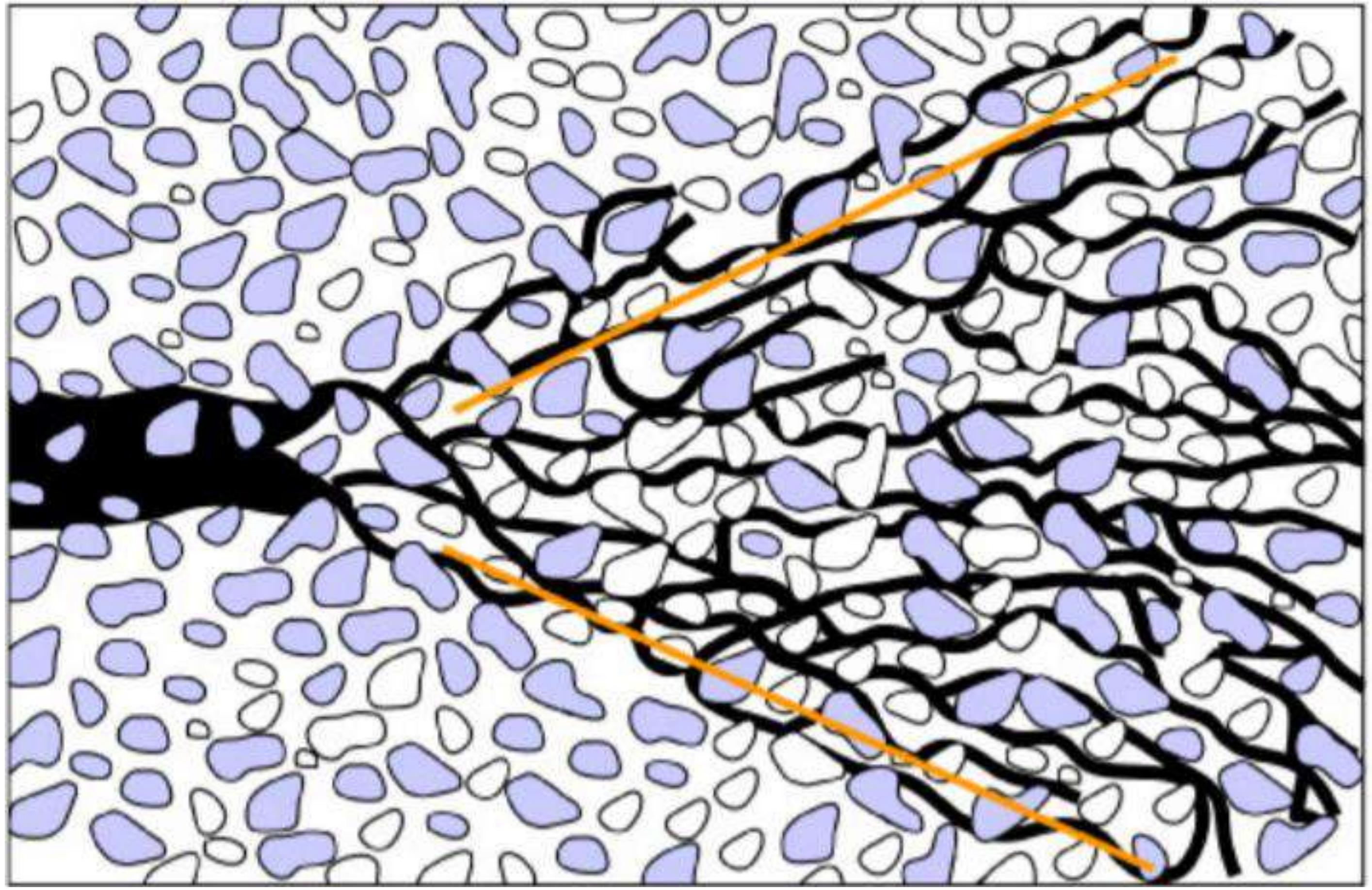
Dispersion can be effectively approximated by the same relationship as diffusion—i.e., that flux is proportional to concentration gradient:

$$J_M = -D_M n \frac{\partial C}{\partial x}$$

Dispersion coefficient, $D_M = \alpha_L u$

α_L = longitudinal dispersivity (units of length)

Traditional View Of Hydrodynamic Dispersion



Transport Equation

Combined transport from advection, diffusion, and dispersion (in one dimension):

$$J = J_A + J_D + J_M$$

$$J = nuC - D^* n \frac{\partial C}{\partial x} - D_M n \frac{\partial C}{\partial x}$$

$$J = nuC - D_H \frac{\partial C}{\partial x}$$

$D_H = D^* + D_M = \tau D_O + \alpha_L u$

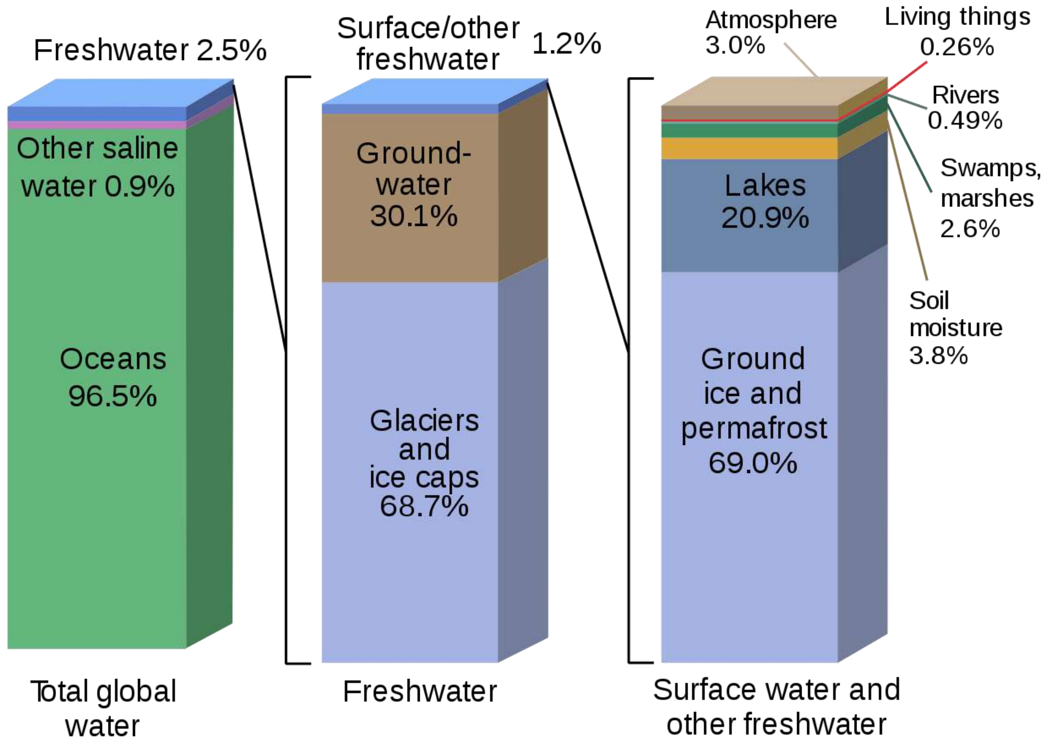
= hydrodynamic dispersion

Engineering Hydrology

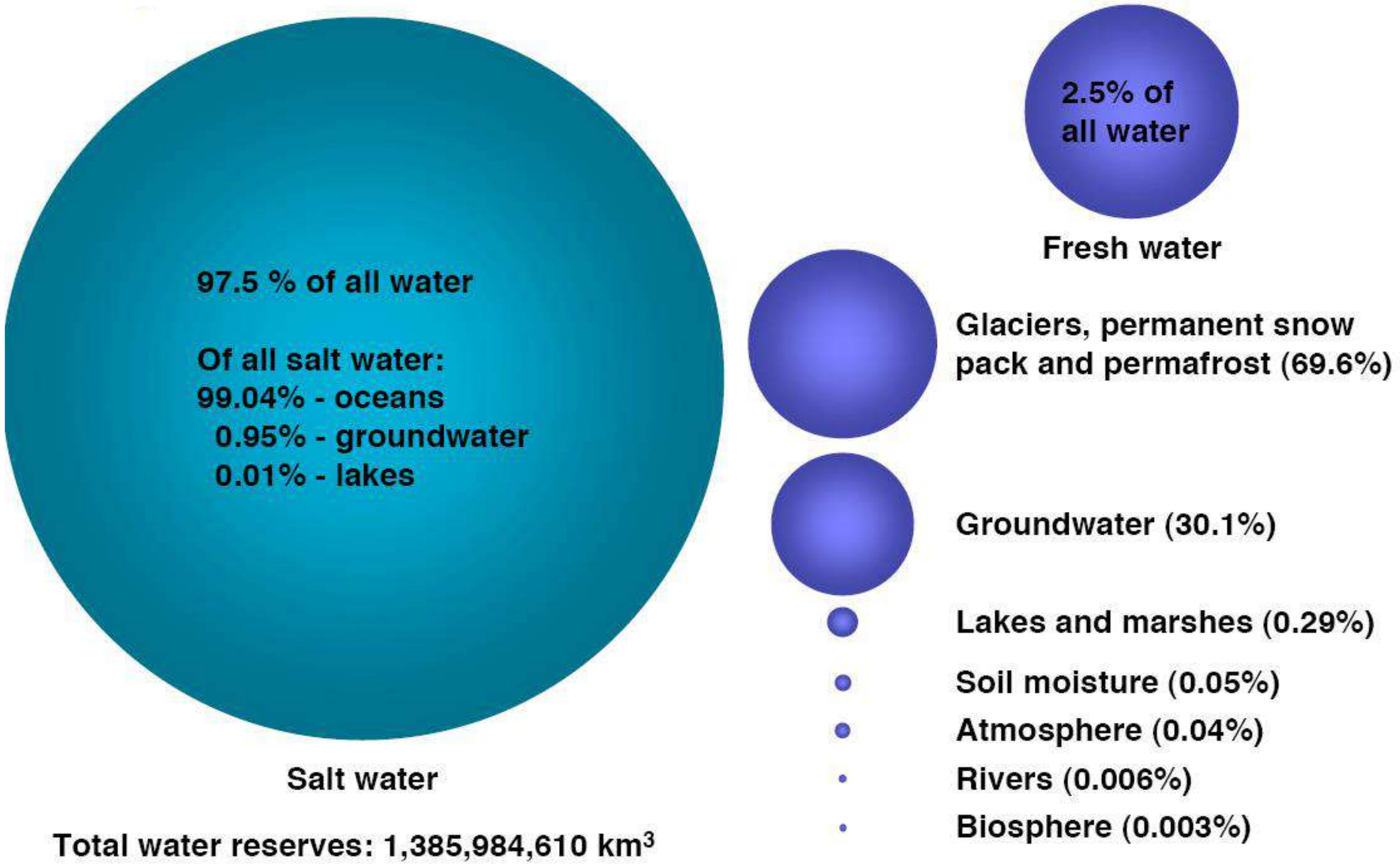
Introduction to water resources

Water resources

- Water resources are natural resources of water that are potentially useful.
- Uses of water include agricultural, industrial, household, recreational and environmental activities.



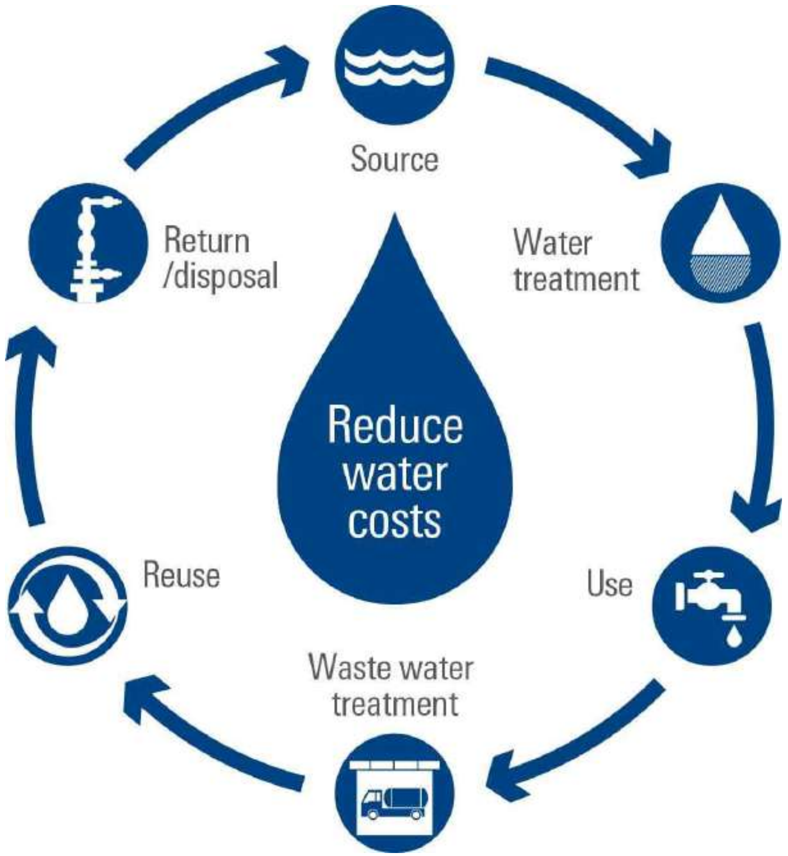
Major Reservoirs of Water



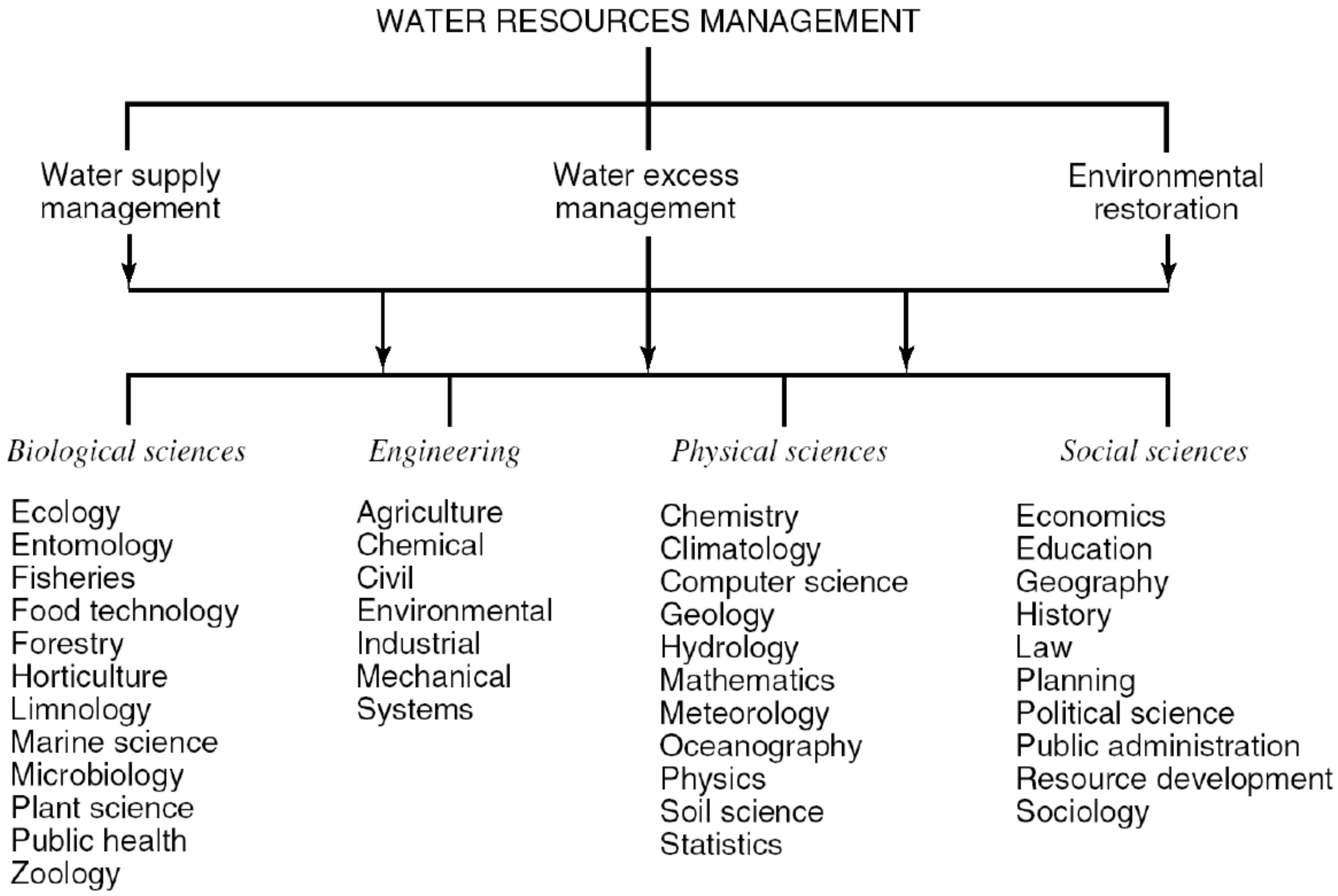
Iceberg and Polar cap store most of the fresh water on Earth.

Water management

- **Water resource management** is the activity of planning, developing, distributing and managing the optimum use of water resources.



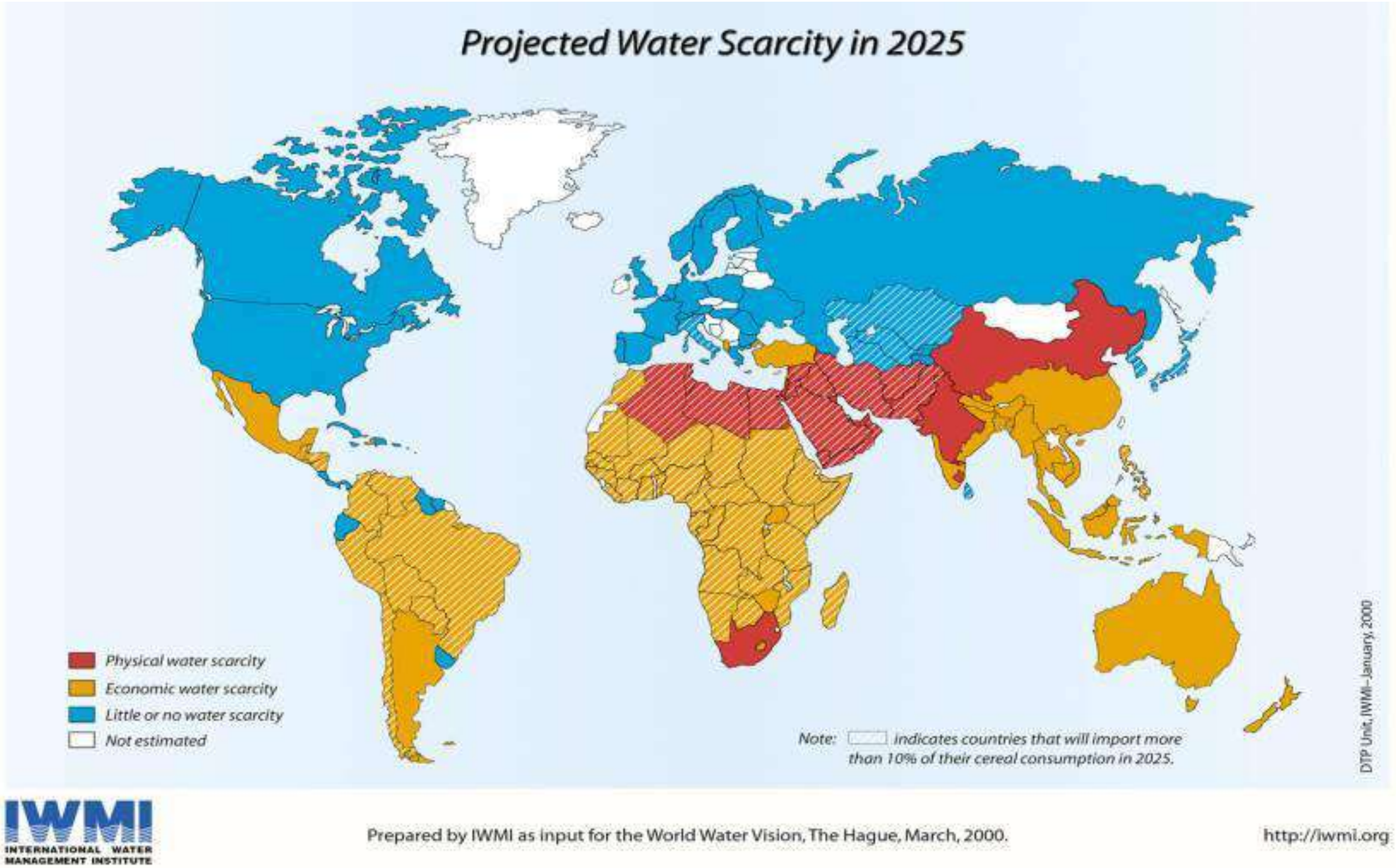
What is Water Resources Engr./Manag.?



The Future?

By the year 2025 nearly 2 billion people will live in regions or countries with absolute water scarcity, even allowing for high levels of irrigation efficiency.

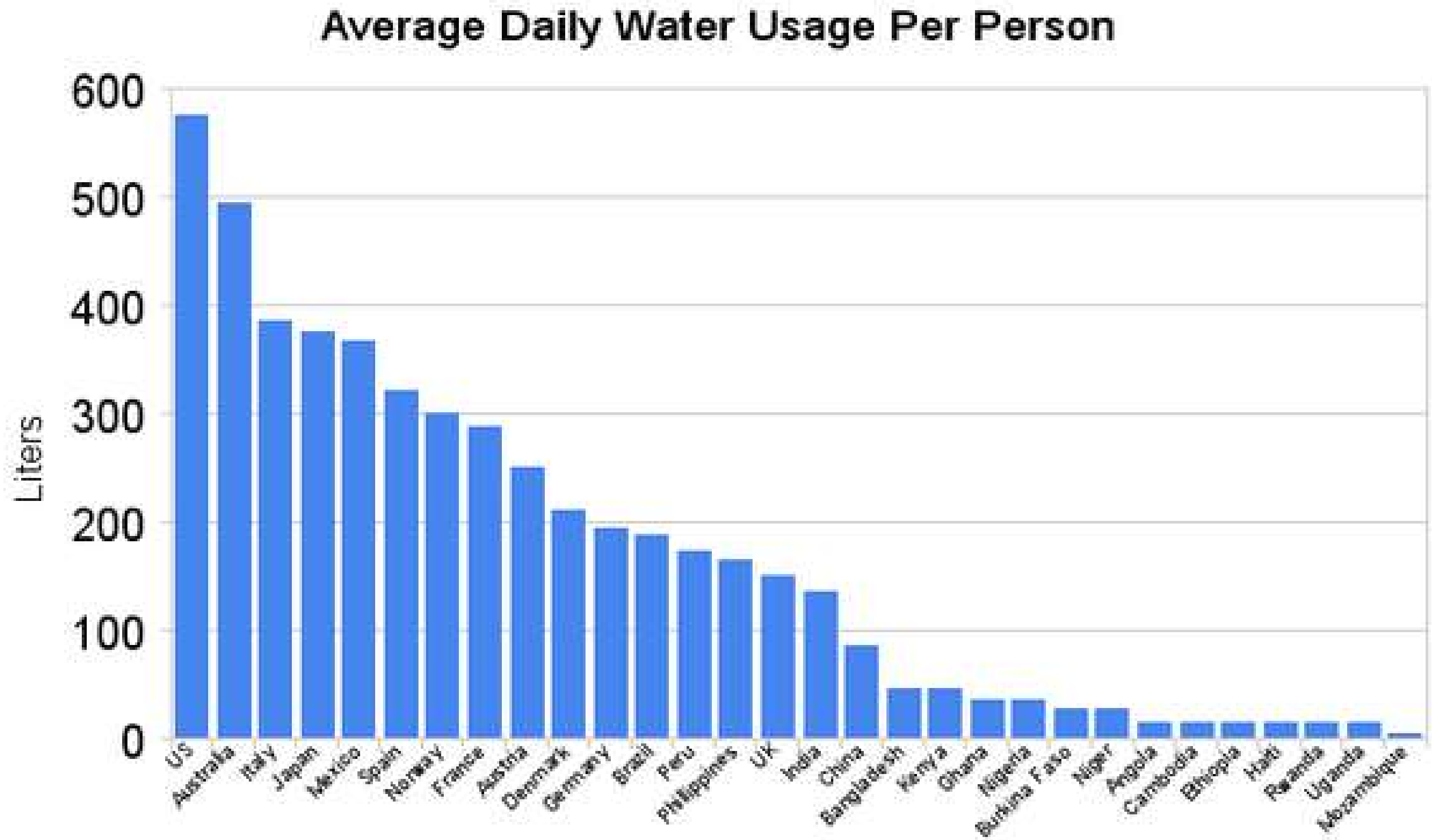
Year	World Population (billions)
2010	6.8
2020	7.6
2030	8.2
2040	8.7



Typical Domestic Water Use

- 100-600L/person/day (high-income countries)
- 50-100L/person/day (low-income)
- 10-40L/person/day (water scarce)

    - Differences in domestic freshwater use:
    - Piped distribution or carried number/type of appliances and sanitation



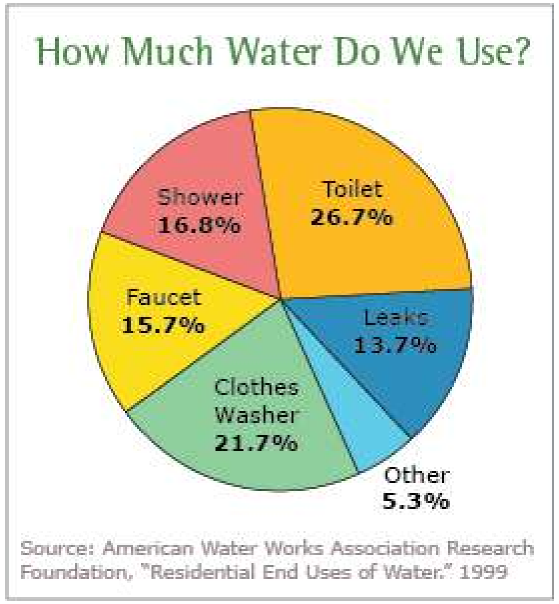
Average Daily Water Usage Per Person
Liters
0
100
200
300
400
500
600
US
Australia
Italy
Japan
Mexico
Spain
Norway
France
Austria
Denmark
Germany
Brazil
Peru
Philippines
UK
India
China
Bangladesh
Kenya
Ghana
Nigeria
Burkina Faso
Niger
Angola
Cambodia
Ethiopia
Haiti
Rwanda
Uganda
Mozambique

Human Usage

What are water needs for humans?

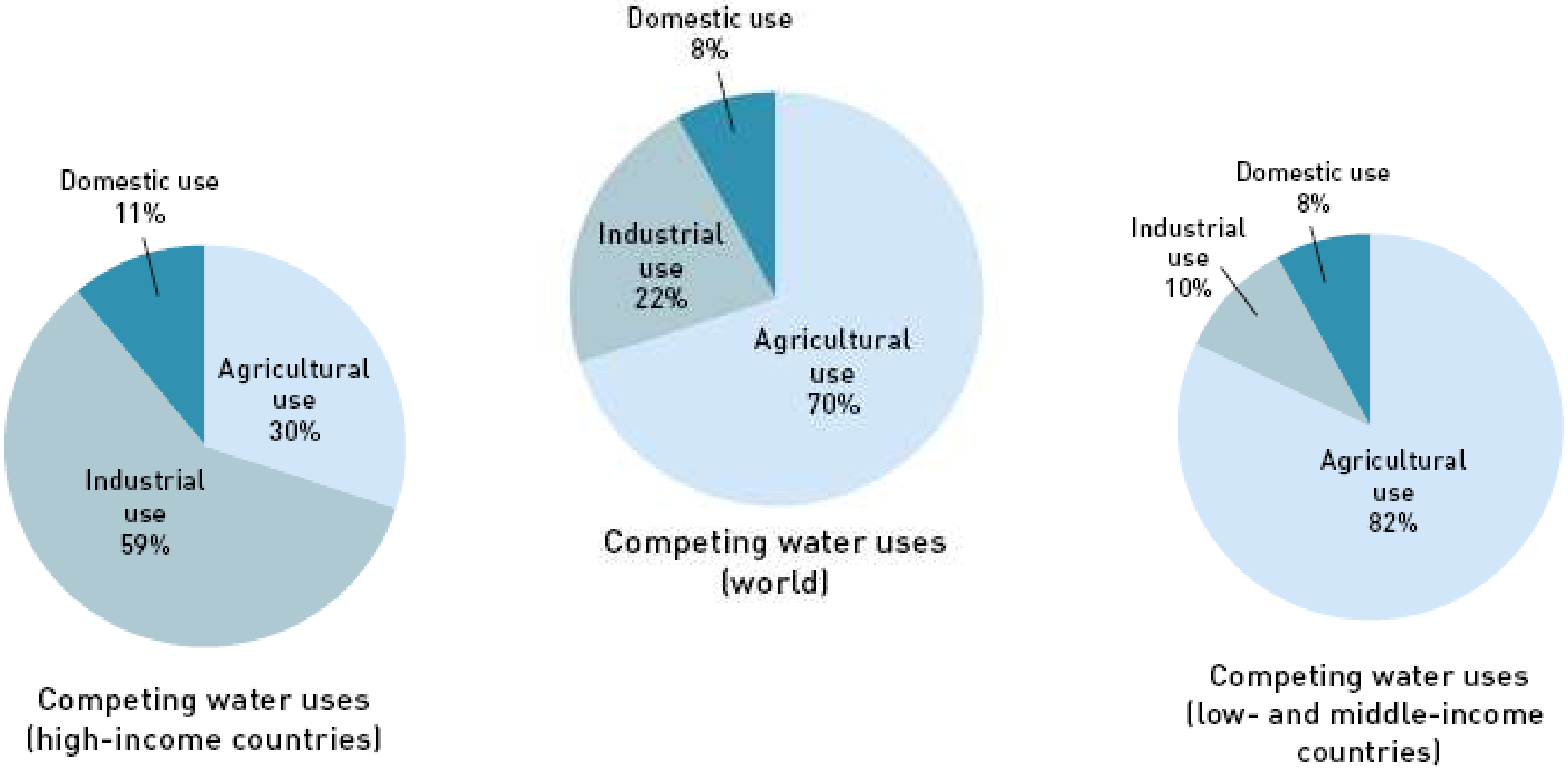
Primitive conditions – 3 to 5 gallons/day
Urban use – 150 gallons/day
US Fresh Water Use – 1,340 gallons/day

Where does the water go? To make things…to clean things….



Item	Gallons
1 pound of cotton	2,000
1 pound of grain-fed beef	800
1 loaf of bread	150
1 car	100,000
1 kilowatt of electricity	80
1 pound of rubber	100
1 pound of steel	25
1 gallon of gasoline	10
1 load of laundry	60
1 ten-minute shower	25-50

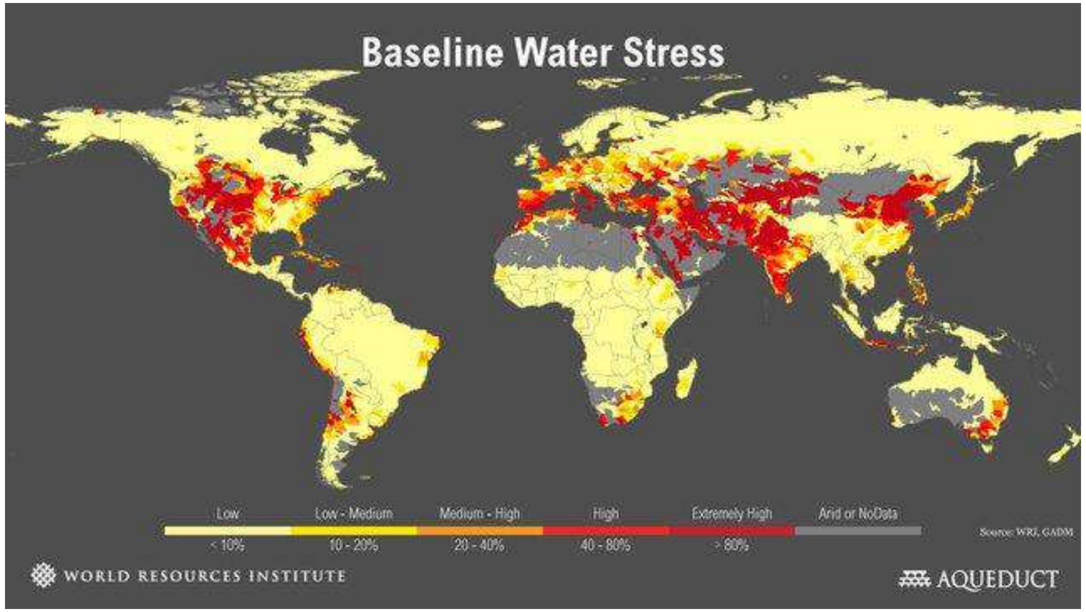
Competing water uses



Water Stress

- Water stress occurs when the demand for water exceeds the available amount during a certain period or when poor quality restricts its use.

- Based on human consumption and linked to population growth
- Domestic requirement:
  - 100L/person/day = 40m^3/person/year
  - 600L/person/day = 240m^3/person/year
- Associated agricultural, industrial & energy need:
  - 20 x 40m^3/person/year = 800m^3/person/year
- Total need:
  - 840m^3/person/year
  - 1040m^3/person/year



Distribution of population and water resources

Threats to fresh water resources

- Climate change causes change in frequencies of droughts and floods.
- Depletion of aquifers caused by over-consumption as a result of population growth.
- Pollution and contamination by sewage, agricultural and industrial runoff.