

UNIT-IIAbstraction from precipitation
and Runoff

Introduction

Evaporation and its process

* It is the process in which a liquid changes to the gaseous state at the free surface below the boiling point through the transfer of heat energy.

* When some molecules possess sufficient kinetic energy, they may cross over the water surface.

* The net escape of water molecules from the liquid state to the gaseous state constitute evaporation.

Evaporation and factors affecting evaporation

Factors affecting evaporation

* The vapour pressure at the water surface and air above.

* The air and water temperature

* Wind speed

* Atmospheric pressure

* Quality of water

* Size of water body

*Humidity

Evaporation Measurement

Measurement of evaporation is very much important in many hydrologic problems.

The amount of water is estimated from a surface by the following methods:

A. Evaporimeter data

B. Empirical evaporation equation

C. Analytical method

Analytical Methods:

a. Water-budget method

b. Energy-balance method

c. Mass-transfer method

8.

(a) Water-budget method:

This method is simplest in all three methods, by using hydrological continuity equation we find out evaporation from the late.

The continuity is written as,

$$P + V_{IS} + V_{IG} = V_{OS} + V_{OG} + E_L + \Delta S + T_L$$

Where

P = precipitation

V_{IG} = Ground water inflow

V_{OG} = Seepage outflow

ΔS = change in storage

V_{IS} = Surface inflow

V_{OS} = Surface outflow

E_L = Evaporation

T_L = Daily transpiration loss

(b) Energy budget method:

* The energy budget method is an application of law of conservation of energy.

* The energy available for evaporation is determined by considering incoming energy, outgoing energy and energy stored in water body over a known time interval.

* Consider the water body, the energy balance to evaporating surface in a period of one day is given by

$$H_n = H_a + H_e + H_g + H_s + H_i$$

γ = reflection coefficient

H_n = net heat energy received by the water surface

$$= H_e (1-\gamma) - H_b$$

$H_c(1-\gamma)$ = incoming solar radiation into a surface to air

H_a = sensible heat transfer from water surface to air

H_e = Heat energy used in evaporation
 $= \rho L E_L$

ρ = density

E_L = evaporation in mm

H_i = Net heat conducted out of the system by water flow

$$E_L = \frac{H_n - H_g - H_s - H_i}{PL(1+\beta)}$$

$\therefore \beta$ = Bowen's ratio

(c) Mass-transfer method:

This method is based on theories of turbulent mass transfer in boundary layer to calculate the of water vapour transfer from the surface to the surrounding atmosphere.

The volume is calculated as,

V_E = Volume of water lost in evaporation

A = Average reservoir surface

$$V_E = A E_{pm} C_p$$

E_{pm} = Pan Evaporation

C_p = Relevant pan coefficient

Evaporation is measured using atmometers:

The various atmometers used for measuring evaporation are:

1. Living stone atmometer

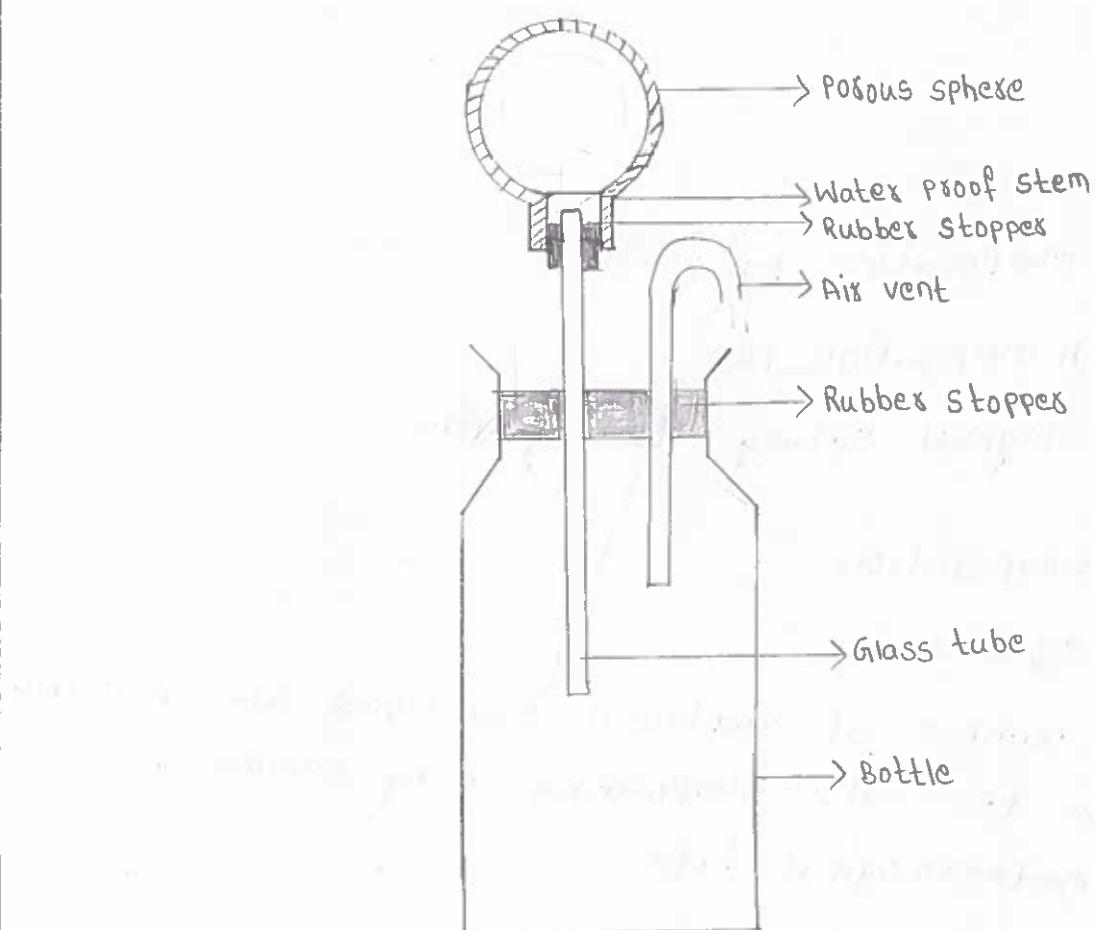
2. Piche atmometer

1. Livingstone atmometer:

* The spherical surface of the livingstone atmometer is made up of porous material with thickness of about 2.5mm and diameter of 5cm. This surface is filled with distilled water.

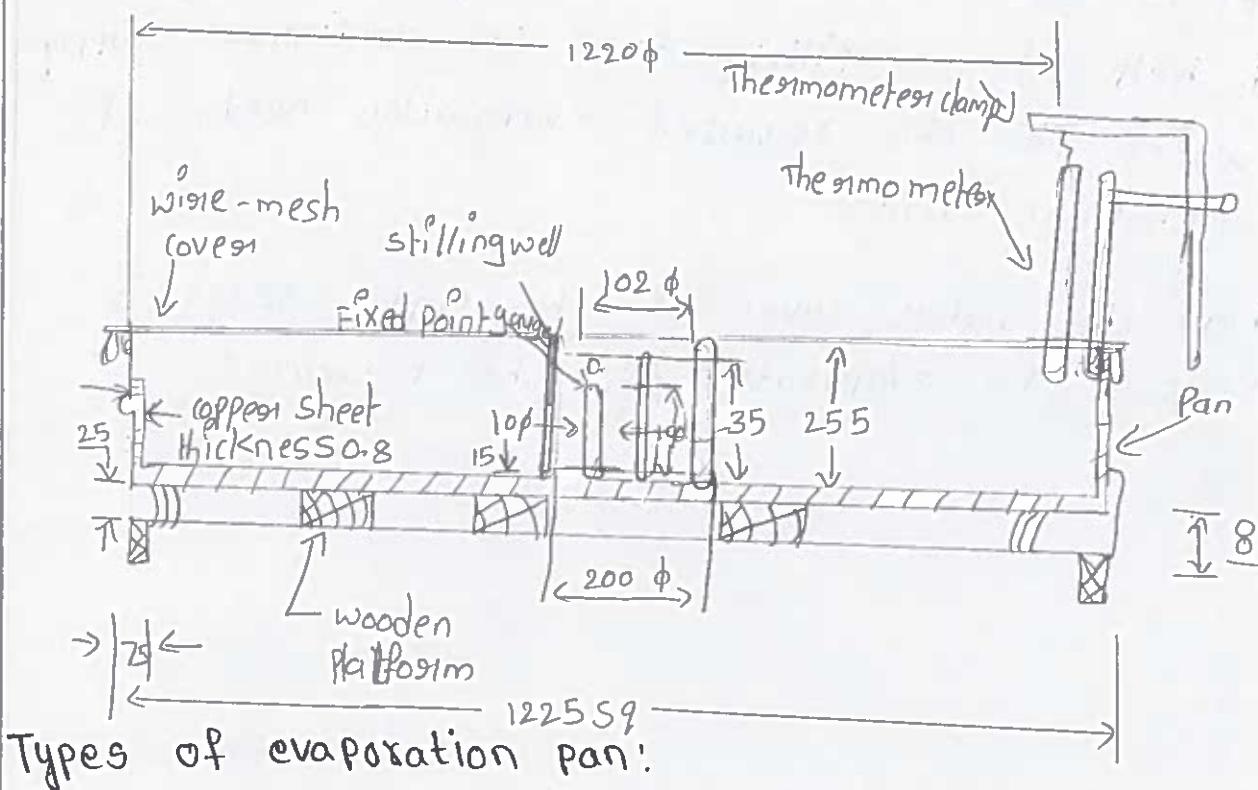
* It is connected to the supply of reservoir with help of a capillary tube for continuous supply of water, for the required evaporation needs of the spherical surface.

* When the water level of the supply reservoir decreases, the evaporation can be measured.



Standard evaporation pan with a neat sketch

- * This pan evaporimeter is also known as modified class A pan and this pan is made up of copper sheet, tinned inside and painted white outside.
- * The top of the pan is covered fully with a hexagonal wire mesh makes the water temperature more uniform during day and night.
- * The evaporation from this pan is 14% less than class A evaporation.



Types of evaporation pan:

1. Class A evaporation pan
2. US geological survey floating pan

Empirical Evaporation

Empirical equations:

- * A large number of empirical equations are available to estimate the take evaporation using commonly available meteorological data

* Most of the formulae from them are based on Dalton's law.

(A) Meyer's formula

$$EL = km [c_w - e_a] \left[1 + \frac{u_g}{16} \right]$$

Where

u_g = Monthly mean wind velocity in km/hr or about 9m above ground level

km = 0.36 for large deep water and 0.50 small shallow water

e_a = Measured at same height at which wind speed is measured

* If the wind velocity data would be available at an elevation other than the needed, then we find out the velocity.

$$U_h = C h^{1/7}$$

(B) Rohwer's formula

* This is another empirical equation to find out the evaporation.

$$EL = 0.771 [1.465 - 0.000732 P_a]$$

$$[0.44 + 0.0733 u_0] (c_w - e_a)$$

Where

EL = Lake evaporation in mm/day

c_w = Saturated vapour in mm of mercury

e_a = Actual vapour pressure in mm of mercury

P_a = Mean barometric reading in mm of mercury

u_0 = Mean wind velocity in km/h at ground level

Evapotranspiration

- * Transpiration is the process by which water leaves the body of a living plant and reaches the atmosphere as water vapour.
- * When the transpiration takes place, the land area in which plants stand also lose moisture by the evaporation of water.
- * since in the process of vegetation growth, it is generally not possible to separate the transpiration and connected evaporation from the plants surroundings. So, evaporation and transpiration are considered under one head called as evapotranspiration.

Various factors of affecting evapotranspiration:

1. climatic factors: climatic factors are mainly responsible for the evapotranspiration, as the evaporation is more during the month of summer, as the amount of solar energy received is high during this period.
2. crop characteristics: At seeding stage evapotranspiration is high and it decreases after growth of seed i.e. higher the crop density, higher is the evapotranspiration.
3. Meteorological factors: Evaporation is mainly influenced by meteorological parameters or factor as the increase in temperature, sunlight and all tractive forces, increases the evapotranspiration but decreases the

humidity.

4. Soil characteristics: Various soil properties after the process of evapotranspiration for e.g. water holding capacity and hydraulic conductivity of soil affect evapotranspiration.

5. Temperature: The rate of evapotranspiration is more influenced by temperature than any other factor.

Measurement of Evapotranspiration

Methods used for measurement of evapotranspiration:

The measurement of evapotranspiration is very much important in hydrology.

The measurement can be done by,

1. Making model
2. Evapotranspiration
3. Empirical equation

1. Making model:

Evapotranspiration can be found out by two model method:

(A) Lysimeter:

- * It is a special water tight tank containing a block of soil and set in a field of growing plants.
- * The plants grown in the lysimeter are same as in the surrounding field.
- * Evapotranspiration is estimated in terms of the amount of water required to maintain constant moisture conditions within the tank, measured by an

arrangement made in lysimeter

- * It should be designed to accurately reproduce the soil condition, moisture content, type and size of the vegetation of the surrounding area.
- * They are buried in ground keeping the same level inside and outside of containers.
- * Lysimeter studies are time consuming and expensive

(B) Field plots

- * A plot is chosen and all the element like precipitation, irrigation input, surface runoff, soil moisture and percolation is measured.

$$\text{Evapotranspiration} = \text{Precipitation} + \text{Irrigation input} - \text{Runoff} \\ - \text{Increase in soil storage}$$

- * As the measurement of percolation is very difficult task in actual field problem so we keep the moisture level of soil at field capacity.

- * This method, provides fairly reliable result.

2. Evapotranspiration equations

- * There are large number of evapotranspiration equations available, they are purely empirical and not theoretical.

- * The most used equation is Penman's equation.

Penman's equation:

- * This equation is based on sound theoretical reasoning and is obtained by combination of energy balance and mass transfer approach.

$$PET = \frac{AH_n + E_a}{A_x}$$

Where,

$PET = \text{Daily potential evapotranspiration (in mm per day)}$

$A = \text{slope of the saturation vapour pressure versus temperature curve at the mean air temperature (in mm of mercury per }^{\circ}\text{C)}$

$H_n = \text{Net radiation (in mm of evaporable water per day)}$

$e_a = \text{parameter including wind velocity and saturation deficit.}$

$\gamma = \text{psychometric constant}$

$$= 0.49 \text{ mm of mercury } ^{\circ}\text{C}$$

Saturation vapour pressure

$$e_w = 4.584 \exp \left[\frac{17.93t}{237.3+t} \right] \text{ mm of Hg}$$

Here,

$t = \text{Temperature (in } ^{\circ}\text{C)}$

Empirical equation:

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where

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Blaney and Criddle methods:

* This is purely empirical formula based on data from arid western United States.

* This formula assumes that the PET is related to the hours of sunshine and temperature, which are taken as a measure of solar radiation on a given area.

Monthly day-time hours percentage Phr for use in Balley-csiddle formula.

North latitude (degree)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
0	8.50	7.66	8.49	8.21	8.50	8.22	8.50	8.49	8.21	8.50	8.22	8.50
10	8.13	7.47	8.45	8.37	8.81	8.60	8.86	8.71	8.25	8.34	7.91	8.10
15	7.94	7.36	8.43	8.44	8.98	8.80	9.05	8.83	8.28	8.26	7.75	7.88
20	7.74	7.25	8.41	8.52	9.15	9.00	9.25	8.96	8.30	8.18	7.58	7.66
25	7.53	7.14	8.39	8.61	9.33	9.23	9.45	9.09	8.32	8.09	7.40	7.42
30	7.30	7.03	8.38	8.72	9.53	9.49	9.67	9.22	8.33	7.99	7.19	7.15
35	7.05	6.88	8.35	8.83	9.76	9.77	9.93	9.37	8.36	7.87	6.97	6.86
40	6.76	6.72	8.33	8.95	10.02	10.08	10.22	9.54	8.39	7.75	6.72	6.52

*The potential evapotranspiration in a crop-growing season is given by

$$E_8 = 2.54K \sum \left[Ph \times \frac{T_F}{100} \right]$$

Where,

E_8 = PET in a crop season, in cm

K = An empirical coefficient, depending on the type of the crop, month and locality

Σ = sum of monthly consumptive use factors for the period.

T_F = Mean monthly temperature, in °F

*The Balley csiddle formula is largely used by irrigation engineers to calculate the water requirement of crops, which is taken as the different PET and effective precipitation.

Average value of K for the season for selected crop is given in table.

Value of K for selected crops:

Crop	Value of K	Range of monthly value
Rice	1.0	0.85 - 1.30
Wheat	0.65	0.50 - 0.75
Maize	0.65	0.50 - 0.80
sugarcane	0.90	0.75 - 1.00
cotton	0.65	0.50 - 0.90
Potatoes	0.70	0.65 - 0.75
Natural vegetation		
a) very dense	1.30	
b) Dense	1.20	
c) Medium	1.00	
d) Light	0.80	

Interception

Interception:

* When a rain falls, it is firstly intercepted by trees, plants, buildings etc. When they become completely wet, the water comes down to the earth surface.

* The initial water intercepted by trees, plants and buildings etc. is required to wet them and after that the water intercepted by them equals evaporation rate. So this complete amount of water is called interception loss.

* It is denoted by,

$$X = a + bt$$

Where,

X = Total interception (in cm)

a = Water required for wetting

b = Evaporation rate from the intercepting surface (in cm/hr)

t = Duration of showers (in hr)

Interception process

* Vegetation cover on the ground, buildings, roads and pavements intercept part of the falling precipitation and temporarily store it on their respective surface.

* This intercepted water is either evaporated back into the atmosphere or mostly falls down to the ground.

* The three main components of interception by vegetal cover are defined below:

(a) Interception loss

* Water which is retained on a surface, as mentioned above and which is later evaporated away.

(b) Through falls

* Water which drips through, comes down from the levels etc. onto the ground surface.

stem flow

* Water which trickles along the twigs and branches and finally down the main trunk onto the ground

surface.

Depression Storage

Depression storage

* When the precipitation reaches to the ground, firstly it must fill all the depression before it can flow over the surface.

* The volume of water trapped in these depression does not contribute to the runoff so these are called depression storage.

* Depression storage depends on following factors:

1. The type of soil
2. condition of surface
3. Nature of depression
4. slope of catchment
5. Antecedent precipitation

* From the experiment on different soil we are able to take some values for depression storage loss during intensive storms.

Sand	0.5cm
Loam	0.4cm
clay	0.25cm

Infiltration

Infiltration and factors affecting on infiltration

* When water is applied to surface of soil, a part of it seeps into the soil. This movement of water through soil is called infiltration.

* Infiltration plays an important role in the process of runoff. It effects the timing, distribution and magnitude of the surface runoff.

Factors affecting infiltration

- Condition of entry surface
- Temperature
- Water quality
- Intensity of rainfall
- Duration of rainfall
- Catchment characteristics
- Presence of ground water table
- Size of properties of soil

Infiltration capacity curve and Horton's equation for infiltration capacity estimating the infiltration rate:

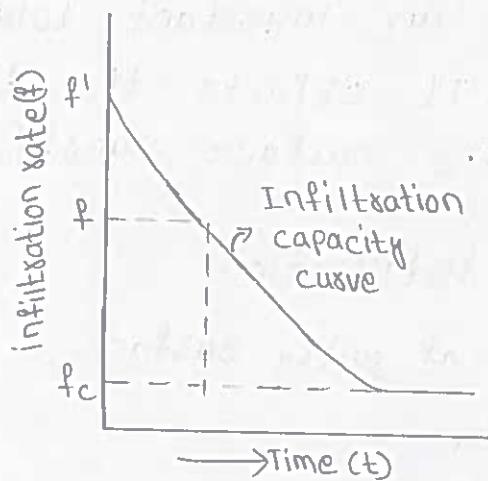
* Infiltration capacity curve represents the variation of infiltration rate with time for a given soil formation.

* The infiltration rate is maximum at the beginning of rainfall and decreases frequently with time.

* The Horton's equation for infiltration capacity curve is given as:

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

* The slope of the line are calculated by determining the infiltration rate (f) at two time interval t_1 and t_2 and plotting straight line with these two points.



Measurement of Infiltration

Various methods of measurement of infiltration:

Infiltration characteristics of a soil at given location can be estimated by,

1. Using flood type infiltrometers
2. Rainfall simulator
3. Hydrograph analysis

1. Using flood type infiltrometers:

This is a simple instrument consisting of a metal cylinder, open at both ends. The cylinder is driven into the ground and water is poured into it from top. As the infiltration proceeds water level goes down, to keep the water level at same initial point we add some water into it then plot a graph of infiltration capacity vs time.

2. Rainfall simulator:

- (a) In this experiment a small land of about 2m x 7m is provided with a series of nozzle on the longer side and arrangement is provided to collect and measure the surface runoff rate.

- b. The nozzles are especially designed to produce artificial rain of various intensities.
- c. By taking various different combination of intensity and duration surface runoff rates and volume are measured in each case.
- d. Rainfall simulator gives lower values than flooding type infiltrometer, because it takes the effect of rainfall impact.

3. Hydrograph analysis:

Infiltration capacity is measured by using runoff hydrographs and corresponding rainfall records.

Modelling Infiltration capacity

Infiltration capacity

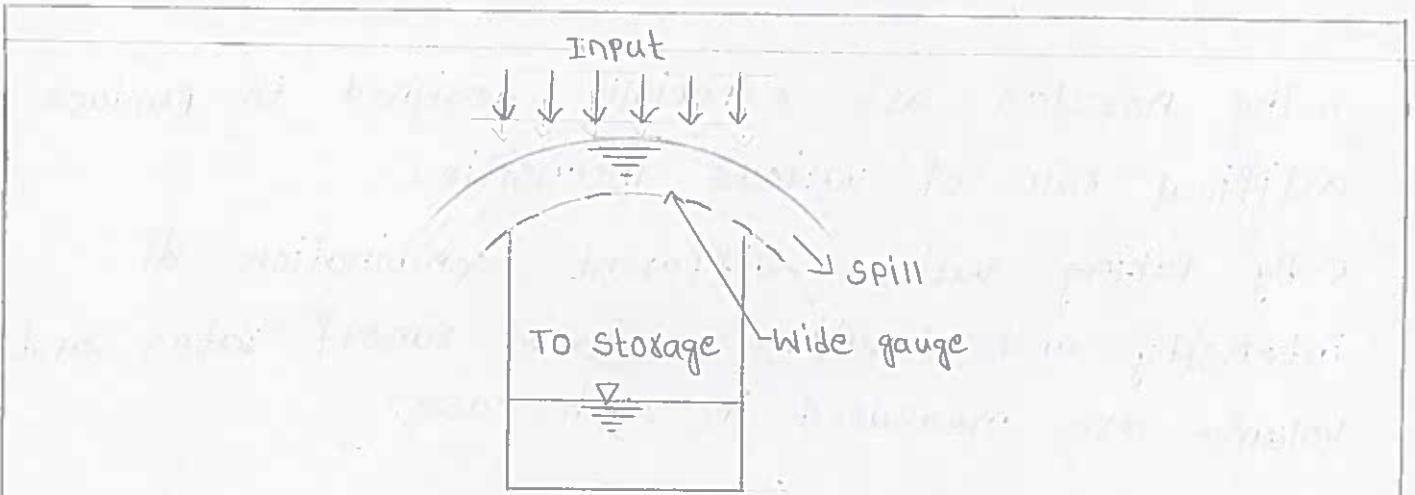
* It is defined by Horton as the maximum rate at which rain can be absorbed by a soil in given condition.

* It is designated as ' F_p ' and expressed in cm/h.

* If the actual rate of infiltration is ' F ' and rainfall intensity is ' i ' then,

$$F = F_p \text{ when } i \geq F_p$$

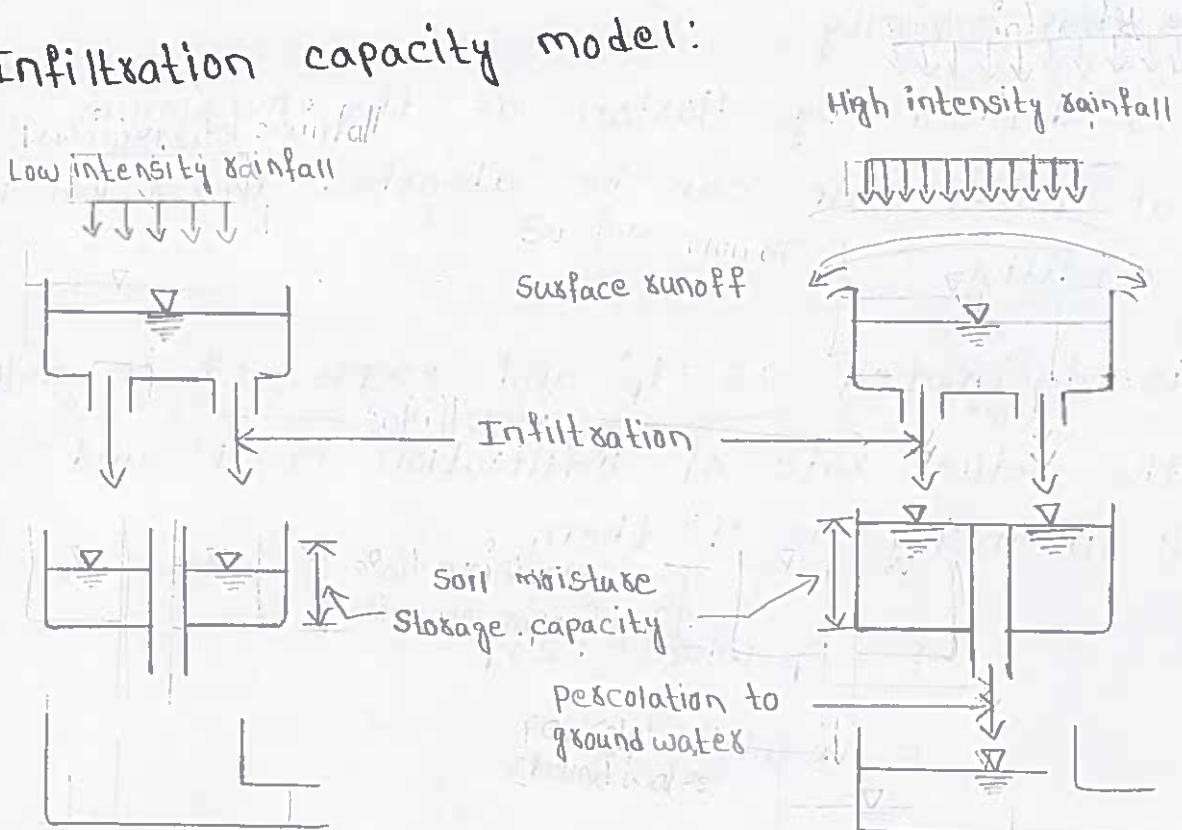
$$F = i \text{ when } i < F_p$$



Analogy for infiltration

* This is the relationship between rainfall intensity and infiltration capacity, which determine how much or falling rain will flow directly over the ground surface and how much will enter the soil to be retained as net moisture storage for some period of time before being either passed downward as percolation or returned to atmosphere by the process of evaporation.

Infiltration capacity model:



(a) No contribution to groundwater flow

(b) To groundwater flow

- * The rainfall intensity is less than maximum infiltration capacity. So there will be no runoff and all water is infiltrated into the ground.
- * The rainfall intensity is so much low that the moisture content not even reach the field capacity so there will be no contribution to ground water flow.
- * But if the rainfall intensity provides more moisture than field capacity then it will certainly contribute to ground water.
- * The rainfall intensity ($i > F_p$) is more than maximum infiltration capacity, so here some part of water infiltration and some part of water move as surface runoff.
- * In this case, there is certainly contribution to ground water flow.

Factors affecting in filtration capacity.

I. Rainfall characteristics:

- * Increased size of raindrop, increase the force by which they strike to the surface.
- * Thus, relationship occurs in size of rain drop and infiltration capacity.
- * This raindrop effect is seen more in clayey surface as compared to sandy surface.

2. Soil characteristics

- * A loose & permeable sandy soil have a larger infiltration capacity than a light clayey soil.
- * A soil with good under drainage have higher infiltration capacity.
- * A dry soil can absorb more water than the soil whose pores are already full of water.

3. Surface cover

A vegetation cover tends to increase infiltration by:

- * Retarding surface flow and thus allowing more time for water to drain water the soil.
- * Shielding the soil surface from direct impact of rain drops, because raindrop causes compaction and reduces infiltration capacity.
- * The root system of the vegetation makes the soil more permeable and thus encourage more rapid passage of infiltrating water.

4. Infiltration water characteristics

- * Water infiltrating into the soil have many impurities both in solution and a suspension.
- * The turbidity of the water, especially the clay and colloid content is an important factor and such suspended particles block the fine pores in the soil and reduce its infiltration capacity.
- * Contamination of the water by dissolved salts can effect the soil structure and effect the infiltration rate.

5. Temperature

- * The viscosity of water changes with temperature.
- * Infiltration capacity will change with the temperature because infiltration capacity is lower in winter and higher in summer.

Classification of infiltration capacities:

- * The steady state infiltration capacity, being one of the main parameters in this soil classification, is divided into four infiltration classes as mentioned below:

Infiltration class	Infiltration capacity (mm/h)	Remarks
Very low	< 2.5	Highly clayey soils
Low	2.5 to 12.5	Shallow soils, clay soils soils low in organic matter
Medium	12.5 to 25.0	sandy loam, silt
High	> 25.0	Deep sands, well drained aggregated soils.

Empirical infiltration equations

1. Horton's equations:

$$F_p = F_c + (F_0 - F_c) e^{-K_n t} \quad \text{for } 0 < t < t_c$$

Where,

F_p = Infiltration capacity at any time t from start of rainfall.

F_0 = Initial infiltration capacity at $t=0$

F_c = ultimate infiltration capacity occurring at $t = t_c$.

k_n = Horton's decay coefficient which depends upon soil characteristics and vegetation cover.

2. Philip's equation

$$F_p = \delta t^{1/2} + kt \text{ and } F_p = \frac{1}{2} \delta t^{-1/2} + kt$$

δ = A function of soil suction potential that is called as absorptivity

k = Darcy's hydraulic conductivity

3. Kostiakov equation

$$F_p = at^b$$

'a' and 'b' = Local parameters with ($a > 0$) and ($0 < b < 1$)

$$F_p = abt^{b-1}$$

4. Green Ampt equation

$$F_p = k \left[1 + \frac{\eta s_c}{F_p} \right]$$

η = porosity of soil

s_c = capillary suction at the wetting front

k = Darcy's hydraulic conductivity

This equation also be written down as,

$$F_p = m + \frac{n}{F_p}$$

Where,

m and n = Green-Amp parameters of infiltration equation

Infiltration indices

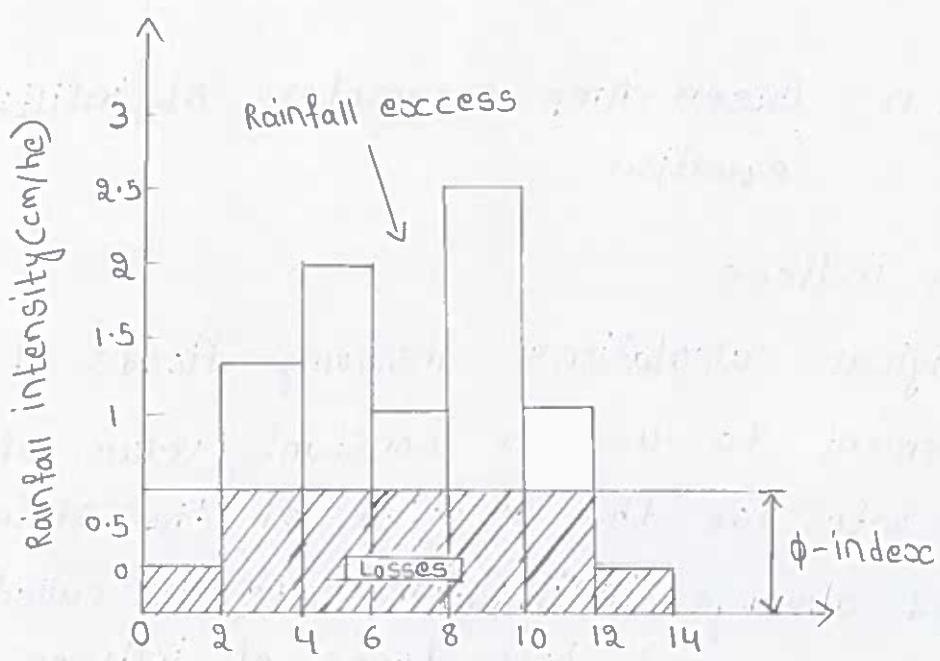
- * In hydrological calculations involving floods it is found convenient to use a constant value of infiltration rate for the duration of the storm.
- * The defined average infiltration rate is called infiltration index and two types of indices are in common use.

1. ϕ -Index

- * It is the average rainfall above which volume is equal to the runoff volume.
- * It is derived from the rainfall hyetograph with the knowledge of the resulting runoff volume.
- * The initial loss is also considered as infiltration.
- * If the rainfall intensity (i) is less than ϕ ($i < \phi$), then $F = i$
- * If the rainfall intensity is larger than ϕ ($i > \phi$), then $F = \phi$ index

F = Infiltration rate

- * The amount of rainfall in excess of the index is called rainfall excess or effective rainfall.
- * CWC gave the following relationship on the basis of rainfall and runoff to the estimation of ϕ index.



ϕ -Index

$$R = \alpha I^{1/2}$$

$$\phi = \frac{I - R}{24}$$

$$\phi\text{-Index} = \frac{P - Q}{t_c}$$

Where

I = Intensity of rainfall (cm/hr)

R = Runoff (cm) from 24 h rainfall intensity

α = A runoff coefficient which depend on
soil-type

S.NO	Types of soil	coefficient
1.	Sandy soil and sandy loam	0.17 to 0.25
2.	coastal alluvium and silty loam	0.25 to 0.34
3.	Red soils, clayey loam, grey and brown alluvium	0.42
4.	Black-cotton and clayey soils	0.42 to 0.46
5.	Hilly soils	0.46 to 50

2. W-Index

- * It is the average infiltration rate during the time rainfall intensity exceeds the capacity rate.
- * It is a refined version of ϕ -index
- * It can be calculated as,

$$W = \frac{P - R - I_a}{t_e}$$

Where,

P = Total storm precipitation (cm)

R = Total storm runoff (cm)

I_a = Initial losses (cm)

t_e = The total time in which the rainfall intensity is greater than W .

- * The minimum value of the W-index is greater than W .
- * W-index is always less than or equal to ϕ -index.

$$W_{index} \leq \phi_{index}$$

$$W_{index} = \frac{P - Q}{t_x}$$

P = Total precipitation

Q = Total runoff

t_x = Duration of rainfall

Reservoir Evaporation

- * Analytical methods used for the estimation of reservoir evaporation. They involve parameters that are difficult to assess or excessive to obtain.

* Empirical equations can at best give approximate values of the correct order of magnitude.

* The water volume lost due to evaporation from reservoir in a month is calculated as

$$V_E = A E_{pm} C_p$$

Where,

V_E = Volume of water lost in evaporation in month (m^3)

A = Average reservoir area during the month (m^2)

E_{pm} = Pan evaporation loss in meters in a month (m)

= EL in mm/day \times Number of days in the month $\times 10^{-3}$

C_p = Relevant pan coefficient

* Evaporation from a water surface is continuous process.

* Typically under India conditions, evaporation loss from a water body is about 160 cm in a year with enhanced values in arid regions.

Methods to reduce evaporation losses

Various methods available for reduction of evaporation losses can be considered in three categories.

1. Reduction of surface area

* Since the volume of water lost by evaporation is directly proportional to the surface area of the water body, the reduction of surface area wherever feasible reduces evaporation losses.

* Measures like having deep reservoirs in place of wider ones and elimination of shallow areas

can be considered under this category.

2. Mechanical covers

- * permanent roofs over the reservoirs, temporary roofs and floating roofs such as rafts and light weight floating particles can be adopted wherever feasible.

- * obviously these measures are limited to very small water bodies such as ponds etc.

3. chemical films

- * this method consists of applying a thin chemical film on the water surface to reduce evaporation.

- * currently this is the only feasible method available for reduction of evaporation of reservoirs upto moderate size.

- * certain chemicals such as cetyl alcohol and stearic alcohol form monomolecular layers on a water surface.

- * These layers act as evaporation inhibitors by preventing the water molecules to escape past them.

potential evapotranspiration over India:

- * Using Penman's equation and the available climatologically data, PET estimate for the country has been made.

- * The mean annual PET (in cm) over various parts of the country is shown in the form of isoleths, the lines on a map through places having equal depths of evapotranspiration.

- * It is seen that the annual PET ranges from 140 to 180cm over most parts of the country.
- * The annual PET is highest at Rajkot Gujsat with a value of 214.5 cm.
- * Extreme south-east of Tamilnadu also show high average values greater than 180cm.
- * The highest PET for southern peninsula is at Tiruchirapalli, Tamilnadu with a value of 209 cm.

Actual evapotranspiration (AET)

- * AET for hydrological and irrigation applications can be obtained through a process water budgeting and accounting for soil plant atmosphere interactions.
- * A simple procedure due to Doorenbos and Pruitt is as follows.
 1. Using available meteorological data the reference crop evapotranspiration (ET_0) is calculated.
 2. The crop coefficient K for the given crop is obtained from published tables. The potential crop evapotranspiration E_{tc} is calculated using equation.

$$E_{tc} = K (ET_0)$$

3. The actual evapotranspiration (ET_a) at any time t at the form having the given crop is calculated as below:

If $AASW \geq (1-p)MASW$

$$ET_a = ET_0$$

.... (known as Potential condition)

If $AASW < (1-p) MASW$

$$E_{ta} = \left[\frac{AASW}{(1-p) MASW} \right] E_{tc}$$

Where,

$MASW$ = Total available soil water over the root depth

$AASW$ = Actual available soil water at time t over the root depth

p = Soil water depletion factor for a given crop and soil complex

= Value of p ranges from about 0.1 for sandy soils to about 0.5 for clayey soils.

Introduction

Runoff:

* Runoff means the draining or flowing off of precipitation from a catchment area through a surface channel.

* It thus represents the output from the catchment in a given interval of time.

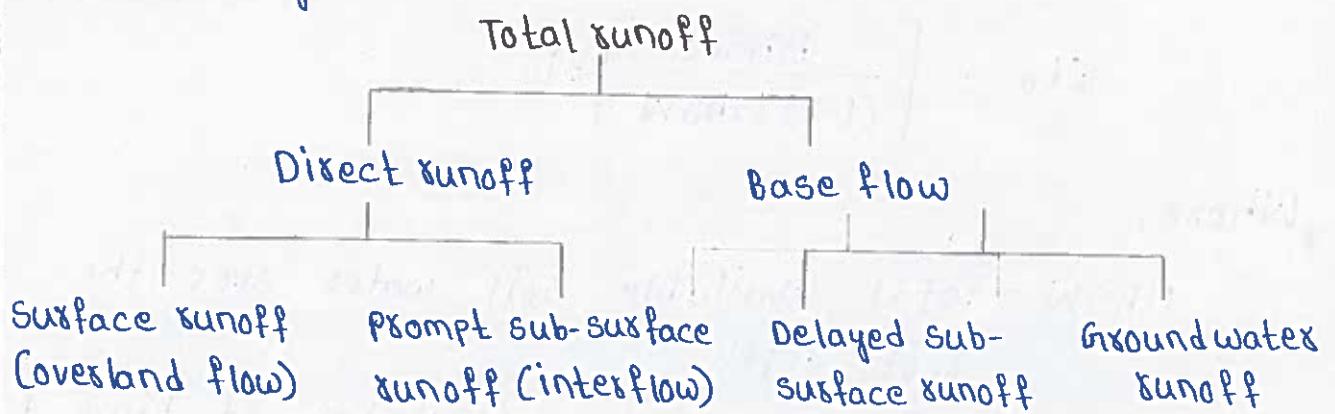
Components of Runoff

* The river flow that appears in the river is not made up of overland flow (surface runoff) only.

* It is actually total runoff contributed to the river in different ways by the drainage basin.

* Depending upon the source from where the portion of total flow gets contributed the components of

total runoff can be recognized as shown below schematically:



* Total runoff consists of two parts namely:

i. Direct runoff:

* It is caused as an immediate result of precipitation.

* Direct runoff is made up of overland flow or surface runoff and that part of infiltration which flows laterally through the unsaturated zone of soil mass and joins the stream flow promptly.

ii. Base flow:

* It is responsible for maintaining a sustained flow throughout the year and is mainly derived from groundwater storage.

* It is made up of groundwater contribution and that portion of infiltration which moves laterally but joins the stream flow quite late after the precipitation has stopped.

* Now it may be appreciated that only part of the rainfall is available for producing overland flow or surface runoff.

* This portion of total rainfall which produces surface runoff is called rainfall excess.

$$\text{Total Rainfall} = \text{Rainfall excess} + \text{Losses}$$

* The term losses includes interception, infiltration, evaporation, depression storage etc.

* Similarly that portion of rainfall which produces direct runoff is called effective rainfall.

$$\text{Effective rainfall} = \text{Rainfall excess} + X$$

Where

X = portion of rainfall which appears in the stream as prompt subsurface runoff.

* obviously when prompt sub-surface runoff is considered together with delayed subsurface runoff.

$$\begin{aligned}\text{Direct runoff} &= \text{surface runoff and effective rainfall} \\ &= \text{Rainfall excess.}\end{aligned}$$

Factors affecting runoff:

Runoff is affected mainly by climatic and physiographic factors.

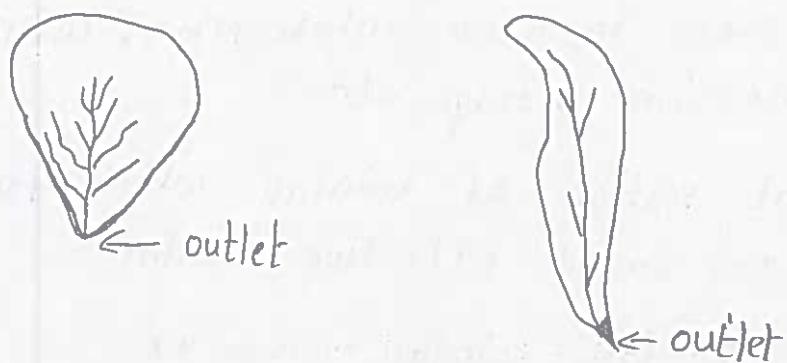
Important factors are in below:

i. Rainfall pattern:

* If the rainfall is very heavy the consequent runoff will also be more.

* If the rainfall is just showery type with low intensity there may not be runoff at all as the rainwater is completely lost in infiltration, evaporation etc.

* If the duration of rainfall is more the runoff will also be prolonged.



2. character of catchment surface:

* If a surface is rocky then the surface absorption will be practically nil and the runoff will be more.

* If the surface is compact clayey type runoff will be more, but if the surface is sandy then the absorption losses will be more and runoff will be less

3. Topography:

* If the surface slope is steep runoff will be more as water will pass over the surface rapidly before losses take place.

* If there are local depressions water will be held up in depression forming lakes, ponds etc., in the catchment.

4. Shape and size of the catchment:

* If the catchment area is large runoff will be more.

* If the catchment area is fan shaped runoff at outlet will be more as all the water contributes to the stream practically at the same time.

* If the catchment is fern shaped the runoff will be less.

5. vegetal cover:

* If there is some sort of vegetal cover over the catchment then evaporation loss will be reduced as sun rays cannot reach the ground surface.

6. Geology of the area:

* If there are fissures, cracks, fault zones present in the catchment then rainwater finds its way out through these openings.

* The water lost may find its way to some other catchment or to groundwater or in the sea.

7. Weather conditions:

* Temperature of the region also affects the runoff to a great extent.

* If temperature is more it renders surface dry and when rain occurs more water is absorbed by the ground surface.

* Evaporation rate will also be more if temperature is high.

Basin Yield

- * The total quantity of surface water that can be expected in a given period from a stream at the outlet of its catchment is known as yield of the catchment in that period.
- * Depending upon the period chosen we have annual yield and seasonal yield signifying yield of the catchment in an year and in a specified season respectively.
- * The annual yield from a catchment is the end product of various processes such as precipitation infiltration and evapotranspiration operating on the catchment.
- * Due to the inherent nature of the various parameters involved in the processes, the yield is a random variable.
- * A common practice is to assign a dependability value (say 75% dependable yield) to the yield.
- * Thus 75% dependable annual yield is the value that can be expected to be equalled or exceeded 75% of times.
- * Similarly, 50% dependable yield is the annual yield value that is likely to be equalled or exceeded 50% of times.
- * The yield of a catchment 'y' in a period Δt could be expressed by water balance equation.

$$Y = R_N + V_Y$$

$$= R_0 + A_b + \Delta S$$

Where,

R_N = Natural flow in time Δt

V_Y = Volume of return flow from irrigation, domestic water supply and industrial use

R_0 = Observed runoff volume at the terminal gauging station of the basin in time Δt .

A_b = Abstraction in time, Δt for irrigation water supply and industrial use and inclusive of evaporational losses in surface water bodies on the stream.

ΔS = change in the storage volume of water storage bodies on the stream.

SCN-CN Method

SCN-CN method of estimation runoff

SCN-CN method

- * This method developed by, Soil conservation services (SCS) of USA in 1969.

- * It is a simple, predictable and stable conceptual method for estimation of direct runoff depth based on storm rainfall depth.

- * It relies on only one parameter, CN.

Basic theory:

- * This method is based on the water balance equation of the rainfall in a known interval of

time Δt , can be expresses as,

$$P = I_a + F + Q \quad (1)$$

Where,

P = Total precipitation

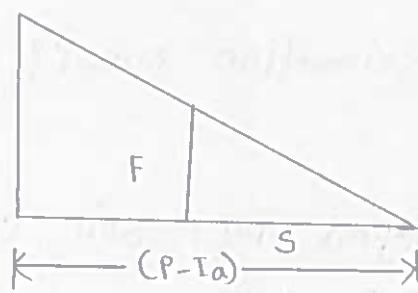
I_a = Initial abstraction

F = cumulative infiltration excluding I_a

Q = Direct surface runoff.

* Two other concepts as below are also used with equation (1).

1. The first concept is that the ratio of actual amount of direct runoff (Q) to maximum potential runoff ($= P - I_a$) is equal to the ratio of actual infiltration (F) to the potential maximum retention (or infiltration), s. This proportionality concept can be shown as below:



Proportionality concept

$$\text{thus, } \frac{Q}{P - I_a} = \frac{F}{S} \quad (2)$$

2. The second concept is that the amount of initial abstraction (I_a) is some fraction of the potential maximum retention (S)

$$\text{thus, } I_a = \lambda S \quad (3)$$

From equation (2) and (3) and using equation (1)

$$Q = \frac{(P - I_a)^2}{P - I_a + S} = \frac{(P - \lambda S)^2}{P + (1 - \lambda)S}$$

$$Q = 0 \text{ for } P \leq \lambda S$$

For operation purpose a time interval

$\Delta t = 1$ day is adopted

P = Daily rainfall

Q = Daily runoff from the catchment

Curve number (CN)

* For convenience in practical application the Soil Conservation Services (SCS) of USA has expressed S (in mm) in term of a dimensionless parameter CN (the curve number) as,

$$S = \frac{25400}{CN} - 254$$

$$= 254 \left[\frac{100}{CN} - 1 \right] \quad (6)$$

* The constant 254 is used to express S in mm the curve number CN is now related to S as,

$$CN = \frac{25400}{S + 254}$$

Range of $100 \geq CN \geq 0$

* A CN value of 100 represents a condition of zero potential retention and $CN = 0$ represent an infinitely abstracting catchment with $S = \infty$.

* This curve Number (CN) depends upon

1. Soil type

2. Land use/cover

3. Antecedent moisture condition

Flow-Duration curve

* The study of stream flow is done by the flow duration curve.

* A flow duration curve of a stream is a plot of discharge against the percent of the time flow is equalled or exceeded.

* The stream flow data is arranged in a descending order of discharges using class intervals if the number of individual values is very large.

* The data used can be daily, weekly or monthly values.

* If N number of data points are used in this listing the plotting position of any discharge Q is,

$$P_p = \frac{M}{N+1} \times 100\%$$

Where,

M = order number of discharge

P_p = percentages probability (or exceeded)
magnitude being equalled or exceeded

* The plot of P_p discharge is the flow duration curve.

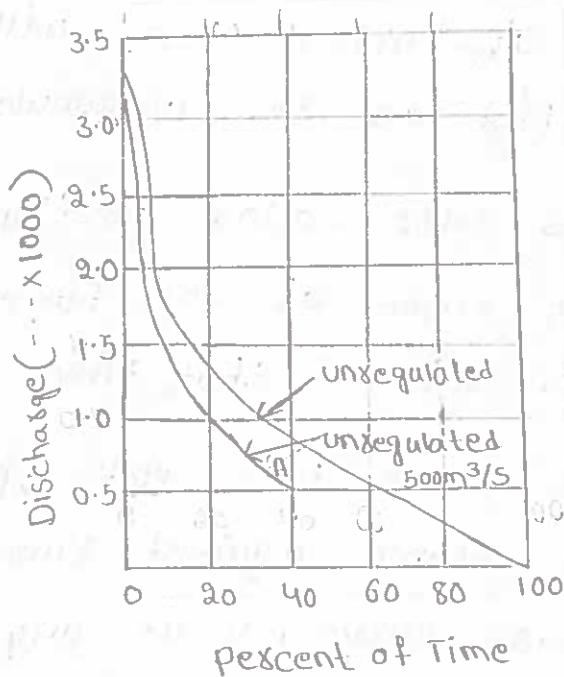
* The ordinate (Q_p) at any percentage probability (P_p) represents the flow magnitude in average year that can be expected to be equalled or

exceeded P_p percent of time and depend as $P_p\%$ dependable flow.

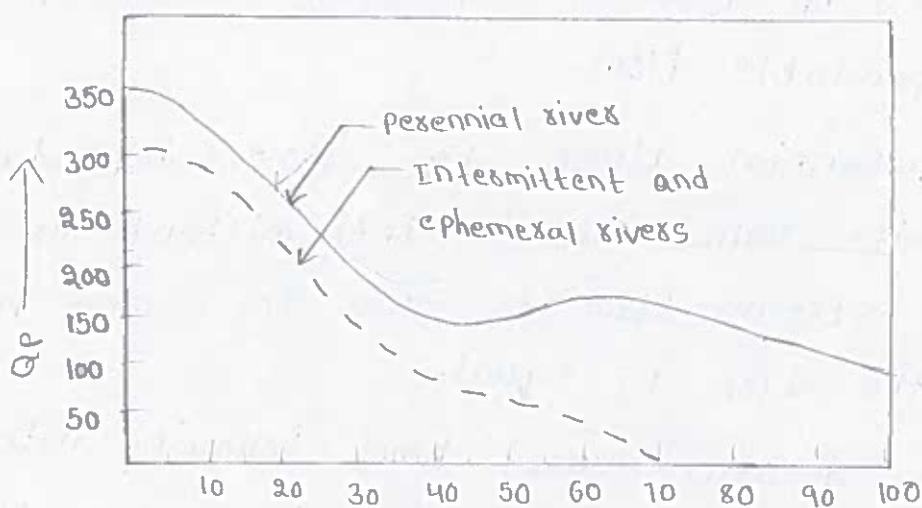
* In a perennial river, $Q_{100} = 100\%$, dependable flow is a finite value. But in intermittent or ephemeral rivers the stream flow is zero for some part of year so the Q_{100} is equal.

* The flow duration curve have following interest:

- The slope of the curve depends upon the interval of data selected.
- The virgin-flow duration curve is a straight line for central region when plotted on a log-log paper. From this, we developed various coefficients, expressing the variabilities of flow in a stream.
- The flow duration curve plotted on a log-log paper is useful in comparing the flow characteristics of stream.
- The serious draw back of flow duration curve is, for a particular flow, it have same value of P_p , whether it occurred in January or June.



Flow is equalled or exceeded



Use

$P_p = \text{percentage probability}$

- * It is used in evaluating the characteristics of the hydro power potential of a river.
- * It is used in the design of drainage system.
- * It is used in flood-control studies.
- * It is used in computing the sediment load and dissolved solid load of a stream
- * It is used in evaluating various dependable flow in the planning of water resource projects.

Flow-Mass curve

- * It is a plot between accumulated flow and time.
- * It is evident that the mass curve will continuously rise, so it is plotted as the accumulated flow.
- * The mass curve is also called as ripple diagram.
- * The slope of mass curve at any time is a measure of the flow rate at that time.
- * As the flow mass curve is a plot of the cumulative discharge volume against time, the ordinate of the mass curve, V at any time t is given by,

$$V = \int_{t_0}^t Q dt$$

Q = Discharge rate

t_0 = Time or beginning of the curve

* Flow mass is an integral curve of the hydrograph.

* The slope of mass curve

$$\frac{dV}{dt} = Q = \text{Rate of flow}$$

* On the basis of use of mass curve, it defines flow mass curve, outflow mass curve, mass curve of demand etc.

* If the mass curve have zero slope, for a particular period of time, it means that there is no inflow in that time period.

* As the water demand throughout the year remain same, so if we draw the demand mass curve that it has the same slope through the period.

Numericals

Estimate the evaporation from a free water surface on November 30th from the following data using Penman's equation.

Given that:

1. Latitude of the place = $180^\circ 45' N$

2. Air temperature = 25°

3. Actual vapour pressure in air = 15.0 mm of mercury

4. Actual sunshine hours = 6.5

5. Atmospheric pressure = 955 mm of mercury

6. Wind velocity 2m above ground 2.8 m/s

i. Saturation vapour pressure, e_w at $180^\circ 45' N$ is

23.76 mm of Hg.

Slope A = 1.40 mm/lc

Mean monthly solar radiation

$H_a = 11.43 \text{ mm water/day}$

Mean monthly sunshine hours, $N = 11.26 \text{ hrs}$

$$\frac{n}{N} = \frac{6.5}{11.26} = 0.577$$

ii. constant, $a = 0.29 \cos (180^\circ 45)$

$$= 0.2746$$

$$b = 0.52$$

iii. Stefan Boltzmann's constant,

$$\sigma = 2.01 \times 10^{-9} \text{ mm/day}$$

Mean air temperature,

$$T_a = 273 + T = 273 + 25 = 298K$$

$$\sigma T_a^4 = 2.01 \times 10^{-9} \times (298)^4 = 15.851$$

For free water surface, $\gamma = 0.05$

$$H_n = H_a (1-\gamma) \left[a + b \frac{n}{N} \right]$$

$$- \sigma T_a^4 (0.56 - 0.092 \sqrt{\gamma} \times \left[0.10 + 0.90 \frac{n}{N} \right])$$

$$= 11.43 (1-0.05) (0.29 + 0.52 (0.577))$$

$$- 15.851 (0.56 - 0.092 \sqrt{0.05} (0.10 + 0.90 \times 0.57))$$

$$H_n = 4.259 \text{ mm of water/day}$$

$$E_a = 0.35 \left[1 + \frac{u_2}{160} \right] (c_w - c_a)$$

$$u_2 = 2.8 \text{ m/s} = 10.08 \text{ km/hr}$$

$$u_2 = 242 \text{ km/day}$$

$$E_a = 7.703 \text{ mm/day}$$

... (by putting all values)

$$\therefore P.E.T = \frac{A H_n + E_a x}{A + x}$$

$$= \frac{(1.40 \times 4.259) + (7.703 \times 0.5)}{1.40 + 0.5}$$

P.E.T = Potential evapotranspiration

$$P.E.T = 5.16 \text{ mm/day}$$

The average rainfall over 45 ha of watershed for a particular storm was as follows:

Time(hrs)	0	1	2	3	4	5	6	7
Rainfall(cm)	0	0.5	1.0	3.25	2.5	1.5	0.5	0

The volume of runoff from this storm was determined as 2.25 ha-m. Establish the ϕ -index

Given:

i. volume of runoff

$$V = 2.25 \text{ ha-m} = 2.25 \times 10^4 \text{ m}^3$$

ii. Area = A = 45ha

$$A = 45 \times 10^4 \text{ m}^2$$

iii. Total runoff,

$$R = \frac{V}{A} = \frac{2.25 \times 10^4}{45 \times 10^4}$$

$$= 0.05 \text{ m} = 5 \text{ cm}$$

iv. ϕ index,

$$R = \sum (i - \phi_i) t$$

$$5 = [(0 - \phi) + (0.5 - \phi) + (1 - \phi) + (3.25 - \phi) + (2.5 - \phi) \\ + (1.5 - \phi) + (0.5 - \phi) + (0 - \phi)] \times 1$$

$$\phi = 0.53 \text{ cm/hr}$$

The rate of rain fall for successive 30 min period of 210 min storm are 4.5, 5, 13, 9.5, 5.5, 5.5 and 4 cm/hr assuming the ϕ index of 4.5 cm/hr, find the net rainfall over the basin in cm, the total rain fall and value of W-index.

Given: ϕ index = 4.5 cm/hr

Time	0	30	60	90	120	150	180	210
Rainfall intensity	0	4.5	5	13	9.5	5.5	5.5	4

a. Total rainfall

$$P = (4.5 + 5 + 13 + 9.5 + 6.5 + 5.5 + 4) \times \frac{30}{30}$$

$$P = 47 \text{ cm}$$

b. Total rainfall excess

$$= [(5 - 4.5) + (13 - 4.5) + (9.5 - 4.5) + (6.5 - 4.5) + (5.5 - 4.5)] \times \frac{30}{30}$$

$$= 16 \text{ cm}$$

$$c. Wi = \frac{P-R}{t_8} = \frac{47-16}{3.5} = 8.857 \text{ cm/hr}$$

The rate of rain fall successive 30 min period of 260 min storm are 5.5, 8, 15, 12.5, 6.5, 6.5 and 4 cm/hrs. Assuming the ϕ index of 4.5 cm/hr, calculate the net rain fall over the basin in cm, the total rain fall and value of W-index.

Given: ϕ index = 4.5 cm cm/hr

Time	0	30	60	90	120	150	180	210
Rainfall intensity	0	5.5	8	15	12.5	6.5	6.5	4

a. Total rainfall

$$P = [5.5 + 8 + 15 + 12.5 + 6.5 + 6.5 + 4] \times \frac{30}{30}$$

$$P = 58 \text{ mm}$$

b. Total rainfall excess

$$\begin{aligned} &= [(5.5 - 4.5) + (8 - 4.5) + (15 - 4.5) + (12.5 - 4.5) + (6.5 - 4.5) \\ &\quad + (4 - 4.5)] \times \frac{30}{30} \end{aligned}$$

$$R = 24.5 \text{ cm}$$

$$C. W_i = \frac{P - R}{t_h} = \frac{58 - 24.5}{3.5}$$

$$= 9.57 \text{ cm/hr}$$

A reservoir with surface area of 450 hectares has the following meteorological values. Estimate the average daily evaporation from the lake. Use Meyers's formula and Rohwer's formula. Take water temperature as 35°C, relative humidity as 60% and wind velocity at 1.55 m above ground as 13 km/h

and mean barometer reading as 760 mm of Hg.

a. Using meyer's formula

$$E = km (e_s - e_a) \left[1 + \frac{u_g}{16} \right]$$

Where,

$km = 0.36$ for large deep water

e_s = saturation vapour pressure at 35°C
 $= 42.81 \text{ mm of Hg}$

$e_a = ?$

Also $\frac{e_a}{e_s} = 50\%$ (Relative humidity)

$e_a = 50\% e_s = 0.5 \times 42.81 = 21.40 \text{ mm of Hg}$

$u_g = ?$

$v_1 = 13 \text{ km/h}$

$$\frac{u_g}{v_1} = \left[\frac{q}{1} \right]^{0.143}$$

$$\therefore u_g = (q)^{0.143} \times 13 \\ = 17.79 \text{ km/h}$$

Substituting values we get,

$$E = 0.36 (42.81 - 21.40) \left[1 + \frac{17.79}{16} \right]$$

$$E = 16.27 \text{ mm/day}$$

\therefore Total evaporation volume in 7 days (1 week)
from 300 hectares of surface area

$$\begin{aligned}
 &= \frac{16.27}{1000 \text{ day}} \times 7 \text{ days} \times (300 \times 10^4 \text{ m}^2) \\
 &= 341670 \text{ m}^3
 \end{aligned}$$

b. Using Rowher's formula

$$E = 0.771 (1.465 - 0.000732 P_a)$$

$$(0.44 + 0.0733 V_{0.6}) (e_s - e_a)$$

where,

$$e_s = 42.81 \text{ mm of Hg}$$

$$e_a = 21.40 \text{ mm of Hg}$$

$$P_a = 760 \text{ mm of Hg}$$

$$\frac{V_{0.6}}{V_1} = \left[\frac{0.6}{1} \right]^{0.143}$$

(cos)

$$V_{0.6} = \left[\frac{0.6}{1} \right]^{0.143} \times 13 \text{ km/h}$$

$$= 12.08 \text{ km/h}$$

$$E = 0.771 (1.465 - 0.000732 \times 760)$$

$$(0.44 + 0.0733 \times 12.08) (42.81 - 21.40)$$

$$= 0.771 (0.90) (1.32) (21.41)$$

$$E = 19.61 \text{ mm/day}$$

Estimate the potential evapotranspiration using Penman method for the following data:

Month - September, latitude - 28°N , Elevation

Temperature - 42.5°C , actual sunshine hours - 13h, wind

Velocity at 4m height - 165 km/day, mean relative humidity - 45% Assume any other data suitably

Given:

$$\text{Latitude} = 28^\circ \text{N}$$

$$\text{Elevation} = R_L = 220 \text{ m}$$

$$\text{Temperature} = 42.5^\circ \text{C}$$

$$\text{Humidity} = 45\%$$

$$\text{Wind velocity at 4m height} = 165 \text{ km/day}$$

From the below table

$$A = 3.54 \text{ mm/}^\circ\text{C}$$

$$e_w = 63.20 \text{ mm or Hg}$$

$$H_a = 11.36 \text{ mm of water per day}$$

$$N = 12.6 \text{ h}$$

$$n/N = 13/12.6 = 1.03$$

From given data,

$$c_a = 63.20 \times 0.75 = 47.4 \text{ mm of Hg}$$

$$a = 0.29 \cos 28^\circ = 0.256$$

$$b = 0.52$$

$$\sigma = 2.01 \times 10^{-9} \text{ mm/day}$$

$$T_a = 273 + 19 = 292 \text{ K}$$

$$-T_a^4 = 14.61$$

γ = Albedo for close-ground green crop is taken 0.25

$$H_n = 11.36 \times (1 - 0.25) \times (0.256 + 0.52 \times 1.03)$$

$$- 14.61 \times (0.56 - 0.092 \sqrt{47.4}) \times (0.10 + (0.9 \times 1.03))$$

$$= 6.74 - (-1.01)$$

$$H_n = 7.84 \text{ mm of water/day}$$

$$E_a = 0.35 \times \left[1 + \frac{165}{160} \right] \times (63.20 - 47.4)$$

$$= 11.23 \text{ mm/day}$$

$$\text{Value of } \gamma = 0.49$$

$$PET = \frac{(1 \times 7.84) + (2.208 \times 0.49)}{(3.54 + 0.49)}$$

$$= 2.21 \text{ mm/day}$$

Saturation vapour pressure of Water

Temperature (°C)	Saturation vapour pressure e_w (mm of Hg)	A (mm/°C)
0	4.58	0.30
5.0	6.54	0.45
7.5	7.78	0.54
10.0	9.21	0.60
12.5	10.87	0.71
15.0	12.79	0.80
17.5	15.00	0.95
20.0	17.54	1.05
22.5	20.44	1.24
25.0	23.76	1.40
27.5	27.54	1.61
30.0	31.82	1.85
32.0	36.68	2.07
35.0	42.81	2.35
37.5	48.36	2.62
40.0	55.32	2.95
45.0	71.20	3.66

$$e_w = 4.584 \exp\left(\frac{17.27t}{237.3+t}\right) \text{ mm of Hg}$$

Where,

t = Temperature in $^{\circ}\text{C}$

Mean monthly solar radiation at top of atmosphere,
 H_e in mm of evaporable water/day

North latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0°	14.5	15.0	15.2	14.7	13.9	13.4	13.5	14.2	14.9	15.0	14.6	14.3
10°	12.8	13.9	14.8	15.2	15.0	14.8	14.8	15.0	14.9	14.1	13.1	12.4
20°	10.8	12.3	13.9	15.2	15.7	15.8	15.7	15.3	14.4	12.9	11.2	10.3
30°	8.5	10.5	12.7	14.8	16.0	16.5	16.2	15.3	13.5	11.3	9.1	7.9
40°	6.0	8.3	11.0	13.9	15.9	16.7	16.3	14.8	12.2	9.3	6.7	5.4
50°	3.6	5.9	9.1	12.7	15.4	16.7	16.1	13.9	10.5	7.1	4.3	3.0

Mean monthly values of possible sunshine hours, N

North latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0°	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1
10°	11.6	11.8	12.1	12.4	12.6	12.7	12.6	12.4	12.9	11.9	11.7	11.5
20°	11.1	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
30°	10.4	11.1	12.0	12.9	13.7	14.1	13.9	13.2	12.4	11.5	10.6	10.2
40°	9.6	10.7	11.9	13.2	14.4	15.0	14.7	13.8	12.5	11.2	10.0	9.4
50°	8.6	10.1	11.8	13.8	15.4	16.4	16.0	14.5	12.7	10.8	9.1	8.1