Chapter 1

Hydrologic Cycle

CHAPTER HIGHLIGHTS

- *Precipitation and frequency of point rainfall and probability*
- *Evaporation, transpiration, infiltration and run-off*

Precipitation and Frequency of Point Rainfall and Probability

Introduction

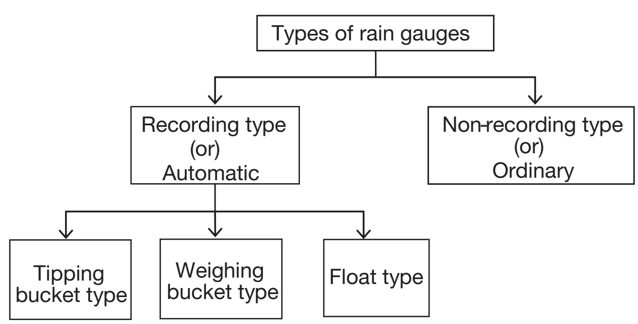
- Hydrologic cyclic involves precipitation, evaporation, transpiration, infiltration and run-off.
- The air mass is said to be continental air mass when originates from land areas and maritime air mass when it originates from sea.
- The surface of contact between two air mass and the surrounding atmosphere is called frontal surface and the intersection of frontal surface with the earth's surface is called surface front.
- Circular area of low atmospheric pressure in which the wind blows in counter-clockwise direction in northern hemisphere and in clockwise direction in southern hemisphere is called cyclone. The centre of cyclonic storm is called eye of the storm.
- The high pressure areas in which the wind blows in clockwise direction in northern hemisphere and anticlockwise in southern hemisphere is called anticyclones.
- This chapter deals with precipitation caused due to above mentioned phenomena.

Precipitation

Any form of moisture reaching the earth's surface from the atmosphere is called precipitation.

- Rainfall with an intensity of 2.5 mm/h is called light rain.
- Rainfall with an intensity between 2.5 mm/h and 7.5 mm/h is called moderate rain.
- Rainfall when exceeds 7.5 mm/h is called heavy rain.
- Precipitation is measured by an instrument called rain gauge which is also known as hyetometer, ombrometer or pluviometer.

Types of Rain Guage



1. **Recording type rain gauge:** Recording type rain gauges are required to record rain fall from the beginning to the end and to measure the intensity of rainfall. There are different types of recording type rain gauges.

   (a) Tipping bucket type: It contains a container divided vertically into two compartments and is balanced in an unstable equilibrium. The rain is led from a conventional collecting funnel into the uppermost compartment and after a predetermined rain has fallen, the bucket becomes unstable in its present position and tips over to the other position of rest.

   The movement of the bucket tips can be used to operate an electric circuit and produce a record.

   The major **disadvantage** of this type of rain gauge is, if the buckets are designed to tip at a convenient frequency for particular intensity of rainfall, they may either tip sooner or later which results in error of recorded rainfall.

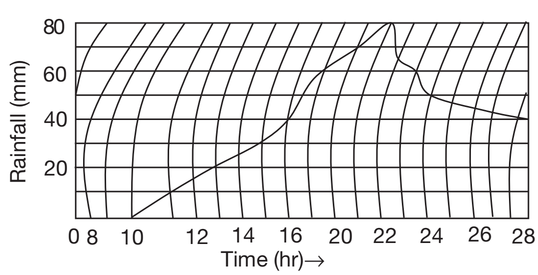
   The biggest **advantage** of tipping bucket gauge is that it is the only recording type which can be used in remote places by installing recorder at convenient and easily accessible location.

   (b) Weighing bucket rain gauge: The weight of rainfall received since the recording began is recorded continuously by transmitting the movement of the platform through a system of links and levers to a pen which makes a trace on a suitably graduated chart secured around a drum. The drum is driven mechanically by a spring clock.

   The main **advantage** of this type of gauge is it can record snow, hail and mixture of rain and snow.

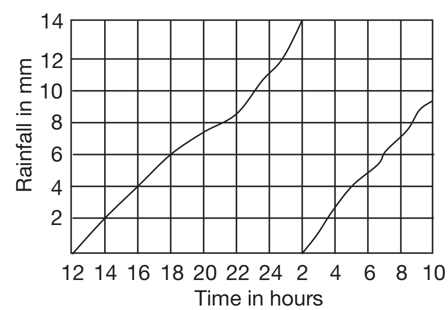
   The **disadvantages** of this gauge are:

- It is affected by temperature and friction.
- Shrinkage and expansion of chart paper caused due to humidity may distort the time and the scale of rainfall.
- Failure of reverse mechanism may lead to loss of record.



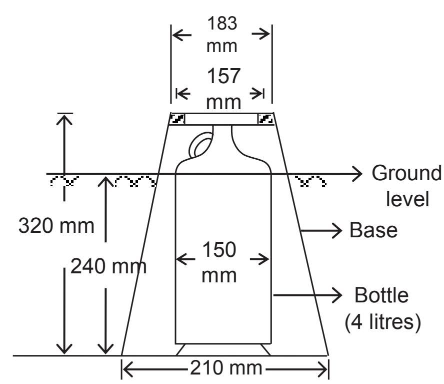
Rainfall chart from weighing bucket

   (c) Float type rain gauge: It is also known as **siphon type** rain gauge. The rainwater entering the gauge at the top is led into the float chamber through a funnel and filter. The purpose of filter is to prevent dust and other particles from entering chamber. The float of the float chamber is connected to open on the other side of the float. As the storm water enters the float chamber through the funnel, the float rises slowly which enables the pen to draw a graph on the chart of a rotating drum. Whenever the float reaches its maximum level the siphon mechanism gets activated and the water flushes out resulting in falling of pen again to initial point. The process get repeated continuously and the resulting graph appears as below.



Rainfall chart from float type raingauge

2. **Non-recording type rain gauge: Symon's gauge** is the standard non-recording type rain gauge prescribed by Indian meteorological department. This raingauge consists of a receiver of capacity 175 mm. The gauge is fixed on a masonry foundation of 60 cm × 60 cm × 60 cm. The rainfall is measured for 24 hours by pouring the water into a measuring jar from the receiver. Sum of all the readings taken at the last 24 hours is recorded as rainfall of the day.



Receiver of rainguage

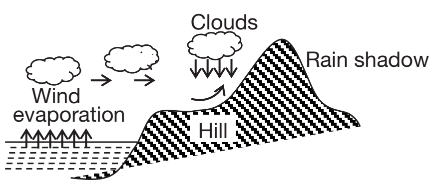
Forms of Precipitation

1. **Drizzle:** Size of droplet is less than 0.5 mm.
2. **Rain:** Size of droplet is more than 0.5 mm.
3. **Glaze:** When the drizzle freezes it is known as glaze.
4. **Sleet:** The frozen rain drops are cooled to ice stage while falling.

5. **Snow:** The water vapour when directly changed to ice is known as snow.
6. **Hail:** Lumps of ice with more than 5 mm diameter is known as hail.

Types of Precipitation

1. **Cyclonic precipitation (Non-frontal):** Lifting of air masses converging into low pressure area of cyclone is known as cyclonic precipitation.
2. **Convective precipitation:** It is caused by rising of warmer and lighter air in colder and denser surroundings.
3. **Orographic precipitation:** This type of precipitation occurs when the warm moisture laden air is lifted upwards due to obstruction of hill. In this case the rainfall occurs only along one side of the hill. The other side is dry and is known as rain shadow region.



Rain Gauge Network

The ratio of total area of the catchment to the total number of gauges in the catchment is known as rain gauge density or network density. The network density for different regions as per world meteorological organization based on the topographic conditions is as follows:

Description	Network density
Flat regions of temperate and tropical zones.	1 gauge for 600 to 900 km^2.
Mountainous areas of temperate and tropical zones.	1 gauge for 100 to 250 km^2.
Arid and polar zones.	1 gauge for 1500 to 10000 m^2.

As per Indian Standards recommendations:

1. Network density for plain areas is one gauge per 520 km^2.
2. Network density for areas with elevation more than 1000 m above MSL is one gauge per 260 to 390 km^2.
3. Network density for areas of heavy rainfall is one gauge per 130 km^2.
   - The optimum number of raingauge stations (N) as per Indian Standards is

$$N = \left[\frac{C_v}{p}\right]^2$$

Where

$$C_V = \frac{S_x}{\bar{x}}$$

s_x = Standard deviation

$\bar{x}$ = Mean of rainfall values of existing stations

p = Desired degree of error in estimating mean rainfall.

If $N < n$ where n is the number of existing stations then no more extra rain gauges are required.

If $N > n$ then number of additional rain gauges required are $(N - n)$.

SOLVED EXAMPLES

Example 1

A catchment has five rain gauge stations. In a year, the annual rainfall recorded by the gauges are 72.3 cm, 86.4 cm, 94.2 cm, 103.8 cm, 71.4 cm respectively. For a 5% error in the estimation of mean rainfall, the number of rain gauges required are__________.

Solution

$$\bar{x} = \frac{1}{n}\sum x_1 = \frac{72.3+86.4+94.2+103.8+71.4}{5} = 85.62 \text{ cm}$$

$$s_x^2 = \frac{\sum(x_i - \bar{x})^2}{n-1}$$

$$= \frac{\begin{bmatrix}(72.3-85.62)^2+(86.4-85.62)^2+(94.2-85.62)^2+\\(103.8-85.62)^2+(71.4-85.62)^2\end{bmatrix}}{5-1}$$

$$\Rightarrow s_x = 14$$

$$C_v = \frac{14}{85.62}\times 100 = 16.35$$

$$N = \left(\frac{C_v}{p}\right)^2 = \left(\frac{16.34}{5}\right)^2 = 10.69 \approx 11$$

Additional number of stations = 11 – 5 = 6.

Estimation of Missing Rainfall Data

1. **Arithmetic mean method:** In this method the missing rainfall P_x is computed by average of rainfall at nearby stations.

$$P_x = \sum_{i=1}^{n}\frac{P_i}{n} = \frac{1}{n}(P_1 + P_2 + \cdots P_n)$$

Where

P_x = Rainfall of missing station

n = Number of index stations (i.e., stations other than missing stations)

Example 2

A rotator shed has four rain gauge stations A, B, C and D. During a storm, rain gauge station A was inoperative, while other stations B, C and D recorded rainfall of 50 mm, 55 mm, 48 mm respectively. The missing storm at station A is ______.

Solution

$$P_A = \frac{P_B + P_C + P_D}{3} = \frac{50 + 5 + 48}{3} = 51 \text{ mm.}$$

2. **Normal ratio method:** In this the rainfall of surrounding index stations are weighed by ratio of normal annual rainfalls by using following equation:

$$P_x = \frac{1}{n}\left[P_1 \times \frac{N_x}{N_1} + P_2 \times \frac{N_x}{N_2} + \ldots P_n \frac{N_x}{N_n}\right]$$

Where

$N_1, N_2, \ldots, N_n$ = Normal annual rainfall of index stations

N_x = Normal annual rainfall of missing station

n = Number of index stations (or) adjacent raingauge stations.

Example 3

A precipitation station X was inoperative when a storm occurred. The storm totals at three stations A, B and C surrounding X were respectively 6.2, 4.3 and 3.2 cm. The normal annual precipitation amounts at stations X, A, B and C respectively 63.2, 71.2, 49.3 and 33.4 cm. The storm precipitation for station X.

Solution

$$P_x = \frac{1}{3}\left[\frac{N_X}{N_A} \times P_A + \frac{N_X}{N_B} \times P_B + \frac{N_X}{N_c} \times P_X\right]$$

$$= \frac{1}{3}\left[\frac{63.2}{71.2} \times 6.2 + \frac{63.2}{49.3} \times 4.3 + \frac{63.2}{33.4} \times 3.2\right]$$

$$= \frac{1}{3}[5.5 + 5.51 + 6.05]$$

$$= 5.68 \text{ cm.}$$

Computation of Average Rainfall Over a Basin

If the catchment area contains more than one rain gauge station, the average precipitation may be done by following methods.

1. **Arithmetic average method:** If P_1, P_2, P_3, …, P_n, etc. are the precipitation values measured at n gauge stations, we have

$$P_{\text{avg}} = \frac{P_1 + P_2 + \cdots + P_n}{n} = \frac{1}{n}\sum_{i=1}^{n} P_i$$

Example 4

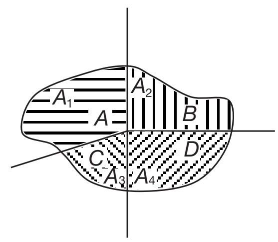
Find the average precipitation of the following stations using arithmetic average method.

Station no:	1	2	3	4	5	6
Precipitation: (mm)	13.4	19.2	15.3	12.2	14.6	15.4

Solution

$$P_{\text{average}} = \frac{13.4 + 19.2 + 15.3 + 12.2 + 14.6 + 15.4}{6} = 15.01 \text{ mm.}$$

2. **Thiessen polygon method:** The adjacent rain gauge stations A, B, C, D, etc., are joined by straight lines. Then perpendicular bisectors for these lines are constructed. The polygons are thus formed by the bisectors are taken into consideration. The areas are named as $A_1, A_2, A_3, \ldots, A_n$. The precipitation at each station is given as $P_1, P_2, \ldots, P_n$.



$$P_{\text{avg}} = \frac{A_1P_1 + A_2P_2 + \cdots + A_nP_n}{A_1 + A_2 + \cdots + A_n}$$

$$= \frac{\sum(A_1 \times P_1)}{\sum A_1} = P_1w_1 + P_2w_2 + \cdots + P_nw_2$$

where $w_1 + w_2 + w_3 + \cdots + w_n = 100$

$$\Rightarrow w_1 = \frac{A_1}{\sum A}$$

$$w_2 = \frac{A_2}{\sum A}$$

$$w_n = \frac{A_n}{\sum A}.$$

3. **Isohyetal method:** An isohyets is a line, on a rainfall map of the basin, joining places of equal rainfall readings. The isohyets are drawn in an area where the average rainfall has to be measured. The areas in between the isohyets are measured as A_1, A_2, A_3, …, A_n. The precipitation of isohyets are P_1, P_2, P_3, P_4, …, P_n. Thus the average rainfall is

$$P_{\text{avg}} = \frac{\sum_{n=1}^{n} A_{n-1} \times \left[\frac{P_{n-1} + P_n}{2}\right]}{\sum_{n=1}^{n} A_{n-1}}$$

Example 5

Find the average rainfall of different areas given below using isoheytal method.

Isohyets (cm)	9	10	11	12	13	14	15
Area between Isohyets (cm^2)		25	75	100	92	73	20

Solution

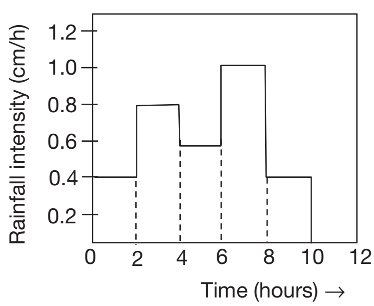
Isohyets (cm)	9	10	11	12	13	14	15
Area between Isohyets (cm^2)		25	75	100	92	73	20
Average precipitation		9.5	10.5	11.5	12.5	13.5	14.5
Product		237.5	787.5	1150	1150	985.5	290

$$P_{avg} = \frac{\sum A \times \left[\frac{P_1 + P_2}{2}\right]}{\sum A} = \frac{4600.5}{385} = 11.94 \text{ cm.}$$

Presentation of Rainfall Data

The rainfall data can be represented by different methods.

1. **Hyetograph method:**

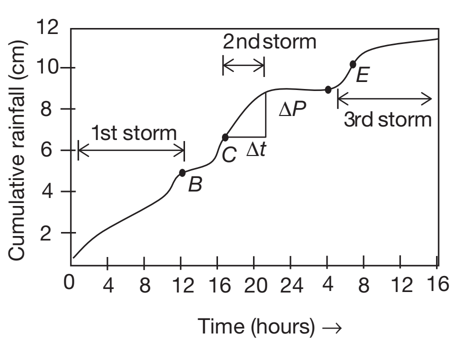


A bar chart showing intensity of rainfall with time is known as hyetograph.

2. **Mass curve of rainfall:** The mass curve is a graph drawn between cumulative depth of rainfall against time. The slope of the mass curve indicates the intensity of rainfall during any period. Thus the intensity of rainfall is given by,

$$i = \frac{\Delta p}{\Delta t}$$

where, ΔP = (change in cumulative rainfall)



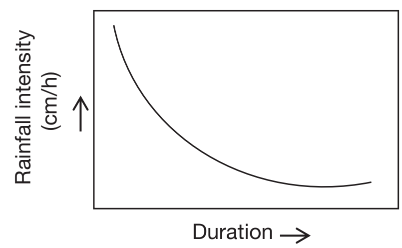
Interpretation of Rainfall Data

The precipitation information may be required for the following:

1. Intensity
2. Duration
3. Frequency
4. Area extent

Intensity Duration Analysis

Greater the intensity of rainfall, shorter the time for which it persists



$$\text{Intensity, } i = \frac{a}{(t+b)^n}$$

Where

t = Time in minutes

a, b, n = Constants to be determined for the area.

Intensity Duration Frequency

From this analysis we can say that for the storm of same duration and larger intensity will have larger return period. The relationship between intensity, duration and return period is given by the equation,

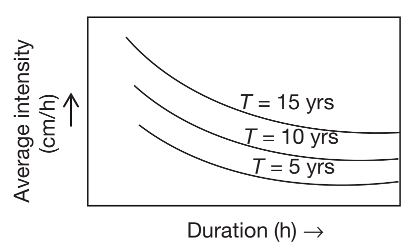
$$i = \frac{KT^x}{(t+b)^n}$$

Where

i = Intensity of rainfall

x, b and n = Constants for catchment

T = Return period in years.



Depth Area Relationship

The average depth of rainfall decreases from maximum value as the area increases for a given rainfall duration. The relationship can be expressed as,

$$\bar{P} = P_n e^{-kA^n}$$

Where

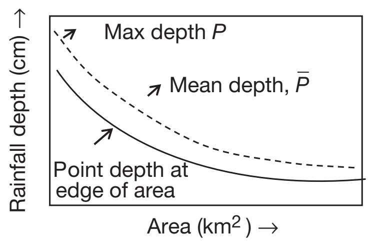
P_n = Highest amount of rainfall observed at the storm centre

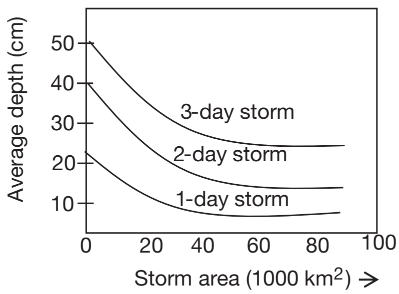
A = Area (km^2)

$\bar{P}$ = Average depth in cm, over the area

k, n = Constants.

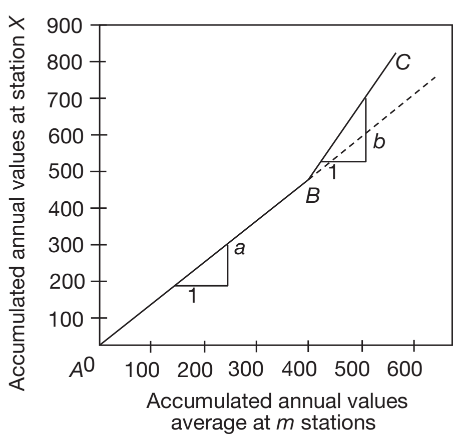
Depth Area Duration





Double Mass Curve of Rainfall

It is a graph plotted between the accumulated annual rainfalls at a given station versus accumulated annual values of the average of group of base stations for various consecutive time periods.



m = Number of base stations used to check inconsistency of rainfall record and to check arithmetical errors in transferring rainfall data from one record to another.

Frequency of Point Rainfall and Probability

- The probability of rainfall whose magnitude is equal to or in excess of specified magnitude (x) is given by,

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

where, T is the recurrence time interval.

- The probability of event not occurring in a given year is $q = 1 - p$.
- The probability of occurrence of event r times in n successive years is $P = {}^nC_r\, p^r q^{n-r}$.
- The probability of event not occurring at all is q^n.
- The probability of event occurring atleast once $1 - q^n = P_{\text{risk}}$.
- The lines connecting points of equal depths of rainfall of a particular return period are known as **isopluvial lines**.
- The greatest rainfall that is possible over a basin for a given duration is known as probable maximum precipitation. The probable maximum precipitation is used in construction of hydraulic structures.

For an annual flood series arranged in decreasing order of magnitude, the return period (T) for a magnitude listed at position m in total of 'n' entries is, $T = \dfrac{n+1}{m}$

California formula: $T = \dfrac{n}{m}$.

Example 6

On the basis of isopluvial maps 60 years, 24 hours maximum rainfall at Chennai is found to be 20 cm. Determine the probability of 24 hours rainfall of magnitude greater than or equal to 20 cm occurring at Chennai.

(i) Once in 10 successive years.
(ii) Atleast once in 10 successive years.

Solution

$$P = \frac{1}{60} = 0.0167$$

$$q = 0.983$$

(i) $p_{1,10} = {}^{10}C_1\, p^1 q^9 = {}^{10}C_1\,(0.0167)^1\,(0.983)^9 = 0.143$

(ii) $p_{\text{risk}} = 1 - q^n = 1 - (0.983)^{10} = 0.157$.

Evaporation, Transpiration, Infiltration and Run-off

Introduction

- Precipitation – Surface run-off = Total loss
  Total loss = Interception + Evaporation + Transpiration + Infiltration + Depression storage + Watershed leakage.
- Interception may be defined as that amount of precipitation water which is intercepted by vegetative foliage, buildings and other objects lying over land surface. Interception does not reach land surface, but is returned back to atmosphere by evaporation.

- The water which is retained in the depressions or ditches is known as depression storage.
- The flow of water from one basin to another basic is known as watershed leakage.

Evaporation

- The process in which the liquid changes to gaseous state at the free surface below boiling point is known as evaporation.
- Rate of evaporation depends on
  1. Vapour pressure
  2. Air and water temperatures
  3. Solar radiation
  4. Wind speed
  5. Atmospheric pressure
  6. Quality of water
- According to Dalton's law,

$$E = c(e_s - e_a)$$

Where

$c = a + bV$

$a = b =$ Constants

$V =$ Wind velocity in km/h

$e_s =$ Saturation vapour pressure at water surface

$e_a =$ Actual vapour pressure of air.

Factors Affecting Evaporation Losses

1. **Nature of evaporating surface:** In wet soil the evaporation is faster and it reduces as the soil becomes dry. The evaporation is more for black cotton soils than red soils.
2. **Area of water surface:** Evaporation loss is directly proportional to the surface area. The greater the surface area more is the evaporation loss.
3. **Depth of water in water body:** As the depth of water body increases evaporation decreases in summer and increases in winter season due to additional heat energy available, which is stored during summer in deep waters.
4. **Humidity:** As the humidity increases evaporation decreases.
5. **Wind velocity:** As the wind velocity increases evaporation loss increases.
6. **Temperature of air:** As the temperature increases the rate of evaporation increases.
7. **Atmospheric pressure:** As the atmospheric pressure increases, evaporation increases.
8. **Quality of water:** As the presence of dissolved salts decreases in the vapour pressure and thus the evaporation reduces.

Estimation of Evaporation

The evaporation loss can be estimated using following methods.

1. **Using evaporation pans:**

   Lake evaporation = Pan coefficient × Pan evaporation

   Pan coefficient for Indian standard evaporimeter is around 0.8.

   Pan coefficient for Class A pan is around 0.7.

   Reservoir evaporation volume rate,

$$V = AE_P\, C_P$$

   Where

   $A =$ Average reservoir area

   $E_P =$ Pan evaporating loss

   $C_P =$ Pan coefficient.

   The empirical equations used in calculation of evaporation are Meyer's formula, Rohwer's formula.

2. **Water budget or water balance method:**

   According to this method,

   ΣInflow − ΣOutflow = Change in storage + Evaporation loss

   $E = \Sigma I - \Sigma O \pm \Delta S$

   $\Rightarrow E = (P + I_{sf} + I_{gf}) - (O_{sf} + O_{gf} + T) \pm \Delta s$

   Where

   $P =$ Precipitation

   $I_{sf} =$ Surface water inflow

   $I_{gf} =$ Ground water inflow

   $O_{sf} =$ Surface water outflow

   $O_{gf} =$ Ground water outflow

   $T =$ Transpiration loss

   $\Delta s =$ Change in storage

3. **Energy balance method:**

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

   $H_n =$ Net heat energy received by water surface

   $H_b =$ Black radiation from the water body

   $H_a =$ Sensible heat transfer from water surface to air $= \beta \rho_w L_a E$

   Where

   $\beta =$ Bowen ratio $= \dfrac{H_a}{H_a}$

   $H_e =$ Heat energy used up in evaporation $= \rho_w L_a E$

   $L_a =$ Latent heat of evaporation

   $H_g =$ Heat flux into the ground

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

H_s = Heat stored in water body

Evaporation,

$$E = \frac{H_n - H_g - H_s - H_i}{\rho w L_a (1+\beta)}.$$

Transpiration

The process in which the water is lost through living plant leaves, during respiration process is known as transpiration. It is measured by phytometer.

Evapo-transpiration

The combination of evaporation and transpiration is known as evapo-transpiration. **Lysimeter** is the instrument which is used to measure evapo-transpiration. Penman's equation and Blaney–Criddle equations are the two equations used to measure evapo-transpiration.

1. **Penman equation:** Evapo-transpiration (or) potential evapo-transpiration = $K \times E$

   Where

   E = Evaporation

   K = Constant

2. **Blaney–Criddle equation:** Evapo-transpiration or potential evapo-transpiration,

$$E_T = \frac{2.54 \times K \times P_h \times T_f}{100}$$

   Where

   E_T = Potential evapo-transpiration (PET) per month (in cm).

   K = Empirical coefficient which depends on crop type

   P_h = Monthly percent of annual day time in hours

   T_f = Mean monthly temperature in °F

   The lines joining places of equal depth of evapo-transpiration or potential evapo-transpiration are known as **isopleths.**

Infiltration

Downward movement of water from soil surface into the soil mass through the pores of soil is known as infiltration. The capacity of any soil to absorb water from rain falling on the surface of land is known as infiltration capacity. The infiltration capacity decreases continuously with time. Infiltration capacity is measured by **infiltrometer**.

Factors Affecting Infiltration

1. **Condition of entry surface:** If the vegetation in a land area increases, the infiltration capacity also increases and vice-versa.
2. **Permeability characteristics of soil formation:** Infiltration is directly proportional to permeability or percolation. As the percolation increases the infiltration also increases. But percolation generally depends on soil composition, permeability, porosity, stratification and presence of organic matter.
3. **Temperature:** As the temperature increases, viscosity of water reduces and thus the infiltration increases. Therefore in summer the infiltration capacity is more than in winter.
4. **Intensity and duration of rainfall:** The more intensity of rainfall the less is the infiltration likewise the more is the duration of rainfall the less is the infiltration. This is because the impact of water causes mechanical compaction and wash of fine particles reducing infiltration.
5. **Quality of water:** The more the impurities present in the soil the less is the infiltration rate, as the impurities in soil block the pores in the soil which does not allow the water to enter inside.
6. **Size and characteristic of soil particles:** As the size or diameter of the soil particles increases the infiltration increases like in granular soils but if soil has swelling minerals then infiltration reduce drastically.
7. **Presence of ground water table:** As the ground water table increases the infiltration decreases.

Horton's Equation: According to Horton's equation

$$\boxed{f_t = f_c + (f_0 - f_c)e^{-kt}}$$

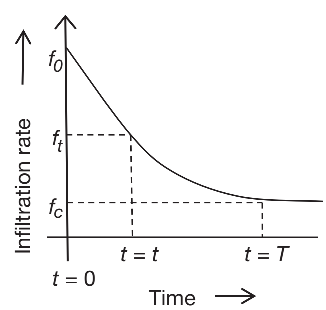
Where

f_t = Infiltration rate at any time t

f_c = Constant infiltration rate attained at time $t = T$

f_0 = Infiltration rate at the beginning

k = Constant depending on soil and vegetation



Example 7

During a 3 hours storm event, it was observed that all observed abstractions other than infiltration are negligible. The rainfall was idealized as 3 one hour storms of intensity 10 mm/h, 20 mm/h and 10 mm/h respectively and the infiltration was idealized as a Horton curve, $f = 6.8 + 8.7\, e^{-t}$ (f in mm/h and t in hour). Find the total infiltration.

Solution

$$f = 6.8 + 8.7\,e^{-t}, f_c = 6.8 \text{ mm/h}$$

$$\text{At } t = 0 \text{ hour}, f = 15.5 \text{ mm/h}$$

$$t = 1 \text{ hour}, f = 10 \text{ mm/h}$$

$$t = 2 \text{ hours}, f = 7.98 \text{ mm/h}$$

$$t = 3 \text{ hours}, f = 7.23 \text{ mm/h} > f_c$$

[In all above cases $f \leq i$ = rainfall

$\therefore$ Infiltration = f (given by Hortons equations)]

Area below Horton's curve from $t = 1$ hour to 3 hours is

$$= \int_1^3 (6.8 + 8.7e^{-t})dt = \left[6.8t + \frac{8.7e^{-t}}{-1}\right]_1^3$$

$$= [6.8 \times 3 - 8.7e^{-3}] - [6.8 \times 1 - 8.7e^{-1}]$$

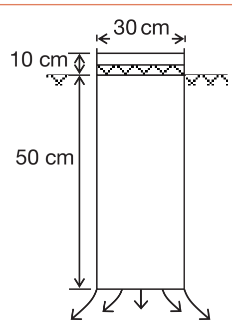
$$= 19.97 - 3.6 = 16.37 \text{ mm.}$$

Measurement of Infiltration by Infiltrometers

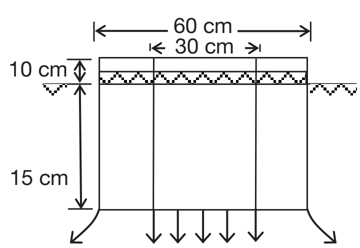
Infiltration is measured by two types of infiltrometers:

1. Single tube infiltrometer
2. Double tube or double ring infiltrometer

Single Tube Infiltrometer	Double Ring Infiltrometer
It consists of metal cylinder of diameter 25–30 cm and height 50–60 cm with both ends open.	The most commonly used flooding type infiltrometer which consists of two concentric rings driven into soil of depth 15 cm. The diameter of rings may vary between 25–60 cm.
The major drawback of single tube infiltrometer is that the infiltrated water percolates laterally at the bottom of the ring and gives more infiltration values.	The outer ring is present to suppress the lateral percolation of water from the inner ring.



Single tube infiltrometer



Double ring infiltrometer

Run-off

Total quantity of water drained into the stream or reservoir for a specified period of a catchment area is known as run-off. Run-off is classified as follows:

Run-off
- Surface run-off
- Subsurface run-off
- Base flow

(Surface run-off + Subsurface run-off = Direct run-off)

Surface run-off: It is the water which travels across the ground surface to the stream.

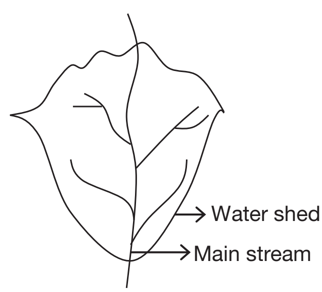
Sub-surface run-off: It is the water that does not percolate deep to meet the ground water, but flows in sub-surface of soil strata in the basin.

Base flow: The water which percolates deep downwards into the soil and meets ground water is known as base flow.

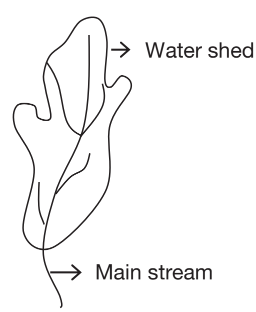
Factors Affecting Run-off

The factors affecting run-off are:

1. **Precipitation characteristics:** Run-off increases with intensity and extent of storm over the catchment. Run-off decreases with increase in infiltration and evaporation.
2. **Shape and size of the catchment:** If the size of catchment is more, then the run-off is more and vice-versa. When shape of the catchment considered is fan shaped catchment, it has less run-off compared to the fern leaf catchment.



Fan shaped catchment



Fern shaped catchment

3. **Topography of catchment:** For a steep slope, the run-off will be greater whereas for a slope with undulations and ruggedness the run-off will be low.
4. **Orientation of watershed:** The north and south orientation of watershed affects the run-off. The windward side of the mountain has high rainfall, hence run-off will be more.
5. **Geological characteristics of basin:** If the surface is rocky, the absorption is nil, hence the run-off will be more. If the surface has fissures, tunnels, or if they are porous, then the run-off will be less as most of the water will be lost by seepage.
6. **Character of catchment surface:** Run-off also depends on surface of the catchment. If the surface is undrained, then the absorption loss is more and run-off is less. If the area of catchment is cultivated, surface run-off will be less.

Run-off by Infiltration Method

Infiltration index: Infiltration index is the average rate of loss such that the volume of rainfall in excess of that rate will be equal to the direct run-off.

The infiltration indices are of two types:

1. ϕ index
2. w-index

ϕ-index:

$$\boxed{\phi = \frac{P - R}{t_e}}$$

P = Total precipitation during periods of run-off
R = Run-off on the surface
t_e = Duration of rainfall excess (run-off) in hours = Total time in which the rainfall intensity is greater than ϕ-index.

w-index: The average infiltration rate during the time in which rainfall intensity exceeds the capacity rate.

$$w = \frac{(P_e - R - \text{Initial loss})}{\text{Time of excess initial loss includes surface retention}}$$

$$\text{Coefficient of run-off, } k = \frac{\text{Run-off}}{\text{Rainfall}}$$

Example 8

The rainfall rates for successive 30 minutes intervals upto 4 hours are given below. If the surface run-off is 3.6 cm, then w-index and ϕ-index are _______.

Time (min)	0	30	60	90	120	150	180	210	240
Rainfall intensity (cm/h)	0	1.3	2.8	4.1	3.9	2.8	2.0	1.8	0.9

Solution

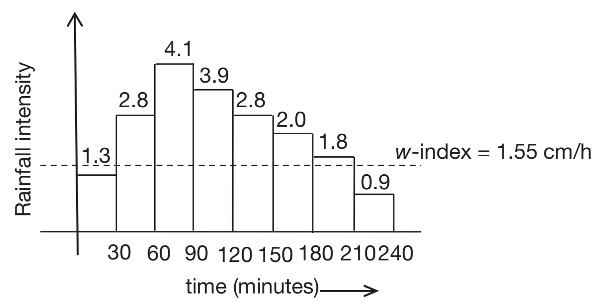
Precipitation $P = (1.3 + 2.8 + 4.1 + 3.9 + 2.8 + 2 + 1.8 + 0.9) \times \frac{30}{60}$

$= 9.8$ cm

Run-off $R = 3.6$ cm

Initial loss = 0

$$\therefore w = \frac{9.8 - 3.6 - 0}{4} = 1.55 \text{ cm/h}$$



Now ϕ greater than w-index = 1.55 cm/h

Taking rainfall greater than w-index.

$$\phi = \frac{P_e - R}{t_e} = \frac{\dfrac{(2.8 + 4.1 + 3.9 + 2.8 + 2 + 1.8)}{2 - 3.6}}{\left(\dfrac{180}{60}\right)}$$

$\phi = 1.7$ cm/h.

Exercises

1. Match the following

	List I		List II
P.	Rainfall intensity	**1.**	Isohyets
Q.	Rainfall excess	**2.**	Cumulative excess rainfall
R.	Rainfall averaging	**3.**	Hyetograph
S.	Mass curve	**4.**	Direct run-off hydrograph

Codes:

	P	Q	R	S		P	Q	R	S
(A)	1	3	2	4	(B)	3	4	1	2
(C)	1	2	4	3	(D)	3	4	2	1

2. Thiessen polygon constructed for a network of 10 rain gauges in a river basin yielded thiessen weights of 0.1, 0.16, 0.12, 0.11, 0.09, 0.08, 0.07, 0.11, 0.06 and 0.1. If the rainfalls recorded at these gauges during a cyclonic storms are 132, 114, 162, 138, 207, 156, 135, 158, 168 and 150 mm respectively. The average depth of rainfall by Thiessen mean method if the area of basin is 5800 km^2, is _________.
(A) 152.3 mm (B) 149.08 mm
(C) 144.23 mm (D) 158.6 mm

3. Rain gauge station X did not function for a part of a month during which a storm occurred. The storm produced rainfall of 84, 70 and 96 mm at three surrounding stations A, B and C respectively. The normal annual rainfalls at stations X, A, B and C are respectively 770, 882, 736 and 944 mm. The missing storm rainfall at station X is
(A) 76 mm (B) 75 mm
(C) 78 mm (D) 80 mm

4. In a Water-shed, four rain gauges I, II, III, IV are installed. The depths of normal annual rainfall at these stations are 60, 75, 80 and 100 cm respectively. The rain guage at station III went out of order during a particular year. The annual rainfall for that year, recorded at the remaining three stations was 90, 60 and 70 cm. The rainfall at station III can be considered as
(A) 60 cm (B) 70 cm
(C) 80 cm (D) 120 cm

5. The average annual rainfalls in cm at 4 existing rain gauge stations in a basin are 105, 79, 70 and 66. If the average depth of rainfall over the basin is essential with 10% error. The additional number of gauges needed are
(A) 0 (B) 3
(C) 1 (D) 2

6. Lysimeter and tensiometer are used to measure respectively, one of the following groups of quantities:
(A) Capillary potential and permeability
(B) Evapo-transpiration and capillary potential
(C) Velocity in channels and vapour pressure
(D) Velocity in pipes and pressure head

7. Consider the following chemical emulsions:
I. Methyl alcohol
II. Cetyl alcohol
III. Stearyl alcohol
IV. Kerosene
Which of the above chemical emulsions is/are used to minimize the loss of water through the process of evaporation?
(A) I only (B) I and IV
(C) II and IV (D) II and III

8. During a 6-hours storm the rainfall intensity was 0.8 cm/h on a catchment of area 8.6 km^2. The measured run-off volume during this period was 256000 m^3. The total rainfall was lost due to infiltration, evaporation and transpiration in cm/h is
(A) 0.8
(B) 0.304
(C) 0.496
(D) Sufficient information is not available

9. The plan area of a reservoir is 1 km^2. The water level in the reservoir is observed to decline by 20 cm in a certian period. During this period the reservoir receives a surface inflow of 10 hectare-metres, and 20 hectare-metres are abstracted from the reservoir for irrigation and power. The pan evaporation and rainfall recorded during the same period at a nearby meteorological station are 12 cm and 3 cm respectively. The calibrated pan factor is 0.7. The seepage loss from the reservoir during this period in hectare-metres is
(A) 0.0 (B) 1.0
(C) 2.4 (D) 4.6

10. The Bowen ratio is defined as
(A) ratio of heat and vapour diffusivities.
(B) proportionality constant between vapour heat flux and sensible heat flux.
(C) ratio of actual evapo-transpiration and potential evapo-transpiration.
(D) proportionality constant between heat energy used up in evaporation and the bulk radiation from a water body.

11. Isopleths are lines on a map through points having equal depth of
(A) rainfall (B) infiltration
(C) evapo-transpiration (D) total run-off

12. The rainfall on 5 successive days in a catchment was 2, 7, 8, 4 and 3 cm. If the ϕ index for the storm is 3 cm/day, the total direct run-off volume generated from a 195 km^2 catchment is
(A) 19.5 Mm^3 (B) 23.4 Mm^3
(C) 15.6 Mm^3 (D) 32.5 Mm^3

13. The vertical hydraulic conductivity of the top soil at certain stage is 0.2 cm/h. A storm of intensity 0.5 cm/h occurs over the soil for an indefinite period. Assuming surface drainage to be adequate, the infiltration rate after storm has lasted for a very long time, shall be
(A) smaller than 0.2 cm/h
(B) 0.2 cm/h
(C) between 0.2 and 0.5 cm/h
(D) 0.5 cm/h

14. A 6 hours rainstorm with hourly intensities of 7, 18, 25, 17, 11 and 3 mm/h produced a run-off of 39 mm. Then, the ϕ-index is
(A) 3 mm/h
(B) 7 mm/h
(C) 8 mm/h
(D) 10 mm/h

15. The parameter in Horton's infiltration equation [$f(t) = f_C + (f_0 - f_C)\, e^{-Kt}$] are given as, f_0 = 7.62 cm/h, f_C = 1.34 cm/h and K = 4.182/hour. For assumed continuous ponding, the cumulative infiltration at the end of 2 hours is
(A) 2.68 cm (B) 1.5 cm
(C) 1.34 cm (D) 4.18 cm

16. The rainfall during three successive 2 hours period are 0.5, 2.8 and 1.6 cm. The surface run-off resulting from this storm is 3.2 cm. The index value of storm is
(A) 0.2 cm/h (B) 0.28 cm/h
(C) 0.3 cm/h (D) 0.8 cm/h

17. During a 3 hours storm event, it was observed that all abstractions other than infiltration are negligible. The rainfall was idealized as 3 one hour storms of intensity 10 mm/h, 20 mm/h and 10 mm/h respectively and the infiltration was idealized as a Horton curve, f = 6.8 + 8.7 exp ($-t$) (f in mm/h and t in hour). What is the effective rainfall?
(A) 10 mm (B) 11.33 mm
(C) 12.42 mm (D) 13.63 mm

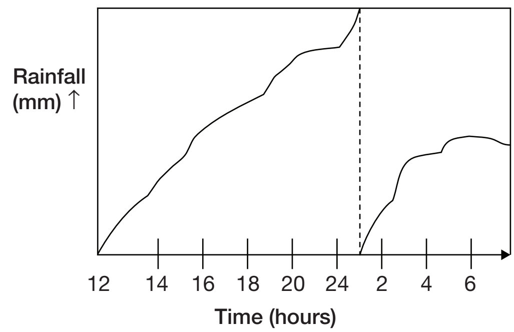
18. Measured infiltration rates, f in cm/h, for every hour from t = 0, when the rainfall just commenced to t = 8 hours are given in the table below. The rainfall lasts over 8 hours. Calculate the total infiltration quantity (in cm) during 8 hours using Horton constant of K = 4 (day^{-1}).

Time (hours)	0	1	2	3	4	5	6	7
f(cm/h)	2	1.1	0.75	0.65	0.55	0.5	0.5	0.5

(A) 4.824 (B) 4.375
(C) 4.543 (D) 4.8

19. The slope of the rainfall mass curve is zero, when it is horizontal. This happens when the intensity for that period is
(A) constant (B) increasing
(C) decreasing (D) zero

20. The following rainfall chart is from which type of rain gauge?



(A) Weighing bucket type
(B) Float type raingauge
(C) Tipping bucket type
(D) Both A and B

21. The average pan coefficient of ISI standard pan is
(A) 0.95 (B) 0.8
(C) 0.7 (D) 0.6

22. Match the parameters in Group A with Group B.

	Group A		Group B
P.	Isonif	**1.**	Line joining points having equal rainfall.
Q.	Isohyte	**2.**	Line joining points having equal snowfall.
R.	Isopleth	**3.**	A line joining points having equal depths of rainfall of particular duration with particular return period.
S.	Isopluvial	**4.**	Line joining points having equal depth of evapo-transpiration

Codes:

	P	Q	R	S		P	Q	R	S
(A)	4	3	2	1	(B)	2	1	4	3
(C)	4	1	3	2	(D)	3	1	4	2

23. The isohyets drawn for a storm which occurred over a drainage basin of area 950 km^2 yielded the following information:

Isohyet Interval in (mm)	95–85	85–75	75–65	65–55
Area between Isohyets in km^2	126	198	224	175

Determine the average depth of rainfall over the basin.
(A) 60.11 mm (B) 68.21 mm
(C) 73.8 mm (D) 80.64 mm

24. Normal annual precipitation of 5 Rain Gauge stations P, Q, R, S, T are 125, 102, 76, 113 and 137 cm. During a particular storm the precipitation recorded by stations P, Q, R, S are 13.2, 9.2, 6.8 and 10.2 cm. Station T was not working. Estimate rainfall during this storm at T.
(A) 10.21 cm (B) 12.86 cm
(C) 13.43 cm (D) 7.89 cm

25. Penmann's equation is based on
(A) energy budgeting only.
(B) energy budgeting and water budgeting.
(C) energy budgeting and mass transfer.
(D) water budgeting and mass transfer.

26. Orographic rain occurs when the air is cooled sufficiently as a result of
(A) lifting due to flow over a mountain barrier.
(B) relative movement of two large air masses.
(C) violent upthrow of air arising from localized heating.
(D) cyclonic conditions.

27. A storm with 14 cm precipitation produced a direct run-off of 8 cm. the time distribution of the storm is as shown in the following table.

Time from Start (h)	Incremental Rainfall in cm
1	1.0
2	2.0
3	2.8
4	3.3
5	2.5
6	1.8
7	0.6

What is the value of ϕ-index of the storm?
(A) 0.5 cm/h (B) 0.7 cm/h
(C) 0.8 cm/h (D) 0.9 cm/h

28. Probability of 10 years flood to occur at least once in the next 4 years is
(A) 25% (B) 35%
(C) 50% (D) 65%

29. Match the following

	List I		List II
a.	Anemometer	**1.**	Humidity
b.	Rain simulator	**2.**	Evapo-transpiration
c.	Lysimeter	**3.**	Infiltration
d.	Hygrometer	**4.**	Wind speed

Codes:

	a	b	c	d		a	b	c	d
(A)	4	3	1	2	(B)	3	4	1	2
(C)	4	3	2	1	(D)	3	4	2	1

30. Common material used as seeds to accelerate the coalescence process in artificial rain making is
(A) silver iodide
(B) ammonium sulphate
(C) potassium chromate
(D) silver nitrate

31. A line on catchment map joining points having equal time of travel of surface run-off is called
(A) isonif
(B) isopluvial
(C) isochrone
(D) isohyet

32. A catchment is in the shape of a hexagon of side 8 km. 6 Rain gauges are installed at each corner and their recorded rainfall are 5 cm, 10 cm, 15 cm, 20 cm, 25 cm, 30 cm. One rain gauge at center recorded rainfall of 40 cm. Find mean precipitation using Theissen polygon method.
(A) 17.5 cm
(B) 20.71 cm
(C) 25 cm
(D) 28 cm

33. An engineer incharge of water has to release water from reservoir for being picked up at a distance of 50 km on D/S side. The average width of stream = 40 m. Mean daily ISI class 'A' pan evaporation for that season is 0.5 m. Estimate mean daily evaporation loss to be considered by engineer in releasing the water in ha-m. (Assume $C_P = 0.8$)
(A) 70
(B) 80
(C) 90
(D) 100

Previous Years' Questions

1. An isolated 4 hours storm occurred over a catchment as follows.

Time	1st hr	2nd hr	3rd hr	4th hr
Rainfall (mm)	9	28	12	7

The ϕ-index of the catchment is 10 mm/h. The estimated run-off depth from the catchment due to above storm is **[GATE, 2007]**
(A) 10 mm (B) 16 mm
(C) 20 mm (D) 23 mm

2. The ratio of actual evapo-transpiration to potential evapo-transpiration is in range of **[GATE, 2012]**
(A) 0 to 0.4 (B) 0.6 to 0.9
(C) 0 to 1 (D) 1 to 2

3. A 1 hour rainfall of 10 cm magnitude at a station has a return period of 50 years. The probability that a

1 hour rainfall of magnitude 10 cm or more will occur in each of two successive years is **[GATE, 2013]**

(A) 0.04 (B) 0.2
(C) 0.2 (D) 0.0004

4. An isohyet is a line joining points of **[GATE, 2013]**

(A) equal temperature.
(B) equal humidity.
(C) equal rainfall depth.
(D) equal evaporation.

Direction for questions 5 and 6:

At a station, Storm I of 5 hours duration with intensity 2 cm/h resulted in a run-off of 4 cm and Storm II of 8 hours duration resulted in a run-off of 8.4 cm. (Assume that ϕ-index is same for both the storms). **[GATE, 2013]**

5. The ϕ-index (in cm/h) is

(A) 1.2 (B) 1.0
(C) 1.6 (D) 1.4

6. The intensity of Storm II (in cm/h) is

(A) 2.0 (B) 1.75
(C) 1.5 (D) 2.25

7. In a catchment, there are four rain-gauge stations, *P, Q, R* and *S*. Normal annual precipitation values at these stations are 780 mm, 850 mm, 920 mm and 980 mm, respectively. In the year 2013, stations *P, Q, R* and *S*, were operative but *P* was not. Using the normal ratio method, the precipitation at station *P* for the year 2013 has been estimated as 860 mm. If the observed precipitation at stations *Q* and *R* for the year 2013 were 930 mm and 1010 mm, respectively, what was the observed precipitation (in mm) at station *S* for that year? **[GATE, 2015]**

8. The average surface area of a reservoir in the month of June is 20 km^2. The same month, the average rate of inflow is 10 m^3/s, outflow rate is 15 m^3/s, monthly rainfall is 10 cm, monthly seepage loss is 1.8 cm and the storage change is 16 million m^3. The evaporation (in cm) is that month is **[GATE, 2015]**

(A) 46.8
(B) 136.0
(C) 13.6
(D) 23.4

Answer Keys

Exercises

1. B	**2.** B	**3.** B	**4.** C	**5.** C	**6.** B	**7.** D	**8.** B	**9.** D	**10.** D
11. C	**12.** A	**13.** B	**14.** C	**15.** D	**16.** C	**17.** D	**18.** B	**19.** D	**20.** B
21. B	**22.** B	**23.** C	**24.** B	**25.** D	**26.** A	**27.** D	**28.** B	**29.** C	**30.** A
31. C	**32.** C	**33.** B							

Previous Years' Questions

1. C	**2.** C	**3.** D	**4.** C	**5.** A	**6.** D	**7.** 1094	**8.** 23.4