

Table of Contents

CHAPTER FOUR.....	2
INFILTRATION AND PERCOLATION	2
4.1 INTRODUCTION	2
4.2 FACTORS AFFECTING INFILTRATION RATE	5
4.3 CHARACTERISTICS OF INFILTRATION AND PERCOLATIONS	8
4.4 COMPONENTS OF INFILTRATION PROCESS	14
4.5 MEASUREMENT OF INFILTRATION METHODS	15
4.5 analysis of percolation (reading assignment).....	21
CHAPTER FIVE	22
RAINFALL-RUNOFF RELATION.....	22
5.1 Rainfall-Runoff Relationships	22
5.2 Rainfall distribution over the basin.....	24
5.3 Rainfall runoff correlation ship.....	26
Chapter 6.....	32
Stream flow measurement.....	32
6.1 Measurement of discharge	32
Introduction to Stream Flow (Discharge Rates) Measurements	32
6.1.1 Area-Velocity method.....	34
6.1.2 The stage-discharge relation	35
6.2 Extreme value statistics.....	36
6.2.1 Flow Frequency	37
6.3 Extreme Probability	40
6.3.1 Selection of Data.....	40
6.3.2 Plotting Positions	41
6.3.3 Theoretical Distributions of extreme	42
6.4 Confidence Limits for the fitted data	50
6.5 Precipitation Probability	51
6.6 Low Flow Analysis	52
6.6 Risk, Reliability and Safety factor	54

CHAPTER FOUR

INFILTRATION AND PERCOLATION

4.1 INTRODUCTION

Infiltration is the flow of water through the soil surface into a porous medium under gravity action and pressure effects.

Infiltrated water first meets the soil moisture deficiency, if any and there after the excess water moves downward to reach the ground table. The vertical movements of water are called **percolation**.

When water applied at the surface of the soil, four-moisture zone in the soil:-

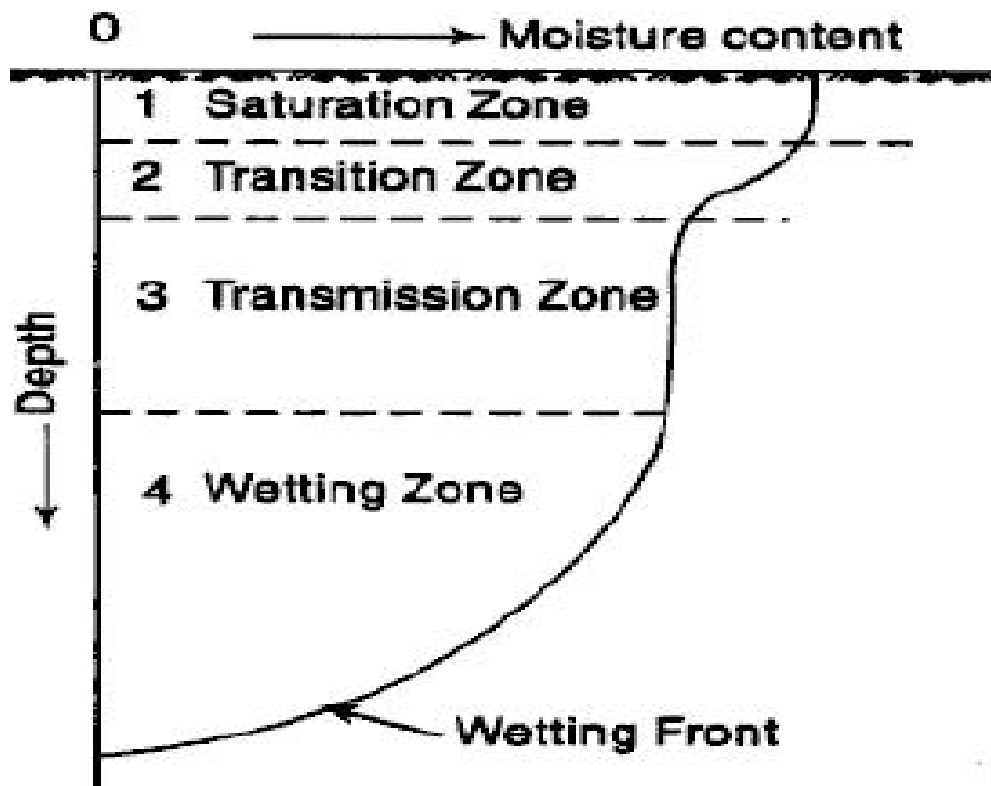


Figure 4.1 moisture zones of soils

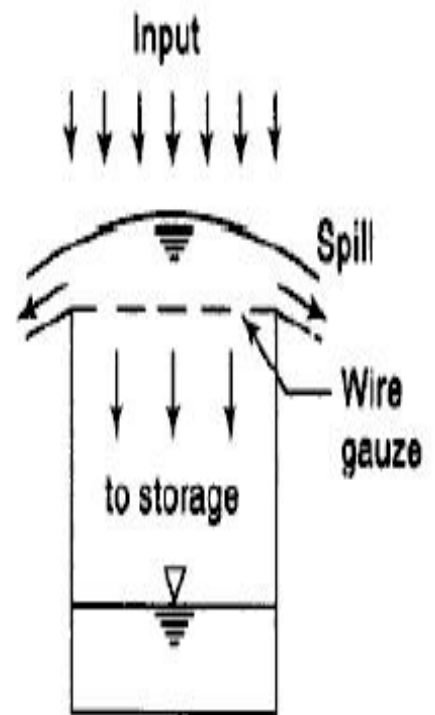
Zone 1: at the top, a thin layer of saturated zone is created. The zones where soil voids space are completely filled with water.

Zone 2: the beneath of zone 1, there is transition zone.

Zone 3: next to lower zone is the transmission Zone where the downward movement motions of the moisture take place. The moisture contents in the in this zone is above the field capacity but below the saturation. Further, it is characteristics by unsaturated flow and fairly uniform moisture content.

Zone 4: The last zone is the *wetting zone*. The soil moisture in this zone will be at or near field capacity and the moisture content decreases with the depth. The boundary of the wetting zone is the wetting front where a sharp discontinuity exists between the newly wet soil and original moisture content of the soil. Depending upon the amount of infiltration and physical properties of the soil, the wetting front can extend from a few centimetres to metres.

The infiltration process can be easily understood



Infiltration characteristics

The infiltration capacity is the maximum rate at which water can be absorbed by a given soil per unit area under given conditions.

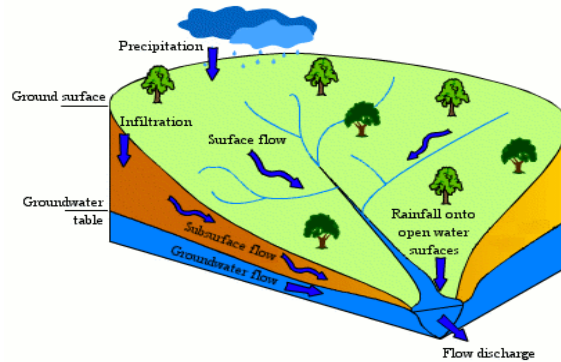


Figure: The infiltration process depending on soil type and flow [Musy,2001]

Infiltration regime $i(t)$ depends on the supply regime (irrigation, rain), but also on soil properties. The cumulative infiltration $I(t)$, is the total amount of water infiltrated during a given period.

$$I(t) = \int_{t=t_0}^t i(t) dt$$

Where: $I(t)$: the cumulative infiltration during the t period (mm)

$i(t)$: the infiltration regime during the t period (mm/hr)

Hydraulic conductivity at saturation k_s , is an essential parameter of infiltration. It represents the limiting value of infiltration if the soil is saturated and homogenous.

Percolation is the vertical water flow in soils (porous unsaturated environment) on the groundwater layer under the influence of gravity. This process follows infiltration and has a major influence on the underground layer water supply.

Net rain is the amount of rain that falls to the ground surface during a shower. The clear rains are deduced from the total rain, diminished by the intercepted fraction of vegetation and that,

which is stored in ground depressions. The difference between the infiltrated rain and the drained rain on the ground surface is called production function.

4.2 FACTORS AFFECTING INFILTRATION RATE

Infiltration rate of the soil is affected by the following factor:

1. Rainfall intensity
2. Soil properties
3. Surface cover
4. Climatic factor

The main factors that influence the infiltration are:

Rainfall factor: it included the following sub factor affecting the infiltration rate:

1. Rainfall intensity
2. Form of precipitation
3. Rainfall duration

Rainfall intensity is expressed as cm/hr, mm/hr is affected by the following ways :

- ✓ When Rainfall intensity is less than the infiltration capacity, in this case rainwater is absorbed by the soil.
- ✓ Rainfall intensity is greater than the infiltration capacity, in this case infiltration rate decreased due to the following reason:
 - ✚ Increment in supply of the moisture to the soil.
 - ✚ In washing of the soil.

If the soil is moisture, result in to reduction of infiltration rate due to decrease in take capacity of the pore space.

2. The Soil properties, type (texture, structure, hydrodynamic characteristics). The soil characteristics influence capillary forces. Soil compaction due to rain drop impact and other effects. The use of hard agricultural equipment can have consequences on the surface layer of soil.

3. The soil coverage.

- ✚ Vegetation has positive influence on infiltration by increasing the time of water penetration in soil;
 - ✚ Types of crop: is also affect infiltration rate; which close growing grass involve high infiltration rate where sparse growing.
 - ✚ the topography and morphology of slopes;
 - ✚ The initial condition of soil humidity. Soil humidity is an important factor of infiltration regime. The infiltration regime evolves differently in time for dry or wet soils;
4. Climatic factor: the infiltration capacity of the soil is affected by climatic factor such as the temperature, seasonal change.

The effected of temperature on the infiltration is described as under:

- ✚ Temperature is reduced water viscosity; causing water enters very rapid into the soil.
- ✚ High soil temperature accelerate the activity of micro-organisms reduce soil temperature

Models Used to Estimate Infiltration Rates : Infiltration processes can be estimated by means of different models:

- ✚ models based on empirical relations involving 2, 3 or 4 parameters;
- ✚ physically based models

Models based on empirical relations

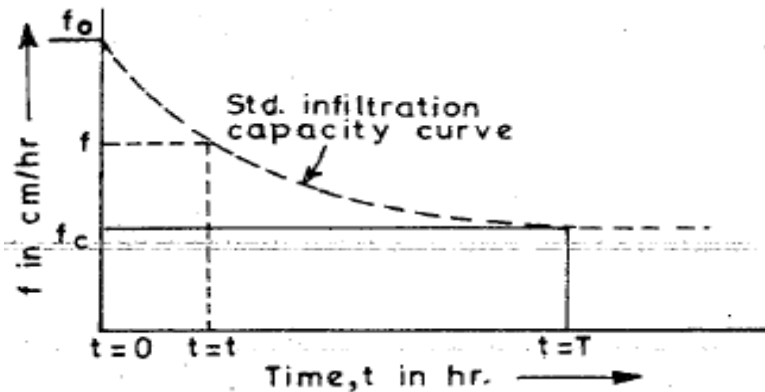
Empirical relations show a decrease of infiltration depending on initial time (either exponential or quadratic function of time), which tends to a limit value, generally k_s , but near 0. An empirical relation is the Horton formula, where the infiltration capacity can be expressed as following [Drobot, 1999]:

Infiltration rate can be estimated by the following method.

1. Horton infiltration equation(1933)

- ✚ For a given area of rainfall intensity rate tend to decrease with the time.
- ✚ The infiltration rate is maxiumum with at the beginning of the storm rainfall that occurs in the dry long period.

- ✚ The infiltration rates gradually decrease in time and reach constant value.



Standard infiltration capacity curve.

where, f_0 = value of infiltration capacity at $t=0$

f_c = constant value of infiltration reached towards the end.

Figure 4.2 Horton infiltration capacity curve

Horton observed that the above fact and concluded that the infiltration begins at the same rate f_0 and exponentially decrease until it reach constant f_c

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

Where f_p = infiltration capacity at any time from starting of rainfall (cm/hr)

f_0 = infiltration capacity at time $t=0$ (mm/hr)

f_c = final infiltration (ultimate) capacity at time $t=t_c$

t = time in hr beginning of the rainfall

k = Horton decay coefficient which depended upon the soil characteristics and vegetation cover.

$$F(t) = \int_0^t f_p(t) dt = f_0 t + \frac{f_0 - f_c}{k} (1 - e^{-kt})$$

$F(t)$ = total quantity of infiltrated water from initial time until the moment t (mm water column)

Physically based models: These models describe in a simplified manner the water movement in soils, especially at the humidity front level, depending on certain physical parameters.

Main functions used at infiltration [Musy,2001]

Author	Function	Legend
Horton	$f_p = f_c + (f_o - f_c)e^{-kt}$	f(t)=infiltration capacity during time [cm/s] fo initial infiltration capacity [cm/s] fc final infiltration capacity [cm/s] k=constant depending on the soil type t=time
Kostiakov	$I = Kt^n$	K,n Kostiakov constants
Dvorak-Mezencev	$i(t) = i_0 + (i_1 - i_0)t^{-\delta}$	I(T)infiltration capacity at time t=1min [cm/s] time [s] constant
Holtan	$i(t) = i_f + CW[(IMD) - F]^n$	C=factor variable from 0.25 to 0.8 W=Holtan equation flow factor experimental constant approximately=1.4
Philip	$f_p = \frac{1}{2}st^{-0.5} + k$	S= sorptivity [cms ^{-0.5}] K= gravity component depending on hydraulic conductivity at saturation [cm/s]
Green &Ampt	$i(t) = k_s \left(1 + \frac{h_0 - h_f}{z_f(t)} \right)$	Ks=hydraulic conductivity at saturation [mm/h] Ho=surface pressure load [mm] Hf=pressure load at the humidity front [mm] Zf=humidity front depths [mm]

4.3 CHARACTERISTICS OF INFILTRATION AND PERCOLATIONS

✓ the characteristics of infiltration and percolations are :

1. Both characteristics of infiltration and percolations process that are moves water in to the pore space of the soil.

2. Infiltration process is occurs close to the surface of the soils. Infiltration water denoted the entry of the rainwater into the earth surface.
3. Downward movement of infiltrated water through the soil and rock. If the infiltration deliver water from the surface of the soil and plant rooting zone and percolations moves through the soil profile and join the groundwater recharge. Flow of water from unsaturated zone to saturated zone is called percolation.

Horton infiltration equation (1933): is expressed the decay of infiltration capacity with the time an exponentially given by:

$$f_p = f_c + (f_o - f_c)e^{-kt}$$

Transposing, $f - f_c = (f_o - f_c) e^{-Kt}$

Taking log on both sides

$$\begin{aligned} \log_{10} (f - f_c) &= \log_{10} (f_o - f_c) - Kt \log_{10} e \\ \text{or } \log_{10} (f - f_c) - \log_{10} (f_o - f_c) &= -Kt \log_{10} e \\ \therefore t &= \frac{-1}{K \log_{10} e} [\log_{10} (f - f_c) - \log_{10} (f_o - f_c)] \\ \text{or } t &= \frac{-1}{K \log_{10} e} \log_{10} (f - f_c) + \frac{1}{K \log_{10} e} \log_{10} (f_o - f_c) \end{aligned}$$

The above equation is of the form

$$Y = mX + C$$

where, $Y = t$,

$$m = \frac{-1}{K \log_{10} e}$$

$X = \log_{10} (f - f_c)$; and

$$C = \frac{1}{K \log_{10} e} \log_{10} (f_o - f_c)$$

and hence, represents a straight line, having a slope = $\frac{-1}{K \log_{10} e}$

The -ve sign shows that as t increases, f decreases, and, therefore, $(f - f_c)$ decreases, and hence $\log (f - f_c)$ decreases. This straight line graph is of the form shown in-Fig.

If two values of f at two known times are known and f_c is also known, the straight line can be drawn through these two points, and the slope of the line measured; and then equating it to $\frac{-1}{K \log_{10} e}$, K can be determined, and hence, an equation for the I.C. curve can be written easily.

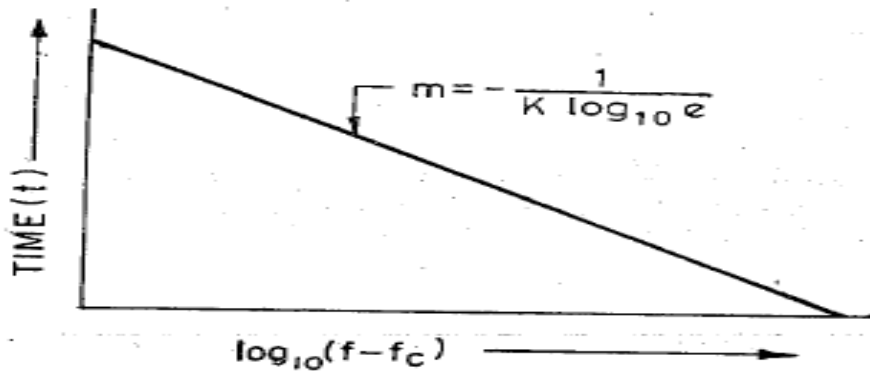


Figure 4.4 I. C.C

Example: The infiltration capacities of the area at the different interval of time are indicated below. Find the equation for the infiltration of the exponential form.

Time in hours	0	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
Infiltration capacity (f) in cm/hr	10.4	5.6	3.2	2.1	1.5	1.2	1.1	1.0	1.0

Solution. Let the equation for the Horton: $f_p = f_c + (f_o - f_c)e^{-kt}$

In this question, the infiltration capacity reaches a constant value equal to $f_c = 1.0$. Now, let us tabulate the values of $(f - f_c)$ and $\log_{10}(f - f_c)$ for various values of t , as shown below:

t in hours	0	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
f in cm/hr	10.4	5.6	3.2	2.1	1.5	1.2	1.1	1.0	1.0
$f - f_c$	9.4	4.6	2.2	1.1	0.5	0.2	0.1	0.0	0.0
$\log_{10}(f - f_c)$	0.973 or +0.973	0.663 or +0.663	0.342 or +0.342	0.042 or +0.042	-1.699 or -0.301	-1.301 or -0.699	-1.00 or -1.00		

Now, plot a graph between t and $\log_{10}(f - f_c)^*$, and pass a straight line through the plotted points as shown in Fig. 4.5.

Measure the slope of this line from the graph. It is equal to

$$-\frac{0.765}{1} = -\frac{1}{1.31}$$

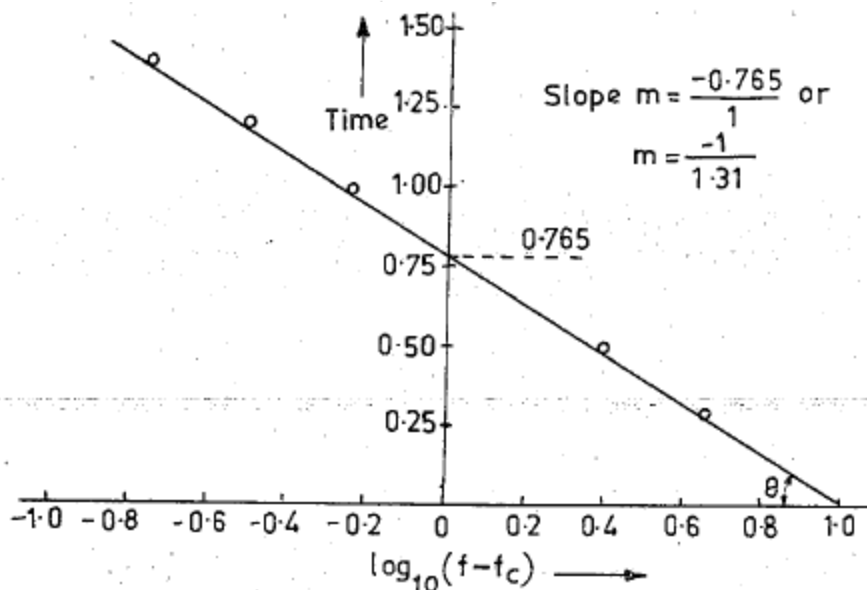
But the slope of this line, when its equation is

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

is represented by $-\frac{1}{K \log_{10} e} \therefore -\frac{1}{K \log_{10} e} = -\frac{1}{1.31}$

or $1.31 = K \log_{10} 2.718 = K \times 0.4343$

or $K = \frac{1.31}{0.4343} = 3.02$



Hence the equation for Horton is given by the:

$$f = 1.0 + (10.4 - 1.0) e^{-3.02t}$$

$$f = 1.0 + 9.4 e^{-3.02t} \quad \text{Ans.}$$

where f is in cm/hr and t is in hours.

Example: assuming the initial infiltration capacity are is 10mm/hr, the final infiltration capacity are rate of 5 mm/h and the constant value (describing the rate of decay of the difference between the initial and final infiltration rates) as 0.95 h^{-1} , calculate the total infiltration. Calculate the total infiltration depth as for the storm lasting 6hr.

Solution: f_0 = Initial infiltration capacity/rate = 10 mm/h.

f_c = Final constant infiltration capacity/rate = 5 mm/h

f = Infiltration rate at any time t .

The equation of infiltration capacity curve is given by: $f_p = f_c + (f_0 - f_c) e^{-Kt}$

where K is a constant having unit of t^{-1}

$$= 0.95 (\text{hour}^{-1})$$

Substituting values, we get

$$f = 5 + (10 - 5) e^{-0.95t} \text{ when } t \text{ is in hr.}$$

To find the total infiltration Σf in mm during 6 hr storm, we have to integrate the above equation of ICC between 0 hr to 6 hr, as

$$\begin{aligned} \sum_0^{6 \text{ hr}} f &= \int_{t=0}^{t=6} 5 + 5 \cdot e^{-0.95t} \\ &= \int_{t=0}^{t=6} 5 + 5 \int_{t=0}^{t=6} e^{-0.95t} \\ &= 5 \left| t \right|_0^6 + 5 \left[\frac{e^{-0.95t}}{-0.95} + c \right]_{t=0}^{t=6} \\ &= \left[5 \times 6 - 0 \right] + 5 \left[- \left\{ \frac{e^{-0.95 \times 6}}{0.95} - \frac{e^0}{0.95} \right\} \right] + 5 \left| c \right|_{t=0}^{t=6} \\ &= 30 + \frac{5}{0.95} \left[e^0 - e^{-5.70} \right] + 5 \left[c - c \right] \\ &= 30 + \frac{5}{0.95} \left[1 - 3.346 \times 10^{-3} \right] \\ &= 30 + 5.25 = \mathbf{35.25 \text{ mm. Ans.}} \end{aligned}$$

Example: the infiltration capacity in the basin is represent by the Horton equation as: $f_p = 3.0 + e^{-2t}$ where $f_p = \text{cm/hr}$ and $t = \text{hour}$. Assuming the infiltration to take place at the capacity rate in the storm of the 60 minutes. estimate the depth of infiltration: i) For the first 30 minute (1/2 hr)

ii) For the second 30 minute (1/2 hr)

Solution:

$$\begin{aligned} F_p &= \int_0^t f_p dt \text{ Where } f_p = 3.0 + e^{-2t} \\ &= \int_0^t (3.0 + e^{-2t}) dt \\ &\text{i) for 30 min (0.5 hr)} \\ &= \int_0^{0.5} (3 dt) + \int_0^{0.5} e^{-2t} dt \\ &= [3(0.5) - 3(0)] - 1/2 [e^{-(0.5)} - e^{(0)}] \\ &= 1.816 \text{ cm.} \end{aligned}$$

$$= \int_0^t (3.0 + e^{-2t}) dt$$

ii) for second 30 min(0.5hr)

$$\begin{aligned} &= \int_{0.5}^1 (3dt) + \int_{0.5}^1 e^{-2t} dt \\ &= [3(1)-3(0.5)] - 1/2[e^{-(1)} - e^{-(0.5)}] \\ &= [3-1.5] - 1/2[e^{-1} - e^{-(0.5)}] \\ &= 1.616\text{cm} \end{aligned}$$

Example: the infiltration capacity of the soil in small watershed was to found to be the 6cm/hr before rainfall event it was to found to be 1.2cm/hr at the end of 8hr of the storm. If the total infiltration during the 8hr of the storm was 15cm. estimate the value of the **decay coefficient** K_n in the Horton infiltration capacity equation.

Solution: Horton equations

$$f_p = f_c + (f_o - f_c)e^{-k_n t}$$

$$\text{And } \mathbf{F_p} = \text{infiltration depth of (cm)} = \int_0^t f_p dt$$

$$F_p = \int_0^t (f_c + (f_o - f_c)e^{-k_n t}) dt$$

$$= \int_0^t f_c dt + \int_0^t (f_o - f_c)e^{-k_n t} dt$$

$$= f_c t + (f_o - f_c) \int_0^t e^{-k_n t} dt$$

$$\text{As } t \longrightarrow \infty, \int_0^t e^{-k_n t} dt \longrightarrow \frac{1}{k_n}, \text{ hence for the large } t \text{ value}$$

$$\text{Therefore } F_p = f_c t + \left(\frac{f_o - f_c}{k_n} \right)$$

$$\text{Hence } F_p = 15\text{cm}, f_o = 6.0\text{cm/hr}, f_c = 1.2\text{cm/hr}, t = 8\text{hr}$$

$$15\text{cm} = \left(1.2 \frac{\text{cm}}{\text{hr}} * 8\text{hr} \right) + \left(\frac{6.0 \frac{\text{cm}}{\text{hr}} - 1.2 \frac{\text{cm}}{\text{hr}}}{k_n} \right)$$

$$K_n = 4.8/5.4\text{hr}^{-1}$$

$$K_n = 0.888\text{hr}^{-1}$$

4.4 COMPONENTS OF INFILTRATION PROCESS

The infiltration process is completed under the three independent sub processes:

1. The entry of the water in to the soil.
2. Water storage in to the soil
3. Water transmutation through the soil.

Increase or decrease in the infiltration rate is due to the effect of the three above sub process which are also considered as the component of the infiltration process are describe under:

Water intake: it is the process of the entry of the water in the soil, depended on the soil wetness soil type, soli compactness, soil characteristics etc.

If the soil in dry condition has high infiltration rate, but the soil has enough moisture much of the water has flow as form of surface runoff.

If initial infiltration rate is high but after sometimes decrease monotonically and approaches asymptotically at the constant rate is called **final infiltration rate**.

Water intake is mainly affected by the following factors:

1. Filling of the pore space with water
At this conditions capillary force is reduced, which cause reduction of the hydraulic gradients. As result water intake through the soil surface gets reduced.
2. Deterioration of the soil structure is mainly due to the breaking or detachments of the soil aggregate by the rain drop during the rainfall, the migrates of the fines over the soil water and entry of the same into the pore space.
3. Compression of the soil: due to the compacting the soil compressed reduced in the size of void. Reduced void space affect the entry of water in to the soil.

Soil moisture storage: it represented the amount of water absorbed by the soil at over at the dry condition

It expressed the as the volume of the water presented in unit volume of the bulk space. Basically adhesion and cohesion are two important forces which attract and retain the moisture in the soil masses. The energy of the water in the soil depended on the soil surface, soil structure and solute contents.

When moisture content is reduced at the saturated stage then soil moisture tension almost zero and water is freely move in the void of the soil.

4.5 MEASUREMENT OF INFILTRATION METHODS

The purpose and types of irrigation method to be the used that decide the method for measuring the infiltration rate of the soil.

For example for the large area infiltration rate is determined based on the soil properties and condition of the vegetation cover.

For the small area of when the detailed information are required to be design the of land management practice.

Infiltration rate is directly assessed the on the basis of runoff rate, assuming that few percentage of the runoff the is entered into the soil by the infiltration phenomena

The following methods are most common for determining the infiltration rate.

1. Cylindrical infiltrometer method
 - 1.1 single infiltrometer method
 - 1.2 single infiltrometer method
2. tube infiltrometr method
3. sprinkling infiltrometer method
4. furrow infiltrometer method

Cylindrical infiltrometer method: is determining the intake chactersthics (infiltration) of irrigated soil. This method is measure the infiltration rate of the soil, better for the small area

Cylindrical infiltrometer method is founds in the following two types:

- ✓ **Single infiltrometer method:** this types of the infiltrometer consists the metal ring to the flood water on the soil surface for the measuring the infiltration rate

The diameter of the metal ring is 30cm and 45-60cm as the length made. Water is flooded in the project site of the ring depth, the volume of the water added in the ring carefully the initially the time for the measurement should be kept shorter. We have measure infiltration rate of the soil so we have controlled lateral movement of the water from bottom of the ring.

✓ **Double infiltrometer method:** it is known as concentric ring infiltrometer.

In this method infiltrometer, , the lateral movement of the water in surrounding soil is checked by the driving additional ring.

The outer rings act as the buffer bounding for the inner Cylinder and ensure downward movement of water in the soil. This method is providing reliable measurement of infiltration rate of the soil.

Example: an infiltration test on a ring with 35cm diameter yields the following data.

<i>Time from the start(min)</i>	0	2	5	10	20	30	60	90	150	210
<i>Cumulative vol of water added(cm³)</i>	0	278	658	1173	1924	2500	3345	3845	4595	5315

- Determine the infiltration capacity rate for the time interval in the experiment.
- What is the ultimate infiltration capacity (f_c).
- What the average infiltration capacity for the 10 and first 30 min of the experiment.

Solution :

$$\text{Area of ring} = 3.14/4(35\text{cm})^2$$

$=962\text{cm}^2$. The Depth of infiltration in any time interval is therefore obtain by the volume of water added to the ring in the time interval by the 962 which added in the given infiltration capacity rate.

1	2	3	4	5	6
Time (min)	Change of time(hr)	Cum.vol of water added (cm^3)	Cum.inf.depth(cm) $F=V/A$	Incremental inf .depth(change F)	Inf.cap (cm/hr) $=\text{Col5/Col2}$
0	0	0	0	0	0
2	0.03	278	0.29	0.29	8.67
5	0.08	658	0.68	0.40	4.74
10	0.17	1173	1.22	0.54	3.21
20	0.33	1924	2.00	0.78	2.34
30	0.50	2500	2.60	0.60	1.20
60	1.00	3345	3.48	0.88	0.88
90	1.50	3845	4.00	0.52	0.35
120	2.50	4595	4.78	0.78	0.31
150	3.50	5315	5.52	0.75	0.21

- a) column 6 is answer
- b) $f_c=0.21\text{cm/hr}$
- c) i. average infiltration capacity t the first 10min=cum depth/change t at 10min
 $=1.22/0.17=7.314\text{cm/hr}$

Example: infiltration capacity data obtained in a cylinder type infiltration test is given below

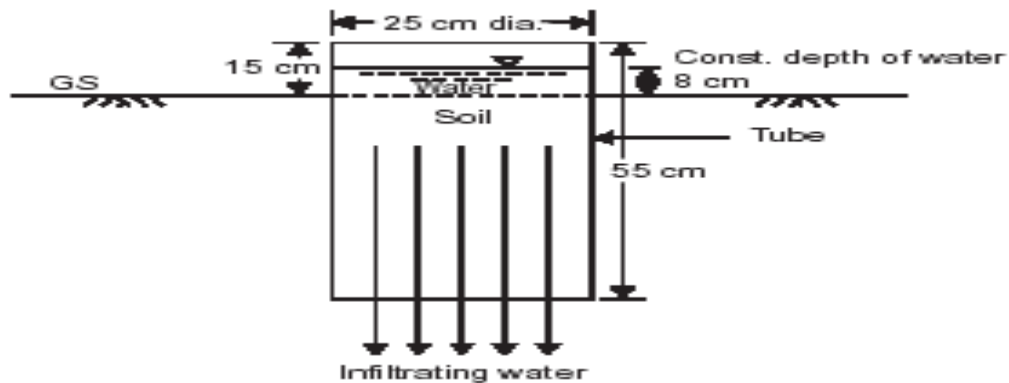
Time from the start(min)	2	5	10	15	25	45	60	75	90	110	130
Cum.inf.depth(cm)	1.75	3.00	3.95	5.58	8.30	9.30	10.20	11.28	12.36		

- plot inf.cap vs time
- plot inf.cap vs cum.inf.depth
- Obtain best value of the parameters in Horton inf.cap. Equation to represent this data set.

1	2	3	4	5	6
Time (min)	Change of time(hr)	Cum.vol of water added (cm ³)	Incremental inf.depth(change F)	Inf.cap (cm/hr) =Col4/Col2	Ln(f _p -f _c)
0	0	0	0	0	0
5	0.08	1.75	1.75	21.0	2.88
10	0.17	3.00	1.25	7.5	2.45
15	0.33	3.95	0.95	3.8	2.1
25	0.42	5.5	1.55	3.717	1.8
45	0.75	7.25	1.75	2.33	0.7
60	1.00	8.3	1.05	1.25	-0.041
75	1.25	9.3	1.00	0.8	-0.3
90	1.50	10.20	0.90	0.6	-1.022
110	1.84	11.20	1.08	0.58	
130	2.17	12.36	1.08	0.48(0.5)	

2. Tube infiltrometer method

This consists of a single tube about 22.5cm diameter and 45-60cm long which is driven in to the ground at least to the a depth up to which the water percolate during the experiment and thus no lateral spreading of the water can occur. the water added into the tube at regular time intervals to maintain constant depth is noted from which the infiltration curve can be drawn.



Example: the cumulative depth of infiltration in experiment on a tube infiltrometer is observed to following the equation. $F=0.165t^{0.65}$ where F =in cm and t =min. determine the equation for inf. rate and average inf. rate.

Solution:

$$\begin{aligned}
 F_p &= \int_0^t f_p dt \\
 f_p &= \frac{dF}{dt} \quad \text{Where } F=0.165t^{0.65} \\
 &= \frac{d(0.165t^{0.65})}{dt} \\
 &= 0.165 \frac{d(t^{0.65})}{dt} \\
 &= 0.165 * 0.65t^{0.65-1}
 \end{aligned}$$

$$= 0.10725t^{-0.35} \frac{\text{cm}}{\text{min}}$$

$$f_p = \frac{0.10725}{0.0167} t^{-0.35} \frac{\text{cm}}{\text{hr}}$$

$$\text{Average inf.cap} = 9.9t^{-0.35} \text{ cm/hr}$$

3. sprinkler tube infiltrometer

- ✓ Is also known as rainfall simulator.
- ✓ It consists of the set of nozzle equipped on the lateral to sprinkle of the water on the the field plot.

The nozzle is designed to simulated size and falling velocity of the water droplet to the natural rainfall.

4.5 analysis of percolation (reading assignment)

CHAPTER FIVE

RAINFALL-RUNOFF RELATION

5.1 Rainfall-Runoff Relationships

Rainfall is primary source of water for generated over land surface.

Runoff is the portion rainfall which enters into the stream immediately after rainfall.

Runoff is classified by the types of flow through the watershed. Runoff types and classification:

- ✓ Channel runoff: Rainfall that fall on the watercourse.
- ✓ Surface runoff: generated when rainfall rate excess the infiltration rate.
- ✓ Subsurface runoff: the horizontal movement of infiltrated water in the soil.
- ✓ Direct runoff: a collected term of runoff type.
- ✓ Base Flow is part of rainfall which enters after falling on to the ground and infiltrate into the soil and meet to the water table.

Then total runoff = DR + base Flow

Factor affecting runoff

There are two basic factors that affect runoff:

1. Physiographic factor
2. Climatic factor

Table 1: Factors affecting flood (runoff) hydrograph

Physiographic factors		Climatic factors	
1	Basin characteristics <ul style="list-style-type: none"> • shape • size • slope • nature of the valley • elevation • drainage density 	1	Storm characteristics: precipitation, intensity, duration, magnitude and movement of storms
2	Infiltration characteristics <ul style="list-style-type: none"> • land use and cover • soil type and geological conditions • lakes, swamps and other storages 	2	Initial losses
3	Channel characteristics: cross-section, roughness and storage capacity	3	Evapotranspiration

Rainfall intensity

The runoff increases with an increase in the intensity of precipitation because an intense rainfall occurs in a short and the evaporation and infiltration losses are relatively small.

- ✓ For rainfall intensities exceeding the infiltration capacity, the runoff increases with increase in intensity.
- ✓ Owing to the storage effects of the basin, however, the increase in the runoff rate is not the same as the increase in rainfall intensity.

Duration of rainfall

- ✓ If rainfall occurs over a long period, the runoff is large because the runoff is proportional to the total rainfall. Moreover, the infiltration capacity decreases with time.
- ✓ Under favorable conditions the infiltrated water may even raise the water table to the ground surface reducing the infiltration to zero leading to serious flood.
- ✓ As a consequence, rains of long duration may produce high rates of runoff even though the intensity is relatively mild.
- ✓ It is pertinent here to consider the duration of rainfall in conjunction with **critical concentration time of the basin t_c** , which is defined as the time taken by a rain drop falling on the remotest point of the basin to reach the basin outlet.

- ✓ If the duration of rainfall is greater than or equal to t_c the whole of the basin is likely to contribute to runoff during the later stages of the storm so that the potential runoff rate is maximum.
- ✓ On the other hand, if the rainfall duration is less than t_c the potential runoff will be lower than the maximum because only part of the basin will be contributing to runoff before rainfall ceases.

5.2 Rainfall distribution over the basin

Uniform areal distribution of rainfall over a basin is rarely observed in nature. Some portion of the basin will receive rainfall which is much less than the average rainfall over the basin while the remaining portion will receive rainfall which is more than the average of the basin. A large areal extent of the rainfall over the catchment produces large runoff.

- ✓ Heavy rain falls in the **lower portions** of the basin will produce a runoff hydrograph with a rapid rise and nearly peak discharge,
- ✓ While heavy rainfall in the **upper portions** will reverse the hydrograph trend with a slow rise and late peak.
- ✓ On the other hand, rainfall distribution **uniformly** over the entire basin will tend to produce increased base flow and consequently a long and slow increase in the hydrograph.

Land use: the manner in which a land is being used is called land use. Rain falling over on a thick forest or vegetated area produces less runoff because of large interception, transpiration and infiltration losses. On the other hand, in urban areas, the losses are less and the runoff is more because of paved areas (no infiltration). In non forested areas the infiltration, interception and evaporation and evapotranspiration losses are less and therefore high runoff rates are expected.

Type of soil

The type of soil has direct influence on its infiltration capacity rate and consequently it also affects the runoff. A light textured soil (sandy soils) consists of coarser soil particles and has large pore spaces → rapid absorption of water → less runoff potential.

Heavy textured soil (clay soils) have fine soil particles → small pore spaces → little absorption of water → huge runoff volume.

Area of the basin

The area of the basin increases as the outlet point shifts downstream.

Area of the basin affects the peak flow and minimum flow in different ways.

- If all other factors including depth and intensity of rainfall remain constant in all instances, the total runoff expressed as depth in cm over the basin will be same for all the basins irrespective of their size.
- The total runoff expressed as volume will be more in the case of large basins associated with higher peak discharges.
- As far as the minimum flow in the stream is concerned, the larger basins will produce higher rates than smaller catchments. This is because after the surface runoff ceases, the flow is entirely drawn from groundwater storage which is large for larger basins,

Shape of the catchment

In approximately square or circular drainage basins the tributaries often tend to become together and join the main stream near the center of the area. → Consequently, the separate runoff peaks generated by heavy rainfall in the individual tributaries are likely to reach the main stream in approximately the same locality and at approximately the same time, thereby resulting in a large and rapid increase in the runoff.

On the other hand, if the basin is long and narrow the tributaries will tend to be relatively short and are more likely to join the main stream at intervals along its length. This means that after a heavy rainfall over the area the runoff peaks of the lower tributaries would have left the catchment before the peaks of the upstream tributaries have reached the basin outlet.

Slope

The slope of the catchment area is an important factor as it decides the relative importance of infiltration, interflow and overland flow.

A catchments having extensive flat area gives rise to low peaks and less runoff whereas a catchment with steep slope produces high peak flood.

Rate of *infiltration* from a flat catchment is more which affects the velocity of overland flow. Therefore, the time of arrival of peak at the outlet is late and so is the total time of runoff for

such flat shaped catchment. The *basin slope* plays an important role in urban hydrology where catchment is usually small. For a high intensity and long duration storm, the effect may be less pronounced.

5.3 Rainfall runoff correlation ship

Runoff is affected by the several factor related to the watershed the behaviors of runoff is very complex, the relationship between rainfall and runoff is uncertain.

There are two type of relation ship

1. Linear relationship
2. Nonlinear relationship

✚ One of the most common methods is to correlate rainfall (P) and runoff (R) which gives accurate estimation.

$R = b + aP$ and the values of the coefficients a and b are given

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

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

$$r = \frac{N(\sum PR) - (\sum P)(\sum R)}{\sqrt{[N(\sum P^2) - (\sum P)^2][N(\sum R^2) - (\sum R)^2]}}$$

The values of r lies between 0 and 1 as R have only positive correlation with P. A value of $0.6 < r < 1.0$ indicates good correlation. Further it should be noted that $R \geq 0$.

✚ The second important correlation method between rainfall (P) and runoff (R)

If the catchment size is very large, we use no correlation ship between P and R so if use the exponential correlation

$$R = \beta P^m$$

Where β and m are constant

Multiply both sides by ln

$$\ln(R) = \ln(\beta) * P^m$$

$$\ln(R) = \ln(\beta) + \ln(P)^m$$

$$\ln(R) = \ln(\beta) + m \ln(P)$$

Methods of runoff computation

Determination of accurate runoff rate (volume) from the watershed is difficult task because runoff is depended upon several related to watershed atmosphere.

Some common method runoff estimation is:

1. Rainfall runoff method
2. Empirical method
3. Rational method
4. Hydrograph method

Computation of runoff using Empirical method

Engineer recognizes the importance of runoff estimating the availability from available data hydrological for the purpose of planning water resource project. Many engineer developed empirical runoff estimation formula can be classified in different upon the basis adopted:

- ✓ Formula that taken area of basin only into consideration
- ✓ Formula that taken one or more basin parameter apart from area and rainfall characteristics into consideration

Runoff Computation method

In this method involved the estimation of runoff by the multiply runoff coefficient to the rainfall depth of the area. It is given:

$$R = CP$$

Where R=runoff (cm)

P=rainfall depth (cm) and C=runoff coefficient

Table 2: Runoff coefficient depending on the factor affecting, the value of runoff coefficient on the different land use condition.

S.No	Area	Runoff Coefficient
1	Urban area cover by:	
	i. Building	0.30
	ii. garden apartment	0.50
2	Commercial industrial area	0.90
3	Forest area	0.50 to 0.20
4	Asphalt or concert pavement	0.85

Example: compute the runoff coefficient of watershed using following data and their corresponding runoff value are:

Rainfall(cm)	5.25	0.387	1.75	2.30	4.30	5.00
Runoff(cm)	3.13	0.105	0.70	1.25	2.77	3.05

Solution:

By the using empirical method: $R = CP$

Where C =total runoff/total precipitation

Total runoff= $3.13+0.105+0.70+1.25+2.77+3.05=11.025\text{cm}$

Total precipitation= $5.25+0.387+1.75+2.30+4.30+5.00=18.987\text{cm}$

C =total runoff/total precipitation= $11.025\text{cm}/18.987\text{cm}=0.5806$

Rational Method

Among various types of empirical relations, rational formula is the most rational method of calculating peak discharge for small catchments.

In this method, it is assumed that the maximum flood flow is produced by a certain rainfall which lasts for a time equal to or greater than the period of concentration time. This concentration time is the time required for the surface runoff from the remotest part of the catchment area to reach the basin outlet.

When the storm continues beyond concentration time every part of the catchment would be contributing to the runoff at outlet and therefore it represents conditions of peak runoff. The runoff rate corresponding to this condition is given by

$$Q = C A I$$

Where A is the area of the catchment, I is the intensity of rainfall and C a runoff coefficient to account for the abstractions from the rainfall.

In this equation, if A and I are substituted in units of acres and inches/h, the runoff is obtained in ft^3/s without requiring any conversation factor. For this reason it is called the rational formula.

- ✓ The formula is called rational because of the units of the quantities considered being numerically constant.

However, in SI system of units when A is in km^2 and I is in cm/h , the runoff rate is given by

$$Q = 2.778 C A I$$

$$Q = \frac{CIA}{3.6} \text{ Where } A \text{ (ha), } I \text{ (mm/hr)}$$

The maximum rainfall intensity depends on duration and frequency. The intensity of rainfall used in the equation above should therefore be corresponding to duration equal to concentration time and desired return period.

This requires an estimate of concentration time which is usually provided by an empirical equation given by Kirpich (1940).

$t_c = 0.02 L^{0.77} S^{-0.385}$ where t_c is time of concentration in min, L is the maximum length of travel of water along the water course in m and S is the slope expressed as the ratio of difference in elevation between the remotest point and the catchment outlet to the length L .

Once the concentration time has been determined, the rainfall intensity can be determined using the intensity-duration-frequency relation applicable to the catchment area in question using eq.

$$i = \frac{CT_r^d}{(t + a)^b} \text{ Where } T_r \text{ is the return period in years and } C \text{ and } d \text{ are regression}$$

constants for a given location.

Once the rainfall intensity and catchment area have been obtained, a runoff coefficient applicable to the given design condition is selected from the table below and the peak runoff estimated from the rational formula.

Runoff coefficient is the ration of peak runoff rate to the rainfall intensity.

Its values are assigned on the basis of land use and soil type (Tab 2). When the watershed has different features regarding land use and soil types, then weighted value of runoff coefficient is determined. For example:

- ✓ Let, if a watershed area is divided into five sub-parts on the basis of soil type and land use practice adopted, having the area a_1, a_2, a_3, a_4 and a_5 and the value of runoff coefficient is C_1, C_2, C_3, C_4 , and C_5 , respectively for the five sub-watersheds.

Then the value of weighted runoff coefficient (C) is given by:

$$C = \frac{C_1 a_1 + C_2 a_2 + C_3 a_3 + C_4 a_4 + C_5 a_5}{a_1 + a_2 + a_3 + a_4 + a_5}$$

$$C = \frac{\sum_{i=1}^n C_i a_i}{A}$$

Example: Compute the value of weighted runoff coefficient of watershed from the following data regarding watershed characteristics.

Land use and topography	Cultivated land Flat, sandy soil	Pasture land Rolling and sandy soil	Populated land flat,, sandy soil
Area (ha)	100	30	75
runoff coefficient	0.30	0.16	0.40

Solution

Using the weighted runoff coefficient formula

$$C = \frac{C_1 a_1 + C_2 a_2 + C_3 a_3}{a_1 + a_2 + a_3}$$

In which, the values of C_1 are obtained from the above table, for a given land use and topographical feature of the watershed. The calculation is shown in the following table.

Land use/ topography	Area (ha)	C	Computation
1. Cultivated land + flat topography + sandy soil	100	0.30	$C = \frac{C_1 a_1 + C_2 a_2 + C_3 a_3}{a_1 + a_2 + a_3}$ $= \frac{100 \times 0.30 + 30 \times 0.16 + 75 \times 0.40}{100 + 30 + 75}$ $= 0.32$
2. Pasture land + rolling topography + sandy soil	30	0.16	
3. Populated land + flat topography + sandy loam soil	75	0.40	

Example: An engineer is required to design a drainage system for an airport with an area of 2.5 km² for 50 years return period. The 50-year rainfall intensity in that region is given by

$$I = \frac{35}{(t + 10)^{0.38}} \text{ Where } I \text{ is intensity in cm/h and } t \text{ is duration in minutes.}$$

If the concentration time for the area is estimated as 50 minutes, what is discharge that must be used to design the system?

Solution

Concentration time $t_c = 50 \text{ min}$

$$\text{Intensity of rainfall for this duration} = I = \frac{35}{(t + 10)^{0.38}} = \frac{35}{60^{0.38}} = \frac{35}{4.74} = 7.384 \text{ cm/h since}$$

the airport is fully paved, it may be considered impervious and the runoff coefficient C may be taken as unity. Therefore

$$Q = 2.778 \text{ } CAI = 2.778 \times 1 \times 2.5 \times 7.384 = 51.25 \text{ m}^3 / \text{s}$$

Therefore the engineer must design the drainage system for a discharge of **51.28 m³/s**.

Example: A culvert is proposed across stream drainage an area of 185 ha. The catchment has a slope of 0.004 and the length of travel for water is 1150 m. Estimate the 25-year discharge if the rainfall intensity is given by

$$I = \frac{1000 T_r^{0.2}}{(t + 20)^{0.7}} \text{ Where } I \text{ is in mm/h, } T_r \text{ is in years and } t \text{ is in minutes. Assume a runoff}$$

coefficient of 0.35.

Solution

$L = 1150 \text{ m}$

$S = 0.004$

$$t_c = 0.0195(1150)^{0.77} (0.004)^{-0.385} = 37.2 \text{ minutes}$$

$$I = \frac{1000 (25)^{0.2}}{(37.2 + 20)^{0.7}} = 112.05 \text{ mm/h} = 11.205 \text{ cm/h}$$

$A = 185 \text{ ha} = 1.85 \text{ km}^2$, $C = 0.35$

$$Q = 2.778 \times 0.35 \times 1.85 \times 11.205 = 20.12 \text{ m}^3 / \text{s}$$

Chapter 6

Stream flow measurement

6.1 Measurement of discharge

Introduction to Stream Flow (Discharge Rates) Measurements

Hydrometry: is a science and practice of water measurement. There are twenty four and above exiting method of discharge measurement.

The subject of Hydrometry is old as human civilization, the early history of Hydrometry presented by a Kulupaila. The oldest hydrometric evidence are making of the flood stage in the river Nile cutoff on steep rock face.

Hydrometry is developed step by the step, have a new technique have techniques have been developed in stream flow measurement.

Discharge: is the volume of water moving down a stream or river per unit of time, commonly expressed in cubic meter per second, cubic feet per second or gallons per day. In general, river discharge is computed by multiplying the area of water in a channel cross section by the average velocity of the water in that cross section.

Discharge = area * velocity.

The USGS uses numerous methods and types of equipment to measure velocity and cross-sectional area, including the following current meter and Acoustic Doppler Current Profiler.

There are different methods of discharge measurement:

- ✚ Current meter method.
- ✚ Slope - area method.
- ✚ Area-velocity method.
- ✚ Water-stage recorder(rating curve method)
- ✚ Pitot tube method
- ✚ Float method.
- ✚ Dilution techniques method
- ✚ Echo sonar method
- ✚ Salt velocity method
- ✚ Critical flow flume :channel transition method
- ✚ Hydraulic model experiment method etc

Streamflow measurement techniques can be broadly classified into two main categories:-

1. Direct measurement(determination)
2. **Indirect measurement**

Direct measurements (determination) are:-

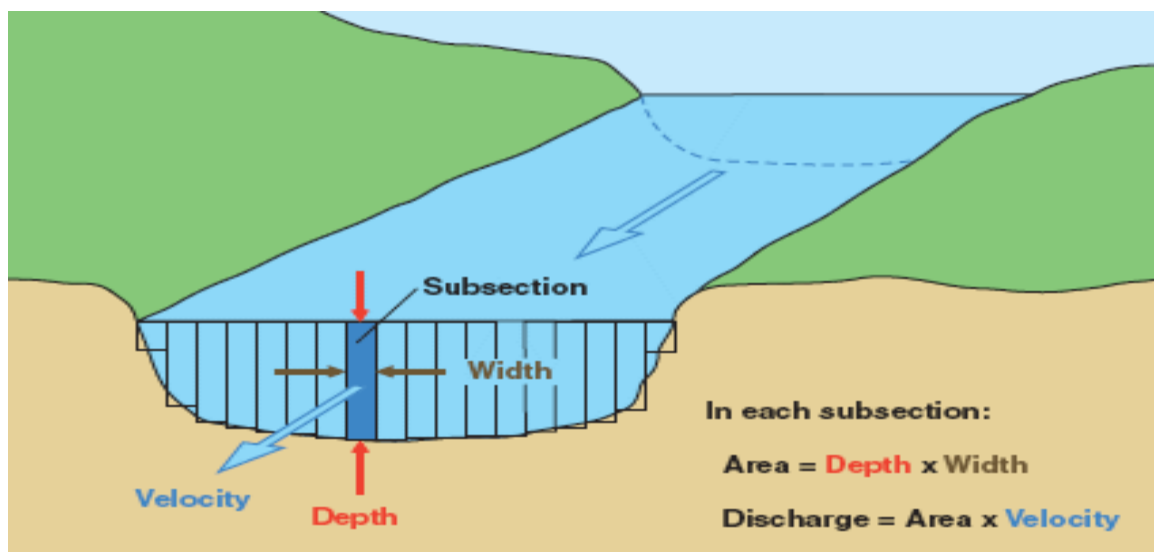
- ✓ Area-Velocity method
- ✓ Stage-discharge method
- ✓ Dilution techniques method
- ✓ Moving boat method etc.

Indirect measurement

- ✓ Slope area method
- ✓ Hydraulic structure method
- ✓ Salt velocity method
- ✓ Echo sounder method ect

Current Meter

The most common method used by the USGS for measuring discharge is the mechanical current-meter method. In this method, the stream channel cross section is divided into numerous vertical subsections (diagram to the left). In each subsection, the area is obtained by measuring the width and depth of the subsection, and the water velocity is determined using a current meter (left-side picture below). The velocity of the stream flow is measured using a current meter. The discharge in each subsection is computed by multiplying the subsection area by the measured velocity.



The total discharge is then computed by summing the discharge of each sub section.

6.1.1 Area-Velocity method

- In this method, the discharge is determined from the area of cross-section and the mean velocity.
- The area of cross-section of the river is determined from the profile of the river bed obtained by the sounding.
- The river cross-section is divided in to a suitable number of vertical segments (or strips).

The total discharge in the river is computed as the sum of the discharges in various segments. The discharge in each segment is equal to the area of the segment multiplied by the mean velocity of flow.

There are two methods of determining the discharge:

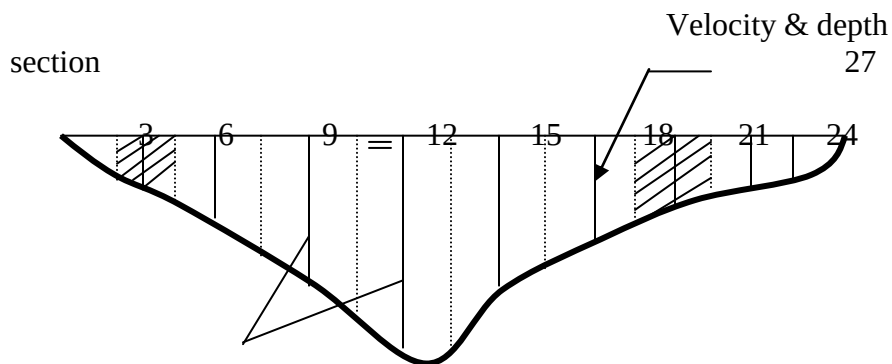
- Mid-section method
- Mean-section method

Mid-section method

In this method, the area of cross-section is divided into several segments, and the mean velocity (V_m) is measured on a vertical line in the middle of the segment. The mean depth of the segment is also taken at the middle of the segment. If b is the width of the segment and d_m the mean depth, the discharge in the segment is given by

$$\Delta Q = (b \times d_m) V_m$$

$$\text{Total discharge } Q = \sum Q$$

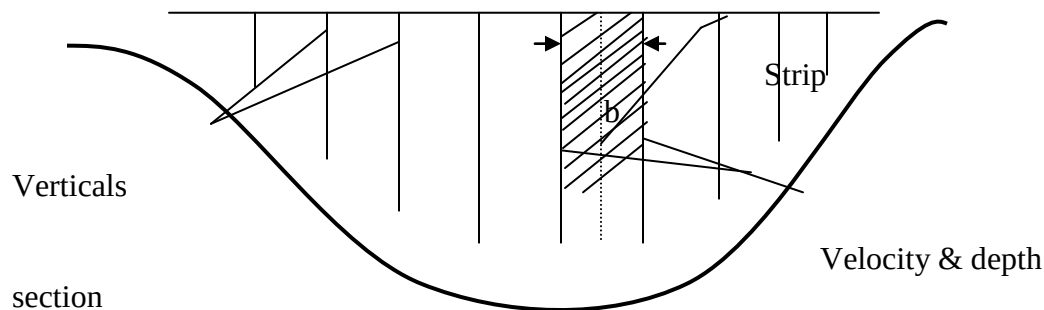


The discharge in the end two triangular strips is usually neglected. However, for greater accuracy, the discharge in these triangular strips should also be calculated by measuring the depth and velocity at the centroids of these strips.

Mean section methods

In this method, the segment is taken between two vertical lines on which the velocity and depth are measured. The velocity in the segment is taken as the average of the mean velocities V_1 and V_2 determined at the two adjacent verticals. Similarly, the depth is also taken as the average of two depths d_1 and d_2 . Thus the discharge in the segment is given by

$$\Delta Q = b \left(\frac{d_1 + d_2}{2} \right) \left(\frac{V_1 + V_2}{2} \right)$$



6.1.2 The stage-discharge relation

Stream-gages continuously measure stage, as stated in the "Measuring Stage" section. This continuous record of stage is translated to river discharge by applying the stage-discharge relation (also called rating).

Stage-discharge relations are developed for stream gages by physically measuring the flow of the river with a mechanical current meter for each measurement of discharge there is a corresponding measurement of stage.

The USGS makes discharge measurements at most stream gages every 6 to 8 weeks, ensuring that the range of stage and flows at the stream gage are measured regularly. Special effort is made to measure extremely high and low stages and flows because these measurements occur less frequently.

The stage-discharge relation depends upon the shape, size, slope, and roughness of the channel at the stream gage and is different for every stream gage.

The development of an accurate stage-discharge relation requires numerous discharge measurements at all ranges of stage and stream flow.

In addition, these relations must be continually checked against on-going discharge measurements because stream channels are constantly changing. Changes in stream channels are often caused by erosion or deposition of streambed materials, seasonal vegetation growth, debris, or ice.

An example of how erosion in a stream channel increases a cross-sectional area for the water, allowing the river to have a greater discharge with no change in stage. New discharge measurements plotted on an existing stage-discharge relation graph would show this, and the rating could be adjusted to allow the correct discharge to be estimated for the measured stage.

6.2 Extreme value statistics

Water resource systems must be planned for future events for which no exact time of occurrence can be forecasted. Hence, the hydrologist must give a statement of the probability of the stream flows (or other hydrologic factors) will equal or exceed (or be less than) a specified value.

These probabilities are important to the **economic and social evaluation of a project**. In most cases, absolute control of the floods or droughts is impossible. Planning to control a flood of a specific probability recognizes that a project will be overtaxed occasionally and damages will be incurred. However, repair of the damages should be ***less costly in the long run than building initially to protect against the worst possible event***.

The ***planning goal is not to eliminate all floods*** but to ***reduce the frequency of flooding***, and hence the resulting damages.

If the ***socio-economic analysis is to be correct***, the ***probability of flooding must be eliminated accurately***. For ***major projects***, the failure of which seriously threatens human life, a more extreme event, the probable maximum flood, has become the standard for designing the spillway.

This chapter deals with ***techniques for defining probability*** from a given set of data and with ***special methods employed for determining design flood for major hydraulic structures***.

Frequency analysis is the hydrologic term used to describe the probability of occurrence of a **particular extreme hydrologic event** (e.g. rainfall, flood, drought, etc.). Therefore, basic knowledge about probability (e.g. distribution functions) and statistics (e.g. measure of location, measure of spread, measure of skewness, etc) is essential. Frequency analysis usually requires recorded hydrological data.

Hydrological data are recorded either as a *continuous record* (e.g. water level or stage, rainfall, etc.) or in *discrete series* form (e.g. mean daily/monthly/annual flows or rainfall, annual series, partial series, etc.).

For planning and designing of water resources development projects, the important parameters are **river discharges** and related questions on the **frequency & duration of normal flows** (e.g. for hydropower production or for water availability) and *extreme flows* (floods and droughts).

6.2.1 Flow Frequency

The question a planner or decision maker would ask a hydrologist concerning normal flows is the length of time (duration) that a certain river flow is expected to be exceeded.

An answer to this question is provided by the flow duration curve (**FDC**) that is the relationship between any given discharge and the percentage of time that the discharge is exceeded. Taking **the n-years of flow records** from a river gauging stations, there are 365(6) n daily **mean discharges**.

The discharge is compiled, starting with the highest values. If N number of **data points** are used for analysis, the plotting position of any discharge (or class value) Q is:

$$P_p = m / (N+1) \quad (5.1)$$

Where, m = is the order number of the discharge (or class value)

P_p = percentage probability of the flow magnitude being equaled or exceeded.

The FDC only applies for the period for which it was derived. If this is a long period, say more than 10 to 20 years, the FDC may be regarded as a *probability curve or flow frequency curve*, which may be used to estimate the percentage of time that a specified discharge will be equalled or exceeded in the future.

FDC Used for:

- ✓ Evaluating the feasibility of the project.

- ✓ To utilize the maximum yield of water in the river
- ✓ To developed the capacity of the project.

Example: draw the FDC for river A by using flow data are given below

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Discharge(m ³ /s)	106.7	107.1	148.2	497	1200	964.7	338.6	177.6	141	141	142.7	126.6

Solution:

Step: 1 arrange data in descending order.

Step2: Give rank (m) for given descending data.

Step3: calculate % of exceedance.

Discharge (m ³ /s)	Descending Order	Rank	%Exceeded or Equaled (m / (N+1))
(a)	(b)	(c)	(d)
106.70	1200	1	8.33%
107.10	964.7	2	16.67%
148.20	497	3	25.00%
497.00	338.6	4	33.33%
1200.00	177.6	5	41.67%
964.70	148.2	6	50.00%
338.60	142.7	7	58.33%
177.60	141	8	66.67%
141.00	141	9	75.00%
141.00	126.6	10	83.33%
142.70	107.1	11	91.67%
126.60	106.7	12	100.00%

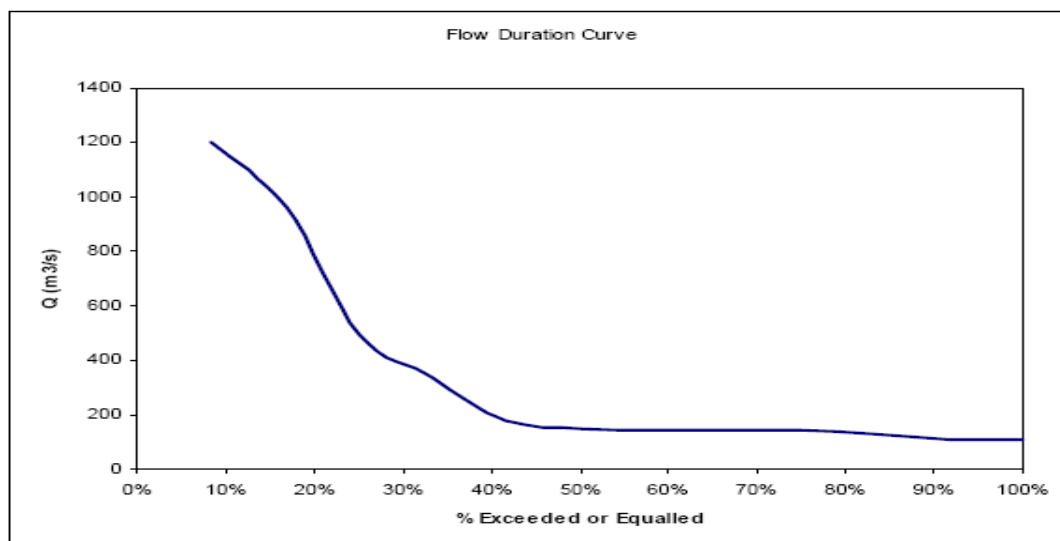


Figure 5.1: Flow Duration Curve

The shape of the flow-duration curve gives a good indication of a catchment's characteristics response to its average rainfall history. An initially steeply sloped curve results from a very

variable discharge, usually from small catchments with little storage where the stream flow reflects directly the rainfall pattern. Flow duration curves that have very flat slope indicate little variation in flow regime, the resultant of the damping effects of large storages.

6.3 Extreme Probability

6.3.1 Selection of Data

If probability analysis is to provide reliable answers, it must start with a data series that is relevant, adequate, and accurate.

Relevance implies that the data must deal with the problem. Most flood studies are concerned with peak flows, and the data series will consist of selected observed peaks. However, if the problem is duration of flooding, e.g., for what periods of time a highway adjacent to a stream is likely to be flooded, the data series should represent duration of flows in excess of some critical value.

Adequacy refers primarily to length of record, but scarcity of data collecting stations is often a problem. The observed record is merely a sample of the total population of floods that have occurred and may occur again. If the sample is too small, the probabilities derived cannot be expected to be reliable.

Accuracy refers primarily to the problem of homogeneity. Most flow records are satisfactory in terms of intrinsic accuracy, and if they are not, there is little that can be done with them. If the reported flows are unreliable, they are not a satisfactory basis for frequency analysis. Even though reported flows are accurate, they may be unsuitable for probability analysis. If changes in the catchment have caused a change in the hydrologic characteristics, i.e., if the record is not internally homogenous. Dams, levees, diversions, urbanization, and other land use changes may introduce inconsistencies. Such records should be adjusted before use to current conditions or to natural conditions. There are two data series of floods:

- (i) **The annual series, and**
- (ii) **The partial duration series.**

The annual series constitutes the data series that the values of the single maximum daily/monthly/annually discharge in each year of record so that the number of data values equals the record length in years. For statistical purposes, it is necessary to ensure that the selected peak discharges are independent of one another.

The partial duration series constitutes the data series with those values that exceed some arbitrary level. All the peaks above a selected level of discharge (a threshold) are included in the series and hence the series is often called **the Peaks over Threshold (POT)** series.

6.3.2 Plotting Positions

Probability analysis seeks to define the flood flow with probability of p being equaled or exceed in any year. Return period T_r is often used instead of probability to describe a design flood. Return period and probability are reciprocals, i.e.

$$p = 1/T_r \quad (5.2)$$

To plot a series of peak flows as a cumulative frequency curves it is necessary to decide on a probability or return period to associate with each peak. There are various formulas for defining this value as shown in table 3.2.

The probability of occurrence of the event r times in n successive years can be obtained from:

Probability of non-exceedance

$$q = 1 - P. \quad (5.3)$$

Table 3.2 Plotting position

Method	P
California	m / N
Hazen	$(m - 0.5) / N$
Weibull	$m / (N+1)$
Chegodayev	$(m - 0.3) / (N+0.4)$
Gringorten	$(m - 3/8) / (N + 1/4)$

Consider, for example, a list of flood magnitudes of a river arranged in descending order as shown in Table 3.3. The length of record is 50 years.

Table 3.3 Calculation of frequency T

Order No. m	Flood magnitude Q (m^3/s)	T in years = $51/m$
1	160	51.00
2	135	25.50
3	128	17.00
4	116	12.75
.	.	.
.	.	.
.	.	.
49	65	1.04
50	63	1.02

The last column shows the return period T of various flood magnitude, Q . A plot of Q Vs T yields the probability distribution.

For small return periods (i.e. for interpolation) or where limited extrapolation is required, a simple best-fitting curve through plotted points can be used as the probability distribution. A **logarithmic scale for T** is often advantageous.

However, when larger extrapolations of T are involved, theoretical **probability distributions** (e.g. **Gumbel extreme-value, Log- Pearson Type III, and log normal distributions**) have to be used. In frequency analysis of floods the usual problem is to **predict extreme** flood events. Towards this, specific extreme-value distributions are assumed and the required statistical parameters calculated from the available data. Using these flood magnitude for a specific **return period** is estimated.

6.3.3 Theoretical Distributions of extreme

Chow has shown that most frequency-distribution functions applicable in hydrologic studies can be expressed by the following equation known as the general equation of hydrologic frequency analysis:

$$x_T = \bar{x} + K\sigma$$

Where x_T = value of the variate X of a random hydrologic series with a return period T , $\bar{x}$ = mean of the variate, σ = standard deviation of the variate, K = frequency factor which depends upon the return period, T and the assumed frequency distribution.

6.3.3.1 Extreme-Value Type I Distribution (Gumbel's Method)

This extreme value distribution was introduced by Gumbel (1941) and is commonly known as Gumbel's distribution. It is one of the most widely used probability distribution functions for extreme values in hydrologic and meteorological studies for prediction of flood peaks, maximum rainfalls, and maximum wind speed, etc. Therefore, this extreme value theory of **Gumbel is only applicable to annual extremes**.

In the Gumbel method the **data are ranked in ascending order** and it makes use of the **probability of non-exceedence $q=1-P$** (the probability that the annual maximum flow is less than a certain magnitude). The return period T is therefore given by:

$$T = 1 / P = 1 / (1-q). \quad (5.4)$$

Gumbel makes use of a reduced variate y as a function of q , which allows the plotting of the distribution as a linear function between y and X (the maximum flow in this case). Gumbel also defined a flood as the largest of the 365 daily flows and the annual series of flood flows constitute a series of largest values of flow. According to his theory of extreme events, the probability of occurrence of an event equal to or larger than a value 0 is

$$P(X \geq x_0) = 1 - e^{-e^{-y}} \quad (5.5)$$

In which y is a dimensionless variable given by

$$y = \alpha(X - a) \quad (5.6)$$

$$a = \bar{x} - 0.45005\sigma_x$$

$$\alpha = \frac{1.2825}{\sigma_x}$$

Thus
$$y = \frac{1.2825(X - \bar{x})}{\sigma_x} + 0.577 \quad (5.7)$$

Where $\bar{x}$ = mean and σ_x = standard deviation of the variate X .

In practice it is the value of X for a given P that is required as such Eq. (3.7) is transposed as

$$y = -1n(-1n(q)) = -1n(-1n(1-p)) \quad (5.8)$$

meaning that the probability of non-exceedence equals:

$$P(X \leq x_0) = q = e^{-e^{-y}} \quad (5.9)$$

Noting that the return period $T = 1/P$ and designating; y_T = the value of y , called the reduced variate, for a given T

$$y_T = - \left[\ln \left(\ln \left(\frac{T}{T-1} \right) \right) \right] \quad (5.10)$$

Or

$$y_T = - \left[0.834 + 2.303 \log \left(\log \left(\frac{T}{T-1} \right) \right) \right]$$

Now rearranging Eq. (3.7) the values of the variate X with a return period T is

$$x_T = \bar{x} + K\sigma_x \quad (5.11)$$

$$K = \frac{(y_T - 0.577)}{1.2825} \quad (5.12)$$

Where

Note that Eq. (5.12) is of the same form as the general equation of hydrologic frequency analysis, Eq. (5.4). Further Eq (5.11) and (5.12) constitute the basic Gumbel's equations and are applicable to an infinite sample size (i.e. $N \rightarrow \infty$).

Since practical annual data series of extreme events such as floods, maximum rainfall depths, etc. all have finite lengths of record; Eq. (5.12) is modified to account for finite N as given below for practical use.

Gumbel's Equation for Practical Use

Equation (5.11) giving the variate X with the return period T is used as

$$x_T = \bar{x} + K \sigma_{n-1} \quad (5.13)$$

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

Where σ_{n-1} = standard deviation of the sample

K = frequency factor expressed as $K = \frac{y_T - \bar{y}_n}{S_n}$

In which y_T = reduced variate, a function of T and is given by (5.14)

$$y_T = - \left[\ln \left(\ln \left(\frac{T}{T-1} \right) \right) \right] \quad (5.15)$$

or

$$y_T = - \left[0.834 + 2.303 \log \left(\log \left(\frac{T}{T-1} \right) \right) \right]$$

$\bar{y}$ = reduced Mean a function of sample size N and is given in Table 3.4

for $N \rightarrow \infty$, $\bar{y}_n \rightarrow 0.577$.

S_n = reduced standard deviation, a function of sample size N and is given in Table 3.5; for $N \rightarrow \infty$, $S_n \rightarrow 1.2825$

These equations are used under the following procedure to estimate the flood magnitude corresponding to a given return period based on annual flood series.

1. Assemble the discharge data and note the sample size N. Here the annual flood value is the variate X. Find $\bar{x}$ and σ_{n-1} for the given data.
2. Using Tables 3.4 and 4.5 determine y_n and S_n appropriate to given N
3. Find y_T for a given T by Eq.(5.15).
4. Find K by Eq.(3.14).
5. Determine the required x_T by Eq.(5.13).

To verify whether the given data follow the assumed Gumbel's distribution, the following procedure may be adopted. The value of x_T for some return periods $T < N$ are calculated by using Gumbel's formula and plotted as x_T Vs T on a convenient paper such as a semi-log, log-log or Gumbel probability paper.

A good fit of observed data with the theoretical variation line indicates the applicability of Gumbel's distribution to the given data series. By extrapolation of the straight-line x_T Vs T, values of $x_T > N$ can be determined easily.

The Gumbel (or extreme-value) probability paper is a paper that consists of an abscissa specially marked for various convenient values of the return period T (or corresponding reduced variate y_T in arithmetic scale). The ordinate of a Gumbel paper represent x_T (flood

discharge, maximum rainfall depth, etc.), which may have either arithmetic scale or logarithmic scale.

Table 3.4: Reduced mean $\bar{y}_n$ in Gumbel's extreme value distribution, N= sample size

N	0	1	2	3	4	5	6	7	8	9
10	0.4952	0.4996	0.5035	0.5070	0.5100	0.5128	0.5157	0.5181	0.5202	0.5220
20	0.5236	0.5252	0.5268	0.5283	0.5296	0.5309	0.5320	0.5332	0.5343	0.5353
30	0.5362	0.5371	0.5380	0.5388	0.5396	0.5402	0.5410	0.5418	0.5424	0.5430
40	0.5436	0.5442	0.5448	0.5453	0.5458	0.5463	0.5468	0.5473	0.5477	0.5481
50	0.5485	0.5489	0.5493	0.5497	0.5501	0.5504	0.5508	0.5511	0.5515	0.5518
60	0.5521	0.5524	0.5527	0.5530	0.5533	0.5535	0.5538	0.5540	0.5543	0.5545
70	0.5548	0.5550	0.5552	0.5555	0.5557	0.5559	0.5561	0.5563	0.5565	0.5567
80	0.5569	0.5570	0.5572	0.5574	0.5576	0.5578	0.5580	0.5581	0.5583	0.5585
90	0.5586	0.5587	0.5589	0.5591	0.5592	0.5593	0.5595	0.5596	0.5598	0.5599
100	0.5600									

Table 3.5: Reduced standard deviation S_n in Gumbel's extreme value distribution, N=sample size

N	0	1	2	3	4	5	6	7	8	9
10	0.9496	0.9676	0.9833	0.9971	1.0095	1.0206	1.0316	1.0411	1.0493	1.0565
20	1.0628	1.0696	1.0754	1.0811	1.0864	1.0915	1.0961	1.1004	1.1047	1.1086
30	1.1124	1.1159	1.1193	1.1226	1.1255	1.1285	1.1313	1.1339	1.1363	1.1388
40	1.1413	1.1436	1.1458	1.1480	1.1499	1.1519	1.1538	1.1557	1.1574	1.1590
50	1.1607	1.1623	1.1638	1.1658	1.1667	1.1681	1.1696	1.1708	1.1721	1.1734
60	1.1747	1.1759	1.1770	1.1782	1.1793	1.1803	1.1814	1.1824	1.1834	1.1844
70	1.1854	1.1863	1.1873	1.1881	1.1890	1.1898	1.1906	1.1915	1.1923	1.1930
80	1.1938	1.1945	1.1953	1.1959	1.1967	1.1973	1.1980	1.1987	1.1994	1.2001
90	1.2007	1.2013	1.2020	1.2026	1.2032	1.2038	1.2044	1.2049	1.2055	1.2060
100	1.2065									

6.3.3.2 Log-Pearson Type III Distribution

This distribution is widely used in USA. In this distribution the variate is first transformed into logarithmic form (base 10) and the transformed data is then analyzed. If X is the variate of a random hydrologic series, then the series of Z variates where

$$Z = \log x \quad (5.18)$$

Are first obtained. For this z series, for any recurrence interval T, equation (3.4) gives

$$Z_T = K_z \sigma_z + Z_{avg} \quad (5.19)$$

Where K_z = a frequency factor which is a function of recurrence interval T and the coefficient of skew C_s ,

$$\sigma_z = \text{standard deviation of the Z variate sample} = \sqrt{\frac{\sum (z - \bar{z})^2}{N-1}}$$

$$\text{and } C_s = \text{coefficient of skew of variate Z} = \frac{N \sum (z - \bar{z})^3}{(N-1)(N-2)(\sigma_z)^3}$$

$$\bar{z} = \text{mean of the z values}$$

$$N = \text{sample size} = \text{number of years of record} \quad (5.20)$$

The variations of $K_z = f(C_s, T)$ is given in Table 3.6. After finding z_T by Eq.(3.19), the corresponding value of x_T is obtained by Eq.(3.18) as $x_T = \text{antilog}(z_T)$. Sometimes, the coefficient of skew C_s , is adjusted to account for the size of the sample by using the following relation proposed by Hazen (1930)

$$\hat{C}_s = C_s \left(\frac{1+8.5}{N} \right) \quad (5.21)$$

Where $\hat{C}_s$ = adjusted coefficient of skew. However the standard procedure for use of Log-Pearson Type III distribution adopted by U.S. Water Resources Council does not include this adjustment for skew. When the skew is zero, i.e. $C_s = 0$, the Log-Pearson Type III distribution reduces to *Log-normal distribution*. The Log-normal distribution plots as a straight line on logarithmic probability paper.

Table $K_z=F(C_s,T)$ for use in Log-Pearson Type III Distribution

Coef. of skew, C_s	Return Period T in years						
	2	10	25	50	100	200	1000
3.0	-0.396	1.180	2.278	3.152	4.051	4.970	7.250
2.5	-0.360	1.250	2.262	3.048	3.845	4.652	6.600
2.2	-0.330	1.284	2.240	2.970	3.705	4.444	6.200
2.0	-0.307	1.302	2.219	2.912	3.605	4.298	5.910
1.8	-0.282	1.318	2.193	2.848	3.499	4.147	5.660
1.6	-0.254	1.329	2.163	2.780	3.388	3.990	5.390
1.4	-0.225	1.337	2.128	2.706	3.271	3.828	5.110
1.2	-0.195	1.340	2.087	2.626	3.149	3.661	4.820
1.0	-0.164	1.340	2.043	2.542	3.022	3.489	4.540
0.9	-0.148	1.339	2.018	2.498	2.957	3.401	4.395
0.8	-0.132	1.336	1.998	2.453	2.891	3.312	4.250
0.7	-0.116	1.333	1.967	2.407	2.824	3.223	4.105
0.6	-0.099	1.328	1.939	2.359	2.755	3.132	3.960
0.5	-0.083	1.323	1.910	2.311	2.686	3.041	3.815
0.4	-0.066	1.317	1.880	2.261	2.615	2.949	3.670
0.3	-0.050	1.309	1.849	2.211	2.544	2.856	3.525
0.2	-0.033	1.301	1.818	2.159	2.472	2.763	3.380
0.1	-0.017	1.292	1.785	2.107	2.400	2.670	3.235
0.0	0.000	1.282	1.751	2.054	2.326	2.576	3.090
-0.1	0.017	1.270	1.716	2.000	2.252	2.482	2.950
-0.2	0.033	1.258	1.680	1.945	2.178	2.388	2.810
-0.3	0.050	1.245	1.643	1.890	2.104	2.294	2.675
-0.4	0.066	1.231	1.606	1.834	2.029	2.201	2.540
-0.5	0.083	1.216	1.567	1.777	1.955	2.108	2.400
-0.6	0.099	1.200	1.528	1.720	1.880	2.016	2.275
-0.7	0.116	1.183	1.488	1.663	1.806	1.926	2.150
-0.8	0.132	1.166	1.448	1.606	1.733	1.837	2.035
-0.9	0.148	1.147	1.407	1.549	1.660	1.749	1.910
-1.0	0.164	1.128	1.366	1.492	1.588	1.664	1.880
-1.4	0.225	1.041	1.198	1.270	1.318	1.351	1.465
-1.8	0.282	0.945	1.035	1.069	1.087	1.097	1.130
-2.2	0.330	0.844	0.888	0.900	0.905	0.907	0.910
-3.0	0.396	0.660	0.666	0.666	0.667	0.667	0.668

The flood-frequency analysis described above is a direct means of estimating the desired flood based upon the available flood-flow data of the catchment. The results of the frequency analysis depend upon the length of data. The minimum number of years of record required to obtain satisfactory estimates depends upon the variability of data and hence on the physical and climatologically characteristics of the basin. Generally a minimum of 30 years of data is considered as essential. Smaller lengths of records are also used when it is unavoidable.

However, frequency analysis should not be adopted if the length of records is less than 10 years.

Flood-frequency studies are most reliable in climates that are uniform from year to year. In such cases a relatively short record gives a reliable picture of the frequency distribution. With increasing lengths of flood records, it affords a viable alternative method of flood-flow estimation in most cases.

A final remark of caution should be made regarding to frequency analysis. None of the frequency distribution functions have a real physical background. The only information having physical meaning is the measurements themselves. Extrapolation beyond the period of observation is dangerous. It requires a good engineer to judge the value of extrapolated events of high return periods. A good impression of the relativity of frequency analysis can be acquired through the comparison of result obtained from different statistical methods. Generally they differ considerably.

Example: Annual maximum recorded floods in a certain river, for the period 1951 to 1977 is given below. Verify whether the Gumbel extreme-value distribution fit the recorded values. Estimate the flood discharge with return period of (i) 100 years and (ii) 150 years by graphical extrapolation.

Year	Max. flood (m ³ /s)	Year	Max. flood (m ³ /s)	Year	Max. flood (m ³ /s)
1951	2947	1960	4798	1969	6599
1952	3521	1961	4290	1970	3700
1953	2399	1962	4652	1971	4175
1954	4124	1963	5050	1972	2988
1955	3496	1964	6900	1973	2709
1956	2947	1965	4366	1974	3873
1957	5060	1966	3380	1975	4593
1958	4903	1967	7826	1976	6761
1959	3757	1968	3320	1977	1971

Solutions: The flood discharge values are arranged in descending order and the plotting position return period T_p for each discharge is obtained as:

Where m = order number. The discharge magnitude Q can be plotted against the corresponding TP on a Gumbel extreme probability paper.

The statistics x and $\sigma n-1$ for the series are next calculated and are shown in table below.

Order number M	Flood discharge x (m^3/s)	T_P (years)	Order number M	Flood discharge x (m^3/s)	T_P (years)
1	7826	28.00	15	3873	1.87
2	6900	14.00	16	3757	1.75
3	6761	9.33	17	3700	1.65
4	6599	7.00	18	3521	1.56
5	5060	5.60	19	3496	1.47
6	5050	4.67	20	3380	1.40
7	4903	4.00	21	3320	1.33
8	4798	3.50	22	2988	1.27
9	4652	3.11	23	2947	-
10	4593	2.80	24	2947	1.17
11	4366	2.55	25	2709	1.12
12	4290	2.33	26	2399	1.08
13	4175	2.15	27	1971	1.04
14	4124	2.00			
$N = 27$ years, $\bar{x} = 4263 \text{ m}^3/\text{s}$, $\sigma_{n-1} = 1432.6 \text{ m}^3/\text{s}$					

Using these the discharge x_T for some chosen return interval is calculated by using Gumbel's formulae [Eqs.(3.15), (3.14) and (3.13)]. From Tables 3.4 and 3.5, for $N = 27$, $y_n = 0.5332$ and $S_n = 1.1004$.

Choosing $T = 100$ years, by Eq.(3.15),

$$y_T = -[\ln(\ln(100/99))] = 4.60014923 \text{ and}$$

$$K = (4.60014923 - 0.5332)/1.1004 = 1.56 \text{ and}$$

$$x_T = 4263 + (3.74 \cdot 1432.6) = 9557.8031 \text{ m}^3/\text{s}.$$

Similarly, values of x_T are calculated for two more T values.

Example: For the annual flood series data given in above table, estimate the flood discharge for a return period of (a) 100 years (b) 200 years and (c) 1000 years by using Log-Pearson Type III distribution.

Solution: The variate $z = \log x$ is first calculated for all the discharges in table below. Then the statistics z , σ_z and C_s are calculated from table to obtain.

$$\sigma_z = 0.1427 \quad C_s = \frac{27 \cdot 0.0030}{(26)(25)(0.1427)^3} = 0.043$$

$$\bar{z} = 3.6071$$

The flood discharge for a given T is calculated as below. Here, values of K_z for given T and $C_s = 0.043$ are read from Table 3.6.

$\bar{z} = 3.6071, \quad \sigma_z = 0.1427, \quad C_s = 0.043$				
T (years)	K_z (from table 3.5) (for $C_s = 0.043$)	$K_z \sigma_z$	$Z_T = \bar{z} + K_z \sigma_z$	$X_T = \text{antilog } z_T$ (m^3/s)
100	2.358	0.3365	3.9436	8782
200	2.616	0.3733	3.9804	9559
1000	3.152	0.4498	4.0569	11400

6.4 Confidence Limits for the fitted data

Since the value of the variate for a given return period, x_T determined by Gumbel's method can have errors due to the limited sample data used; an estimate of the confidence limits of the estimate is desirable. The confidence interval indicates the limits about the calculated value between which the true value can be said to lie with a specific probability based on sampling errors only. For a confidence probability c , the confidence interval of the variate x_T is bound by value x_1 and x_2 given by

$$x_{1/2} = x_T \pm f(c) S_e \quad (3.16)$$

Where $f(c)$ = function of the confidence probability c determined by using the table of normal variate as

C in per cent	50	68	80	90	95	99
f(c)	0.674	1.00	1.282	1.645	1.96	2.58

$$S_e = \text{probable error} = b \frac{\sigma_{n-1}}{\sqrt{N}}$$

$$b = \sqrt{1 + 1.3K + 1.1K^2} \quad (3.16a)$$

K = frequency factor given by Eq. (3.14)

σ_{n-1} = standard deviation of the sample

N = sample size

It is seen that for a given sample and T , 80% confidence limits are twice as large as the 50% limits and 95% limits are thrice as large as 50% limits.

In addition to the analysis of maximum extreme events, there also is a need to analyze minimum extreme events; e.g. the occurrence of droughts. As rainfall or river flows do have a lower limit of zero, neither the Gumbel nor Gaussian distribution is an appropriate tool to analyze minimum values. Because the logarithmic function has a lower limit of zero, it is often useful to first transform the series to its logarithmic value before applying the theory. Appropriate tools for analyzing minimum flows or rainfall amounts are the Log-Normal, Log-Gumbel, or Log-Pearson distributions.

Example: Data covering a period of 92 years for a certain river yielded the mean and standard deviation of the annual flood series as 6437 and 2951 m³/s respectively. Using Gumbel's method, estimate the flood discharge with a return period of 500 years. What are the (a) 95% and (b) 80% confidence limits for this estimate?

Solution: From Table 3.4 for N = 92 years, $y_n = 0.5589$, and $S_n = 1.2020$. Then

$$y_{500} = -[\ln((\ln(500/499)))] = 6.21361$$

$$K_{500} = (6.21361 - 0.5589)/1.2020 = 4.7044,$$

$$\text{Hence, } x_{500} = 6437 + 4.7044 \times 2951 = 20320 \text{ m}^3/\text{s}.$$

Probability error

$$b = \sqrt{1 + 1.3(4.7044) + 1.1(4.7044)^2}$$

$$= 5.61$$

$$Se = \text{probability error} \times 2951 / \sqrt{92} = 1726$$

(a) For the 95% confidence probability $f(c) = 1.96$ and

by Eq.(3.16) $x_{1/2} = 20320 \pm (1.96 \times 1726)$, which results in $x_1 = 23703 \text{ m}^3/\text{s}$ and $x_2 = 16937 \text{ m}^3/\text{s}$.

Thus the estimated discharge of 20320 m³/s has a 95% probability of lying between 23700 and 16940 m³/s.

(b) For 80% confidence probability, $f(c) = 1.282$ and by Eq.(3.16)

$x_{1/2} = 20320 \pm (1.282 \times 1726)$, which results in $x_1 = 22533 \text{ m}^3/\text{s}$ and $x_2 = 18107 \text{ m}^3/\text{s}$. Thus the estimated discharge 20320 m³/s has an 80% probability of lying between 22533 and 18107 m³/s.

6.5 Precipitation Probability

The preceding discussions on flood probability apply generally to precipitation. Annual maximum hourly or daily amounts ordinarily conform to Gumbel Type I, Log-Pearson or Log-Normal distribution. In humid areas, where the mean is high, monthly, seasonal, or annual totals will approximate a normal distribution. In drier areas a skew distribution such as the Log-Pearson, Log-Normal may give a better fit.

6.6 Low Flow Analysis

Characterization of the magnitude, frequency, and duration of low stream flows and droughts is vital for assessing the reliability of flows for all in-stream and withdrawal uses and for defining resource shortages and drought.

Definitions and Basic Concepts

Low Stream flows

The objective of low-flow analysis is to estimate the frequency or probability with which stream flow in a given reach will be less than various levels. Thus the flow-duration curve; is an important tool of low-flow analysis; from it one can readily determine the flow associated with any exceedence or non-exceedence probability. Most of the time, the flow exceeded 95% of the time, q_{95} , is a useful index of water availability that is often used for design purposes.

Droughts: are extended severe dry periods. To qualify as a drought, a dry period must have duration of at least a few months and be a significant departure from normal.

Drought must be expected as part of the natural climate, even in the absence of any long term climate change. However, “permanent” droughts due to natural climate shifts do occur, and appear to have been responsible for large scale migrations and declines of civilizations through human history. The possibility of regional droughts associated with climatic shifts due to warming cannot be excluded.

Droughts begin with a *deficit in precipitation* that is unusually extreme and prolonged relative to the usual climatic conditions (**meteorological drought**). This is often, but not always, accompanied by unusually high temperatures, high winds, low humidity, and high solar radiation that result in increased evapo-transpiration.

Agricultural drought the conditions commonly produce extended periods of unusually low soil moisture, which affect agriculture and natural plant growth and the moisture of forest floor.

Hydrological drought: As the precipitation deficit continues, stream discharge, lake, wetland, and reservoir levels, and water-table decline to unusually low levels. When precipitation returns to more normal values, drought recovery follows the same sequence: meteorological, agricultural, and hydrological.

Drought analysis

The objective of drought analysis is to characterize the magnitude, duration, and severity of meteorological, agricultural, or hydrological drought in a region of interest. The analysis process can be structured in terms of five questions:

1. What type of drought of interest?
2. What averaging period will be used?
3. How will “drought” be quantitatively defined?
4. What are the magnitude-frequency relations of drought characteristics?
5. How are regional aspects of drought addressed?

Drought type:

As noted, one may be interested in one or more of the basic types of drought, each reflected in time series of particular types of data: meteorological (precipitation); agricultural (soil moisture); or hydrological (stream flow, reservoir levels, or ground water levels)

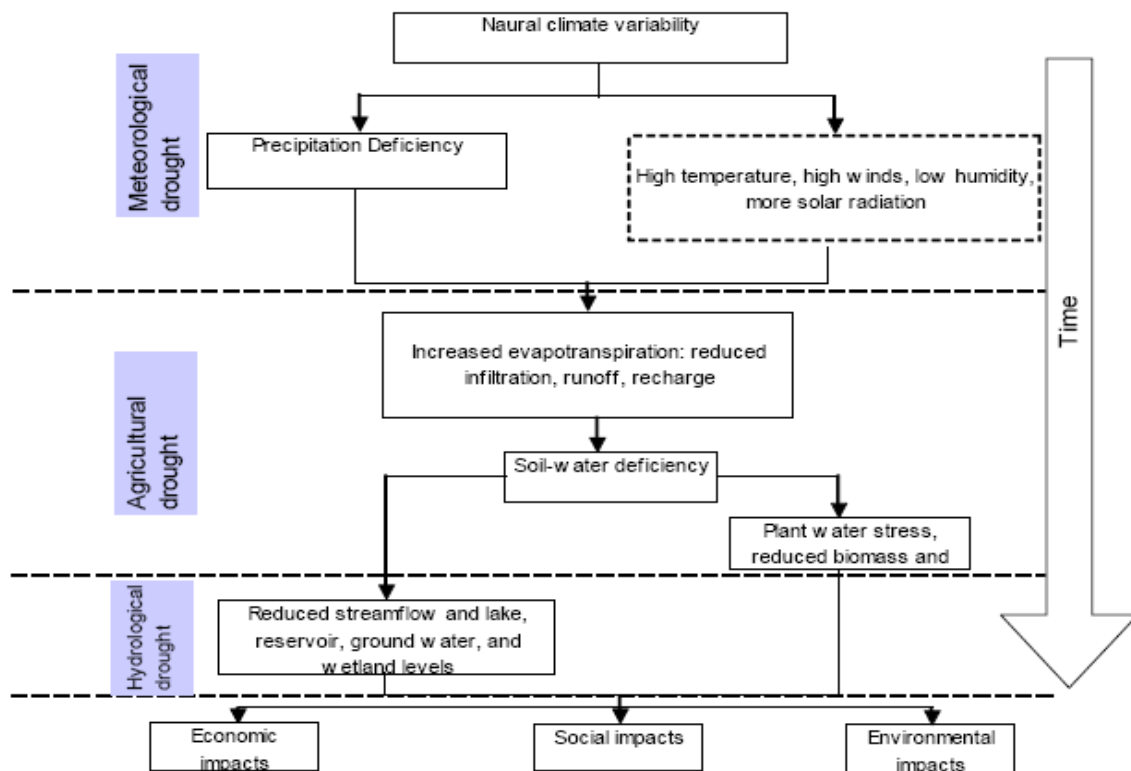


Figure : Sequence of drought impacts

Duration, D = length of period for which $X < X_0$;

Severity, S = cumulative deviation from X_0 ;

Intensity (or magnitude), $I = S/D$.

Note that if X is stream flow $[L^3T^{-1}]$, then the dimensions of S are $[L^3T^{-1}] \times [T] = [L^3]$ and the dimensions of I are $[L^3T^{-1}]$

Magnitude- Frequency Relations:

Once the severities, durations, and intensities of “drought” have been determined for a given time series, the magnitude-frequency characteristics of each of those quantities can be analyzed.

6.6 Risk, Reliability and Safety factor

Risk and Reliability: The designer of a hydraulic structure always faces a nagging doubt about the risk of failure of his structure. This is because the estimation of the hydrologic design values (such as the design flood discharge and the river stage during the design flood) involve a natural or inbuilt uncertainty and as such a hydrological risk of failure.

As an example, consider a weir with an expected life of 50 years and designed for a flood magnitude of return period $T=100$ years. This weir may fail if a flood magnitude greater than the design flood occurs within the life period (50 years) of the weir.

The probability of occurrence of an event ($x \geq x_T$) at least once over a period of n successive years is called the **risk, R** . Thus the risk is given by $R = 1 - (\text{probability of non-occurrence of the event } x \geq x_T \text{ in } n \text{ years})$

$$\bar{R} = 1 - (1 - P)^n = 1 - \left(1 - \frac{1}{T}\right)^n \quad (3.24)$$

Where P = probability $P(x \geq x_T) = \frac{1}{T}$ T = return period

The reliability R_e , is defined as

$$R_e = 1 - \bar{R} = \left(1 - \frac{1}{T}\right)^n \quad (3.25)$$

It can be seen that the return period for which a structure should be designed depends upon the acceptable level of risk. In practice, the acceptable risk is governed by economic and policy considerations.

Safety Factor: In addition to the hydrologic uncertainty, as mentioned above, a water resource development project will have many other uncertainties. These may arise out of structural, constructional, operational and environmental causes as well as from non-technological considerations such as economic, sociological and political causes. As such, any water resource development project will have a safety factor for a given hydrological parameter M as defined below.

Safety factor (for the parameter M) = (SF) m=

$$= \frac{\text{Actual value of the parameter M adopted in the design of the project}}{\text{Value of the parameter M obtained from hydrological considerations only}}$$

$$= C_{am} / C_{hm} \quad (3.26)$$

The parameter M includes such items as flood discharge magnitude, maximum river stage, reservoir capacity and free board. The difference ($C_{am} - C_{hm}$) is known as *Safety Margin*.

Example: A bridge has an expected life of 25 years and is designed for a flood magnitude of return period 100 years. (a) What is the risk of this hydrological design? (b) If 10% risk is acceptable, what return period will have to be adopted?

Solution:

(a) The risk R for n = 25 years and T = 100 years is:

$$\bar{R} = 1 - \left(1 - \frac{1}{100}\right)^{25} = 0.222.$$

Hence the inbuilt risk in this design is 22.2%.

$$(b) \text{ If } \bar{R} = 10\% = 0.10, \quad 0.10 = 1 - \left(1 - \frac{1}{T}\right)^{25} \Rightarrow \left(1 - \frac{1}{T}\right)^{25} = 0.90 \text{ and } T = 238 \text{ years}$$

Say 240 years. Hence to get 10% acceptable risk, the bridge will have to be designed for a flood of return period $T = 240$ years.