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TABLE 3.15. DETERMINATION OF IRRIGATION REQUIREMENTS OF LUDHIANA WHEAT PERIOD OF GROWTH : 3rd NOV. TO 12th MARCH (131 DAYS)

Interval (1)	*No. of days upto mid point of interval* (2)	*% of growing season = col. (2) × 100/131* (3)	*Ep (cm)* (4)	*K* (5)	$C_u = K E_p$ *(cm)* (6)	R_e *(cm)* (7)	$NIR = C_u - R_e$ *(cm)* (8)	$FIR = \frac{NIR}{\eta_a}$ *(cm)* (9)	$GIR = \frac{FIR}{\eta_c}$ *(cm)* (10)
Nov. 3–30	14	11	15.8	0.30	4.7	–	4.7	6.9	8.6
Dec. 1–31	44	33	13.1	0.77	10.1	0.8	9.3	13.7	17.1
Jan. 1–31	75	57	12.8	0.90	11.5	0.6	10.9	16.0	20.0
Feb. 1–29	105	80	15.0	0.76	11.4	–	11.4	16.8	21.0
March 1–12	125	95	16.2	0.58	9.4	–	9.4	13.8	17.3
					Σ = 47.1		Σ = 45.7	Σ = 67.2	Σ = 84.0

Column 1: This denotes the monthly periods of growth.

Column 2: This denotes the number of days up to the mid point of the interval.

Column 3: This denotes the mid-point interval of growth (column 2) expressed as percentage of the total period of growth.

Column 4: This gives the pan evaporation data (E_p) for the various periods of growth of the crop.

Column 5: This gives the pan evaporation coefficient K for different % of growing season. Its values may be taken from available tables (such as Tables 3.13 or 3.14).

Column 6: This gives the monthly values of consumptive use C_u determined from the Eq. $C_u = KE_p$, in cm of water.

Column 7: This gives the data about the effective rainfall (R_e) during various periods.

Column 8: This gives the net irrigation requirement. If no additional water is required for leaching or other operations requiring deep percolation of water, consumptive irrigation requirement (CIR) and net irrigation requirements will be equal. Hence $NIR = C_u - R_e$.

Column 9: This gives the field irrigation requirement, by dividing NIR by water application efficiency. In the Table, η_a has been assumed to be 0.68.

Column 10: This gives the gross irrigation requirement (GIR) by dividing FIR by water conveyance efficiency η_c. In the Table η_c has been assumed to be 0.80.

Example 3.18. *Table below gives the details for a certain crop. Using Blaney-Criddle equation and a crop factor k = 0.75, determine the following (i) consumptive use, (ii) consumptive irrigation requirement, (iii) field irrigation requirement, if water application efficiency is 0.7. The latitude of the place is 30° N.*

Month (1)	*Monthly temp (Av.)°C* (2)	*Monthly % of day time hours of the year* (3)	*Useful Rain fall (cm)* (4)
Nov.	*19.0*	*7.19*	–
Dec.	*16.0*	*7.15*	*1.2*
Jan.	*12.5*	*7.30*	*0.8*
Feb.	*13.0*	*7.03*	–

Solution

The data of column 3 of the Table are taken from the sunshine table (Table 3.9). The monthly temperature and useful rainfall data are average values for the last 10 years. The consumptive use is computed from the Blaney-Criddle equation:

$$C_u = k\,\Sigma f$$

where $f = \frac{p}{40}[1.8\,t + 32]$

Computations are done in the tabular form below :

Month (1)	*t° C* (2)	*p%* (3)	*f* (4)
Nov.	19.0	7.19	11.9
Dec.	16.0	7.15	10.9
Jan.	12.5	7.30	9.9
feb.	13.0	7.03	9.7
			Σf = 42.4

$$C_u = k\Sigma f = 0.75 \times 42.4 = \mathbf{31.8\ cm}$$

$$R_e = 1.2 + 0.8 = 2.0 \text{ cm.}$$

$$\text{CIR} = C_u - R_e = 31.8 - 2.0 = 29.8 \text{ cm.}$$

NIR = CIR (since no water is used for deep percolation)

$$\text{FIR} = \frac{\text{NIR}}{\eta_a} = \frac{29.8}{0.7} = \mathbf{42.6\ cm.}$$

Example 3.19. *Compute the consumptive use of rice for the month of January by using Penman's formula, for the following data available at the field.*

1. *Latitude of place* : *20°N*
2. *Mean monthly temperature* : *15°C*
3. *Relative humidity in January* : *50%*
4. *Elevation of area* : *250 m*
5. *Wind velocity at 2 m height* : *25 km/day*

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Solution

From Table 3.10, we obtain the following for mean temperature $t_m = 15°C$

(*i*) Saturation vapour pressure, $e_s = 12.79$ mm Hg

(*ii*) Slope of the curve between e_s and t_m, $A = 0.80$ mm per °C

From Table 3.11, $R_A = 10.8$ mm of H_2O per day at latitude 20° N, in Jan.

From Table 3.12, $N = 11.1$ h for latitude 20°, in Jan.

From Table 3.9, monthly percentage of day time hours, $n\,(=p) = 7.74$ h for Jan at latitude of 20°N

$$\therefore \quad \frac{n}{N} = \frac{7.74}{11.1} = 0.697$$

$$e_a = e_s \,.\, R_H = 12.79 \times 0.5 = 6.395 \text{ mm Hg}$$

$$E_a = 0.002187\,(160 + u_2)\,(e_s - e_a)$$

$$= 0.002187\,(160 + 25)\,(12.79 - 6.395) = 2.59 \text{ mm/day}$$

Rice is a close crop for which the reflection coefficient r may be taken equal to 0.2. Take $\alpha = 0.49$ mm Hg/°C and $\sigma = 2.01 \times 10^{-9}$ mm/day

Also, T_a = mean air temp. in °K = 273 + 20 = 293°K

$$\therefore \quad H = R_A\,(1 - r)\,(0.29 \cos \varphi + 0.55\, n/N) - \sigma\, T_a^4\,(0.56 - 0.092\sqrt{e_a})\,(0.10 + 0.9\, n/N)$$

$$= 10.8\,(1 - 0.2)\,(0.29 \cos 20° + 0.55 \times 0.697) - 2.01 \times 10^{-9}\,(293)^4 \times (0.56 - 0.092\sqrt{6.395}) \times (0.10 + 0.9 \times 0.697)$$

$$= 5.67 - 3.53 = 2.14 \text{ mm of } H_2O/\text{day}$$

$$\therefore \quad E_t = \frac{A\,H + \alpha\,E_a}{A + \alpha} = \frac{0.8 \times 2.14 + 0.49 \times 2.59}{0.8 + 0.49} = 2.31 \text{ mm/day}$$

$$= 2.31 \times 31 \text{ mm/month} = \mathbf{71.6\ mm} \text{ of water for January}$$

3.15. SOIL FERTILITY

A soil is fertile when it contains :

(*i*) Ample supplies of organic materials.

(*ii*) The source of nitrogen.

(*iii*) Sufficient soluble compounds of the mineral elements needed for the growth of food plants.

The above requirements coupled with satisfactory surface topography, physical properties, subsoil drainage and application of adequate water at proper intervals leads to the production of rich crops.

Maintenance of soil fertility

Soil fertility can maintained by the following :

(*i*) By use of proper cultivation methods.

(*ii*) By spreading all the farmyard manure which supply organic materials as well as fertilising elements.

(*iii*) Planting of different crops in rotation on different areas.

(*iv*) Application of carefully selected commercial fertilizers.

(*v*) Ploughing under or disking-in of crop, plants or native vegitation or green manures adds organic matter and fertilising elements. Deep ploughing is undesirable.

(*vi*) *Stubble-mulch farming* : It is a recently developed method of crop tillage that leaves the stubble and other residues of the preceeding crop on or close to the soil surface to provide a surface mulch. The mulch tends to conserve moisture and soil fertility. It reduces compaction of the surface soil by rainfall, decreases surface run-off and largely prevent soil erosion by wind.

(*vii*) Suitable procedures for reducing or controlling erosions may constitute important role in maintaining soil fertility.

(*viii*) Irrigation with silty water.

(*ix*) Soils of acidic nature may show improvement with the application of calcium oxide to the extent of 1000 kg per hectare. Shortage of lime leads to dark colour of leaves and its excess may lead to their scorching.

3.16. CROP ROTATION

The term rotation of crops is somewhat self explanatory. It implies that nature of the crop sown in a particular field is changed year after year.

Necessity for rotation

The necessity for rotation arises from the fact that soil gradually losses its fertility if the same crop is sown every year and the field has to be allowed to lie fallow in order to regain its fertility. The effect of fallow is obtained by rotation of crops.

All crops require similar type of nutrients for their growth but all of them do not take in the same quantities or proportions; some crop favours certain plant nutrients and take them more than the others. Thus if a particular crop is grown year after year, the soil gets deficient in the plant food favoured by that crop. If different crops are to be raised there would certainly be more balanced fooding and soil deficient in one particular type of nutrient is allowed to recoupe.

Crop diseases and insect pests will multiply at an alarming rate, if the same crop is to be grown continuously. Rotation will check this disease.

A leguminous crop (such as gram) if introduced in rotation will increase nitrogen content of the soil thus increasing its fertility.

There could be deep rooted crops and shallow rooted crops in rotation and so they shall draw their food from different depths of soil. The soil will thus be better utilised. Rotation of crops in the long run is beneficial to the farmer and soil both as there would be a rotation of cash crops, fooder crops and soil renovating crops.

The following rotations have been found useful :

(*i*) Introduction of groundnut in the usual cotton jowar rotation as per the experiments in Central Province, Hyderabad.

(*ii*) In Northern India, cotton is known to have improved when it follows berseen on fields manured with phosphate.

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(*iii*) In Madras, Bajra when rotated with cotton has proved to be superior to Jowar being rotated with cotton.

(*iv*) Cotton gives good result after gram or fallow.

(*v*) Wheat does well after-sugar-cane and gowara.

In general the following rotation of the crops give good results :

1. Wheat–great millet–gram
2. Rice–gram
3. Cotton–wheat–gram
4. Cotton–wheat–sugarcane
5. Cotton–great millet–gram.

The reason for gram being one in various rotation combinations is its being leguminous crop giving nitrogen to the field.

3.17. ASSESSMENT OF IRRIGATION WATER

The water which has been supplied for irrigation to the farmers is at the Government expenses. Some nominal charges must, therfore, be levied on the farmers for using this water. The fixation of such charges is known as *assessment* of irrigation water. The returns on the capital investment is based upon the estimate of such water charges. A knowledge of the same is, therefore, very essential to the engineers.

The charges must be levied on the farmers for the following reasons :

(*i*) To recover the cost of construction of the project by which it has been possible to supply water.

(*ii*) To recover the maintenance cost of the various works and staff for certain improvement.

(*iii*) To collect some revenue for the nation.

(*iv*) To check the cultivators against uneconomical and careless use of water.

Methods of Assessment

There are five methods of assessment :

(*i*) Assessment on area basis or crop rate basis

(*ii*) Volumetric assessment

(*iii*) Assessment on seasonal basis

(*iv*) Composite rate basis

(*v*) Permanent assessment

1. ***Assessment on Area Basis or Crop Rate Basis***

Under this system of assessment of irrigation, area sowing crops is recorded by a 'patrol' both at the time of sowing and maturity. At the end of the crop period a 'demand statement' for each irrigator is prepared. The measurements are checked by various officials including Zilledar, Deputy Collector, Sub-Divisional Officer and the Divisional Canal Officer. Checking of irrigated area is an important part of Canal Officers' duty at all levels upto Divisional Officer. For failure of crops for reasons beyond the control of the irrigator or for shortage of water supply, remission may be given to the farmers.

Special charges are levied in addition to the usual charges under the Canal Act for the following :

(*a*) Unauthorised irrigation comprising use of unanthorised water course.

(*b*) Cuts in channel banks

(*c*) Damaging the oulets

(*d*) Opening outlets at unanuthorised time

(*e*) Irrigation out of sanctioned turn

(*f*) Wasting water.

Special charges may go up 6 times the normal charges.

Almost all the canal irrigated lands in India are assessed for water on the area basis and crop rate basis. The rates for different crop have been fixed on the basis of

(1) Cash value for crop and hence its paying capacity.

(2) Water requirements of the crop.

(3) Time of demand for water *vis-a-vis* the available supplies in a river.

For illustration, the following information for a few principle crops is given (Table 3.16).

TABLE 3.16

S.No.	*Crops*	*Yield in kg/hectare*	*Water rates in Rs./hectare*	
			Punjab	U.P.
1.	Rice	320	Rs. 49	Rs. 79
2.	Sugarcane	1200	Rs. 82	Rs. 149
3.	Cotton	260	Rs. 34	Rs. 30
4.	Wheat	560	Rs. 32	Rs. 30
5.	Maize	560	Rs. 32	Rs. 22

The system of assessment on the basis of area has a number of disadvantages, notably amongst them are as follows :

1. The cultivators near the head reaches of the canal use more water and deprive the area near the tail, of their required share of water.

2. Since the charges are not levied on the basis of actual quantity of water used, cultivators make a wasteful use of water.

2. ***Volumetric Assessment***

The method involves levying charges on actual volume of water supplied. This will be an ideal system under which the irrigator has an incentive for economic use of water and shortfalls in supplies can be distinctly located. It is, however, not a very practical method for India due to the necessity of installation of numerous water meters on irrigation outlets scattered all over the channel and difficult to maintain, besides a heavy initial cost.

In addition to the cost, the method has the following short comings :

1. A whole time staff is needed to keep records of the meters.
2. The meters may not work on small heads at the outlet.
3. Silt and debris may obstruct the flow through the metered oultlet.

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4. The cultivators may pilfer water by unauthorised methods.

5. The internal distribution of volumetric supplies and apportionment of dues between petty shareholders may be difficult.

The only possible place for such assessment is tube-well, where water is sold out on a volumetric basis by litres per rupee or by units rate of electric power consumed, as a tube well operator is there to keep the full record. The only other feasible proposal is to sell out water on volumetric basis to co-operative societies or panchayats of irrigation who should be responsible both for internal distribution as well as collection and payment of canal dues for the same.

3. ***Assessment on Seasonal Basis***

In this method the rate of assessment is based on the type of crop grown in a particular tract during certain crop season. This method is not in vogue in India.

4. ***Composite Rate Basis***

Composite rate is a combination of water charges and the land revenue. Some states prefer to collect both the revenues together and hence the name.

5. ***Permanent Assessment or Betterment Levy Basis***

The cultivators in a particular area may have their own source of water supply under ordinary conditions and may not use water from a canal which has been aligned in that area only to protect it in drought period. The farmers of that area are levied at a fixed rate every year due to such provisions. Such a levy is known as *betterment levy*. During the draught periods, the farmer will be authorised to use water from such a canal without paying extra charges above the betterment levy.

Internal Distribution of Water

Internal distribution of water is carried out on a 'wara bandi' system fixed by the Divisional Canal Officer. Under this system each shareholder is given his turn in hours according to the area, out of seven days in a week. In the absence of 'wara bandi', the distribution is done by cultivators themselves.

Efficiency of Distribution

In arid and fertile areas, the value of canal water is really great and efficiency of equitable distribution has to be ensured both in the interest of irrigation as well as for economical and efficient use of water. The main disturbing factor in the equitable distribution is the upsetting of channel regime by silting, which has to be specially set right by remodelling. The efficiency of the actual performance of the water utilisation on outlets is kept under constant watch by the following methods :

1. Watching the gauges and noting changes in levels, if any by silting and over-drawing.
2. Actual discharge observation of the non-modular outlets by portable flumes.
3. Watching monthly data calculations or depth of water utilised per hectare for the channel and final crop delta as compared to previous figures.
4. By plotting efficiency diagrams for the outlets on a channel showing authorised and actual irrigation percentages which bring prominently to notice shortfalls and excess and the urgency of the steps to be taken for rectification of defects. Shortfalls may be due to main distribution requiring rectification by remodelling.

5. In the absence of a dependable metering head of the channel its percentage of the normal discharge table must be checked every month and at a few more sites along the length for a channel.

3.18. EXAMPLES FROM COMPETITIVE EXAMINATIONS

Example 3.20. *Wheat is to be grown in field having a field capacity equal to 27% and the permanent wilting point is 13%. Find the storage capacity in 80 cm depth of soil, if the dry unit weight of the soil is 1.5 g/cc. If the irrigation water is to be supplied when the average soil moisture falls to 18%, find the water depth required to be supplied to field if the field application efficiency is 80%. What is the amount of water needed at the canal out let if the water lost in the water course and the field channel is 15% of the out let discharge ?* ***(Civil Services Exam. 1980)***

Solution

(*a*) Maximum storage capacity = available moisture

$$= \frac{\gamma_d \cdot d}{\gamma_w}[F_c - w_c] = \frac{1.5 \times 80}{1}[0.27 - 0.13] = \mathbf{16.8\ cm}$$

(*b*) Depth of irrigation water $\frac{\gamma_d \cdot d}{\gamma_w}[F_c - m_0] = \frac{1.5 \times 80}{1}[0.27 - 0.18] = \mathbf{10.8\ cm}$

(*c*) Field irrigation requirement $= \frac{10.8}{0.8} = \mathbf{13.5\ cm}$

(*d*) Amount of water needed at the canal outlet $= \frac{13.5}{0.85} \simeq \mathbf{15.9\ cm}$

Example 3.21. *A canal takes off a reservoir to irrigate the areas as shown in the Table. 40% of the water required for irrigation is assumed to be available directly from precipitation. Channel conveyance losses are 15%. Reservoir losses are 10%. What would be the capacity of the reservoir needed ? (The reservoirs to be filled only once a year).*

Crop	Base period (days)	Duty at the field (ha/cumec)	Area under crop (ha)
Wheat	120	1800	500
Sugarcane	320	800	600
Rice	120	900	300
Cotton	200	1400	1200
Bajra	100	1200	500

(Civil Services Exam. 1980)

Solution : The required computations are done in a tabular form below.

Crop	Base period B (days)	Duty at field (D) ha/cumec	$\Delta = 8.64\frac{B}{D}$ (m)	Area A (ha)	Volume = Δ × A ha-m
(1)	(2)	(3)	(4)	(5)	(6) = (4) × (5)
Wheat	120	1800	0.576	500	288.0
Sugarcane	320	800	3.456	600	2073.6
Rice	120	900	1.152	300	345.6
Cotton	200	1400	1.234	1200	1481.1
Bajra	100	1200	0.72	500	360.0
				ΣV	= 4548.3

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However, 40% of the required water is available from precipitation.

$\therefore$ Capacity of reservoir $= \dfrac{0.6 \times 4548.3}{0.85 \times 0.9} \simeq$ **3568 ha-m**

Example 3.22. *The gross commanded area for a distributory is 10000 hectares, 75% of which can be irrigated. The intensity of irrigation for Rabi season is 60% and that for Kharif season is 30%. If the average duty at the head of the distributory is 2500 hectares per cumec for Rabi season and 1000 hectares per cumec for Kharif season, determine the discharge required at the head of the distributory from average demand consideration.* ***(Civil Services Exam. 1988)***

Solution

Gross commanded area = 10000 hectares

Culturable commanded area = 0.75 × 10000 = 7500 hectares.

Area under irrigation in Rabi season = 7500 × 0.6 = 4500 hectares

Area under irrigation in Kharif season = 7500 × 0.3 = 2250 hectares.

$\therefore$ Discharge for Rabi $= \dfrac{4500}{2500} = 1.8$ cumec

Discharge for Kharif $= \dfrac{2250}{1000} = 2.25$ cumec.

$\therefore$ Required discharge at the head of distributory = **2.25 cumecs**

Example 3.23. *Work out the irrigation schedule based on the soil moisture concept, given the following information. Also extract the data on the total depth of irrigation water required and the respective dates of irrigation water supply.*

(a) *The crop is grown in a appropriate soil with no restrictive layers within the top 1.5 m depth of soil.*

(b) *Normal root zone depth of the crop is 1.2 m*

(c) *Bulk density of soil is 1.35*

(d) *Field capacity is 18% and permanent wilting point is 7%.*

(e) *Moisture level in the soil is be maintained at not less than one third of available retention. Irrigation will then be done over a duration of 2 days at a uniform rate of supply and at a uniform rate of advance to fully and just compensate for the depletion.*

(f) *No extra water is ever required for leaching.*

(g) *Sowing is done on 1 November when the soil moisture is left just at field capacity in the entire root zone.*

(h) *For the crop, at the location, the average evapo-transpiration rates are :*

1 Nov – 30 Nov.	*: 1.1 mm/day*
1 Dec. – 31 Dec.	*: 1.7 mm/day*
1 Jan. – 31 Jan.	*: 2.4 mm/day*
1 Feb – 28 Feb.	*: 1.5 mm/day*
1 March – 25 March	*: 3.5 mm/day*

(i) *Harvesting is done on or after 26 March.*

(j) *There is expected an effective rainfall of 24 mm during 4 January and 19 January, both days inclusive, with uniform intensity.*

(k) *By the end of the crop growth season, only the minimum water needed to be left unused in the root zone.* ***(Engg. services Exam. 1990)***

Solution

Field capacity, $F_c = 18\%$

Wilting coefficient, $w_c = 7\%$

$\therefore$ Available moisture = 18 – 7 = 11%

$\therefore$ $m_0 = w_c + \dfrac{1}{3}$ available moisture $= 7 + \dfrac{1}{3} \times 11 = 10.67\%$

$\therefore$ $d_w = \dfrac{\gamma_d \cdot d}{\gamma_w}[F_c - m_0] = S_g \cdot d\,[F_c - m_0]$

Note that in the above question, bulk density has been erroneously given as 1.35. Actually, it is the *apparent density* or apparent specific gravity S_g.

$\therefore$ $d_w = 1.35 \times 1.2\,[0.18 - 0.1067] \simeq 0.1187$ m = **11.87 cm**

Hence irrigation water will be supplied as and when this 11.87 cm depth of stored moisture gets consumed by evapo-transpiration.

(a) Irrigation requirements from 1 Nov. to 3 Jan. (when rains start)

Depth of water consumed by evapo-transpiration during this period

= 1.1 × 30 (i.e. between 1 Nov. – 30 Nov.) + 1.7 × 31 (i.e. between 1 Dec–31 Dec.)

+ 2.4 × 3 (i.e. between 1 Jan – 3 Jan) = 92.9 mm = 9.29 cm ...(i)

This is less than d_w = 11.87 cm. *Hence no irrigation water is required during this period.*

(b) Irrigation requirements after 3rd Jan.

Rainfall intensity between 4 Jan to 19 Jan. $= \dfrac{24}{16} = 1.5$ mm/day.

Consumptive use during this period = 2.4 mm/day.

$\therefore$ Amount of water consumed from soil during this period of 4 Jan. to 19 Jan. (16 days)

= (2.4 – 1.5) × 16 = 14.4 mm = 1.44 cm ...(ii)

Hence total water withdrawn from soil from 1 Nov. to 19 Jan.

= 9.29 + 1.44 = 10.73 cm

$\therefore$ Balance left in soil, to be used by crop before next irrigation.

= 11.87 – 10.73 = 1.14 cm = 11.4 mm.

Rate of evapo-transpiration for the remaining period in Jan = 2.4 mm/day

Hence the above water is consumed in 11.4/2.4 = 4.75 day $\simeq$ 4 days (say)

Hence next irrigation will be needed after 4 days of stoppage of rainfall, i.e. on 24th Jan.

The irrigation water is supplied for 2 days (i.e. for 24th and 25th Jan). Hence *depth of water required in the first irrigation* = 10.73 + 4 × 0.24 + 2 × 0.24 = **12.17 cm**

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(c) ***Irrigation requirements from 26 Jan. to 25 March***

Water consumed between 26 Jan – 31 Jan. $= 2.4 \times 6 = 14.4$ mm

Water consumed between 1 Feb – 28 Feb. $= 1.5 \times 28 = 42.0$ mm

Water consumed between 1 March – 25 March $= 3.5 \times 25 = 87.5$ mm

Total 143.9 mm

This is greater than $d_w = 118.7$ mm

Hence next water supply is started after x days of March, where

$$x = \frac{118.7 - (14.4 + 42)}{3.5} = 17.8 \text{ days (i.e. 17 days)}$$

Hence second irrigation is required on 18th March.

Required water depth $= 143.9 - 118.7 = \mathbf{25.2\ mm}$

Hence the irrigation schedule is as follows.

(*i*) First watering on 29 and 30 Jan $= \mathbf{12.17\ cm}$

(*ii*) Second watering on 18th March $= \mathbf{2.52\ cm}$

Example 3.24. *A certain crop is grown in an area of 3000 hectares which is fed by a canal system. The data pertaining to irrigation are as follows :*

Field capacity of soil $= 26\%$

Optimum moisture $= 12\%$

Permanent wilting point $= 10\%$

Effective depth of root zone $= 80$ cm

Relative density of soil $= 1.4$

If the frequency of irrigation is 10 days and the overall efficiency is 23%, find (i) the daily consumptive use (ii) The water discharge in m^3/sec. required in the canal feeding the area. ***(Civil Services Exam. 1990)***

Solution

$$d_w = S_g \cdot d\,[F_c - m_0] = 1.4 \times 80\,[0.26 - 0.12] = 15.68 \text{ cm}$$

Frequency of irrigation = 10 days.

$$\therefore \text{ Daily consumptive use} = \frac{15.68}{10} = 1.568 \text{ cm} = \mathbf{15.68\ mm}$$

$$\text{Total water required in 10 days} = A \times d_w = 3000 \times 10^4 \times \frac{15.68}{100} = 4704000 \text{ m}^3$$

$$\therefore \text{ Discharge in the canal} = \frac{4704000}{10 \times 24 \times 3600} \simeq \mathbf{5.45\ cumecs}$$

Example 3.25. *The consumptive use requirements of a crop are 0.2 cm per day for days 1 to 15, 0.3 cm per day for days 16 to 40 ; 0.5 cm/day for days 41 to 50 and 0.1 cm/day for days 51 to 55. Effective rainfall of 3.5 cm, distributed uniformly during the 36th and 45th days (both inclusive) is predicted. Compute the total quantity of water (in cu. m) to be delivered to a 50 hectares plot for the whole crop season with a pre-sowing requirement of 5 cm of water.* ***(Gate 1991)***

Solution : ***Water requirements per hectare:***

(*i*) 1 to 15 days i.e. 15 days @ 0.2 cm/day $= \frac{15 \times 0.2}{100} \times 10^4 = 300 \text{ m}^3$

(*ii*) 16 to 40 days i.e. 25 days @ 0.3 cm/day $= \frac{25 \times 0.3}{100} \times 10^4 = 750 \text{ m}^3$

(*iii*) 41 to 50 days i.e. 10 days @ 0.5 cm/day $= \frac{10 \times 0.5}{100} \times 10^4 = 500 \text{ m}^3$

(*iv*) 51 to 55 days i.e. 5 days @ 0.1 cm/day $= \frac{5 \times 0.1}{100} \times 10^4 = 50 \text{ m}^3$

Pre-sowing requirement $= \frac{5}{100} \times 10^4 = 500 \text{ m}^3$

Total $= 2100 \text{ m}^3$

Effective rainfall / hectare during 36th and 45th day (i.e. 10 days)

$$= \frac{3.5}{100} \times 10^4 = 350 \text{ m}^3$$

Net water quantity to be delivered per hectare $= 2100 - 350 = 1750 \text{ m}^3$

$\therefore$ Quantity for water to be delivered for 50 hectares

$$= 50 \times 1750 = \mathbf{87500\ m^3}$$

Example 3.26. *The following data pertains to the healthy growth of a crop.*

(*i*) *Field capacity of soil* $= 30\%$

(*ii*) *Permanent wilting percentage* $= 11\%$

(*iii*) *Density of soil* $= 1300\ kg/m^3$

(*iv*) *Effective depth of root zone* $= 700$ *mm*

(*v*) *Daily consumptive use of water for the given crop* $= 12$ *mm*

For healthy growth moisture content must not fall below 25% of the water holding capacity between the field capacity and the permanent wilting point. Determine the watering interval in days. ***(Engg. Services Exam. 1992)***

Solution

Water holding capacity above wilting point $= F_c - w_c = 30 - 11 = 19\%$

$\therefore$ Optimum moisture $m_0 = 30 - 0.75 \times 19 = 15.75\%$

$$\therefore \quad d_w = \frac{\gamma_d \cdot d}{\gamma_w}\,[F_c - m_0] = \frac{1300}{1000} \times 700\,[0.30 - 0.1575] = 129.68 \text{ mm}$$

Daily consumptive use = 12 mm

$$\therefore \quad \text{Watering interval} = \frac{129.68}{12} = 10.80 \simeq \mathbf{10\ days}$$

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Example 3.27. *A water course commands an irrigated area 1000 hectares. The intensity of irrigation of rice in this area is 70%. The transplantation of rice, crop takes 15 days and during transplantation period, total depth of water required by the crop on the field is 500 mm. During the transplantation period, the useful rain falling on the field is 120 mm. Find the duty of irrigation water for crop on the field during transplantation at the head of the field and also at the head of the water course, assuming loss of water to be 20% in the water course. Also, calculate the discharge required in the water course.* ***(Engg. services Exam. 1993)***

Solution : Area under irrigation = 1000 × 0.7 = 700 hectares

Effective depth of water required during transplantation period

$$= 500 - 120 = 380 \text{ mm} = 0.38 \text{ m}$$

$$\therefore \text{ Duty of water at the field} = \frac{8.64\ b}{\delta} = 8.64 \times \frac{15}{0.38} = \mathbf{341\ hec/cumec.}$$

$$\text{Duty at the head of water course} = 341 \times \frac{80}{100} = 272.8 \text{ hec/cumec}$$

$$\text{Discharge required in water, course} = \frac{700}{272.8} \simeq \mathbf{2.57\ cumecs}$$

Example 3.28. *The base period, intensity of irrigation and duty of water for various crops under the canal system are given. Determine the reservoir capacity if the culturable commands area is 4000 hectares, canal losses are 25% and reservoir losses are 15%.*

Crop	Base period (days)	Duty at field (hec/cumec)	Intensity of irrigation
Wheat	120	1800	20%
Sugar cane	360	1700	20%
Cotton	180	1400	10%
Rice	120	800	15%
Vegetable	120	700	15%

(Engg. Services Exam. 1994)

Solution: The computations are done in the Tabular form below. Note that Quantity of water $= Q$ (in cumecs) × B (days) $= 8.64 \times 10^4\ QB\ \text{m}^3$.

Crop	Base period (days)	Intensity of irrigation	Area under crop (hectares)	Duty (ha/cumec)	Discharge required (cumecs)	Quantity of water (m^3)
(1)	(2)	(3)	(4)	(5)	(6) = (4)/(5)	(7)= $8.64 \times 10^4 \times$ (6) × (2)
Wheat	120	20	8000	1800	4.444	46.08×10^6
Sugar cane	360	20	8000	1700	4.706	146.38×10^6
Cotton	180	10	4000	1400	2.857	44.43×10^6
Rice	120	15	6000	800	7.5	77.76×10^6
Vegetable	120	15	6000	700	8.571	88.87×10^6
					Total	403.52×10^6

$$\therefore \text{ Volume of required at head of canal} = \frac{403.52 \times 10^6}{0.75} = 538.03 \times 10^6\ \text{m}^3$$

$$\therefore \quad \text{Storage capacity} = \frac{538.03 \times 10^6}{0.85} \simeq \mathbf{633 \times 10^6\ m^3}$$

PROBLEMS

1. Discuss in brief the functions of irrigation water. What are the standards of irrigation water ?

2. Describe with the help of a diagram various forms of a soil moisture. What do you understand by the available moisture ?

3. Write notes on the following :

(*i*) Saturation capacity, (*ii*) Field capacity, (*iii*) Wilting point, (*iv*) Optimum water.

4. What do you understand by evapo-transpiration ? How is it determined ?

5. Explain the terms 'duty' and 'delta'. Derive a relationship between the two.

6. What are the factors affecting duty ? How can duty be improved ?

7. Define the following :

G.C.A., C.C.A., Kor depth, Kor period, outlet factor, capacity factor, nominal duty, open discharge, Rabi and Kharif crops.

8. What do you understand by crop rotation ? What are its advantages ?

9. Discuss various methods of assessment of irrigation water.

10. A field channel has culturable commanded area of 2000 hectares. The intensity of irrigation for gram is 30 % and for wheat is 50 %. Gram has a kor period of 18 days and kor depth of 12 cm, while wheat has a kor period of 15 days and a kor depth of 15 cm. Calculate the discharge of the field channel.

[**Ans.** 1.624 cumecs]

11. The discharge available from a tube-well is 120 m^3/hour. Assuming 3200 hours of working for a tube-well in a year, estimate the culturable area that this tube-well can command. The intensity of irrigation is 50 % and the average depth of Rabi and Kharif crops is 48 cm.

[**Ans.** 160 hectares]

12. A water course command an irrigated area of 800 hectares. The intensity of irrigation of rice in this area is 50 %. The transplantation of rice crop takes 15 days and total depth of water required by the crop is 60 cm on the field during the transplantation period, given that the rain falling on the field during this period is 15 cm. Find the duty of irrigation water for the crop on the field during transplantation, at the head of the distributory, assuming losses of water to be 20 % in the water course. Also calculate the discharge required in the water course.

[**Ans.** (*i*) 217 hec/cumec on the field.
(*ii*) 172.8 hec/cumec on the head of W.C.
(*iii*) Q=2.32 cumecs]

13. The left canal of a tank irrigation scheme carries a discharge of 10 cumecs and has a culturable commanded area of 800 hectares. The intensity of Rabi crop is 70 %

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and the base period is 110 days. The right canal of the scheme carries a dicharge of 24 cumecs and has a culturable commanded area of 15000 hectares. The intensity of Rabi crop is 80 % and the base period is 110 days. Compare the efficiency of the two canal systems.

[**Ans.** Left canal more efficient]

14. What do you understand by the following terms :
Crop ratio, overlap allowance, capacity factor and full supply coefficient.

SECTION-II

WATER RESOURCES ENGINEERING

Chapters :

4. HYDROLOGY
5. GROUND WATER : WELL IRRIGATION
6. RESERVOIR PLANNING
7. DAMS-I : GENERAL
8. DAMS-II : GRAVITY DAMS
9. DAMS-III : ARCH AND BUTTRESS DAMS
10. DAMS-IV : EARTH AND ROCKFILL DAMS
11. DAMS-V : SPILLWAYS
12. DIVERSION HEADWORKS

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4

Hydrology

4.1. HISTORY OF HYDROLOGY

Water is the prime necessity for all forms of life. Human civilisation has progressed from early era with utilisation of available water resources. Civilisation flourished wherever water was available, and it collapsed wherever water resources depleted. It is learnt from Vedic literature that ground water was abundantly utilised for use. Archaeological excavations at Mohan Jodaro reveal that people of Indus Valley (3000 B.C.) had good knowledge of ground water development through wells. Later, surface water resources available through rivers, lakes, ponds were developed. People of Vedic period had knowledge of the hydrologic cycle. As more and more water was needed, people learnt the principles of hydrology by experience and consequently, reservoirs were built to store rain water for use in the periods of dry season. Chanakya (300 B.C.) described the use of raingauge in his book *'Arthashastra'*. Apart from Indus Valley, people of Nile Valley also had the knowledge of hydrology. A.K.Biswas in his book *'History of Hydrology'* describes these developments in a greater detail. According to him : *"It is interesting to know that the river Nile was dammed in 300 B.C. to divert its water in near by land. Around the same time a method was devised to record the fluctuations in the river Nile. A well developed water supply and drainage system existed in Indus Valley during 2750 B.C"*. Varahamihira's 'Brihatsamhita' (505-587 A.D) contains the descriptions of raingauges, wind vane and procedures for prediction of rainfall.

The Europeans started using the knowledge of hydrologic cycle much later—some time around 1500 A.D. Chow in his book 'Hand Book of Applied Hydrology (1964) classifies the history of hydrology into the following eight periods :

1. Prior to 1400 AD : Period of *speculation*
2. 1400 to 1600 : Period of *observation*
3. 1600 to 1700 : Period of *measurement*
4. 1700 — 1800 : Period of *experimentation*
5. 1800 — 1900 : Period of *modernization*
6. 1900 — 1930 : Period of *empiricism*
7. 1930 — 1950 : Period of *rationalisation.*
8. 1950 — todate : Period of *theorization*

In India, the period of empiricism may be taken to have started some time in the middle of nineteenth century and continued upto first quarter of twentieth century,

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During this period, development of empirical formulae, tables and curves took place through investigators like Binnie, Barlow, Beale and Whiting, Strange, Ryves, Dickens, Inglis, Lacey, Nawab Jung Bahadur, Kanwar Sain etc.

4.2. THE HYDROLOGIC CYCLE

An irrigation engineer is not only concerned with the collection and distribution of water for irrigation, but it is also essential for him to know about the occurrence, distribution and movement of water on the earth. *Hydrology* is the science which deals with the occurrence, distribution and movement of water on the earth, including that in the atmosphere and below the surface of the earth. Water occurs in the atmosphere in the form of vapour, on the surface as water, snow or ice and below the surface as ground water occupying all the voids within a geologic stratum.

Except for the deep ground water, the total water supply of earth is in constant circulation from earth to atmosphere, and back to the earth. The earth's water circulatory system is known as the *hydrologic cycle*. Hydrologic cycle is the process of transfer of moisture from the atmosphere to the earth in the form of precipitation, conveyance of the precipitated water by streams and rivers to ocean and lakes etc., and evaporation of water back to the atmosphere. Fig. 4.1 illustrates, diagrammatically, the complete hydrologic cycle.

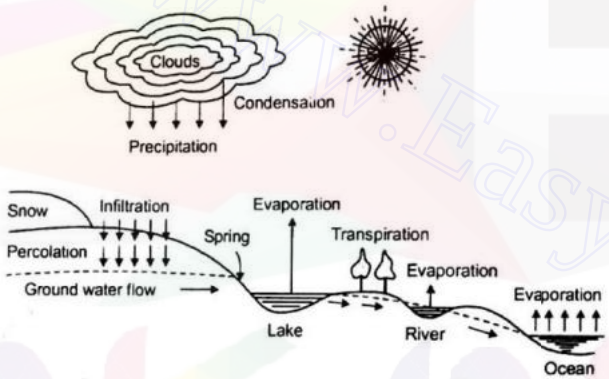

FIG. 4.1 THE HYDROLOGIC CYCLE.

The hydrologic cycle consists of the following processes :

1. **Evaporation and Transpiration (*E*)**

The water from the surfaces of ocean, rivers, lakes and also from the moist soil evaporates. The vapours are carried over the land by air in the form of clouds. *Transpiration* is the process of water being lost from the leaves of the plants from their pores. Thus, the total evaporation (*E*), inclusive of the transpiration consists of:

(*i*) Surface evaporation,
(*ii*) Water surface evaporation: (*a*) From river surface; (*b*) From oceans,
(*iii*) Evaporation from plants and leaves (transpiration), and
(*iv*) Atmospheric evaporation.

2. **Precipitation (*P*)**

Precipitation may be defined as the fall of moisture from the atmosphere to the earth surface in any form. Precipitation may be two forms :

(*a*) *Liquid precipitation* : *i.e.* rainall.

(*b*) *Frozen precipitation* : This consists of :
(*i*) Snow (*ii*) Hail
(*iii*) Sleet (*iv* Freezing rain

3. **Run Off (*R*)**

Run off is that portion of precipitation that is not evaproated. When moisture falls to the earth's surface as precipitation, a part of it is evaporated from the water surface, soil and vegetation and through transpiration by plants, and the remainder precipitation is available as run off which ultimately runs to the ocean through surface or sub-surface streams. Thus run off may be classified as follows :

(1) ***Surface run off.*** Water flows over the land and is first to reach the streams and rivers, which ultimately discharge the water to the sea.

(2) ***Inter-flow or sub-surface run off.*** A portion of precipitation infiltrates into surface soil and depending upon the geology of the basins, runs as sub-surface runoff and reaches the streams and rivers.

(3) ***Ground water flow or base flow.*** It is that portion of precipitation, which after infiltration, percolates down and joins the ground water reservoir which is ultimately connected to the ocean.

Thus, the hydrologic cycle may be expressed by the following simplified equation:

$$\text{PRECIPITATION} = \text{EVAPORATION} + \text{RUN OFF}$$
$$(P) = (E) + (R)$$

provided adjustment is made for the moisture held in storage at the beginning and at the end of the period.

4.3. METEOROLOGICAL DATA :

The hydrology of a place depends upon (*i*) climate (*ii*) topography and (*iii*) geology. *Climatic factors* of importance are :

(*a*) Precipitation and its mode of occurrence
(*b*) Humidity (*c*) Temperature
(*d*) Radiation (*e*) Wind velocity

The *climate* is largly dependent on the geographical position of the place on earth's surface. *Topography* is important in its effect on precipitation and the occurrence of lakes, marshland and high and low rates of runoff. *Geology* of a place influnces its topography, and it also affects the ground water zone.

HUMIDITY

Humidity is the state of the atmosphere in relation to the amount of water vapour it contains. Air easily absorbs moisture in the form of *water vapour*. The amount of moisture absorbed depends on the temperature – the higher the temperature, the more vapour the air can hold as shown in Fig. 4.2. Water vapour present in the atmosphere is very important to the hydrologist since the atmospheric water is the source of precipitation and it materially controls the rate of evaporation from land and water surfaces. The water vapour exerts a *partial pressure* (known as vapour pressure) which is usually measured in either *bars* (1 bar $=100\ \text{kN/m}^2$, 1 millibar $= 10^2\ \text{N/m}^2$) or mm height of column of mercury (1 mm Hg $= 1.33$ millibar)

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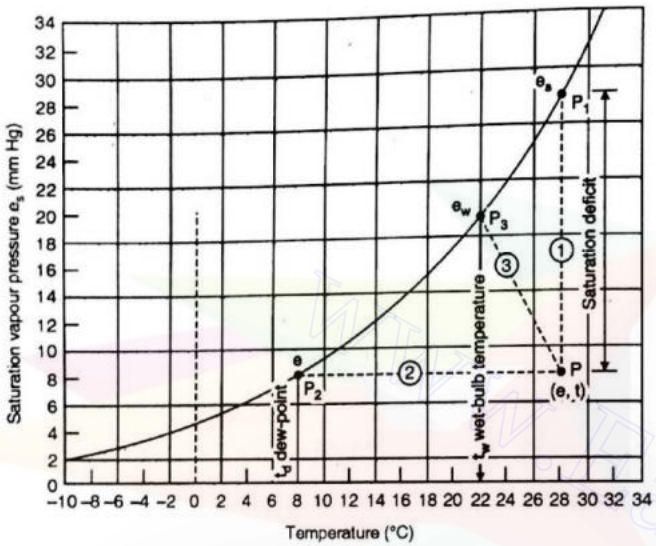

FIG. 4.2. SATURATION VAPOUR PRESSURE OF WATER IN AIR

When an evaporating surface of water is enveloped in air and subject to heat energy, evaporation of the water into the air will take place until a state of equilibrium is reached when air gets saturated with vapour and it no lager can absorb more vapour. At that time, for the particular temperature of the system, the vapour pressure is known as *saturation vapour pressure* (e_s). The variation of e_s with temperature (t) is shown in Fig. 4.2. Let us now consider a mass of atmospheric air, represented by point P, having temperature t and vapour pressure e. If P lies below the $e_s - t$ curve, the air mass can absorb more water vapour. If this happens under a constant temperature (t), then P will move vertically up to a position P_1 until air gets saturated. The increase ($e_s - e$) is known as *saturation deficit*. Alternatively, if change of humidity took place while it was cooled, point P will move to position P_2 till it gets saturated. This temperature (t_d) of P at its new position P_2 is known as *dew point*. If water is allowed to evaporate freely, neither of the above two would happen, and point P will move to P_3, whereby its humidity and vapour pressure will rise but its temperature will fall, since evaporation requires heat which will be drawn from air itself. This heat is known as *latent heat of evaporation*. At P_3, the saturation vapour pressure is known as e_w and temperature (t_w) is known as *wet-bulb temperature*.

Relative humidity (h) is a measure of air's capacity, at its existing temperature, to absorb further moisture, and is defined by the relation :

$$h = \frac{e}{e_s} \times 100 \qquad ...(4.1)$$

The value of e for air temperature t can be obtained from the relation :

$$(e_w - e) = \gamma (t - t_w) \qquad ...(4.2)$$

where t_w = wet bulb temperature
t = dry bulb temperature
e_w = corresponding partial pressure at t_w
γ = psychrometer constant.

TEMPERATURE

Air temperature is recorded by thermometers housed in open louvered boxes kept about 1.25 m above ground. The temperature *decreases* at an average rate of 6.5° C per 1000 m increase in altitude within the troposphere, but is relatively constant in the lower part of stratosphere. Temperature is measured in degrees Celsius, commonly, though erroneously called Centigrade.

Lapse rate : The rate of change of temperature in the atmosphere with height is called *lapse rate.*

Inversion : It is the negative lapse rate, where by, temperature increases with altitude. This is possible on clear nights, when the cooling of the earth, by onward radiation, can be such that a *temperature inversion* occurs, with warmer air overlying the surface layer.

Normal daily temperature : This is taken as average daily mean temperature for a given data for a specific 30-year period.

Mean daily temperature : Many temperature observations are made using *maximum* and *minimum thermometers*. These record, by indices, the maximum and minimum temperature experienced since the instrument was last set. The *mean daily temperature* is the average of maximum and minimum and is normally within a degree of the true average as continuously recorded.

Degree day : *The degree* day is a departure of one degree for one day in the mean daily temperature from a specified base temperature.

Dew point (t_d) : It is defined as the temperature at which the air mass just becomes saturated if cooled at constant pressure with moisture neither added nor removed.

RADIATION

Sun's radiation reaching the earth's surface is the main source of energy input, which is responsible for the change of state of molecules of water from liquid to gas. Most meteorological recording stations are equipped with *radiometers* to measure both the incoming *short wave radiation* as well as *net radiation*. Net radiation is the algebraic radiation of all incoming radiation and the *reflected* short wave and long wave radiation from the earth's surface. The net radiation is important for evaporation studies. The values of mid-monthly intensity of solar radiation on horizontal surface in mm of water evaporation per day are given in Table 3.11.

WIND

Winds are one of the major factors that affect the climate of a place. The wind speed is measured by *anemometer* while the wind direction is measured by *wind vane*. A *cup anemometer* may consist of three or four cups rotating about a vertical axis.

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METEOROLOGICAL OBSERVATION ARRAY : Now-a-days, a *meteorological observation array* available in the form of a *compact instrument* for making meteorological observations at regular, short time interval. It consists of the following :

(1) On left lower arm : Instrument for measurement of net radiation.
(2) On right lower arm : wet and dry bulb thermometers
(3) On left lower : wind direction
(4) On right upper arm : wind run
(5) On top : solar and sky radiation
(6) In the middle distance a raingauge with anti-splash screen.

These instruments record automatically on magnetic tape, the various hydrological data collected by the array.

4.4. HYDROLOGICAL DATA

We have seen in § 4.2 that the main components of the hydrologic cycle are (*i*) precipitation (*ii*) evaporation, including transpiration, and (*iii*) runoff, including direct runoff, infiltration, deep percolation and ground water runoff (effluent stream). Apart from information about the above components, information about climate, meteorology and geology is also required. The following *hydrological data* are required :

1. ***Weather and climate records*** : Data about temperature, humidity, radiation, wind etc, since these directly affect hydrological parameters.

2. ***Precipitation data*** : The study of precipitation forms a major portion of the subject of hydro-meteorology. The precipitation data helps in predicting runoff volume and its peak. It is also helpful in estimating the *water-budget-equation* for the basin. It gives indication to the further potential for expansion of water needs and plan accordingly.

3. ***Stream flow data*** : This helps in the plannig of reservoirs, design of spillways, bridges, culverts, levees, and water power development and installation. The data is utilized for determination of maximum (peak) flood, flood magnitude, flood frequency, reservoir elevations, water budget etc.

4. ***Evaporation and transpiration data*** : This data is required for determining (*i*) water budget for the river basin, (*ii*) reservoir capacity for water resources development and (*iii*) evaporation supression technique.

5. ***Infiltration characteristics of the area*** : This data helps in determining rainfall excess and run off computation.

6. ***Ground water characteristics*** : This helps in estimation and location of ground water reservoir, for ground water development.

7. ***Physical and Geological characteristics*** : This helps in the determination of runoff pattern and silt load movement. *Indian Meteorological Department* (IMD) is largely responsible for the collection for meteorological data, along with some State Government agencies. The Central Water Commission (CWC) moniters the stream flow data of major rivers.

4.5. THE WATER BUDGET

(*a*) **Global Water Budget** : Water is the most important natural resource which is vital for all forms of life on the earth. Water is a crucial element in development

planning. The total quantity of water in the World is roughly 1360 million cubic kilometers (M km^3; 1 M km^3 = 10^{15} m^3) out of which about 97.2 % is held up in seas and oceans while about 2.1 % is frozen in ice caps, and about 0.31% is available as deep ground water. Thus about 99.6% of total water is of no use to man. Table 4.1 gives the inventory of earth's water.

TABLE 4.1. ESTIMATED EARTH'S WATER INVENTORY

Location	*Water Volume*, M km^3 (= 1 × 10^{15} m^3)	*% of Total Water*
1. Fresh water (lakes)	0.125	0.621
2. Rivers	0.00125	
3. Soil moisture	0.065	
4. Ground water (a) < 0.8 km deep (b) > 0.8 km deep	 4.125 4.125	
5. Saline lakes and inland seas	0.105	0.008
6. Atmosphere	0.013	0.001
7. Polar ice caps, glaciers and snow	29.2	2.1
8. Seas and snow	1320.0	97.25
Total	1360 M km^3 (= 1.360 × 10^{18} m^3)	100.00

(*b*) **India's Water Budget** : India has a geographical area of nearly 3.3 million square kilometers. Normal annual rainfall varies from 100 mm in Western Rajasthan to over 11000 mm at Cherrapunji in Meghalaya. The annual average rainfall over the country is of the order of 1170 mm depth which is nearly 4000 km^3. Of the total precipitation, a part goes towards increasing ground water storage, a part is lost as evapo-transpiration and the remaining appears as surface water.

The average flow in the river system of the country has been estimated to be 1880 km^3. The recent estimates made by Central Water Commission (CWC) indicate that the water resources utilisable through surface structures is about 690 km^3 only, which is about 36% of the total. The prelminary estimates of the Central Ground Water Board indicate that the utilisable ground water is about 450 km^3. According to Nag and Kathpatia, total moisture in atmosphere has been estimated as 770 M ha-m during June to Septemter and 340 M ha-m in the rest of the period, out of which about 25 to 30 % moisture comes back as rainfall over the sub-continent.

4.6. PRECIPITATION

To the hydrologist, precipitation is the general term for all forms of moisture emanating from the clouds and falling to the ground. The following are the essential requirements for precipitation to occur :

1. Some mechanism is required to cool the air sufficiently to cause condensation and droplet growth.

2. Condensation nuclii are also necessary for formation of droplets. They are usually present in the atmosphere in adequate quantities.

3. Large scale cooling is essential for significant amount of precipitation. This is achieved by lifting of air. Thus a meteorological phenomenon of lifting of air masses

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is essential to result precipitation.

4.6.1. Types of Precipitation. Precipitation is often classified according to the factors responsible for lifting. Broadly speaking, there are four types of precipitation:

(1) Cyclonic precipitation. (2) Convective precipitation.
(3) Orographic precipitation. (4) Precipitation due to turbulent ascent.

1. Cyclonic Precipitation : Cyclonic precipitation results from lifting of air masses converging into low pressure area of cyclone. The cyclonic precipitation may be divided into (*a*) frontal precipitation, and (*b*) non-frontal precipitation.

(a) Frontal Precipitation. A border region between two adjacent air masses having different characteristics such as temperature and humidity is called a *front*. When a flow of warm and moist air mass from the south meets cold air mass of polar region, the cold air being heavier, under run the warm air flow in the form of flat wedge forcing the warm air aloft. The lifted warm air mass cools down at high altitudes, causing precipitation. A front may be warm front or cold front depending upon whether there is active or passive ascent of warm air mass over cold air mass.

(b) Non-frontal Precipitation. In the case of non-frontal precipitation, the moist warm air mass is stationary and the moving cold air mass meets it. Thus, due to lightness of the warm air there is passive ascent of warm air over cold air owing to the active under cutting. When the lifted warm air cools down at higher altitude precipitation occurs.

2. Convective Precipitation : Convective precipitation is caused by natural rising of warmer lighter air in colder, denser surroundings. The difference in temperature may result from unequal heating at the surface, unequal cooling at the top of the air layer, or mechanical lifting when air is forced to pass over a denser colder air masses. Convective precipitation is spotty and its intensity may vary from light showers to cloud bursts.

3. Orographic Precipitation : Orographic precipitation is due to the lifting of warm moisture laden air masses due to topographic barriers (such as mountains). As it reaches higher elevation, it comes in contact with cold air and precipitation occurs. The zone to the other side of the mountain will be the zone of rain shadow area where the rainfall may not occur, as shown in Fig. 4.3. All the precipitation we have in Himalayan region is because of the orographic ascent of air masses, rich in moisture content because of their long travel over oceans.

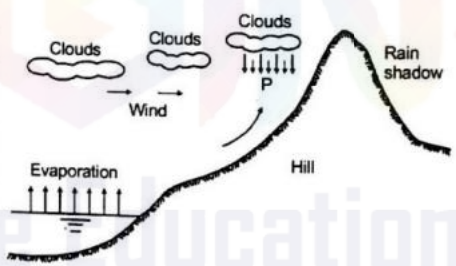

FIG. 4.3. OROGRAPHIC FRECIPITATION

4. Precipitation Due to Turbulent Ascent : Air mass is forced to rise up due to greater friction of earth surface after its travel over ocean. The air mass rises up because of increased turbulence and friction, when it ultimately condenses and precipitation occurs. Winter rainfall in Madras State is mainly due to this process.

In nature, the effects of these various types of cooling are often inter-related and the resulting precipitation cannot be identified as being of any one type.

4.6.2. Forms of Precipitation

The various forms of precipitation are : Drizzle, rain, glaze, sleet, snow, snow flakes and hail.

Drizzle : When the size of water droplets is under 0.5 mm, and its intensity is < 1 mm per hour. Because of the lightness, the droplets appear to be floating in air.

Rain : When the size of the drops is more than 0.5 mm. The upper size of water drop is generally 6.25 mm, as drops greater than this tend to break up as they fall through the air.

Glaze : When the drizzle or rain freezes as it comes in contact with cold objects, it is known as glaze.

Sleet : It is frozen rain drops cooled to the ice stage while falling through air at sub-freezing tempera ture.

Snow : Pricipitation in the form of ice crystals resulting from sublimations (*i.e.* water vapour changed directly to ice).

Snowflakes Number of ice crystals fused together form snow flakes.

Hail : Hail is lumps or bulbs of ice over 5 mm diameter formed by alternate freezing or melting as they are carried up and down in highly turbulent air currents

4.6.3. Rainfall in India

The major rainfall season in India is from June to October. India lies in the tropical belt (i.e. North of Equator) and has the following four distinct weather periods:

(*i*) Monsoon period (*ii*) Post-monsoon period
(*iii*) Winter rainfall period and, (*iv*) Summer rainfall period.

(i) Monsoon period (June to October) : A major part of India (excluding Jammu Kashmir and South Eastern parts) gets more than 75% of rainfall due to monsoon winds which originate in the Indian ocean and proceed to the sub-continent. Fig. 4.4 gives the dates of onset (shown by solid lines) and dates of withdrawals (shown by dotted lines) of monsoons in different parts of India. The monsoon winds advancing from south-western direction breaks up into two distinct branches : (*i*) Bay of Bengal branch and (*ii*) Arabian sea branch. The Arabian sea branch touches Kerala while the Bay of Bengal branch reaches the north-eastern states of India, practically at the same time (i.e. 1st June) and cause heavy rainfall. The Arabian sea branch moves northwards causing heavy precipitation in western ghats while the Bay of Bengal branch moves westward, causing rain in West bengal, Orissa,

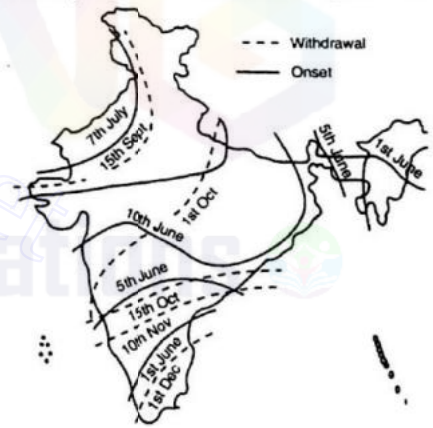

FIG. 4.4. DATES OF ONSET AND WITHDRAWAL OF MONSOON RAINFALL IN INDIA.

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Bihar, U.P. and Delhi. Central India, Punjab, Haryana and Himachal Pradesh get rain from the Arabian sea branch. Both the branches form a low pressure region, known as *monsoon trough* extending from Bay of Bengal to Rajasthan. The total rainfall in various parts of India vary widely — 200-400 cm in north-eastern states, 200-300 cm in western ghat regions, 120-160 cm in Orissa and West Bengal and 100-120 cm in Punjab, U.P. and Haryana region.

(*ii*) ***Post monsoon period (Oct-Nov.)*** : The south-western monsoon retreats in October and November and at the same time north-eastern wind becomes active, causing rain. In addition, tropical cyclones are formed in both Bay of Bengal as well as Arabian sea, resulting in intense rainfall that cause heavy loss of life, specially in the south eastern states of Indian Peninsula. Light rain is also caused in the south eastern part of south peninsula, due to winds blowing over Bay of Bengal and touching the south eastern part.

(*iii*) ***Winter rainfall period (December-February)*** : Eastern parts of southern India get winter rainfall due to low pressure pockets created in Bay of bengal. During the same period, western disturbances of extra-tropical origin travel eastward, causing precipitation in the form of rain and showers in northern region of north India, including Jammu and Kashmir.

(*iv*) ***Summer rainfall period (March-May)*** : Summer rainfall, also called *pre-monsoon showers*, occurs in parts of eastern coast and north-eastern states, due to localised convective currents. Pre-monsoon rainfall also takes place in West Bengal, Orissa and Andhra Pradesh, due to *cyclonic storms*, caused due to low pressure pockets developed over Bay of Bengal.

4.7. MEASUREMENT OF RAIN FALL

Rainfall is the source of all water used for irrigation purposes and, therefore, a knowledge of its amount, character, seasons or periods and the effects produced by it is of prime importance to all whose duty is to design, carry out, improve, or maintain irrigation works. The amount of precipitation is expressed as the depth in centimetres (or inches) which falls on a level surface, and is measured by *rain-gauge*. The following are the main types of rain-gauges used for measurement of rainfall :

1. *Non-automatic rain-gauge*. This is also known as non-recording rain-gauge. Symon's rain-gauge is the instrument prescribed by use at all Government rain-gauge stations throughout India.

2. *Automatic rain-gauge*. These are integrating type recording rain-gauges and are of three types :

(*i*) Weighing bucket rain-gauge. (*ii*) Tipping bucket rain-gauge.
(*iii*) Float type rain-gauge.

1. Symon's Rain-gauge : Symon's rain-gauge is most common type of non-automatic rain-gauge, and is used by Meteorological Department of Government of India. As shown in Fig. 4.5, it consists of cylindrical vessel 127 mm (or 5") in diameter with a base enlarged to 210 mm (or 8") diameter. The top section is a funnel provided with circular brass rim exactly 127 mm (5") internal diameter. The funnel shank is inserted in the neck of a receiving bottle which is 75 to 100 mm (3 to 4") diameter. A receiving

bottle of rain-gauge has a capacity of about 75 to 100 mm of rainfall and as during a heavy rainfall this quantity is frequently exceeded, the rain should be measured 3 or 4 times in a day on day of heavy rainfall lest the receiver fill should overflow. A cylindrical graduated measuring glass is furnished with each instrument, which reads to 0.2 mm. The rainfall should be estimated to the nearest 0.1 mm.

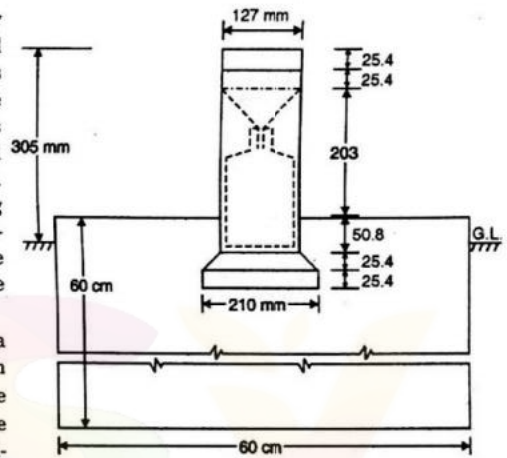

FIG. 4.5 SYMON'S RAIN-GAUGE (ADOPTEDBY METEOROLOGICAL DEPT. OF GOVT. OF INDIA)

The rain-gauge is set up in a concrete block 60 cm × 60 cm × 60 cm (2′× 2′× 2′), as shown in Fig. 4.5. The rim should be 305 mm (12") above the surface of the ground. The following important points should be kept in mind *while selecting the site for a rain-gauge station* :

1. The site where a rain-gauge is set up should be an open place.
2. The distance between the rain-gauge and the nearest object should be atleast twice the height of the object. In no case should it be nearer to the obstruction than 30 metres.
3. The rain-gauge should never be situated on the side or top of a hill if a suitable site on a level ground can be found.
4. In the hills, where it is difficult to find level space, the site for the gauge should be chosen where it is best shielded from high winds, and where the wind does not cause eddies.
5. A fence, if erected to protect the gauge from cattle etc. should be so located that distance of the fence is not less than twice its height.

2. Weighing Bucket Type Rain-gauge

Self recording gauges are used to determine rates of rainfall over short periods of time. The most common type of self-recording gauge is the *weighing bucket type*, as shown in Fig. 4.6.

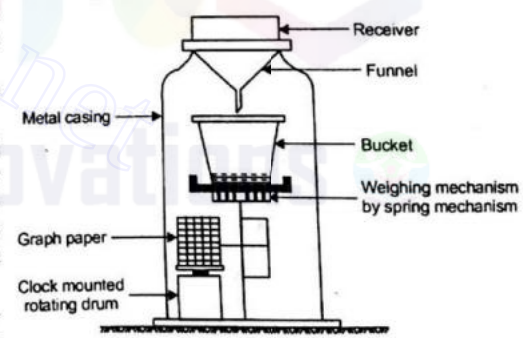

FIG. 4.6. WEIGHING BUCKET TYPE RAIN-GAUGE.

The weighing bucket rain-gauge essentially consists of a receiver bucket supported by a spring

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or lever balance or any other weighing mechanism. The movement of the bucket due to its increasing weight is transmitted to a pen which traces the record on a clock-driven chart.

3. Tipping Bucket Type Rain-gauge

A Steven's tipping bucket type rain-gauge consists of 300 mm diameter sharp edge receiver (Fig. 4.7). At the end of the receiver is provided a funnel. A pair of buckets are pivoted under the funnel in such a way that when one bucket receives 0.25 mm (0.01 inch) of precipitation it tips, discharging its contents into a container bringing the other bucket under the funnel. Tipping of the bucket completes an electric circuit causing the movement of pen to mark on clock driven revolving drum which carries a record sheet. The electric pulses generated due to the tipping of the buckets is recorded at the control room far away from the rain gauge station.

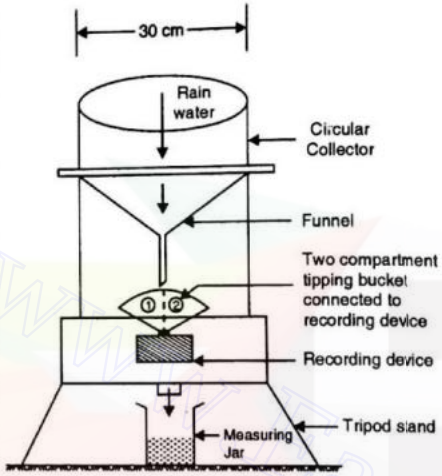

FIG. 4.7. TIPPING BUCKET TYPE RAIN-GAUGE.

4. Float (or Syphon) Type Rain-gauge

The working of a float or syphon type rain-gauge is similar to the weighing bucket type gauge. A funnel receives the rain water which is collected in a rectangular container. A float is provided at the bottom of the container. The float is raised as the water level rises in the container, its movement being recorded by a pen moving on a recording drum actuated by a clock work. When the water level in the container rises so that the float touches the top, the siphon comes into operation, and releases the water ; thus all the water in the box is drained out.

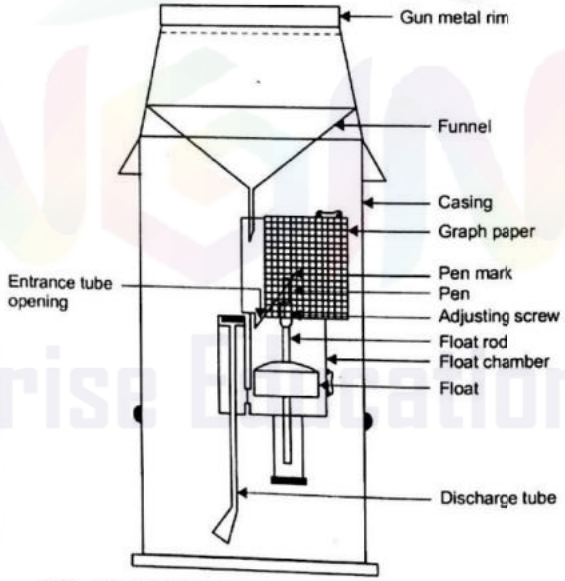

FIG. 4.8. FLOAT TYPE AUTOMATIC RAIN-GAUGE.

Advantages of Recording Rain-gauges

Following are the advantages of recording type rain-gauge over the non-recording type :

1. The rainfall is recorded automatically and therefore, there is no necessity of any attendant.
2. The recording rain-gauge also gives the *intensity* of rainfall at any time while the non-recording gauge gives the total rainfall in any particular interval of time.
3. As no attendant is required such rain-gauge can be installed in far-off places also.
4. Possibility of human error is obviated.

Disadvantages

1. It is costly in comparison with non-recording gauge.
2. Fault may develop in electrical or mechanical mechanism or recording the rainfall.

Sources of Errors in Recording the Measurements

1. Mistakes in reading the scale of the gauge.
2. Some amount of water will be displaced by the measuring stick of water which may creep up the stick ; this may increase the error by 1 %.
3. Dents in the collector rim may change its receiving area.
4. Funnel and inside surface require about 2.5 mm of rain to get moistened when the gauge is initially dry. This may amount to the extent of 25 mm per year in some areas.
5. There is some loss resulting from rainfall splash from the collector.
6. The most serious error is the deficiency of measurements due to wind. Vertical acceleration of air forces upwards over a gauge gives an upward acceleration to precipitation about to enter the gauge and results in deficient catch.
7. Inclination of gauge may cause lesser collection. A 10% inclination gives about 1.5 % low catch.

Some more Errors Associated with Tipping Bucket

8. There is difficulty in the measurement of jogs on a record paper due to their close vicinity during heavy precipitation.
9. When the intensity is not the same as at the time of calibration of the jog, the record may show higher or lower intensity according to the variation in precipitation.
10. Tipping of the buckets may be affected due to rusting or accumulation of dirt at the pivot.
11. No rainfall is recorded during tipping of the bucket.

Microwave Radar for Measurement of Rainfall

A microwave radar (1 to 20 cm wavelength) can be used to obtain, roughly, information on rainfall distribution within its scanning area. The image on the radar screen can be interpreted as an approximate indication of rainfall intensity, since the

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amount of reflected energy is dependent on the raindrop size and the distance from transmitter and the drop size is roughly correlated with rain intensity. A calibration may also be made from actual rain-gauge measurements in the area scanned by the radar.

Totaliser : A *totaliser*, used mainly for measuring rainfall for hydrologic purposes, consists of a large container with a funnel like opening which can hold rain catch of large quantity. It is mostly used to measure rainfall at a remote place, at a large interval of time, say one weak, one fortnight or a month. To record snow as precipitation at a remote location, a storage gauge or stand pipe gauge in used. Such a stand pipe or storage gauge is normally of 305 mm in diameter, with enough height, with an antifreeze chemical (such as calcium chloride solution) to melt the snow. Since precipitation is measured at intervals, a thin layer of oil is spread to prevent evaporation.

4.8. RAINGAUGE NETWORK

It is absolutely essential to design a proper network of raingauges in a given catchment (water shed) to collect the necessary precipitation data. *The raingauge density* or *network density* is defined as the ratio of total area of catchment to the total number of gauges in the catchment. A question that freqently arises concerns the *number* and *type* of gauges that are necessary to ensure accurate assessment of a catchment's rainfall. The World Meteorological Organisation (WMO) has laid down the following norms for *minimum network density* (Table 4.2)

TABLE 4.2

Region	*Description*	*Network density*	
		Minimum	*Tolerable*
I	Flat region of temperate, mediterranean and tropical zones	1 gauge for 600 to 900 km^2	1 gauge for 900 to 3000 km^2
II	Mountaneous areas of temperate, mediterranean and tropical zones	1 gauge for 100 to 250 km^2	1 gauge for 250 to 1000 km^2
III	Arid and Polar zones	1 gauge for 1500 to 10000 km^2	—

Ten percent of these gauges should be of recording type to enable the determination of rainfall intensities.

IS Code Recommendations

IS : 4987-1968 has recommended the following densities :

(*i*) One gauge per 520 km^2 in plain areas, with denser network for the areas lying in the path of low pressure systems.

(*ii*) One gauge per 260 to 390 km^2 in regions with average elevation of 1000 m above mean sea level.

(*iii*) One gauge per 130 km^2 in predominantly hilly regions with heavy rainfall, higher density being preferred wherever possible.

It is also recommended that 10% of the gauges are of recording type. The network arrived at based on the above recommendations should be so located that all the gauges will have more or less equal Thiessen weights.

The optimum No. of rain gauge stations (N), as per ISI is given by

$$N = \left[\frac{C_v}{p}\right]^2 \quad ...(4.3)$$

where C_v = coefficient of variation of the rainfall values of existing stations.

$$= \frac{s_x}{\bar{x}} \times 100 \quad ...(4.4)$$

s_x = standard deviation

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

p = desired degree of error in estimating mean rainfall.

Both C_v and p should be expressed as percentage. If $N < n$, where n is the number of existing stations, the existing network estimates the average depth of rainfall with an error less than allowable value p and no more gauges are required. If, however, $N > n$, the number of additional rain gauge stations will be $(N - n)$, and these should be distributed in different zones (caused by isohyetes) in proportion to their areas, i.e. depending upon the spatial distribution of the existing raingauge stations and the variability of the rainfall over the basin.

Saturated network

In important projects, rainfall has to be estimated with greater accuracy. Hence p will be small and thus N will be large. The net work of raingauge stations should be so set that any addition of raingauge stations will not appreciably alter the average depth of rainfall estimated. Such a network is known as *saturated net work*.

Example 4.1. *A catchment has five raingauge stations. In a year, the annual rainfall recorded by the gauges are 78.8 cm, 90.2 cm, 98.6 cm, 102.4 cm and 70.4 cm. For a 6 % error in the estimation of the mean rainfall, determine the additional number of gauges needed.*

Solution

$$\bar{x} = \frac{1}{n}\Sigma x_i = \frac{78.8 + 90.2 + 98.6 + 102.4 + 70.4}{5}$$

$$= 88.08 \text{ cm.}$$

The *standard deviation* of the rainfall is given by

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

$$= \left[(78.8 - 88.08)^2 + (90.2 - 88.08)^2 + (98.6 - 88.08)^2 + (102.4 - 88.08)^2 + (70.4 - 88.08)^2\right] \div (5 - 1) = 179.732$$

$$\therefore \quad s_x = 13.41$$

Hence $$C_v = \frac{s_x}{\bar{x}} \times 100 = \frac{13.41}{88.08} \times 100 = 15.22$$

$$N = \left(\frac{C_v}{p}\right)^2 = \left(\frac{15.22}{6}\right)^2 = 6.43 \approx 7$$

Additional number of stations $= 7 - 5 = \mathbf{2}$

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4.9. ESTIMATION OF MISSING RAINFALL DATA

Sometimes, it may not be possible to measure the rainfall at a particular measuring station due to absence of the observer or instrument failure or any other reason. In that case, the prediction of the missing data can be made with the help of available data of nearby measuring stations, using the following prominent methods :

1. Arithmetic mean method
2. Normal ratio method
3. Inverse distance method by U.S. Weather Service.

1. Arithmetic mean method : According to this method, the missing rainfall P_x of the station X is computed by simple arithmetic average of the rainfall at the nearby stations (known as *index stations*) in the following form :

$$P_x = \sum_{i=1}^{n} P_i/n = \frac{1}{n}(P_1 + P_2 + ...P_n) \qquad ...(4.5)$$

where n = number of index stations.

The above method is used only under the following conditions :

(*i*) The normal annual rainfall of the missing station is within 10% of the normal annual rainfall of the index stations.

(*ii*) Data of at least three index stations should be available.

(*iii*) The index stations should be evenly spaced around the missing station and should be as close as possible.

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

$$P_x = \frac{1}{n}\left[P_1\frac{N_x}{N_1} + P_2\frac{N_x}{N_2} + ... P_n\frac{N_x}{N_n}\right] = \frac{N_x}{n}\left[\frac{P_1}{N_1} + \frac{P_2}{N_2} + ... \frac{P_n}{N_n}\right] \qquad ...(4.6)$$

where $N_1, N_2 ..... N_n$ = normal annual rainfall of index stations.

N_x = normal annual rainfall of missing station

n = number of index stations.

The above method is used when the normal annual precipitation of the index stations differ more than 10% of the missing station. Here also, the data of atleast three index stations should be available, and all these index stations should be evenly spaced.

3. Inverse distance method (U.S. Weather Service method)

In this method a set of rectangular co-ordinate axes are passed through the missing rain gauge station so that its co-ordinates are (0,0). The co-ordinates (x_i, y_i) of each index station, surrounding the missing station are found. The weightage (W_i) of each index station is represented by the inverse of the square of its distance from the missing station, and is given by

$$W_i = \frac{1}{D_i^2} = \frac{1}{x_i^2 + y_i^2} \qquad ...(4.7\,a)$$

The missing rainfall data of the station X is then computed from the following equation :

$$P_x = \frac{\sum_{i=1}^{n} P_i W_i}{\sum_{i=1}^{n} W_i} \qquad ...(4.7)$$

The above method gives good results and is therefore the most acceptable method for scientific analysis. However, the limitation of the method is that it estimates missing rainfall between the highest and the lowest values of the index stations.

Example 4.2. *A watershed has four rain gauge stations, A,B,C and D. During a storm, rain gauge station A was inoperative, while stations B,C and D, surrounding station A, recorded rainfall of 48 mm, 51 mm and 45 mm respectively. Estimate the missing storm precipitation of station A, using arithmetic mean method.*

Solution

From Eq. 4.5 $\quad P_A = \frac{1}{3}(P_B + P_C + P_D) = \frac{1}{3}(48 + 51 + 45) = \mathbf{48\ mm}$

Example 4.3. *A precipitation station X was inoperative for some time during which a storm occurred. The storm totals at three stations A, B and C surrounding X, were respectively 6.60, 4.80 and 3.70 cm. The normal annual precipitation amounts at stations X, A, B and C are respectively 65.6, 72.6, 51.8 and 38.2 cm. Estimate the storm precipitation for station X.*

Solution : If N_X, N_A, N_B and N_C are the average annual precipitation amounts at X, A, B and C and P_A, P_B and P_C are the storm totals of stations A, B and C surrounding X, the storm precipitation P at station X is given by.

$$P_X = \frac{1}{3}\left[\frac{N_X}{N_A} \times P_A + \frac{N_X}{N_B} \times P_B + \frac{N_X}{N_C} \times P_C\right] \qquad ..(1)$$

$$P_X = \frac{1}{3}\left[\frac{65.6}{72.6} \times 6.6 + \frac{65.6}{51.8} \times 4.80 + \frac{65.6}{38.2} \times 3.70\right] = \frac{1}{3}(18.33) = \mathbf{6.11\ cm}$$

Example 4.4. *In a river basin a station A was inoperative during a storm, while stations B,C, D and E, surrounding A were in operation, registering 74 mm, 88 mm, 71 mm and 80 mm of precipitation. The coordinates of B,C,D and E are (9,6), (12, – 9), (– 11, – 6) and (– 7, 7) respectively, with co-ordinates of A as (0,0). Estimate the missing storm precipitation of station A by the inverse distance method.*

Solution:

$D_b^2 = (9)^2 + (6)^2 = 117$; $W_b = 1/D_b^2 = 1/117 = 8.547 \times 10^{-3}$

$D_c^2 = (12)^2 + (-9)^2 = 225$; $W_c = 1/D_c^2 = 1/225 = 4.444 \times 10^{-3}$

$D_d^2 = (-11)^2 + (-6)^2 = 157$; $W_d = 1/D_d^2 = 1/157 = 6.369 \times 10^{-3}$

$D_e^2 = (-7)^2 + (7)^2 = 98$ $\quad W_e = 1/D_e^2 = 1/98 = 10.204 \times 10^{-3}$

$$\therefore \quad P_x = \frac{\Sigma P_i W_i}{\Sigma W_i} = \frac{74 \times 8.547 + 88 \times 4.444 + 71 \times 6.369 + 80 \times 10.204}{8.547 + 4.444 + 6.369 + 10.204} = \mathbf{77.5\ mm}$$

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4.10. COMPUTATION OF AVERAGE RAINFALL OVER A BASIN

In order to compute the average rainfall over a basin or catchment area, the rainfall is measured at a number of rain-gauge stations suitably located in the area. The network density of rain-gauge depend upon the uses for which the rainfall data is intended. A network should be so planned as to have a representative picture of the areal distribution of rainfall. There should be no concentration of gauges in heavy rainfall areas at the expense of dry areas, or *vice versa*.

If a basin or catchment area contains more than one rain-gauge station, the computation of average precipitation or rainfall may be done by the following methods:

1. Arithmatic average method. 2. Thiessen polygon method.
3. Isohyetal method. 4. Grid point method

1. Arithmatic Average Method

If the rainfall is uniformly distributed on its areal pattern, the simplest method of estimating average rainfall is to compute the arithmatic average of the recoreded rainfall values at various stations. Thus, if $P_1, P_2, P_3, ...P_n$ *etc., are the precipitation or rainfall values measured at n gauge stations, we have*

$$P_{av} = \frac{P_1 + P_2 .....+ P_n}{n} = \frac{1}{n} \sum_{i=1}^{n} P_i \qquad ...(4.8)$$

The procedure is illustrated in Table 4.3.

TABLE 4.3. ARITHMATIC AVERAGE METHOD

Station No.	*Precipitation (mm)*	*Average Precipitation*
1	12.6	
2	18.8	
3	14.8	
4	10.4	
5	16.2	
Sum	$\Sigma P = 72.8$ mm	$P_{av} = \frac{72.8}{5} \approx 14.6$ mm

2. *Thiessen Polygon Method*

The arithmatic average method is most approximate method since rainfall varies in intensity and duration from place to place. Hence rainfall recorded by each rain-gauge station should be weighed according to the area it is assumed to represent.

Thiessen polygon method is a more common method of weighing the rain-gauge observations according to the area. Thiessen polygon method is also called *weighted mean method* and is more accurate than the arithmatic average method.

Procedure (Fig. 4.9)

1. Join the adjacent rain-gauge stations, *A, B, C, D,* etc., by straight lines.
2. Construct the perpendicular bisectors of each of these lines.
3. A Thiessen network is thus constructed. The polygon formed by the perpendicular bisectors around a station encloses an area which is everywhere closer to that station than to any other station. Find the area of each of these polygons shown hatched in Fig. 4.9.

4. Multiply the area of each Thiessen polygon by the rain-gauge value of the enclosed station.
5. Find the total area (ΣA) of the basin.
6. Compute the average precipitation or rainfall from the equation :

$$P_{av} = \frac{A_1 P_1 + A_2 P_2 + ... + A_n P_n}{A_1 + A_2 ... + A_n} = \frac{\Sigma (A \times P)}{\Sigma A} \qquad ..(4.9)$$

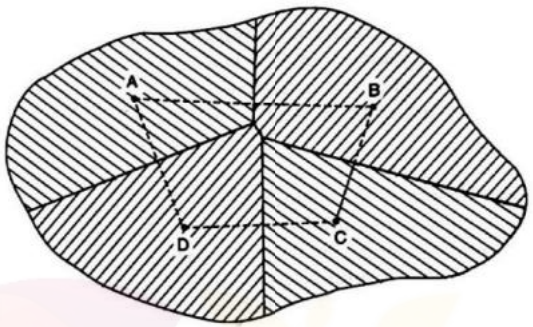

FIG. 4.9 THIESSEN POLYGON METHOD.

or $$P_{av} = P_1 W_1 + P_2 W_2 + ... P_n W_n \qquad ...(4.9\ a)$$

where $W_1, W_2 ..... W_n$ are Thiessen weights computed as $W_1 = A_1/\Sigma A$, $W_2 = A_2/\Sigma A ..... W_n = A_n/\Sigma A$, such that $W_1 + W_2 + ... W_n = 1.00$

The calculations are illustrated in a Table below :

TABLE 4.4. THIESSEN POLYGON METHOD

Rain gauge station	*Area of Thiessen Polygon (A)*	*Precipitation (P)*	*A × P*
A	45 sq. km	30.8 mm	1386
B	38 sq. km	34.6 mm	1315
C	30 sq. km	32.6 mm	978
D	40 sq. km	24.6 mm	974
Sum	153 sq. km		4663

$$P_{av} = \frac{\Sigma A \times P}{\Sigma A} = \frac{4663}{153} = \mathbf{30.5\ mm}$$

Defects of Thiessen polygon method

1. A new Thiessen diagram is required if there is an addition or deletion of rain gauge station for the basin.
2. No account is taken of the orographic features of the catchment.
3. The assumption of linear variation of precipitation between two stations is not desirable since the precipitation is influenced by a large number of meteorological and catchment characteristics.
4. The method does not consider topographic features and other barriers.

3. Isohyetal Method

The basic assumption in the Thiessen Polygon method is that a rain-gauge station best represents the area which is close to it. However, this may not always be valid,

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specially when the rainfall is controlled by topography or results from intense convection. The Isohyetal method is the most elaborate and accurate in such conditions.

An *Isohyet* is a line, on a rainfall map of the basin, joining places of equal rainfall readings. An *isohyetal map* showing contours of equal rainfall presents a more accurate picture of the rainfall distribution over the basin.

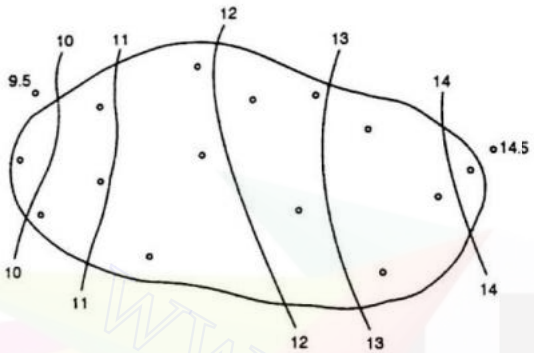

FIG. 4.10. ISOHYETAL METHOD.

Procedure

1. From the rainfall values recorded at various rain-gauge stations, prepare the isohyetal map for the storm causing the rainfall over the area.
2. Measure the areas enclosed between successive isohyets with the help of planimeter.
3. Multiply each of these areas by the average rainfall between the isohyets.
4. The average rainfall is then computed from the expression :

$$P_{av} = \frac{\Sigma A \times \left[\frac{P_1 + P_2}{2}\right]}{\Sigma A} \quad ...(4.10)$$

The calculations are illustrated in a Table below :

TABLE 4.5. ISOHYETAL METHOD

Isohyets (cm)	*Area between Isohyets (A) (Sq. km.)*	*Average precipitation* $\frac{1}{2}(P_1 + P_2)$	*Product* $A \times \frac{(P_1 + P_2)}{2}$
9			
	22	9.5	209
10			
	80	10.5	840
11			
	105	11.5	1208
12			
	98	12.5	1225
13			
	78	13.5	1053
14			
	16	14.5	232
15			
Sum	399		4767

$$P_{av} = \frac{\Sigma A \times \left[\frac{P_1 + P_2}{2}\right]}{\Sigma A} = \frac{4767}{399} = \mathbf{11.92\ cm.}$$

Isohyetal method gives better results than the previous two methods, provided isohyets are drawn by an experienced hydrologist with due consideration of the topographical and other influences. However, the major demerit of the method is that a separate isohyet is required to be drawn for each storm. If monthly rainfall is to be computed by the isohyetal method, then for each month of each year, one set of isohyet is to be drawn. Due to this, the work is increased drastically. However, since this method takes into account the topographical features, it is largely used to compute the average precipitation during storms for flood studies of various projects.

4. Grid point method

In this method, all the grid stations are marked on the map of the basin, along with the depth of precipitation. On this map, drawn to a suitable scale, a uniform rectangular grid at some suitable spacing is super-imposed. At the corners of the grid points, precipitation is estimated suitably by considering the weather and storm characteristics of the basin. The *average* precipitation of the four grid corners is then multiplied by the area of the grid, to give the average precipitation volume of the grid. The sum of all such products divided by the total area of the basin will give the average precipitation for the basin.

Mean Annual rainfall

Mean annual rainfall is usually calculated by taking the simple average of total rainfall of several consecutive years. Great variations are recorded in the annual rainfall at the same station, and a rainfall record for considerable number of years is necessary to get a reliable estimate of mean annual rainfall at any place. The greater is the number of the years considered, the more correct will be the mean value so obtained. From the study of rainfall records of a large number of different places extending over many years, it has been found that 35 years rainfall records are required for a reliable estimate of the mean annual rainfall of any place. Sir Alexander Binnie has shown that if the available rainfall records are for a period lesser than 35 years, there will be error in the computed mean rainfall, as given by Table 4.6.

TABLE 4.6

Period in years	*5*	*10*	*15*	*20*	*25*	*30*	*35*
Percentage error in mean rainfall	14.9	8.2	4.8	3.3	2.8	2.3	1.8

Example 4.5. *Fig. 4.11 shows the map of Cauvery basin with rainfall observations in cm of water marked at various rain gauge stations. Compute the average rainfall by (1) Arithmetic average method (2) Isohyetal, method and (3) Thiessen Polygon method.*

Solution

(i) Arithmetic Average Method: It is clear from Fig. 4.11 that stations having gauge

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readings as 53, 81 and 63 are located outside the basin. Hence they are not included in taking the arithmetical average.

$\therefore$ Arithmetic mean $= \frac{1}{9}(58 + 61 + 69 + 56 + 84 + 86 + 69 + 79 + 71) = 70.34$ cm.

$\therefore$ Average rainfall = **70.34 cm.**

(ii) Isohyetal method: The isohyets are drawn, just as contours, as shown in Fig. 4.11. Area between adjacent isohyets are determined by a planimeter. The calculations are shown in Table below

TABLE 4.7 (a)

Isohyet (cm)	*Area enclosed between Isohyets (A) cm²*	*Average Precipitation* $\frac{1}{2}(P_1 + P_2)$	*Product =* $A \times \frac{(P_1 + P_2)}{2}$
86			
	0.43	85.5	36.80
85			
	5.20	82.5	429.00
80			
	4.00	77.5	310.00
75			
	5.04	72.5	365.40
70			
	5.85	67.5	395.00
65			
	4.53	62.5	283.00
60			
	4.09	57.5	235.00
55			
	1.27	52.5	66.80
50			
Sum	30.41		2121.00

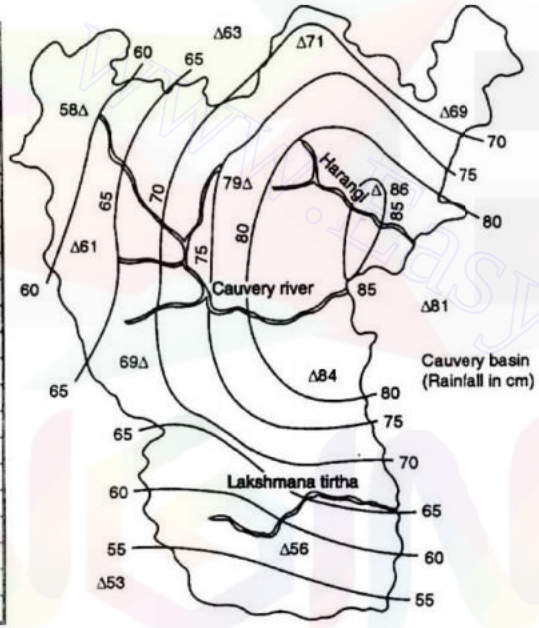

FIG. 4.11.

$$P_{av} = \frac{\Sigma A \frac{(P_1 + P_2)}{2}}{\Sigma A} = \frac{2121.0}{30.41} \simeq 69.7 \text{ cm}$$

(iii) Thiessen Polygon Method: The polygons are drawn as explained in § 4.10 and are shown in Fig. 4.12. Area of each polygon is determined by planimeter. The calculations are shown in Table below.

TABLE 4.7 (b)

Area of Thiessen Polygon A (cm²)	*Observed precipitation P (cm)*	*Product A × P*
3.26	58	189.0
0.39	63	24.6
1.61	71	114.2
2.04	69	140.8
2.46	86	211.5
0.84	81	68.0
3.91	84	328.5
5.09	56	285.0
0.41	53	217.5
3.94	69	272.0
2.06	61	125.7
4.40	79	347.5
Sum 30.41		2324.3

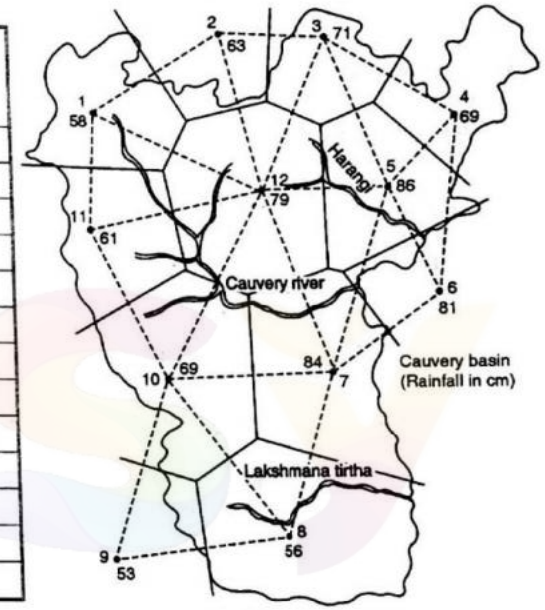

FIG. 4.12

Hence $P_{av} = \frac{\Sigma AP}{\Sigma A} = \frac{2324.3}{30.41} = \mathbf{76.4}$ cm.

4.11. PRESENTATION OF RAINFALL DATA

There are three methods of presentation of rainfall data collected through measurements at a given station :

(*i*) Hyetograph method

(*ii*) Mass curve of rainfall method

(*iii*) Point rainfall method

1. Heytograph Method

A hyetograph is a bar graph showing the intensity of rainfall with time as shown in Fig. 4.13. The hyetograph can be prepared either from the mass curve of rainfall, or directly from the data obtained from automatic raingauges.

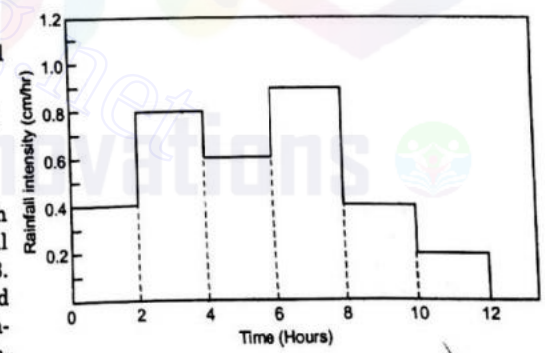

FIG. 4.13. HYETOGRAPH OF STORM

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2. Mass Curve of Rainfall

A mass curve of rainfall is a plot of cumulative depth of rainfall against time, as shown in Fig. 4.14. The steepness of the curve indicates the intensity of rainfall. A horizontal portion of the curve indicates that there was no rainfall during that period.

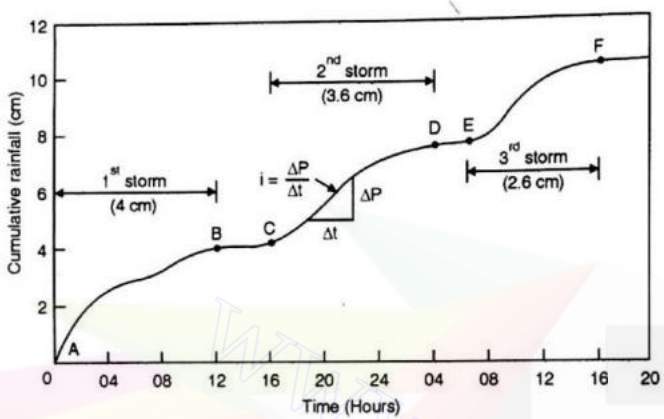

FIG. 4.14. MASS CURVE OF RAINFALL

Thus, in Fig. 4.14, A to B is the first period of rainfall. There was no rainfall from B to C, and therefore the curve is horizontal. C to D shows the second period of rainfall, while E to F shows third period of storm. The mass curve of rainfall is a rising curve. The intensity of rainfall during any period is given by

$$i = \frac{\Delta P}{\Delta t} \quad ...(4.11)$$

A mass curve of rainfall is very useful in extracting the information on the duration and magnitude of a storm. The *mass curve of a design storm* can be obtained by maximising the mass curves of the severe storms in the basin.

3. Point Rainfall Method : The rainfall data of a station is known as *point rainfall* or *station rainfall*. This data can be presented as daily, weekly, monthly, seasonal or annual values. The point rainfall data is presented graphically as plots of magnitudes vs chronological time in the form of a bar diagram. Point precipitation data are used collectively to estimate the areal variability of rainfall. It is also used in deriving the intensity-duration-frequency curves.

4.12. INTERPRETATION OF RAINFALL DATA

Generally, the precipitation information may be required under the following headings:

(*i*) Intensity (*i*) (*ii*) Duration (*t*)

(*iii*) Frequency (*f*) (*iv*) Areal extent

Intensity of rainfall : The intensity of rainfall (*i*) is defined as the rate at which rainfall occurs, and is expressed as cm/h or mm/h. The non-recording type raingauge, however, measures/records only rainfall depth (P) in a day, or in a duration (t) of the rainfall. In that case, the intensity of rainfall is given by

$$i = \frac{P}{t}$$

in which i is the rainfall intensity, P is the rainfall amount and t is the duration of rainfall. However, in the case of recording type raingauge, the duration and depth of rainfall both are recorded simultaneously in the form of *mass curve* on the raingauge recording chart.

The intensity of rainfall is classified into the following three types :

(*i*) Light intensity rainfall : 2.5 mm/h

(*ii*) Moderate intensity rainfall : 2.5 to 7.5 mm/h

(*iii*) Heavy intensity : > 7.5 mm/h

Frequency of rain fall : The frequency of rainfall of a *specified period* in determined assuming that the rainfall is a random variable and the mathematical theory of probability is applicable. The design of hydraulic structures, such as flood control structures, soil conservation structures, waste-water systems, drains and culverts etc. is based on the probability of the occurrence of extreme rainfall and therefore the run off.

(a) Frequency of Point Precipitation : The *frequency* of a rainfall is the number of time that a given magnitude of rainfall may occur in a given period. The study of the *probability* of occurence of a particular extreme rainfall (such as 24-h maximum rainfall) is of extreme importance to the determination of design flood. This is determined with the help of *frequency analysis*. For such an analysis, the point rainfall data at a place are arranged in a chronological order to constitute a *time series*. For example, let us assume that we have maximum 24-h rainfall data for 30 years, recorded at a station. The highest value of 24-h rainfall depth in the set occurs once in 30 years, or it's frequency of occurrence is 30 years. Again, the second highest 24-h rainfall depth occurs twice in the record of 30 years, and hence it has a frequency of 15 years, and so on for other data. The *recurrence interval* is the interval in years for occurrence of the event of the same magnitude and is the reciprocal of the frequency.

Thus the *recurrence interval*, also known as *return period*, is given by

$$T = \frac{1}{P_{ro}} \quad ...(4.12)$$

where P_{ro} is the probability of occurrence.

For the frequency analysis, various events are arranged in descending order of magnitude, and each event is assigned an order number m, with $m = 1$ for the first entry, $m = 2$ for the second entry and so on, till the last entry (event) has $m = N =$ number of years of record.

The probability P_{ro} of an event being equalled or exceeded is given by the following formulae :

(*i*) *California formula* : $P_{ro} = \frac{m}{N}$ or $T = \frac{N}{m}$ ...(4.13)

(*ii*) *Hazen formula* : $P_{ro} = \frac{2m-1}{2N}$ or $T = \frac{2N}{2m-1}$ ...(4.14)

(*ii*) *Weibull formula* : $P_{ro} = \frac{m}{N+1}$ or $T = \frac{N+1}{m}$ ...(4.15)

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Out of these, *Weibull formula* is most widely used.

Fig. 4.15 shows a log log plot between rainfall and frequency. From the above plot, rainfall magnitude of specific duration for any recurrence interval can be estimated.

Frequency (f) : The probability of occurrence of an event, expressed as a percentage is known as frequency (f). Thus

$$f = 100\,P_{ro} = \frac{1}{T} \times 100 \qquad ...(4.16)$$

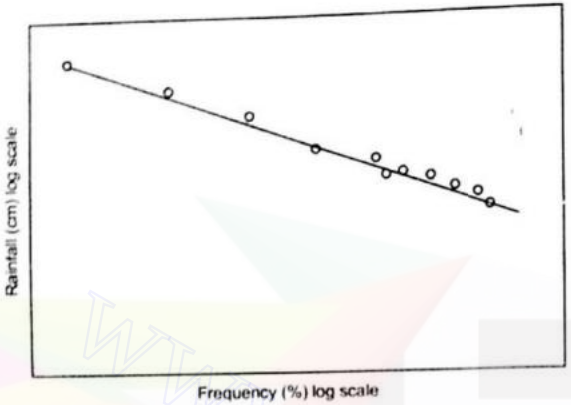

FIG. 4.15. RAINFALL FREQUENCY CURVE

We shall discuss here the following :

1. Intensity duration analysis
2. Intensity-duration-frequency relationship
3. Depth area relationship
4. Depth area duration relationship.

1. INTENSITY DURATION ANALYSIS

It has generally been observed that greater the intensity of rainfall, shorter is the length of time it continues. As the duration of storm increases, the maximum intensity of storm decreases. Sherman gave the following relation between intensity and duration :

$$i = \frac{a}{(t+b)^n} \qquad ...(4.17)$$

where i = intensity of rainfall (cm/hr)

t = time in min. (time duration)

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

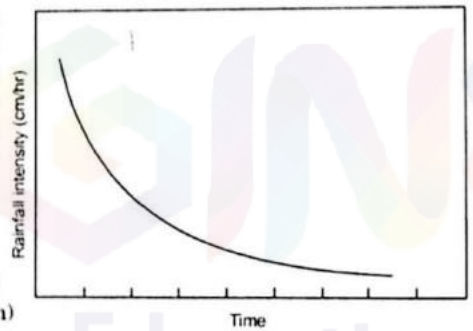

FIG. 4.16. INTENSITY DURATION CURVE

The curve (Fig. 4.16) represented by Eq. 4.17 will be hyperbolic. Paulhus suggests that if rainfall is plotted against duration in a log-log scale, the Word's greatest recorded rainfalls lie on or just under a straight line whose equation is

$$R = 16.6\,D^{0.475} \qquad ...(4.18)$$

where R = rainfall (inches), D = duration (hours)

The World's hightest recorded intensities are of the order of 40 mm in a min., 200 mm in 20 min., and 26 m in a year.

2. INTENSITY DURATION FREQUENCY RELATIONSHIP

It is observed that a storm of any given duration will have larger intensity if it's *return period* is large. This means that for storm of given duration, storms of higher intensity in that duration are rarer than storms of smaller intensity. The relationship between intensity, duration and return period can be expressed by the following

$$i = \frac{K\,T^x}{(t+b)^n} \qquad ...(4.19)$$

where x, b and n = constants for the catchment

T = return period (years)

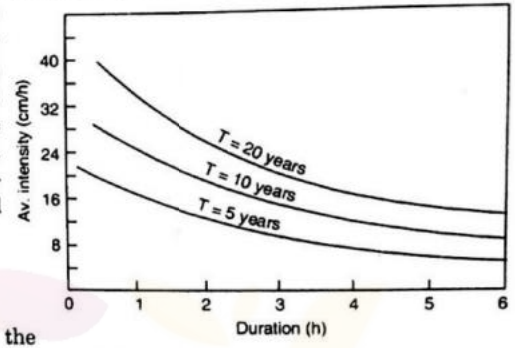

FIG. 4.17. INTENSITY DURATION FREQUENCY CURVES

Typical values of the constants K, b, n and x (Eq. 4.19) are given in Table 4.8. These values are based on studies conducted by the Central Soil and Water Conservation Research and Training Institute, Dehradun.

TABLE 4.8. TYPICAL VALUES OF CONSTANTS K, b, n and x

S.N.	Place in India	Values of constants			
		K	b	n	x
1.	Bellary	6.16	0.5	0.694	0.972
2.	Bhopal	6.93	0.5	0.189	0.878
3.	Chandigarh	5.82	0.4	0.160	0.750
4.	Nagpur	11.45	1.25	0.156	1.032
5.	Raipur	4.68	0.15	0.139	0.928

Sherman gave the following relations :

$$i = \frac{K\,T^x}{t^n} \qquad ...(4.20)$$

and,

$$i = \frac{40\,T^{0.27}}{(t+T)^{0.7}} \qquad ...(4.21)$$

Fig. 4.17 shows the plot between i, T and t, expressed by Eq. 4.20. These relationships will be represented by straight line when plotted on log log scale.

Depth duration frequency curves

When intensity of rainfall, given by Eq. 4.19, is converted into the depth of rainfall (*i.e.* depth $= i \times t$), and results

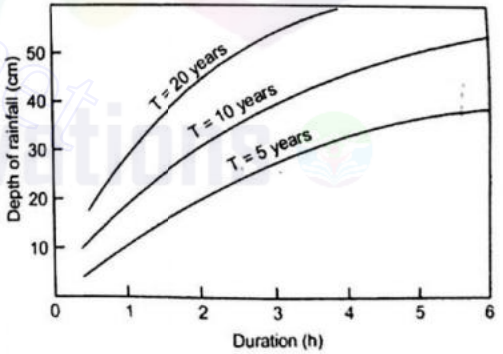

FIG. 4.18. DEPTH-DURATION-FREQUENCY CURVES

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are plotted, we get depth duration frequency curves of the form shown in Fig. 4.18.

3. DEPTH AREA RELATIONSHIP

The areal distribution characteristics of a storm of given duration is reflected in the depth area relationships and depth area curves. Precipitation rarely occurs uniformly over the whole area. For a rainfall of a given duration, the average depth of rainfall decreases from the *maximum* (or highest) value as the considered area increases. The relationship is expressed by the following equation :

$$\overline{P} = P_n \, \varepsilon^{-kA^n} \qquad ...(4.22)$$

where P_n = highest amount of rainfall observed at the storm centre

A = area (km^2)

$\overline{P}$ = average depth in cm, over the area

k, n = constants

The above relationship is shown in Fig. 4.19

On the basis of 42 severemost storms in North India, Dhar and Bhattacharya (1975) gave the following values of k and n for storms of different duration (Table 4.9).

TABLE 4.9. TYPICAL VALUES OF k and N

Duration of storm	*k*	*n*
1 day	8.256×10^{-4}	0.6614
2 days	9.877×10^{-4}	0.6306
3 days	1.745×10^{-3}	0.5961

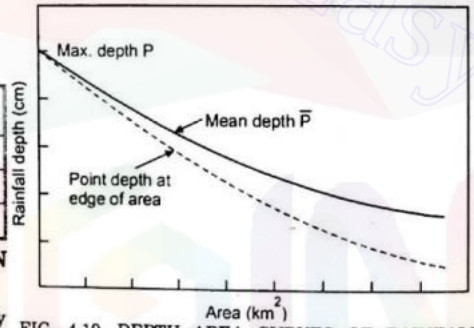

FIG. 4.19. DEPTH AREA CURVES OF RAINFALL

4. DEPTH AREA DURATION CURVES

Rainfall rarely occurs uniformly over the whole of the catchment. Variations in total depth of rainfall and intensity occur from the centres to the peripheries of storms. The knowledge of maximum depth of rainfall occurring on areas of various sizes for storms of different durations is of great importance in many hydrological design problems. The development of relationship between maximum depth, area and duration for a region is known as DAD analysis. DAD analysis is performed to determine the maximum amounts of precipitation of various durations over areas of various sizes.

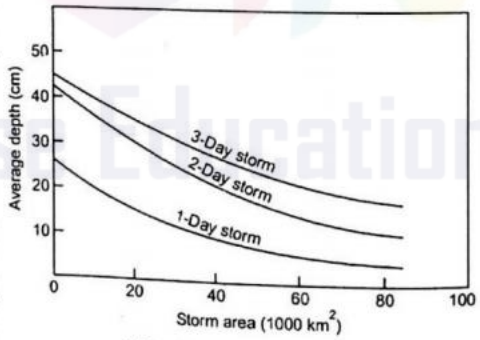

FIG. 4.20. DAD CURVES

DOUBLE MASS CURVE OF RAINFALL

Double mass curve is a technique used for checking the consistency of a record. The trend in the rainfall records at a station may slightly change after some years due to change in the environment of a station, or tampering of the instrument or shift in the observation practices. The change due to meteorological factors will equally affect all stations in the test and thus will not cause a lack of consistency created by the external effects.

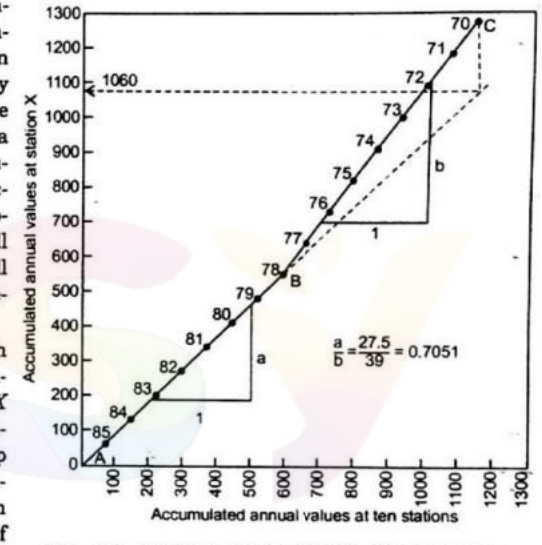

FIG. 4.21. DOUBLE MASS CURVE OF RAINFALL

A double mass curve is a graph plotted between the accumulated annual rainfall at a given station X (test station) versus accumulated annual values of the average of group of base stations, for various consecutive time periods, as shown in Fig. 4.21. A break in the slope of the resulting plot indicates a change in the precipitation regime of station X. The precipitation values at the station X, beyond the period of break are corrected by the following relationship :

$$P_{xc} = P_x \cdot \frac{a}{b} \qquad ...(4.23)$$

where P_{xc} = corrected precipitation at the test station X, at any time period t

P_x = recorded precipitation at the test station X, at time period t.

Example 4.6. *The annual rainfall at station X and the average of annual rainfalls at 10 surrounding base stations in cm are given below for a period of 16 years, starting from 1970.*

Year	*Rainfall at X (cm)*	*10-Station Average (cm)*	*Year*	*Rainfall at X (cm)*	*10 Station average (cm)*
1970	95	75	1978	75	75
1971	75	55	1979	65	65
1972	90	70	1980	70	90
1973	85	65	1981	87	86
1974	95	75	1982	67	68
1975	90	70	1083	62	67
1976	100	70	1984	55	62
1977	90	70	1985	69	77

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(i) Check whether the data at station X is consistent.

(ii) In which year a change in regime is indicated ?

(iii) Compute the adjusted annual rainfalls at X for the affected period.

Solution

Computations for cumulative rainfalls at X and at average of 10 surrounding stations are arranged in tabular form as under, starting from data of most recent year.

Year	Annual rainfall at X (cm)	Cumulative rainfall at X (cm)	Av. of annual at 10 base stations (cm)	Cumulative rainfall of base stations (cm)
1985	69	69	77	77
1984	55	124	62	139
1983	62	186	67	206
1982	67	253	68	274
1981	87	340	86	360
1980	70	410	90	450
1979	65	475	65	515
1978	75	550	75	590
1977	90	640	70	660
1976	100	740	70	730
1975	90	830	70	800
1974	95	925	75	875
1973	85	1010	65	940
1972	90	1100	70	1010
1971	75	1175	55	1065
1970	95	1270	75	1140

The data are plotted as shown in Fig. 4.21

From Fig. 4.21, we observe that the graph is not having uniform slope. There is break at point B. Hence record at X is not consistent. Thus change in the regime is indicated in 1978 corresponding to point B.

From Fig. 4.21, we observe that $\frac{a}{b} = 0.7051$

Hence data beyond point B are to be corrected in the ratio a/b. Adjusted cumulative in 1970, at station $X \approx 1060$ cm.

$$P_{xc} = P_x \cdot \frac{a}{b} = 0.7051 \cdot P_x$$

The corrected rainfall data at X are tabulated as under :

Year	Observed rainfall at X (= P_x)	Adjusted rainfall at X $P_{xc} = 0.7051\ P_x$
1970	95	67
1971	75	53
1972	90	63
1973	85	60
1974	95	67
1975	90	63
1976	100	71
1977	90	63

4.13. PROBABLE MAXIMUM PRECIPITATION (PMP)

(a) Probable maximum precipitation

For the safe design of a hydraulic structure, even a 50 year or 100 year precipitation may be inadequate due to unusual meteorological combinations resulting in a very high precipitation. The *probable maximum precipitation*, commonly known as PMP, for a region is the precipitation resulting from the most critical meteorological combinations that are considered probable of occurrence. It can be defined as that rainfall over a basin which would produce the flood flow with virtually no risk of being exceeded. For the determination or estimation of PMP, the knowledge of an experienced hydro-meteorologist is required. Over the past 40 years, there has been an increasing use of the science of hydro-meteorology (*i.e.* science of meteorology in combination with hydrology), by engineers concerned with water resources and flood control. Hydrometeorology, has been largely developed in USA. The PMP can be estimated by maximising the different parameters like humidity, temperature, wind velocity and other connected meteorological factors of an observed severe storm over the basin. There are two approaches for determining PMP :

(*i*) Meteorological approach

(*ii*) Statistical approach

As has been pointed out in § 4.12, World's greatest observed point rainfall lie on or just under a straight line whose equation is

$$R = 16.6\, D^{0.475} \qquad ...(4.18)$$

where R is the rainfall in inches and D is the duration in hours.

Extreme point rainfalls recorded in the British Isles, extracted from more than half a million station years of data, lie close to a line of equation

$$R = 106\, D^{0.46} \qquad ...(4.24)$$

where R is in mm and D in hours.

From the statistical studies, PMP can also be estimated from the following equation

$$\text{PMP} = \overline{P} + K\sigma \qquad ...(4.25)$$

Where $\overline{P}$ = mean of annual maximum rainfall series

σ = standard deviation of the series

K = frequency factor, which is usually in the neighbourhood of 15

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Maximum and minimum rainfall

The magnitudes of maximum rainfall and minimum rainfall within specified time period can be determined by the use of frequency formula given by Hazen :

$$T = \frac{2N}{2m-1} = \frac{N}{m-0.5} \quad ...(4.26)$$

where T = recurrence interval within which the event is either equal to or greater than the specified amount.

and m = rank number assigned to the event.

Procedure for determination of maximum rainfall

1. Arrange the rainfall data in *descending* order and assign rank number (m) to each rainfall event, the total number of event being equal to N.
2. Compute recurrence interval (T) for each event, using Eq. 4.26.
3. Plot a graph between recurrence interval (T) as abscissa and corresponding rainfall as ordinate.
4. Determine the expected *maximum* rainfall magnitude for any desired value of T from this graph.

See Example 4.13 for illustration.

Procedure for determination of minimum rainfall

1. Arrange the rainfall data in *ascending* order and assign rank number (m) to each rainfall event, the total number of events being equal to N.
2. Compute recurrence interval (T) for each event, using Eq. 4.26.
3. Plot a graph between recurrence interval (T) as abscissa and corresponding rainfall as ordinate.
4. Determine the expected *minimum* rainfall magnitude for any desired value of T from this graph.

See Example 4.13 for illustration.

Isopluvial Maps : We have seen earlier that the standard IDF curves indicate extreme rainfall intensities of different duration for different frequencies (T). As an alternative, IMD (Indian Meteorological Department) has standardised *isopluvial maps*, indicating extreme point rainfall values of different durations and for different frequencies over the whole country. An *isopluvial line* is a line of *equal rainfall*, each for a particular duration and a particular frequency. The isopluvial maps for rainfall of duration 15 minutes, 30 min., 45 min, 1 hr., 3 hr, 6 hr, 9 hr, 12 hr, 15 hr, etc. with recurrence intervals of 2, 5, 10, 25, 50 years have been published by IMD as well as by CWC. From these maps, the total rainfall depth at a particular location, for different durations and return periods can be determined.

Example 4.7. *The ordinates (in mm) of a rainfall mass curve for a storm, which commenced at 06.30 hours, recorded by self recording raingauge at 15 minutes interval are as under:*

0, 12.4, 22.1, 35.1, 52.7, 63.7, 81.9, 109.2, 123.5, 132.6, 143.3, 146 and 146. Construct the hyetograph of this storm for a uniform interval of 15 minutes.

Solution

The computations are done in tabular form below, which is self explanatory. The corresponding rainfall hyetograph is shown in Fig. 4.22.

Time	*Cumulative rainfall (mm)*	*Rainfall in successive 15 min. interval (mm)*	*Rainfall intensity (mm/h)*
06.30	0	–	–
06.45	12.4	12.4	49.6
07.00	22.1	9.7	38.8
07.15	35.1	13.0	52.0
07.30	52.7	17.6	70.4
07.45	63.7	11.0	44.0
08.00	81.9	18.2	72.8
08.15	109.2	27.3	109.2
08.30	123.5	14.3	57.2
08.45	132.6	9.1	36.4
09.00	143.3	10.7	42.8
09.15	146.0	2.7	10.8
09.30	146.0	0.0	0.0

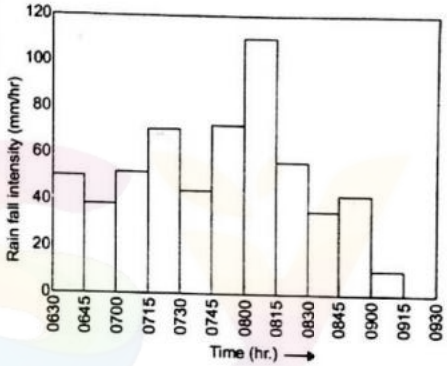

FIG. 4.22. RAINFALL HYETOGRAPH.

Example 4.8. *For the storm of Example 4.7, compute the maximum rainfall intensities for durations of 15, 30, 45, 60, 90 and 120 minutes and plot the intensity duration graph.*

Solution : The computations are done in Tabular form below.

Time	*Cumulative Rainfall (mm)*	*Rainfall in any possible time interval of*					
		15 min.	*30 min.*	*45 min.*	*60 min.*	*90 min.*	*120 min.*
06.30	0						
06.45	12.4	12.4					
07.00	22.1	9.7	22.1				
07.15	35.1	13.0	22.7	35.1			
07.30	52.7	17.6	30.6	40.3	52.7		
07.45	63.7	11.0	28.6	41.6	51.3		
08.00	81.9	18.2	29.2	46.8	59.8	81.9	
08.15	109.2	**27.3**	**45.5**	56.5	**74.1**	**96.8**	
08.30	123.5	14.3	41.6	**59.8**	70.8	**101.4**	**123.5**
08.45	132.6	9.1	23.4	50.7	68.9	97.5	120.2
09.00	143.3	10.7	19.8	34.1	61.4	90.6	121.2
09.15	146.0	2.7	10.4	22.5	36.8	82.3	110.9
09.30	146.0	0.0	2.7	13.4	22.5	64.1	93.3

In the above table, the bold figures denote the maximum rainfall depth for the respective durations. Thus, the maximum rainfall depth of 15 min, 30 min, 45 min, 60 min, 90 min and 120 min. durations are respectively 27.3, 45.5, 59.8, 74.1 101.4 and 123.5 mm.

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∴ Max. intensity for 15 min. duration
$= i_{15} = 27.3/0.25 = 109.2$ mm/h

Max. intensity for 30 min. duration
$= i_{30} = 45.5/0.5 = 91$ mm/h

Max. intensity for 45 min. duration
$= i_{45} = 59.8/0.75 = 79.7$ mm/h

Max. intensity for 60 min. duration
$= i_{60} = 74.1/1 = 74.1$ mm/h

Max. intensity for 90 min. duration
$= i_{90} = 101.4/1.5 = 67.6$ mm/h

Max. intensity for 120 min. duration
$= i_{120} = 123.5/2 = 61.75$ mm/h

Fig. 4.23 shows the max. intensity duration curve for the given storm.

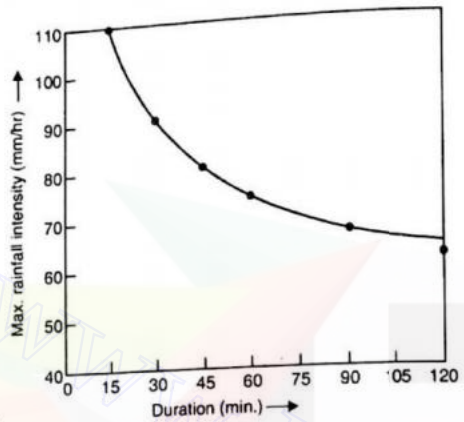

FIG. 4.23. INTENSITY DURATION CURVE

Example 4.9. *The values of annual precipitation at a rain-gauge station in mm per year, in chronological sequence from 1972 to 1981 are indicated below :*

475; 377; 731; 1066; 361; 305; 926; 628; 409; 236; 337 and 853.

Estimate the value of precipitation which has a recurrence interval of 6 years, using the probability or statistical method.

Solution

Total No. of years for which record is available $= N = 12$ years.

Recurrence interval $= T = 6$ years.

∴ Ranking of storm $= m = N/T = 12/6 = 2$

Hence we should pick up the 2nd severest storm. From the records, we find that the most severe storm is 1066 mm and the next severe storm is 926 mm. Hence the value of precipitation, which has a recurrence interval of six years is **926 mm.**

Example 4.10. *Using depth-area curve, estimate the average depth of precipitation that may be expected over an area of 1800 sq. km due to a storm of 15th July 1992, lasting for 24 hours, assuming the storm to be located at the centre of the area . The isohyetal map for the storm gave the following areas enclosed between different isohyets:*

Isohyet (mm)	25	24	23	22	21	20	19	18	17	16
Enclosed area (sq. km)	407	1008	1522	1909	2216	2460	2651	2782	2910	2936

Solution : In order to plot the depth-area curve, let us first compute the *equivalent-uniform depths* (EUD) of rainfall (i.e. mean depth of rainfall) over increasing area of the basin. The computations are done in a tabular form below.

Isohyet (mm)	*Area enclosed between isohyets and boundary of basin (km^2)*	*Net incremental area between isohyets (km^2)*	*Average rainfall on incremental area (mm)*	*Rainfall volume on incremental area (mm. km^2)*	*Cumulative volume (mm. km^2)*	*Equivalent uniform depth EUD (mm)*
(1)	*(2)*	*(3)*	*(4)*	*(5) = (3) × (4)*	*(6) = Σ(5)*	*(7) = (6)/(2)*
25	407	407	25.5 (say)	10378	10378	25.50
24	1008	601	24.5	14724	25102	24.90
23	1522	514	23.5	12079	37181	24.43
22	1909	387	22.5	8707	45888	24.04
21	2216	307	21.5	6600	52488	23.69
20	2460	244	20.5	5002	57490	23.37
19	2651	191	19.5	3724	61214	23.09
18	2782	131	18.5	2424	63638	22.87
17	2910	128	17.5	2240	65878	22.64
16	2936	26	16.5	429	66307	22.58

In the above Table, cols. (1) and (2) correspond to the given data. Column (3) gives the net incremental area between the isohyets, while col.(4) gives the average rainfall on the incremental areas. Column (5) gives the rainfall-volume over incremental areas and is equal to cols. (3) × (4). Col. (6) gives the cumulative volume upto the isohyets under consideration. Lastly, the EUD of Col. (7) is obtained by dividing Col. (6) by Col. (2).

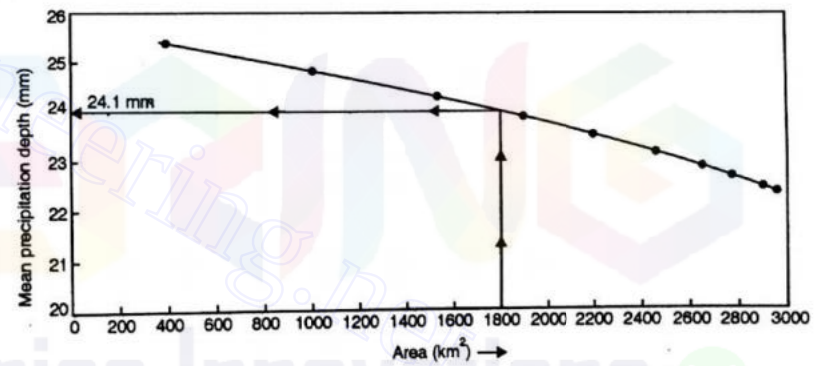

FIG. 4.24. DEPTH-AREA CURVE FOR 1 DAY RAINFALL.

Fig. 4.24 shows the plot between mean depth of rainfall and area enclosed between the isohyets and boundary of the basin. From the above *depth-area curve*, we obtain average depth of precipitation = **24.1 mm** for an area of 1800 sq. km.

Example 4.11. *Table below gives the recorded annual 24 h maximum rainfall data at a certain location, for a period of 20 years. Prepare the rainfall frequency curve and determine the following :*

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(a) *24 h max. rainfall with return period of 8, 15 and 25 years recurrence interval.*

(b) *24 h max. rainfall with 40%, 24% and 8% probability.*

What would be the probability of a rainfall of magnitude equal to or exceeding 100 mm occurring in 24 h at the location ?

Year	Rainfall (mm)	Year	Rainfall (mm)	Year	Rainfall (mm)	Year	Rainfall (mm)
1981	116	1986	64	1991	66	1996	95
1982	126	1987	102	1992	76	1997	108
1983	142	1988	92	1993	86	1998	71
1984	88	1989	78	1994	68	1999	80
1985	82	1990	73	1995	69	2000	65

Solution :

To start with, the values of rainfall are arranged in the decreasing order with their corresponding years as shown in the Table below. Column (3) of the table shows the ranking (m) of the storm. The probability of occurrence is computed from Weibull formula (Eq. 4.15) and entered in col. (4), while the recurrence interval ($T = 1/P_{ro}$) is entered in col. (5) of the Table. Here, $N = 20$.

Year	Rainfall mm	Ranking (m) of the storm	Probability (%) $p_{ro} = \frac{m}{N+1} \times 100$	Recurrence interval (years) $T = 1/P_{ro} = 100/p_{ro}$
(1)	(2)	(3)	(4)	(5)
1983	142	1	4.76	21.0
1982	126	2	9.52	10.5
1981	116	3	14.29	7.0
1997	108	4	19.05	5.25
1987	102	5	23.81	4.2
1996	95	6	28.57	3.5
1988	92	7	33.33	3.0
1984	88	8	38.10	2.63
1993	86	9	42.86	2.33
1985	82	10	47.62	2.1
1999	80	11	52.38	1.91
1989	78	12	57.14	1.75
1992	76	13	61.90	1.62
1990	73	14	66.67	1.5
1998	71	15	71.43	1.4
1995	69	16	76.19	1.31
1994	68	17	80.95	1.24
1991	66	18	85.71	1.17
2000	65	19	90.48	1.11
1984	64	20	95.23	1.05

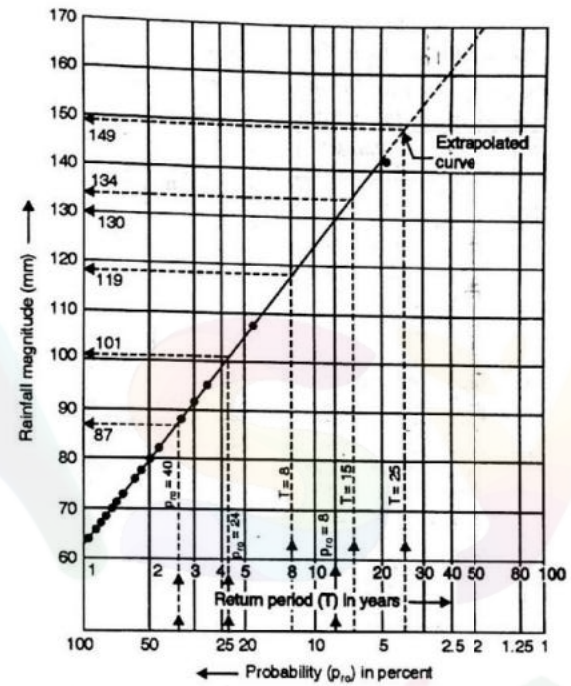

FIG. 4.25. FREQUENCY CURVE

The rainfall frequency curve is prepared by plotting the annual rainfall and corresponding probabilities on semi-log graph paper, shown in Fig. 4.25. Using this curve, the values of rainfall at the desired recurrence intervals and desired probabilities can be read out. The values so obtained are given in the Table below.

T (years)	Rainfall (mm)	p_{ro} (%)	Rainfall (mm)
8	119	40	87
15	134	24	101
25 (extrapolated)	149	8	130

Also, for rainfall = 100 mm, we get $T = 4$ years and $p_{ro} = 25\%$

Example 4.12. ***IDF Curves*** : *Rainfall data, for rains of duration of 5 min., 10 min., 20 min, 30 min., 60 min, 90 min. and 120 min., at a certain station, available for a period of three decades were analysed and ten worst storms of each of these durations are shown in their decreasing order in Table below. Plot the IDF curves for storms of return periods of 10, 2, and 1 years. Use California formula.*

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5 min. duration		10 min. duration		20 min. duration		30 min. duration		60 min. duration		90 min. duration		120 min. duration	
Year	Rain (mm)	Year	Rain (mm)	Year	Rain (mm)	Year	Rain (mm)	Year	Rain (mm)	Year	Rain (mm)	Year	Rain (mm)
1955	10.6	1955	14.7	1955	19.3	1955	20.8	1955	25.5	1962	29.0	1962	34.7
1967	9.4	1962	12.8	1962	16.8	1962	18.6	1962	22.8	1951	28.1	1962	30.7
1962	9.1	1962	11.4	1962	15.2	1962	16.3	1951	20.2	1951	25.2	1951	27.3
1981	9.0	1951	10.8	1968	13.8	1968	14.6	1973	17.2	1968	21.3	1968	24.8
1976	8.2	1972	10.3	1972	13.2	1972	14.2	1966	16.6	1972	19.4	1972	21.4
1973	7.7	1981	9.8	1981	12.4	1978	13.2	1961	15.8	1961	17.7	1964	19.2
1978	6.3	1976	9.5	1976	12.0	1981	12.6	1977	14.8	1977	16.5	1961	18.1
1951	5.6	1978	8.3	1978	11.2	1976	12.1	1981	14.2	1964	16.0	1978	17.6
1962	4.5	1965	6.4	1965	10.0	1965	11.4	1956	13.5	1974	15.8	1974	17.1
1956	3.5	1959	6.2	1959	8.9	1059	10.0	1962	13.2	1956	15.0	1956	16.5

Solution : The return period for each event by the relation $T = N/m$, where $N = 10$, in the present case and tabulate the results as shown below.

Rank (m)	Rainfall during							$T = N/m$
	5 min. duration	10 min. duration	20 min. duration	30 min. duration	60 min. duration	90 min. duration	120 min. duration	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	10.6	14.7	19.3	20.8	25.5	29.0	34.7	10
2	9.4	12.8	16.8	18.6	22.8	28.1	30.7	5
3	9.1	11.4	15.2	16.3	20.2	25.2	27.3	3.33
4	9.0	10.8	13.8	14.6	17.2	21.3	24.8	25
5	8.2	10.3	13.2	14.2	16.6	19.4	21.4	20
6	7.7	9.8	12.4	13.2	15.8	17.7	19.2	1.37
7	6.3	9.5	12.0	12.6	14.8	16.5	18.1	1.43
8	5.6	8.3	11.2	12.1	14.2	16.0	17.6	1.25
9	4.5	6.4	10.0	11.4	13.5	15.8	17.1	1.11
10	3.5	6.2	8.9	10.0	13.2	15.0	16.5	10

The next step would be to compute the average intensity of rainfall, during each duration/storm, for the required return periods of 10, 2 and 1 years, and tabulate the results as shown below.

Duration t (min.)	P (mm)	$i = \frac{P}{t} \times 60$ (mm/hr)	Duration (min.)	P (mm)	$i = \frac{P}{t} \times 100$ (mm/hr)	Duration t (min.)	P (mm)	$i = \frac{P}{i} \times 60$ (mm/hr.)
(a) T = 10 years			(b) T = 2 years			(c) T = 1 year		
5	10.6	127.2	5	8.2	98.4	5	3.5	42
10	14.7	88.2	10	10.3	61.8	10	6.2	37.2
20	19.3	57.9	20	13.2	39.6	20	8.9	26.7
30	20.8	41.6	30	14.2	28.4	30	10.0	20.0
60	25.5	25.5	60	16.6	16.6	60	13.2	13.2
90	29.0	19.3	90	19.4	12.9	90	15.0	10.0
120	34.7	17.4	120	21.4	10.7	120	16.5	83

Fig. 4.26 shows the intensity duration frequency (IDF) curves for $T = 10, 2$ and 1 years.

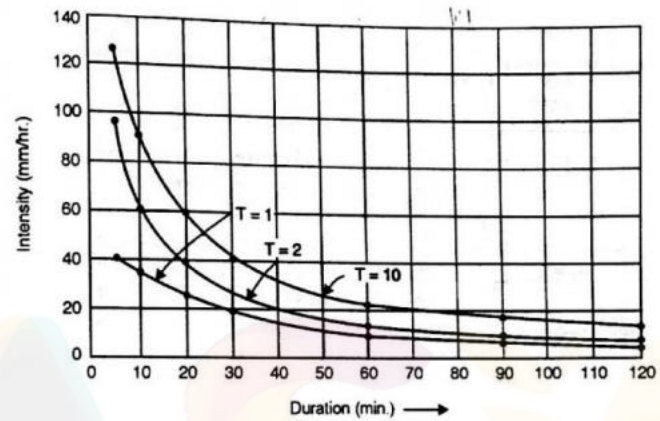

FIG. 4.26. IDF CURVES.

Example 4.13. ***Maximum and minimum rainfall*** : *The rainfall data recorded at a rain gauge station are given below.*

Year	Rainfall (cm)	Year	Rainfall (cm)	Year	Rainfall (cm)	Year	rainfall (cm)
1951	61	1956	30	1961	54	1966	82
1952	50	1957	46	1962	70	1967	78
1953	75	1958	52	1963	34	1968	58
1954	32	1959	72	1964	63	1969	56
1955	36	1960	40	1965	68	1970	65

Compute the values of maximum and minimum rainfall values at 15 years recurrence interval.

Solution : Here, $N = 20$

(a) *Computation of maximum rainfall*

For computation of maximum rainfall, arrange the rainfall data in descending order and assign rank number to each rainfall event. Using Hazen's formula, compute recurrence interval (T) for each event. Finally plot a curve between T (on x-axis) and rainfall depth (on y-axis), as shown in Fig. 4.27.

From this curve, we obtain *max. rainfall* of 79 cm for $T = 15$ years.

(b) *Computation of minimum rainfall*

For computation of minimum rainfall, arrange the rainfall data in ascending order and assign rank number to each rainfall event. Using Hazen's formula, compute recurrence interval T for each event. Finally, plot a curve between T (on x-axis) and rainfall depth (on y-axis), as shown in Fig. 4.28. From this curve, we obtain *minimum rainfall* of 31 cm for $T = 15$ years.

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COMPUTATION OF MAXIMUM RAINFALL

Rainfall (cm)	*Rank number (m)*	$T = \frac{N}{m - 0.5}$
82	1	40
78	2	13.33
75	3	8
72	4	5.71
70	5	4.44
68	6	3.64
65	7	3.08
63	8	2.67
61	9	2.35
58	10	2.11
56	11	1.90
54	12	1.74
52	13	1.60
50	14	1.48
46	15	1.38
40	16	1.29
36	17	1.21
34	18	1.14
32	19	1.08
30	20	1.03

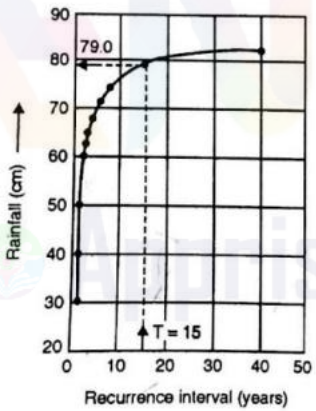

FIG. 4.27

COMPUTATION OF MINIMUM RAINFALL

Rainfall (cm)	*Rank number (m)*	$T = \frac{N}{m - 0.5}$
30	1	40
32	2	13.33
34	3	8
36	4	5.71
40	5	4.44
46	6	3.64
50	7	3.08
52	8	2.67
54	9	2.35
56	10	2.11
58	11	1.90
61	12	1.74
63	13	1.60
65	14	1.48
68	15	1.38
70	16	1.29
72	17	1.21
75	18	1.14
78	19	1.08
82	20	1.03

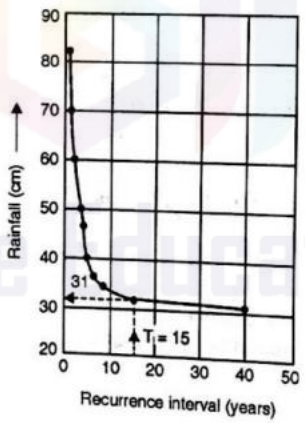

FIG. 4.28

4.14. LOSSES OR ABSTRACTIONS FROM PRECIPITATION

When precipitation takes place on land surface, whole of it is not available as runoff because of losses that take place during or after the precipitation. Important losses consist of (*i*) interception (*ii*) evaporation (*iii*) transpiration, (*iv*) infiltration, (*v*) depression storage, and (*vi*) watershed leakage. Out of these, evaporation, transpiration and infiltration are the major losses.

Thus, Precipitation − Surface runoff = Total loss.

where Total loss = Interception + Evaporation + Transpiration + Infiltration + Depression storage + Watershed leakage.

Interception : Interception may be defined as that amount of precipitation water which is intercepted by vegetative foliage, buildings and other objects lying over the land surface. Interception does not reach the land surface, but is returned back to the atmosphere by evaporation. This *interception storage* is the amount of precipitated water which wets the initially dried surface of the object lying *above* the ground surface. Various factors that affect interception are (*i*) storm factor (*ii*) plant-factor, (*iii*) season of the year, and (*iv*) prevailing wind.

Depression storage : A catchment area generally has many depressions of shallow depth and of varying size and shape. When precipitation takes place, water runs towards these depressions and fill them before actual overland flow or run off towards a stream takes place. The depression storage is therefore defined as the water retained in these depressions/ditches. The size of depression may vary from micro to large capacity. These depressions form miniature reservoirs detaining water temporarily. The water stored in these depressions partly evaporates and partly infiltrates into the ground to meet the ground water reservoir, if any. The following relationship may be used for computing the depression storage.

$$V_{ds} = K\,[1 - e^{-P_e/K}] \qquad ...(4.27)$$

where V_{ds} = Volume of water stored in surface depression.

P_e = Rainfall excess (volume of rainfall in excess of infiltration and interception).

K = Depression storage capacity of the basin.

The above relationship gives an exponentially decaying curve and attains value of K when the ratio P_e/K increases.

Following are the factors that affect depression storage :

(*i*) Land form, (*ii*) Soil characteristics (*iii*) topography, (*iv*) antecedent precipitation index, and (*v*) man made disturbance, like terrace farming etc.

Watershed leakage : Adjacent basins are separated by ridge lines, so that rainfall falling over a basin flows towards the drainage lines (i.e. streams etc.) of the basin. Watershed leakage may be defined as flow of water from one basin to another basin, or from one basin to the sea through major

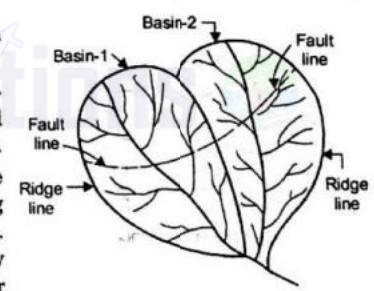

FIG. 4.29. WATERSHED LEAKAGE.

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faults, fissures or other geographical features (Fig. 4.29). Due to these faults/fissures, underground hydraulic conduits so formed convey the discharge falling over a part of the catchment.

4.15. EVAPORATION

Evaporation and evapo-transpiration are the two most important phases of hydrologic cycle which redistribute the heat energy between surfaces and atmosphere. Evaporation is the process in which liquid changes to gaseous state at the free surface, below the boiling point through the transfer of heat energy. It is a continuous natural process by which a substance changes from liquid to gaseous state. The main source of evaporation is the solar radiation. For arid regions, the loss due to evaporation may be as high as 90% of the annual precipitation.

The rate of evaporation is dependent on the following factors :

(*i*) Vapour pressure at the water surface and air above.
(*ii*) Air and water temperatures
(*iii*) Solar radiation
(*iv*) Wind speed
(*v*) Atmospheric pressure
(*vi*) Nature and size of evaporating surface
and (*vii*) Quality of water.

Dalton's law of evaporation

From the Dalton's law of evaporation, the rate of evaporation (E) can be related to vapour pressure as under :

$$E = C\,(e_s - e_a) = (a + b\,v)(e_s - e_a) \qquad ...(4.28)$$

where E = evaporation loss (mm/day)

e_s = saturation vapour pressure at water surface temperature in millibar.

e_a = actual vapour pressure of the air above.

C = a constant whose value depends upon various factors such as barometric pressure, wind velocity, humidity etc.

$= a + bv$ ...(4.28 *a*)

a , b = constants

v = wind speed in km/h

For evaporation to continue, e_a should be less than e_s. Evaporation will be high if $(e_s - e_a)$ is large. Evaporation will be zero when $e_s = e_a$.

Factors affecting evaporation losses

Evaporation losses depend upon (*i*) Nature of evaporating surface (*ii*) Area of water surface (*iii*) Depth of water in the water body (*iv*) humidity (*v*) wind velocity, (*vi*) temperature (*vii*) atmospheric pressure and (*viii*) quality of water.

(*i*) ***Nature of evaporating surface*** : Different evaporating surfaces like soil, barren land, forest area, houses and lakes affect evaporation to the extent they have the potential. Black cotton soils help to evaporate the soil water faster than red soil because such soils have the potential to absorb incoming radiation more effectively. Evaporation from wet soil is faster and it reduces gradually as the soil becomes drier.

(*ii*) ***Area of water surface***: The evaporation loss directly depends upon the area of the water surface — greater the area, greater will be the water loss due to evaporation.

(*iii*) ***Depth of water in water body*** : Deep water bodies evaporate slower than shallow water bodies in summer while in winter season, they evaporate faster.

(*iv*) ***Humidity*** : Evaporation is inversely proportional to humidity. If the humidity in the atmosphere is more, evaporation will be less.

(*v*) ***Wind velocity*** : Wind removes the overlying vapour from an evaporating body thereby increasing the rate of evaporation. However, high wind speed may not necessarily remove water vapour from a small water body. There is thus a relation between the wind speed and size of the water bodies or evaporating surface.

(*vi*) ***Temperature of air*** : Increase in air temperature increases the evaporation rate though not always proportionately. For the same temperature, colder months have less evaporation than summer months due to combined effect of other environmental parameters.

(*viii*) ***Atmospheric pressure*** : As per Dalton's law, evaporation will be less if the atmospheric pressure (e_a) is more. Thus, at higher altitudes, evaporation loss is more while in deep valleys, evaporation is less.

(*viii*) ***Quality of water :*** The presence of dissolved salts in water reduces the saturation vapour pressure (e_s) of water which consequently reduces the rate of evaporation. For example, the Bay of Bengal has salt concentration of 3.15%, and its evaporation rate is nearly 3% less than the evaporation from fresh water.

Estimation of evaporation from surfaces of water bodies : The following are prominent methods of estimation of evaporation loss from surfaces of large water bodies :

(*i*) Measurement using evaporation pans
(*ii*) Use of empirical equations.
(*iii*) Water budget method
(*iv*) Energy budget method

1. Measurement by evaporation pans : The most reliable method for the estimation of evaporation from large water bodies is that by measurements from evaporation pans. Fig. 4.30 shows one such evaporation pan recommended by IS : 5973-1970. This evaporimeter is a modified version of US Weather Bureau Class-A pan. The pan, 1.22 m in diameter and 0.255 m deep, is made of 0.9 mm thick copper sheet with hexagonal wire netting of galvanised iron mesh covering it to protect water from birds, and also to make the water temperature more

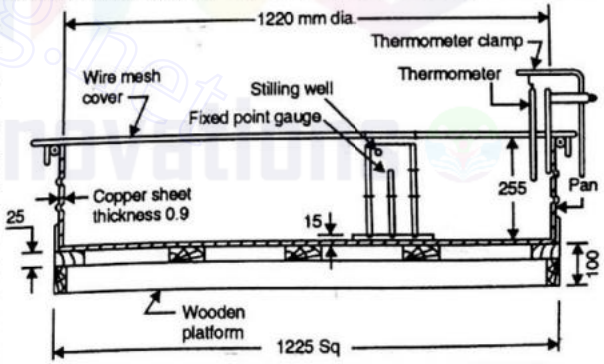

FIG. 4.30. INDIAN STANDARD EVAPORATION PAN

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uniform during day and right. The pan placed over a square wooden platform of 1.225 m width and 10 cm height, so that circulation of air is possible all around the pan. This also helps to thermally insulate the pan completely from ground. Water level in the pan is recorded by a point gauge arrangement placed inside a stilling basin. Measurement is taken atleast once a day by adding water to the pan by a calibrated cylindrical glass jar to bring the water level to the previous position. This gives directly the evaporation depth over the time lapse. Similarly, if there is rainfall exceeding the depth of evaporation, then water is taken out of the pan in the same way by measuring jar and knowing the depth of rainfall from the rain gauge, the evaporation depth is found by subtraction.

The evaporation recorded by a pan differs from that of a lake or reservoir due to the following reasons :

(*i*) Depth of exposure of pan above ground.
(*ii*) Colour of the pan
(*iii*) Height of the rim.
(*iv*) Heat storage and heat transfer capacity with respect to reservoir
(*v*) Pan diameter
(*vi*) Variation in vapour pressure, wind speed and water temperature.

Due to these reasons, the lake evaporation will be less than the pan evaporation, the two being related as under :

Lake evaporation = Pan coefficient × Pan evaporation

The pan coefficient for the Indian Standard evaporimeter is around 0.8.

2. Use of empirical equations

There are a large number of empirical equations for estimating the evaporation loss. However, we shall consider here the following two popular formulae :

(*i*) Meyer's formula. (*ii*) Rohwer's formula.

(i) Meyer's formula (1915)

$$E = K_m (e_s - e_a)\left[1 + \frac{V_9}{16}\right] \quad ...(4.29)$$

where E = evaporation from the water body, in mm/day.
e_s = saturation vapour pressure at the water-surface temperature in mm of mercury.
e_a = actual vapour pressure of overlying air at the specified height (i.e. 9 m here), in mm of mercury
V_9 = monthly mean wind velocity in km/h at a height of 9 m above the ground
K_m = coefficient accounting for various other factors
= 0.36 for large deep waters.
= 0.50 for small shallow waters.

(iii) Rohwer's formula (1931)

$$E = 0.771\,(1.465 - 0.000732\,P_a)\,(0.44 + 0.0733\,V_{0.6})\,(e_s - e_a) \quad ...(4.30)$$

where E, e_s and e_9 have the same meanings as in Meyer's formula.
$V_{0.6}$ = mean wind velocity in km/h at 0.6 m above the ground level.

Thus, Rohwer's formula takes into account a correction for the effect of pressure, in addition to the wind speed effect. It is known that in the lower part of the atmosphere, upto a height of about 500 m above the ground level, the wind velocity is assumed to follow the 1/7 *power law* as under :

$$V_h = Ch^{1/7} \quad \text{or} \quad \frac{V_{h1}}{V_{h2}} = \left(\frac{h_1}{h_2}\right)^{1/7} \simeq \left(\frac{h_1}{h_2}\right)^{0.143} \quad ...(4.31)$$

where V_h is the wind velocity at height h above the ground.

3. Water budget or water balance method : This method balances all the incoming, outgoing and stored water in a lake or reservoir over a period of time, using the following equation :

Σ Inflow − Σ Outflow = Change in storage + Evaporation loss

or

$$E = \Sigma I - \Sigma O \pm \Delta S \quad ...(4.32\ a)$$

The above equation can be generalised as under, taking all the factors of inflow and outflow :

$$E = (P + I_{sf} + I_{gf}) - (O_{sf} + O_{gf} + T) \pm \Delta S \quad ...(4.32)$$

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, which may be neglected.
ΔS = change in storage.

The above method does not give accurate results because it is very difficult to measure I_{gf} and O_{gf} for a lake/reservoir.

4. Energy budget or energy balance method

This method uses the conservation of energy by incorporating all the incoming, outgoing and stored energy of a lake/reservoir in the following from :

$$H_n = H_a + H_e + H_g + H_s + H_i \quad ....(4.33)$$

where H_n = net heat energy received by water surface $= H_c(1-r) - H_b$
$H_c(1-r)$ = incoming solar radiation into a surface of reflection coefficient (albedo) r

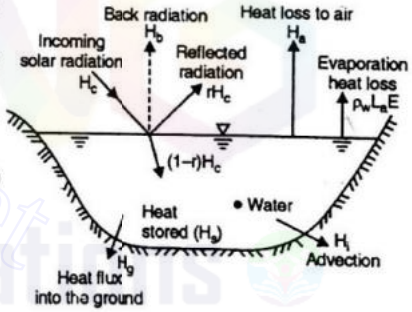

FIG. 4.31. ENERGY BALANCE IN A WATER BODY

The value of r for water surface approximates 0.05. For newly laid snow, $r = 0.90$.

H_b = back radiation (long wave) from the water body.
H_a = sensible heat transfer from water surface to air
H_e = heat energy used up in evaporation $= \rho_w L_a E$,

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where ρ_w = density of water, L_a = latent heat of evaporation.
H_g = heat flux into the ground, H_s = heat stored in water body
H_i = net heat conducted out of the system by water flow (advected energy)

In the above equation, all the energy terms are in calories per square mm per day. All the terms, except H_a can either be measured or evaluated. For small time periods, the terms H_s and H_i can be neglected. However, the sensible heat term H_a can be estimated by using Bowen's ratio (β) by the following expression :

$$\beta = \frac{H_a}{\rho_w L_a E} = 6.1 \times 10^4 P_a \frac{T_w - T_a}{e_s - e_a} \quad ...(4.34)$$

where T_w = temperature of water surface in °C
T_a = temperature of air in °C
P_a = atmospheric pressure in mm of mercury

Combining Eqs. 4.33 and 4.34, we obtain the following equation for evaporation E :

$$E = \frac{H_n - H_g - H_s - H_i}{\rho_w L_a (1 + \beta)} \quad ...(4.35)$$

The above method gives satisfactory results, with errors of the order of about 5%, when applied to periods less than a week.

Transpiration and Evapo-transpiration : *Transpiration* is the process in which water is lost through the living plants, during the respiration process, and back to the atmosphere. *Evapo-transpiration* is a combined term of evaporation and transpiration, defined as the total loss of water through evaporation and transpiration from the plants.

For detailed discussion, reference may be made to Chapter 3.

Example 4.14. *The following Table gives data from a Class-A plan. Assuming a pan coefficient of 0.8, calculate the daily lake evaporation and average evaporation for one week.*

Date	1-7-90	2-7-90	3-7-90	4-7-90	5-7-90	6-7-90	7-7-90
Rainfall (mm)	0	6	8	12	9	5	0
Water added (mm)	+ 12	+ 5	+ 2	– 3	+ 1	+ 6	+ 11

Solution : The computations are arranged in a tabular form below, which is self explanatory.

Date	Water added or taken out (mm)	Rainfall (mm)	Pan evaporation (mm)	Lake evaporation (mm)
(1)	(2)	(3)	(4) = (2) + (3)	(5) = 0.8 × (4)
1-7-90	+ 12	0	12	9.6
2-7-90	+ 5	6	11	8.8
3-7-90	+ 2	8	10	8.0
4-7-90	– 3	12	9	7.2
5-7-90	+ 1	9	10	8.0
6-7-90	+ 6	5	11	8.8
7-7-70	+ 11	0	11	8.8
			Sum	59.2

$$\text{7 day's average evaporation} = \frac{\Sigma E}{7} = \frac{59.2}{7} \simeq \mathbf{8.46\ mm}$$

Example 4.15. *A reservoir with average surface spread of 4.8 km² in the first week of November has the water surface temperature of 30°C and relative humidity of 40%. Wind velocity measured at 3.0 m above the ground is 18 km/h. The mean barometer reading is 760 mm of Hg. Calculate the average evaporation loss from the reservoir in mm/day and the total depth and volume of evaporation loss in the first week of November. Use both Meyer's equation as well as Rohwer's equation. Take saturation vapour pressure at 30°C as 31.81 mm of Hg.*

Solution : (a) *Using Meyer's formula*

$$E = K_m (e_s - e_a)\left[1 + \frac{V_9}{16}\right]$$

Given : $e_s = 31.81$ mm Hg. Relative humidity $R_H = 40\% = 0.4$

∴ $e_a = e_s \cdot R_H = 31.81 \times 0.4 = 12.724$ mm Hg.

$$V_9 = V_2\left(\frac{9}{3}\right)^{1/7} = 18 \times 1.1699 = 21.06 \text{ km/h}$$

$K_m = 0.36$ for large, deep waters

$$\therefore \quad E = 0.36\,(31.81 - 12.724)\left[1 + \frac{21.06}{16}\right] = 15.91 \text{ mm /day}$$

∴ Total depth of evaporation in one weak $= 7 \times 15.91 = \mathbf{111.4\ mm}$

Total volume of water evaporated $= (111.4 \times 4.8 \times 10^6)\ 10^{-3}$
$= 0.5347 \times 10^6\ m^3 = \mathbf{53.47}$ hectare–m

(b) *Using Rohwer's formula*

$$E = 0.771\,(1.465 - 0.000732\,P_a)\,(0.44 + 0.0733\,V_{0.6})\,(e_s - e_a)$$

where $e_s = 31.81$ mm Hg and $e_a = 12.724$ mm Hg, as earlier.
$P_a = 760$ mm Hg.

$$V_{0.6} = \left(\frac{0.6}{2}\right)^{1/7} \times 18 = 15.16 \text{ km/h}$$

$$\therefore \quad E = 0.771\,(1.465 - 0.000732 \times 760)\,(0.44 + 0.0733 \times 15.16)\,(31.81 - 12.724)$$
$= 20.74$ mm/day

∴ Total evaporation for one week $= 20.74 \times 7 \simeq \mathbf{145.2\ mm}$

∴ Total volume of water evaporated $= (145.2 \times 4.8 \times 10^6)\ 10^{-3} = 0.697 \times 10^6\ m^3$
$= \mathbf{69.7}$ **hectare–m**

Thus, we find that Rohwer's formula gives about 30% higher results than Meyer's formula.

4.16. INFILTRATION

Infiltration may be defined as the downward movement of water from soil surface, into the soil mass through the pores of the soil. When rain water falls on the ground, a small part of it is initially absorbed by the top thin layer of soil so as to replenish the *soil-moisture deficiency*, and thereafter, excess water infiltrates downwards to join

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ground water. *In simple terms, infiltration is the entry or passage of water into the soil through soil surface.* Once water enters into the soil, the process of transmission of water in the soil, known as *percolation*, takes place, thus removing the water from near the surface to down below. Infiltration and percolation are directly inter-related. When percolation stops, infiltration also stops. The terms *infiltration* was first used by Horton (1935) to describe the phenomen of soaking water into the soil or absorbed by the soil. He defined it as the entry of water into soil through the surface layer of the soil, vertically. Infiltration is a major process continuously affecting the magnitude, timing and distribution of surface run off at any measured outlet of a basin.

Infiltration capacity

The capacity of any soil to absorb water from rain falling continuously at an excessive rate goes on decreasing with time, until a minimum rate to infiltrate is reached (Fig. 4.32). At any instant, the *infiltration capacity* (f_0) of a soil is the maximum rate at which water will enter the soil in a given condition. The *infiltration rate* at any instant is the rate at which water actually enters the soil during a storm, and is equal to the infiltration capacity (f_0) or the rainfall rate, whichever is less.

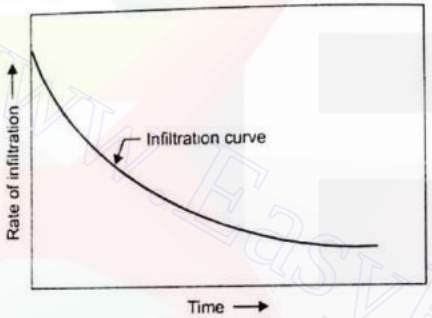

FIG. 4.32. INFILTRATION CAPACITY CURVE

Effects of infiltration : The following are the *effects* of infiltration

1. It reduces the magnitude of the flood
2. It delays the time of arrival of water to the channel
3. If recharges the ground water reservoir.
4. It reduces soil erosion
5. It fills the soil pores to its field capacity, thus making water available to plants.
6. It sustains green vegetation cover on the ground surface and thus helps in reducing dust storms.

Factors affecting Infiltration

Following are various factors, both meteorological as well as the characteristics of soil media, on which infiltration rate and infiltration capacity depends.

1. Condition of entry surface : Vegetation cover versus bare land

If the area is covered by grass, vegetation and bushy plants, infiltration capacity will be more. On the contrary if the soil surface is bare, the impact of rain drops falling on the surface will cause in-washing of finer particles of the soil and will clog the surface, thus resulting in the retardation of infiltration. The vegetation cover also provides a layer of decaying organic matter, which promotes activities of burrowing insects etc. which in turn produce spongy permeable soil structure resulting in increased infiltration. In addition to this, the vegetation cover removes soil moisture through transpiration thus tending to reduce infiltration during initial periods of rain.

2. Permeability/percolation characteristics of soil formation

The infiltration will continue only when percolation continues. The infiltrated water must be transmitted down by the force of gravity and capillary action. Percolation, however, depends upon several factors such as soil and its composition, permeability, porosity, stratification, presence of organic matter and presence of salts.

3. Antecedent moisture conditions in soil

Infiltation rate will depend on initial moisture conditions of soil. When the soil moisture is high, the infiltration rate (f_t) will be low. When water falls on a dry surface, the upper surface becomes wet while the lower parts of the soil remain comparatively dry initially. This results in a large difference of capillary potential, due to which a down ward force will act on the water, in addition to the normal force of gravity. This will result in rapid infiltration. For the second storm in succession, the soil will have lesser rate of infiltration than the first maiden storm of the season.

4. Temperature

The viscosity of water changes with temperature. The flow of water within the body of the soil is laminar, and the flow is directly related to viscosity. In summer, therefore, infiltration will be higher due to less viscous water, in comparison to winter. In sub zero temperature, crystallisation of water in the pores blocks the passage, thus reducing or even stopping the infiltration.

5. Intensity and duration of rainfall

When the precipitation takes place with heavy intensity, the impact of water causes mechanical compaction and in-wash of fine particles, resulting in faster decrease in the rate of infiltration. However, rainfall of lesser intensity result in higher infiltration rate. The rainfall with higher duration will result in lower infiltration in comparison to the same quantity of rain falling as n number of isolated storms.

6. Movement of man and animals

When there is heavy movement of man and /or animals, the soil gets compacted, resulting in reduction in the infiltration rate.

7. Change due to human activities

Cultivation of barren land, by growing crops and grass cover, results in increased rate of infiltration. On the other hand, construction of roads, houses, factories, play grounds, including over-grazing of pastures results in reduction in infiltration capacity.

8. Quality of water

Silts and other impurities present in incoming water result in retardation of infiltration rate due to clogging of soil pores. The salts present in water affect the viscosity of water and may react with soil to form complexes that reduce the porosity of soil.

9. Presence of ground water table

Presence of ground water table reduces infiltration. For infiltration to continue, the position of ground water table should not be very close.

10. Size and characteristics of soil particles : The infiltration rate is directly proportional to the grain size/diameter, for granular soils. However, if the soil has swelling minerals like illite and montmorillonite, the infiltration rate will reduce drastically.

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11. Catchment parameters

It is well known now, from exhaustive studies, that the infiltration capacity decreases with increase in drainage density (i.e. length of all the stream of a basin divided by its catchment area). Similarly, the infiltration capacity (cm/hour) decreases with increase in the runoff rate (m^3/sq.km). Similarly, the infiltration capacity (cm/h) decrease with increase in sediment yield rate (m^3/sq.km)

Infiltration capacity curve (I.C. curve)

Infiltration capacity curve for a given soil formation graphically represents the variation of infiltration capacity (f_t) with time during or a little after rainfall. As stated earlier, the infiltration rate is maximum (f_0) at the beginning of the rainfall and thereafter, infiltration rate decreases exponentially with time.

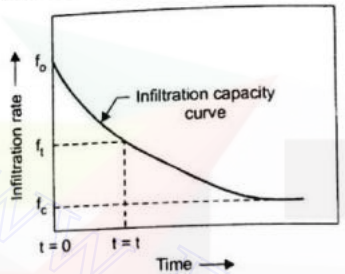

FIG. 4.33. INFILTRATION CAPACITY CURVE

Horton's equation

Horton gave the following equation for finding infiltration rate (f_t) at any time period (t)

$$f_t = f_c + (f_o - f_c)\, e^{-kt} \qquad ...(4.36)$$

where f_t = infiltration rate at any time t

f_c = constant infiltration rate at time $t = T$ (say)

f_o = Infiltration rate in the beginning ($t = 0$)

k = a constant which depends on the soil and vegetation.

Solution of Horton's equation

Transposing and taking log on both sides.

$$\log_{10}(f_t - f_c) = \log_{10}(f_o - f_c) - kt \log_{10} e$$

From which $$t = -\frac{1}{k \log_{10} e}\left[\log_{10}(f_t - f_c) - \log_{10}(f_o - f_c)\right]$$

or $$t = -\frac{1}{k \log_{10} e}\log_{10}(f_t - f_c) + \frac{1}{k \log_{10} e}\log_{10}(f_o - f_c) \qquad ...(4.36\ a)$$

The above equation is the equation of a straight line of the form $y = mx + c$ where $y = t$, $m = -\frac{1}{k \log_{10} e}$,

$x = \log_{10}(f_t - f_c)$ and $c = \frac{1}{k \log_{10} e}\log_{10}(f_o - f_c)$

The slope of the line is $\frac{-1}{k \log_{10} e}$, where the negative sign shows that as t increases, f_t decreases and hence $(f_t - f_c)$ and $\log_{10}(f_t - f_o)$ also decreases as is clear from the straight line of Fig 4.34. The value of slope can be measured by knowing the values of f_t at two timings t_1 and t_2 and drawing a straight line through these two points. Knowing the slope

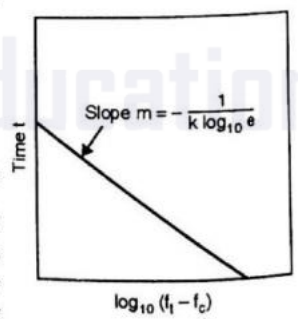

FIG. 4.34

m of the line, the value of constant k is known. Thus, the equation of the curve can be written easily in terms of known parameters k and f_c.

Field Measurement of infiltration rate

Infiltration in the field can be measured with the help of two types of *infiltrometers:* (*a*) single cylindrical or single tube infiltrometers and (*a*) concentric double cylindrical or double ring infiltrometers.

Single tube infiltrometer : It consists of a hollow metal cylinder of 30 cm diameter and 60 cm length with both ends open. The cylinder is driven in the ground such that 10 cm of it projects above the ground. The cylinder is filled with water, such that a head of 7 cm within the infiltrometer is maintained above ground level. Due to infiltration of water, the water level in the cylinder will go on decreasing. Water is added to the cylinder, through graduated jar or burette, so as to maintain constant level. The volume of water added over a predetermined time interval gives the infiltration rate for that time interval. The observations are continued till almost uniform infiltration rate is obtained, which may take about 3 to 6 hours, depending upon the type of soil. A plot of time in abscissa against rate of water added in mm/h gives the infiltration capacity curve for the area. The major draw back of the single tube infiltrometer is that infiltrated water percolates laterally at the bottom of the ring as shown in Fig. 4.35. Hence it does not truly represents the area through which infiltration takes place.

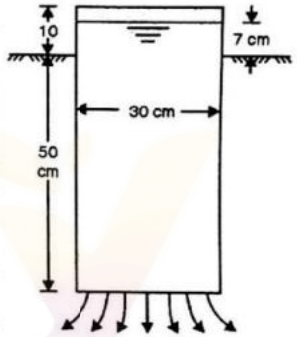

FIG. 4.35. SINGLE TUBE INFILTROMETER

Double tube (or double ring) infiltrometer

The above defect of lateral percolation of water is rectified in the double tube infiltrometer which consists of two concentric hollow rings (or cylinders) driven into the soil uniformly without any tilt and disturbing the soil, to the least depth of 15 cm. The diameter of the rings may vary from 25 to 60 cm (Fig. 4.36). Water is applied in both the inner and outer rings to maintain a constant depth of about 5 cm. Water is replenished after the level falls by about 1 cm. The water depth in the inner and outer rings should be kept the same during the observation period. However, the measurement includes the recording of volume of water added into the *inner compartment*, to maintain the constant water level and the corresponding elapsed time. As the purpose of the outer ring is to suppress the lateral percolation of water from the inner ring, the water added to it need not be measured though water is added to it to maintain the same depth as the inner ring. Observations are continued till constant infiltration rate is observed.

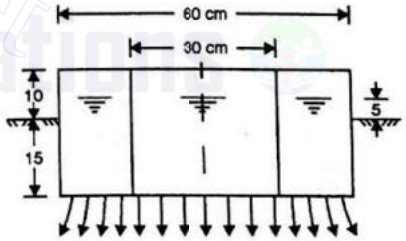

FIG. 4.36. DOUBLE RING INFILTROMETER

Example 4.16. *The following observations were taken from a double tube infiltrometer with*

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inside ring diameter of 30 cm. Plot the infiltration capacity curve and find the constant rate of infiltration that the experimental field have towards the end. Also, compute the average infiltration rate for the first 10 and first 30 minutes.

Time (min.)	0	2	5	10	20	30	45	60	80	100	120	150	180
Cumulative volume (cm^3)	0	200	470	840	1405	1840	2245	2510	2745	2885	2990	3130	3270

Solution : Area of infiltrometer $= \frac{\pi}{4}(30)^2 = 706.86\ cm^2$

The computations are arranged in a tabular form, which is self explanatory

Time (min.)	Time increment Δt (hours)	Cumulative vol. of water added (V)(cm^3)	Cumulative infiltration $F = V/A$ (cm)	Incremental infiltration ΔF(cm)	Infiltration rate $f_t = \Delta F/\Delta t$ (cm/ h)
0	0	0	0		
2	0.0333	200	0.283	0.283	8.50
5	0.0500	470	0.665	0.382	7.64
10	0.0833	840	1.188	0.523	6.28
20	0.1667	1405	1.988	0.800	4.80
30	0.1667	1840	2.603	0.615	3.69
45	0.2500	2245	3.176	0.573	2.29
60	0.2500	2510	3.551	0.375	1.50
80	0.3333	2745	3.883	0.332	1.00
100	0.3333	2885	4.081	0.198	0.59
120	0.3333	2990	4.230	0.149	0.45
150	0.5000	3130	4.428	0.198	0.40
180	0.5000	3270	4.626	0.198	0.40

Fig. 4.37 shows the graph between rate of infiltration (f_t) in cm/hr as ordinate vs. time in minutes as abscissa. From the graph as well as the above Table, constant rate of infiltration, $f_c = 0.40$ cm/hr, which is also the minimum infiltration capacity.

Also, average rate of infiltration for the first 10 minutes $= \frac{1.188}{(10/60)} \simeq$ **7.13 cm/hr**

Average rate of infiltration for the first 30 minutes $= \frac{2.603}{(30/60)} =$ **5.21 cm/hr.**

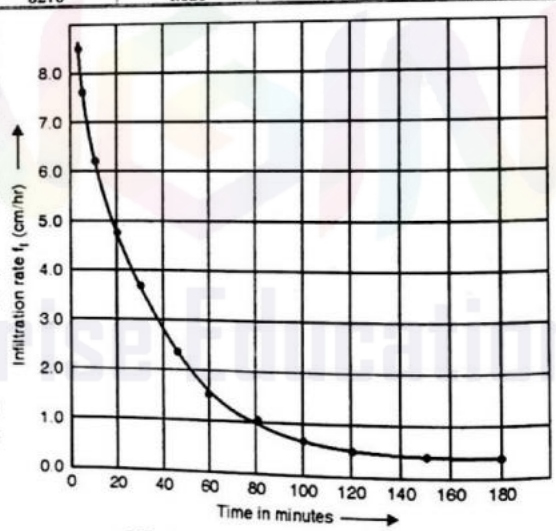

FIG. 4.37. INFILTRATION CURVE

4.17. RUN-OFF

The term runoff is used for water that is on the 'run' or in a flowing state, in contrast to the water held in depression storage and water evaporated in the atmosphere. The run off of a catchment area in any specified period is the total quantity of water draining into a stream or into a reservoir in that period. This can be expressed as (*i*) centimetres of water over a catchment, or (*ii*) the total water in cubic-metre or hectare-metres for given catchment. *Runoff* is broadly classified into three types

1. Surface runoff
2. sub–surface runoff } Direct runoff

and 3. Base flow.

As discussed earlier, the rainfall is disposed off in the following manner :

1. Basin Recharge.
2. Direct run-off (or simply run-off).
3. Percolation down to ground water.
4. Evaporation and transpiration.

1. **Basin Recharge** : It consists of :

(*i*) Rain intercepted by leaves and stems of vegetation.

(*ii*) Water held up in surface depressions, commonly known as the *depression storage.*

(*iii*) Soil moisture held as capillary water in pore spaces of soil or as hygroscopic water absorbed on the surface of soil particles.

2. **Direct Run-off**

Direct run-off is that water which reaches the stream shortly after it falls as rain. Direct run-off consists of :

(*i*) Overland flow or surface run-off.

(*ii*) Sub-surface runoff or interflow (influent stream).

Overland flow is that portion of water which travels across the ground surface to the nearest stream. However, if the soil is permeable, water percolates into it, and when it become saturated, flows laterally in the surface soil to a stream channel. The essential condition for *interflow* or *influent stream* is that the surface soil is permeable, but the sub-soil is relatively impermeable so that water does not percolate deep to meet the ground water.

3. **Percolation Down to Ground Water (Base Flow)**

If the sub-soil is also permeable, water percolates deep downwards to meet the ground water. Much of the low water flow of rivers is derived from the ground water. Stream channels which are below the ground water table are called *effluent streams.*

Schematic representation of runoff process

Fig. 4.38 shows the schematic representation of process of runoff resulting from precipitation over a basin.

Fig. 4.39 shows the forms of runoff in the hydrologic cycle.

Some basic terms used in hydrology

1. Basin : A basin, also called a *drainage basin*, *catchment* or *watershed*, is the area bounded by the highest contour called ridge line from where precipitated water

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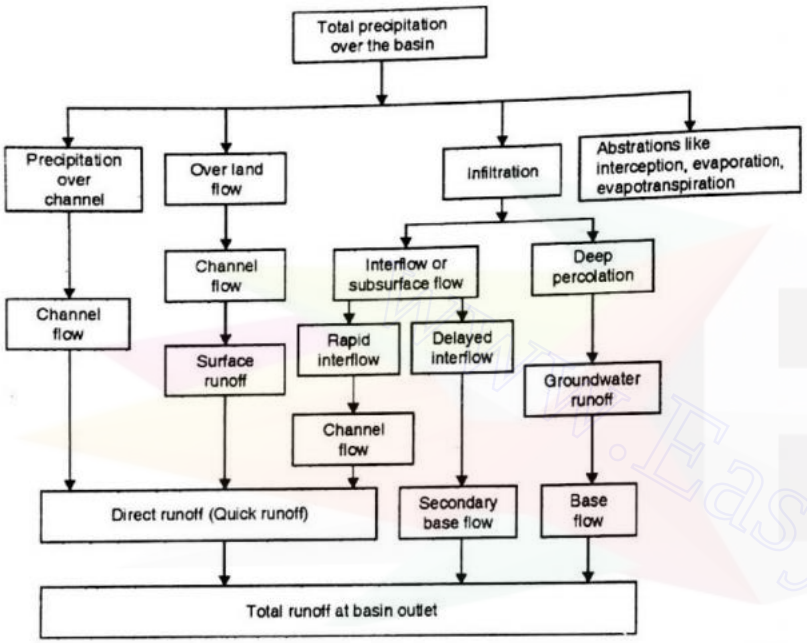

FIG. 4.38. SCHEMATIC REPRESENTATION OF RUNOFF PROCESS RESULTING FROM PRECIPITATION OVER THE BASIN

is collected by surface and subsurface flows and drained out through a natural stream or river. Adjacent basins are divided by ridge lines. The total area of a basin is known as the catchment area.

2. *Stream* : Stream is a natural flow channel towards which the water from a basin flows. The stream drains out the water so collected, into a larger water body.

3. *Overland flow* : Overland flow is that portion of rain water which flows over the land surface in the form of sheet of water to join the nearest stream.

4. *Surface runoff* : Surface runoff is the part of the precipitation and other drainage water of a basin which moves over the natural land surface and then through a network of channels of gradually large sections.

5. *Stream flow* : Stream flow or the *total runoff* consists of surface flow, subsurface flow, ground water flow (or base flow) and the flow due to precipitation falling directly on the stream.

6. Drainage density : Drainage density (D_d) is defined as the ratio of the total length of all streams of the catchment divided by its area.

Thus,
$$D_d = \frac{L_s}{A} \qquad ...(4.37)$$

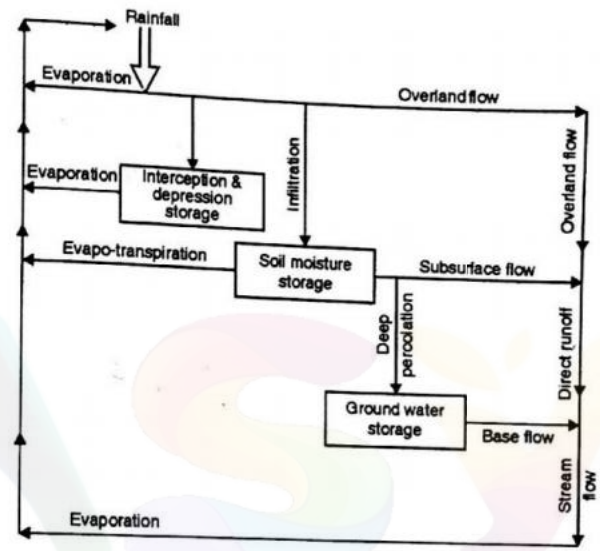

FIG. 4.39. FORMS OF RUNOFF IN THE HYDROLOGIC CYCLE

where L_s = total length of all streams in a basin

and A = drainage area of basin.

The drainage density indicates the drainage efficiency of the basin — the higher the value, the quicker the runoff.

7. *Stream density* : Stream density (D_s) is defined as the number (N_s) of the streams of given order per sq. km of the catchment area.

Thus,
$$D_s = \frac{N_s}{A} \qquad ...(4.38)$$

8. *Centroid of the basin* : It is the point of weighted centre of a watershed.

9. *Form factor* : Horton (1932) defined form factor (F_f) as the ratio of the watershed area (A) to the square of its length (L^2). It is also defined as the ratio of average width (W_b) of the basin to its length (L_b) measured between the stream outlet to the most remote point on the basin.

The average width (W_b) is obtained by dividing the watershed area (A) with the axial length of the same. Thus,
$$F_f = \frac{W_b}{L_b} = \frac{A/L_b}{L_b} = \frac{A}{L_b^2} \qquad ...(4.39)$$

10. *Compactness coefficient* (C_c) : Strahler (1964) defined it as the ratio of the perimeter of the basin to the circumference of a circle whole area is the area of the basin.

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Thus, $$C_c = \frac{P}{\sqrt{4\pi A}} = \frac{0.2821P}{\sqrt{A}} \geq 1 \quad ...(4.40)$$

where P = perimeter of the basin in km.

A = area of the basin in sq. km.

11. Elongation ratio (E_r) : Elongation ratio, introduced by Schuman (1956) is the ratio of the diameter of a circle of the same area of the basin to the maximum length of the basin.

Thus $$E_r = \frac{1}{L}\sqrt{\frac{A}{0.786}} \leq 1 \quad ...(4.41)$$

12. Circularity ratio (C_r) : Circularity ratio, proposed by Millar (1956) is the ratio of the area of the basin to the area of a circle having the same perimeter as the basin.

Thus, $$C_r = 12.57\frac{A}{P^2} \leq 1 \quad ...(4.42)$$

4.18. FACTORS AFFECTING RUN-OFF

The principal factors affecting the flow from a catchment area are :

1. Precipitation characteristics.
2. Shape and size of the catchment.
3. Topography.
4. Geological characteristics.
5. Meteorological characteristics.
6. Character of the catchment surface.
7. Storage characteristics.

1. Precipitation Characteristics

This is most important factor on which run-off depends. Important precipitation characteristics are :(*i*) intensity (*ii*) duration (*iii*) aerial distribution (*iv*) direction of storm movement, (*v*) form of precipitation and (*vi*) evapo-transpiration. The more the rainfall, more will be the run-off. Run-off depends on the type of the storm causing precipitation, and also upon its duration. Run-off also increases with the intensity of rainfall. Run-off also increases with the extent of the storm over the catchment. If the rainfall intensity is very less, and it rains as light showers, much of the water will be lost in infiltration and evaporation etc., and the run-off will be less. Greater evapo-transpiration will result in lesser runoff.

Similarly, if the precipitation is in the form of snow, or if water freezes as it falls, it will be retained in the catchment till temperature increases. Thus run-off will be less.

2. Shape and Size of the Catchment

The run-off from a cathment also depends upon the size, shape and location of the catchment. More intense rainfalls are generally distributed over a relatively smaller area ; a stream collecting water from a small catchment area is likely to give greater run-off intensity per unit area. In the case of a very big catchment, uniform rain seldom falls over the entire area, with the result that only very few tributaries of the stream feed water to main stream during a particular storm. Thus run-off intensity of larger stream, per unit catchment area is lesser.

In the case of a fan or sector shaped catchment [Fig. 4.40 (*a*)] all the tributaries are appoximately of the same size. Such catchment gives greater run-off since the peak flood from the tributaries is likely to reach the main stream approximately at the same time. In the case of a fern leaf catchment [Fig. 4.40 (*b*)], the tributaries are generally of different lengths, and meet the main stream at the regular intervals. In such a narrow catchment, the peak flood intensity is reduced since discharges are likely to be distributed over a long period of time.

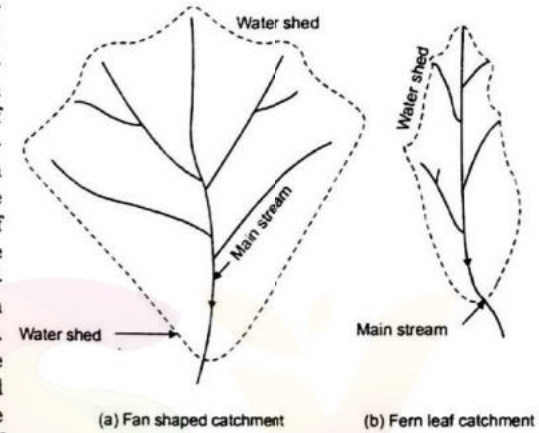

FIG. 4.40. EFFECT OF SHAPE OF THE CATCHMENT

3. Topography of Catchment

The run-off depends upon whether the surface of the catchment is smooth or rugged. If the surface slope is steep, water will flow quickly, and absorption and evaporation losses will be less, resulting in greater run-off. If the catchment is mountainous, and is on the windward side of the mountains, the intensity of rainfall will be more, and hence run-off will also be more.

4. Orientation of watershed : The orientation of watershed affects the evaporation and transpiration loss by influencing the amount of heat received from the sun. The North and South orientation of watershed affects the melting time of collected snow and hence the runoff. Similarly, in mountaneous watershed, the windward side of the mountain receives comparatively higher intense rainfall than the leeward side.

5. Geological Characteristics of basin

Geological characteristics of the catchment area is an important factor affecting the run-off. These include the type of surface soil and sub-soil, type of rock and their permeability characteristics. If the soil and sub-soil is pervious, seepage will be more and this in turn reduces the peak flood. If the surface is rocky, the absorption will be practically nil, and run-off will be more. However, if the rocks have fissures, or if they are porous or have lava tunnels etc., most of the water will be lost by way of seepage, and surface run-off will be very small. However, if this seeping water has the outlet in the stream of the catchment, most of the water flows back to the stream during its period of low flow.

6. Meteorological Characteristics

Temperature, wind and humidity also affect the run-off. If the temperature is low and the ground is saturated and frozen, it gives rise to greater run-off. However, if the whole of the stream freezes, the peak floods will be reduced. On the other

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hand, high temperature and greater wind velocity give rise to greater evaporation loss and reduce the run-off. The peak flood depends upon the direction of movement of the storm causing rainfall with relation to the direction of the stream. If the storm centre moves against the direction of the stream, the run-off from various points along the catchment reaches the stream at different timings, with the result that the peak flow is reduced. On the other hand, if the storm centre moves in the direction of flow of the stream, and practically with the same velocity, the run-off tends to reach at the same time resulting in a higher peak flow.

7. Character of the Catchment Surface

The run-off also depends upon the surface conditions — whether the surface is drained or undrained, natural or cultivated, and whether it is bare or covered with vegetation etc. If the surface has no natural drainage, absorption loss will be more. If more area of a catchment is cultivated, surface run-off will be less. The presence of vegetal cover reduces the run-off specially during smaller storms. However, for a bigger storm after the vegetal cover gets saturated, water runs from the surface freely as if there was no vegetation.

8. Storage Characteristics of the Catchment

The artificial storage such as dams, weirs etc. and natural storage such as lakes, ponds etc. tend to reduce the peak flow. They also give rise to greater evaporation losses. If the tributaries of a river discharge into a lake, and the river takes off from the lake, the peak floods in the river will be reduced. The storage into the pervious surface soil and sub-soil tends to reduce the peak flow and tend to regularise the flow of a stream.

4.19. COMPUTATION OF RUN-OFF

The run-off from a catchment can be computed daily, monthly or yearly. Following are some of the methods of computing the run-off :

(a) By linear or exponental regression
(b) By empirical equations and Tables.
(c) By Infiltration method.
(d) By Unit Hydrograph.
(e) By Rational method.

The unit hydrograph method and the rational method have been discussed in subsequent articles.

(a) Runoff by linear or exponential regression : Because of several factors affecting runoff resulting from a given rainfall, the relationship between these two is quite complex. However we may use *straight-line regression* for small and medium sized catchments and exponential form of regression for large catchments.

1. Straight line regression between P and R : The equation of linear regression line between observed values of R and P is

$$R = aP + b \qquad ...(4.43)$$

where a and b are constants representing abstractions. The values of a and b are given by the following equations :

$$a = \frac{N(\Sigma P.R) - (\Sigma P)(\Sigma R)}{N(\Sigma P^2) - (\Sigma P)^2} \qquad ...(4.43\ a)$$

and

$$b = \frac{\Sigma R - a\,\Sigma P}{N} \qquad ...(4.43\ b)$$

and coefficient of correlation,

$$r = \frac{N(\Sigma PR) - (\Sigma P)(\Sigma R)}{\sqrt{[N(\Sigma P^2) - (\Sigma P)^2] \times [N(\Sigma R^2) - (\Sigma R)^2]}} \qquad ...(4.43\ c)$$

2. Exponential regression between P and R : For large catchments, it is advantageous to use the following exponential relationship:

$$R = \beta P^m \qquad ...(4.44)$$

where β and m are constants. Taking logarithms of both the sides, we get

$$\log_e R = m \log_e P + \log_e \beta$$

which is a linear form, from which the values of coefficients β and m can be computed, as explained above, from observed sets of values of P and R.

(b) RUN-OFF BY FORMULAE AND TABLES

1. Run-off Coefficient :

The run-off and the rainfall can be inter-related by run-off coefficient, by the expression.

$$R = kP$$

where R = run-off in cm; P = rainfall in cm; k = run-off coefficient.

The run-off coefficient naturally depends upon all the factors which affect the run-off. This method is used only for small water control project, and should be avoided for the analysis of major storms. The customary values of k are given below :

Area		*k*
Urban residentials :	Single Houses	0.3
	Garden apartments	0.5
Commercial and Industrial		0.9
Forested areas, depending on soil		0.05 – 0.2
Parks, farm land, pasture		0.05 – 0.3
Asphalt or concrete pavement		0.85

Barlow's Table. T.G. Barlow (1912) carried out studies of catchments mostly under 140 sq km in the United Provinces (U.P.) and gave the following values of k (in percentage) for various classified catchments.

TABLE 4.10. BARLOW'S TABLE

Class	*Description of Catchment*	*Run-off percent*
A	Flat, cultivated and black cotton soils	10
B	Flat partly cultivated : various soils	15
C	Average	20
D	Hills and plains with cultivation	35
E	Very hilly and steep, with hardly any cultivation	45

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The above values of run-off percentages are for average monsoons. These are to be multiplied by the following coefficients (Table 4.11) according to the nature of season.

TABLE 4.11. BARLOW'S COEFFICIENT

Nature of season	*Class of Catchment*				
	A	*B*	*C*	*D*	*E*
(1) Light rain (upto 25 mm/day); no heavy downpour	0.7	0.8	0.8	0.8	0.8
(2) Average or varying rainfall (25-75 mm/day); no continuous downpour	1.0	1.0	1.0	1.0	1.0
(3) Continuous downpour greater than 75 mm/day	1.5	1.5	1.6	1.7	1.8

2. ***Strange's Tables and Curves.*** W.L Strange (1928) gave Tables and curves for run-off resulting from rainfall in the plains of South India. The following Tables and graphs are for the Konkan region of Maharashtra. Strange's tables and curves give run-off for daily rainfall, and take into account three types of catchments (*i.e.* good, average and bad), and three surface conditions, (*i.e.* dry, damp and wet) prior to the rain.

TABLE 4.12. DAILY RUN-OFF ACCORDING TO STRANGE

Note. For good and bad catchment, add or deduct upto 25% of yield.

Daily Rainfall (mm)	*Run-off percentage and yield when the original state of ground was*					
	Dry		*Damp*		*Wet*	
	%	*Yield (mm)*	*%*	*Yield (mm)*	*%*	*Yield (mm)*
6.25	...	...	...	...	8	0.5
12.5	...	...	6	0.75	12	1.5
18.75	...	...	8	1.50	16	3.0
25	3	0.75	11	2.75	18	4.5
31.25	5	1.56	14	4.37	22	6.88
37.5	6	2.25	16	6.00	25	9.37
43.75	8	3.5	19	8.31	30	13.1
50	10	5.0	22	11.00	34	17.0
62.5	15	9.37	20	18.15	43	26.9
75	20	15.00	37	27.75	55	41.25
100	30	30.00	50	50.00	70	70.00

3. ***Inglis's Formula.*** : C.C. Inglis gave the following formulae, derived from data collected from 37 catchments in the Bombay Presidency :

For Ghat areas (western ghats)

$$R = 0.85\ P - 30.5 \quad (\text{ when } R \text{ and } P \text{ are in cm}) \qquad ...(4.45)$$

For Non-ghat areas (Plain regions)

$$R = 0.00394\,P^2 - 0.0701\,P \quad \text{where } R \text{ and } P \text{ are in cm.} \qquad ...(4.46)$$

4. ***Lacey's Formula***

$$R = \frac{P}{1 + \dfrac{304.8\,F}{P\,S}}$$

(where P and R are in cm) ...[4.47]

where S = Catchment factor

and F = Monsoon duration factor.

Corresponding to the five classes of catchments, defined by Barlow, Lacey gave the following values of the catchment factor (S).

TABLE 4.13

Class of catchment	*Values of S*
A	0.25
B	0.60
C	1.00
D	1.70
E	3.45

Lacey also divided the monsoon into three classes, depending upon its duration and gave the following values of monsoon duration factors :

TABLE 4.14

No.	*Class of monsoon*	*Monsoon Factor (F)*
1.	Very Short	0.50
2	Standard length	1.00
3.	Very Long	1.50

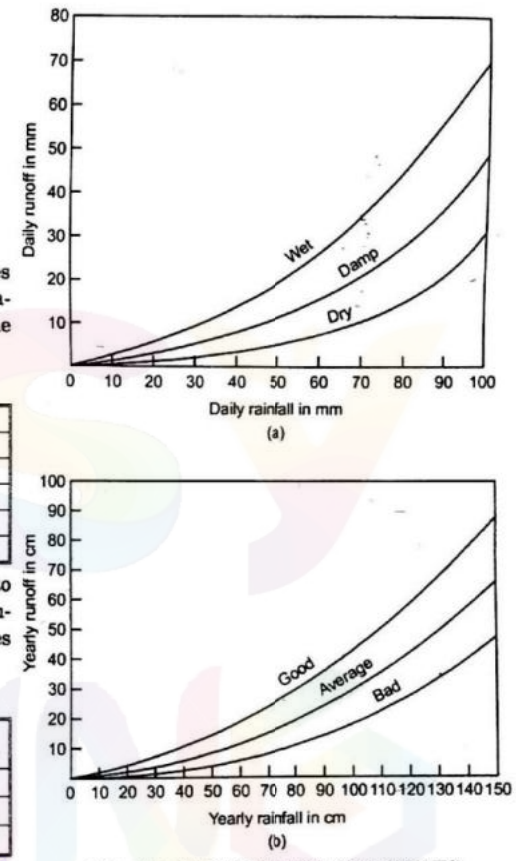

FIG. 4.41 STRANGE'S RUN-OFF CURVES.

5. ***Khosla's formula (1960)***

$$R_m = P_m - 0.48\,T_m \qquad ...(4.48)$$

where R_m = monthly runoff in cm.

where T = mean temperature in °C on the entire catchment.

P_m = monthly precipitation in cm.

The temperature introduced in the formula takes into account various factors affecting losses by evaporation, transpiration, sunshine and wind velocity.

6. ***ICAR Formula (For Nilgiri hills)***

$$R = 1.511\,(P^{1.44})\,(T_m)^{-1.34}\,(A^{-0.0613}) \qquad ...(4.49)$$

where A = Watershed area km^2

P and R = annual rainfall in cm

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7. *Dhir, Ahuja and Majumdar formulae*

$R = 120\,P - 4945$ (for Chambal, Rajasthan) ...(4.50 *a*)

$R = 435\,P - 17200$ (for Tapi, Gujrat) ...(4.50 *b*)

$R = 13400\,P - 575000$ (for Damodar Valley, West Bengal) ...(4.50 *c*)

$R = 34.6\,P - 1510$ (for Tawa, M.P.) ...(4.50 *d*)

$R = 13.18\,P + 86.5$ *(for Machakund, A.P.)* ...(4.50 *e*)

8. *UP Irrigation Research Institute formula*

$R = 5.45\,P^{0.6}$ (for Ganga, Haridwar) ...(4.51 *a*)

$R = 0.35\,P^{1.1}$ (for Vamuma at Tajewala) ...(4.51 *b*)

$R = 2.7\,P^{0.8}$ (for Sarda at Bana Basa) ...(4.51 *c*)

(C) RUN-OFF BY INFILTRATION METHOD

Infiltration is defined as the movement of water through the soil surface and into the soil. The capacity of any soil to absorb water from rainfall falling continuously at an excessive rate goes on decreasing with time, until a minimum rate to infiltration is reached. At any instant, the *infiltration capacity* of a soil is the maximun rate at which water will enter the soil in a given condition. The *infiltration rate* is the rate at which water actually enters the soil during a storm, and is equal to the infiltration capacity or the rainfall rate, whichever is less. The *infiltration capacity* of a soil can be determined experimentally by subjecting an experimental plot to rainfall rates in excess of infiltration capacity, and by measuring the surface run-off (Fig. 4.42). For small areas having uniform infiltration characteristics, the run-off volume can be estimated by subtracting infiltration from the design rainfall.

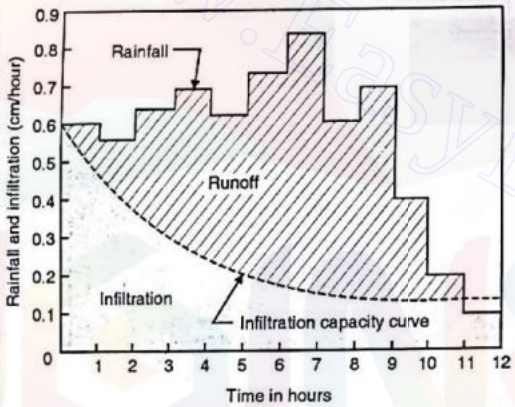

FIG. 4.42. INFILTRATION CAPACITY CURVE AND RUN-OFF

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. Estimate of run-off volume from large areas having heterogeneous infiltration loss and rainfall characteristics, are made by use of *infiltration indices.*

There are two types of infiltration indices :

(i) Average infiltraion rate or W-index and (ii) Φ-index.

The *W*-index is calculated from the expression :

$$W_i = \frac{P - R - S_R}{t_r} \text{ cm/hr} \qquad ...(4.52)$$

where t_r = duration of rainfall in hours., S_R = *surface retention.*

The Φ-index is defined as the average rate of rainfall above which the rainfall volume equal the run-off valume. Alternatively, it is defined as the average rate of loss such that the volume of rainfall in excess of that rate will be equal to volume of direct runoff. The runoff volume, above Φ-index is usually known as *rainfall excess* or *effective rainfall.*

Thus, $$\Phi_i = \frac{P - R}{t_r} \qquad ...(4.53)$$

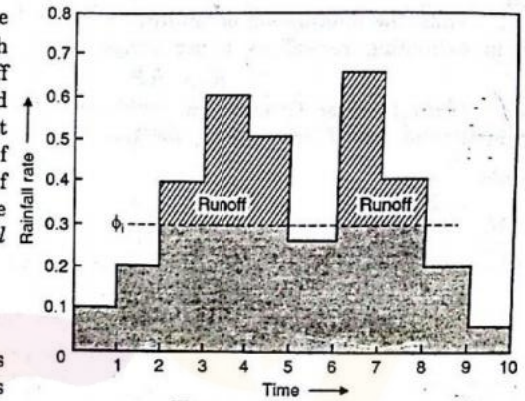

FIG. 4.43. Φ-INDEX AND RUN-OFF.

Thus, we find that *W*-index is essentially equal to Φ-index minus average rate of retention by interception and depression storage, and therefore, $W_i < \Phi_i$.. Again refer Fig. 4.44, from which

$$\Phi_i = \frac{\text{Total infiltration during periods of rainfall excess}}{\text{Total period of rainfallexcess } (t_{re})}$$

or $$\Phi_i = \frac{A_2 + A_4 + A_6}{t_{re1} + t_{re2} + t_{re3}}$$

where A_2, A_4, A_6 = infiltration during periods of rainfall excess

$t_{re1}, t_{re2}, t_{re3}$ = individual periods of rainfall excess

and W_i

$$= \frac{A_1 + A_2 + A_3 + A_4 + A_5 + A_6 + A_7}{t_r}$$

where t_r = total period of rainfall

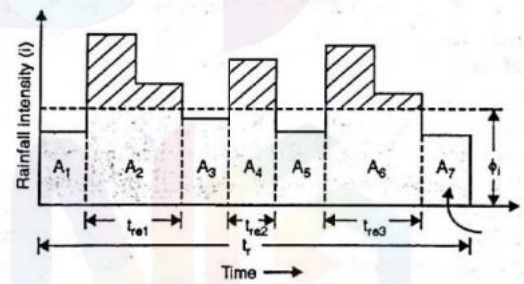

FIG. 4.44. DETERMINATION OF φ AND W_i

However, if there is uniform rain as shown in Fig. 4.45, Φ_i and W_i would be equal.

For flood forecasting, approximate index values must be derived by correlation with those factors which determine the index at any time. In such an approach, there seems to be no advantage over the method discussed earlier, in which the run-off and rainfall are correlated. However, the infiltraion index can be used to estimate the run-off coefficient (*k*) from the relation,

$$k = \frac{i - W_i}{i} \qquad ...(4.54)$$

where i = rainfall intensity (cm/hr).

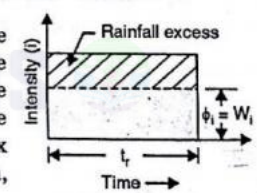

FIG. 4.45

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Thus, the information on infiltration can be used to estimate the run-off coefficient k in computing run-off as a percentage of rainfall, by the relation :

$$R = kP$$

Central Water Commission (CWC) gave the following equation, on the basis of rainfall and runoff co-relations, for the determination of Φ-index.

$$R = \alpha (i)^{1.2}$$

and

$$\Phi_i = \frac{i - R}{24} \qquad ...(4.55)$$

where R = runoff in cm from in 24 h rainfall.

i = rainfall intensity in cm/day

α = a coefficient which depends upon the soil type as given in Table 4.15.

TABLE 4.15. VALUE OF COEFFICIENT α

S.N.	Soil Type	α
1.	Sandy soil and sandy loam	0.17 to 0.75
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 0.5

If sufficient data is not available, Φ-index value may be assumed equal to 0.1 cm/h for the purpose of estimating maximum floods.

Effective rainfall hyetograph (ERH)

As seen earlier, a hyetograph is a plot of the intensity of rainfall against the time interval, and it is represented as a bar chart. If this hyetograph is prunned by deducting losses (i.e. initial loss and infiltration losses), the resulting hyetograph is known as *effective rainfall hyetograph* (ERH), or *hyetograph of rainfall excess* or *supra rainfall*

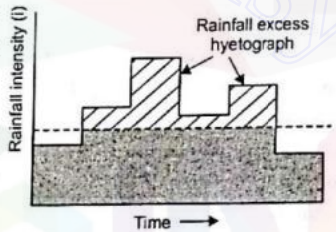

FIG. 4.46. EFFECTIVE RAINFALL HYETOGRAPH (ERH)

Example 4.17. *A watershed has the following data :*

1. *Area of watershed : 82 km²*
2. *Distance between the outlet and further most point : 12.6 km*
3. *Total length of channels of various orders : 440 km*
4. *Elevation difference between outlet and further most point : 656 m*

Determine (a) drainage density (b) form factor (c) channel slope and (d) average over land flow length.

Solution

(a) Drainage density, $D_d = \dfrac{\text{Total channel length}}{\text{Area of basin}} = \dfrac{440}{82} = \mathbf{5.37\ km/km^2}$

(b) Form factor, $F_f = \dfrac{A}{L_b^2} = \dfrac{82}{(12.6)^2} = \mathbf{0.517}$

(c) Channel slope $S = \dfrac{\Delta H}{L_b} = \dfrac{656}{12.6 \times 1000} = \dfrac{1}{\mathbf{19.21}}$

(d) Average overland flow length, $L_0 = \dfrac{1}{2\,D_d} = \dfrac{1}{2 \times 5.37} = 0.093\ \text{km} = \mathbf{93\ m}$

Example 4.18. *The rainfall rates for successive 30-minutes intervals upto 4 hours are given below. If the surface runoff is 3.6 cm, determine Φ and W indices.*

Time (minutes)	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 : (a) ***Computation of Φ-index***

Let i = rate of rain in cm/h and Φ-index be expressed in cm/h.

Then total $R = \Sigma (i - \Phi_i)\, t$ where t is the time in hours.

Assuming Φ_i to be greater than 1.3 cm/h, but less that 1.8 cm/h we have

$$3.6 = [(2.8 - \Phi_i) + (4.1 - \Phi_i) + (3.9 - \Phi_i) + (2.8 - \Phi_i) + (2.0 - \Phi_i) + (1.8 - \Phi_i)]\,\frac{30}{60}$$

From which we get Φ_i = **1.7 cm/h**

Since this is greater than 1.3 and less than 1.8 cm/h, the above computations are correct.

(b) ***Computation of W-index***

$$W_i = \frac{P - R - S_R}{t_r}$$

Here $P = 1.3 + 2.8 + 4.1 + 3.9 + 2.8 + 2.0 + 1.8 + 0.9)\,\dfrac{30}{60} = 9.8$ cm

$R = 3.6$ cm; $S_R = 0$ and $t_r = 4$ hours

$\therefore \quad W_i = \dfrac{9.8 - 3.6 - 0}{4} =$ **1.55 cm/h**

Example 4.19. *Table below gives the time distribution of a rainfall lasting for nine hours. If the direct runoff is 9.3 cm, determine the Φ-index of the storm and time of rainfall excess.*

Time from start (h)	1	2	3	4	5	6	7	8	9
Incremental rainfall in each hour (cm)	0.7	1.4	2.4	3.7	2.9	2.6	1.7	0.8	0.5

Solution

Total rainfall = 0.7 + 1.4 + 2.4 + 3.7 + 2.9 + 2.6 + 1.7 + 0.8 + 0.5 = 16.7 cm

Total runoff = 9.3 cm

∴ Total infiltration = 16.7 − 9.3 = 7.4 cm

First trial : Let the time of rainfall excess (t_{re}) be 9 hours

Then $\Phi_i = \dfrac{7.4}{9} = 0.822$ cm/hour.

This value of Φ_i makes rainfalls of first, eighth and ninth hour ineffective, as these magnitudes are less than 0.822 cm/hour.

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Second trial : Hence assume $t_{re} = 6$ hours in the second trial.

For this revised period, infiltration $= (16.7 - 9.3) - (0.7 + 0.8 + 0.5) = 5.4$ cm

$$\therefore \quad \Phi_i = \frac{5.4}{6} = 0.9 \text{ cm/hour.}$$

This value of Φ_i is satisfactory, since it gives $t_{re} = 6$ hours. Let us verify the *rainfall excess* (i.e. direct runoff) for these values.

Time from start (h)	1	2	3	4	5	6	7	8	9
Rainfall excess $= P - \Phi_i$	0	0.5	1.5	2.8	2.0	1.7	0.8	0	0

From the above table, rainfall excess (i.e. direct runoff) $= 9.3$ cm

Hence $\Phi_i = 0.9$ **cm/hour** and $t_{re} = 6$ **hours**

Example 4.20. *Table below gives the observed values of yearly precipitation (P) and corresponding yearly runoff (R) for a catchment, for a period of 16 years. Develop a linear correlation equation between P and R.*

Year	*1970*	*1971*	*1972*	*1973*	*1974*	*1975*	*1976*	*1977*
P (cm)	72.2	70.1	73.3	42.5	81.3	50.6	52.9	59.4
R (cm)	24.1	22.7	25.6	11.3	28.4	12.7	13.4	15.7
Year	*1978*	*1979*	*1980*	*1981*	*1982*	*1983*	*1984*	*1985*
P (cm)	60.3	64.3	68.8	56.7	77.2	40.5	44.1	65.5
R (cm)	16.2	17.7	19.2	14.9	25.4	10.6	11.7	17.9

Solution: Here, $N = 16$. Let the regression equation be $R = aP + b$.

Values of a and b are given by Eqs. 4.43.

The computations required for determination of a and b are done in a tabular form below.

S.N. of year	*P (cm)*	P^2 *(cm²)*	*R (cm)*	R^2 *(cm²)*	*PR (cm²)*
1	72.2	5212.8	24.1	580.8	1740.0
2	70.1	4914.0	22.7	515.3	1591.3
3	73.3	5372.9	25.6	655.4	1876.5
4	42.5	1806.3	11.3	127.7	480.3
5	81.3	6609.7	28.4	806.6	2308.9
6	50.6	2560.4	12.7	161.3	642.6
7	52.9	2798.4	13.4	179.6	708.9
8	59.4	3528.4	15.7	246.5	932.6
9	60.3	3636.1	16.2	262.4	976.9
10	64.3	4134.5	17.7	313.3	1138.1
11	68.8	4733.4	19.2	368.6	1321.0
12	56.7	3214.9	14.9	222.1	844.8
13	77.2	5959.8	25.4	645.2	1960.9
14	40.5	1640.3	10.6	112.4	429.3
15	44.1	1944.8	11.7	136.9	516.0
16	65.5	4290.2	17.9	320.4	1172.5
Σ	979.7	62356.9	287.5	5654.5	18640.4

From the Table, we have $\Sigma P = 979.7$; $(\Sigma P)^2 = (979.7)^2 = 959812$; $\Sigma P^2 = 62356.9$

$\Sigma R = 287.5$; $(\Sigma R)^2 = (287.5)^2 = 82656$; $\Sigma R^2 = 5654.5$

$\Sigma PR = 18640.4$

$$\therefore \quad a = \frac{N(\Sigma PR) - (\Sigma P)(\Sigma R)}{N(\Sigma P^2) - (\Sigma P)^2} = \frac{16 \times 18640.4 - (979.7) \times (287.5)}{16 \times 62356.9 - 959812} = \mathbf{0.4376}$$

$$b = \frac{\Sigma R - a\Sigma P}{N} = \frac{287.5 - 0.4376 \times 979.7}{16} = -8.826$$

Hence the equation is $\boldsymbol{R = 0.4376P - 8.826}$

Example 4.21. *For a catchment of 8.6 km² area, the mass curve of rainfall of 4 hours storm is given below. Determine the effective rainfall hyetograph and the volume of direct runoff from the catchment due to the above storm, taking Φ-index for the catchment as 0.8 cm/hour.*

Time from start of storm (h)	0	0.5	1	0.5	2	2.5	3	3.5	4
Accumulated rainfall (cm)	0	0.4	1.1	2.3	3.8	4.8	5.6	6.2	6.7

Solution : For any time interval Δt, effective rainfall $P_e = P - \Phi_i \Delta t$, or $= 0$, whichever is larger. For the data given above, $\Delta t = 0.5$ hours. Hence $\Phi_i \Delta t = 0.8 \times 0.5 = 0.4$ cm. The computations for ordinates of effective rainfall hyetograph are done in a tabular form below. Column (7) gives the ordinates of *effective rainfall hyetograph* (ERH). Fig. 4.47 gives the ERH of the storm.

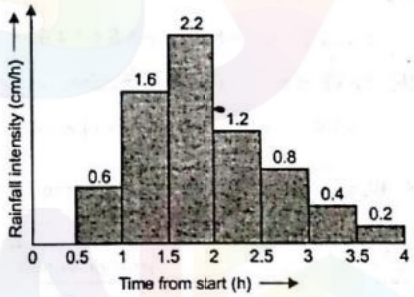

FIG. 4.47. EFFECTIVE RAINFALL HYETOGRAPH

Time from start (h)	*Time interval Δt (hours)*	*Accumulated rainfall (cm)*	*Depth of rainfall in Δt (cm)*	*Φ_i . Δt (cm)*	*Effective rainfall P_e (cm)*	*Intensity of effective rainfall (cm/h)*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)= (4) − (5)*	*(7) = (6)/Δt*
0	-	0	-	-	-	-
0.5	0.5	0.4	0.4	0.4	0	0
1.0	0.5	1.1	0.7	0.4	0.3	0.6
1.5	0.5	2.3	1.2	0.4	0.8	1.6
2.0	0.5	3.8	1.5	0.4	1.1	2.2
2.5	0.5	4.8	1.0	0.4	0.6	1.2
3.0	0.5	5.6	0.8	0.4	0.4	0.8
3.5	0.5	6.2	0.6	0.4	0.2	0.4
4.0	0.5	6.7	0.5	0.4	0.1	0.2

Direct runoff due to storm = Total effective rainfall = (Σ ordinates of ERH). Δt

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$= (0.6 + 1.6 + 2.2 + 1.2 + 0.8 + 0.4 + 0.2) \times 0.5 = \mathbf{3.5\ cm}$

Volume of direct runoff $= \frac{3.5}{100} \times 8.6\,(1000)^2 = \mathbf{30.1 \times 10^4\ m^3}$

Example 4.22. *The rate of rainfall for successive 30 minutes periods of a 4-hour storm are as follows :*

3.5, 6.5, 8.5, 7.8, 6.4, 4.0, 4.0, 6.0 cm/hr

Taking a value of Φ-index as 4.5 cm/hour compute the following :

(a) Total rainfall (b) Total rainfall excess, and (c) W_i.

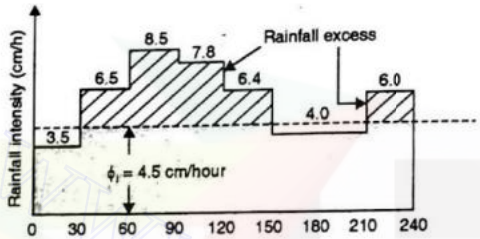

FIG. 4.48

Solution : The rainfall hyetograph is shown in Fig. 4.48 along with Φ-index

(a) Total rainfall,

$$P = (3.5 + 6.5 + 8.5 + 7.8 + 6.4 + 4.0 + 4.0 + 6.0) \times \frac{30}{60} = \mathbf{23.35\ cm}$$

(b) Total rainfall excess = Hatched area

$$= [(6.5 - 4.5) + (8.5 - 4.5) + (7.8 - 4.5) + (6.4 - 4.5) + (6.0 - 4.5)]\frac{30}{60} = \mathbf{6.35\ cm}$$

(c) $W_i = \frac{P - R}{t_r} = \frac{23.35 - 6.35}{4} = \mathbf{4.25\ cm/hour}$

Example 4.23. *A catchment area of 40 km² has one recording gauge. During a storm, the following mass curve of rainfall was recorded.*

Time from start of rainfall (h)	0	2	4	6	8	10	12	14
Accumulated rainfall (min.)	0	8	22	74	92	105	114	120

If the volume of runoff due to the storm measured is $2.0 \times 10^6\ m^3$, estimate the Φ-index of the catchment

Solution

Total run off volume $= 2.0 \times 10^6\ m^3$; Catchment area $= 40 \times (1000)^2\ m^2$

$\therefore$ Total runoff depth, $R = \frac{2.0 \times 10^6}{40 \times 10^6} = 0.05\ m = 50\ mm$

Total rainfall, $P = 120$ mm

$\therefore$ Total losses $= P - R = 120 - 50 = 70$ mm

Duration of rainfall, $t_r = 14$ hours.

$\therefore$ $W_i = \frac{P - R}{t_r} = \frac{120 - 50}{14} = 5$ mm/h

It is to be noted that Φ_i will be more than this. Hence infiltration loss in every 2 hour interval will be more than 2×5 or more than 10 mm. Table below gives the

incremental rainfalls in each 2 hour interval. From the column (3) of the table, we find that there is no rainfall excess in 3 intervals of time, out of 7 time intervals of 2 hours each. Hence *rainfall excess* is available only in 4 time intervals of 2 hours each. Hence time of effective rainfall, $t_{re} = 4 \times 2 = 8$ hours only.

Time from the start of storm (h)	*Accumulated rainfall (mm)*	*Incremental rainfall during each interval (mm)*
(1)	(2)	(3)
0	0	-
2	8	8*
4	22	14
6	74	52
8	92	18
10	105	13
12	114	9*
14	120	6*

Total rainfall excess $= (P - R) - (8 + 9 + 6) = 70 - 23 = 47$ mm

$\therefore$ $\Phi_i = \frac{47}{8} \simeq \mathbf{5.88\ mm/h}$

Example 4.24. *A 12-hour storm rainfall with the following depths in cm occurred over a basin :*

2.0, 2.5, 7.6, 3.8, 10.6, 5.0, 7.0 10.0, 6.4, 3.8, 1.4 and 1.4.

The surface run-off resulting from the above storm is equivalent to 25.5 cm of depth over the basin. Determine the average infiltration index for the basin.

Solution : Total rainfall in 12 hours

$= 2.0 + 2.5 + 7.6 + 3.8 + 10.6 + 5.0 + 7.0 + 10.0 + 6.4 + 3.8 + 1.4 + 1.4 = 61.5$ cm

Total run-off in 12 hours = 25.5 cm

$\therefore$ Total infiltration in 12 hours $= 61.5 - 25.5 = 36$ cm

$\therefore$ Average infiltration $= \frac{36}{12} = 3.0$ cm/hour.

It will be observed from the above data that rainfall is less than average infiltration in 1st, 2nd, 11th and 12th hour. Hence during these hours, rate of infiltration will be equal to the rainfall. In the central period, the rainfall is more than infiltration.

Hence if f is the average rate of infiltration during the central 8 hours, we have

$$8f + 2.0 + 2.5 + 1.4 + 1.4 = 36$$

or

$$8f = 36 - 7.3 = 28.7$$

$\therefore$ $f = \frac{28.7}{8} \approx 3.6$ cm/hour.

$\therefore$ Average rate to infiltration $\approx$ **3.6 cm/hour.**

Example 4.25. *From the storm data given in the previous example, determine the average depth of hourly rainfall excess for a basin of area of 120 hectares. The basin consists of areas A_1, A_2 and A_3 having average infiltration indices given below:*

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Area designation	A_1	A_2	A_3
Area (hectares)	20	40	60
Infiltration Index (Φ_i) *cm/hour*	7.6	3.8	1.0

Solution

The run-off coming out from the individual areas A_1, A_2 and A_3 will have to be spread over the entire basin and hence its depth will be reduced. The calculations are arranged in the tabular form below.

Time (h)	*Rainfall (cm)*	*Rain-fall excess from*			*Average rain-fall excess on basin from*			*Total hourly rainfall excess in cm/ hour over the entire basin*
		Area A_1 ($\Phi_i = 7.6$)	*Area* A_2 ($\Phi_i = 3.8$)	*Area* A_3 ($\Phi_i = 1.0$)	$A_1 = (3) \times \frac{20}{120}$	$A_2 = (4) \times \frac{40}{120}$	$A_3 = (5) \times \frac{60}{120}$	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	2.0	–	–	1.0	–	–	0.50	0.50
2	2.5	–	–	1.5	–	–	0.75	0.75
3	7.6	–	3.8	6.6	–	1.27	3.30	4.57
4	3.8	–	–	2.8	–	–	1.40	1.40
5	10.6	3.0	6.8	9.6	0.50	2.27	4.80	7.57
6	5.0	–	1.2	4.0	–	0.40	2.00	2.40
7	7.0	–	3.2	6.0	–	1.07	3.00	4.07
8	10.0	2.4	6.2	9.0	0.40	2.07	4.50	6.97
9	6.4	–	2.6	5.4	–	0.87	2.70	3.57
10	3.8	–	–	2.8	–	–	1.40	1.40
11	1.4	–	–	0.4	–	–	0.20	0.20
12	1.4	–	–	0.4	–	–	0.20	0.20

4.20. HYDROGRAPH ANALYSIS

A *hydrograph* is a graph showing variations of discharge with time, at a particular point of a stream. It shows the time distribution of total runoff at the point of measurement. As the runoff includes the contributions from surface run off, subsurface runoff (or inter flow) and ground water runoff (or base flow), the hydrograph can be regarded as an integral expression of the physiographic and climatic characteristics that govern the relations between rainfall and runoff. The factors affecting the hydrograph at a place being complex and inter-related, a basin may not produce two exact hydrographs with two similar precipitations as input, nor can two basins of the same drainage

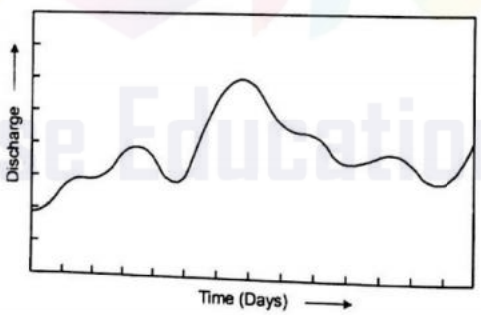

FIG. 4.49. STORM HYDROGRAPH

area produce the same flood hydrographs with similar precipitation. Since a hydrograph is generated from runoff due to precipitation resulting from either an isolated storm or a series of consecutive storms, (known as complex storm) it is also known as a *storm hydrograph*. The hydrograph resulting from an isolated storm will be a single peaked hydrograph, while there will be a multi-peaked hydrograph (Fig. 4.49) resulting from a complex storm.

Components of a single peaked hydrograph

Fig. 4.50 shows a single peaked hydrograph resulting from an isolated storm. The rainfall hyetograph, along with infiltration curve, is shown on the top of the diagram.

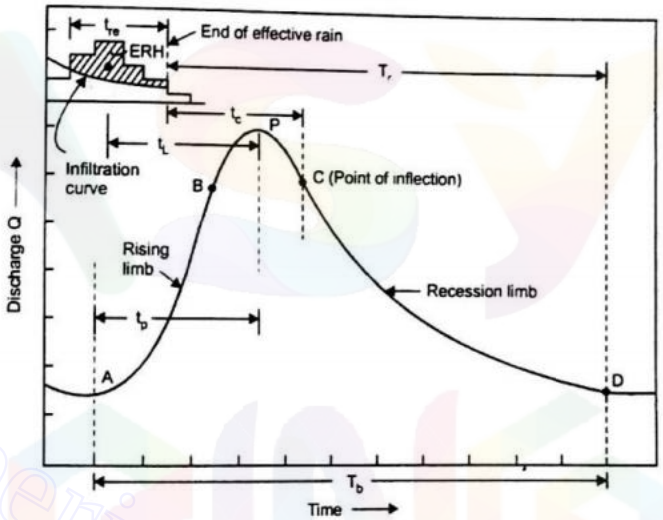

FIG. 4.50. COMPONENTS OF A SINGLE PEAKED HYDROGRAPH

There are three essential components of a single peaked hydrograph resulting from an isolated storm :

(*i*) The rising limb (*AB*) (*ii*) The peak or crest element (*BPC*) and (*iii*) The recession limb (*CD*)

(*i*) *Rising limb*

The rising limb *AB* (Fig. 4.50) is the ascending portion of the hydrograph corresponding the increase of discharge due to gradual formation of storage in the channels existing in the area and also over the watershed surface. The rising limb is also known as the *concentration curve*. In the early period of a storm, there are initial losses as well as high infiltration losses and hence the discharge rises slowly. As the time increases, the initial losses stop and the infiltration rate also decreases. Due to this, more and more discharge from the distant parts reach the basin outlet (i.e. the point of measurement). Point *A* is the starting point while *B* is the point of inflection. The shape of the

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rising limb is controlled by the characteristics of basin and duration, intensity and uniformity of the rain. The initial portion of the rising curve is concave due to the following reasons:

1. Greater losses due to interception, surface detention, evaporation and infiltration during initial period of rainfall.

2. Heavier concentration of area between adjacent isochrones is laid between middle and upper part of the watershed.

(ii) *The peak or crest segment (BPC)*

The peak or crest segment includes the part of the hydrograph from the inflection point (B) on the rising limb to an inflection point (C) on the recession limb. Crest segment is one of the most important component of the hydrograph because it indicates the peak flow rate. The peak represents the arrival of flow at the outlet from all parts of the basin. For large catchment, the peak flow (point P) occurs after the cessation of rainfall. The time interval between centre of mass of rainfall to the peak (designated as t_L) is controlled by the characteristics of both the basin as well as the storm. The peak may be sharp or flat depending upon the rainfall-catchment characteristics. Multiple peaked complex hydrographs in a basin can occur when two or more storms occur in close succession. The *point of inflection* represent the change point of contribution of the catchment to the channel system. The end of the crest segment, corresponding to the inflection point C, marks the time when direct runoff from the overland flow (excess rainfall) into the stream outlet ceases. The point of inflection (C) represents the condition of maximum detention storage (i.e. depth of water built-up over the land surface).

(iii) *The recession limb (CD)*

The recession limb extends from the point of inflection (point C) of the crest segment to the point D, the point of commencement of the natural ground water flow. The recession limb indicates the storage contribution from surface storage (which includes both the surface detention and channel storage), interflow and ground water flow. Since the depletion of this detention storage takes place after the cessation of rainfall, the shape of the recession curve depends only on the basin characteristics and is independent of rainstorm characteristics. The *recession curve can be considered as a rate of discharge resulting from be draining off process.* The equation of the recession curve may be expressed in the following form (Barnes, 1940) :

$$Q_{rt} = Q_{ro} K_r^t \qquad ...(4.56)$$

where Q_{rt} = discharge at any time interval t (days) after the point of inflection C

Q_{ro} = discharge at the point of inflection C (at $t = 0$)

K_r^t = recession constant with a value less than unity.

Barnes observed that the above equation holds good for the lower portion of the curve where the contribution is mainly from ground water. For the upper portion of the curve where the contribution of discharge is from all the three phases (i.e. surface storage, subsurface flow and ground water flow) the recession constant K_r^t is composed of all the three components, and is given by

$$K_r^t = K_{rs} \cdot K_{ri} \cdot K_{rg} \qquad ...(4.57)$$

where K_{rs} = recession constant for surface storage (value varying from 0.08 to 0.4)

K_{ri} = recession constant for interflow (value varying from 0.55 to 0.9)

and K_{rg} = recession constant for ground water flow (value varying from 0.9 to 1)

Time parameters used in hydrograph analysis

1. ***Effective time duration*** (t_{re}): It is the net duration of precipitation during which rainfall rates are more than infiltration rates.

2. ***Lag time or basin lag*** (t_L) : It is the time interval between the centre of mass of *net rainfall* (or rainfall excess) and centre of mass of runoff hydrograph. *More commonly,* it is also taken as the time lapse between the centre of mass of effective rainfall and the peak (P) of the hydrograph, as marked in Fig. 4.50.

3. ***Time to peak*** (t_p) : It is the time interval between the starting of the rising limb (A) to the peak (P) of the hydrograph, as shown in Fig. 4.50.

4. ***Time of concentration*** (t_c) : The time of concentration (t_c) is defined in two ways. In terms of physical characteristics of watershed, it is defined as the travel time of a water particle from the hydraulically most remote point in the basin to the outflow location. However, based on rainfall and hydrograph characteristics, it is taken as the time from the end of the net rainfall to the point of inflection (C) of the falling limb of the hydrograph. It is estimated by the following formula by Kirpich (1940)

$$t_c = \frac{0.000323\, L^{0.77}}{S^{0.385}} \qquad ...(4.58)$$

where t_c = time of concentration, in hours

L = maximum length of travel of water in metres.

S = slope of the channel $= H/L$

H = difference in elevation between the remote point in the channel and the outlet point.

5. ***Recession time*** (T_r) : It is the duration of direct runoff after the end of the effective rainfall duration. Thus, it is the difference in time between the end of effective rainfall and lowest point (D) of the recession limb.

6. ***Time base of hydrograph*** (T_b) : It is the time from which *direct runoff* begins to the time when it stops. In other words, it is the time from the beginning point (A) to the end point (D) of the direct runoff.

Separation of base flow

There are three popular methods of separation of base flow and direct runoff in a single peaked storm hydrograph shown in Fig. 4.50. The point A on the hydrograph (Fig. 4.50), which represents the beginning of the direct runoff, can be easily identified in view of sharp change in the run off rate at that point. But, the point D which marks the end of the direct runoff can not be easily located. However, an empirical equation for the time interval N (days) from the peak (P) to the point D is :

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$$N = 0.827\,A^{0.2} \qquad ...(4.59)$$

where A = area of drainage basin in km^2

Another empirical equation to determine N is given by

$$N = a\,t_p \qquad ...(4.60)$$

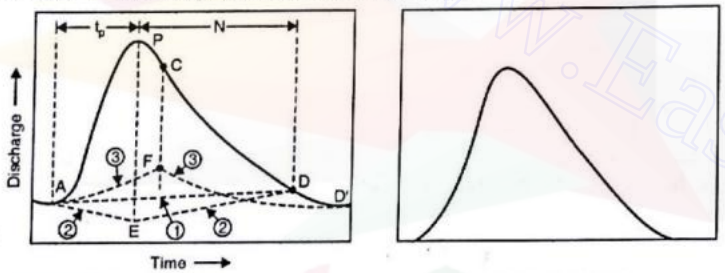
where t_p = time to peak = time interval between beginning point A and peak P.

a = constant whose value may be taken between 2 to 4 for small basins and 4 for large basins.

Thus the two points where the direct runoff begins (i.e. point A) and ceases (i.e. point D) are identified.

Method 1 : Straight line method

Fig. 4.51 (a) shows the two points A and D which mark the beginning and end of direct runoff. In the straight line method, points A and D are joined by a straight line AD. This is the simplest method of separation.



(a) Three methods of separation (b) Resulting DRH

FIG. 4.51.

Method 2 : Two lines method

This is most widely used method in which the base flow is separated from direct runoff by two lines. The first line AE is obtained by extending the base flow curve, existing prior to the commencement of the surface runoff, till it intersects a vertical line, drawn from the peak (P) in a point E. Point E (so obtained) and point D, located earlier, are joined by a straight line. The segments marked by two line AE and ED demarcate the base flow and direct runoff.

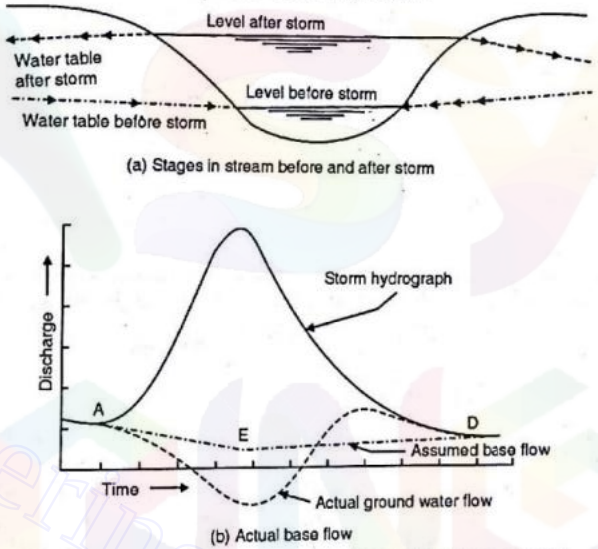
Method 3 : Curves extension method

This method consists of extending the base flow curve on recession side backward till it intersects a vertical line through the point of inflection (C), in point F. Thus, in Fig. 4.51 (a), $D'F$ is the curve extended backwards. Points A and F are then joined by an arbitrary smooth curve. Thus the two segments marked by two curves AF and FD' demarcate the base flow and direct runoff. This method is preferred where the stream and ground water table are hydraulically connected and flow from ground water storage (the contribution of which may be significant) reaches the stream quickly.

The surface runoff hydrograph obtained after the base flow separation is known as *direct runoff hydrograph* (DRH), such as the one shown in Fig. 4.51 (b).

Actual base flow or depletion curve

The base flow or depletion curve AED (or AD, or AFD') determined above (Fig. 4.51 a) are, theoretical and may not represent actual conditions at the site. Actual contribution of ground water is shown by dotted line in Fig. 4.52 (b). As shown in Fig. 4.52 (b), when the water level before the storm is low, there is a flow from ground water to the stream. But as the water level in the stream is raised due to storm, there is a flow from the stream to the ground water. As the flood level in the stream recedes, the ground water again starts contributing to the stream. Thus, AED denotes the ground water line only if there were no flood. However, since the ground water contribution is small percentage of total flow, it is usually considered justified that the flow above the line AED is due to direct runoff.



(a) Stages in stream before and after storm

(b) Actual base flow

FIG. 4.52. ACTUAL BASE FLOW OR DEPLETION CURVE.

4.21. COMPUTATION OF DIRECT RUN-OFF OR RAIN FALL EXCESS FROM STORM HYDROGRAPH.

Procedure (Refer Table 4.16).

1. Find the ordinates of storm hydrograph, representing total discharge Q at a given time interval, say t hours.

2. Separate the ground water flow. Find the ordinates of the base flow at the same time interval.

3. Find the ordinates of direct run-off by subtracting the ordinates of base flow from total discharge ordinates.

4. The direct run-off in depth of water (in cm) is found from the expression

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$$\text{Direct run-off} = \frac{\text{Total volume of direct run-off}}{\text{Area of basin}} = \left[\frac{(\Sigma O) \times t \times 60 \times 60}{A \times 10^6}\right] \times 100$$

$$= 0.36 \frac{(\Sigma O) \times t}{A} \text{ cm.} \qquad ...(4.61)$$

where t = Time interval between successive ordinates in hours.
A = Area of basin in sq. km.
Q = Discharge in cumecs.
ΣO = Sum of discharge ordinates (direct run-off) in cumecs.

TABLE 4.16

Date and Time (1)	*Ordinate of hydrograph : Total Q (cumecs)* (2)	*Base flow (cumecs)* (3)	*Direct run-off (O)* (4)
14-8-65			
0500	14	14	0
0800	25	12	13
1100	51	11	40
1400	65	10	55
1700	54	11	43
2000	28	13	15
2300	14	14	0
			ΣO = 166

For the example of Table 4.16, if area of the basin is 30 sq. km,

$$\text{Direct run-off} = 0.36 \frac{(\Sigma O) \times t}{A} = 0.36 \frac{166 \times 3}{30} = \mathbf{5.98\ cm}$$

4.22. UNIT HYDROGRAPH (UH)

A unit hydrograph is a hydrograph representing 1 cm (or 1 inch) of run off from a rainfall of some *unit duration* and *specific areal distribution*. Unit duration refers to the duration of a run-off producing rainfall-excess, that results in a unit hydrograph. For example, if a unit hydrograph results from a 3 hours unit rainfall duration, it is known as a 3-hours unit hydrograph, meaning thereby a hydrograph produced by surface run-off from a storm lasting for 3 hours and yielding rainfall excess of 1 cm. The unit duration may vary from one day for large catchments to a few hours for a small catchments. Experience has shown that best unit duration is about one fourth of the *basin lag*, the time from the centre of mass of net rainfall to the peak of the hydrograph. Sherman (1942) suggested the following values of *unit time duration* (Table 4.17)

TABLE 4.17. SUGGESTED VALUES OF UNIT TIME DURATION

Area of Basin	*Unit time duration (hours)*
> 2500 km^2 (1000 mile^2)	12 to 24 (preferably 12)
250 – 2500 km^2 (100 – 1000 mile^2)	6, 8 or 12
50 – 250 km^2 (20 mile^2)	2
Small areas	One third to one fourth of the time of concentration.

The basis of the unit hydrograph concept, first given by L.K.Sherman (1932) is that if two identical rain storms could occur over a drainage basin with identical conditions prior to the rain, the hydrographs of run-off from the two storms would be expected to be the same. The basic premise implies that the rainfall excess of n centimetres within the selected unit duration will give a run-off hydrograph having ordinates n times as great as those of unit hydrograph of the same unit duration.

Assumptions of Unit Hydrograph Theory. The assumptions of unit hydrograph theory must be properly understood before applying it to actual problems, as these assumptions impose certain limitations which must be carefully noted. The various assumptions are given below.

1. The effective rainfall is uniformly distributed within its duration of specified period of time.
2. The effective rainfall is uniformly distributed throughout the whole area of the drainage basin.
3. The base or time duration of the hydrograph of direct run-off due to an effective rainfall of unit duration is constant.
4. The ordinates of direct run-off of common base-time are directly proportional to the total amount of direct run-off represented by each hydrograph.
5. For a given drainage basin the hydrograph of run-off due to a given period of rainfall reflects all the combined physical characteristics of the basin.

CONSTRUCTION OF UNIT HYDROGRAPH

The following are the steps for constructing a unit hydrograph of some unit duration from a storm hydrograph of the same unit duration (Fig. 4.53 and Table 4.18):

1. From the past records, select some unit period of intense rainfall duration corresponding to an isolated storm uniformly distributed over the area.

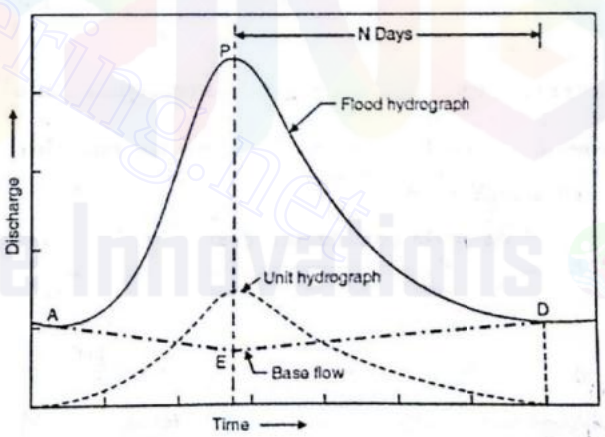

FIG. 4.53. CONSTRUCTION OF UNIT HYDROGRAPH

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TABLE 4.18

Date	Hour	Total Q (cumecs)	Base flow (cumecs)	Ordinates of direct run-off (cumecs)	Ordinates of unit hydrograph
(1)	(2)	(3)	(4)	(5)	(6) = (5) / D. R. O. in cm
12 Aug.	0600	6	6.0	0	0
	0800	8	6.0	2.0	0.08
	1000	10	5.5	4.5	0.19
	1200	16	5.0	11.0	0.47
	1400	28	4.5	23.5	0.99
	1600	42	4.0	38.0	1.61
	1800	60	3.5	56.5	2.39
	2000	80	3.0	77.0	3.25
	2200	110	2.5	107.5	4.54
13 Aug.	2400	100	2.5	97.5	4.11
	0200	90	2.5	87.5	3.70
	0400	80	3.0	77.0	3.25
	0600	68	3.0	65.0	2.74
	0800	56	3.5	52.5	2.22
	1000	45	3.5	41.5	1.75
	1200	35	4.0	31.0	1.31
	1400	26	4.0	22.0	0.92
	1600	18	4.5	13.5	0.57
	1800	11	4.5	6.5	0.27
	2000	9	5.5	4.0	0.17
	2200	8	5.5	2.5	0.11
14 Aug.	2400	7	5.5	1.5	0.06
	0200	6	6.0	0	0
				$\Sigma O = 822$	

2. From the past records of the river discharge for that storm, plot the storm hydrograph for some days before and after the period of rainfall of that unit duration.

3. By the method indicated in § 4.20, separate the ground water flow (base flow) from the direct run-off.

4. Subtracting the ordinates of base flow from the total ordinates, find the ordinates of direct run-off.

5. Calculate direct run-off n (in centimetres) by the expression :

$$\text{Direct run-off, } n = 0.36 \frac{(\Sigma O) \times t}{A} \text{ cm} \qquad ...(4.61)$$

where ΣO = Sum of the discharge ordinates (direct run-off) in cumecs.
t = Time interval between successive ordinates in hours.
A = Area of drainage basin in sq. km.

6. Calculate the ordinates of unit hydrograph by the relation :

$$\text{Ordinate of unit hydrograph} = \frac{\text{Ordinate of direct run-off}}{\text{Direct run-off } n \text{ in cm}}$$

The calculations may be arranged in a tabular form shown in Table 4.18. From Table 4.18, $\Sigma O = 822$.

Area of basin = 25 sq km.

$$\therefore \quad \text{Direct run-off} = 0.36 \frac{(\Sigma O) \times t}{A} = \frac{0.36 \times 822 \times 2}{25} = 23.7 \text{ cm.}$$

APPLICATION OF THE UNIT HYDROGRAPH TO THE CONSTRUCTION OF A FLOOD HYDROGRAPH RESULTING FROM RAINFALL OF UNIT DURATION

The unit hydrograph can be used to construct a flood hydrograph resulting from rainfall of the same unit duration for which the unit hydrograph is available. The number of unit hydrographs for a given drainage basin are theoretically infinite since there may be one for every possible duration of rainfall and every possible distribution pattern in a basin. Practically only a limited number of unit hydrographs can be used for a given basin. The unit hydrograph selected for computing the flood hydrograph should be corresponding to the storm of like duration and pattern. However, a tolerance of as much as 25 % of the unit-hydrograph duration can ordinarily be accepted without much serious error. Thus a 6-hour unit hydrograph may be applied for storms of 4.5 to 7.5 hours duration. Alternatively, unit hydrograph having a similar range in duration may be averaged to obtain an average unit hydrograph.

Procedure. The calculations for the storm hydrograph corresponding to n cm of rainfall-excess (or direct runoff) are done in the tabular form below (Table 4.19).

Direct run-off ordinates = (ordinates of unit hydrograph) × n cm.

TABLE 4.19 ($n = 8$ cm)

Date	Hour	Ordinates of unit hydrograph (cumecs)	Ordinates of direct runoff (4) = (3) × n	Base flow (cumecs)	Total discharge ordinates
(1)	(2)	(3)	(4)	(5)	(6) = (4) + (5)
22 August	0600	0.00	0	4.0	4
	0900	0.12	0.96	3.5	4.46
	1200	0.35	2.80	3.0	5.80
	1500	0.88	7.04	2.5	9.54
	1800	1.50	12.00	2.0	14.00
	2100	2.80	22.40	1.5	23.90
	2400	2.00	16.00	1.8	17.80
	0300	1.85	14.80	2.1	16.90
	0600	1.53	12.24	2.4	14.64
	0900	1.26	10.08	2.7	12.78
	1200	0.84	6.72	3.0	9.72
	1500	0.50	4.00	3.3	7.30
	1800	0.35	2.80	3.6	6.40
	2100	0.12	0.96	3.8	4.76
	2400	0.00	0.0	4.0	4.0

APPLICATION OF UNIT HYDROGRAPH TO CONSTRUCTION OF A FLOOD HYDROGRAPH RESULTING FROM TWO OR MORE PERIODS OF RAINFALL

A unit hydrograph of some specific unit duration can also be utilised for construction of flood hydrograph resulting from the rainfall lasting for a long duration. The essential condition, however, is that the storm pattern should be the same as that for the unit

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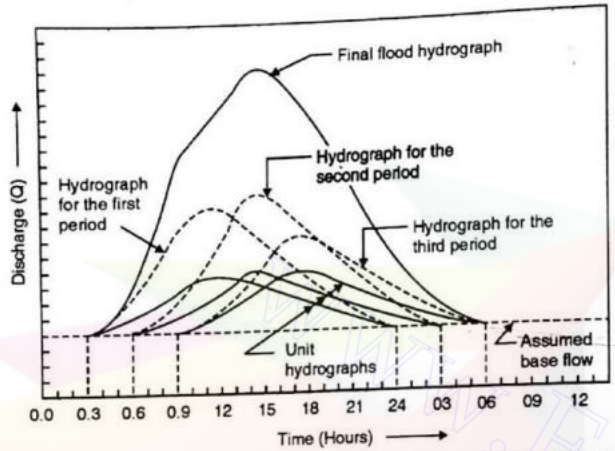

FIG. 4.54. FLOOD HYDROGRAPH RESULTING FROM A STORM OF LONGER DURATION

hydrograph. As an example, let us say that a 3-hours unit-hydrograph is available, and it is required to compute the flood hydrograph resulting from a rainfall lasting for 9 hours with variable intensities of rainfall — the intensity rates having n_1 cm/3-hours for the first period of 3 hours, n_2 cm/3 - hours for the second 3 hours, and n_3 cm/3-hour for the last 3 hours. The storm is divided into 3 parts, and the flood hydrograph of each part is computed separately and added. The hydrographs for the second part of the storm starts 3 hours later than that for the first part. Similarly, the hydrograph for the third part of the storm starts 6 hours later than that for the first, or 3 hours later than that for the second part (Fig. 4.54). See Example 4.28 for illustration.

4.23. S-HYDROGRAPH (SUMMATION HYDROGRAPH)

S-hydrograph or S-curve is a hydrograph that is produced by a continuous effective rainfall at a constant rate for indefinite period. It is a continuous rising curve, in the form of letter S, till *equilibrium* is reached. At the time of equilibrium, it will represent a constant rate of continuous effective rainfall, say R_0 cm per hour. At the time of equilibrium, the S-curve will represent a run-off discharge given by

$$Q_0 = \frac{(A \times 100 \times 100)\, R_0}{100 \times 3600} = \frac{A\, R_0}{36} \text{ cumecs} \qquad ...(4.62)$$

where A is the catchment area in hectares.

If the catchment area A is in square kilometres, the discharge represented by S-curve, at the time of equilibrium is given by

$$Q_0 = \frac{(A \times 1000 \times 1000)\, R_0}{100 \times 3600} = 2.778\, A\, R_0 \text{ (cumecs)} \qquad ...(4.63)$$

The S-hydrograph or S-curve is constructed by adding together a number of unit hydrographs of unit time duration (T_0) spaced at a unit time duration T_0 (*i.e.* duration of effective rainfall). This is illustrated in Table 4.20 and Fig. 4.56.

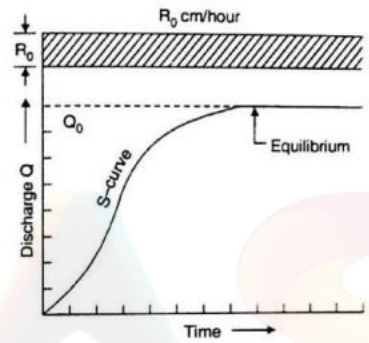

FIG. 4.55. S-HYDROGRAPH

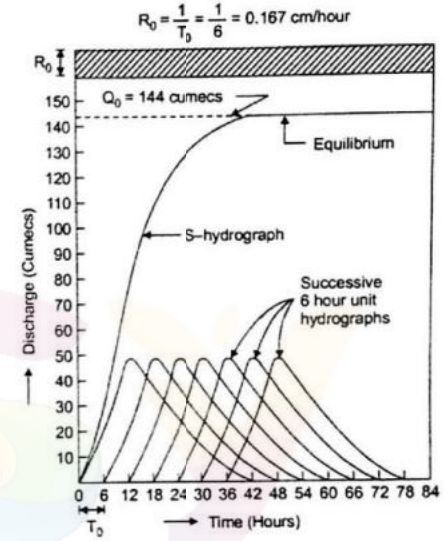

FIG. 4.56. DERIVATION OF S-HYDROGRAPH FROM UNIT HYDROGRAPH

TABLE 4.20. COMPUTATIONS FOR S-HYDROGRAPH

Time	*Ordinate of unit hydrograph*	*Ordinates of successive unit hydrographs*						*Ordinate of S-hydrograph*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*
00	0	–	–	–	–	–	–	0
03	9	–	–	–	–	–	–	9
06	20	0	–	–	–	–	–	20
09	35	9	–	–	–	–	–	44
12	49	20	0	–	–	–	–	69
15	43	35	9	–	–	–	–	87
18	35	49	20	0	–	–	–	104
21	28	43	35	9	–	–	–	115
24	22	35	49	20	0	–	–	126
27	17	28	43	35	9	–	–	132
30	12	22	35	49	20	0	–	138
33	9	17	28	43	35	9	–	141
36	6	12	22	35	49	20	0	144
39	3	9	17	28	43	35	9	144
42	0	6	12	22	35	49	20	144

Let us have a 6-hour unit hydrograph and construct a S-curve from it. Here T_0 = 6 hours. Column 1 of Table 4.20 shows the time intervals while column 2 shows the ordinates of a 6-hour unit hydrograph for a drainage basin having area A = 311

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sq. km. Columns 3, 4, 5, 6, 7, 8 show the ordinates of successive unit hydrographs, each shifted by the unit time interval = T_0 = 6 hours. Column 9 shows the horizontal summation of the ordinates of the original unit hydrograph (column 2) and various successive unit hydrographs. Evidently, column 9 gives the ordinates of S-hydrograph. The summation is continued upto the time equal to the base of the unit hydrograph minus one unit duration (T_0 = 6 hrs.) to reach the equilibrium rate of discharge. It should be noted that the ordinates of S-hydrograph approach the rate corresponding to the effective rainfall (R_0) at the time of equilibrium. For the present case, the equilibrium discharge is given by

$$Q_0 = 2.778\,AR_0 \qquad ...(4.63)$$

where R_0 = constant rate of continuous effective rainfall $= \frac{1}{T_0}$ cm/hour $= \frac{1}{6}$ cm/hour

A = catchment area in sq. km = 311 sq. km

$$\therefore \quad Q_0 = \frac{2.778 \times 311}{6} = 144 \text{ cumecs.}$$

This rate is reached in Table 4.20 at 36 hours (= base period – T_0 hours).

Alternative Method

An *alternative simple method* to compute ordinates of S-hydrograph is illustrated in Table 4.21 for the same data. Column 1 shows Line No., Column 2 shows time, while column 3 shows the ordinates of unit hydrograph. Column 5 shows the ordinates of S-hydrograph (to be computed) in which the values in the first two lines (upto T_0 = 6 hours) are the same as the corresponding values of unit hydrograph in column (3). These two values of Lines 1 and 2 of column (5) are entered in column 4 (offset ordinates) at an offset = T_0 = 6 hours against line 3 and 4 respectively.

TABLE 4.21. COMPUTATIONS FOR S-HYDROGRAPH (ALTERNATIVE METHOD)

Line No. (1)	*Time (hours)* (2)	*Ordinates of 6-hours unit hydrograph* (3)	*Off-set ordinates* (4)	*Ordinates of S-hydrograph (R_0=1/6 cm/hr.)* (5)
1	00	0	–	0
2	03	9	–	9
3	06	20	0	20
4	09	35	9	44
5	12	49	20	69
6	15	43	44	87
7	18	35	69	104
8	21	28	87	115
9	24	22	104	126
10	27	17	115	132
11	30	12	126	138
12	33	9	132	141
13	36	6	138	144
14	39	3	141	144
15	42	0	144	144

Now lines 3 and 4 of columns (3) and (4) are respectively added horizontally, and entered in lines 3 and 4 of column (5), thus giving values of ordinates as 20 + 0 = 20 and 35 + 9 = 44 cumecs. These two values of lines 3 and 4 of column (5) are shifted to lines 5 and 6 respectively of column 4. Now lines 5 and 6 of columns (3) and (4) are respectively added horizontally and entered in lines 5 and 6 respectively, of column 5 thus getting ordinates of 69 and 87. This process of shifting or offsetting the ordinates of column (5) by time interval T_0, entering into column (4) and adding with corresponding ordinates of column (3) to get new ordinates for column (5) is continued, till the base of the unit hydrograph is reached, or till the equilibrium discharge is reached. Sometimes, the computed ordintes of S-curve may not fall along a smooth curve. In that case, smoothening is carried out and the corresponding new ordinates along smoothened curves are found.

It should be noted that the S-hydrograph so derived from a 6 hours unit hydrograph represents contant $R_0 = 1/T_0$ = 1/6 cm/hour. The technique of constructing a S-hydrograph is very useful in deriving a unit hydrograph of shorter or longer unit duration from a given unit hydrograph of same unit duration. This is explained in the next article.

4.24. CONSTRUCTION OF UNIT HYDROGRAPH OF DIFFERENT UNIT DURATION FROM A UNIT HYDROGRAPH OF SOME GIVEN UNIT DURATION

(a) Construction of Longer Period Unit hydrograph from a Given Unit Hydrograph of Shorter Unit period

Let it be required to derive a unit hydrograph of unit duration t_o hours, from a unit hydrograph of unit duration T_0 where $t_0 > T_0$. If t_0 is an integral multiple of T_0, this can be done by the simple principle of superposition.

Let it be required to derive a unit hydrograph of 6 hour unit duration (t_0 = 6 hours) from a given unit hydrograph of 2 hour duration (T_0 = 2 hours). This can be obtained by taking the sum of the ordinates of the *three* unit hydrographs of 2 hours duration, each lagging from the other by 2-hours, and dividing the sum by 3. This is illustrated in Fig. 4.57, in which it is clear that the peak discharge (Q_m') of the new hydrograph is less than Q_m of the original hydrograph, and also that the peak occurs later. If, however, t_0 is not an integral multiple of T_0, the method of S-hydrograph is used, as described below.

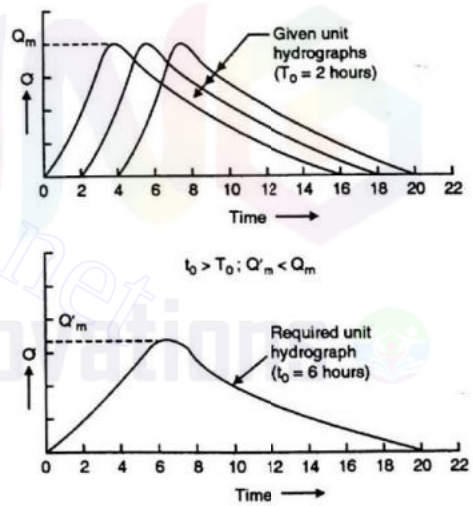

FIG. 4.57

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