Chapter 1

Introduction
Hydrological cycle
Water budget
Precipitation

Hydrology (definition)

- hydrology is a "science that treats all the waters of the earth, their occurrence, circulation and distribution, their chemical and physical properties, and their reaction with their environment including their relations to living things"
-
- We concerned with hydrology since our water supplies are taken from sources (streams, aquifers, ..etc) which are fed by precipitation.

Application of hydrology include:

- Determining water balance of a region (see subsequent discussion)
- Predicting floods and droughts
- Designing irrigation projects
- Preventing catastrophic events due to excess flooding
- Provide means to supply drinking water to communities
- Helps design dams, reservoirs, sewers, bridges and other structural and hydrologic projects

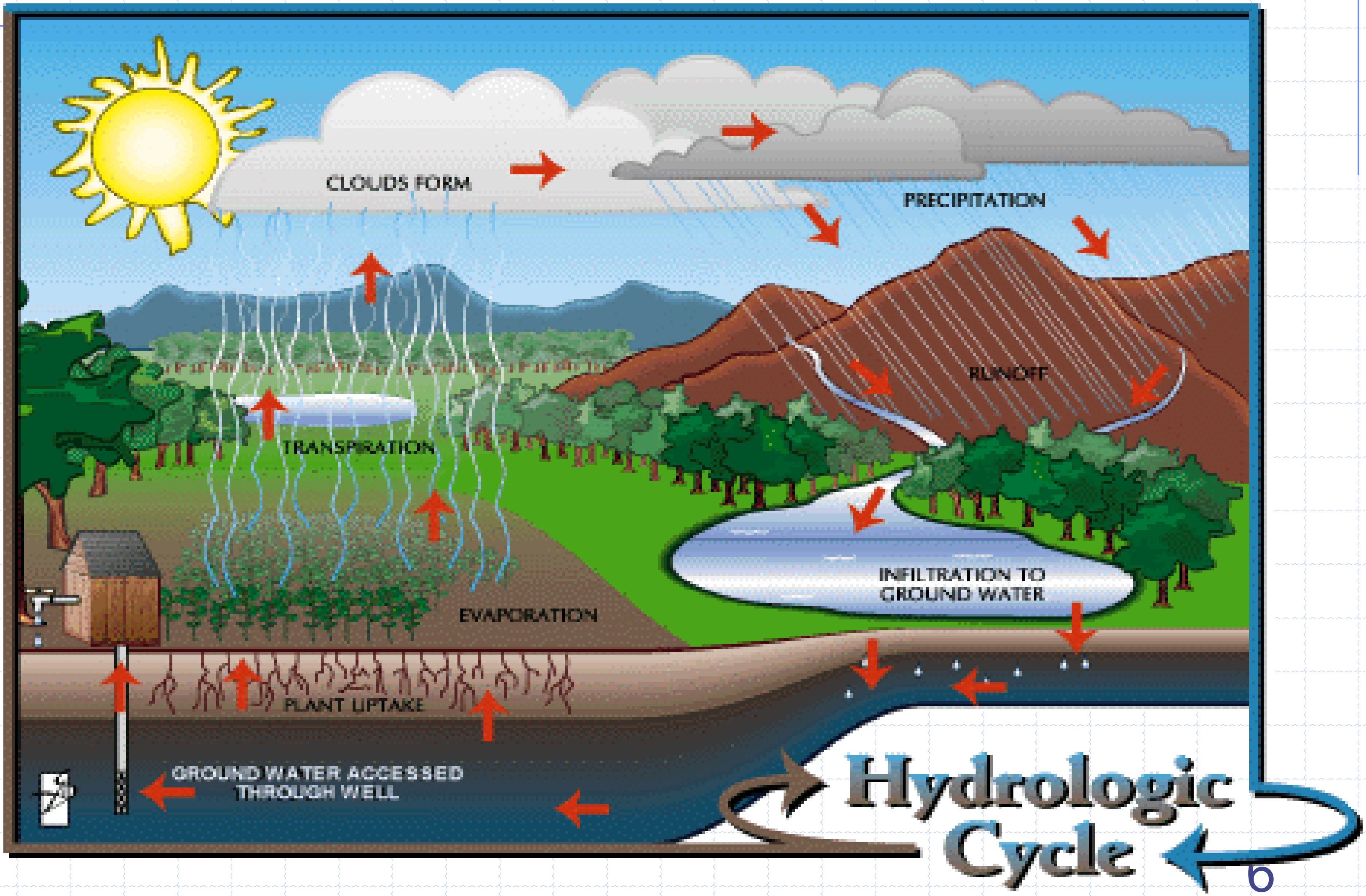
Hydrologic Cycle:

- **Hydrologic cycle <u>is the water circulatory system on earth.</u> The cycle has no beginning or end as the evaporated water rises to atmosphere due to solar energy.**
- **The evaporated water can be carried hundreds of miles before it is condensed and returned to earth in a form of precipitation**
- **Part of the precipitated water is intercepted by plants and eventually returned to the atmosphere by evapotranspiration from plants and upper layers of soil, runs overland eventually reaching open water bodies such as streams, oceans or natural lakes or infiltrates through the ground forming deep or shallow groundwater aquifers.**

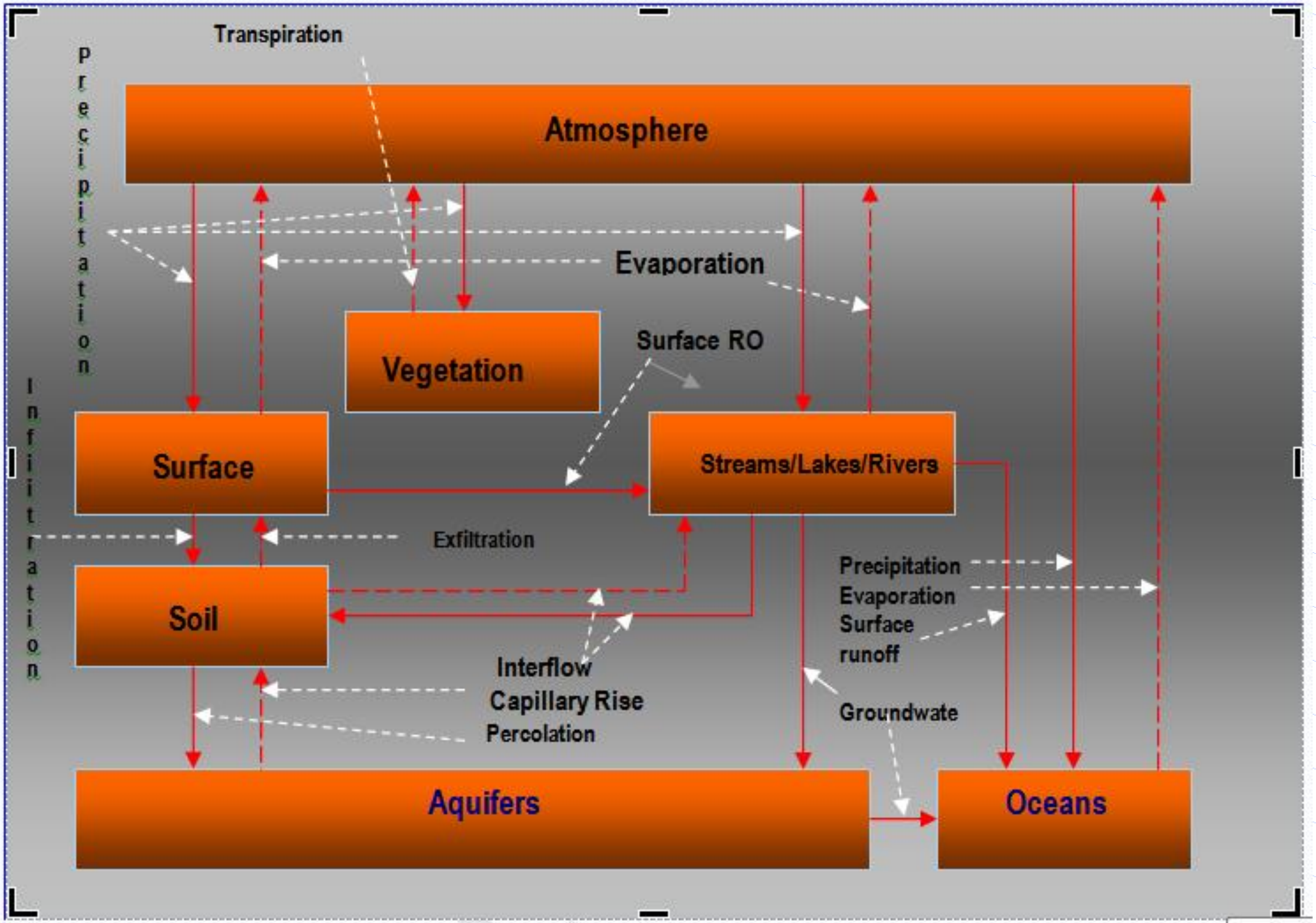
Hydrologic Cycle:

- A good portion of the precipitated water evaporates back to the atmosphere thereby completing the hydrologic cycle. Elements of hydrologic cycle are:
  - Evaporation, E
  - Transpiration, T
  - Precipitation, P
  - Surface runoff, R
  - Groundwater flow, G, and,
  - Infiltration, I

Hydrologic Cycle in Visual Form:



System Concept in Hydrologic Cycle:



Hydrological cycle

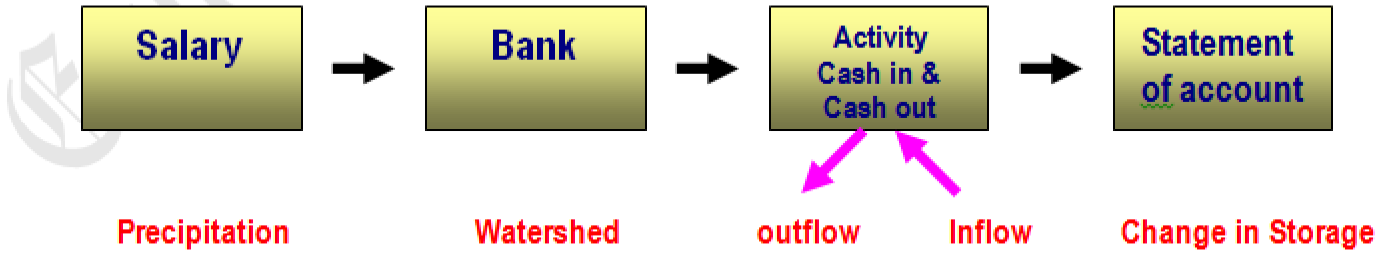
- Involves the following processes
  - A portion known as the interception is retained on buildings, trees, and plants. This is eventually evaporated, the remaining quantity is known as the effective precipitation.
  - Some the effective precipitation is evaporated into the atmosphere directly.
  - Another portion is infiltrated into the ground. A part of the infiltration in the root zone is consumed by plants.
  - The water that percolates deeper into the ground constitutes the groundwater flow.
  - If the precipitation exceeds the combined evaporation and infiltration, puddles known as depression storage are formed.

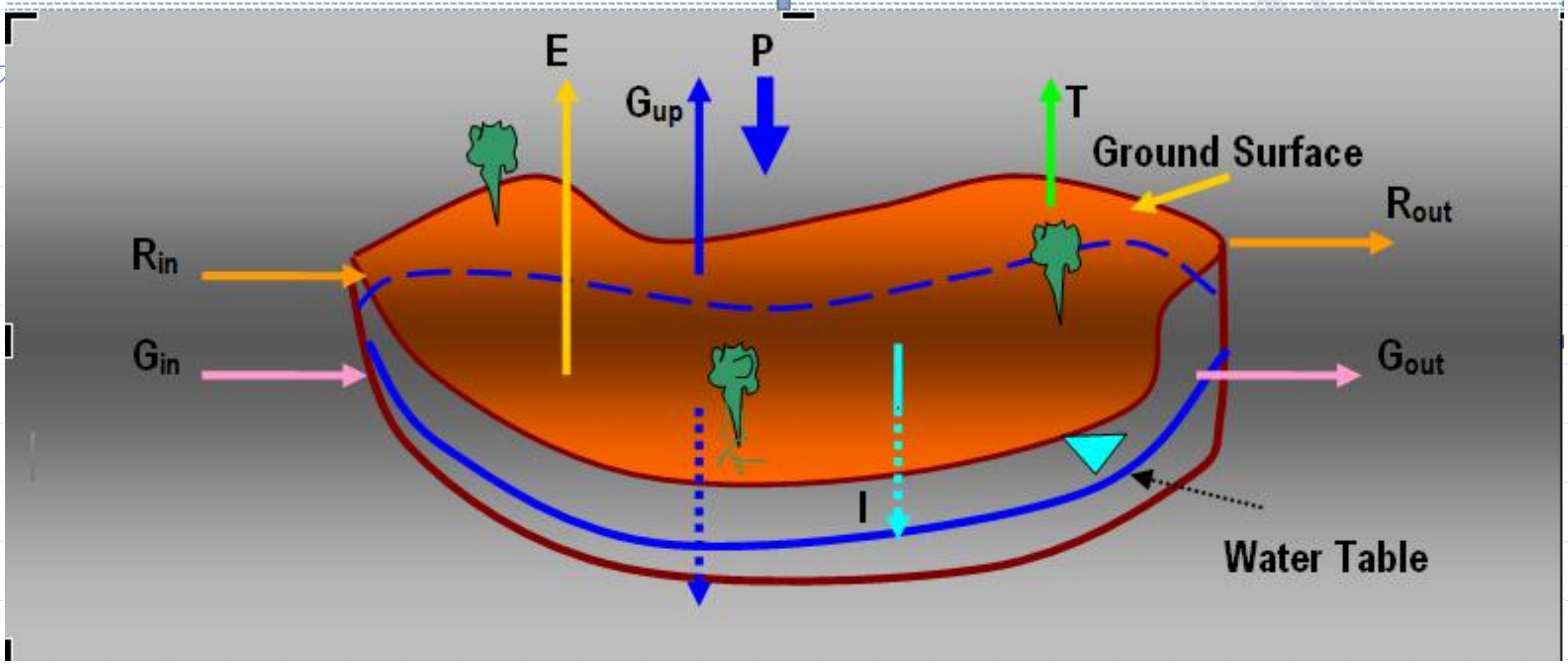
Hydrological cycle ‵ continue′

- After the puddles are filled, the water begins flowing over the surface to join stream channel.
- Runoff can not occur unless a layer of water is formed (detention storage)
- The destination of all streams is open bodies of water, i.e., oceans, seas, rivers
- The evaporation from all bodies together with transpiration caries moisture to the atmosphere. This results in forming clouds that contribute to the precipitation in step 1.

Hydrologic Budget

- Estimate components of hydrologic cycle in order to design projects and, more importantly protect the public from excessive floods and draughts
- Accounting technique that is not unlike keeping track of money in the bank




E
P
G up
T
Ground Surface
R out
R in
G in
G out
I
Water Table

- The hydrologic budget is a quantitative accounting technique
- The components of water budget are inflow, outflow and storage.

$$\Sigma \text{ INFLOWS} - \Sigma \text{ OUTFLOWS} = \Delta \text{ STORAGES}$$

- Or,in mathematical term

$$I - O = \partial S / \partial t$$

- Breaking system into individual component as shown in schematic figure:

$$P - E + ([(R_{in} + G_{in})] - (R_{out} + G_{out})] - T = dS/dt$$

- Where:
- P: Areal mean rate of precipitation (L/T)
- E: Evaporation (L/T)
- R_{in}, G_{in}: Inflow from surface and groundwater (L/T)
- R_{out}, G_{out}: Outflow from surface and groundwater (L/T)
- S: Storage (L) and,
- T: Transpiration (evaporation from plants, L/T)

Breaking the above into surface and subsurface balance equations:

Surface: $P + R_{in} - R_{out} + \cancel{G_{up}} - \cancel{I} - E - T = \Delta S_s$

Subsurface: $\cancel{I} + G_{in} - G_{out} - \cancel{G_{up}} = \Delta S_g$

The water budget formula is often used to estimate the amount of evaporation and evapotranspiration. Combining & dropping subscripts to represent net flows we get hydrologic budget formula,

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

Balance Equation for Open Bodies with Short Duration:

- And, for an open water bodies, short duration,

$$I - O = \Delta S/\Delta t$$

Where,
I = inflow volume per unit time
O = Outflow per unit time

Balance Equation for Urban Drainage:

For urban drainage system, ET (evapotranspiration) is often neglected,

- $$P - I - R - D = 0$$

  - P = precipitation
  - I = infiltration
  - R = direct runoff
  - D = Combination of interception and depression storage

Illustrative Example:

In a given year, a 10,000 Km^2 watershed received 30 cm of precipitation. The annual rate of flow measured in the river draining the area is 60 m^3/sec. Estimate the Evapotranspiration. Assume negligible change of storage and net groundwater flow.

Solution:

Combining E and T, then ET = P – R

In the above, the precipitation term P is given in cm and the runoff term R is given in discharge unit. Since units in the equation must be consistent, and since the area of the watershed is constant, the volume of flow into the watershed is converted to equivalent depth.

Volume due to runoff = 60 m^3/s x 86400 sec/day x 365 day/yr = 1.89216×10^9 m^3

= 1.89216×10^9 m^3 x $(100\ cm/m)^3$ = 1.89216×10^{15} cm^3

Equivalent depth = volume of water / area of watershed

= 1.89216×10^{15} / [(10,000) $(100{,}000\ cm/km)^2$] = 18.92 cm

Amount of Evapotranspiration ET = P – R = 30 – 18.92 = <u>11.08 cm / yr</u>

Illustrative Example: (From Viessman 2003)

The drainage area of a river in a city is 11,839 km^2. If the mean annual runoff is determined to be 144.4 m^3/s and the average annual rainfall is 1.08 m, estimate the ET losses for the area. Assume negligible changes in groundwater flow and storage (i.e. G and $\Delta S = 0$).

Solution:

Then: ET = P – R, converting runoff from m^3/yr to m/yr, then,

$$R = [144.4\ m^3/s \times 86400\ s/day \times 365\ day/yr] / [11{,}839\ km^2 \times 10^6\ m^2/km^2] = 0.38\ m$$

$$ET = P - R = 1.08 - 0.38 = \underline{0.7\ m}$$

Illustrative Example:

At a particular area, the storage in a river reach is 40 acre – ft. The inflow at that time was measured to be 200 cfs and the outflow is 300 . The inflow after 4 hours was measured to be 260 and the outflow was 270. Determine a) the change in storage during the elapsed time and b) The final storage volume.

a) Average inflow rate = (200 + 260) / 2 = 230 cfs
Average outflow rate = (300 + 270) / 2 = 285 cfs and Since : $I - O = \Delta S / \Delta t$

$\Delta S/\Delta t = 230 - 285 = -55$ cfs

$\Delta S = (-55)(4 \text{ hr}) = -220$ cfs-hr = (- 220 cfs-hr) (60 x 60 Sec / 1-hr) (1 acre – ft / 43,560 ft^3) =
= - 18.182 acre-ft

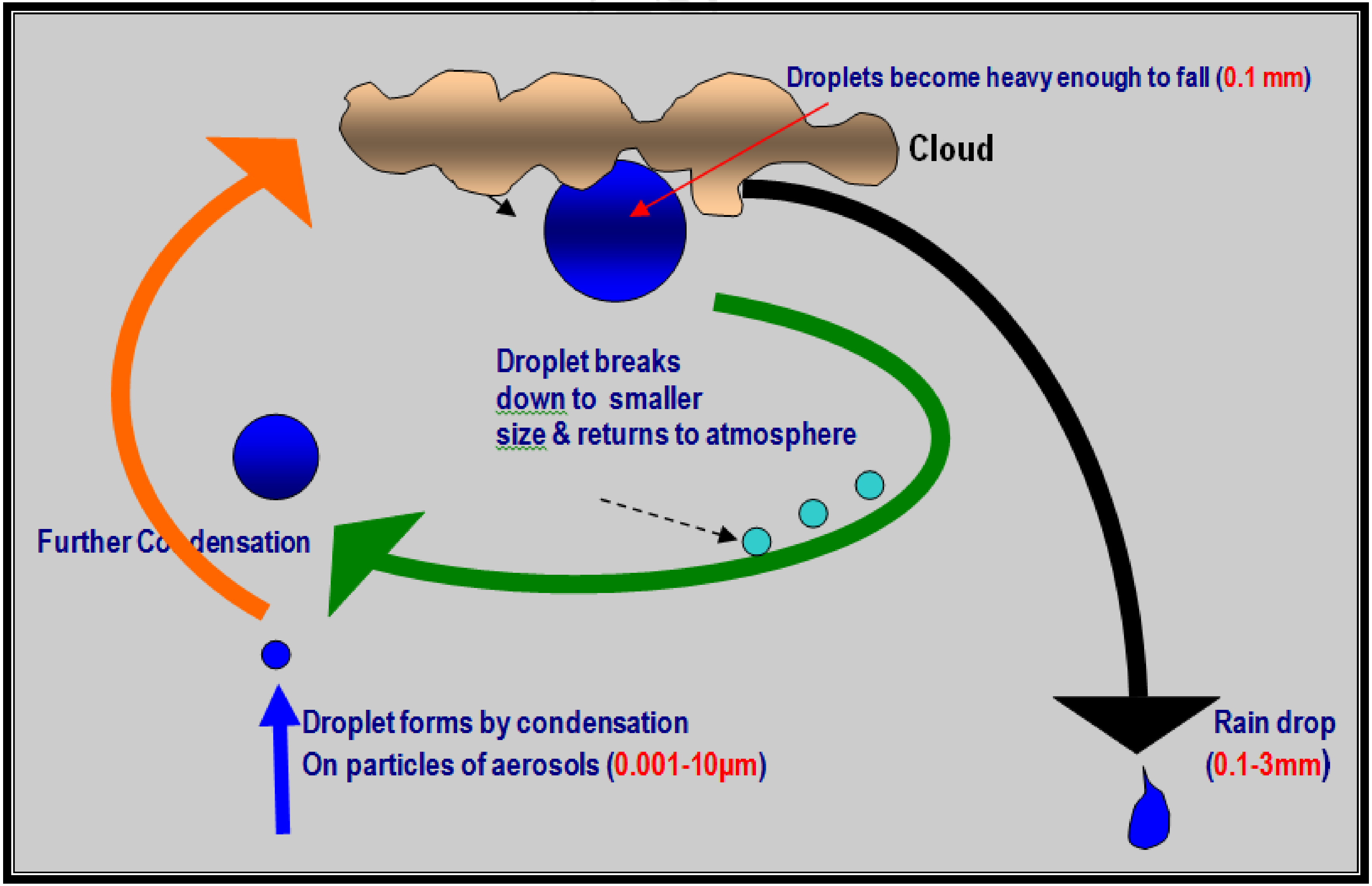
b) $S_2 = 40 - 18.182 = 21.82$ AF

Precipitation:

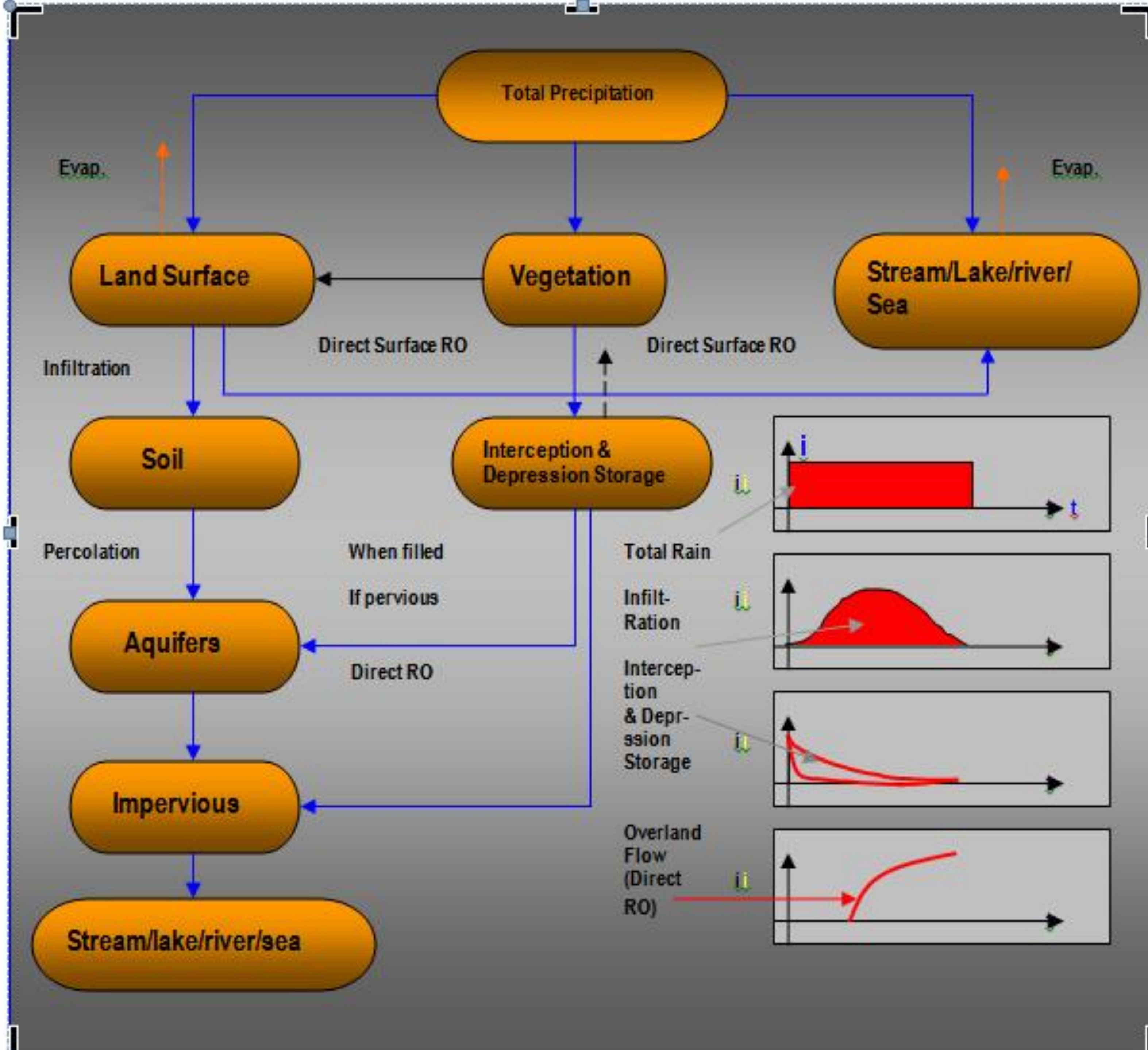
- Precipitation is the discharge of water out of the atmosphere.
- The principal form of precipitation is rain and snow and to a lesser extent is hail, sleet.
- physical factor producing precipitation is the condensation of water droplets due to atmosphere cooling

The steps required to form precipitation include:

1. Cooling which condensate moist air to near saturation,
2. Phase change of water vapor to liquid or solid and,
3. Growth of water droplet to perceptible size. This mechanism requires cloud elements to be large enough so that their falling speed can exceeds the upward movement of the air. If the last step does not occur, cloud will eventually dissipate.

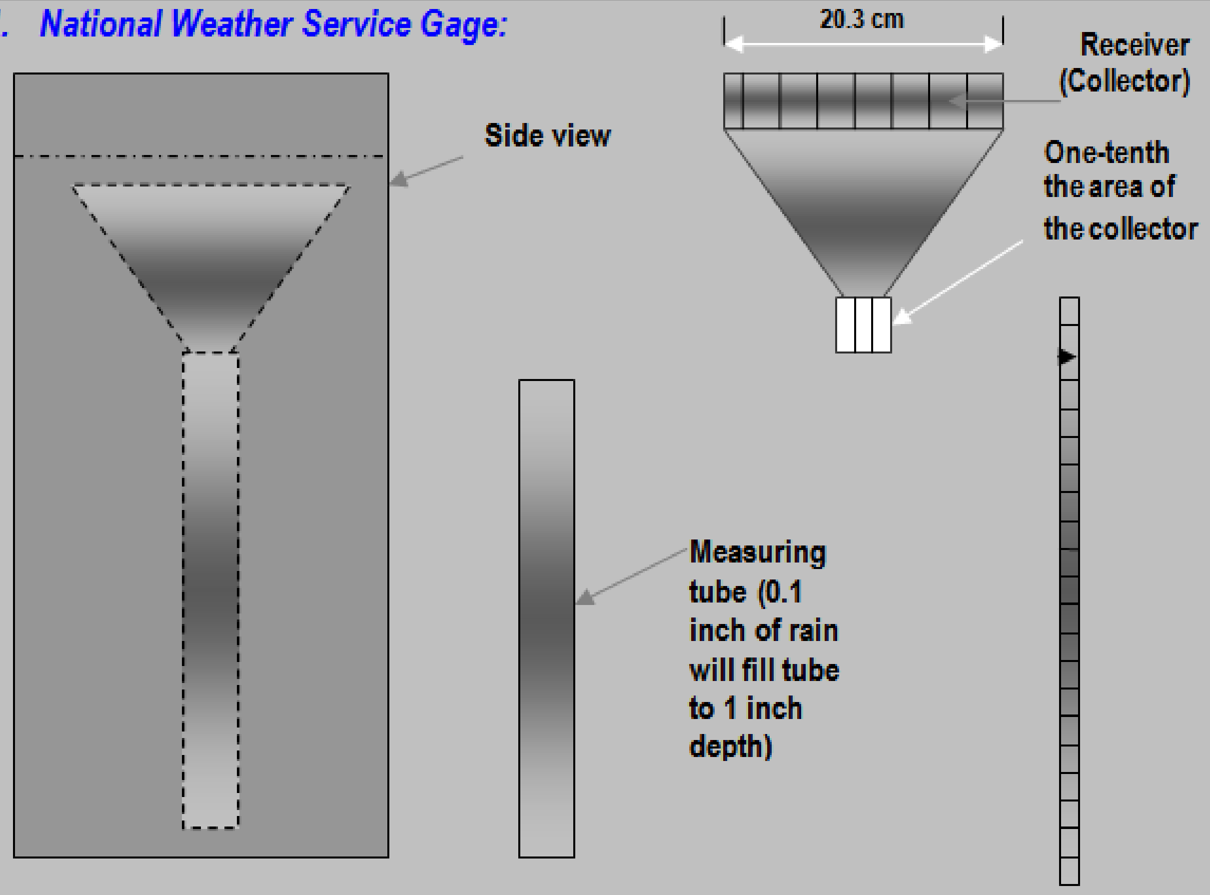

Droplets become heavy enough to fall (0.1 mm)
Cloud
Droplet breaks
down to smaller
size & returns to atmosphere
Further Condensation
Droplet forms by condensation
On particles of aerosols (0.001-10μm)
Rain drop
(0.1-3mm)

Distribution of Precipitation:



Measurement of Precipitation:

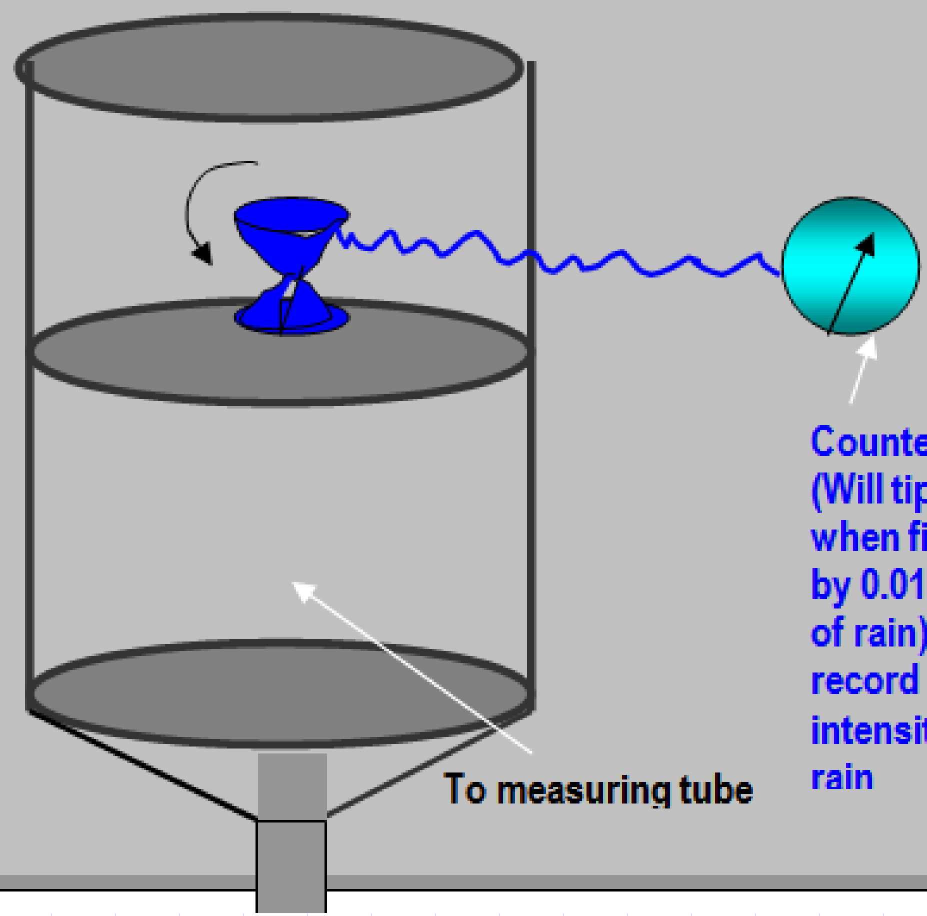
1. National Weather Service Gage:



Errors:

- Splashing
- Moisture deficiency of gage
- Wind blowing

2. Tipping Bucket Gage:



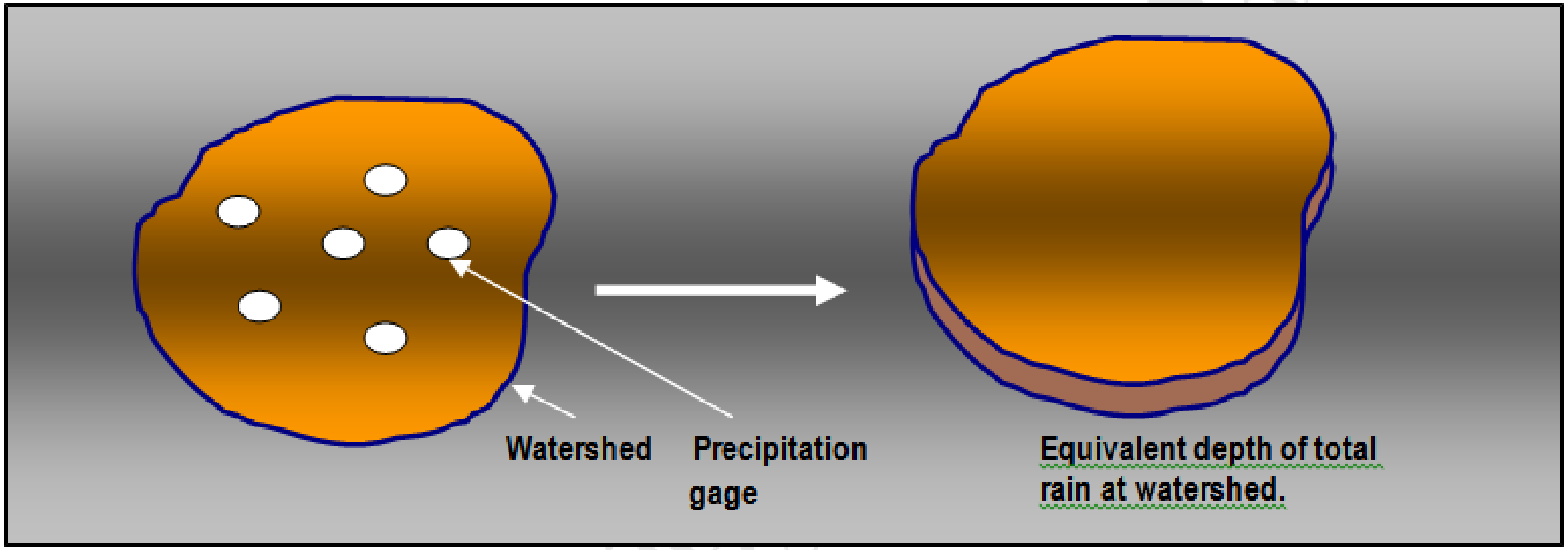
- ***Depression Storage*: This is the part of precipitation that is intercepted by holes in the ground and uneven surfaces. This part of storage will eventually be evaporated or slowly seeps underground.**

- ***Infiltration*: This portion of precipitation makes its way to replenish groundwater through seepage.**

- ***Overland Flow:* This portion of precipitation is the access water after the local rate of infiltration reaches its maximum. It develops as a film of water that moves overland eventually reaching streams, reservoirs or lakes.**

Methods of Estimating Areal Precipitation in the Ground:

a) **Arithmetic Mean:** Equal weights are assigned to all gage stations.



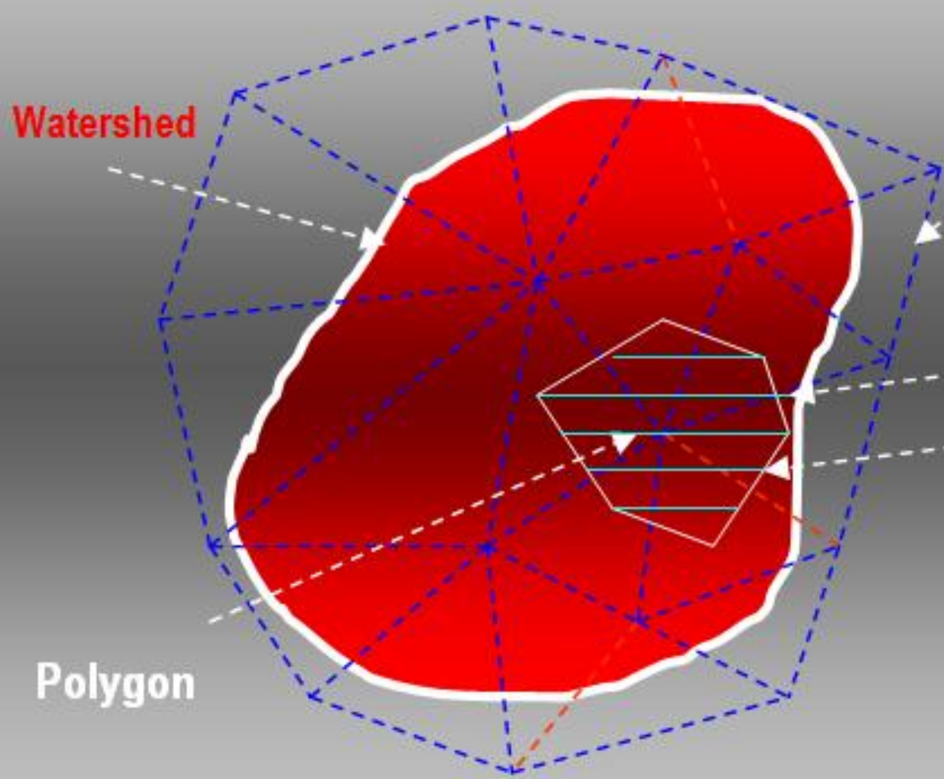
b) Thiessen Polygon: Each gage is assigned an area bounded by a perpendicular bisect between the station and those surrounding it. The polygon represent their respective areas of influence (see figure). The average precipitation is calculated as:

$$\text{Average PPT} = \sum A_i\, p_i \,/\, A_T$$

Illustrative Method:

Observed Precipitation (L)	Area of Polygon (L^2)	Precipitation x Area (L^3)
P_1	A_1	$P_1 A_1$
P_2	A_2	$P_2 A_2$
P_3	A_3	$P_3 A_3$
P_n	A_n	$Pn\, A_n$

$$\text{Average P} = (P_1 A_1 + P_2 A_2 + P_3 A_3 + \dots + Pn\, A_n) \,/\, (A_1 + A_2 + A_3 + \dots + A_n)$$



Theissen method provides weighting factors for each gage by enabling data from adjacent areas to be incorporated in calculating the mean value of precipitation

Perpendicular bisector
Area a representing gage P_1

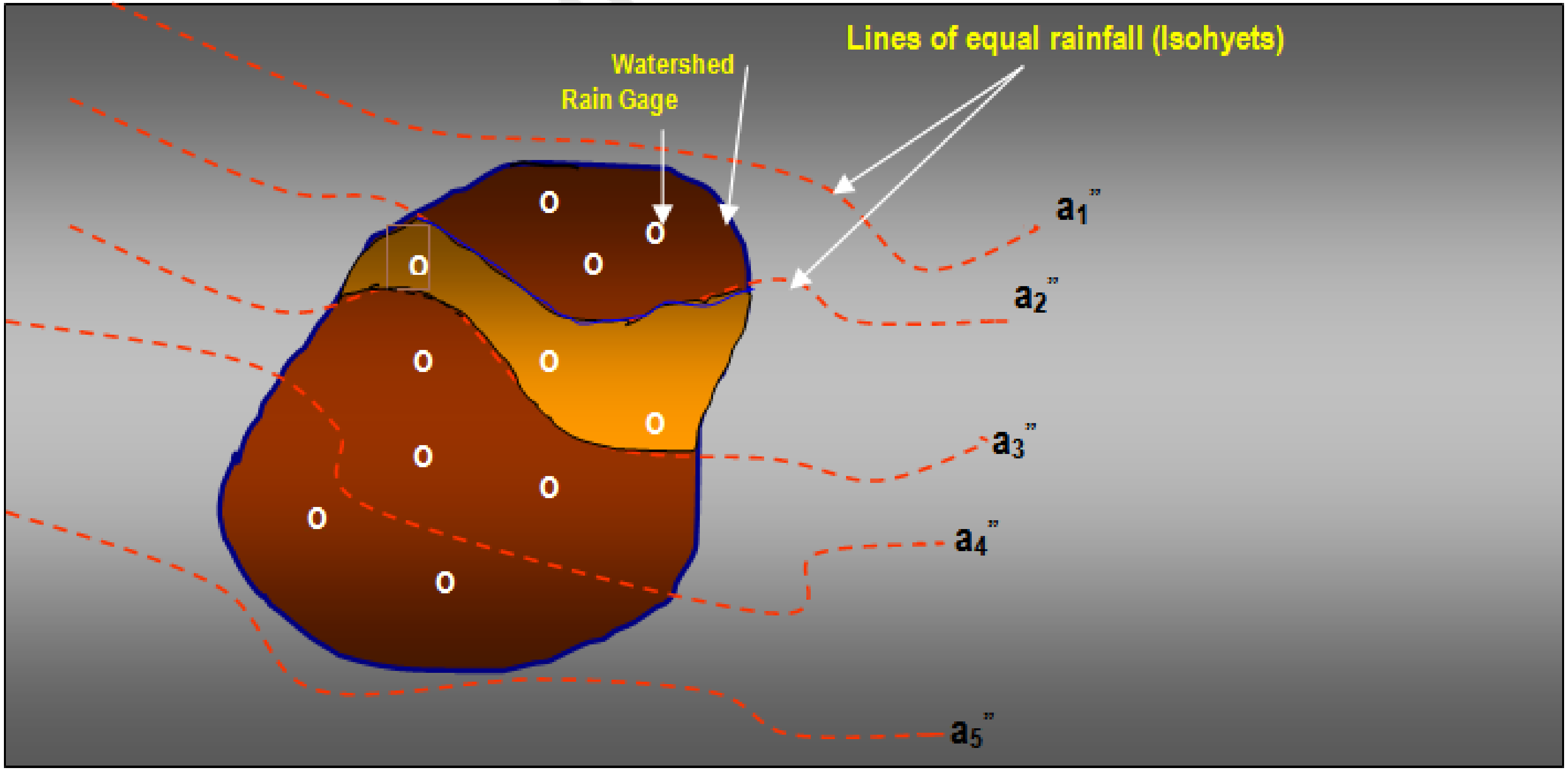
<u>Computation Procedure:</u>

The average precipitation is computed by multiply the precipitation of each station by its assigned area, adding them and dividing the total area of the watershed.

$\text{Average PPT} = \sum a_i p_i / A_T$

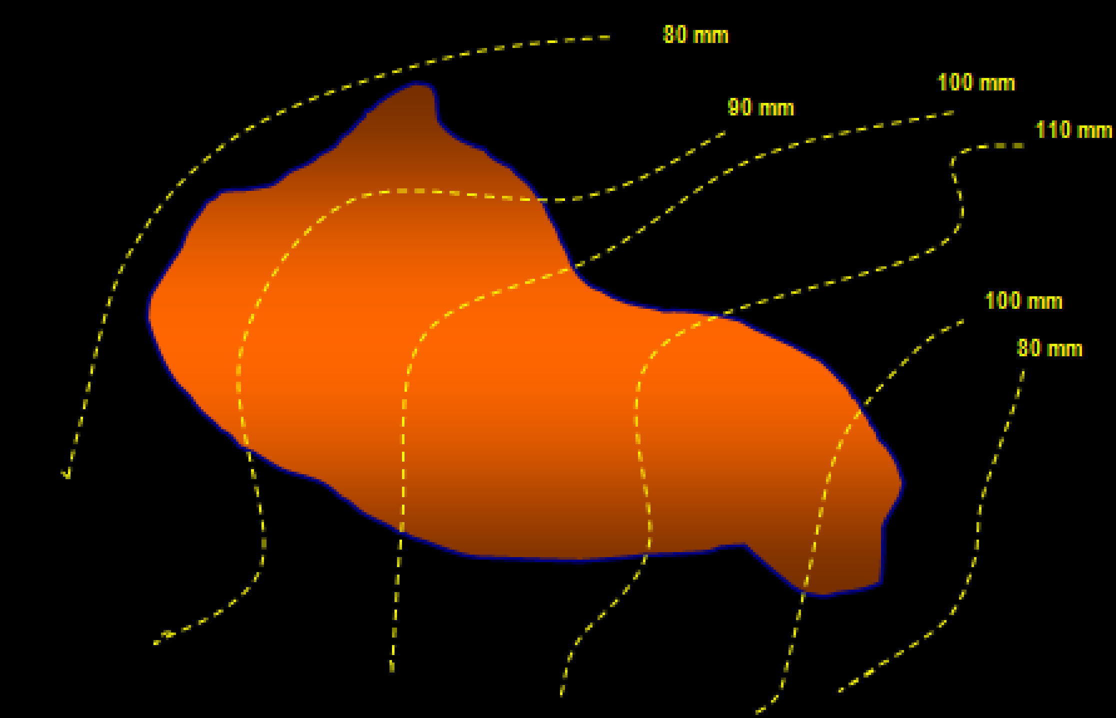
c) Isohyetal Method: The area between two successive isohyets is measured using planimeter or simply by counting sub grids. The average precipitation is computed by multiplying the average precipitation between two successive isohyets by the inter-Isohyetal area, adding them and dividing by the total area of the watershed.

Average PPT = $\sum a_i p_i / A_T$



The method of calculation is similar to that of Thiessen method except the area is the one bounded by two isohyets.

Illustrative Example:



Average PPT	Area	Product
87	120	10440
95	156	14820
105	190	19950
105	140	14700
95	60	5700
	Σ 666	Σ 65610

Ave PPT = 65610/ 666
= 98.51 inch

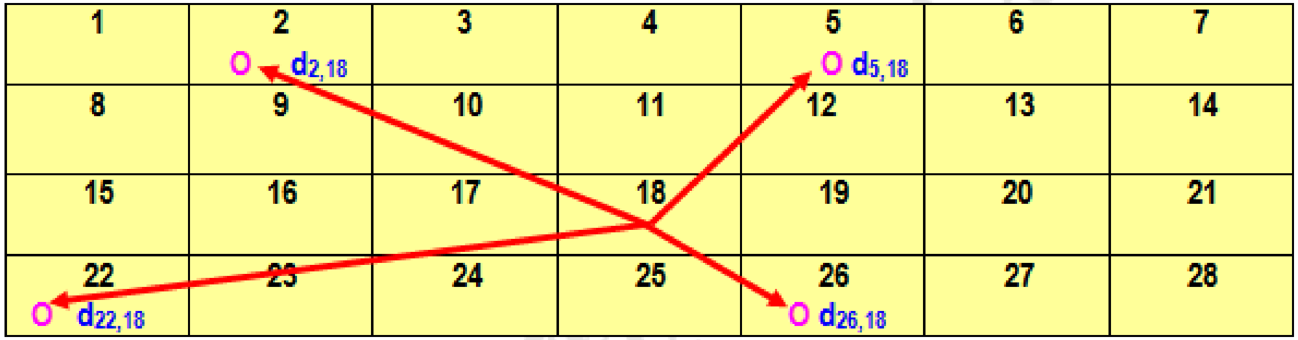
Adjusted values

Alternative Method:

- **Inverse Distance Method:** The method is based on the assumption that the precipitation at a given point is influenced by all stations. The method of solution is to subdivide the watershed area into m rectangular areas. The mean precipitation is calculated using the following formula:

$$P = 1/A \sum_{j=1}^{m} A_j \left(\sum_{i=1}^{n} d_{ij}^{-b} \right)^{-1} \sum_{i=1}^{n} d_{ij}^{-b} P_i$$

- Where: m is the number of the subareas, A_j is the area of the j^{th} sub area, A is the total area, d_{ij} is the distance from the center of the j^{th} area to the i^{th} precipitation gage, n is the number of gages and b is a constant and in most applications, it is taken as equal to 2. Note that if b is 0, the equation is reduced to the following:
- $P = 1/A \sum A_j P_i$



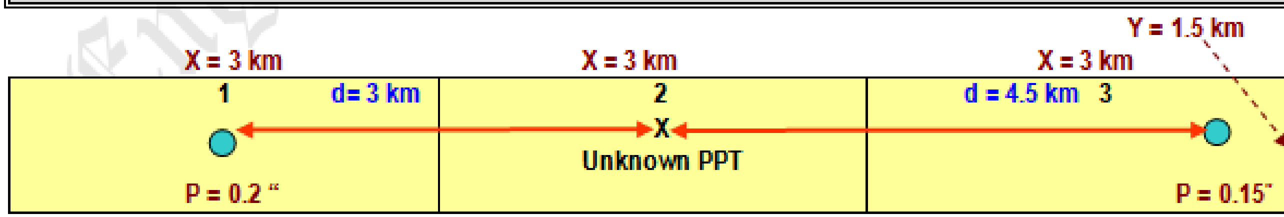
O: Precipitation Gage

For example, the precipitation over sub area 18 is determined as:

$$P_{18} = [\sum_{i=1}^{4} d^{-2}_{i,18} \; P_i \; / \; (\sum_{i=1}^{4} d^{-2}_{i,18})$$

Illustrative Example:

The sub areas shown below are 4.5 km² each, find the precipitation x in subarea shown below:



$P_2 = \sum d^{-2}_{i,2} P_i / (\sum d^{-2}_{i,2})$

$P_2 = [d^{-2}_{1,2}] P_1 / [d^{-2}_{1,2} + d^{-2}_{3,2}] + [d^{-2}_{3,2}] P_3 / [d^{-2}_{1,2} + d^{-2}_{3,2}]$

$P_2 = [(3)^{-2}] (0.2) / (0.111+ 0.0494) + (4.5)^{-2} (0.15) / (0.111+ 0.0494 = 0.13854 + 0.04619 = 0.1847$

Methods of Estimating Missing Precipitation:

- a) Normal Ratio Method:

The missing precipitation at station x is calculated by using weights for precipitation at individual stations. The precipitation at station x is,

$$P_x = \sum_{i=1}^{n} w_i P_i$$

- where n is the number of stations and w_i designates the weight for station i and computed as

$$\mathbf{w_i = A_x / n A_i}$$

- Where A_i is the average annual rainfall at gage i, A_x is the the average annual rainfall at station x in question.
- Combining the above two equations,

$$\mathbf{P_x = (A_x / n) \sum_{i=1}^{n} P_i / A_i}$$

Illustrative Example:

The following data was taken from 5 gage stations:

Gage	Average Annual Rainfall (cm)	Total Annual Rainfall (cm)
A	32	2.2
B	28	2.0
C	25	2.0
D	35	2.4
X	26	?

Solution:

$P_x = w_A P_A + w_B P_B + W_C P_C + W_D P_D$

$= (A_x / n A_A) P_A + (A_x / n A_B) P_B + (A_x / n A_C) P_C + (A_x / n A_D) P_D$

$= (26 / 4 \times 32)(2.2) + (26 / 4 \times 28)(2.0) + (26 / 4 \times 25)(2.0) + (26 / 4 \times 35)(2.4) = 1.877$ cm

Then: P_x = 1.877 cm

b) Quadrant Method:

- To account for the closeness of gage stations to the missing data gage, quadrant method is employed. The position of the station of the missing data is made to be the origin of the four quadrants containing the rest of stations. The weight for station i is computed as:

$$w_i = \sum_{i=1}^{4} (1 / d^2_i)$$

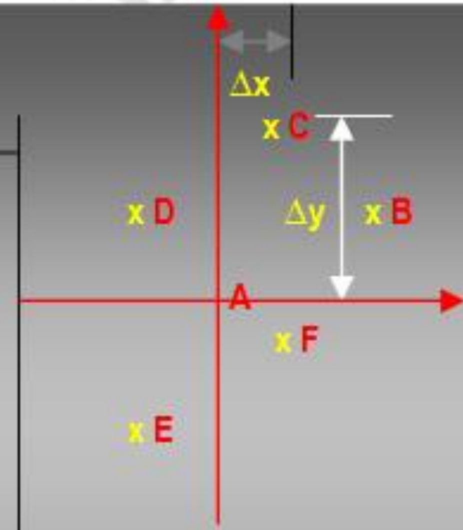
and the missing data is calculated as,

$$P_x = \sum_{i=1}^{n} w_i \, . \, P_i \; / \; \sum_{i=1}^{n} w_i$$

Illustrative Example:

Point PPT	PPT	ΔY	ΔX	(D^2)*	$W=1/D^2$	P x W
A	??	0	0	-	++	++
B	1.6	2	4	20-	0.05	0.08
C	1.8	6	1	37	0.027	0.49
D	1.5	2	3	13	0.0769	0.1154
E	2.0	3	3	18	0.056	0.1112
F	1.7	2	2	8	0.125	0.2125
					$\sum$ 0.3345	0.5677

* $D^2 = \Delta X^2 + \Delta Y^2$



P_A = 0.5677 / 0.3345

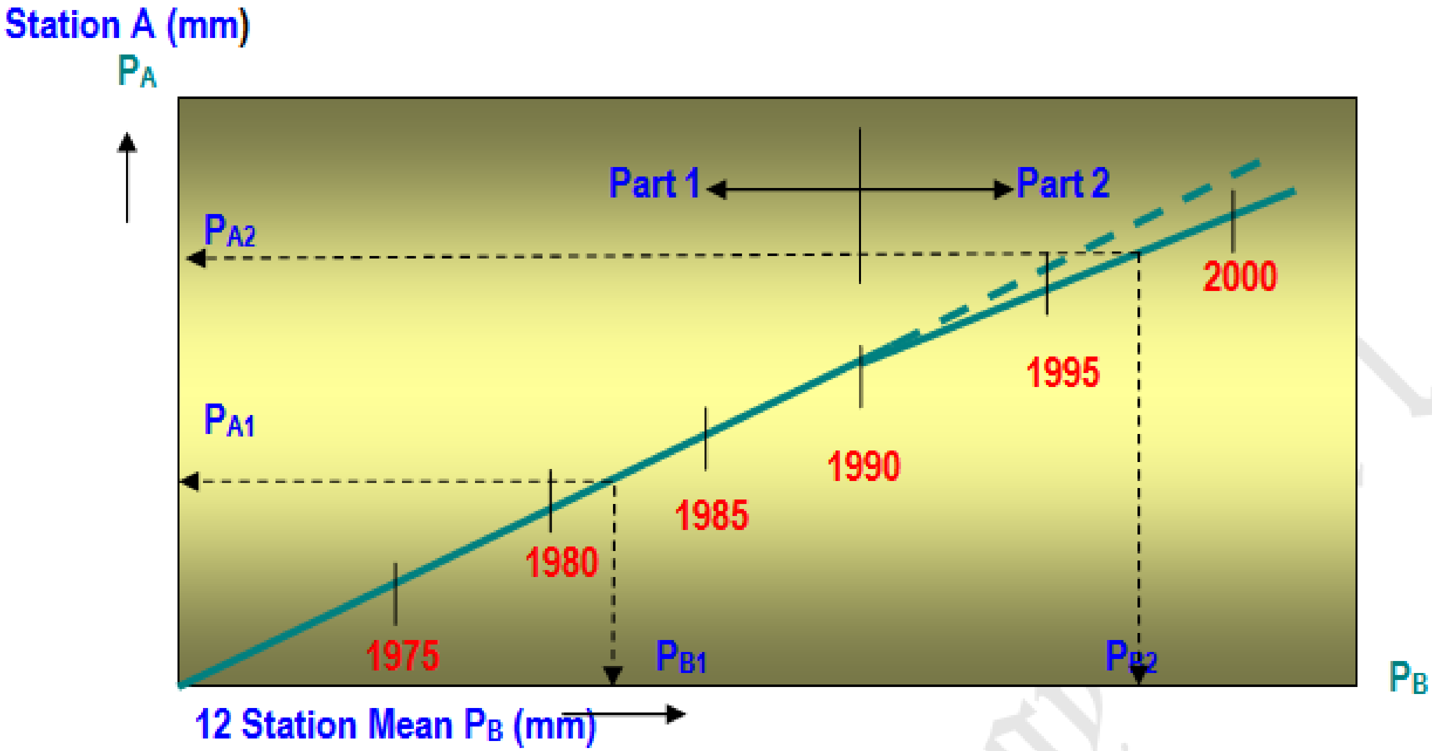
= 1.7

Gauge Consistency:

Double Mass Curve

- The inconsistency could be attributed to environmental changes such as sudden weather changes that adversely effect gage reading, vandalism, instrument malfunction, etc
- Double Mass Curve is a plot of accumulated annual or seasonal precipitation at the effected station versus the mean values of annual or seasonal accumulated precipitation for a number of stations surrounding the station that have been subjected to similar hydrological environment and known to be consistent

- **The double mass curve produced is then examined for trends and inconsistencies which is reflected by the change of slope. A typical Double Mass Curve of infected station (station A) versus mean values of similar stations is shown below**

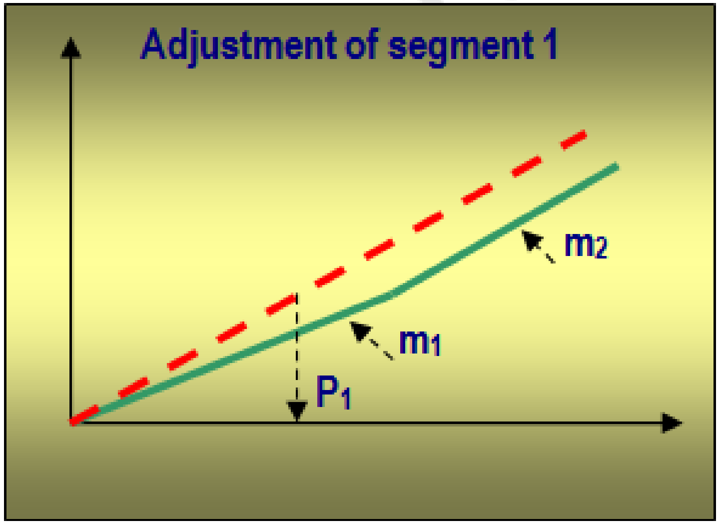


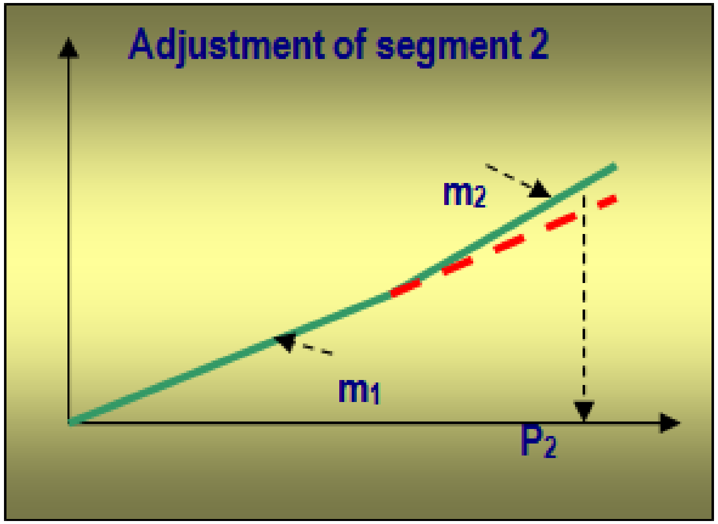
Method of Correction: (READ ONLY)

As shown in the figure, the slope of the Double Mass Curve changed abruptly from m_1 prior to 1990 to m_2 after 1990. The record can then be adjusted using the following ratio:

$P_a = (m_a/m_o)\, p_o$ where: m_a (adjusted) & m_o (observed)

In the above, subscript a denotes adjusted and o denotes observed. If the initial part of the record need to be adjusted then m_2 is the correct slope and P_{A2} and P_{B2} are correct. So, if m_2 is the correct slope, the slope m_1 should be removed from P_{A1} and replaced by m_2 by using the formula: $p_{A1} = (m_2 / m_1)\, P_{A1}$ where p_{A1} is the adjusted data.





$p_1 = (m_2 / m_1) P_1$ $p_1 = (m_1 / m_2) P_2$

Illustrative Example (McCuen 1998)

Gage H was permanently relocated after a period of 3 years. Adjust the double mass curve and find the values of h_{79}, h_{80} and h_{81}.

year	E	F	G	H	Total ∑E+F+G	Cumulative E+F+G	Cumulative H	h
1979	22	26	23	28	71	71	28	24.7
80	21	26	25	33	72	143	61	29.1
81	27	31	28	38	86	229	99	33.5
82	25	29	29	31	83	312	130	
83	19	22	23	24	64	376	154	
84	24	25	26	28	75	451	182	
85	17	19	20	22	56	507	204	
86	21	22	23	26	66	573	230