1 General Aspects

Hydrology is the science of occurrence, circulation and distribution of water of the earth and its atmosphere.

Interception: Short term retention of rainfall by vegetation.

Infiltration: Movement of water into the soil of the earth's surface.

Percolation: Movement of water from one soil zone to lower soil zone.

Hydrological Budget Equation

$$\text{Inflow} - \text{Outflow} = \text{storage}$$

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

P = Precipitation

R = Runoff

G = Net Groundwater flow

E = Evaporation

T = Transpiration

ΔS = Net increase in storage

$$\text{Residence time} = \frac{\text{Volume of water in a phase}}{\text{Average slow rate in the phase}}$$

Instruments used in measurement	
1. Relative humidity	Psychrometer
2. Humidity	Hygrometer
3. Temp and Humidity	Thermohygrometer
4. Intensity of Radiation	Pyrheliometer
5. Wind speed	Anemometer
6. Rainfall depth	Ombrometer/Pluviometer
7. Transpiration	Phytometer

8. Evapotranspiration	Lysimeter
9. Evaporation	Atmometer
10. Hydraulic conductivity	Permeameter
11. Infiltration capacity	Rainfall simulator

Isopleth: A line drawn on map along which the value of a particular phenomenon is uniform.

Name	Isopleth
1. Isobar	Pressure
2. Isobath	Depth in sea
3. Isobront	Thunderstorm
4. Isohaline	Salinity
5. Isohels	Sunshine
6. Isohyets	Rainfall
7. Isonif	Snowfall
8. Isoryme	Frost
9. Isotherm	Temperature
10. Isopleths	Evapotranspiration

2 Precipitation and Its Measurement

Fall of water in **various forms** on the earth from the clouds.

Types of Precipitation
- Convective: Due to heating of air
- Orographic: Mountain barrier
- Cyclonic: Unequal heating of earth
- Frontal: Contrasting our mass from opposite direction

Forms of precipitation
- Rain (0.5mm-6mm)
- Snow (density = 0.1 gm/cc)
- Sleet (snow + rain)
- Hail (5mm-50mm)
- Drizzle (intensity < 0.1 cm/hr)
- Glaze: Freezes on ground contact

Types of Gauges
- Non-recording rain guage (How much rain occurred)
  - Symon's rain guage
- Recording rain guage (How and when that occurred) continuous plot of rainfall against time
  - Tipping bucket
    - Intensity of Rainfall
  - Weighing type
    - Mass curve of rainfall
    - Snow measurement
  - Natural syphon
    - Also known Float type
    - Mass curve of rainfall

Rain guage Network density = Area covered per guage

As per I.S : 4987 – 1968	One station per
In Plains	520 km^2
Moderately Elevated Area	260 – 390 km^2
Hilly Area's	130 km^2

Note:
As per WMO, 10% of the rain guage stations should be self recording type.

Adequacy of Rain Guage Stations

1. Mean Rainfall $P_m = \dfrac{P_1 + P_2 + ... + P_n}{n}$

   P_1, P_2 = rainfall recorded at stations 1 and 2 etc.

2. Standard deviation

   $$\sigma_{n-1} = \sqrt{\frac{(P_1 - P_m) + (P_2 - P_m)^2 + ... + (P_n - P_m)^2}{(n-1)}}$$

   if $n < 30$ then σ_{n-1}
   otherwise σ_n

3. Coefficient of variation $C_v = \dfrac{\sigma_{n-1}}{P_m}$

4. Optimum number of stations $N = \left(\dfrac{C_u}{\varepsilon}\right)^2$

   ε = Allowable degree of error

   Generally $\varepsilon \nless 0.1$

Normal Precipitation: Average Value of rainfall **30 yrs** data of particular date or month.

Average Annual Precipitation: Average Value of annual rainfall values for last **35 yrs**.

Estimation of Missing Data

1. Arithmetic mean method: If normal precipitation of the selected stations is **within** 10% of that of station with missing data

   $$P_x = \frac{P_1 + P_2 + ... + P_n}{n}$$

2. Normal ratio method: If normal precipitation of the selected station is **beyond** 10% of that of station with missing data.

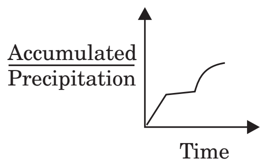
   $$\frac{P_x}{N_x} = \frac{1}{n}\left(\frac{P_1}{N_1} + \frac{P_2}{N_2} + ... + \frac{P_n}{N_n}\right)$$

   P = Precipitation
   N = Normal precipitation

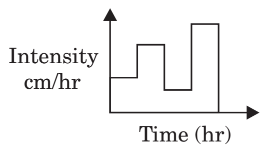
Inconsistency of Records: Corrected by double mass curve in which **previous records** are made consistent with present day environmental and land use conditions.

Presentation of rainfall data

- Mass curve



- Hyetograph



- Moving average
  - Gives trend of rainfall curve
  - Moving average curve of large no. of years will be smoother than moving average curve of less number of years.

Calculation of Average Depth

Arithmetic Mean Method

- Least accurate
- Rain guages only inside catchment area

$$P_m = \frac{P_1 + P_2 + \ldots + P_n}{n}$$

Thiessen Polygon

- Consider's rain guage outside catchment also
- Topographical influence not taken care of
- Perpendicur bisector's of triangles made by joining rain guages

$$P_m = \frac{P_1A_1 + P_2A_2 + \ldots + P_nA_n}{A_1 + A_2 + \ldots + A_n}$$

Isohyetal Method

- Most accurate

$$P = \frac{A_1\left(\frac{P_1 + P_2}{2}\right) + A_2\left(\frac{P_2 + P_2}{2}\right) + \ldots + A_{n-1}\left(\frac{P_{n-1} + P_2}{2}\right)}{A_1 + A_2 + \ldots + A_n}$$

Depth Area Duration Curve

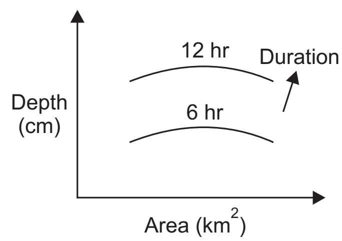
$$\overline{P} = P_o e^{-KA^n}$$

$\overline{P}$ = Average depth

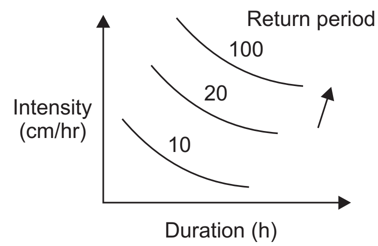
P_o = Highest storm at storm centre

A = Area

Note :- Depth decrease with Increase in Area



DAD curve



IDF curve
Intensity-duration-frequency

3 Abstractions from Precipitation

Abstractions are Evaporation (E), Transpiration (T), Interception (I), Depression storage (DS) and Infilteration (IL).

Evaporation:

$E_L = C(e_w - e_a)$ Dalton's law

E_L = Rate of Evaporation (mm/day)

e_w = Saturation vapour pressure

e_a = Actual vapour pressure

Note:

1. Evaporation increases with decrease in atmospheric pressure.
2. Evaporation from sea water is less than fresh water due to salinity
3. Highest rate of evaporation from deep water bodies in winters

Measurement of Evaporation

Evaporimeter

Concept of pan coefficient C_p

Lake evaporation $= C_p \times$ pan evaporation

C_p = 0.7 class A Land pan

= 0.8 ISI/US as floating pan

Empirical Formulae

$$E_L = km\,(e_w - c_a)\left(\frac{1 + u_9}{16}\right)$$

u_9 = monthly mean wind velocity at 9m above the ground

km = 0.36 Large deep water

km = 0.5 Shallow, small water

$u_h = ch^{1/7}$

Analytical Methods

Water Budget Equations (Hydrological continuity)

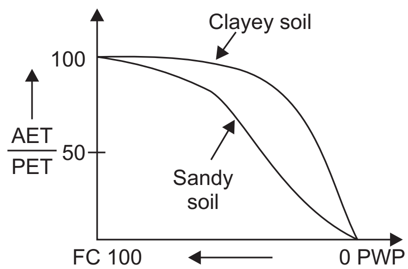
Energy Balance (law of conservation of energy)

Mass transfer (Theories of turbulent mass transfer)

Note:

Lake evaporation can be reduced by reducing the surface area, by providing mechanical cover or by chemical films of **cetyl Alcohol** (Hexa decanon) or **stearyl Alcohol** (octadecanol)

Evapotranspiration



AET → Actual Evapotranspiration

PET → Potential Evapotranspiration

PWP → Permanent wilting point

FC → Field capacity

- Estimation of **PET** is done by Penman's Equation and Blaney Criddle formula
- **Penman's Equation** is based on **energy balance** and **mass transfer**
- **Blaney–criddle formula**

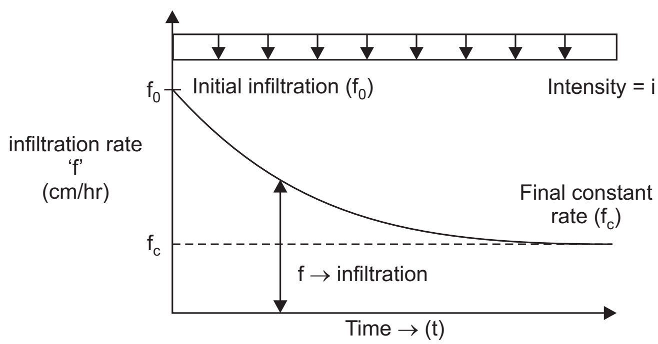
$$PET = 2.54\ k\ \Sigma \frac{P_h T_f}{100}$$

K = Empirical coefficient

P_h = Monthly % of annual day time hrs

T_f = Mean monthly temp in °F

Horton's Infiltration Curve



$$f = f_c + (f_o - f_c)e^{-\alpha t}$$

$f = f_c \qquad i > f_c$

$f = i \qquad i < f_c$

Infiltration Indices

φ Index	**W–Index**
Average rainfall above which the rain fall volume is equal to run off volume	It excludes DS and Interception loss $W = \frac{IL}{t} = \frac{P - Q - S}{t}$

(*a*) Rainfall Intensity – φ Index = Effective Rainfall Intensity

(*b*) Rain fall Intensity – W-index = Effective Rain fall Intensity + Depression Storage + Interception

4 Runoff

Hydrograph: Discharge in a stream plotted against time chronologically

Type's

- Long term hydrograph
  - Annual hydrograph
  - Monthly hydrograph
  - Seasonal hydrograph
- Short term hydrograph
  - Flood hydrograph

Note:
Long term hydrograph's are used in calculating surface water potential of stream, Reservoir studies and drought studies.

Runoff characteristics of stream

- Perennial: Carries flow throughout the year
- Intermittent: Limited contribution from ground water
- Ephemeral: Lasting for a very short time

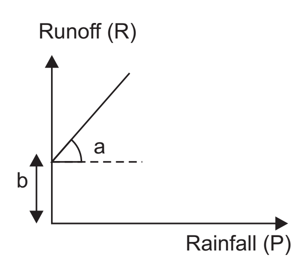
Note:
Influent Streams are those which raise the "Ground water table" and become ephemeral while **Effluent streams** are those in which water comes from nearby high "Ground water table".

Rainfall Runoff Relationship

$$R = aP + b$$

$$a = \frac{N \Sigma PR - (\Sigma P)(\Sigma R)}{N \Sigma P^2 - (\Sigma P)^2}$$

$$b = \frac{\Sigma R - a \Sigma P}{N}$$



Coefficient of correlation

$$r = \frac{N \Sigma PR - (\Sigma P)(\Sigma R)}{((N \Sigma P^2 - (\Sigma P)^2)(N \Sigma R^2 - (\Sigma R)^2)}$$

Khosla's formula for **Monthly** Runoff:

Runoff = Rainfall – losses

Losses = 0.48 (mean monthly Temp (T_m))

It is indirectly based on **Water -budget equation**

5 Drought

$$\text{Index of wetness} = \frac{\text{Rainfall in a year}}{\text{Average Annual rainfall}} \times 100$$

% Rain deficiency = 100% – Index of wetness

Droughts (Deficiency in precipitation)

Meterological

As per IMD

Hydrological

Marked depletion of surface water and ground water

Agriculture

Extreme crop stress and wilting conditions

$$\text{Aridity Index} = \frac{\text{PET - AET}}{\text{PET}}$$

PET = Potential Evapotranspiration

AET = Actual Evapotranspiration

Decrease from normal precipitation	Classification
< 25%	No drought
26 – 50%	Moderate
> 50%	Severe

AI Anomaly	Classification
0–25	Mild
26-50	Moderate
>50	Severe

Note:

Drought prone area is an area in which probability of drought is between 0.2 to 0.4. If probability is greater than 0.4 then its chronically drought prone area.

6 Stream Flow Measurement

Stage : Height of the water surface in the river above some arbitrary datum

Measurement of stage

- Manual
  - Staff gauge
  - Wire gauge
- Automatic
  - Float gauge recorder
  - Bubble gauge

Current meter: Mechanical device to measure velocity of stream. It is caliberated in Towing Tank.

$$V = a\,N_s + b$$

N_s = Number of revolutions per sec

a, b = Current meter constants.

Velocity distribution in the vertical section across stream is **logarithmic**

Measurement of discharge

- Direct determination
  - Area velocity method
  - Moving boat method
  - Dilution Technique
    - Plateau method
    - Gulf method
  - Electromagnetic method
  - Ultra Sonic method
- Indirect determination
  - Hydraulic Structures
  - Slope–Area method (Trial and error method)

$$K = \frac{1}{n} AR^{2/3}$$

$$A = \frac{A_1 + 2A_i + A_2}{4}$$

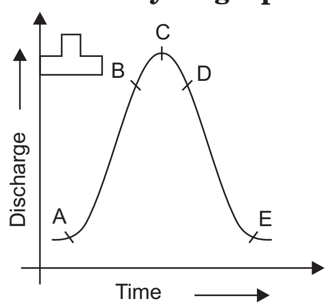
$$P = \frac{P_1 + 3P_i + P_2}{4}$$

$$R = A/P$$

A_i, P_i $\Rightarrow$ Area perimeter of intermediate Sections

7 Hydrology

Flood Hydrograph



AB → Rising limb → depends on duration, intensity and distribution of rainfall

BCD → Crest segment

DE → Recession Falling limb → depends on catchment characteristics

Shape of the flood hydrograph generally depends on (*a*) catchment shape (*b*) Size of catchment (*c*) Slope (*d*) drainage density (*e*) Rainfall intensity (*f*) Rainfall duration (*g*) Distribution of rainfall (*h*) Direction of storm movement

Unit Hydrograph: A hydrograph of **direct runoff** resulting from 1 cm of **effective rain fall** applied **uniformly** over a basin area at a **uniform rate** during a **specified period** of time (D–*hr*)

Assumptions of Unit hydrograph: Time Invariance and Linear Response

Limitations : Area between 2 km^2 to 5000 km^2, No large storage, precipitation in the form of rainfall only.

S–Curve hydrograph: Hydrograph of direct runoff resulting from a continuous effective rainfall of uniform intensity $\frac{1}{D}$ cm/hr. S-curve hydrograph attains an equilibrium discharge (Q_e) approximately at the end of base period of the unit hydrograph

$$Q_e = A\frac{1}{D}\ \text{Km}^2 - \text{cm/hr} = 2.778\frac{A}{D}\ \text{m}^3/\text{sec}$$

A = Area (km^2)

D = Duration (hr)

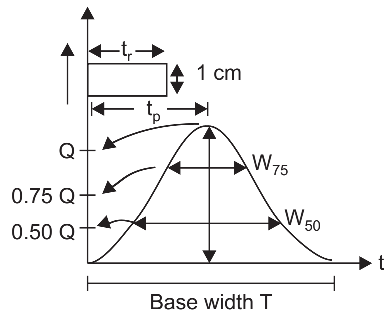
Synthetic unit hydrograph (SUH) : It is made for ungauged basin area's Basin parameters and unit hydrograph parameters of the ungauged, **hydrometeorologically homogenous** area are selected to basin parameter and unit hydrograph of gauged station**s.**

Three parameters for development of SUH;

(*i*) Basin time width T

(*ii*) Peak discharge Q_p

(*iii*) Lag time t_p



$$t_p = C_t (L.L_{ca})^{0.3}$$

$$T = 72 + 3t_p$$

$$Q_p = \frac{2.78\, C_p A}{t_p}$$

C_t = 1.35 to 1.65

L = Basin length along the water course

L_{ca} = Centroid distance from gauging point

A = Area in Km^2

W_{75}, W_{50} = width of SUH at 75% and 50% of peak discharge

Instantaneous Unit hydrograph: Unit hydrograph of Infinitesimal duration

- Independent of rainfall characteristics and depends only on catchment characteristics

$$u(t) = \frac{1}{i}\frac{dS}{dt}$$

$u(t)$ = Ordinate of instantaneous hydrograph

i = Intensity of rainfall

S = Ordinate of S–curve

- Ordinate of IUH is the **slope of S–curve** of intensity 1cm/hr

Note:

Unit hydrogarph → Sherman

Synthetic unit hydrograph → synder

Instantaneous unit hydrograh → Clark model based on Time Area Histogram

8 Floods

Standard Project flood (SPF): Flood from most severe combination of the meteorological and hydrological conditions excluding extremely rare combination.

Maximum Project flood (MPF): It includes extremely rare and catastrophic floods.

Probable maximum precipitation (PMP): Greatest or extreme rainfall of a given duration that is physically possible over a station.

Selecting Design Flood: Central Water Commission

Spillway for projects with Storage > 60 M m^3	PMP
Permanent barrage and minor dams with storage < 60 M m^3	SPF
Pick up wier's	Return period of 100 or 50 year's
Aqueducts $\longrightarrow$ Waterways $\rightarrow$ Foundation free board	T = 50 years T = 100 years

Emperical Formula's for flood peak

(*a*) Dicken Formula used in Central and Northern parts of the country.

$Q_P = C_D A^{3/4}$ $Q_P \rightarrow m^3/sec$ $C_D \rightarrow 6 \text{ to } 30$ $A \rightarrow km^2$

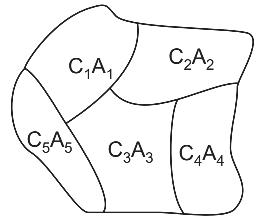
(*b*) Ryves Formula used in Tamil Nadu, Parts of Andhra Pradesh and Karnataka

$Q_P = C_R A^{2/3}$ $C_R \rightarrow$ Ryves coefficient

(*c*) Inglis Formula used in western ghats of Maharastra

$$Q_P = \frac{124\ A}{\sqrt{A + 10.4}}$$

Rational Method



$$Q_P = C\,i\,A$$

$$C = \text{Runoff coefficient} = \frac{\text{Runoff}}{\text{Rainfall}}$$

$$C_{eq} = \frac{C_1A_1 + C_2A_2 + \ldots + C_nA_n}{A_1 + A_2 + \ldots + A_n}$$

i = Intensity of Rainfall, depends on time of concentration (t_c) and Return period of rainfall $\left(T = \frac{1}{\text{Probability of excedence}}\right)$

Time of Concentration, by Kirpich Equation

$$t_c = 0.01947\left(\frac{L}{\sqrt{S}}\right)^{0.77}$$

L = Maximum length of travel by water

S = Slope of Catchment

Note:
Rational formula is found to be suitable for peak flow prediction in small catchment upto 50 km^2 in area.

Estimation of Design Flood for a particular return period: Gumble's method

- It is based on **extrapolation** for large return period

$$X_T = \overline{X} + K\,\sigma_{n-1}$$

X_T = Value of variate of return period T

$$\overline{X} = \frac{\Sigma x}{n}$$

n = Number of years of record

$$\sigma_{n-1} = \sqrt{\frac{\Sigma(x-\bar{x})^2}{n-1}}$$

K = Frequency factor

$$K = \frac{y_T - \bar{y}_n}{S_n}$$

y_T = Reduced variate $\quad y_T = -\ln \ln \left(\frac{T}{T-1}\right)$

$\bar{y}_n$ = Mean of reduced variate

S_n = Std. deviation of reduced variate

For $n > 50$ $\quad y_n = 0.577 \quad S_n = 1.2825$

Confidence Limit

$$X_{1/2} = X_T + f(\alpha)\, S_e$$

$f(\alpha)$ = function of confidence probability 'α'

α **in percentage**	50	68	80	90	95	99
f(α)	0.674	1.0	1.282	1.645	1.96	2.58

$$S_e = \text{Probable error} = \frac{b\,\sigma_{n-1}}{\sqrt{n}}$$

where $\quad b = \sqrt{1 + 1.3\,k + 1.1\,k^2}$

k = frequency factor

Risk-Reliability

Probability of exceedence is p

Return period $T = \frac{1}{p}$

Probability of Non occurrence $q = 1 - p$

Risk → Probability of exceedence atleast once = $\mathbf{1 - q^n}$.

Reliability → Probability of Non-occurrence = $\mathbf{q^n}$.

Probability of exceedence of m times in n years = ${}^nc_m\, p^m\, q^{n-m}$

Probability of exceedence of exactly 1 time in n years = ${}^nc_1\, pq^{n-1}$

9 Flood Routing

It is the technique to determine the flood hydrograph at a section of a river by utilizing the data of flood flow at one or more upstream sections.

Techniques of, Flood Routing

- Lumped Routing (Hydrological)
  - Q = f(t) at a given x-location
  - only continuity equation used
    - Reservoir/storage Routing
    - Channel Routing
- Distributed Routing (Hydraulic)
  - Q = $f(x, t)$ ats function of both time and space
  - Both continuity and momentum equation's use

Equations used in flood Routing

- Continuity Equ
  - Steady flow
    - Inflow-outflow=storage
  - Unsteady flow

    $$\frac{\partial q}{\partial x} + T\frac{\partial y}{\partial t} = 0$$

- Momentum Equ

  $$\frac{\partial y}{\partial x} + \frac{V}{g}\frac{\partial V}{\partial x} + \frac{1}{g}\frac{\partial V}{\partial t} = S_o - S_f$$

Unsteady flow equation + Momentum Equ → Saint venant's equ. for gradually varied unsteady f_i

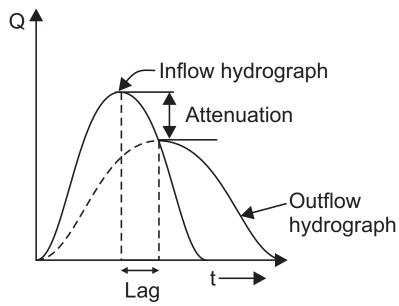
Reservoir Routing: It is done by

1. Standard 4th order Runge-kutta method (Numerical method)
2. Good rich method
3. Modified Pul's method

(2 and 3: Graphical method)

$$\left(\frac{I_1+I_2}{2}\right)\Delta t - \left(\frac{Q_1+Q_2}{2}\right)\Delta t = S_2 - S_1$$

In an uncontrolled outlet of a level pool routing following inflow and outflow hydrographs will be achieved



Attenuation: Reduction in peak

Lag: Time difference in two peaks

Note:

→ The peak of outflow hydrographs will occur at the point of intersection of inflow and outflow hydrograph.

→ Storage is max. at point of intersection.

Channel Routing: Storage is function of both inflow and outflow

$S = K[x I^m + (1-x)Q^m]$ Muskingum equation

x = weighing factor, depends on shape of wedge

k = Storage time constant, has dimensions of time, and approximately equal to the time of travel of flood wave through channel reach.

I = Inflow Q = Outflow

m = 0.6, for artificial channel

m = 1 for natural channel.

$$S_2 - S_1 = k[x(I_2 - I_1) + (1-x)] \quad ...(1)$$

$$S_2 - S_1 = \left(\frac{I_2+I_1}{2}\right)\Delta t - \left(\frac{Q_2+Q_1}{2}\right)\Delta t \quad ...(2)$$

From 1 and 2,

$$Q_2 = C_0\, I_2 + C_1 I_1 + C_2 Q_1$$

$$C_0 = \frac{-kx + 0.5\Delta t}{K - Kx + 0.5\Delta t} \qquad C_1 = \frac{Kx + 0.5\Delta t}{K - Kx + 0.5\Delta t} \qquad C_2 = \frac{K - Kx - 0.5\Delta t}{K - Kx + 0.5\Delta t}$$

$$C_0 + C_1 + C_2 = 1 \qquad 2Kx < \Delta t < Kx$$

Trap efficiency of Reservoir: Ability of reservoir to trap and retain incoming sediments.

$$\text{Trap efficiency} = f\left(\frac{\text{Capacity}}{\text{Inflow}}\right)$$