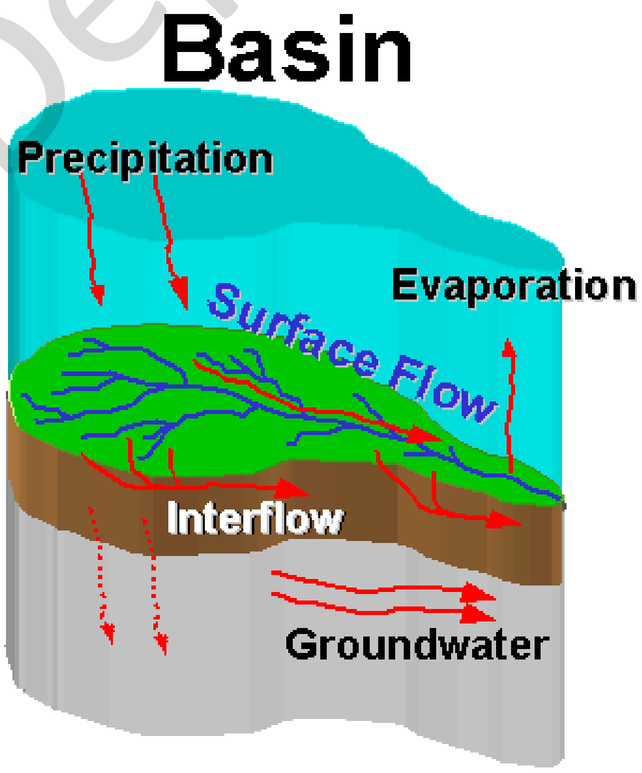
Chapter 2

Hydrologic Processes

Basin Characteristics

- Basin characteristics define system's response.
- For any section on a river, the area above that section which gives all its surface waters to this river passing through that section is called the basin (drainage basin, catchment, watershed)



http://www3.gov.ab.ca/env/water/GWSW/quantity/learn/What/HC_HydroCycle/HC_Images/HC3_basin.gif

Basin

- Basin is a transfer system which converts precipitation into streamflow.
- Engineering hydrology mainly deals with:
  - Monthly and annual volumes of water available for storage and use
  - Low flow rates which restrict in stream uses of water
  - Floods
- Detailed analysis of flood hydrographs is usually required in
  - Flood forecasting
  - Flood damage mitigation (flood control)
  - Design flows for hydraulic structures

Basin Characteristics

Geomorphologic Characteristics
- Area
- Shape
- Slope

constant

Hydrologic Characteristics
- Stream shape
- Infiltration capacity
- Vegetal cover
- Soil physics

change with time
(i.e. one storm to another, one season to the next)

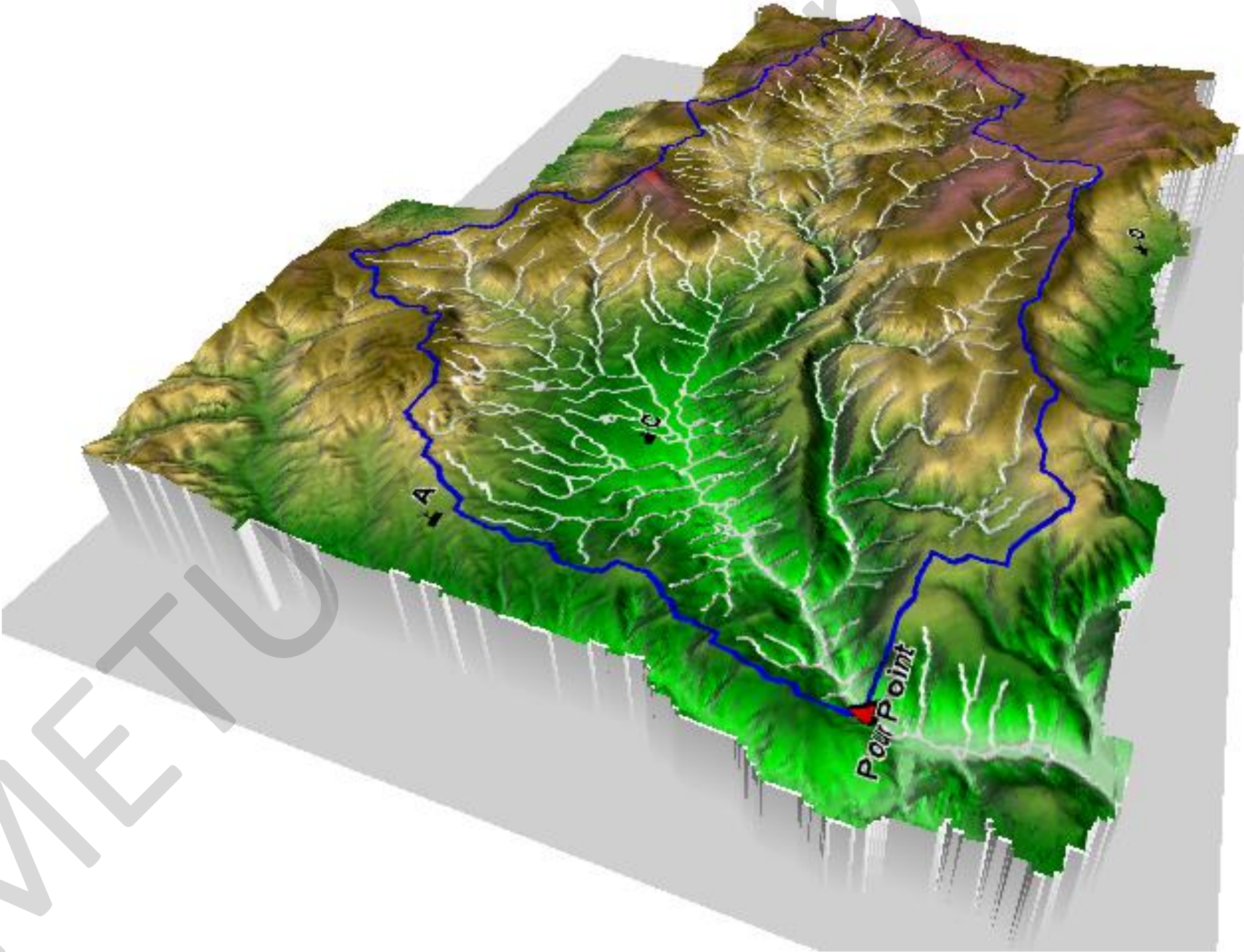
Perimeter = Boundary = Basin Divide
(Passes through highest points between adjacent basins)

Area, Perimeter and Shape of the Basin

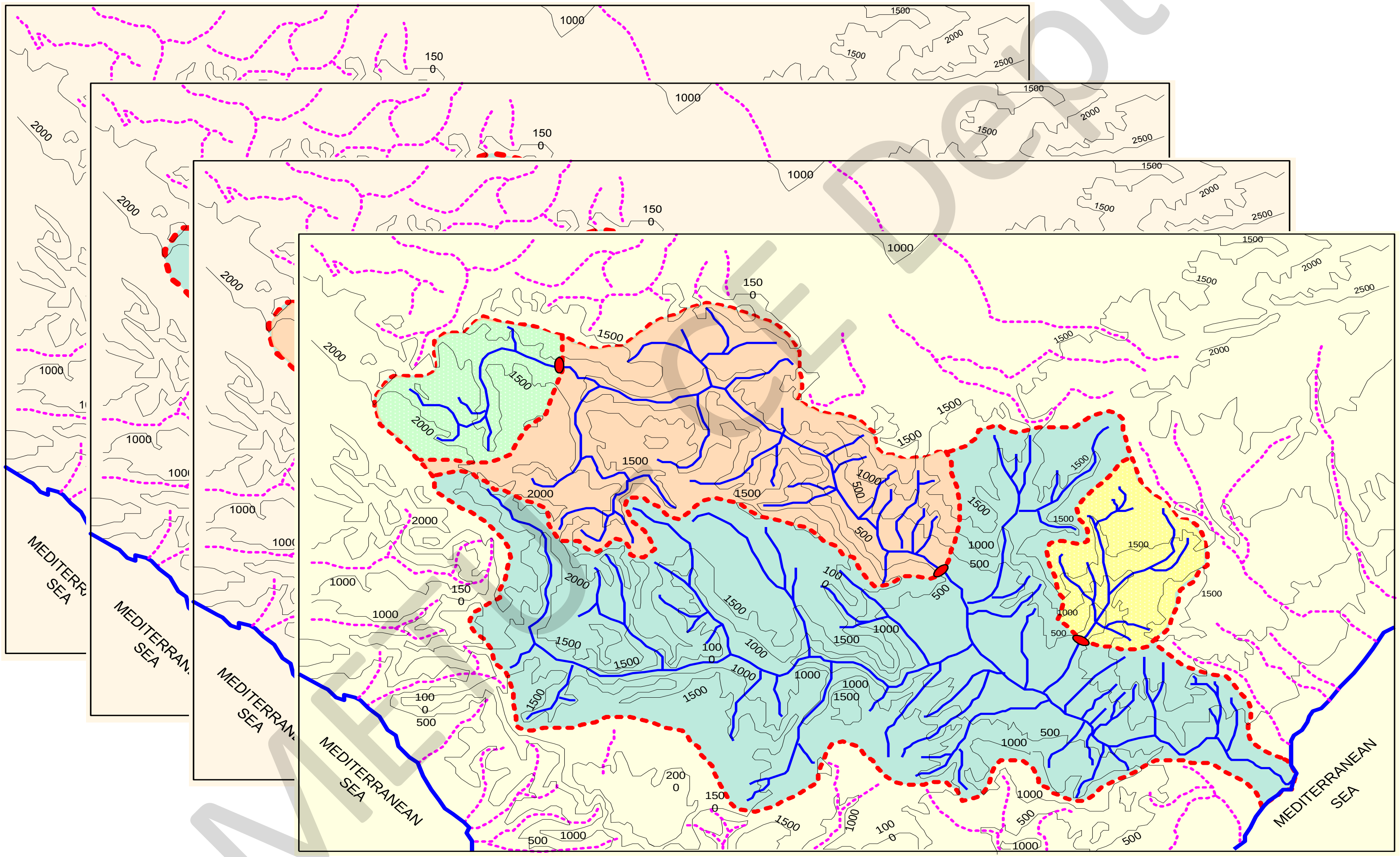
- The line that separates adjacent basins, passing through the highest points between them and leaving all branches of different rivers at opposite sides, is called water divide or basin boundary.
- The area in this boundary is the drainage area or simply area of the basin.
- The length of the boundary is called the perimeter.
- Area & perimeter are measured on the topographic map as their horizontal projection values.

Area, Perimeter, and Shape of the Basin

Sohu Basin found from digital elevation model (DEM)



Area, Perimeter and Shape of the Basin



Situation in Turkey

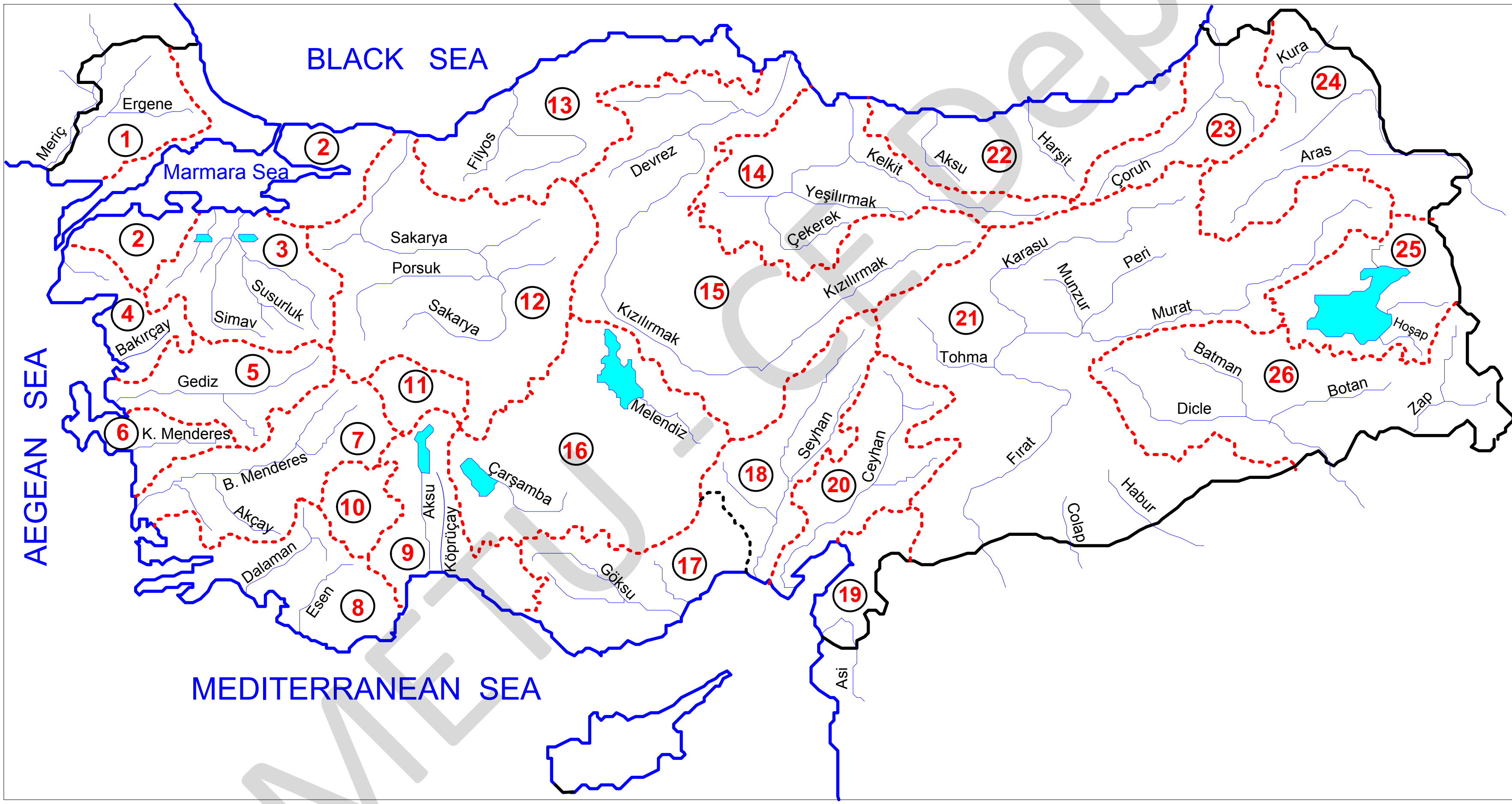


Figure 4.1 Streamflow measuring regions in Turkey

Area, Perimeter, and Shape of the Basin

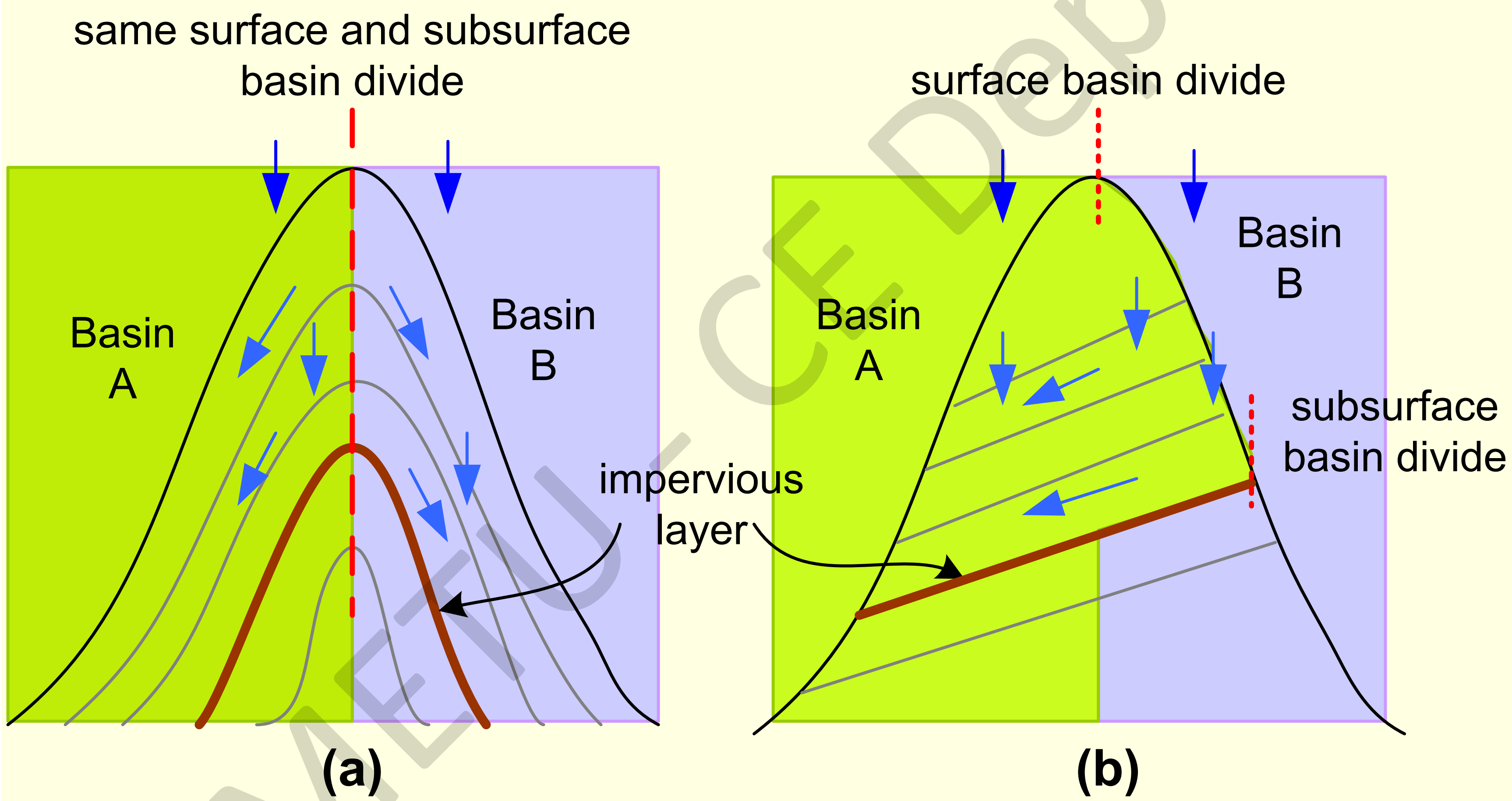
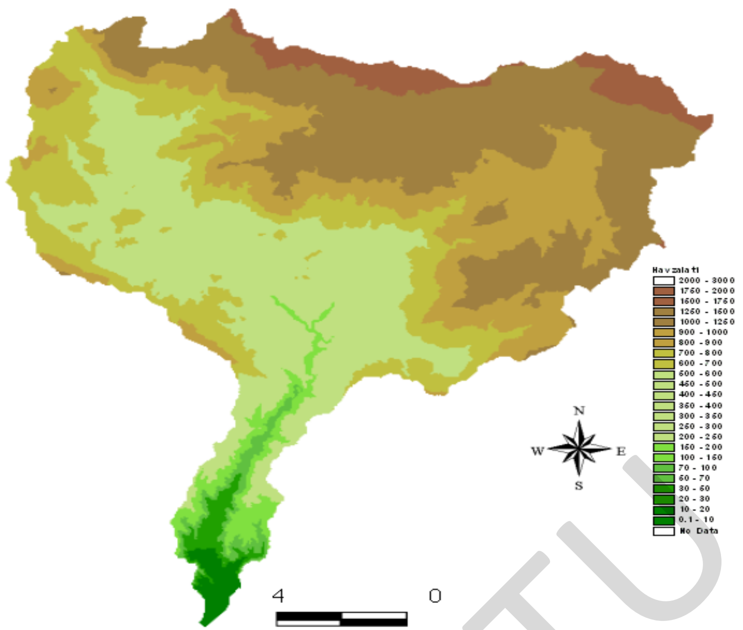
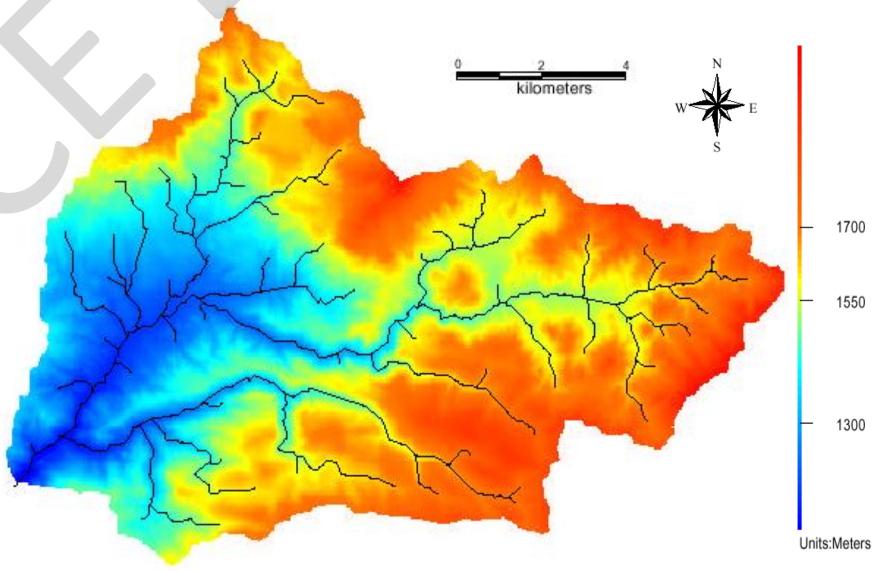


Figure 6.4 Water divide for surface and subsurface basins

Different basin shapes from Turkey

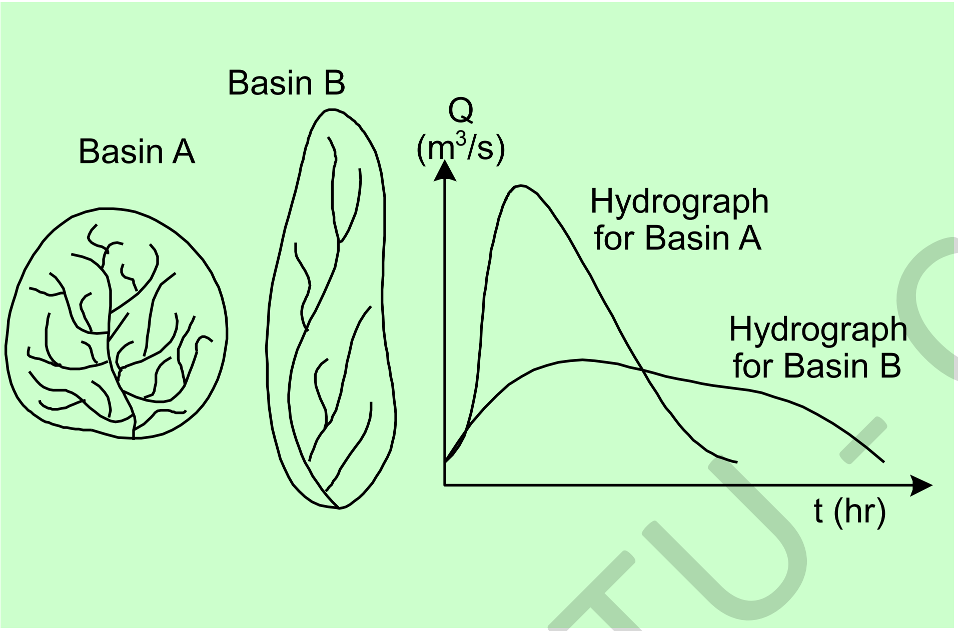


Çayboğazı Basin

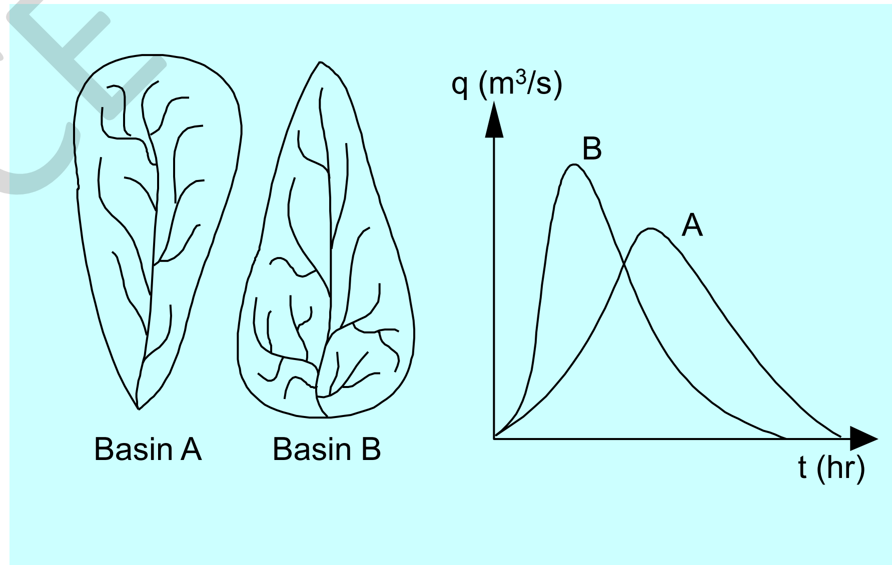


Sohu Basin

Shape & Orientation



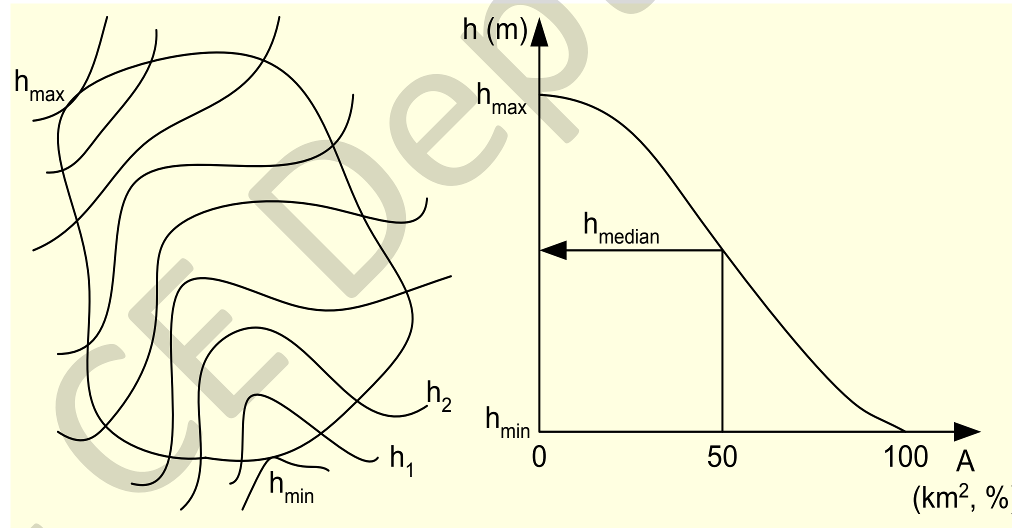
Response of the basin to ppt
for circular and elongated basins

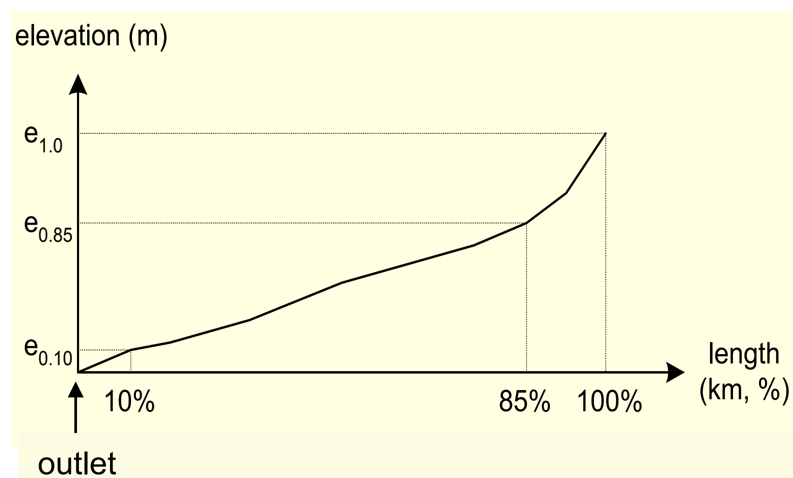


Early or late peak in hydrograph wrt
the orientation of a pear-shaped basin

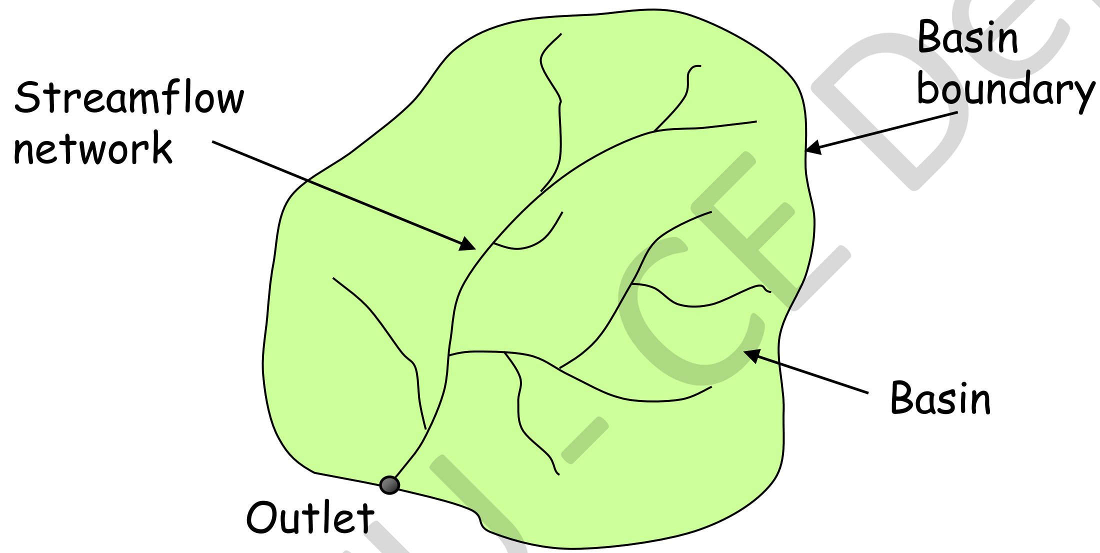
Gradient

- Area-elevation (hypsometric) curve
- Relief
  - Max. relief (diff. between highest and lowest points)
  - Max. basin relief (diff. between highest on the boundary and lowest points)
- Slope of the river bed is found from the longitudinal profile of the river.



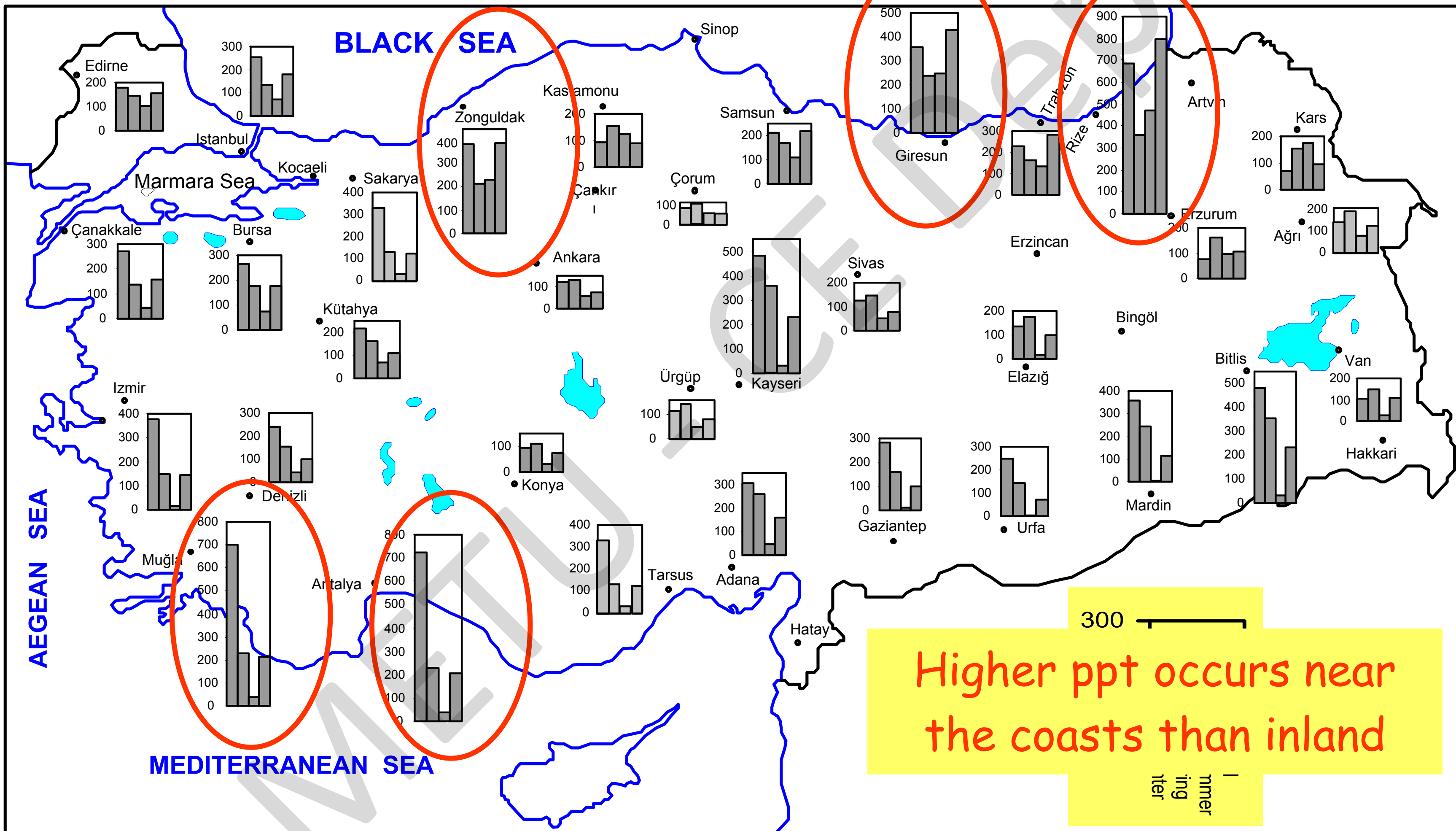


Precipitation → all forms of water coming from the atmosphere to the Earth



- Mean annual precipitation on Earth → 800 mm.
- Mean annual precipitation in Turkey → 643 mm.
  - lowest in Himmetdede (Kayseri), 63.3 mm (1933)
  - highest in Rize, 4043.3 mm (1931)

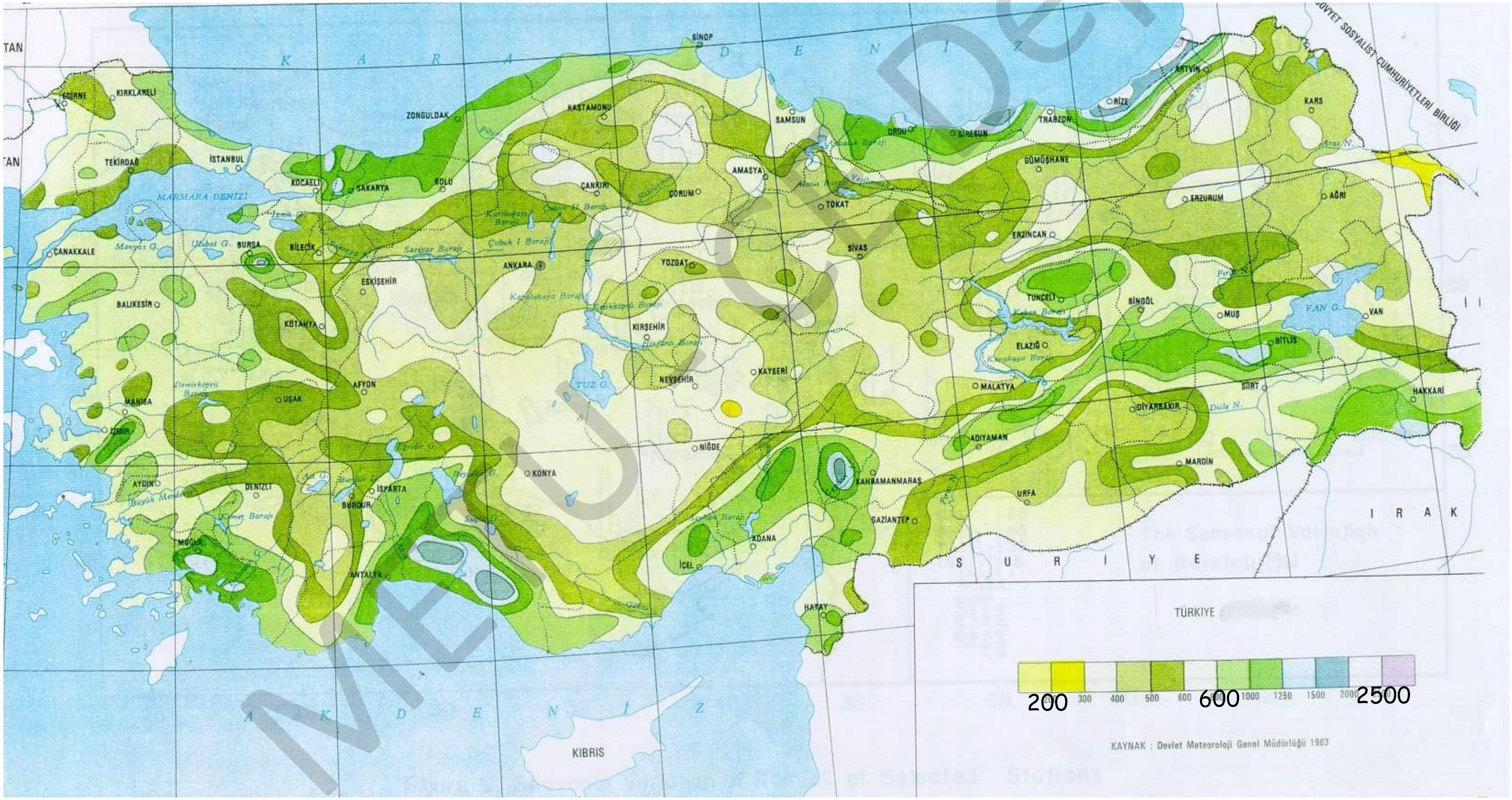
PRECIPITATION → varies in area & in time



Higher ppt occurs near the coasts than inland

Figure 3.1 Distribution of seasonal rainfall in Turkey

Distribution of mean annual rainfall



MEASUREMENT OF PRECIPITATION

- TOTAL DEPTH WITHIN A CERTAIN PERIOD OF TIME
- ITS VARIATION IN THIS PERIOD WITH THE FOLLOWING

TYPES OF MEASURING INSTRUMENTS:

1. NON-RECORDING RAIN GAGES
2. RECORDING RAIN GAGES

http://www.fotolibra.com/gallery/451724/homemade-rain-gauge/

Rainfall intensity can be calculated

http://wb8.itrademarket.com/pdimage/78/987978_raingaugehd2013-2013-d_m_uk.jpg

Weighing Gauges (recording rain gauge)

- Generally a daily chart is used for the diagrams
- For remote locations weekly charts can also be used (revolving drum completes one revolution in seven days)
- Weekly charts donot have the same detail as daily charts.

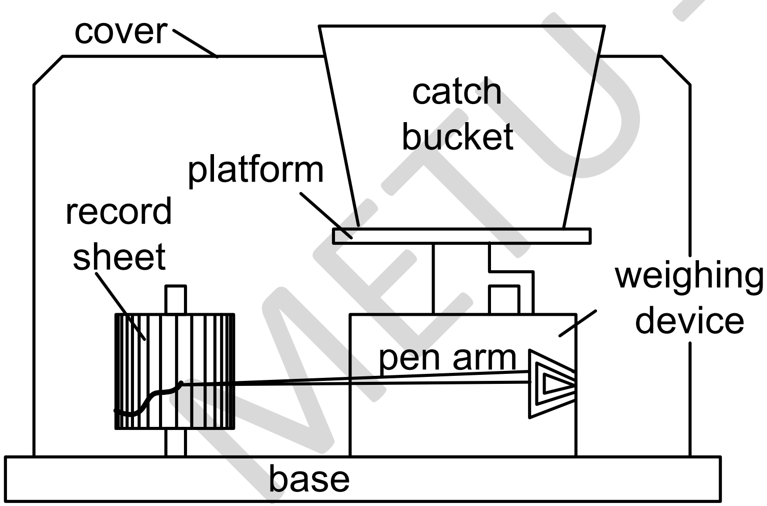


Figure 3.5a Recording rain gauge (Weighing type)

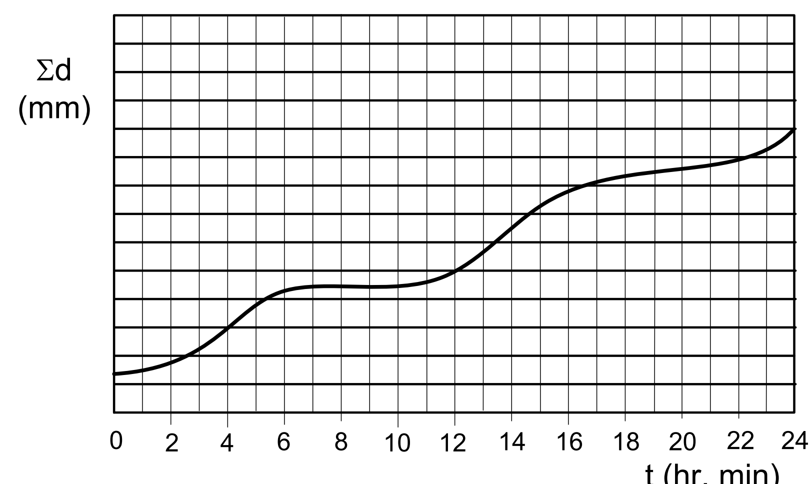
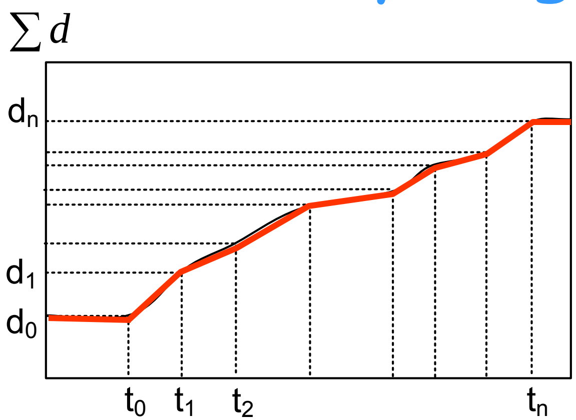


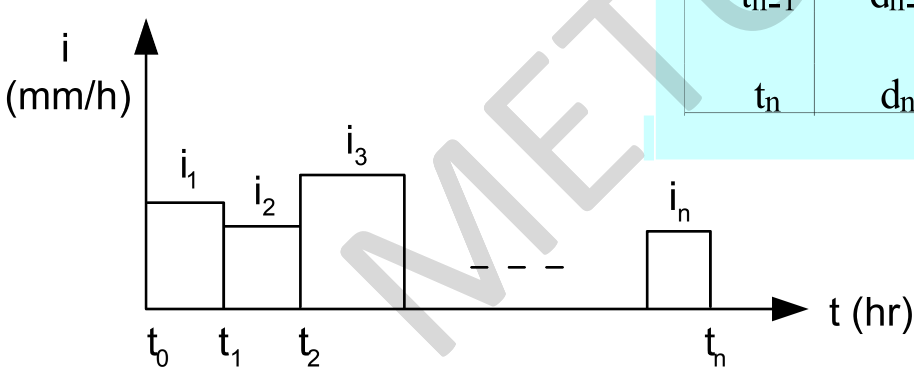
Figure 3.5b Recorded diagram

Hyetograph from a Recorded Diagram



Recorded diagram

Time (min)	Σ Depth (mm)	Δt (min)	Δd (mm)	Intensity (mm/hr)
t_o	d_o			
		$\Delta t_1 = t_1 - t_o$	$\Delta d_1 = d_1 - d_o$	$i_1 = (\Delta d_1 / \Delta t_1)/60$
t_1	d_1			
		$\Delta t_2 = t_2 - t_1$	$\Delta d_2 = d_2 - d_1$	$i_2 = (\Delta d_2 / \Delta t_2)/60$
t_2	d_2			
.	.	.	.	.
.	.	.	.	.
t_{n-1}	d_{n-1}			
		$\Delta t_n = t_n - t_{n-1}$	$\Delta d_n = d_n - d_{n-1}$	$i_n = (\Delta d_n / \Delta t_n)/60$
t_n	d_n			

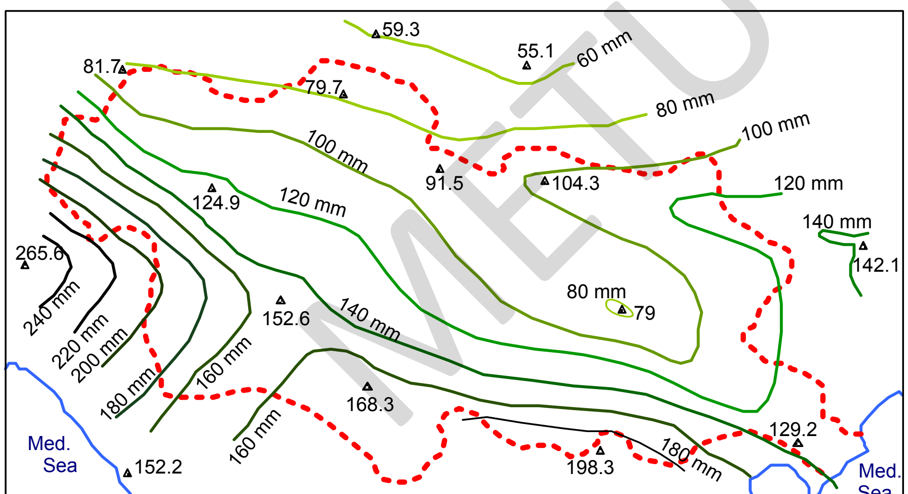


Hyetograph

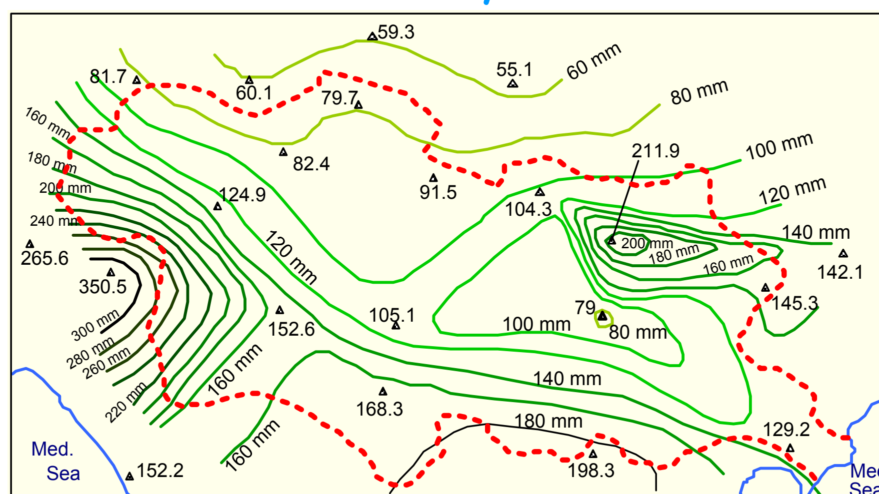
Network of Precipitation Stations

- Designing a network for precipitation stations in an area is a difficult task
  - AIM: spatial variation of precipitation in the area
  - DEPENDS ON: the purpose of data collection
  - DEPENDS ON: the available funds
- The average error ↓ as the number of stations ↑

The effect of network density



a) areal mean precipitation = 126.25 mm (with 15 stations)



b) areal mean precipitation = 130.86 mm (with 21 stations)

AREAL MEAN PRECIPITATION

PPT GAUGES ⟶ POINT VALUES ⟶ AREAL VALUES

METHODS: ARITHMETIC MEAN, THIESSEN POLYGONS, ISOHYETAL MAP

a) ARITHMETIC MEAN METHOD

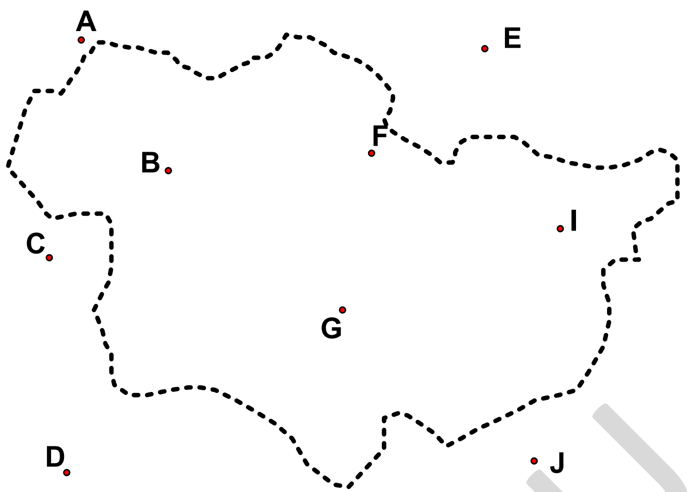
- TAKE ONLY INSIDE STATIONS
- GET SIMPLE AVERAGE

$$P_{ave} = \frac{\Sigma p_i}{n}$$

p_i = rainfall observed at the ith station

n = number of stations inside the basin

ARITHMETIC MEAN METHOD



Take ONLY inside stations

$$P_{ave} = \frac{P_B + P_F + P_G + P_I}{4}$$

AREAL MEAN PRECIPITATION

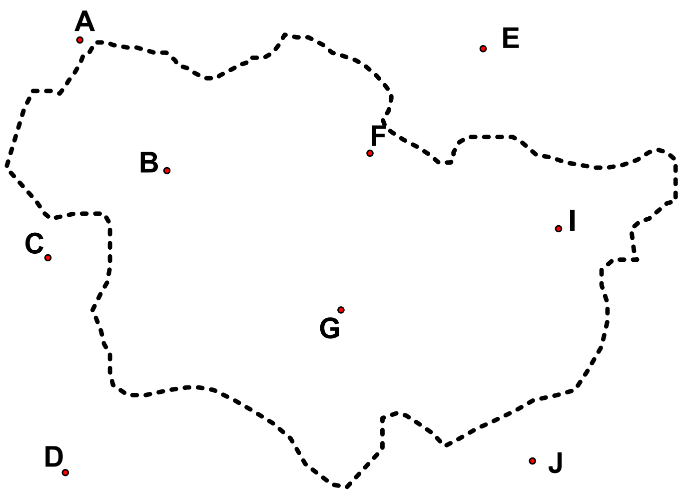
b) THIESSEN POLYGONS METHOD

- INCLUDE ADJACENT OUTSIDE STATIONS AS WELL
- CONNECT STATIONS BY STRAIGHT LINES TO MAKE EQUILATERAL TRIANGLES
- DRAW BISECTORS & OBTAIN POLYGONS
- GET WEIGHTED AVERAGE BY AREAS

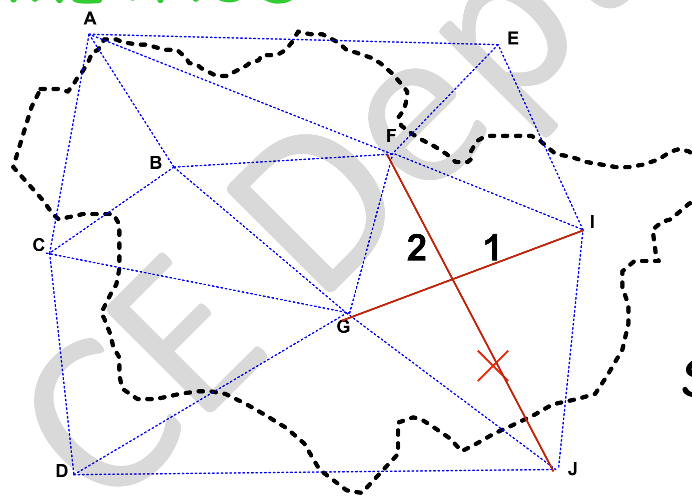
$$P_{ave} = \frac{\Sigma p_i a_i}{\sum a_i}$$

a_i = in-region portion of the area of the polygon surrounding this station

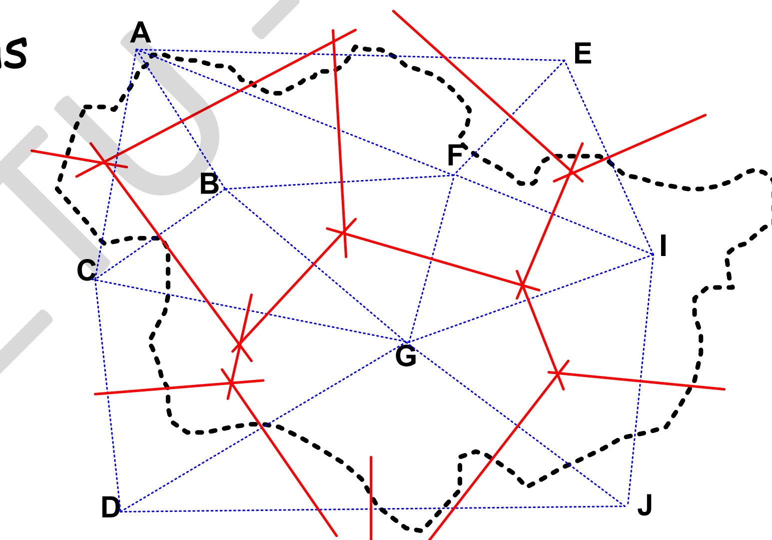
THIESSEN POLYGONS METHOD



Take all the stations



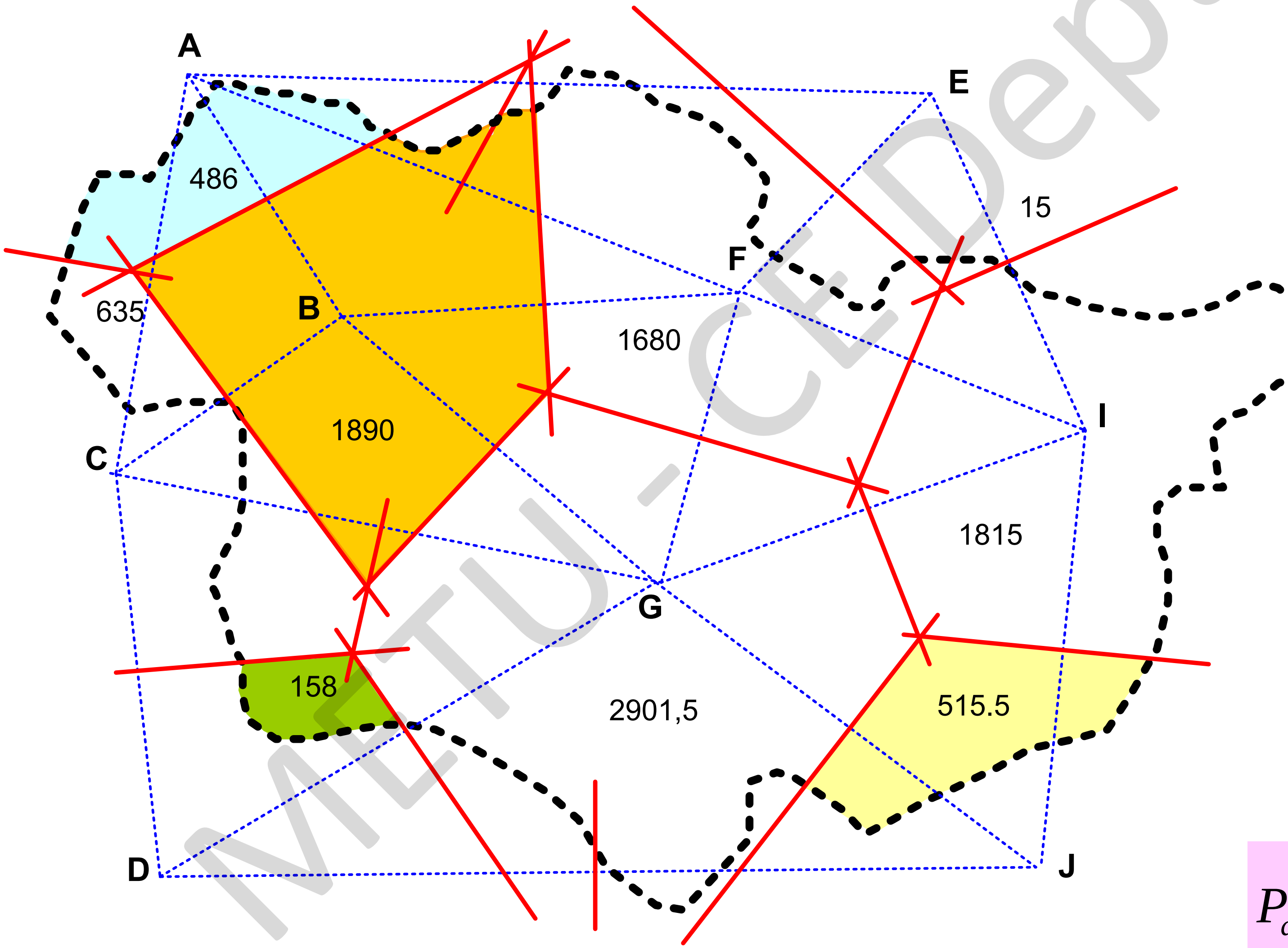
Stations are joined to obtain triangles



Bisectors are drawn to form polygons

$$P_{ave} = \frac{\sum p_i a_i}{\sum a_i}$$

THIESSEN POLYGONS METHOD



$$P_{ave} = \frac{\sum p_i a_i}{\sum a_i}$$

AREAL MEAN PRECIPITATION

c) ISOHYETAL MAP METHOD

- PLOT ISOHYETS (EQUAL PRECIPITATION LINES)

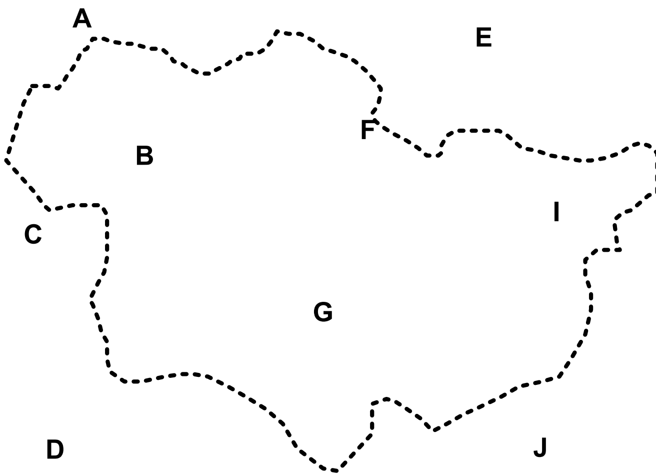
  (ASSUME LINEAR CHANGE BETWEEN STATIONS)
- DETERMINE MEAN PRECIPITATION BETWEEN ISOHYETS
- GET WEIGHTED MEAN

$$P_{ave} = \frac{\Sigma \overline{p}_i a_i}{\sum a_i}$$

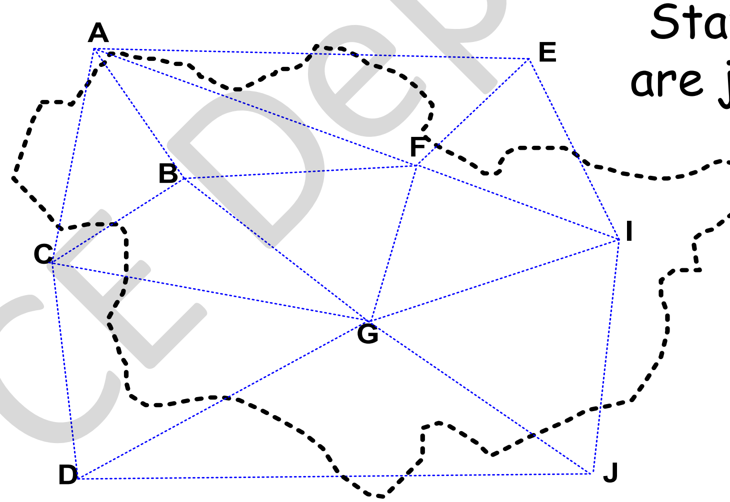
$\overline{p}_i$ = average precipitation between isohyets

a_i = area between isohyets

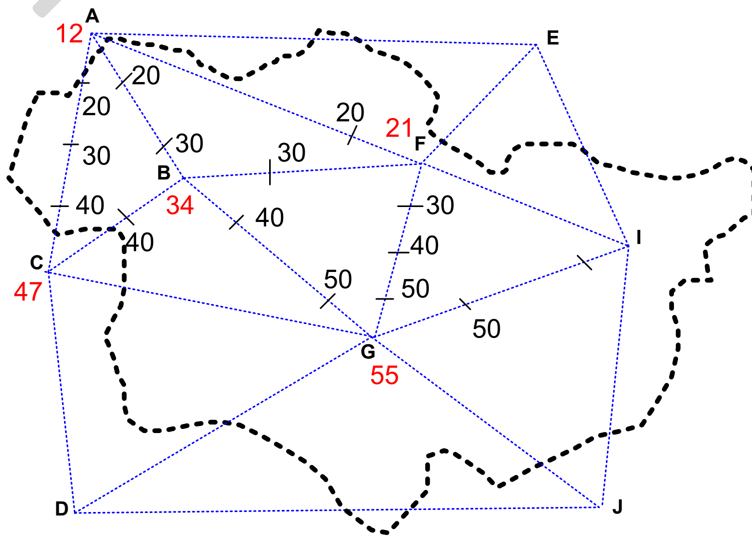
ISOHYETAL MAP METHOD



All the stations are taken

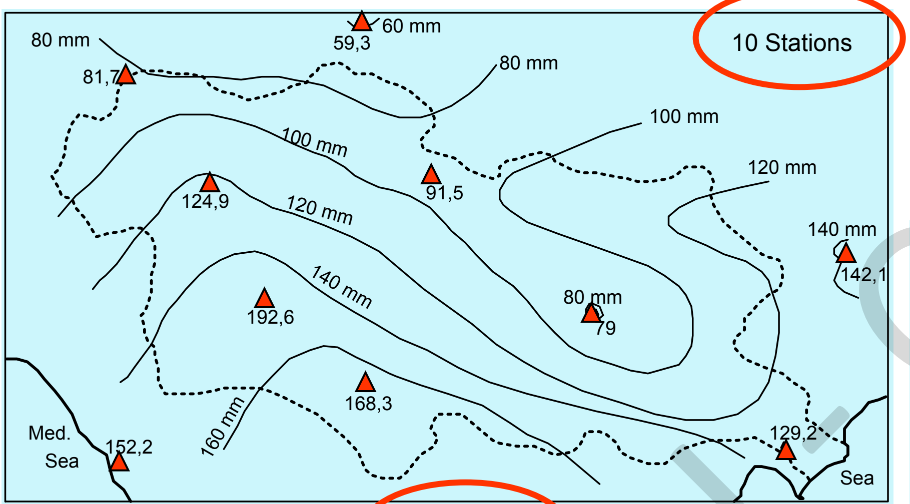


Stations are joined

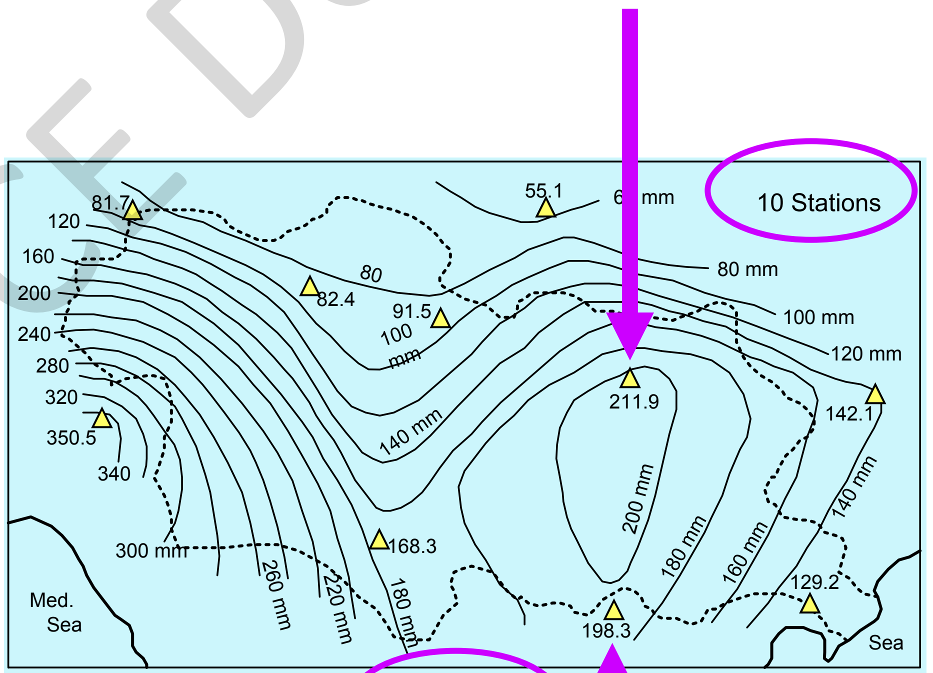


Points having certain precip. values are determined (assuming linear change)

Change in areal mean precipitation with orientation of stations



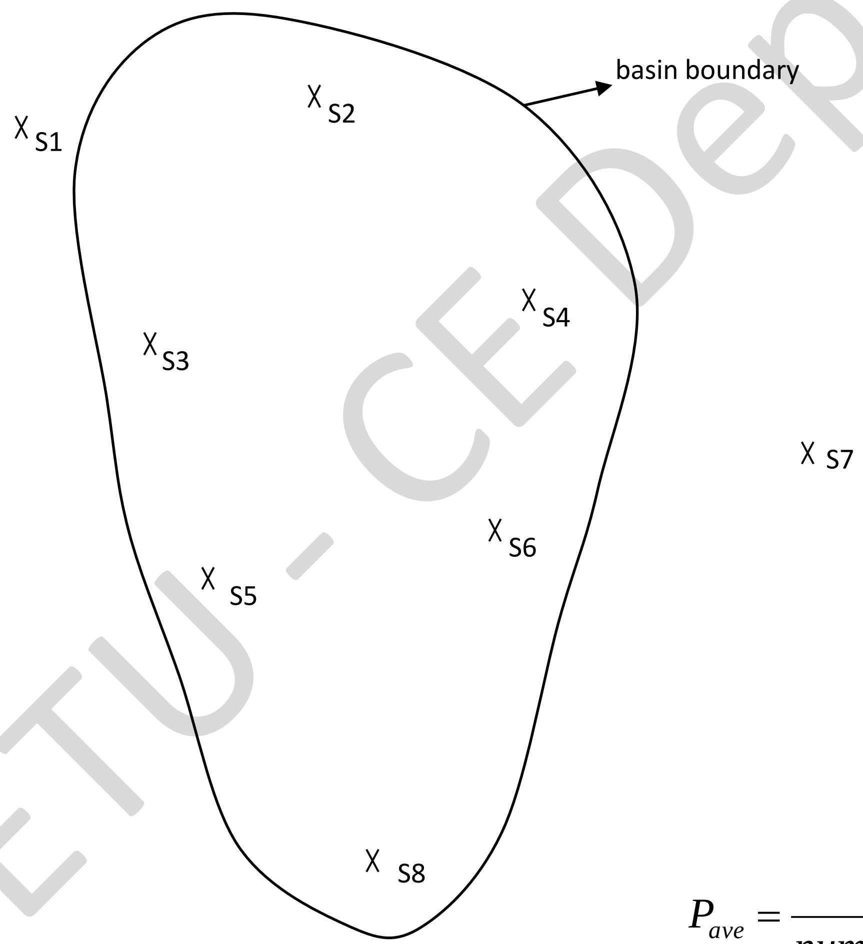
a) Areal mean precipitation = 119.26 mm



b) Areal mean precipitation = 168,20 mm

The number & location of stations are very important!

Example 1-a: Calculate average precipitation using Arithmetic Mean Method based on the figure and table shown below



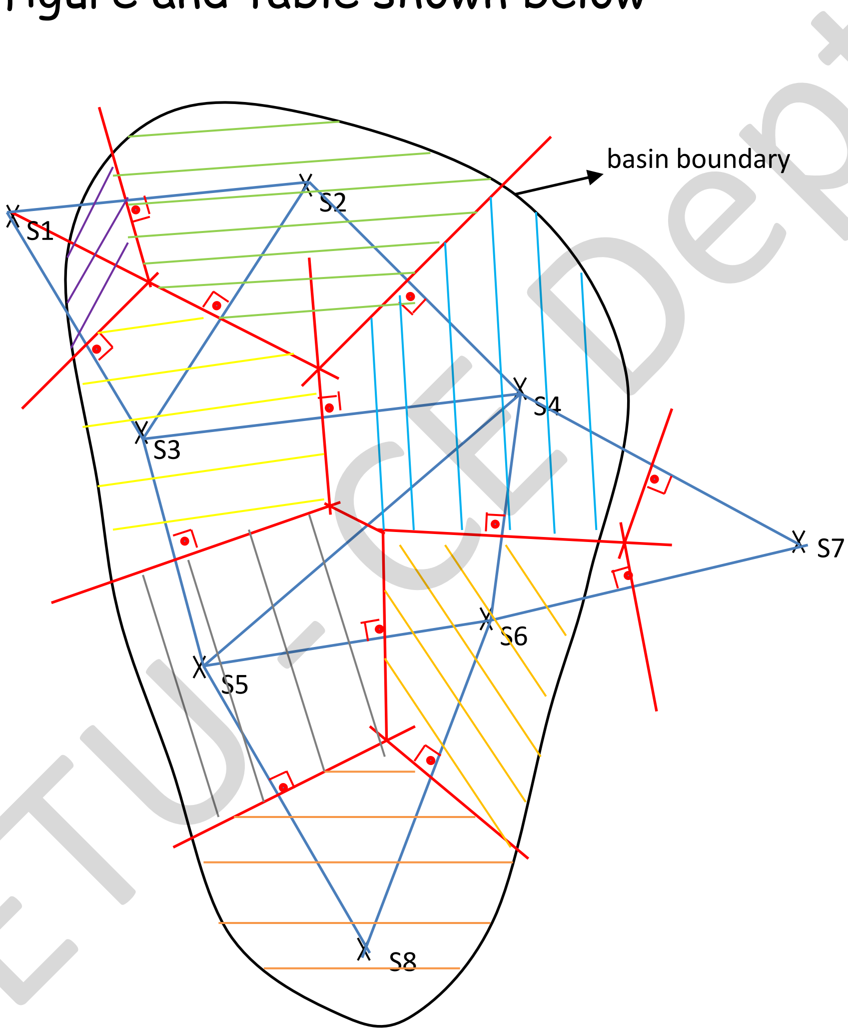
	Measured Precipitation P_i (mm)
S1	30
S2	40
S3	30
S4	30
S5	20
S6	20
S7	15
S8	10

$$P_{ave} = \frac{\sum Pi}{number\ of\ stations}$$

$$P_{ave} = \frac{40+30+30+20+20+10}{6}$$

$$P_{ave} = 25\ mm$$

Example 1-b: Calculate average precipitation using Thiessen Polygons Method based on the figure and table shown below



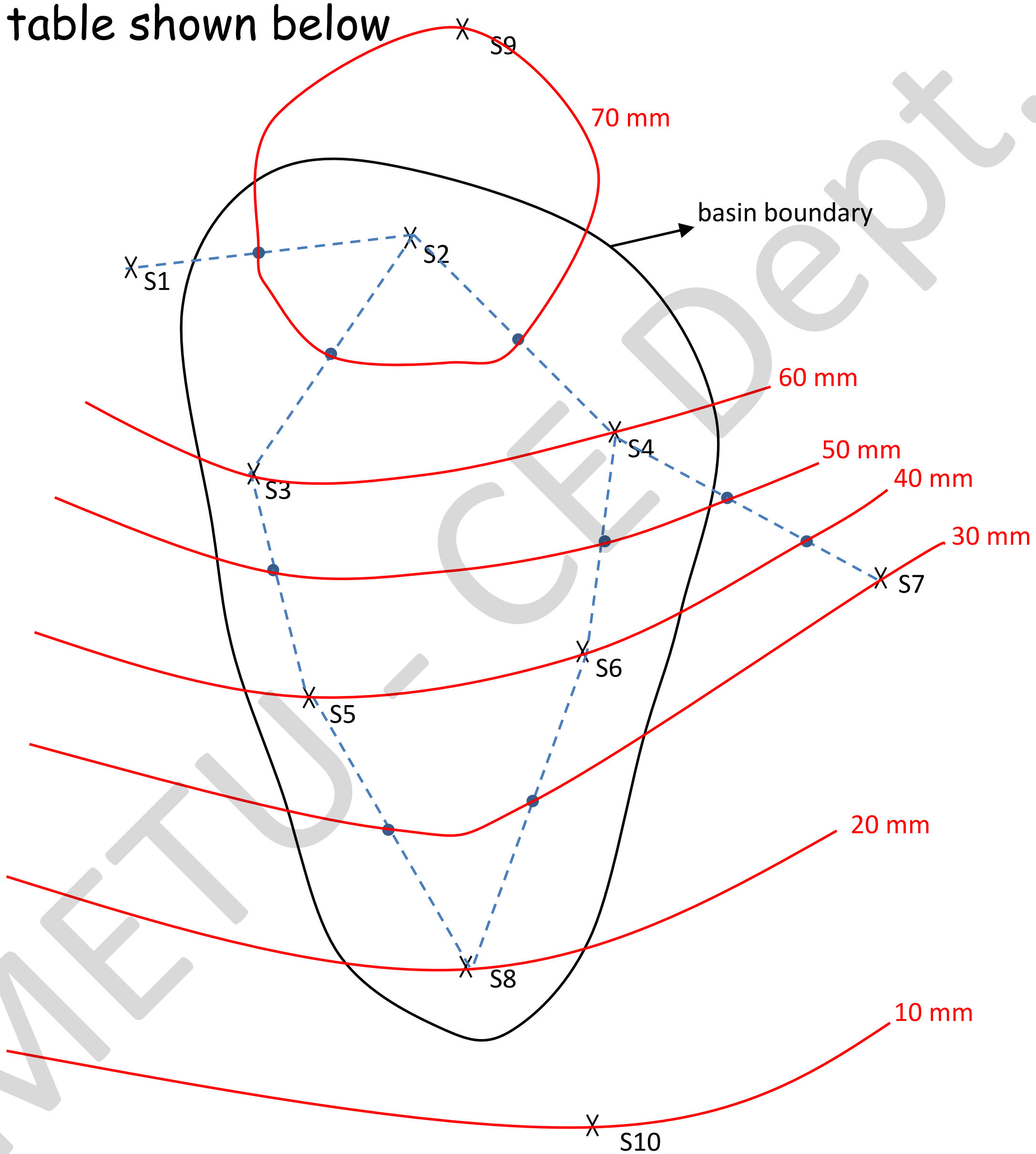
	Area of Influence a_i (mm)	Measured Precipitation P_i (mm)
S1	30	30
S2	120	40
S3	110	30
S4	170	30
S5	165	20
S6	150	20
S7	-	15
S8	145	10

$$P_{ave} = \frac{\sum a_i P_i}{\sum a} = \frac{30x30 + 120x40 + 110x30 + 170x30 + 165x20 + 150x20 + 145x10}{30 + 120 + 110 + 170 + 165 + 150 + 145}$$

$$P_{ave} = 24.6\ mm$$

Example 1-c: Calculate average precipitation using Isohyetal Map Method based on the figure and table shown below

	Measured Precipitation P_i (mm)
S1	60
S2	80
S3	60
S4	60
S5	40
S6	40
S7	30
S8	20
S9	70
S10	10



Slice	P_i (mm)	A_i (km^2)
>70	74	20
60-70	65	40
50-60	55	45
40-50	45	35
30-40	35	40
20-30	25	30
<20	17	15

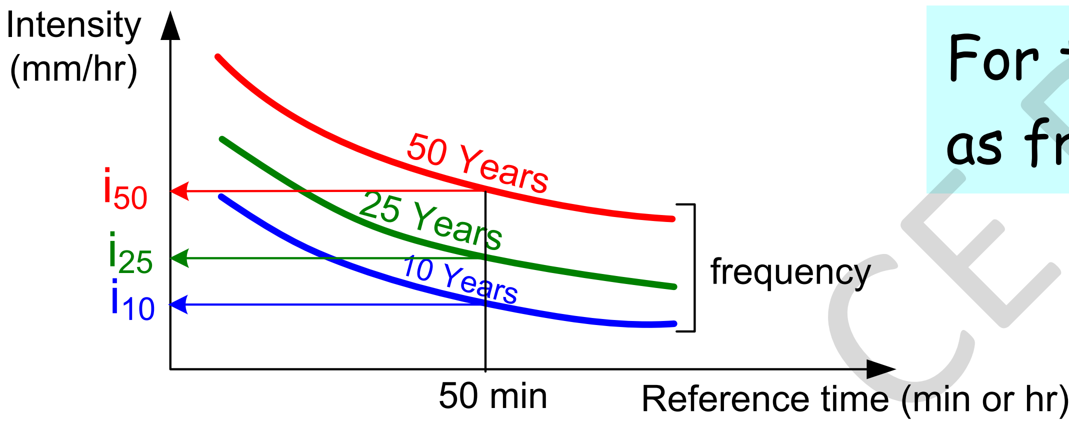
$$P_{ave} = \frac{\sum \overline{P}_i a_i}{\sum a} = \frac{74x20 + 65x40 + 55x45 + 45x35 + 35x40 + 25x30 + 17x15}{20 + 40 + 45 + 35 + 40 + 30 + 15}$$

$$P_{ave} = 46.8\ mm$$

Intensity-Duration-Frequency Curves

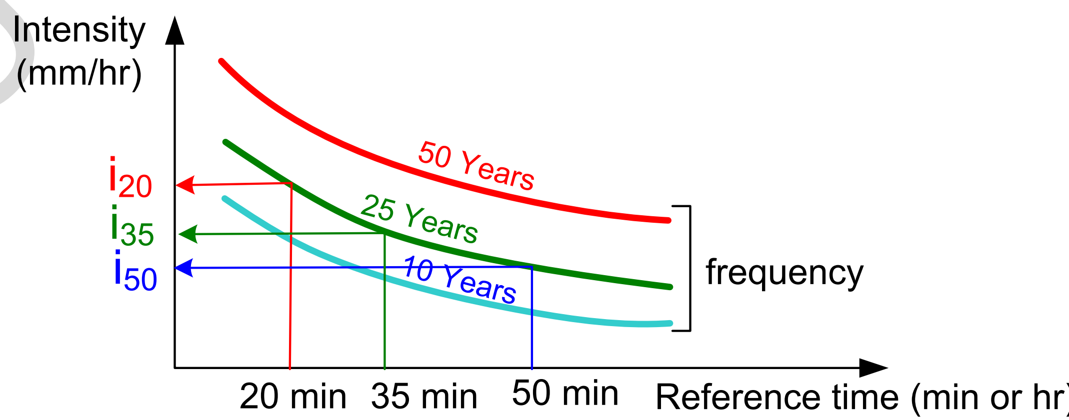
- In general, the higher the intensity of the rainfall the shorter the duration of it will be.
- Intensity - duration – frequency (I-D-F) relationship is important for engineers in designing hydraulic structures.
- It is shown by a family of curves.
- Each curve is drawn for a certain frequency, and indicates the change of intensity wrt the time interval called the reference time interval, (duration of the storm).

Intensity - Duration - Frequency Curves

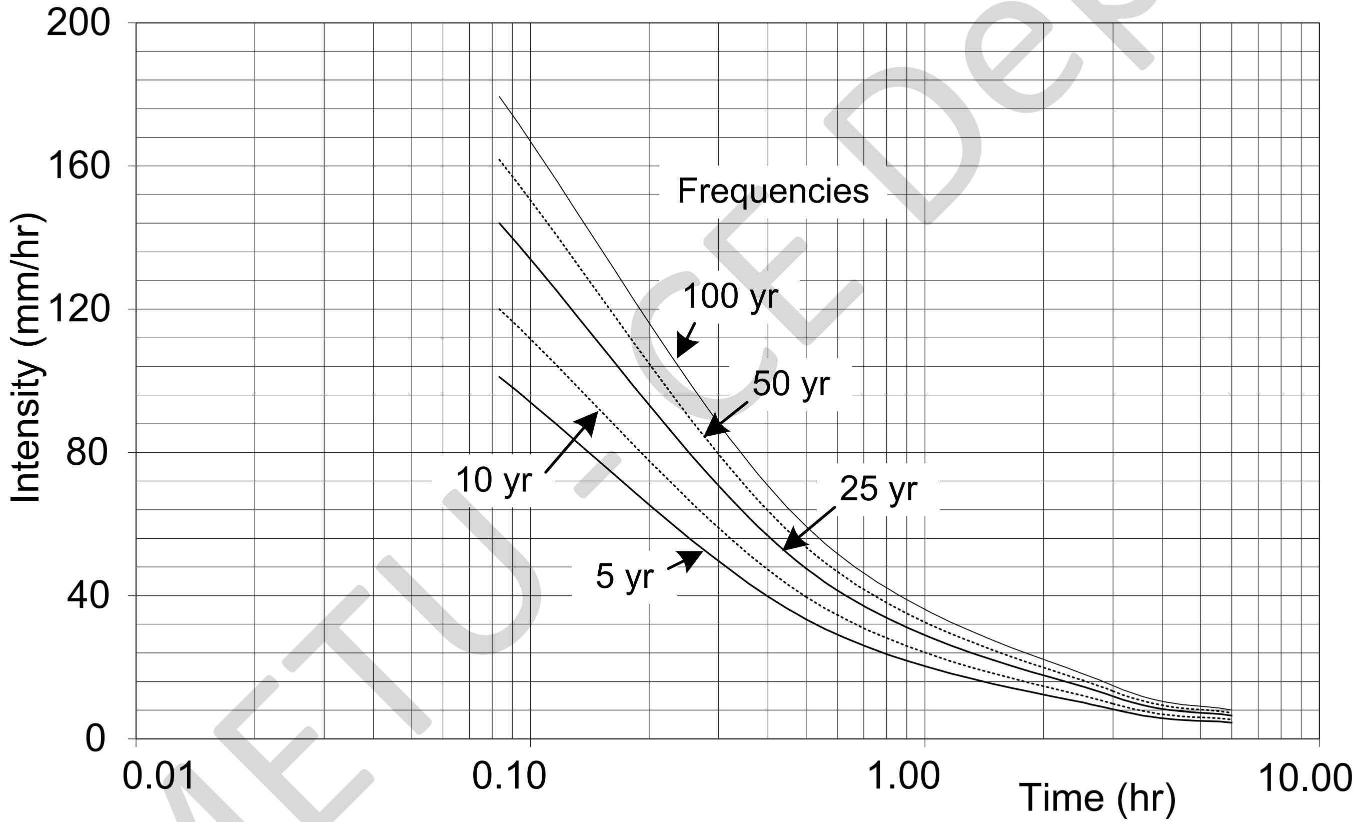


For the same duration:
as frequency ↑ intensity ↑

For the same frequency:
as duration ↑ intensity ↓



Statistical analysis of maximum storms (observed in the study area) are used to generate these curves!



Obtained from 37 years of data

Figure 3.24 Intensity-Duration-Frequency Curves for Ankara
(on Semi-log scale)

These curves should be generated for every station.

Example from Turkey

Table 3.3 Greatest Observed Point Rainfalls in Turkey*

Duration	Depth (mm)	Location	Date (year)
5 min.	27.4	Mardin	1982
10 min	36.7	Mardin	1982
15 min	45.6	Zonguldak	1955
30 min	71.6	Yalova	1977
1 hr	110.0	Rize	1957
2 hr	159.0	Rize	1957
3 hr	174.0	Rize	1957
4 hr	180.1	Zonguldak	1955
5 hr	181.6	Zonguldak	1955
6 hr	193.4	Zonguldak	1955
8 hr	283.5	Zonguldak	1955
12 hr	317.4	Zonguldak	1955
18 hr	413.1	Zonguldak	1955
24 hr	438.8	Zonguldak	1955

RATIONAL FORMULA [$A<100$ km^2]

- A method to relate rainfall on a basin to the corresponding runoff.
- Extensively used in urban hydrology to estimate peak flow.
- Very important parameter for storm water system design.

$Q_p \; \alpha \; A^n$	n = power, A=area, Q_p=peak flow
$Q_p \; \alpha \; i.A$	i = intensity (n=1)
$Q_p = C.i.A$	C = runoff coefficient

RATIONAL FORMULA

$$Q_p = \frac{CiA}{3.6}$$

$$Q_p = 0.278\,CiA$$

Q_p = peak flow (m^3/s)
C = runoff coefficient
i = average rainfall intensity (mm/hr)
Rain continues at least for t_c hours
t_c = time of concentration
A = area (km^2)

C is a function of surface characteristics
If surface conditions change → Divide into subareas

$$Q_p = 0.278\, i \sum_{j=1}^{n} C_j A_j$$

A_j = areas of subbasins
C_j = runoff coeff.s for subbasins
n = number of subbasins

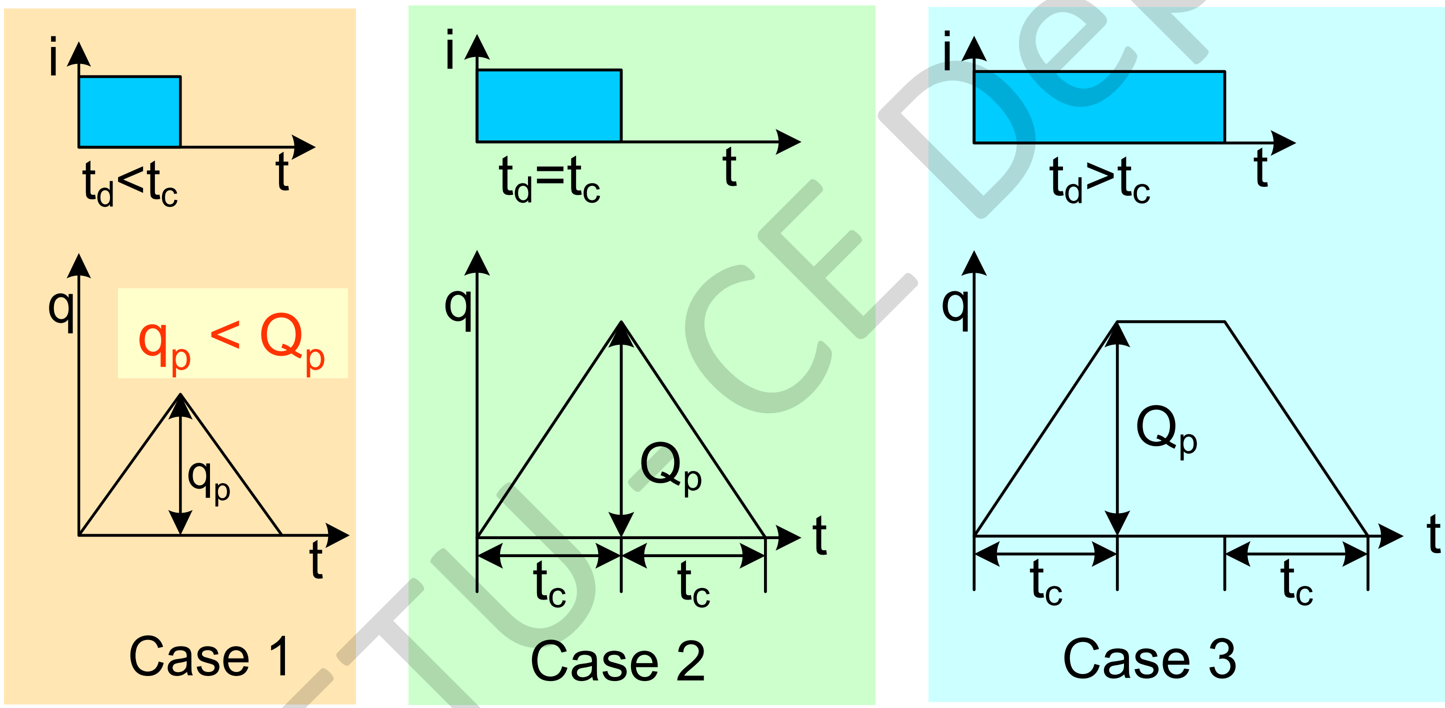
Rational Formula

- Time of concentration, t_c: time necessary for raindrops falling at the farthest point of the basin to flow to the outlet point.
- Intensity of rainfall i, is assumed to be constant during concentration time t_c, and the peak flow Q_p, occurs after the period t_c.
- Runoff coefficient, C is the least precise variable.

  Its use in the formula implies a fixed ratio of peak runoff rate to rainfall rate for the drainage basin, which in reality is not the case.

$$Q_p = 0.278CiA$$

The effect of rainfall duration t_d:



Q_p = peak flow rate

t_d = duration of rainfall

t_c = time of concentration

Typical C coefficients for 5 to 10-yr frequency design

Description of area	Runoff coefficient	Description of area	Runoff coefficient
Business		Streets	
Downtown areas	0.70 – 0.95	Asphalt	0.70 – 0.95
Neighborhood areas	0.50 – 0.70	Concrete	0.80 – 0.95
		Brick	0.70 – 0.85
Residential		Drives and walks	0.75 – 0.85
Single-family areas	0.30 – 0.50		
Multiunits, detached	0.40 – 0.60	Roofs	0.75 – 0.95
Multiunits, attached	0.60 – 0.75		
Residential (suburban)	0.25 – 0.40	Lawns; soil:	
Apartment dwelling areas	0.50 – 0.70	Flat, 2%	0.05 – 0.10
		Average, 2-7%	0.10 – 0.15
Industrial		Steep, 7%	0.15 – 0.20
Light areas	0.50 – 0.80		
Heavy areas	0.60 – 0.90	Lawns; Heavy soil:	
Railroad yard areas	0.20 – 0.40	Flat, 2%	0.13 – 0.17
Parks and cemeteries	0.10 – 0.25	Average, 2-7%	0.18 – 0.22
Playgrounds	0.20 – 0.35	Steep, 7%	0.25 – 0.35
Unimproved areas	0.10 – 0.30		

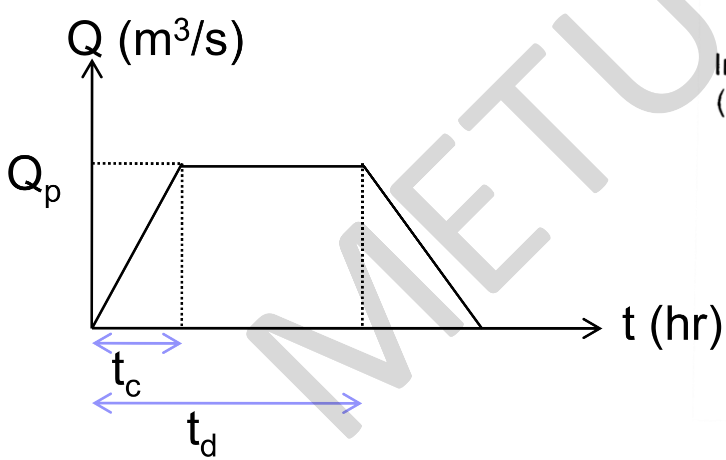
RATIONAL FORMULA

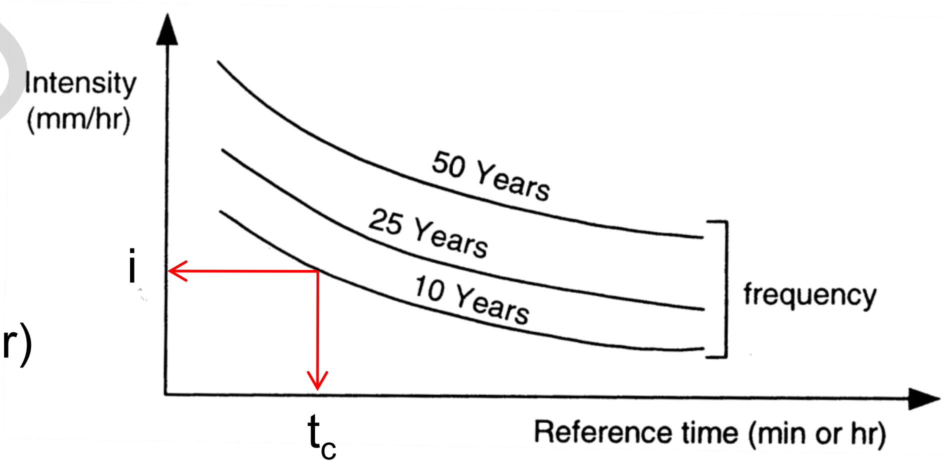
STEPS IN COMPUTATION:

1. ESTIMATE t_c
2. ESTIMATE C
3. SELECT A RETURN PERIOD T_r AND DETERMINE i FROM I-D-F CURVES FOR THAT REGION
4. DETERMINE Q_p USING THE FORMULA

RATIONAL FORMULA

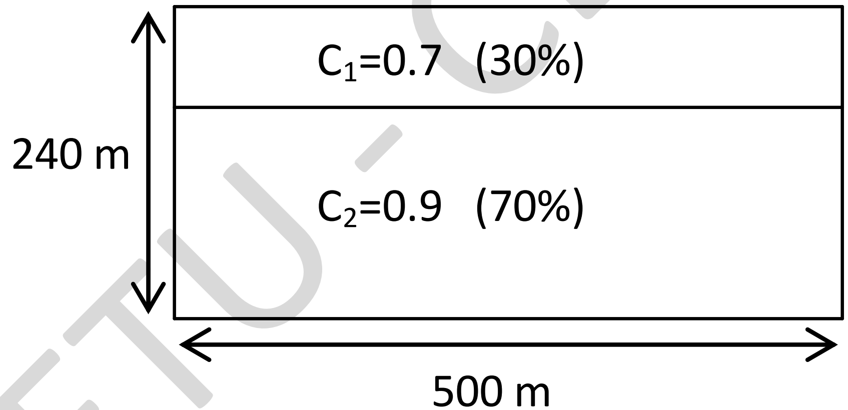
- Rational formula requires estimation of C and i
- C is the least precise variable & it depends on
  - Imperviousness
  - Slope
  - Vegetation
  - Ponding characteristics of the surface





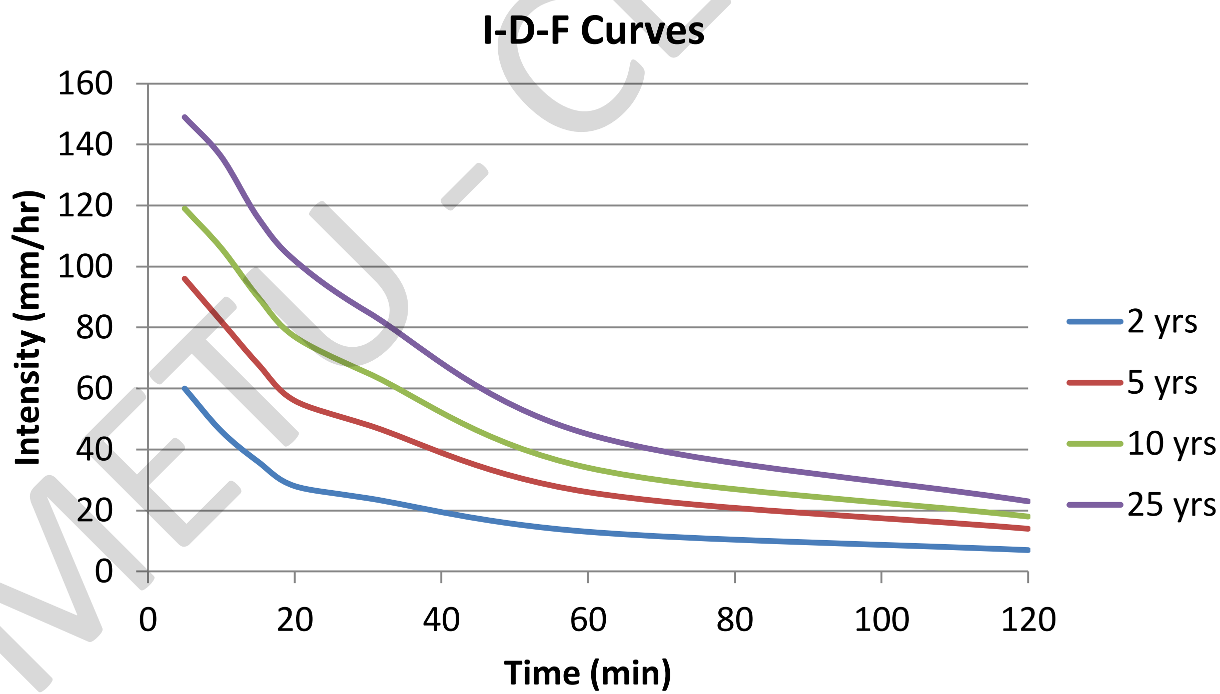
Example 2

A parking lot has a size of 240 m by 500 m and a concentration time (t_c) of 20 minutes. Runoff coefficients for 30% and 70% of this area are C_1=0.7 and C_2=0.9 respectively. Rainfall intensities obtained from intensity-duration-frequency (I-D-F) curves of nearest precipitation station to this lot are tabulated below. Determine the 10-year peak discharge value at the outlet of this basin (lot) in m^3/s.



Intensities of Rainfall (mm/hr)

Return Period *(year)*	***Time of Concentration*** *(min)*						
	5	***10***	***15***	***20***	***30***	***60***	***120***
2	60	46	36	28	24	13	7
5	96	82	68	56	48	26	14
10	119	106	90	77	65	34	18
25	149	136	116	102	85	45	23



Solution:

Rational formula: $Q_{peak} = C * i * A$

Conventional use of rational formula: $Q_{peak} = 0.278\, C * i * A = \dfrac{C * i * A}{3.6}$

where, *C* = runoff coefficient (dimensionless), *i* = intensity (mm/hr), *A* = area of the basin (km^2)

$$C = C_1 * 0.3 + C_2 * 0.7 = 0.7 * 0.3 + 0.9 * 0.7 = 0.84$$

$$A = 240 * 500 = 120000\, m^2 = 120000 / 10^6 = 0.12\, km^2$$

Use of the I-D-F table: t_c = 20 min, T_r = 10 years, i = 77 mm/hr

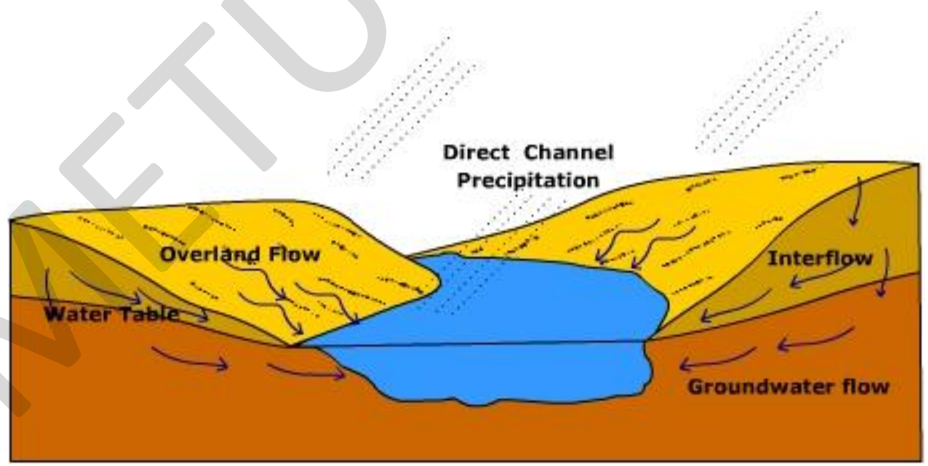
$$Q_{peak} = 0.278\, C * i * A$$

$$Q_{peak} = 0.278 * 0.84 * 77 * 0.12 = 2.16\, m^3 / s$$

Further information for the design of the related culvert: use Manning equation

STREAMFLOW

- The most important element of hydrologic cycle
- Basin converts precipitation into streamflow
  - Basin = Drainage Basin = Catchment = Watershed = Subbasin
  - Area = Drainage Area
  - Perimeter = Boundary = Basin Divide

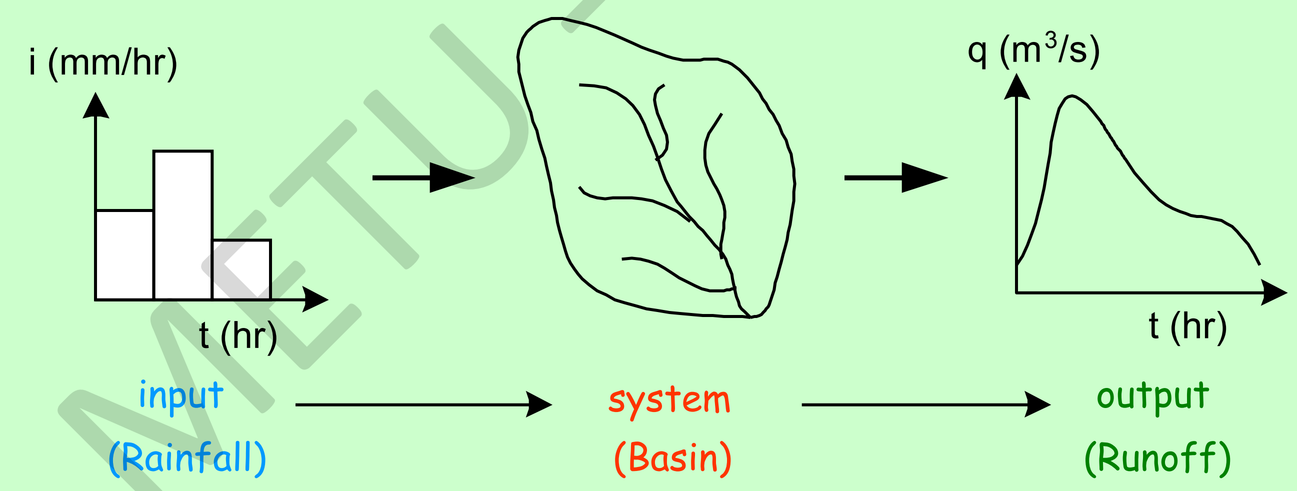


http://www.uwsp.edu/geO/faculty/ritter/geog101/textbook/fluvial_systems/channel_geometry_and_flow.html

Streamflow

Most important element of hydrologic cycle for the hydrologist because streams are the best renewable sources of water for all kinds of demands.

Streamflow = f(meteorological factors, basin characteristics, human activities)



Basin as a system

STREAMFLOW

- Streamflow measurements are made by three government organizations in Turkey,
  - State Water Works (DSI),
  - Electrical Power Resources Survey and Development Administration (EIEI),
  - Former General Directorate of Rural Services (KHGM).
- The first two institutions measure the discharges in 26 regions, which cover the whole country.
- KHGM measures only small creeks (upstream branches)

Vegetal Cover

Influences rainfall – runoff process

1. Interception

   Back to the atmosphere

2. Water Consumption

   Transpiration, reduction of moisture, infiltration ↑es

3. Mechanical Resistance

   Water will stay longer on land, infiltration ↑es

4. Plant Roots

   Loosening of soil, increasing voids, emptying water in voids, infiltration ↑es

Infiltration vs Surface Runoff

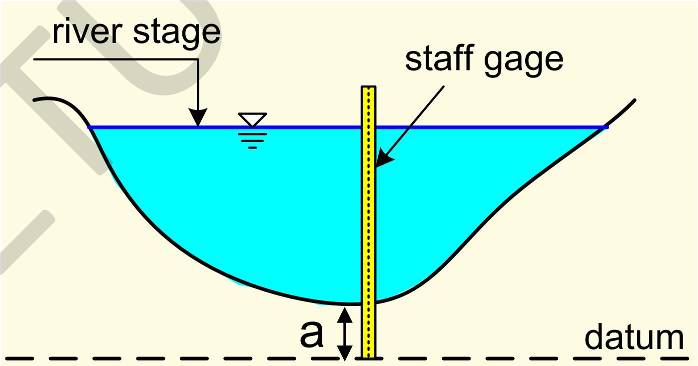
Estimation of rates or volumes of flow is necessary

Measurement of stage :

- Non-recording (Manual)
- Recording

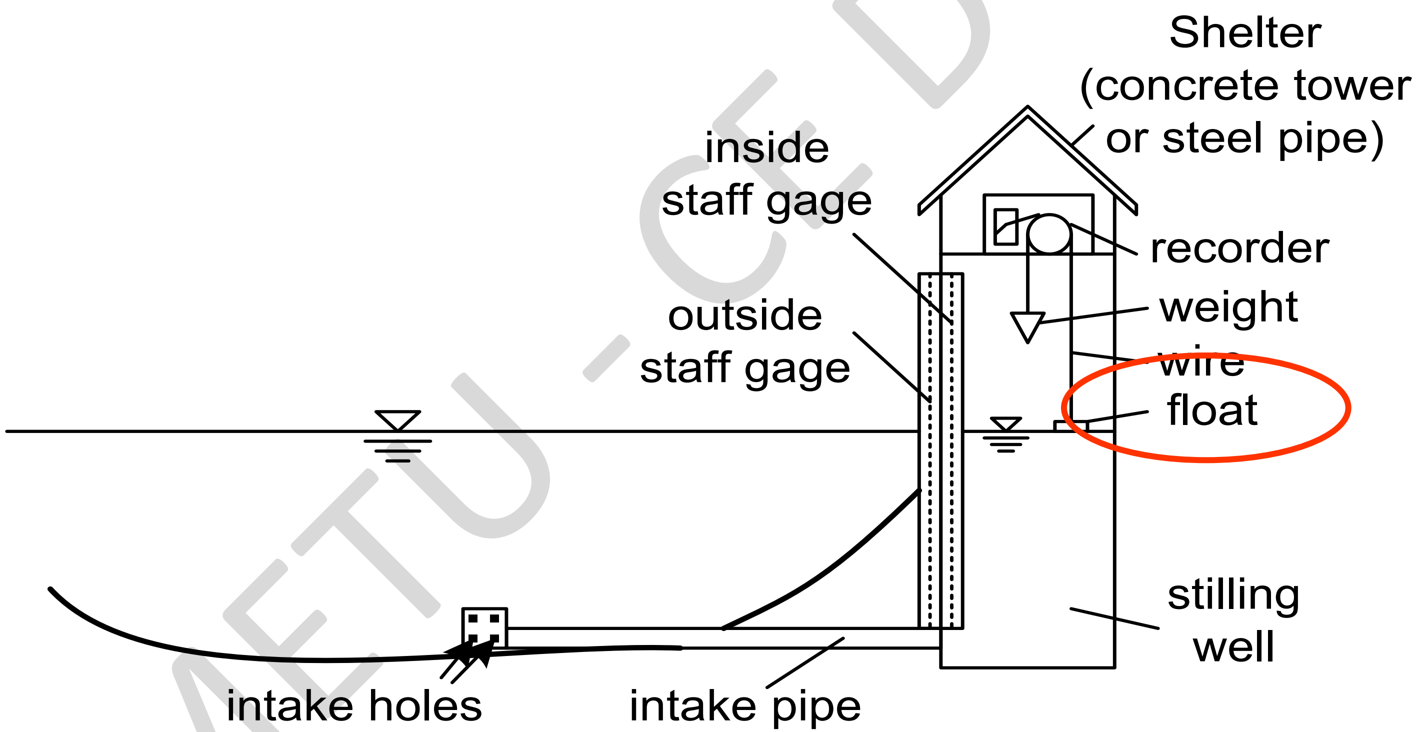
Gages

Stage is elevation above a zero datum (arbitrary)



Recording Gage

Ex: float-type water-stage recorder



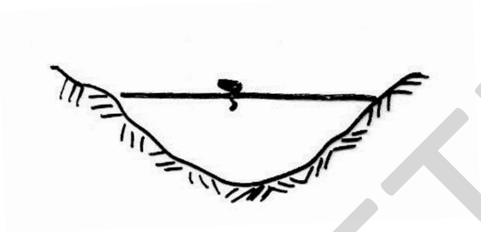
Discharge Computation by Velocity Measurements

Stage Record $\xrightarrow[\text{calibration}]{\text{by}}$ Discharge Record

- Calibration is accomplished by relating
  - Field measurements of discharge

    with

    river stage values



$$Q = a \times v$$

Q = discharge
a = area
v = velocity

- Velocity measurement is necessary & it is done by current meter

$$v = a + bN$$

a, b = constants of the instrument
N = number of revolutions per second

STREAMFLOW - Discharge Computation

Velocity measurement made at a single point cannot be assumed to give the average velocity since the velocity varies drastically in a x-section.

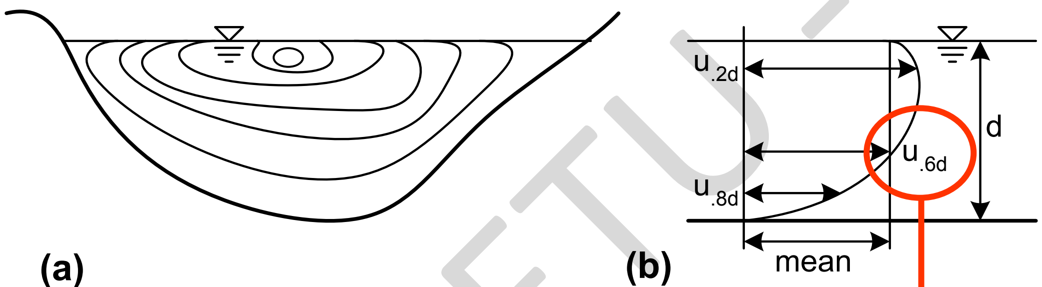
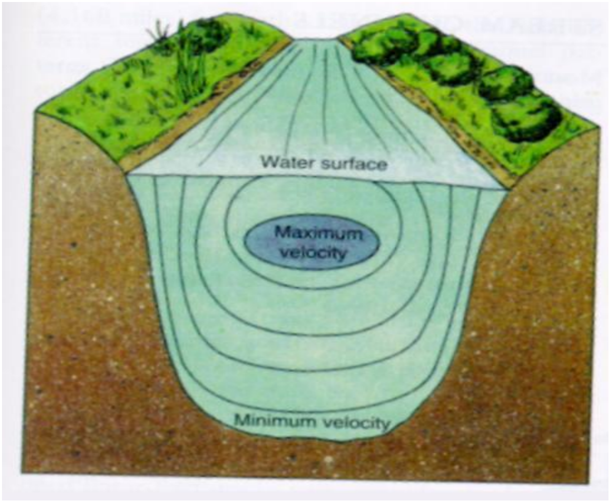
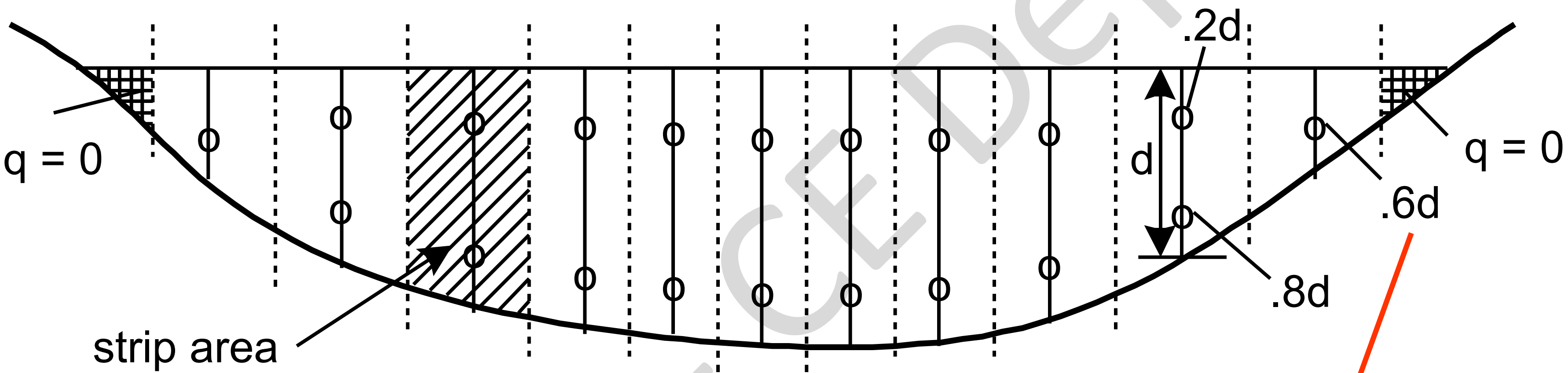


Figure 4.5 Velocity change in (a) cross-section (b) vertical



approximately average velocity of the cross-section

In practice stream is divided into a number of vertical sections (strips) ⇨ No section should have more than 10% of total flow!



$q_i = a_i \times v_{i,mean}$

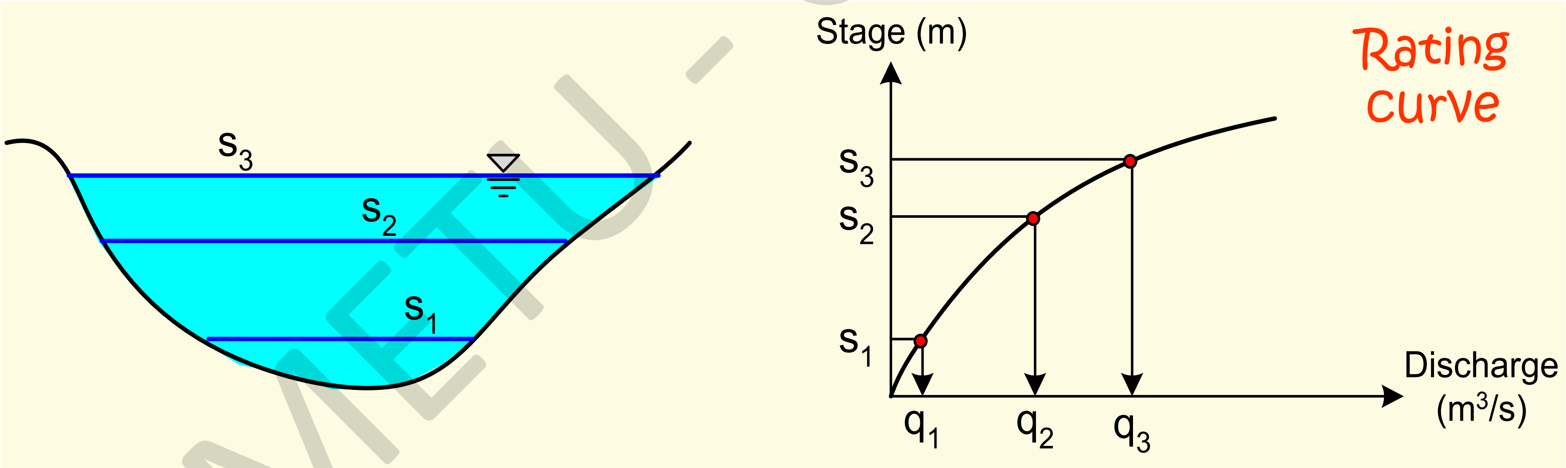
One measurement at 0.6d if water is shallow

$$v_{mean} = v_{0.6d} = \frac{v_{0.2d} + v_{0.8d}}{2}$$

$$Total\ \ discharge, Q = \sum q_i = \sum (a_i \times v_i)$$

Obtaining Rating Curve

- Take different stages
- Determine discharge for each stage
- Plot them against each other

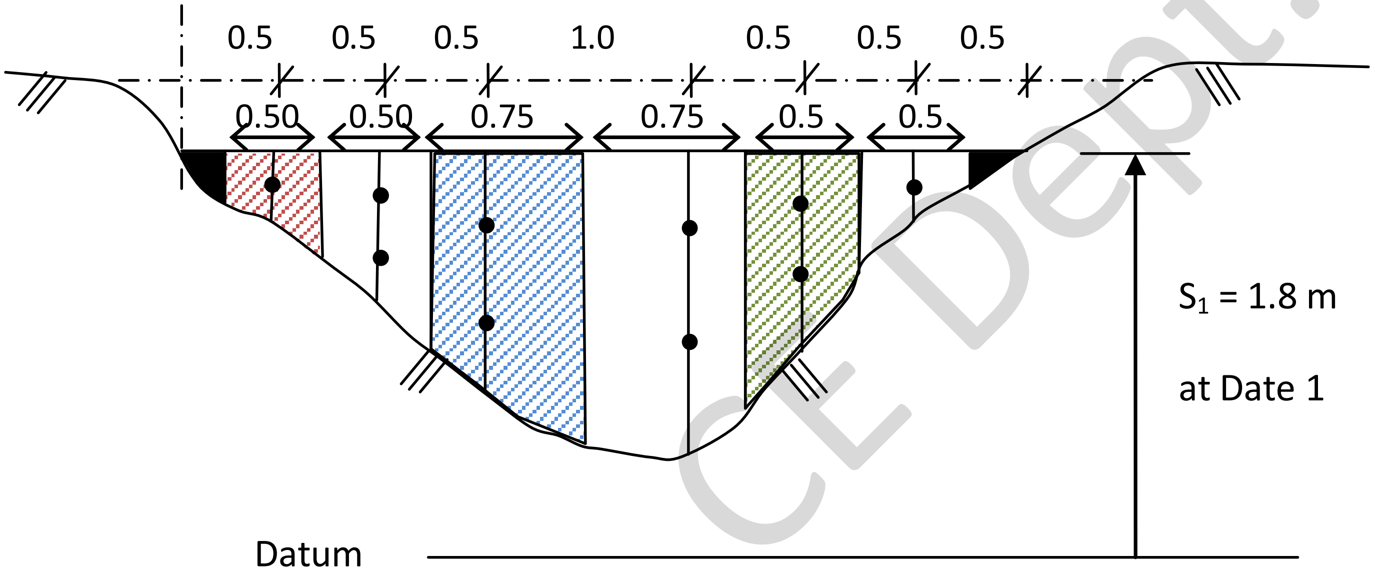


Example 3 (Discharge computation & Stage-Discharge relationship)

The data below were obtained from velocity measurements at a stream gaging station at Date 1 (where stage, s_1, was 1.8 m). Compute the total discharge at the station.

Distance from the left bank (m)	**Total depth** (m)	**Velocity** (m/s)		
		at 0.2*depth	at 0.8*depth	at 0.6*depth
0.0	0	-	-	-
0.5	0.4	-	-	0.72
1.0	0.7	0.95	0.74	-
1.5	1.2	1.28	1.14	-
2.5	1.4	1.29	1.15	-
3.0	0.8	1.04	0.88	-
3.5	0.3	-	-	0.63
4.0	0	-	-	-

Solution:



Average velocity (m/s)	0.72	0.845	1.21	1.22	0.96	0.63
Slice area (m^2)	0.20	0.35	0.90	1.05	0.40	0.15
Slice discharge (m^3/s)	0.144	0.296	1.089 *	1.281 *	0.384 *	0.095

Total discharge = 3.289 m^3/s obtained at Date 1 = Q_1

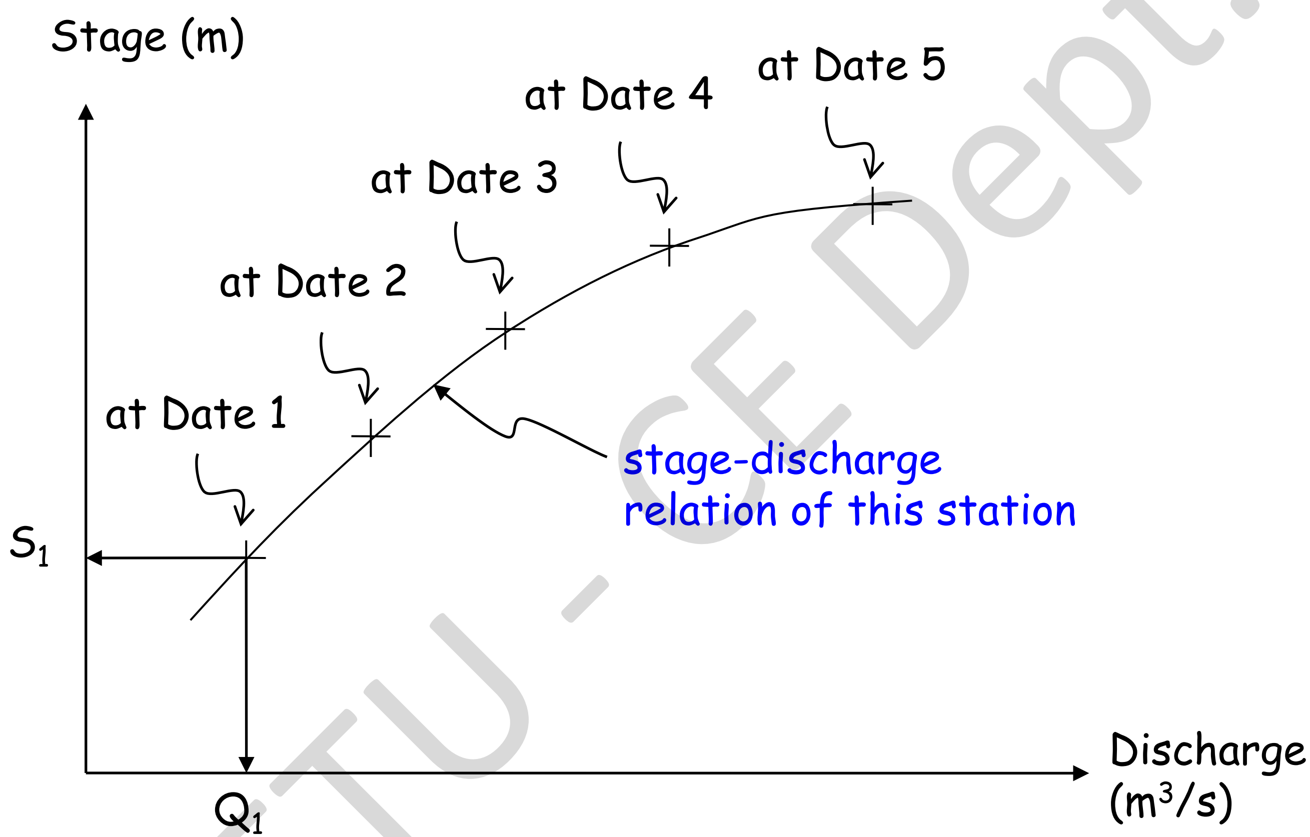
Check slice discharges based on the total discharge:

$q_3, q_4, q_5 \quad < \quad 0.10 * 3.289\ m^3/s$

Thus, number of slices at this cross-section should be increased (Q_1 will be computed once more).

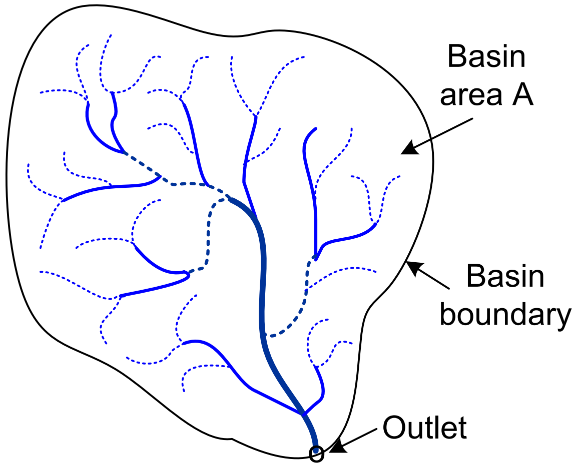
<u>Further information for obtaining stage-discharge relationship:</u>

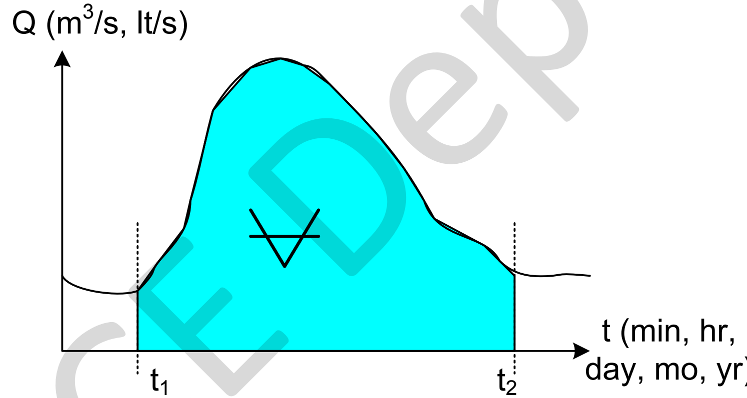
<u>Go to the station at different time (at different water stages) and conduct similar works in order to be able to obtain stage discharge relationship of this station.</u>



Stage (m)
at Date 5
at Date 4
at Date 3
at Date 2
at Date 1
stage-discharge
relation of this station
S_1
Q_1
Discharge
(m^3/s)

Interpretation of Streamflow Data





Discharge → m^3/s, lt/s

Volume → $10^6\ m^3$ ($V = \int_{t_1}^{t_2} Q(t)dt$)

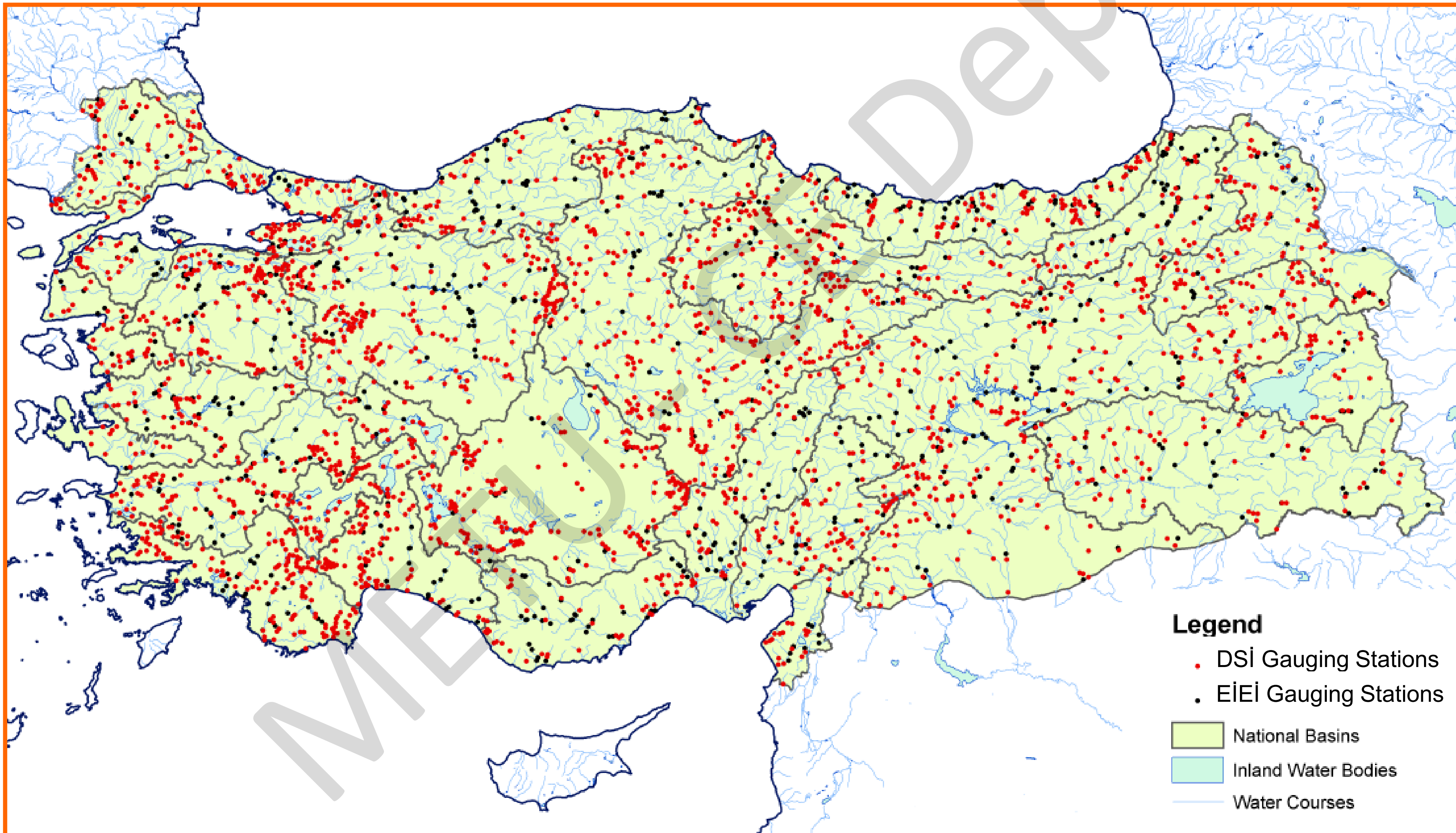
Yield (Productivity) → $m^3/s/km^2$, $lt/s/km^2$ (Q/A)

Depth → mm, cm (V/A)

Water Year → Oct. 1 - Sep. 30

(not to divide the flood season)

STREAM GAGING STATIONS IN TURKEY



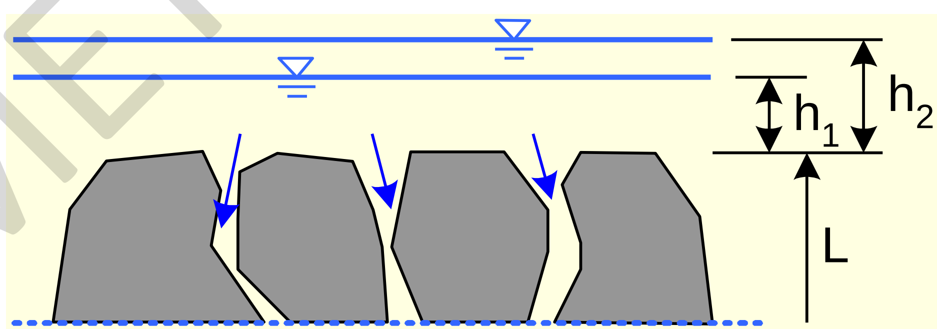
INFILTRATION

- Entrance of water into the soil through pores and openings on the surface (up to a depth of 20-50 cm) → infiltration
- The vertical movement of water through the soil → percolation
- Infiltration rate & total amount of infiltrated water is a function of basin & rainfall characteristics

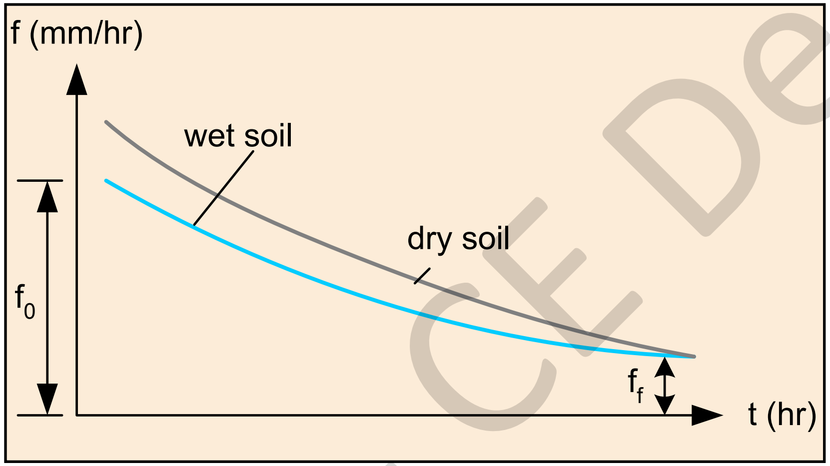
soil type, moisture content, permeability, land cover, depth to gw, drainage conditions

intensity, total volume

- Infiltration Capacity → Max. Rate at which water enters the soil (f_o)
- Infiltration capacity, f_0 changes with
  - Physical characteristics of soil
  - Initial moisture content of soil
  - Slope of the ground surface
  - Depth of surface detention
  - Vegetal cover



- Infiltration rate ↓es with time approaching a constant value, f_f as the soil profile becomes saturated.



- Infiltration Rate (Horton's Method)

$$f = f_f + (f_o - f_t) \times e^{-k \times t}$$

f_o = initial infiltration rate (mm/hr)

f_f = final infiltration rate (mm/hr)

k = constant (1/hr)

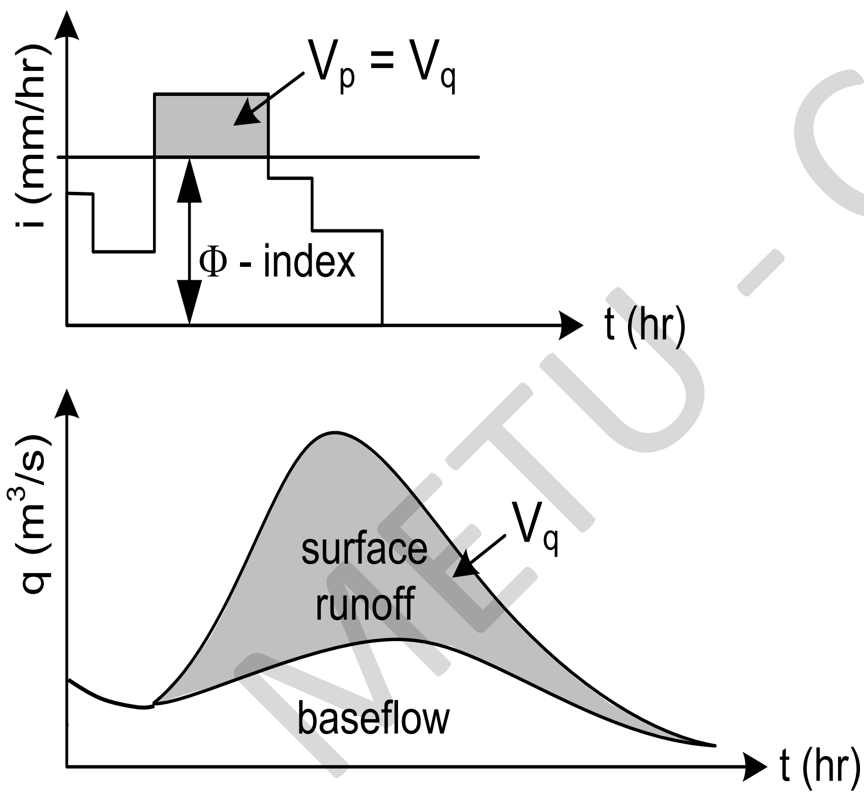
= f(soil type, vegetal cover)

t = time from beginning of the rain (hr)

Infiltration Index

- Although infiltration changes with time during a storm, it is <u>accepted to be constant</u> for hydrograph analysis problems. Because:
  - it is difficult to obtain actual infiltration for each storm,
  - it is difficult to deal with varying infiltration rate.
- Infiltration idices are used to approximate average infiltration loss from rainfall.

Φ - index → indicates the average infiltration rate above which the depth (or volume) of rainfall is equal to depth (or volume) of surface runoff.

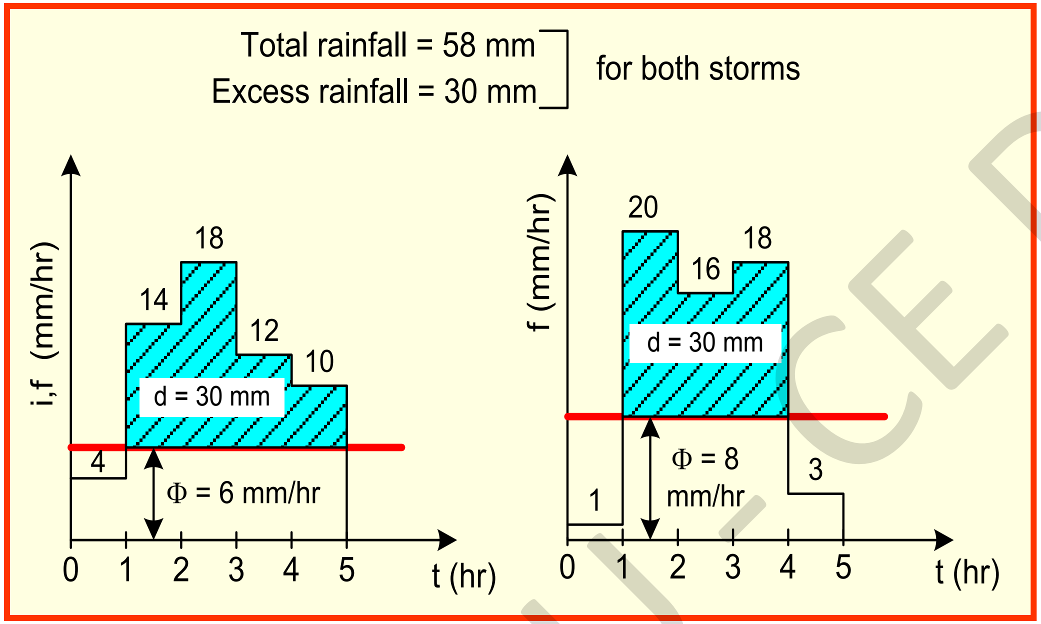


$$V_p = V_q \qquad (d_p = d_q)$$

$V_p(d_p)$ = Volume (depth) of effective precipitation

$V_q(d_q)$ = Volume (depth) of surface runoff

- An example for the Φ-index:



- Φ-index is an over simplification of infiltration process, but especially for large basins it gives reasonable results for studies of storm runoff.

Example 4

Cumulative rainfall values of a storm which occurred on a basin and the resulting total hydrograph are given below. The area of the basin is 700 km^2. Determine,

i. Depth of surface runoff,

ii. Hyetograph of the storm,

iii. Φ-index,

iv. Duration of excess rainfall,

v. Total infiltrated water.

Time (hr)	0	2	4	6	8	10	12	14	16	18	20	22	24
Cumulative Depth (mm)	0	0	22	48	54	54							
Streamflow (m^3/s)	28	28	80	200	440	640	530	335	220	175	122	60	28

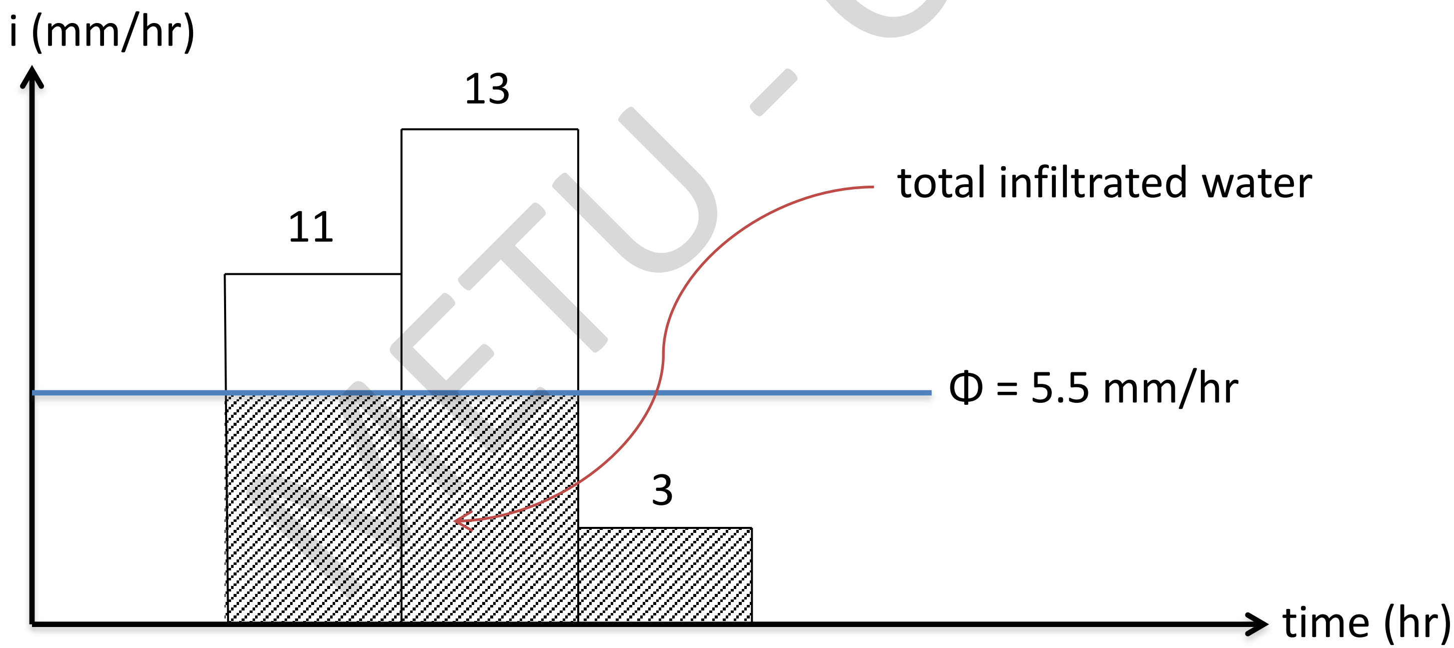
Solution

(i) $d_{SR} = (\Sigma Q_{SR}\, dt) / A_{basin}$

$\Sigma Q_{SR} = (80\text{-}28) + (200\text{-}28) + (440\text{-}28) + (640\text{-}28) + \ldots = 2522\ m^3/s$

$d_{SR} = (2522*2*3600) / (700*10^6) = 0.02594\ m = 26\ mm$

(ii)



Solution

(iii) $(11-\Phi)*2 + (13-\Phi)*2 = 26$

$\Phi = 5.5$ mm/hr

(iv) Duration of excess rainfall is 4 hours

(v) Total infiltrated water = 5.5*4 + 3*2 = 28 mm