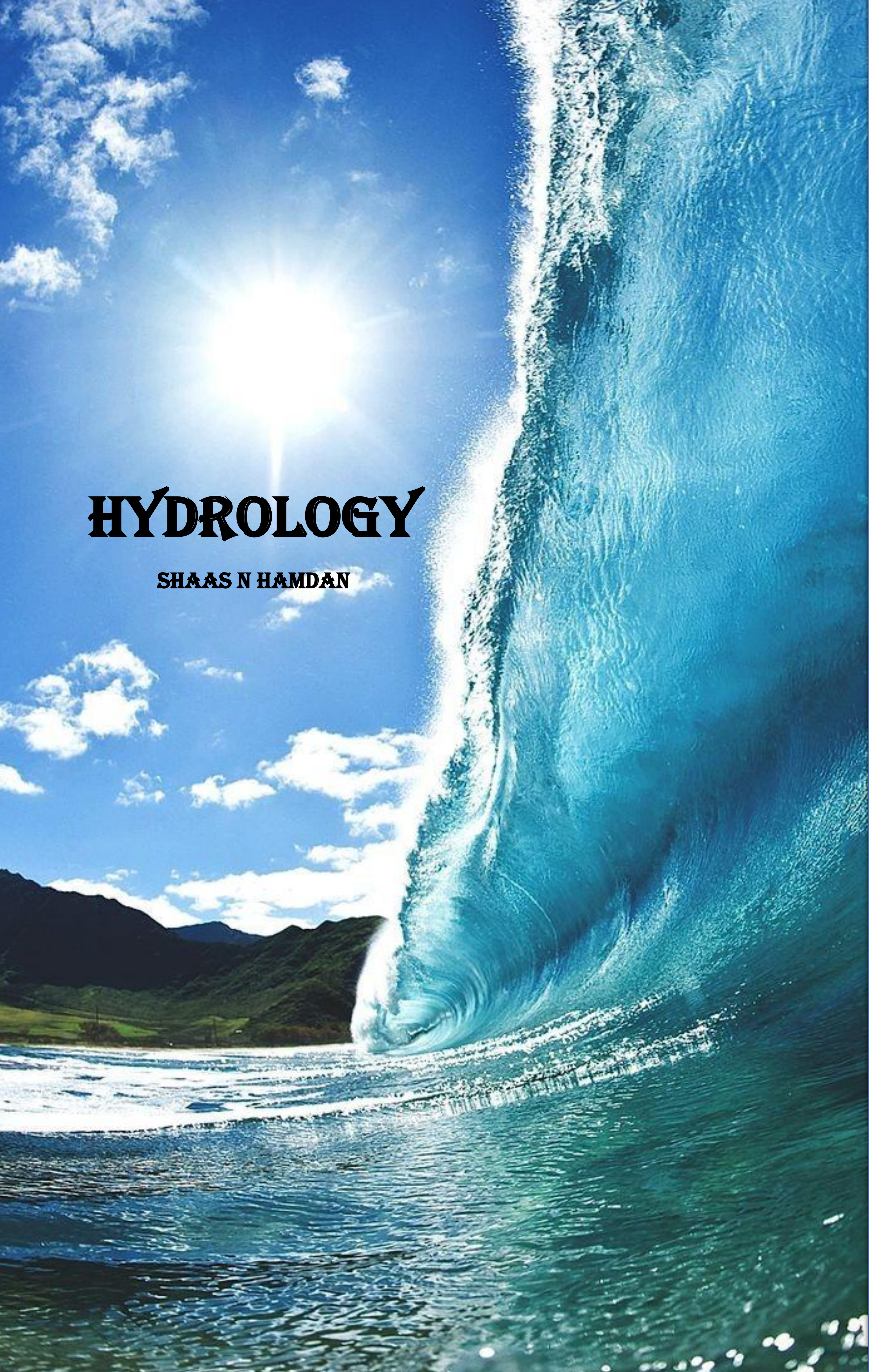


HYDROLOGY

SHAAS N HAMDAN

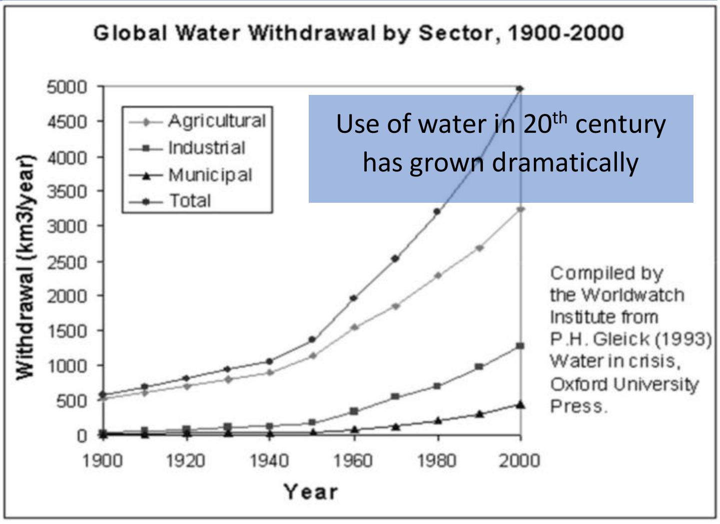
INTRODUCTION TO HYDROGEOLOGY

Hydrology "water science": is the Study of occurrence & movement of water on & beneath the surface of the Earth finite though renewable resource

- ➢ finite in quantity, unlimited in supply, use rate is limited by 'recycling times'
- ➢ Hydrologic sciences have pure & applied aspects

- Surface water hydrology focuses on atmospheric or soil waters, shallow groundwater, rivers, lakes, ocean, & sea

Applications of Hydrology	Used in
Resources Management	Water supply, & wastewater
Environmental Protection hydrology	Soil contamination, Surface & groundwater pollution, Wetlands
Engineering hydrology	Design of dams, culverts, bridges, & Hillslope stability
Natural Hazards	Flood mitigation, Drought, Slope failure
Agriculture	——



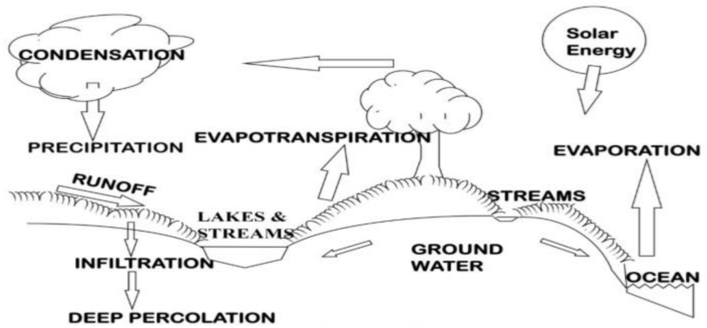
- **Transport & transformation processes within definite reservoirs**: Carbon, Rock, & Wdramaticall
- **Reservoir (M)**: amount of material with physical, chemical, & biological characteristics that can be considered as a homogeneous (box or compartment, M is in mass units "g" or "moles")
  - ➢ e.g. O_2 in atm, C in living organic matter in the Ocean, & Water in the Ocean
- **Flux (F)**: is the amount of material transferred from one reservoir to another per unit of time (M/s, M/s.L²)
  - ➢ e.g. rate of evaporation from surface Ocean, & rate of deposition of carbon (on marine sediments)
- **Source (I or Q)**: A flux of material into a reservoir
- **Sink (O or S):** A flux of material out of a reservoir
- Volume (M) of water at Earth's surface = 1.37×10^9 km³
- The Oceans cover 71% of the surface (29% for the continent masses above sea level)

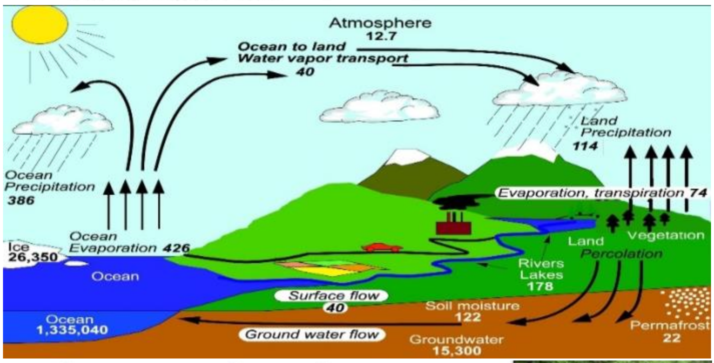
Reservoir	Volume [km³]	% by volume
Biosphere	0.6×10^3	0.00004%
Rivers	1.7×10^3	0.0001%
Atmosphere	13×10^3	0.001%
Lakes	125×10^3	0.01%
Groundwater	9500×10^3	0.68%
Glacial & land ice	29000×10^3	2.05%
Oceanic & sea ice	$1,370,000\times10^3$	97.25%
Total	$1,408,640\times10^3$	100%

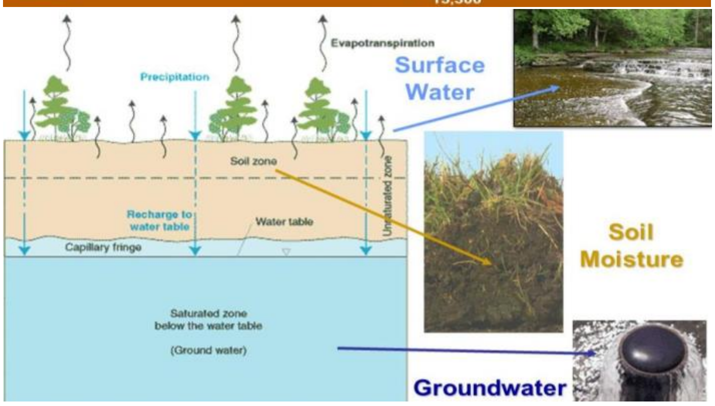
- ***yearly evaporation:*** 84% from the Oceans & 16% from surface of continents
- ***yearly precipitation:*** 75% Oceans & 25% continents
- During the year, the atmosphere transports 9% of Oceans' evaporation to the continents which returned via surface streams & as groundwater

HYDROLOGIC CYCLE

- **Reservoirs or stocks of water:** the places where water is located in the earth's atmosphere system (movements, or fluxes of water between reservoirs)







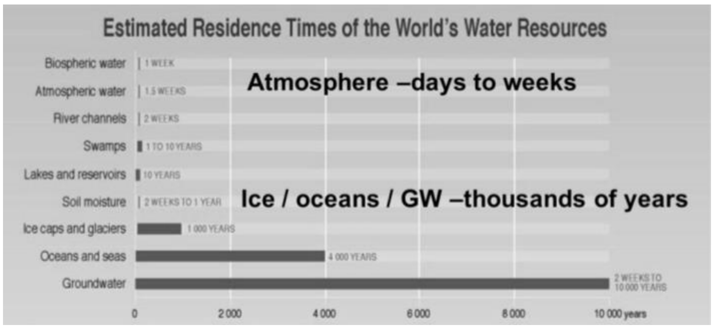
- Pathways for movement of water: ***Precipitation*** (snow rainfall), ***Interception*** (vegetation, building), ***Depression storage*** (puddles, & lakes), ***Evaporation***, ***Transpiration***, ***Infiltration***, ***Groundwater flow***, & ***Stream flow***
- **Transpiration**: when Plants absorb groundwater & pump it into the atmosphere
- **Evaporation**: liquid → vapor, at T below boiling point
- **Sublimation**: ice → gaseous phase
- **Saturation point (Sp)**: is the volume of air that contains as much water vapor as possible at a given temperature
- **Relative humidity (RH)**: water vapor in air as % of Sp
- **Condensation** occurs when saturation point is exceeded
- **Dew point**: Temperature at which condensation occurs

RESIDENCE TIME (T_R)

- **Residence time (t_R):** is the average time taken by water to spends within a reservoir

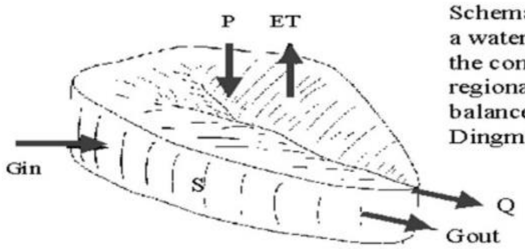
$$t_R (or\ \tau_r) = \frac{S\ or\ V}{I} = \frac{S\ or\ V}{O} = \frac{water\ stored\ in\ reservoir}{inflow\ or\ out\ flow\ rate}$$

- atm: a few days, Rivers: about 20 days, Groundwater: 100's – 1000's yr, Glaciers: 10,000 yr



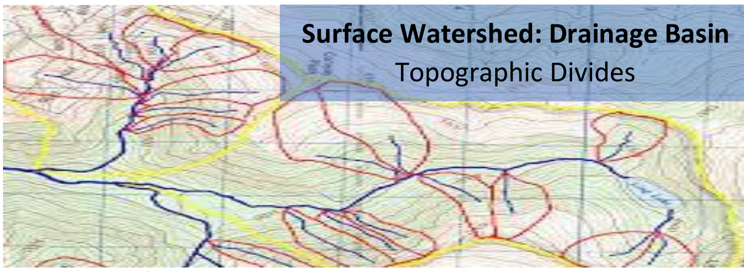
HYDROLOGIC SYSTEMS

- **Hydrologic system**: is an area or stock of water for which inflows & outflows can be identified
- Water cannot be created or destroyed within the area (i.e. it is a conservative quantity)
- If inflows ≠ outflow, there must be a change in storage
- **Watershed:** Area drains to a common (single) outlet
  - **Watershed**: Land area that contributes surface runoff to a point of interest
  - **Outlet**: ocean, lake, or cross section of the stream
- **Synonyms**: includes drainage basin, & catchment area
  - **Catchment**: area over which precipitation falls (in which water flowing across the land surface drains into a particular stream or river via a single outlet)
  - **Drainage basin**: tract of land (surface & subsurface) basin drained by a river & its tributaries



Schematic diagram of a watershed, showing the components of the regional water balance (after Dingman, 1994)

- **Divides**: boundaries of watershed, or places where slope changes it's direction (it's mapable)
  - are topographic highs, & Streams never cross them
  - Divides separate area where water will flow to basin outlet from areas that drains elsewhere



WATER BALANCE

- **Water balance (or water budget)**: law of conservation of mass of water in a closed system

$$\Delta storage = Input - Output = inflow - outflow$$

$$\frac{dv}{dt}\left[\frac{in\ L^3}{sec}\right] = I - O = V_{inflow\ rate} - V_{outflow\ rate}$$

$$\Delta S = P - ET - R$$

- **Continental Water Balance:** No change in storage

$$\frac{dv}{dt} = 0 = P - ET - R - G$$

P: precipitation onto land, ET: evapotranspiration from land, R:surface runoff, G: groundwater flow, all with L^3/s

- Water vapor density varies with T, Must express water vapor in "liquid water equivalent LWE" units
- **Ocean Water Balance**:

$$\frac{dv}{dt} = 0 = P - E + R + G$$

- **Water Balance Equation**

$$\Delta S = I - Q(volume) = i - q(fluxes)$$

$$p + G_{in} = Q + ET + G_{out} \pm \Delta S$$

  - Water balance is often used to estimate parameters that are difficult to measure

$$p + G_{in} = Q + ET + G_{out}$$

  - Total runoff for region: $R_O = Q + G_{out}$

$$G_{in} = G_{out} \rightarrow p = Q + ET \rightarrow R_O = Q = P - ET$$

- **Runoff (R_O)** depend on meteorology factor & vegetation
- **Infiltration**: outflow from surface, but it is an input to groundwater so its net effect is 0

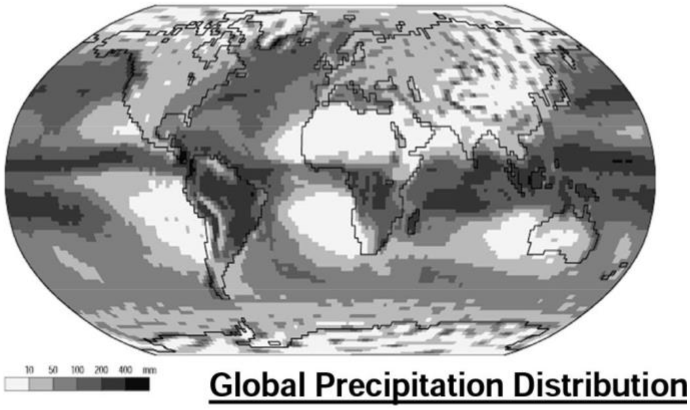
	Surface Water	Groundwater
Turnover Rate	11 – 14 days	Up to 5,000 year
Estimating Volume	Easy	Difficult
Amounts	Less abundant	More abundant
Accessiblity	Accessible	Less accessible

PRECIPITATION

- **Precipitation**: Primary (aerial) input, Used to estimate streamflow, & groundwater infiltration
- **Formation of Precipitation**: conditions for precipitation
  1. **Condensation** onto nuclei
  2. **Cooling** of atmospher
  3. **Growth** of water droplets
  4. Mechanism to cause sufficient **density of droplets**
- **Classification of Precipitation**
  1. **Snow**: ice crystals of hexagonal form (several cm's)
  2. **Hail**: balls of ice (5 - 125 mm, & sp. Grav. 0.7 - 0.9)
  3. **Rime**: ice granule forming by rapid freezing of super cooled water drops, they are white & opaque
  4. **Glaze**: smooth ice coating surfaces of rain & drizzle
  5. **Rain**: water drops (> 0.5mm)

Rainfall	Intensity of Precipitation
Drizzle (mist)	0.1 - 0.5mm diameter, mm/hr
Intensity	Light 2.5 mm/hr
Moderate	2.8 - 7mm /hr
Hilly & Heavy	> 7.6 mm/hr

  6. **Sleet**: frozen rain drops, falling via air at freezing T
  7. **Dew**: moisture condensed from the atmosphere in small drops upon cool surfaces



Global Precipitation Distribution

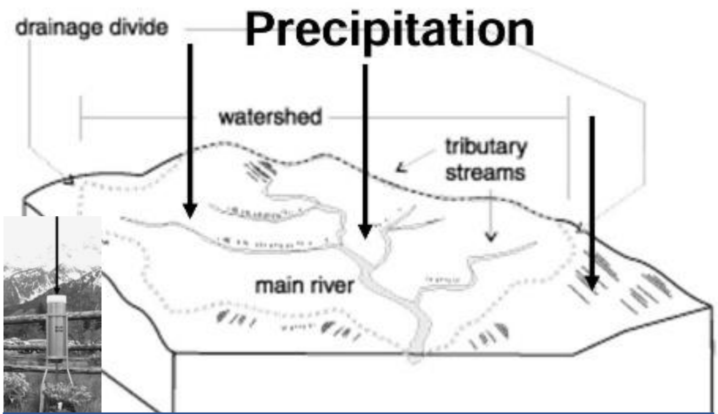
Annual rainfall ranges from 0 –1000 inches

GAUGES

- **Amount**: daily totals or storm event totals (mm)
- **Intensity**: rate of precipitation (mm/h, or mm/day)
- **Duration**: how long the event lasted (h, day)

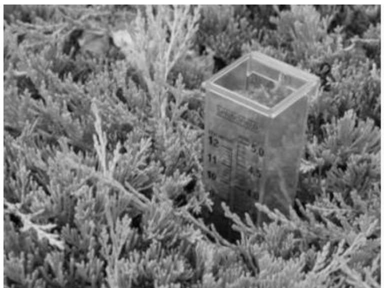
Measuring Precipitation

- **Recording rain gages**: weighing, float, & Tipping bucket
- **Non-recording**: cylindrical container type
- **Use of Radar**
- **Non-Recording gauges**
  - ➢ **Storage gages**: yield accumulation between visits (usually at 9:00am Daly)
  - ➢ **Collect rain (Type A) or snow (Nipher):** Snow melted to obtain water equivalent
  - ➢ **Calibrated to read depth of precipitation** (mm) = volume divided by area of gauge orifice = V/A
- **Snow board & measuring stick**: Use ruler to measure snow accumulation on ground (cm), Depth of water equivalent assumed to be 1/10 of snow depth based on snow density of 100 kg/m^3
- **Snow surveys:** e.g. traverse 6 - 10 locations 30m apart
- **snow sampler (long tube)** used to extract snow
  - ➢ markings on outside of tube indicate depth of snow
  - ➢ weight of sampler unit minus tare weight gives snow water equivalent of snow column removed
- **Snow pillow:** Bucket rain gauge, 2 small buckets on fulcrum, as one fills it tips & other start collecting rain
- **Recording gauges**
  - ➢ **Optical sensor**: distance to surface of water or snow

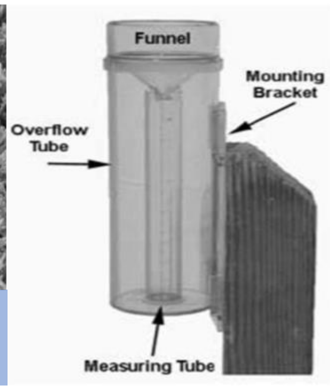


Most field based methods yield point estimates

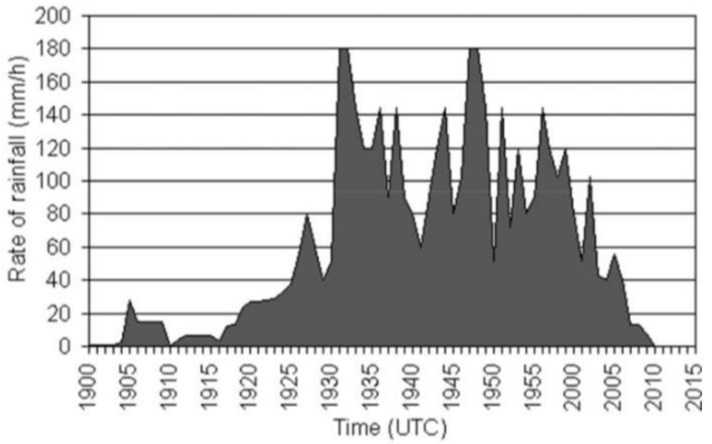
- Types of Gauges
  1. **Weighing Rain Gauge**
  2. **Non-recording Gaige: Backyard Gauge**

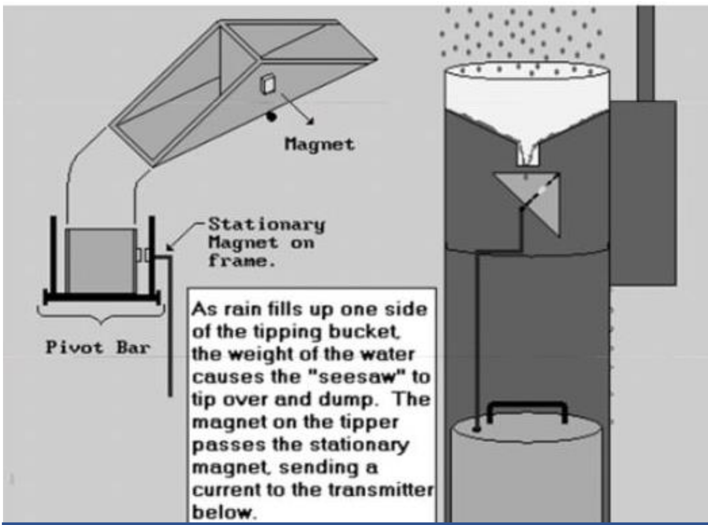


Backyard Gauge
Non-recording Gauge



  3. **Recording Gauges:** Cost more, but require less effort in data collection (Amount, Time of Occurrence, Duration, & Intensity)



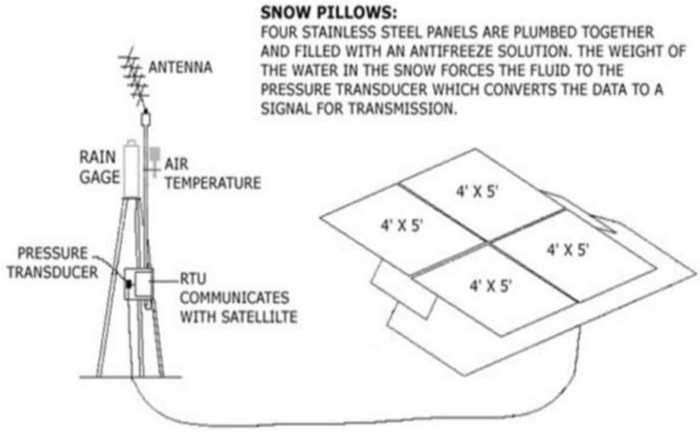


Gauge Location: Place in Open Area

- **Problems with Rain Gauges:** Wind, Evaporation, Wetting, & Splashing
- **Effects of Wind on Measurements:** Snow more susceptible to wind error than rain**,** if wind velocity 80km/h → catches < 50% true rainfall & < 25% snowfall
- **Wind Shield** is used to Minimize Wind Effect
  - ➢ There is no standard height for collection putting gauge, Closer to the ground reduces wind effects, but If too close to ground-backsplash
  - ➢ Most gauges 2m off the ground
  - ➢ Ground Shields or Turf Walls or for snow-Drifts entering into the gauge
- **Evaporation & Wetting** Handling Traces Problematic → Bridging Clogging

SNOW MEASUREMENTS

- Water equivalent for snow 1:10 – 1:12 equivalency
- Snow doesn't infiltrate when it falls whin melts
- No need for continuous measurements
- **Blowing Snow (Drifts)** Amount that Falls
- **Areal Snowcover** For Predicting Meltwater Final distribution is what matters Better to measure cover post drift
- **Snow Measurement**
  1. **Snow Core (Board):** Square piece of wood or concrete measure depth daily, take core & melt clear board daily
  2. **Snow Pillow (Plates):** Set on firm horizontal surface convert pressure of snow to weight (corresponds to water equivalency)



- **Snow Surveys** due to wind causes spatial variability
  1. **Weekly Snow Profiles (Course)** Stakes in Ground, chosen site carefully (Vegetation Differences)
  2. **Snow Traverse** End of the Season, Meltwater, By Hand or Aerially Topography

Measuring Devices

Totalayzars : yearly measuring



- **Manual Gauges**
  - ➢ 127mm copper gauges or 100 mm plastic gauges
  - ➢ Contents are emptied daily (9am) into a graduated cylinder (read daily)
  - ➢ Depths read with an accuracy of 0.1 mm
  - ➢ Measured depth attributed to precipitation in previous 24 hours
- **Manual Storage Gauges**
  - ➢ Weekly or monthly readings
  - ➢ Larger version of the manual gauge
  - ➢ Tend to be less accurate due to size & evaporation
  - ➢ Depth read with a graduated dipstick
- **Automatic Recording Gauges**
  - ➢ **Tipping Bucket:** small buckets of 0.2mm capacity, number of tips of the bucket are counted and timed, Results are recorded on a continuous chart
  - ➢ **Tilting siphon**: Rainfall enters a floating chamber. As the float rises, a continuous record is produced on a chart. When full, the chamber is emptied; repeat!

ESTIMATE OF PRECIPITAION

- **Ground based radar** Estimate precipitation (1-10^4km²)
- **Airborne observations** Passive gamma (H_2O molecules in snow absorb gamma radiation to high degree)
- **Satellite imagery** estimate precipitation from cloud properties (microwaves), Map coverage of snow on ground (Landsat infrared & Radarsat)
  - ➢ Exposure, Instrumental, & Observation
- **Network of Gages**
  - ➢ The areal or spatial distribution of precipitation is related to meteorological & topographical factors
  - ➢ The number of precipitation gage stations per area (precipitation gage density) is less for flat regions than mountainous in temperate climate

Regions	Ideal	Acceptable
Flat temperate Mediterranean & tropical zone	1 station for 600-900 km²	1 station for 900-300 km²
Mountainous temperate Mediterranean & tropical	1 station for 10^3-250 km²	1 station for 250-10^3 km²
Arid & polar	1 station for 1500-10^3 km²	

- 10% of rain gage stations should be equipped with self recording gages to know the intensity of rainfall
- The optimal number of stations exist to have assigned % in the estimation of mean rainfall is obtained as:

$$N = \left(\frac{Cv}{\varepsilon}\right)^2$$

N = optimal number of stations; ε = allowable error in estimating the mean rainfall; Cv = coefficient of variance of the rainfall values at the existing m station

- **Adequacy of rain gage stations:** If there are m stations in the catchment each recording rainfall values P1, P2, P3,…, Pn the coefficient of variance can be calculated by

$$Cv = \frac{(100\sigma_{m-a})}{P}$$

σ_{m-1} = standard deviation; P = average precipitation

Example A catchment area has 6 rain gages. In a year the annual rainfall recorded by the gages are as follows

Station	A	B	C	D	E	F
Rainfall[cm]	82.6	102.9	180.3	110.3	98.8	136.7

For a 10% error in the estimation of the mean rainfall, calculate the optimum number of stations in the catchment

Solu. M = 6, P = 118.6, σ = 35.4, ε = 10

$$\text{Cv} = \frac{(100x35.04)}{118.6} = 29.54 \rightarrow N = \left(\frac{29.54}{10}\right)^2 = 8.73 \approx 9$$

3 more additional stations are required

MISSING PRECIPITATION DATA

- Often we need to estimate the missing record if observation or Instrument failure using surrounding stations missing data "constructed"
- **Arithmetic mean,** Use 3 stations as close to that of the missing record - ideally, these stations should be evenly spaced around that of the missing record & Can only use if normal annual precipitation at each of these index station within 10% of that with missing record
- **The normal annual precipitation is 30 years**
- **Normal-Ratio Method:** if index stations differ by > 10%

$$P_x = \frac{1}{n}\Sigma_i^1 P_i\left(\frac{N_x}{N_i}\right)$$

- **Inverse distance (Quadrant method)**: weighting factor

$$P_x = \frac{\Sigma_{i=1}^n d_i^{-2} p_i}{\Sigma_{i=1}^n d_i^{-2}}$$

Pi = Observed precipitation of known (i) stations
Nx = Normal annual precipitation of unknown (x) station
Ni = Normal annual precipitation of i station
di = is the distance from station x to station I

Station	Observed P	Normal (N)	Distance
A	200	1090	5.5 km
B	150	1205	7.0 km
C	170	1117	12.0 km
X	X	1180	–

Arithematic mean $P_x = \frac{200+150+170}{3} = 173mm$

Normal-Ratio Method $P_x = \frac{\left[\left(\frac{1180}{1090}\right)200+\left(\frac{1180}{1205}\right)150+\left(\frac{1180}{1117}\right)170\right]}{3} = 173mm$

Inverse distance $P_x = \frac{\left[\left(\frac{200}{30.25}\right)+\left(\frac{150}{49}\right)+\left(\frac{170}{144}\right)\right]}{0.0604} = 180mm$

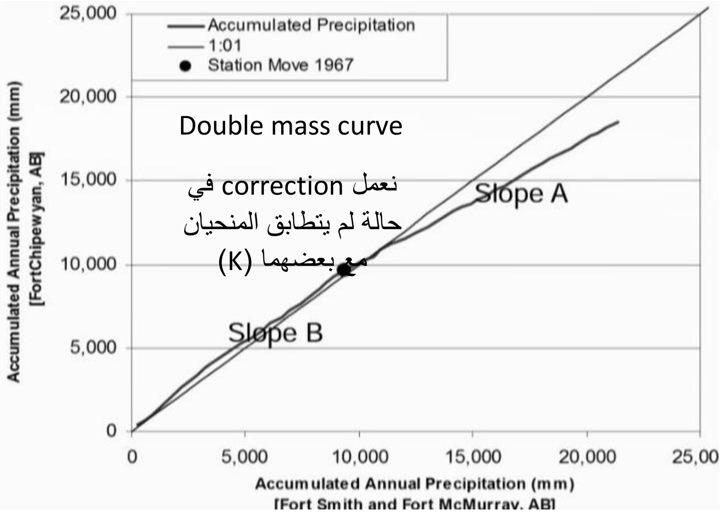
RAINFALL MEASUREMENTS

- **The Sources of Error** (Exposure, Instrumental Error, & Observational Error) exposure has the most serious impact on accuracy. In a sense, can never know the "true" value & Readings can be consistent
- **Important for long-term data analysis:** Checking the consistency of precipitation record
- **double mass curve method (homogeneous records):** select several nearby stations
  - ➢ **homogeneous**: no discontinuity to gauge relocation
  - ➢ average the annual totals of the reference stations for each year (e.g. 1975 = 200 + 300 +400 = 300 mm)
  - ➢ Need to determine consistency of gauge & adjust
  - ➢ If change persists for ≥ 5 years & then only if: clearly associated with a change in measurement conditions, determined to be statistically significant (analysis of variance/covariance)
  - ➢ Typically only used for annual average amounts
  - ➢ High variability of shorter periods mask inconsistenc
- Factors affect gauge catch (consistency)
  1. Changes in type, location, & gauge environment
  2. Trees grow, buildings constructed, locations change

Double mass analysis example				
Year	St E	Cum E	St A-D	Cum A-D
1985	35	35	28	28
1986	37	72	29	57
1987	39	111	31	88
1988	35	146	27	115
1989	30	176	25	140
1990	25	201	21	161

- **Correcting rain gages:** Need to adjust rain gauge E for future analysis, Multiply data for period before the change by K, then Multiply values before change by K

$$K = \frac{slope_{after\ change}}{slope_{before\ change}}$$

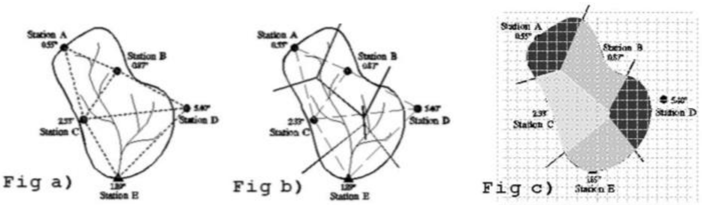


ESTIMATING PRECIPITATION

FROM POINT VALUES

- **Arithmetic Mean:** Simplest method, computation of mean areal $P_n = \frac{1}{N}\Sigma_{i=1}^{n} P_i$
- **satisfactory method** if gages are uniformly distributed & if individual variations are not great
- **Thiessen Polygon Method:** Construct polygons by connecting stations with lines & Bisect the polygon sides to estimate the area of each stations
  - **Most widely used method**
  - Unique for each gage network, Allows for areal weighing of precipitation data, & doesn't allow for orographic effects (due to elevation changes)

$$P = \frac{P_1A_1 + \cdots + P_nA_n}{\Sigma A} = \frac{1}{A}\Sigma_{i=1}^{m} P_i A_i = \Sigma_{i=1}^{m} P_i \frac{A_i}{A}$$



St.	Rainfall (in)	Isohyert (inch)	Area of Station	Station weight	Areal precipitation
A	0.55	0.50	7.250	0.06	0.03
B	0.87	1.00	24.00	0.21	0.21
C	2.33	2.00	11.90	0.10	0.20
D	5.40	3.00	44.85	0.38	1.14
E	1.89	4.00	10.10	0.09	0.36
		5.00	7.700	0.07	0.35
		6.00	2.200	0.02	0.12
		2.00	8.600	0.07	0.14
Total (sum)			116.60		2.55

Station weight = Area of station/sum of area

Areal precipitation = Isohyert (in) x Station weight

Watershed precipitation = 2.55in

- **Isohyetal Method:** One of most accurate methods
  - Magnitude & extent of resultant rainfall areas are calculated, Difficult to draw accurately
  - Can overlay topographical maps to take into account orographic effects & storm morphology

- **Distance Weighting Method:** based on distances from the centroid of the basin, estimated average

Example distance weighting computation of mean areal precipitation for A river basin

St	P	d	d²	d⁻²	Wt%	Weighted P
A	0.55	1.1	1.21	0.83	0.096	0.053
B	0.87	0.5	0.25	4.00	0.463	0.403
C	2.33	0.6	0.36	2.78	0.322	0.750
D	5.40	1.4	1.96	0.51	0.059	0.319
E	1.89	1.4	1.96	0.51	0.059	0.112
Total				8.63		1.637

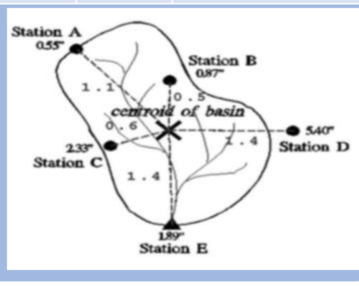
$$Wt.P = \Sigma Wt\% \times P$$

$$Wt\% = d^{-2}/\Sigma d^{-2}$$

P = precipitation

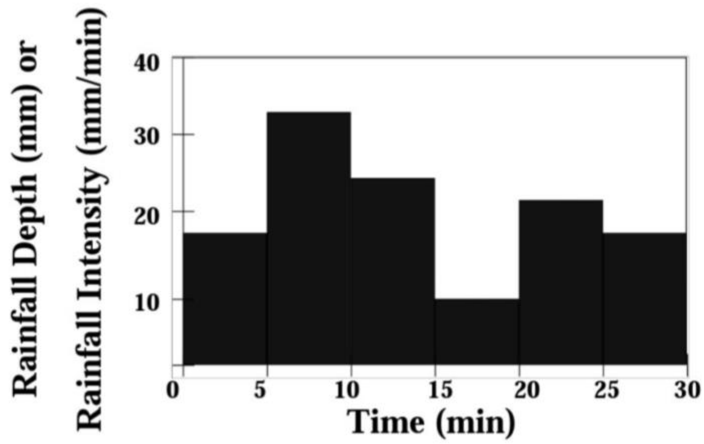
d = distance

Wt% = Wight of P



RAINFALL REPRESENTATION

- concerned with two things during a particular storm or period of time Rainfall amount (mm) Rainfall Intensities (mm/hr) because:
  1. Amounts & intensities related to runoff amounts
  2. Indicate the severity of an individual storm compared to other storms in the same area
- **Rainfall Hyetographs**: Plot of rainfall intensity (in/hr), Used as input to hydrologic computer models
  - Bar chart of rainfall amounts or intensities over time
  - Area under the curve is rainfall depth over storm



- **Cumulative Mass Curve:** plot of cumulative rainfall for rainfall events, Obtained directly from recording gage, used to determine volume & intensity variations

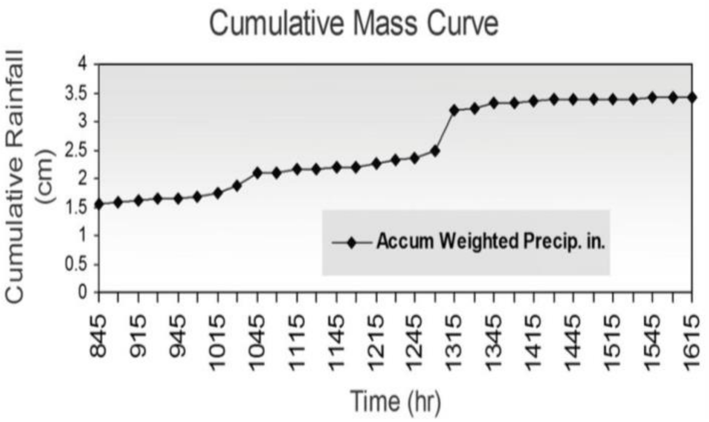
Time	Wt.P	Time	Wt.P	Time	Wt.P	Time	Wt.P
0845	1.55	1045	2.09	1300	2.48	1500	3.39
0900	1.58	1100	2.11	1215	3.18	1515	3.40
0915	1.60	1115	2.15	1330	3.22	1530	3.40
0930	1.63	1130	2.17	1345	3.31	1545	3.41
0945	1.66	1145	2.18	1400	3.33	1600	3.41
1000	1.68	1200	2.20	1415	3.36	1615	3.42
1015	1.75	1215	2.25	1430	3.38	1630	3.43
1030	1.88	1230	2.31	1445	3.39	1745	3.44

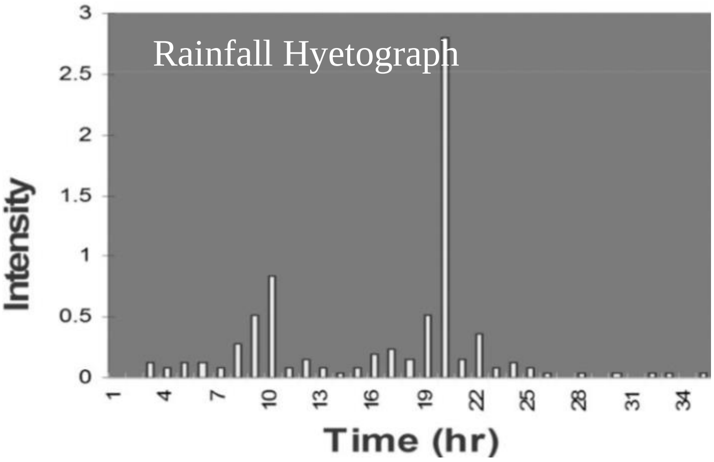
Step 1: Calculate the intensity of rainfall in [in/hr]

$$cum.\,rainfall\ intensity = \frac{Wt_x - Wt_{x-1}}{\Delta t\ (0.25)}$$

In	Wt.P	In	Wt.P	In	Wt.P	In	Wt.P
	1.55	0.84	2.09	0.52	2.48	0.00	3.39
0.12	1.58	0.08	2.11	2.80	3.18	0.04	3.40
0.08	1.60	0.16	2.15	0.16	3.22	0.00	3.40
0.12	1.63	0.08	2.17	0.36	3.31	0.04	3.41
0.12	1.66	0.04	2.18	0.08	3.33	0.00	3.41
0.08	1.68	0.08	2.20	0.12	3.36	0.04	3.42
0.28	1.75	0.20	2.25	0.08	3.38	0.04	3.43
0.52	1.88	0.24	2.31	0.04	3.39	0.00	3.44

Step 1: plot a curves





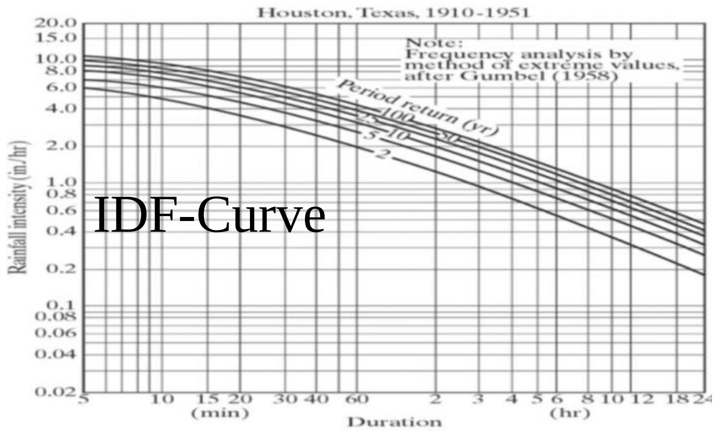
INTENSITY, DURATION, & DEPTH

- **Characteristics of Rain storms**:
    1. **Intensity [mm-in/hr]**: Instantaneous value, recorded as an average value over a time step
    2. **Duration**: from start to end of a storm & of a critical period within a storm
    3. **Depth** Accumulated rainfall depth over the duration

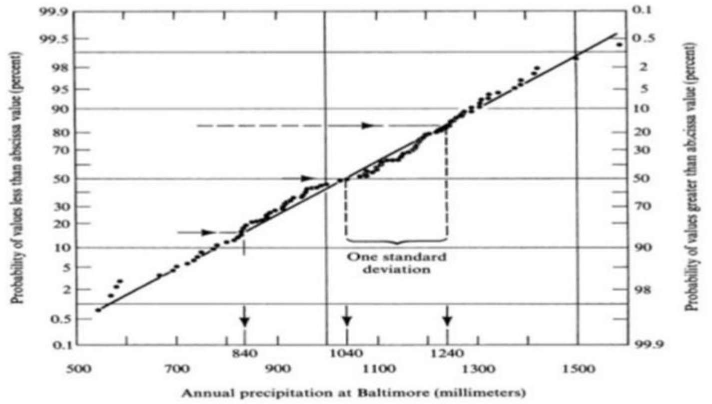
$$Intensity\ (I) = \frac{depth\ (d)}{Duration\ (D)}$$

- **Frequency of rain storms** A storm is characterized by Depth (average intensity) & Duration
- **Return period:** average time between storms with same duration & the same or greater depth

Depth [in]	Duration [hr]	Intensity [in/hr]	Frequency [yr]
5.8	8	0.78	100
3.3	4	0.82	10
1.6	2	0.80	2



- **Frequency Analysis:** Frequency of a hydrologic event is the probability that some value of a discrete variable will occur or some value of a continuous variable will be equaled or exceeded in any given year
    1. graphical frequency analysis
    2. frequency analysis using frequency factors
- **Graphical Frequency Analysis:** Frequency of an event obtained by using of "plotting position" formulas
- **Weibull** the most efficient & commonly used where m is ranked fro lowest to highest for n values, P is estimate of the probability of values being ≤ ranked values



- **Return period:** average # of yr during which a storm of a given magnitude expected to occur (equaled or exceeded), simply inverse of probability (1/P)
- **Frequency**: percentage of years during which a storm of a given magnitude equaled or exceeded F = 1/T*100

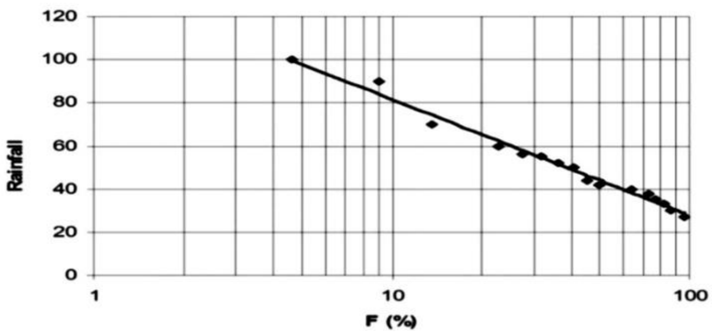
Example: The annual rainfall at a place for period of 21yr is given below. Draw the frequency curve & determine rainfall of 5yr & 20yr return period, rainfall occurs 50% of the time, rainfall of probability of 0.75, probability of occurrence of rainfall of 75cm & its return period

#	Year	Rainfall [cm]	#	Year	Rainfall [cm]
1	1950	50	11	1960	40
2	1951	60	12	1961	56
3	1952	40	13	1962	52
4	1953	27	14	1963	42
5	1954	30	15	1964	38
6	1955	38	16	1965	27
7	1956	70	17	1966	40
8	1957	60	18	1967	100
9	1958	35	19	1968	90
10	1959	55	20	1969	44

First step: Rearrange the number & calculate the frequency

Rank	#	Year	R	F	Rank	#	Year	R	F
1	18	1967	100	4.60	11	14	1963	42	50.0
2	19	1968	90	9.10	14	03	1952	40	63.7
3	07	1956	70	13.6	14	11	1960	40	63.7
5	02	1951	60	22.7	14	17	1966	40	63.7
5	08	1957	60	22.7	16	38	1955	38	72.8
6	12	1961	56	27.3	16	15	1964	38	72.8
7	10	1959	55	31.8	17	09	1958	35	77.3
8	13	1962	52	36.4	18	05	1954	30	86.4
9	01	1950	50	40.9	20	04	1953	27	95.5
10	20	1969	44	45.5	20	16	1965	27	95.5

Second step: plot frequency curve for annual rainfall



Risk Example probability of the 100yr, 1hr storm occurring within the next 20yr is

$$R = 1 - (1 - I/T)^n$$

$$R = 1 - (1 - 0.01)^{20}$$

$$R = 0.18$$

- Design problems often require the estimation of expected intensities for a critical time pcurve (e.g. analysis of 5-, 10-, 20-, 60-min maximum rainfall occurrences would yield a family of curves)
- The greater the intensity the shorter the duration
- **Probable Maximum Precipitation (PMP):** maximization of the meteorological factors that operate to produce a maximum storm (maximum amount of precipitation & duration that expected to occur on a drainage basin)
  - ➢ Has a low and unknown probability of occurrence
- **IDF curves:** relation at a location constitutes objective tool to quantify precipitation uncertainty, as a design rainfall event determined for a particular water project
  - ➢ To perform the analysis, long term precipitation data for a recording rain gage must be available.
  - ➢ recommended that a station with at least 20yt of good quality information be selected, but the longer the record the more accurate the analysis
  - ➢ **Design problems** require estimation of expected intensities for a critical time period (e.g. analysis of 5, 10, 20, 60 min max rainfall occurrences would yield a family of curves)
  - ➢ Usual method of presenting these data is to convert depth in in. to an intensity in in./hr & summarize data in intensity- duration-frequency curves
  - ➢ The greater the intensity the shorter the duration
- **Procedure of Analysis**

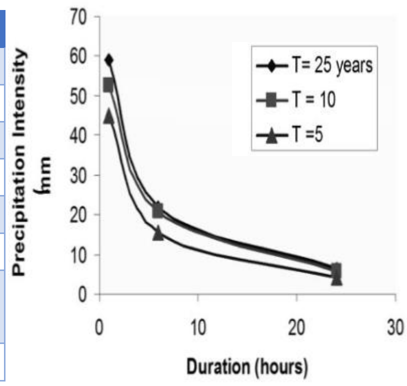
1. Select specific duration of rainfall(interval) **ts=Δt=hr**
2. Find the max. precipiation intensity (mm/hr) of the selected duration for every yr (determine max slope in the recording gage chart for every year) **p=ΔP/ts**
3. Rearrange precipitation intensities in decreasing order of magnitude & assign a rank to each value. A rank m = 1 is assigned to the highest intensity & m = N to the lowest (N = number of years of records)
4. Estimate the return period corresponding to each intensity by the relative position of p with repect to the ranked series **T = (N+1)/m**
5. Repeat steps (1) through (4) for other durations
6. Interpolating in the table, select an even return period (T = 20yr). Plot p versus ts for the given T & draw smooth curve through the points

Example: The following table contains the maximum 1, 6, 24 hr rainfall intensity at a location for 24yr. Perform IDF curve

Year	1hr	6hr	24hr	Year	1hr	6hr	24hr
1970	20.1	6.70	2.90	**1981**	46.2	8.70	2.20
1971	42.9	10.6	3.70	**1982**	35.1	10.7	2.80
1972	38.1	9.10	3.10	**1983**	38.9	7.70	1.90
1973	30.2	6.80	1.70	**1984**	23.1	9.30	2.70
1974	25.9	10.2	2.60	**1985**	16.5	6.60	2.20
1975	35.8	16.6	5.90	**1986**	21.8	13.7	5.70
1976	28.7	7.20	3.30	**1987**	45.2	10.8	3.10
1977	27.2	6.10	1.70	**1988**	39.4	15.8	4.10
1978	52.8	22.1	6.60	**1989**	40.9	12.0	3.50
1979	26.4	8.60	2.40	**1990**	39.4	10.5	3.10
1980	52.3	19.4	4.80	**1991**	44.5	7.80	2.00

Sol.

T (yr)	1hr	6hr	24hr
25.0	58.9	22.1	6.60
12.5	52.8	19.4	5.90
8.30	52.3	16.6	5.70
6.30	46.2	15.8	4.80
5.00	45.2	15.5	4.10
4.20	44.5	13.7	3.90
.	.	.	.
.	.	.	.
1	16.5	6.1	1.7



3 years moving average

- نحسب المتوسط لكل 3سنوات، ونضع قيمة المتوسط عند السنة الوسطى
- القيمة الاخيرة نجمعها مع قبل الاخيرة ومع القيمة الاولى، القيمة الاولى نجمعها مع القيمة الثانية والاخيرة، لحساب المتوسط
- ثم نرسم منحنى نمثل عليه النقاط، محور الصادات هو السنوات ومحور السينات هو المتوسط
- نحسب المتوسط الكلي ونمثله على شكل خط متقطع

Yr	R	Calculations	Average
1990	**670**	**(864 + 670 + 760)/3**	**765**
1991	**760**	**(670 + 760 + 780)/3**	**737**
1992	**780**	**(760 + 780 + 650)/3**	**730**
1993	**650**	**(780 + 650 + 910)/3**	**780**
...	**...**	**...**	**...**
1998	**854**	**(981 + 854 + 864)/3**	**900**
1999	**864**	**(854 + 864 + 670)/3**	**796**

EVAPORATION

- **Evaporation**: water is transferred form the land & water masses of the earth to the atmosphere
- **Transpiration**: water is transferred from land to atmosphere through plants
- **Evapotranspiration**: evaporation + transportation, hard to compute them separately and therefore combined
- **Importance of understanding evaporation**: Reservoir capacity, Irrigation needs
- **Factors affecting evaporation:**
  1. **Availability of energy (latent heat)**
  2. **Vapour Pressure (Saturation deficit, e_s-e_a)**
  3. **Temperature:** Warm water evaporate faster (less latent heat required), & Warm air hold more vapor
  4. **Wind:** Removes saturated air & maintains vapor P
  5. **Transpiration (Vegetation)**

Q_e = mL_e = E x (1cm²)$_\rho L_e$

$$E = \frac{Q_e}{\rho L_e}\ [in\ \frac{cm}{day}]$$

Qe: Energy for evaporation [cal/cm²day], m:mass [g]

E : evaporation [cm/day], Le : latent heat [cal/g]

ρ: density of evaporated water (g/cm³)

- Saturation point when P = E (E stop)
- **Dalton's Law:** E rate α (saturation – actual) vapour P

E = C (e_s – e_a)

e_s < e_a (-E): condensation, e_s > e_a (+E) Evaporation

e_s = e_a (E = 0) : No evaporation or condensation

- **T:** Warm water evaporate faster (less Le required)

Le = 597.3 – (0.57 x T) [cal/g], T in °C

WATER BUDGET METHOD

Δstorge = input – output

ΔS = P – (E + GW)

E = (I + P) – (O + GW + ΔS)

I : inflow [cm], P: precipitation [cm], O: outflow [cm]

E : Evaporation [cm], GW: Groundwater seepage [cm]

- **Limitation**: Estimation of seepage (GW), & precipitation

MASS TRANSFER METHOD

- Evaporation driven by Vapor P gradient & Wind speed

E = N*u*(e_s – e_a) = (a + bu)(e_s – e_a)

$$N = \frac{2.91x10^{-2}}{A^{0.05}\ [inm^2]}$$

e_s: saturation P above surface T, e_a: P at level above surface

u: wind speed above surface, A: surface area of the water

E: a coefficient (equation constant)

(a, b): empirical constants

Example determine lake evaporation for a month in which

1. average air temperature = 20°C
2. average water temperature = 15 °C
3. average wind speed at 8m = 15 km/h
4. average relative humidity is 50%

Using Meyer's formula [U in Km/h, e in mb]

$$E = 0.360\left(1 + \frac{u_8}{16}\right)(e_s - e_a)\ [cm/day]$$

Solution

$$e_s = 2.7489x10^8 exp\left(\frac{-4278.6}{T_d + 242.79}\right)$$

Air T above surface ≈ water temperature ≈ 15 °C

$$e_s = 2.7489x10^8 \exp\left(\frac{-4278.6}{15 + 242.79}\right) = 17.0mb$$

P at 8m: T = 20°C

$$e_s = 2.7489x10^8 \exp\left(\frac{-4278.6}{20 + 242.79}\right) = 23.3mb$$

$$R_H = \frac{e}{e_s} = \frac{actual\ vapor\ P}{saturation\ vapor\ P}$$

E = RH x es = 0.5 x 23.3 = 11.7 mb

$$E = 0.360\left(1 + \frac{25}{16}\right)(17.0 - 11.7) = 0.37\frac{cm}{d}$$

0.37cm/d = 11.1 cm/month

- **The rate of evaporation depend on:**
  1. Vapor pressure at the water surface & air
  2. Air & water temperature, & Size of the water body
  3. Wind speed, & Atmospheric pressure
- Evaporation is the difference between 2 rates:
  1. **rate of vaporization**: determined by T
  2. **rate of condensation**: determined by vapor P
- Evaporation directly proportional to the difference in vapor P between water surface (e_w) & the atmosphere (e_a), & this difference is called ***vapor pressure deficit*** (e_d)

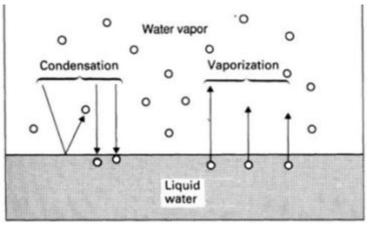


FIGURE 4.2.1 Molecular exchange between liquid water and water vapor. Not all the molecules hitting the surface are captured, but some condense at a rate which is proportional to the vapor pressure of the moist air: molecules with enough energy vaporize at a rate determined by the surface temperature.

e_d = e_w – e_a

- **Dalton's Law:** E rate α the difference between the saturation vapor pressure at the water T ***e_w*** & the actual vapor pressure ***e_a*** in the air

E_L = Ce_d = C(e_w – e_a)

[E_L] = mm/day, [***e_d***] = mmHg

Evaporation stop if *e_w = e_a*, & *e_w >e_a* → condensation

MEASUREMENTS

- Indirectly using the hydrologic budget (**E =P-ΔS-T-G-Q**), Energy budget, & Pan evaporation (empirically)
- **Types of evaporimeter:** water containing pans, exposed to the atmosphere & the loss of water by evaporation measured at regular intervals
  1. ***Class A Pan***: standard pan of a diameter 1210mm & 255mm depth used in the US Weather Bureau, made of unpainted galvanized Fe-sheet placed on a wooden platform of 15cm height
  2. **ISI Standard Pan** (modified Class A pan): 1220mm with 255mm depth, made of copper sheet (0.9mm). A fixed point gage indicates water level
  3. **Colorado Sunken Pan**: 992mm² & 460mm deep, made of unpainted galvanized Fe-sheet & burried into the ground within 100 mm of the top
  4. **US Geological Survey Floating Pan**: square pan 900 mm side & 450 mm depth supported by drum float
- **Evaporation pans:** Provides inexpensive & reasonable estimating, Not always operational, & Better for design
- **Pan Coefficient:** Evaporation pans are not exact models of large reservoirs & have the following drawbacks
  1. ***Differ in the heat-storing capacity & heat transfer*** from the sides & bottom
  2. ***Evaporation depends on pan size***
  3. ***The height of rim affects the wind action***
  4. ***The heat transfer*** characteristics of the pan material is different from that of reservoir
  - ➢ So, evaporation should be corrected to lake under similar climatic & exposure conditions. Thus a coefficient is introduced as:

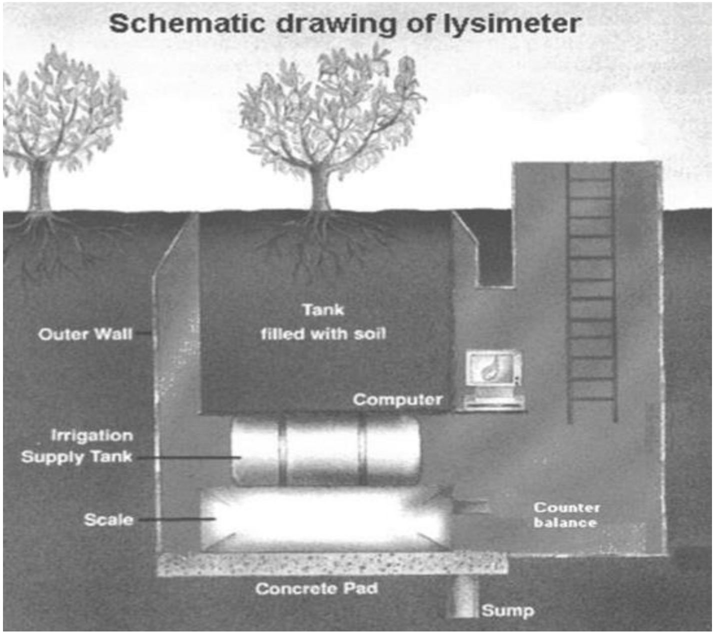
Lake Evaporation = C_p x pan evaporation

Type of pan	Average value (C_p)	Range
Class A pan	**0.70**	**0.60 – 0.80**
ISI pan	**0.80**	**0.75 – 0.86**
Colorado Sunken	**0.78**	**0.75 – 0.86**
USGS Folting pan	**0.80**	**0.70 – 0.82**

- **Evaporation station:** The WMO (work meteorological organization) recommends the minimum network of evaporimeter stations
  - ➢ **Arid zone:** one station for every 30,000 km²
  - ➢ **Humid temperate**: one station for every 50,000 km²
  - ➢ **Cold regions:** one station for every 100,000 km²

EVAPOTRANSPIRATION

- **Importance of Evapotranspiration**
  1. water resources planning, & operation of reservoir
  2. hydroelectric power generation
  3. agricultural practices: irrigation, & choosing crops
  4. understand functioning of an ecosystem
  5. prediction of the impact of climate change
- **Physics of Evapotranspiration:** evaporation occurs by exchange of water between air & a free water surface
- **water surface**: lake, river, inside plant leaves, adhering to soil particle, soil or vegetation during or after a rain
- **Transpiration**: loss of water from cuticle or the stomatal openings in leaves of pants
- water is vaporized within the leaf in intercellular spaces & passes out of the stomata by molecular diffusion
- stomata are pores on the underside of a leaf that open to allow diffusion of CO_2 into leaf during photosynthesis
- when stomata open water vapor from wet cell diffuses to atmosphere, & transpired water replaced by water taken up by roots
- **Controls on evapotranspiration:** available of energy, air mass characteristics (T & vapor content), wind, surface cover (open water or vegetated), & availability of water
- **Measurement:** Water budget, Field plots, Lysimeters, Meteorological data (using ***lusimeter***)



- **Thornthwait equation** uses only monthly T

$$E_T = 1.6L_a\left(\frac{10T}{I_t}\right)^a$$

$$a = 6.75x10^{-7}I_t^{-3} - 7.71x10^{-5}i_t^{-2} + 1.792x10^{-2}I_t + 0.49239$$

Et : monthly PET (cm)

La: adjustment for the numbers of hours of day light & days in the month, related to the latitude of the place

T : mean monthly air temperature C°

It : the total of 12 monthly values of heat index

$$i = \Sigma_1^{12} i\,, where\ i = \left(\frac{T}{5}\right)^{1.514}$$

- **Turc equation**: used to calculate the actual ET

$$E_t = \frac{P}{\left(0.9 + \frac{P^2}{L^2}\right)^{½}}$$

L = 300 + 25T + 0.05T³ (limited to area T)

Et: the actual evaporation accurding to turc (mm)

P: is the annual precipitation in (mm)

T: is the mean temperature in C°

لحساب ال L من هذه المعادلة نفترض ان E = P