Lecture Notes

Course: Watershed Hydrology (SWC-201)

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Lecture – 1
Introduction

Definition and Importance

Hydrology, by its term meaning is the science of water. However it does not gives a complete view of hydrology in respect to water generating source for creating water resource on earth system, essential for mankind. After a great exercise and deal the scientists defined the hydrology as the science dealing the occurrence of rainfall, its distribution & circulation on and below the earth and physical and chemical reaction with earth materials.

In hydrology, the land unit is the **watershed**, which also may be referred to as a **basin** or **catchment**. A watershed is defined as an area of land in which all of the incoming precipitation drains (i.e., "sheds") to the same place – toward the same body of water or the same topographic low area (e.g., a sinkhole) – as a result of its topography. This means that a watershed's boundary is defined by its topographic high points. Watersheds are fairly simple to identify in mountainous or hilly terrain because their boundaries are defined by ridges (Figure 1). However, in flatland watersheds, such as in the Coastal Plain of the Southeast, identifying topographic high points can be very challenging because the highest and lowest elevations may differ only by a few centimetres. The study of hydrology is important to have the information is following aspects:

- The variation of water production from catchments can be calculated and described by hydrology.
- Engineering hydrology enables us to find out the relationship between a catchments's surface water and groundwater resources
- The expected flood flows over a spillway, at a highway at a Culvert, or in an urban storm drainage system can be known by this very subject.
- It helps us to know the required reservoir capacity to assure adequate water for irrigation or municipal water supply in droughts condition.
- It tells us what hydrologic hardware (e.g. rain gauges, stream gauges etc) and software (computer models) are needed for real-time flood forecasting
- Used in connection with design and operations of hydraulic structure
- Hydrology is an indispensable tool in planning and building hydraulic structures.
- Hydrology is used for city water supply design which is based on catchments area, amount of rainfall, dry period, storage capacity, runoff evaporation and transpiration.
- Dam construction, reservoir capacity, spillway capacity, sizes of water supply pipelines and affect of afforest on water supply schemes, all are designed on basis of hydrological equations.
- Crop planning based on available water in the area.

Divisions of Hydrology:

Hydrology can generally be divided into two main branches

Engineering Hydrology: Engineering hydrology deals with the planning, design and Operation of Engineering projects for the control and use of water

Applied Hydrology: Applied hydrology is the study of hydrological cycle, precipitation, runoff, relationship between precipitation and runoff, hydrographs, Flood Routing

Chemical Hydrology: Study of chemical characteristics of water.

Eco-hydrology: Interaction between organisms and the hydrological cycle.

Hydrogeology: Also referred to as geo-hydrology, is the study of the presence and movement of ground water.

Hydro-informatics: is the adaptation of information technology to hydrology and water resource applications

Hydrometeorology: It is the study of the transfer of water and energy between land and water body surfaces and the lower atmosphere.

Isotope Hydrology: It is the study of isotropic signatures of water (origin and age of water).

Surface Water Hydrology: It is the study of hydrologic processes that operate at or near earth's surface.
Ground Water Hydrology: It is the study of underground water.

The Hydrologic Cycle

It refers to the continuous circulation of water within the earth's hydro-sphere.
Water moves into and from the various sources on, over and below the earth, with the total mass of water remaining fairly constant. The water cycle is highly crucial to maintain the life on earth, as it replenishes the world's freshwater resources and moderates extremes in climate. The physical processes involved in hydrologic cycle are

- Evaporation
- Condensation
- Sublimation
- Precipitation
- Transpiration,
- Interception,
- Infiltration,
- Percolation and
- The runoff

Sun is the source of energy to activate
Evaporation - It involves the vaporization of water from the water sources due to heat energy of solar radiation. The evaporated water gets converted into cloud. Through which water gets fall on the earth system in terms of precipitation. In water transfer process about 90% of atmospheric water is contributed by evaporation.
Condensation- It refers to the transformation of evaporated water vapours into liquid water droplets suspended in the air as clouds or fog. It is important process to convert the evaporated water into liquid state enabling formation of clouds with the aid of condensation nuclei.
Sublimation- This is the process in which there is direct conversion of solid ice into water vapour. By this process water mass is also added to atmosphere for cycling.
Precipitation- It is the fall of atmospheric water to the ground surface. Under this process the water becomes available for its distribution (surface and sub-surface) and circulation on the above and below the earth surface. It mostly takes place in the form of liquid (rainfall) and very little in solid form (snow, sleet, hail fog etc.)
Transpiration- It is a process of water loss from plants' leaves through respiration. The water loss through transpiration and evaporation coupled together is referred to Evapotranspiration (ET). In hydrologic cycle about 10% water or moisture is added to the atmosphere by transpiration process.
Interception- This is the process in which a part of precipitation is abstracted by the objects lying on the ground surface. The objects may be the crop, tree, natural vegetations and any other in live or dead conditions. Intercepted precipitated water is ultimately lost through evaporation process. Rate and quantity of water loss under this process varied with the type and characteristics of vegetation/objects and climatic condition, mainly.
Infiltration- It is defined as the entry of water into the soil by crossing the imaginary boundary between soil and atmosphere and its rate called infiltration rate. Under this process the precipitated water moves into the soil media and ultimately joins to the water –table or deposited on impervious layer, if there occurs across water movement path. It is treated as the input process for ground water occurrence.
Runoff- The flow of joined rain water in the stream is designated as the channel flow or the runoff. The characteristics associated to the climate and watershed affects the quantum of runoff at the outlet. Runoff is categorised into surface and sub-surface runoff. In which surface runoff is that part of the runoff which travels over the ground surface thought the channels/ streams /rivers to reach

the basin outlet, and sub- surface or indirect runoff points to the flow of precipitated water below the soil surface leading to water- table. The view of hydrologic cycle is presented in Fig-

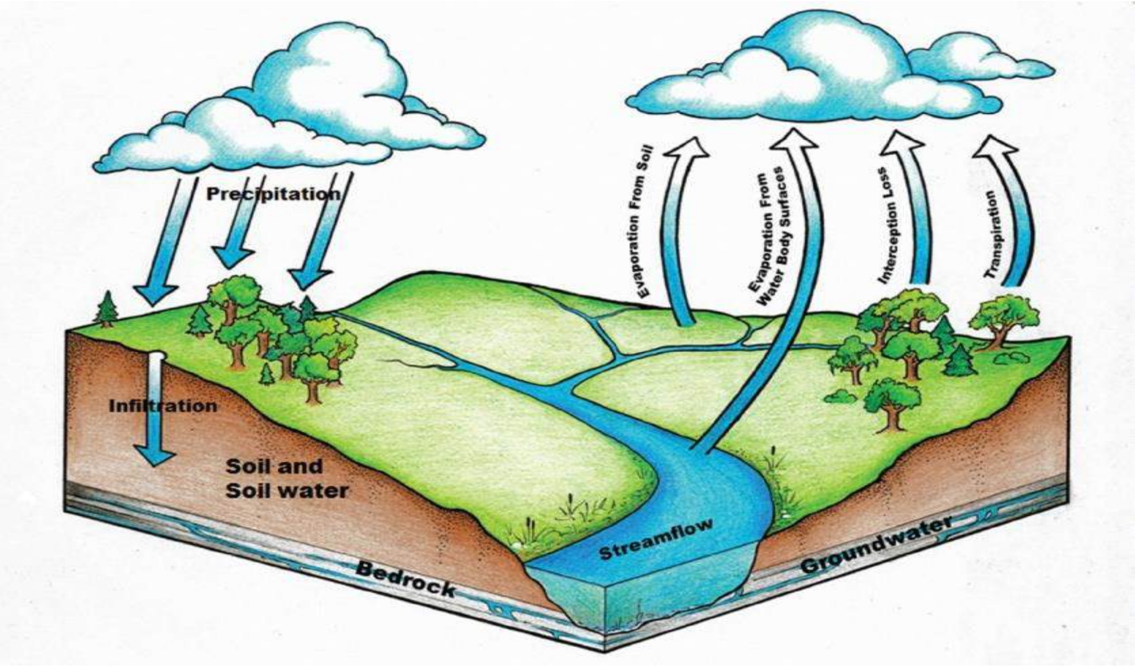


Fig- View Hydrologic cycle

Hydrologic Budget

It consists of inflows, outflows, and storage, presented by the following equation:
Inflow = Outflow +/- Changes in Storage

Inflows contribute or add water to the different parts of the hydrologic system, outflows remove water from them, and storage is the retention of water by parts of the system. Since, water movement is cyclical; therefore, an inflow for one part of the system is an outflow to another.

As example, for an aquifer the percolation of water into the ground is the inflow to the aquifer while discharge of groundwater from the aquifer to a stream is an outflow. Over time, if inflows to the aquifer are greater than its outflows, the amount of water stored in the aquifer will increase. Conversely, if the inflow to the aquifer is less than the outflow, the amount of water stored decreases.

Assignment - *Describe various atmospheric/weather variables affecting hydrologic cycle.*

Suggested Reference

1. Watershed Hydrology- R. Suresh
2. Soil & Water Conservation Engineering- R. Suresh
3. Hydrology and Soil Conservation – G. Das
4. Engineering Hydrology – K. Subramanya

Lecture- 2

Watershed- Concept and Laws

Definition- Watershed is an isolated area with a well demarcated boundary line, draining the rainwater to a single outlet. Within the boundary a watershed contains various natural resources such as the soil, water and natural vegetations. Also, there is a network of stream system to drain the rain water. The stream network is also called drainage system of watershed.

A watershed having the measured hydrological parameters such as rainfall, runoff and others is called gauged watershed. For hydrological study of watershed the hydrological input data is essential.

There is a variation in one to other watersheds regarding shape, size, morphology and other aspects. This variation enforces to cause variations in rainfall- runoff – soil erosion /loss relationship. The stream network system makes the watershed dynamic in regard to hydrologic processes. View of watershed is shown in figure-1.

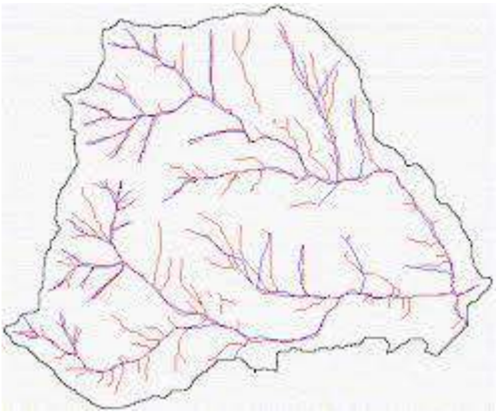


Figure-1.0 View of Watershed

Watershed Component

The followings are the major components of the watershed,

1. Watershed boundary,
2. Stream network,
3. Watershed soils/land ,and
4. Land use system.

Boundary- It defines the size and shape of watershed. Boundary of a watershed may be the any continuously elevated ridge lines covering a particular extent of land segment. Also the river line, roads, etc may be as the watershed boundary.

Stream Network- The watershed within it boundary assembles several interconnected streams leading to the outlet. Stream network constitutes drainage system for the watershed. Drainage system is assessed by the term called drainage density, which is defined as the ratio of total length of steams to the total area of watershed. A watershed with high drainage density is highly drained and vice- versa. In addition, the stream frequency which is the ratio of total number of streams to the area of watershed also signifies the degree of watershed drainage.

Soil- There is possibility of a large variation in occurrence of soil in respect to its type, geography/topography etc in the watershed. Availability of good and healthy soil makes the watershed more productive which force the population to a good level with their high standard of livings. In hilly watersheds; however, the availability of land for cultivation is very limited, normally located at the river bed and few at the slope faces, which may be under constraint of high slope. The soils at steep slopes cannot be directly used because of problems in use of tillage or cultural practices for crop growing. Normally, such steep lands are converted into terraces of different types depending on the soil types and rainfall of the area for cultivating the crops.

Land use- Mainly, the land use system comprises, agricultural, orchard, forest land, grassland / pasture and waste land uses. The waste land use may be with vegetation or without vegetations. Land use system affects the hydrological behaviour of watershed. For example, a watershed dominated by the forest land use system involves very less runoff or rain water availability for harvesting point of view than another watershed which involves very less extent of forest lands. To a large extent the land use system maintains the watershed towards its management aspects.

Watershed Morphology- It includes overall surface characteristics of watershed including the stream network comprising the stream ordering, stream length, stream slope, areal aspect , relief aspects etc mainly. Related to watershed morphology there are various laws defining the features of watershed; they are the law of steam order, law of stream length, law of stream slope, law of stream area etc.

Stream order: In order to facilitate the study of watershed behaviour on morphological aspects the stream ordering is followed as an approach for categorizing the streams into different orders as per their sequence of their origin. This also provides a basis for dividing the entire area of watershed for grouping, stream wise. There has been devised a rule for proving order to a given stream of watershed. For stream ordering the watershed map containing the stream network is essential.

Rule-1: The finger tips like streams are taken first for ordering. These are provided stream order –Ist.

Rule-2: When two same order streams join together the resulting steam will be of next higher order. Say for example, if Stream A and B of Ist order join together the order of resulting stream C will be 2nd order.

Rule-3: If a lower order stream joins to a higher order stream the order of resulting stream will be the same, i.e., remain the higher order as it is.

(Fig-2.0 illustrates the procedure of stream ordering).

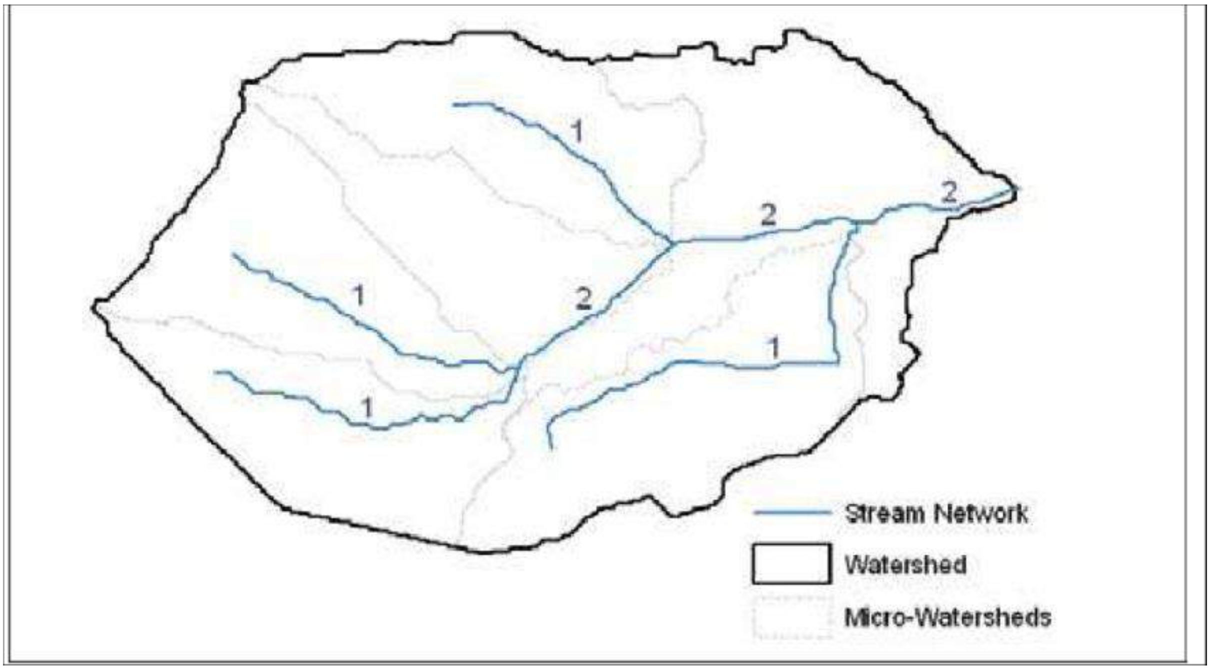


Figure- 2.0 . Stream ordering

Law of Stream Number

It states that the number of stream of each order forms an inverse geometric sequence with the stream order number, expressed as,

$$N_u = R_b^{k-u}$$

Where,

N_u = Number of steam of order u. The number of stream of any order u is fewer than for next lower order, but more in numbers than the next higher order

R_b = Bifurcation ratio, defined as the ratio of number of stream segments of a given order u to the number of stream segment of next higher order, expressed as under,

K = trunk order of stream segment in the watershed.

$$R_b = \frac{N_u}{N_{u+1}}$$

Problem(1) *Under morphological study of a watershed the following details have been collected:*

i. Total number of Ist order streams = 35

ii. Trunk order stream = 3.

Determine bifurcation ratio of watershed.

Solution – Using following formula for bifurcation ratio,

$$N_u = R_b^{K-U}$$

in which, N_u is the number of stream of order u (in present case it is taken as Ist order, which total number is given as 35); K is the trunk order stream (3) and u is the order of stream is given as 1. Substituting the values in above formula and solving, we have,

$$35 = R_b^{3-1}$$

$$R_b = \mathbf{5.92} \ \boldsymbol{Ans.}$$

Problem.(2) *Using following data set predict the shape of three different watersheds based on bifurcation ratio.*

S. No	*Parameter*	*Watershed*		
		A	*B*	*C*
1.	*Number of stream of order u (N_u)*	*25*	*20*	*14*
2.	*Number of stream of order u+1 (N_{u+1})*	*1*	*3*	*5*

Solution- Using following formula for bifurcation ratio,

$$R_b = \frac{N_u}{N_{u+1}}$$

Accordingly, the computed R_b is shown below,

S. No	Parameter	Watershed		
		A	B	C
1.	Number of stream of order u (N_u)	25	20	14
2.	Number of stream of order u+1 (N_{u+1})	1	3	5
3.	Bifurcation ratio (R_b)	25	6.66	2.80

The computed value of bifurcation ratio of watersheds A, B and C advocates following views about their shapes,

S. No.	Particular	Watershed		
		A	B	C
1.	Bifurcation ratio	25	6.66	2.80
2.	Watershed shape	Elongated or leaf shape	Semi- elongated shape	Approaching semi – circular

Law of Stream Length

The law of stream length states that the mean length of stream segment of successive order basin approximates a direct geometric sequence represented by the following expression

$$\bar{L}_u = \bar{L}_1 . R_l^{u-1}$$

In which $\bar{L}_u$ is the mean length of stream of order u; $\bar{L}_1$ is the mean length of stream of order 1; R_l is the length ratio and K is the trunk order of the stream. The length ratio is given as under,

$$R_l = \frac{\bar{L}_u}{\bar{L}_{u-1}}$$

This equation is the non- linear equation, which can be linearize by taking of the equation.

Law of Stream Area

It states that the mean area of drainage basin of progressively higher order stream constitute a direct geometric sequence, expressed as under,

$$\bar{A}_u = \bar{A}_1 . R_a^{u-1}$$

In which $\bar{A}_u$ is the mean area of drainage basin of stream of order u; $\bar{A}_1$ is the mean area of drainage basin of stream of order 1; R_a is the area ratio and K is the trunk order of the stream, is analogous to length ratio. This equation is the non- linear equation, which can be linearize by taking log of the equation.

Law of Stream Slope

It is inverse geometric series law. It states that the stream slope is progressively increased with increase in their order. Mathematically, it is expressed as under,

$$\bar{S}_u = \bar{S}_1 . R_s^{k-u}$$

In which $\bar{S}_u$ is the mean slope of stream of order u; $\bar{S}_1$ is the mean slope of stream of order 1; R_s is the slope ratio (constant) and K is the trunk order of the stream, is analogous to bifurcation ratio. This equation is the non- linear equation, which can be linearize by taking log of the equation.

Drainage Density

Drainage density of a watershed is the ratio of cumulative length of streams of all orders existing in the watershed to the total area of watershed projected on horizontal plane. It is expressed by the following expression,

$$D_d = \frac{\sum_{i=1}^{k} . \sum_{i=1}^{N} L_u}{A_k}$$

In which D_d is the drainage density of a watershed (km per sqkm); A_k is the drainage area of trunk order stream, which refers to the total area watershed. Drainage density varies among watersheds.

Problem (3)- *The order-wise stream lengths of two different watersheds are given as under.*

Particular	*Watershed-A*			*Watershed-B*			
Stream order	*I*	*II*	*III*	*I*	*II*	*III*	*IV*
Stream length, m	*500*	*210*	*55*	*3500*	*2350*	*1900*	*750*
Area of watershed, ha	*100*			*100*			

Determine drainage density and narrate which watershed is dominated by overland flow, and why.

Solution- Using following formula for drainage density:

$$D_d = \frac{\sum_{i=1}^{K} L_{u_i}}{A_u}$$

In which, in case of

Watershed- A: $\sum_{i=1}^{K} L_{u_i}$ = (500 +210 + 55) =765m and $A_u = 100ha$. Substituting value of the parameter in above formula and solving, we have,

$$D_d = \frac{765}{100 \; x \; 10000} = 0.000765 \; m^{-1}$$

Watershed- B: $\sum_{i=1}^{K} L_{u_i}$ = (3500 +2350 +1900 + 750) =8500m and $A_u = 100ha$. Substituting value of the parameter in above formula and solving, we have,

$$D_d = \frac{8500}{100 \; x \; 10000} = 0.0085 \; m^{-1}$$

On comparison of drainage density of both the watersheds, it is found that the watershed – A comprises very less value of drainage density than the watershed-B, which signifies the watershed –A to be under more influence of overland flow.

Stream Frequency

It is defined as the ratio of cumulative number of streams of all order existing in a watershed to the total area of watershed, expressed by the following formula,

$$F = \frac{\sum_{i=1}^{k} N_u}{A_k}$$

Associated parameters have already been defined above. This morphological parameter is used for assessing the stream network of watershed.

Problem (4). *The order wise number of streams of a given watershed is mentioned below.*

Stream order	*I*	*II*	*III*	*IV*
Stream length (m)	*450*	*175*	*30*	*1*

Determine stream frequency, if area of watershed is 100ha.

Solution- The formula for drainage density is given as under:

$$F = \frac{\sum_{i=1}^{K} N_{u_i}}{A_u}$$

in which, $\sum_{i=1}^{K} N_{u_i}$ = (450 +175 + 30 +1) =656.0 and $A_u = \ 100ha$. Substituting value of the parameter in above formula and solving, we have,

$$F = \frac{656}{100\ x\ 10000} =$$

$$= \mathbf{6.56x\ 10^{-4} m^{-2}} \textbf{ Ans.}$$

Problem (5) *A watershed comprises its drainage density as 0.005m^{-1}. Calculate length of overland flow of watershed, if its channel slope is 0.5% and average ground slope is 1.5%.*

Solution- The formula for length of overland flow, accounting the effect of channel slope and average ground slope, is given as under:

$$L_g = \frac{1}{2D_d\sqrt{1-\left(\frac{\theta_c}{\theta_g}\right)}}$$

in which D_d is the drainage density of watershed (0.005m^{-1}); θ_c is the slope of channel (0.005) and θ_g is the average ground slope of watershed is given as 0.015. Substituting these values in above formula and solving, we have,

$$L_g = \frac{1}{2\ x\ 0.005\sqrt{1-\left(\frac{0.005}{0.015}\right)}}$$

$$= \mathbf{122.0m\ Ans.}$$

Relief

It is defined as the elevation difference between the reference points located in the damage basin.

Relief Ratio

It is the ratio of relief to the horizontal distance on which relief is measured.

Maximum Basin Relief

It is the elevation difference between basin outlet and the highest point located at the perimeter of the basin.

Relative Relief

It is the ratio of maximum basin relief to the basin perimeter, expressed as under,

$$R_{hp} = \frac{H}{P} x100$$

In which, R_{hp} is the relative relief (%); H is the maximum basin relief (m) and P is the basin perimeter (m)

Problem (6) *A watershed of 100ha size has been surveyed for determining its relief status. The measured elevations in different aspects are given as under:*

1. *Elevation of watershed out let= 12.5m*
2. *Elevation of highest point located at watershed boundary =7.75m*
3. *Elevation of highest point within boundary = 9.75m*
4. *Elevation of lowest point within watershed = 11.35m*

Determine followings:

- *i. Maximum relief and*
- *ii. Maximum basin relief.*

Solution- Computations are presented as under:

1. *Maximum relief*- It is the elevation difference between highest and lowest points located within watershed. Accordingly,

   R_{max} = 11.35-9.75= **1.60m Ans.**
2. *Maximum basin relief*- It is the elevation difference between basin outlet and highest point located at watershed perimeter. Accordingly,

Rb_{max} = 12.5- 7.75= **4.75m Ans.**

Problem (7)-. *In a watershed the elevations of highest points (A) and lowest point (B) are 12.50 and 15.50m, respectively. Determine relief ratio, if horizontal distance between both the points is 1500m.*

Solution- Relief ratio is presented by the following relationship,

$$R_h = \frac{H}{L}$$

in which, H is the relief is elevation difference between highest and lowest points is 15.5- 12.5m=3.0m and L is the horizontal distance between both the points is given as 1500m. Accordingly,

$$R_h = \frac{3.0}{1500}$$

$$= \mathbf{0.002}\ \boldsymbol{Ans}.$$

Problem (8). *Determine the value of relative relief of a watershed, if maximum basin relief is 3.75m and perimeter of drainage basin is 1250m.*

Solution- Using following formula for relative relief of watershed,

$$R_{hp} = \frac{H}{p}\ x\ 100$$

in which, H is the maximum basin relief, given as 3.75m and p is the perimeter of watershed is 1250. Therefore,

$$R_{hp} = \frac{3.75}{1250}\ x\ 100$$

$$= \mathbf{0.30}\%\ \boldsymbol{Ans}$$

Problem (9). *The elevation of outlet and highest point located at basin perimeter is 15.0 and 11.45m, respectively. The length of basin perimeter is 2.55km. Determine the value of maximum basin relief and relative relief of watershed.*

Solution- Computations are presented as under:

1. *Maximum basin relief*- It is the elevation difference between basin outlet and highest point located at watershed perimeter. Accordingly, 15-11.45=**3.55m Ans.**
2. Relative relief- It is given by the following formula,

   $$R_{hp} = \frac{H}{p}\ x\ 100$$

   in which, H is the maximum basin relief, given as 3.55m and p is the perimeter of watershed is 2550m. Therefore,

   $$R_{hp} = \frac{3.55}{2550}\ x\ 100$$

   $$= \mathbf{0.14}\%\ \boldsymbol{Ans}$$

Suggested References

5. Soil & Water Conservation Engineering- *R. Suresh*
6. Hydrology and Soil Conservation – *G. Das*

Lecture-3

Clouds- It is the source of precipitation**.** Precipitation is resulted mainly from two types of clouds. They are the nimbostratus and cumulonimbus type clouds. The nimbostratus clouds appear at mid height in dark gray colour result the rainfall throughout day, continuously. The cumulonimbus clouds are low lying in the sky. These appear as thick puffy columns climbing into the atmosphere. These are thunderstorm clouds, cause intense, short rain bursts, heavy snowfall, hail etc.

Precipitation- The moisture emanating from the cloud and falling to the earth surface is called precipitation. Precipitation in the form of rainfall develops water resource potential of the region, on which various activities like crop cultivation; industrial needs, house hold needs, water requirement for electricity generation etc are met. Also, the precipitation is important

- Precipitation replenishes the water to the earth.
- Without precipitation the earth would behave like desert. The amount and duration of precipitation affect the water level and water quality as well.
- Precipitation supplies freshwater to an estuary, which is important source of dissolved oxygen and nutrients.
- Drought effects are lowered.

Forms of Precipitation

Precipitation is water released from clouds in the form of rain, freezing rain, sleet, snow, or hail. It is the primary connection in the water cycle that provides for the delivery of atmospheric water to the Earth. Most precipitation falls as rain.

Broadly, precipitation takes place in liquid and solid forms. Liquid form of precipitation comprises the forms of rainfall and drizzle, mainly. Liquid precipitation is any precipitation that falls as a liquid and remains liquid after striking on object, i.e. the earth surface.

Liquid form of Precipitation

Rainfall- It is in liquid form (drops) falling from the clouds to the earth surface. Size of water droplets is about to 0.5 mm or little bit bigger. Rate of rainfall varies from time to time. A light rain ranges from 2.5mm/h, moderate rain from 2.5-7.5mm/h and heavy rain above 7.5mm/h. Rainfall is the most important component of hydrologic cycle which replenishes large percentage of fresh water on earth. Rain and drizzle are beneficial for plants.

Drizzle- It is also in liquid form but its droplets size is less than 0.5mm diameter. Its intensity is lesser than 2.5mm/h. It contributes moisture to the lower atmosphere effective for cooling and generating warm air mass to create cloud in the sky. Drizzle usually falls from low stratus clouds and is frequently accompanied by fog.

Acid rain- It occurs when rain becomes mixed with pollutants such as Sulphur Oxides and Nitrous Oxides. It kills plants and pollutes the water sources lying on the earth surface.

Solid form of Precipitation

Various forms are the snow, sleet, hail etc,

Snow- It consists of white or translucent ice crystals. Originally these are highly complex, hexagonal, branched structures. Snow falls as a combination of individual ice-crystals, fragments of crystals, or clusters of crystals.

Snow pellets – These are small hails, appear in the form of white, opaque, round/ conical. Average diameter varies from 0.08 to 0.2 inch. Have tendency to burst upon striking a hard surface. These occur almost exclusively in snow showers.

Hail- These are opaque ball of hard ice, ranging in diameter from 1/8 inch or so to 5 inches or larger. Hails are basically the ice that falls from the sky, often in round shape. Hailstones are large chunks of ice that fall from large thunderstorms.

Precipitation size and speed

Have you ever watched a raindrop hit the ground during a large rainstorm and wondered how big the drop is and how fast it is falling? Or maybe you've wondered how small fog particles are and how they manage to float in the air. The table below shows the size, velocity of fall, and the density of particles (number of drops per square foot/square meter of air) for various types of precipitation, from fog to a cloudburst.

Types	**Intensity (cm/h)**	**Median diameter (mm)**	**Numbers of drops (per sqm)**
Fog	(0.013)	0.01	67,425,000
Mist	0.005	0.1	27,000
Drizzle	0.025	0.96	151
Light rain	0.10	1.24	280
Moderate rain	0.38	1.60	495
Heavy rain	1.52	2.05	495
Excessive rain	4.06	2.40	818
Cloudburst	10.2	2.85	1,220

(Source: Lull, H.W., 1959, Soil Compaction on Forest and Range Lands, U.S. Dept. of Agriculture, Forestry Service, Misc. Publication No.768)

Precipitation Types

Orographic precipitation- This type of precipitation is caused by air masses striling some natural topographic barriers like mountains. The greater amount of precipitation falls on the windward side. Few important features are given as under:

- Lifting of warm air mass is due to orographic barriers causing formation of cloud and precipitation thereof.
- Rainfall is steady rainfall.
- Southern slope of the Himalayas is a good example of this type of precipitation.
- Similarly, the winds coming from ocean strike the western slopes of coastal ranges causing heavy rains are another example of orographic precipitation.
- The rainfall at u/s side is intense to that of the d/s side.
- The d/s orographic precipitation is called Rain shadow.

Cyclonic precipitation-

Cyclone is atmospheric disturbance caused by air mass circulating clockwise in southern and anticlockwise in northern hemispheres. Basically, cyclone is violently rotating wind storm. The precipitation as result of cyclone is termed as cyclonic precipitation. Cyclone is very large mass of air ranging from 800 to 1600km in diameter and moving with the velocity of 50 kmph. Few important features are mentioned below:

- The cyclonic precipitation occurs in the form of drizzle, intermediate rain or steady rain.
- Precipitation caused by cold front is intense and of short duration.
- Precipitation caused by warm front is more continuous

Convective Precipitation- In this precipitation the lifting of warm air mass is due to convective effect, called convective uplift. **The convective uplift** takes place especially when air near to ground gets warm due to sun energy, and begins to rise upward in the sky. The process of rising of warm air mass and its cooling is governed by adiabatic **cooling process**. This leads to the formation of clouds and precipitations, sometimes. In this precipitation the precipitation occurs in the form of showers of high intensity and for short duration.

Rainfall Measurement

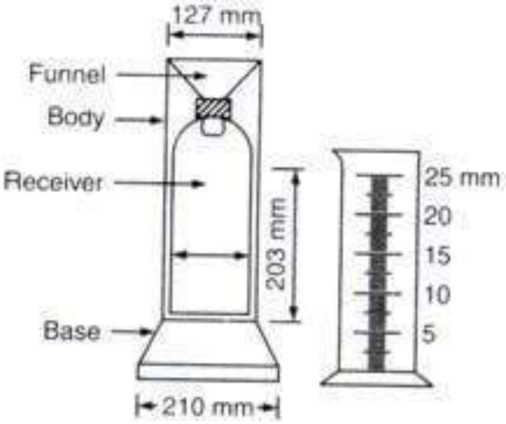
Rain gauge- The rain gauge is the instrument used for rainfall measurement. The measured rainfall is termed as the point rainfall. The point rainfall is used for determining the mean areal rainfall by using various computing methods. The mean aerial rainfall can be used for determining the volume of rainwater received over the surface area of watershed by multiplying the mean depth of rainfall and area of watershed/region.

Types of Rain gauge

Broadly, it is classified as

1. Non- recording type; and
2. Recording type rain gauge.

Non- Recording Type Rain gauge (Simon type) - It is most common type of rain gauge, consists of 127mm diameter cylindrical vessel with a base width 210mm diameter for making stability. At top a funnel is provided with circular brass rim which is exactly 127mm to fit into vessel correctly. This funnel shank is inserted in the receiving bottle placed below. The height of receiving bottle is 75 to 100mm. The bottle receives the rainfall. Capacity of receiving bottle is to measure the rainfall depth is 100mm. During heavy rainfall, the rainfall amount is likely to exceed the bottle capacity. In this condition it is suggested to take the observations frequently, normally 3 to 4 times in a day. The water collected in the receiving bottle is measured by a graduated measuring cylinder. The measuring accuracy of graduated cylinder is being up to 0. 1mm. The timing of rainfall measurement is uniformity done, every day at 8:30Am IST. For accurate measurement the proper care, maintenance and inspection of rain gauge should be carried out during dry weather.



Recording Type Rain gauge It records the information about start and end of rainfall event taking place. With the help of this information, one can determine the rainfall intensity and depth of the place under measurement. The following rain gauges are commonly used as recording type rain gauge,

1. Float type rain gauge,
2. Weight type rain gauge, and
3. Tipping bucket type rain gauge.

Float Type Rain Gauge- It is also known as natural siphon type rain gauge. In India this rain gauge is adopted as the standard recording rain gauge. Working of this rain gauge is similar to the weighing type rain gauge. In this a funnel receives the rain water which is collected into a container equipped with a float at the bottom. The position of float rises as the water level rises in the container depending on rain water coming into. The movement of float is transmitted to a pen which traces a curve on the rain chart mounted on a clockwise rotating drum. When float rises to the top of container the siphon comes into action and drain the total water from the container. At this stage the pen traces a straight line. If rainfall is continued and water is coming into the container then further float rises up and pen traces the curve. This process is continued. If rainfall is stooped the pen traces a horizontal line on the chart. The obtained curve is the mass curve. View of this rain gauge is shown in Fig-.

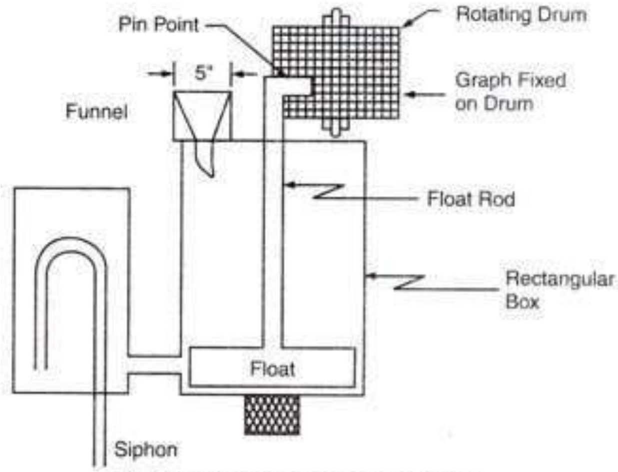
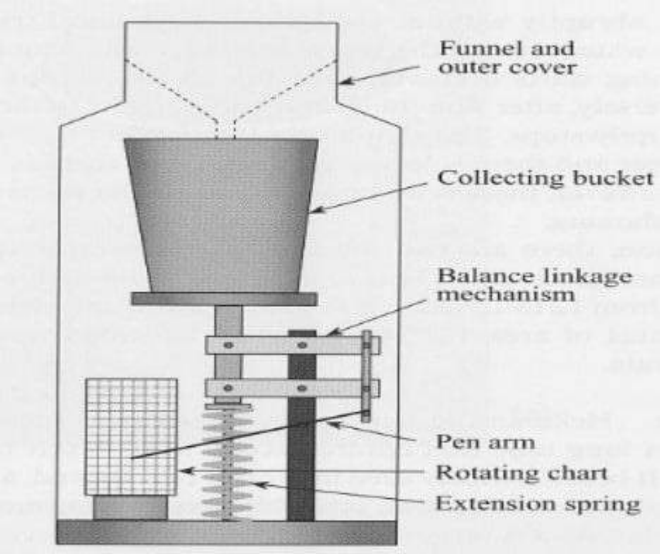


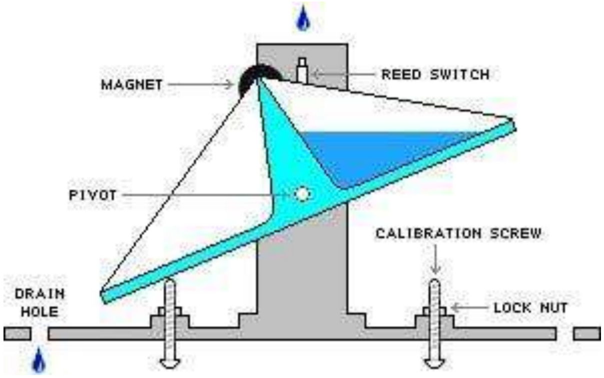
Fig. 2.5. Recording type rain-gauge

Weighing Type Rain Gauge- It is most common self-recording rain gauge, consists of a receiver (bucket) supported by a spring/ lever balance or some other weighing mechanism. The movement of bucket due to its increasing weight because of accumulation of rainwater is transmitted to a pen, which traces a curve on the rain chart wrapped on clock. The obtained rainfall record in terms of curve is mass curve, i.e. the plot of cumulative rainfall vs elapsed time. View of rain gage is shown in Fig-



Tipping Bucket Type Rain Gauge- It is a 30cm size rain gauge, used as recording type rain gauge. US weather bureau uses this rain gauge for measuring the rainfall. Its construction includes a 30cm diameter sharp edged receiver. At its end a funnel is provided for directing the rainwater into the receiver. One pair of buckets is pivoted on a fulcrum below the funnel in such a way that when one bucket receives 0.25mm depth of rainfall, it tips and empties its rainfall into the container, and immediately the second bucket comes below the funnel (Fig..).

The rainfall measurement is recorded in terms of number of tips made for a given rainfall event, which is indicated on a dial actuated by electrical circuit. .



Assignment- ***Describe various types of rain gauges used for recording the rainfall data with a neat sketch.***

Suggested Reference

7. Watershed Hydrology- R. Suresh
8. Soil & Water Conservation Engineering- R. Suresh
9. Hydrology and Soil Conservation – G. Das
10. Engineering Hydrology – K. Subramanya

Lecture-4

Rain gauge Installation

The surrounding exposure of rain gauge station affects the catching of rainfall by a raingauge. Therefore, before establishment of raingauge, the selection of a suitable place is very important, otherwise the rainfall measurement would not be accurate as should be. There are few important points to follow for installation of raingauge station in the area.

1. The ground surface must be level and firm. The places such as the building roof, sloppy surface, and terrace wall should be avoided.
2. In hilly areas the valley and hill top should not be selected for installation of the raingauge.
3. The site should be representative of the area or watershed.
4. Wind affected site should be avoided.
5. Site should be open from all the sides.
6. In forest area the raingauge should be instated at the distance twice the height of tallest tree from the forest plantation. Also the gauge's upper point should make an angle ranging from 20 to 30 degree from the upper point of the raingauge.
7. The receiver's height from the ground surface should be around 75cm.
8. The position of raingauge must be vertical.

Rain gauge Distribution

The rain gauge distribution in watershed for measurement of rainfall, in accurate way is very important. If number of rain gauge differs than the required depending on the areal extent and topography, there is likely to get effects on the results various estimates. The topography and extent of area of watershed decide the number of rain gauge stations to be there. The number of rain gauge stations for highly undulating watershed comparatively more to that of the flat topography watershed. Rain gauge stations as per WMO and IMD is described below,

As per WMO

1**.** Flat reasons of temperate mediterrian and tropical reasons

Ideal	-600 to 900 sq km per raingauge
Acceptable	- 900 to 3000 sq km/per raingauge

2. For mountainous reasons of temperate, mediterrian and tropical reasons

Ideal -	100 to 250 sq km/per raingauge
Acceptable -	250 to 1000 sq km/per raingauge

3. In arid and polar zones – 1500 to 10,000 sq km per raingauge

As per IMD

1. Plain reasons - 520sqkm/raingauge
2. Reasons of average elevation - 260-360 sq km/per raingauge
3. Pre dominantly hilly reasons with heavy rainfall – 130 sq km/per raingauge

Note: 10% of total raingauge required is taken as recording type of raingauge for installation.

Problem (1)- *In watershed the tipping bucket type rain gauge is installed for taking measurement. Determine the depth of rainfall, if rainfall duration is 2.30 hour.*

Solution- The following standards are involved with the tipping bucket type rain gauge:

1. For single tipping, the time involvement = 6 to 7 seconds
2. Capacity of one compartment is =0.25mm.

As per above, total number of tipping = $\frac{2.30x3600}{6} = 1380$

Therefore, depth of rainfall=1380x0.25=345mm **Ans.**

Problem (2)- *In a watershed of mountainous region of temperate zone determine the number of ideal and acceptable rain gauge stations, if area of watershed is 1500sqkm.*

Solution- As per WMO, the distribution of rain gauge station in mountainous watershed of temperate regions is as per below:

Ideal- 1 station/100 to 250sqkm; and acceptable- 250 to 1000sqkm.

Accordingly, the number of rain gauge stations would be as below:

Ideal- $\frac{1500}{200} = 7.5 = 8.0$

(Assuming 1station/200sqkm)

Acceptable-$\frac{1500}{750}$ =2.0

(Assuming 1 station/750sqkm)

Raingauge Adequacy – It Is determined by using the following formula

$$N = \left(\frac{C_v}{\varepsilon}\right)^2$$

Where, N= adequate No. of raingauge stations

C_V= Coefficient of variations in percent

ε = percent allowable error taken as 10%

Problem (3)- *In a watershed there are total 7 rain gauge stations, out of which one is siphon type rain gauge. On the basis of statistical analysis of long term rainfall data of said watershed the coefficient of variation is obtained as 35%. Determine the adequate number of rain gauge stations to be in the watershed. Take the value of allowable percent error in estimation as 10%.*

Solution- Adequacy of rain gauge stations is given by the following formula,

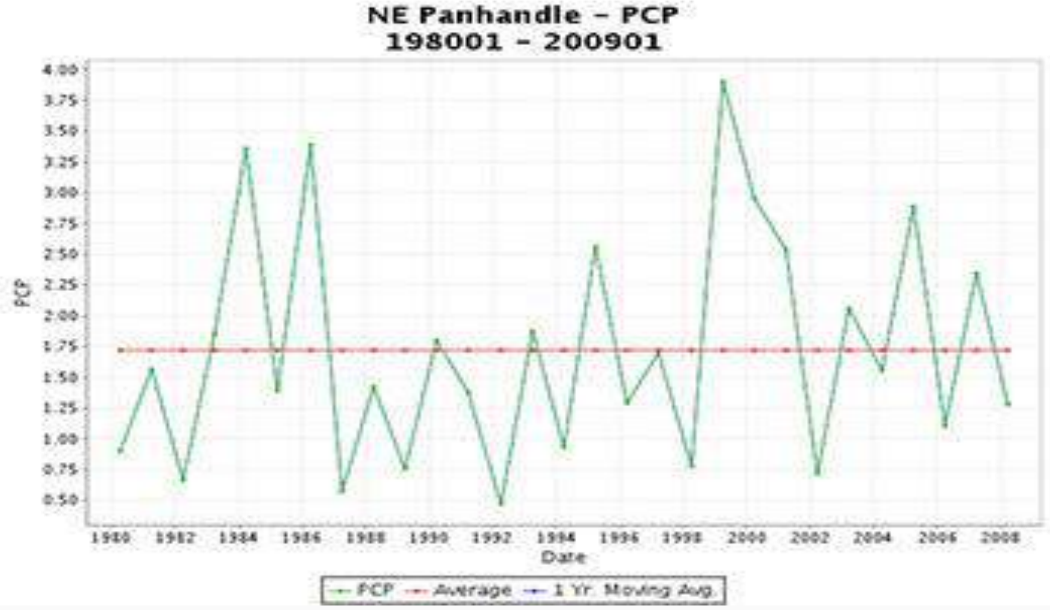
$$\sqrt{N} = \left(\frac{C_v}{\epsilon}\right)$$

in which, N is the adequate number of rain gauge stations to be; $C_v$is the coefficient of variation given as 35% and percent allowable error is 10%. Substituting these values in above formula; and after solving, we have,

$$\sqrt{N} = \left(\frac{35}{10}\right)$$

N= 12.25 = 12.0

Normal Rainfall- It is an average of the rainfall values over a 30-year period. Rainfall may very often be either above or below the seasonal average, or "normal."



Common Errors in Rainfall Measurement

Few important errors in rainfall measurement by the raingauge are mentioned as under,

1. In non- recording type raingauge (Symons's type) about 2% error is introduced due to displacement of water level by measuring scale.
2. Possibility of errors due to initial wetting of dried surface of the catch can or receiver.
3. The dents in catch can or receiver also introduces errors in measurement.
4. A high temperature cause evaporation loss also signifies a kind of errors in rainfall measurement. The errors may be up to 2%.
5. A high wind velocity deflects the rainfall to fall at the mouth of the rain gauge, introduces an errors in rainfall catching. The research revealed that at the wind velocity of 10mile per hour the catching of rainfall is declined to the tune of about 17% while at 30mile per hour it may be up to 60%.

Missing Rainfall Data

In normal course, sometime what happens, because of several reasons such as absence of observer, instrumental fault etc there is short breaks in the rainfall records. In this condition to fill the break the estimation of missing rainfall data is essentially required. The following methods are commonly used for computing the value of missing rainfall data

1. Arithmetic Mean Method
2. Normal Ratio Method

Arithmetic Mean Method- This method follows following formula for determining the mean aerial rainfall,

$$P_x = \frac{1}{n}\sum_{i=1}^{i=n} P_i$$

in which 'n' is the number of raingauge stations in nearby area, 'Pi' is rainfall depth at ith station and 'Px' is missing rainfall data. Solve example….. illustrates the computation procedure.

Normal Ratio Method- This method is used when normal annual rainfall at any of the index station differs from the interpolation station by more than 10%. Missing rainfall data is predicted by weighing the rainfall of index stations by the ratios of their normal annual rainfall. Formula is given as under,

$$P_x = \frac{1}{n}\sum_{i=1}^{i=n} \frac{N_x}{N_i} P_i$$

For 3 number of defined index raingauge stations the above formula is expanded as

$$P_x = \frac{1}{3}\left[\frac{N_x}{N_1}P_1 + \frac{N_x}{N_2}P_2 + \frac{N_x}{N_3}P_3\right]$$

in which Px is the missing rainfall at raingauge station 'x' of a given rainfall event, Pi is the precipitation for the same period and same rainfall event of "ith" raingauge station among group of index stations, Nx the normal annual rainfall (NAR) of station x and Ni the normal annual rainfall of 'ith' station.

The solve example – illustrates the procedure.

Problem ()- *In a watershed four rain gage stations namely a, B, C and D are instatlled for recording rainfall data. The normal annual rainfall of these four stations is 75, 60, 70.5 and 87 cm, respectively. The rain gauge station A does not have the annual rainfall observation for one year during total length of record, because of disorder of the rain gauge. Calculate the missing value of rainfall data of rain gauge station A, if the annual rainfall recorded at other three stations for that particular year was 85, 67.5 and 75 cm, respectively at B, C and D, respectively.*

Solution- The variation in normal rainfall data is more than 20% at all the four rain gauge stations. In this condition, the normal ratio method for computing the missing value of annual rainfall of station A is suitable. Accordingly, the formula for computing the missing annual rainfall is given as under.

$$P_1 = \frac{N_1}{m-1}\left(\frac{P_2}{N_2} + \frac{P_3}{N_3} + \frac{P_4}{N_4}\right)$$

in which, $P_2 = 85cm; P_3 = 67.5cm;\ P_4 = 75cm, and\ N_1 = 75cm; N_2 = 60cm; N_3 = 70.5cm; N_4 = 87cm\ and\ m = 4$. Substituting these values in above formula and solving , we have,

$$P_1 = \frac{75}{4-1}\left(\frac{85}{60} + \frac{67.5}{70.5} + \frac{75}{87}\right)$$

$$= 81cm\ \boldsymbol{Ans}.$$

Assignment- **(1) Describe design of rain gauge network.**

(2) Describe WMD and IMD guidelines for distribution of rain gauge.

Suggested Reference

11. Watershed Hydrology- R. Suresh
12. Soil & Water Conservation Engineering- R. Suresh
13. Hydrology and Soil Conservation – G. Das
14. Engineering Hydrology – K. Subramanya

Lecture-5

Mean Areal Rainfall

Average rainfall is the representative of large area, which is computed with the help of rainfall data generated from well distributed raingauge network system of the watershed. The computing methods are elaborated as under,

1. Arithmetic or station average method
2. Thiessen Polygon Method
3. Isohyetal Method.

Arithmetic Average Method

This method computes arithmetic average of the rainfall by considering point rainfall observations of all the raingauge stations installed in the area. This method computes accurate value when rainfall is uniformly distributed in the entire area, as in this situation equal weightage of area is assigned to the point rainfall data. Formula is given as under,

$$\overline{P} = \frac{1}{n}\sum_{i-1}^{n} P_i$$

where $\bar{P}$ is the mean rainfall is over an area, P is the point rainfall at individual station i, and n is the total number of stations.

Solve problem (1) illustrates the computation procedure.

Problem (1)- *In a topographically homogeneous watershed total four number of non- recording and one recording type rain gauges have been installed for recording the rainfall measurements. The point rainfall of four non- recording type rain gauge stations have been observed to the tune of 250,175,225 and 270mm, respectively during a given rainfall event. Determine the mean areal rainfall of the watershed for the said rainfall event.*

Solution- The mean areal rainfall of the watershed can be computed by using the simple arithmetic mean method, given as under:

$$P_a = \frac{P_1+P_2+P_3+P_4}{4}$$

$$= \frac{250+175+225+270}{4}$$

$$= 230mm$$ **Ans.**

Thiessen Polygon Method

This is a graphical method for computing MAP. It computes by weighing the relative area of each raingauge station equipped in the watershed. It follows the concept that the rainfall varies by its intensity and duration, spatially. Therefore, the rainfall recorded by each station should be weighed as per the influencing area (polygons). This method computes better for the areas having flat topography and size ranging from 500 to 5000 km^2. Computing steps are described as under,

1. Plot the locations of raingauge stations on map of the area drawn to a scale.
2. Join each station by straight line.
3. Draw perpendicular bisectors of each line. These bisectors form polygons around each station. Area enclosed within polygon is the effective area for the station. For a raingauge station close to the boundary, the boundary lines forms its effective area.
4. Determine effective area of each raingauge station. For this the planimeter can be used.
5. Calculate MAP by using the following formula,

$$\overline{P} = \frac{\sum_{i-1}^{n} P_i A_i}{A}$$

in which, P_i is the rainfall depth of raingauge station i and A is the total area of watershed.

Solve problem(2) illustrates the computation procedure.

Problem (2)- *Compute the mean areal rainfall of the watershed by using Theissen Polygone Method. The details are cited below.*

Rain gauge station	*A*	*B*	*C*	*D*	*E*

Measured rainfall (cm)	*10.5*	*11.56*	*9.57*	*10.50*	*11.63*
Area of enclosed polygon (sqkm)	*15.0*	*23.5*	*35.9*	*8.50*	*12.35*

Solution- In Theissen Polygon Method the following formula is used for computing the value of mean areal rainfall depth**.**

$$\bar{P} = \frac{\sum_{i=1}^{n} P_i A_i}{A}$$

in which, P_i is the rainfall depth for rain gauge station i and A_i is the area of polygon enclosed by the rain gauge station i and A is the total area of watershed. Computation is shown below.

Rain gauge station	Measured rainfall (cm)	Enclosed area of polygon (sqkm)	Rainfall x enclosed area of polygon (cm.sqkm) Col.II x Col.IV
I	II	III	IV
A	10.5	15.0	157.50
B	11.56	23.5	271.66
C	9.57	35.9	343.56
D	10.50	8.5	89.25
E	11.63	12.35	143.63
Total		**95.25**	**1005.60**

Therefore, mean areal rainfall= 1005.60/95.25=10.56cm **Ans.**

Isohyetal Method

This is also a graphical method, in which an isohyets map is prepared with the help of measured rainfall data of various raingauge stations located in the watershed. An isohyet map includes a network of isohyet lines. Each line represents a fixed value of rainfall depth. Computation of MAP under this method is done by using following steps,

1- Collect the map of area/watershed. The map should to the scal.
2- Draw isohyet map with the help of measured rainfall data of various raingauge stations installed in the watershed.
3- Find the area enclosed between each isohyet.
4- Multiply the area enclosed between each isohyet by the average precipitation, i..e $A\left(\frac{P_1+P_2}{2}\right)$.
5- Find the sum of product of area enclosed and average of rainfall for all segments of Isohyet map.
6. Divide the sum of the values found in step- 5 by the total area of the watershed to get MAP of watershed.

Computing formula is mentioned as under,

$$\bar{P} = \frac{A_1\left(\frac{P_1+P_2}{2}\right) + A_2\left(\frac{P_2+P_3}{2}\right) + A_3\left(\frac{P_3+P_4}{2}\right)}{A}$$

Solve problem (3) illustrates the computation procedure.

Problem (3)- *In a watershed total five rain gauge stations (A, B, C, D, and E) are installed for taking rainfall measurements. Calculate the mean areal rainfall depth using Isohyetal Method for a particular rainfall event. The details about measured rainfall and area enclosed by respective rain gauge station are given as under.*

Rain gauge station	*A*	*B*	*C*	*D*	*E*	*F*
Measured depth of rainfall (cm)	*5.35*	*4.75*	*6.45*	*5.00*	*4.55*	*3.50*
Area enclosed by isohyets (sqkm)	*75*	*125*	*65*	*70*	*100*	*70*

Solution- In Isohyetal method of mean areal rainfall computation the following formula is used.

$$\bar{P} = \frac{\left(\frac{P_1+P_2}{2}\right)A1+\left(\frac{P_2+P_3}{2}\right)A2+\left(\frac{P_3+P_4}{2}\right)A3+\cdots}{A}$$

Computation is shown as below.

Rain gauge station	Measured rainfall depth(cm)	Isohyet area (sqkm)	Average of rainfall of two consecutive isohyets (cm)	P_{av} x enclosed isohyet area (sqkm.cm)
I	II	III	IV	V

A	5.35	75.0	-	-
B	4.75	125.0	5.05	378.75
C	6.45	65.0	5.60	700.00
D	5.00	70.0	5.73	372.45
E	4.55	100.0	4.78	334.60
F	3.50	70.0	4.03	403.0
Total		505.00	25.19	2188.80

The mean areal rainfall is equal to 2188.8/505= 4.33cm **Ans**

Suggested Reference

15. Watershed Hydrology- R. Suresh
16. Soil & Water Conservation Engineering- R. Suresh
17. Hydrology and Soil Conservation – G. Das
18. Engineering Hydrology – K. Subramanya

Lectures-6

Rainfall Analysis

Mass Curve- It is the plot of accumulated rainfall against time, in chronological order (Fig-). The rainfall record generated by float type and weighing-bucket type gauges is in terms of mass curve. Mass curve acts as tool to determine the duration & magnitude and intensity of rainfall event. In case of the observation of non-recording rain gauges, the mass curve is prepared on the basis of knowledge of approximate beginning and end of rainfall event and by taking guidance from the mass curve of adjacent recording raingauge stations.

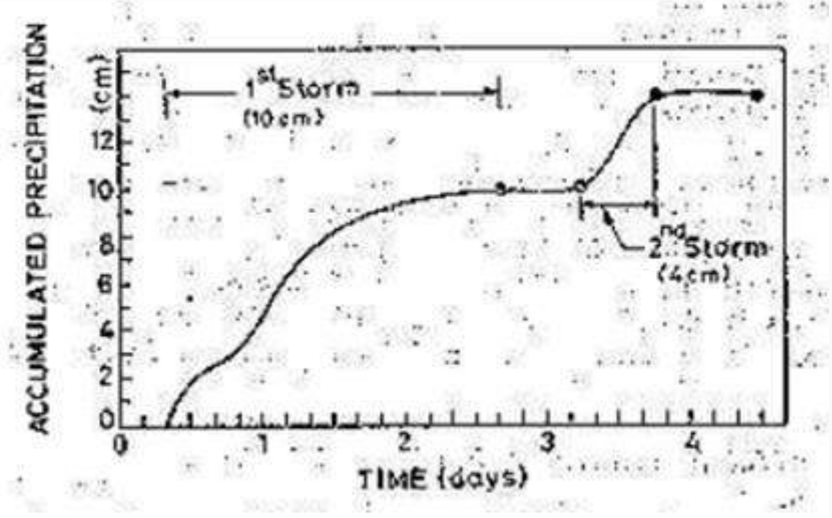


Fig.1. View of mass curve of rainfall

Double Mass Curve- It is used to check the consistency of many kinds of hydrologic data. Also, it can be used to adjust inconsistent rainfall data. The plotting between cumulative data of one variable versus the cumulative data of a related variable, if produces a straight line indicates consistency in record, otherwise, break in the double-mass curve shows inconsistency in record. The break point indicates the time from when there is development of inconsistency, which could be because of several reasons like change in original location/ exposure of the instrument/ device used for measurement.

Consistency of Rainfall Data

In the condition when a long time has been to a raingauge establishment, then there is possibility of change in the surroundings of the rain gauge in reference to the original condition. In result the rainfall to be measured by the raingauge gets change, and thus the rainfall data becomes inconsistence. The change in raingauge surroundings may be due to various reasons, such as,

1. Construction of new infrastructures like buildings apartments etc.
2. Plantation of orchards etc.
3. Introduction of instrumental errors.
4. Repetition of observational errors from a certain period.

Consistency test provides the time from when the inconsistency is introduced in the data. It is tested with the help of double mass analysis method. The stepwise procedure is described as under,

1. Collect the rainfall data (normally annual) of the raingauge station which consistency is to be tested (say station X) and of the surrounding rain gauge stations.
2. Find the mean of the surrounding rain gauge data called base station data.
3. Calculate the cumulative rainfall of inconsistence raingauge station and of the base stations.
4. Plot the cumulative rainfall of base station on X -axis and corresponding rainfall of station X on Y-axis. It is shown in Fig-
5. Find the regime where rainfall data are under inconsistence nature. It can be demarcated by getting the change in slope of the plotted curve.

6. Rectify the inconsistence nature of the data, by multiplying a factor to them. The multiplying factor is the ratio of slope of straight line of consistence data to the slope of inconsistence data.

Hyetograph-Hyetograph is the plot of rainfall intensity vs time presented as bar chart (Fig.). It is derived with the help of mass curve. Hyetograph represents the characteristics of a rainfall event and acts as a tool to develop a design storm for predicting extreme floods. Also, a hyetograph casts the information about total depth of rainfall occurred during rainfall event. Hyetograph is used hydrological analysis of catchment for (i) predicting flood; (ii) for estimating runoff and (iii) for deriving unit hydrograph.

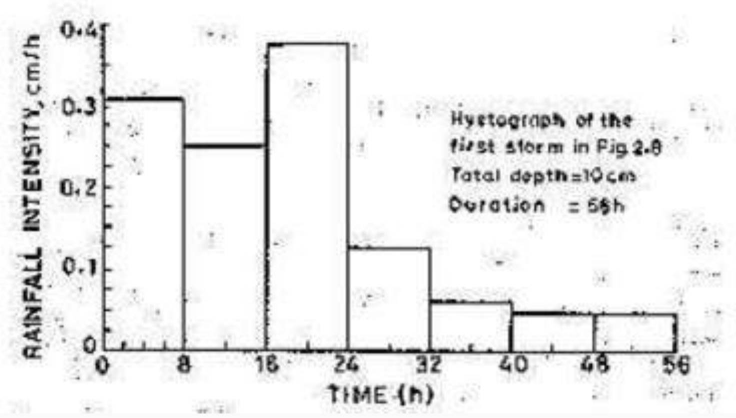


Fig. View of hyetograph of a storm

Problem (1)- *The rainfall intensity vs time data derived from the mass curve of a specific rainfall event is given as under:*

Rainfall time (hour)	*0-1.5*	*1.5-3.0*	*3.0-4.5*	*4.5 – 6.0*	*6.0 – 7.5*	*7.5 – 9.0*
Rainfall intensity (cm/h)	*3.50*	*5.25*	*6.00*	*5.00*	*6.25*	*3.50*

Determine the depth of rainfall of the rain event.

Solution- The relationship between rainfall intensity and time is the hyetograph. Area of hyetograph represents the depth of rainfall. Calculation is shown in following table.

Rainfall time interval (hour)	Rainfall intensity (cm/h)	Time (hour)	Depth of rainfall (cm) Col. (2)x Col.(3)
(1)	(2)	(3)	(4)
0 -1.5	3.50	1.5	5.250
1.5- 3.0	5.25	1.5	7.875
3.0 – 4.5	6.00	1.5	9.000
4.5 – 6.0	5.00	1.5	7.500
6.0 – 7.5	6.25	1.5	9.375
7.5 – 9.0	3.50	1.5	5.250
Total depth of rainfall			**44.250 cm**

Total rainfall depth is computed as 44.25cm. **Ans.**

Problem (2)- *Using the data of above problem; calculate the depth of effective rainfall if average loss of rainwater during rainfall duration is @2.50cm/h.*

Solution- Effective rainfall depth is determined by subtracting the loss of rain water during rainfall. The average loss of rainwater is termed as ϕ- index. In this problem the ϕ- index is given as 2.50cm/h. Calculation is presented in following table.

Rainfall time interval (hour)	Rainfall intensity (cm/h)	Time (h)	Depth of rainfall (cm) Col. (2)x Col.(3)
(1)	(2)	(3)	(4)
0 -1.5	3.50	1.5	5.250
1.5- 3.0	5.25	1.5	7.875
3.0 – 4.5	6.00	1.5	9.000

4.5 – 6.0	5.00	1.5	7.500
6.0 – 7.5	6.25	1.5	9.375
7.5 – 9.0	3.50	1.5	5.250
Total depth of rainfall			**44.250 cm**

Effective rainfall depth= Total rainfall depth- Loss of rainwater during rainfall
= (44.25- 9x2.5) cm
= 21.75cm. **Ans**

Depth-Area Relationship

This relationship provides the view about variation in overall depth of rainfall with respect variation in aerial extent of watershed. In general, for a rainfall of specific duration the average depth decreases with increase in area, exponentially. Depth- area relationship is presented below,

$$\overline{P} = P_0 \exp(-KA^n)$$

in which $\overline{P}$ is the average depth of rainfall (cm) over an area A (km²), P_0 is the highest rainfall depth (cm) at the storm centre and K and n are the constant for the region specific. Dhar and Bhattacharya (1975) have determined the value of K and n for different duration storms on the basis of 42 severe most storms in north India, shown in Table-.

Duration	K	n
1 day	0.0008526	0.6614
2 days	0.0009877	0.6306
3 days	0.0017454	0.5961

In this formula to determine the exact or accurate value of P0 is not possible, because it is very unlikely that the established raingauge station coincides the storm centre. Considering this fact in view the analysis of rain events covering a large area the highest station rainfall is taken as the average depth over an area of 25 km².

Problem (3)- *Determine the average depth of rainfall in the watershed of 1000sqkm size by using Depth- Area relationship, if the highest rainfall at the centre of rain storm is 15cm. Take the constants* $K=8.256x10^{-4}$ *and* $n=6.614x10^{-1}$.

Solution - The depth- area relationship is given by the following expression,

$$\overline{P} = P_0 e^{-KA^n}$$

in which, $\overline{P}$ is the average depth of rainfall (cm); P_0 is the highest rainfall depth at the centre of storm (cm):A is the area of watershed; and K and n are the empirical constants.

Substituting the values of different parameters in above formula, and solving, we have,

$$\overline{P} = 15e^{-8.256x0.00010x1000^{0.6614}}$$

= **6.21cm Ans.**

Rainfall Intensity – Return Period Relationship

Return period or recurrence interval is the number of years in which an event can be expected once.

The relationship between rainfall intensity and return period is very important to determine the rainfall intensity for different return periods or rainfall frequencies, which is mainly required for computation of runoff rate to be used for design of hydraulic structures. For example the soil conservation structures like drop structures, grassed waterways, farm ponds, reservoirs, dams etc are designed on the basis of runoff rates for different return periods.

The rainfall duration increases when intensity decreases and vice-versa. The rainfall intensity increases when return period increases and vice-versa. The formula for rainfall intensity – return period is presented by the following expression.

$$i = \frac{KT^a}{(t+b)^d}$$

in which, i is the rainfall intensity (cm/h) for given return period (T, year) and duration of rainfall (h) and K ,a ,b and d are the regional constants.

Solve problem (3) illustrates the computation procedure.

Problem (4)- *Calculate the rainfall intensity of 1000 sqkm size catchment for 25-yeras return period to be used for design of semi- permanent gully control structure. Take the duration of rainfall is 6.0 hours and constants, K=45.216; a= 0.50; b=4 and d=0.6870.*

Solution- The formula for rainfall intensity – return period is presented by the following expression.

$$i = \frac{KT^a}{(t+b)^d}$$

in which, i is the rainfall intensity for given return period and duration of rainfall (cm/h) and K ,a ,b and d are the empirical constants.

Substituting the values of above parameters in above formula and solving, we have,

$$i = \frac{45216x\ 25^{0.50}}{(6+4)^{0.6870}}$$

$$= \frac{226.08}{4.864}$$

$$= 46.45cm/h$$ **Ans.**

Rainfall Frequency

It is also known as plotting position. The design of hydraulic structures, flood control structures, soil conservation structures, drains, culverts etc are based on probability of occurrence of extreme rainfall events. The relationship for plotting position/rainfall frequency is given by the Weibul's equation presented as under:

$$p_{\%} = \frac{m}{n+1} x100$$

in which, $p_{\%}$ is the plotting position; m is the rank number of event after arranging in descending order and n is the length of record. In terms of return period (T) the relationship as under,

$$T = \frac{1}{p_{\%}}$$

Solve example illustrates the computation procedure.

Problem (5)- *Determine the plotting position of highest rainfall of 50cm during 50 years period.*

Solution- The relationship for plotting position is given by the Weibul's, given as under:

$$p_{\%} = \frac{m}{n+1} x100$$

In which, $p_{\%}$ is the plotting position; m is the rank number of event after arranging in descending order and n is the length of record. Sustituing the values of different parameters (m=1 and n=50) in above formula, and solving, we have,

$$p_{\%} = \frac{1}{50+1} x100$$

$$= 1.96\%$$ **Ans**

Problem (6) - *At Pusa Farm (Samastipur), Bihar the highest rainfall depth to the tune of 25cm was recorded in the years 1987 and 1995 during 75 years period. Determine their plotting positions and return periods.*

Solution- In this case the highest rainfall 25cm is observed in the years 1987 and 1995. The rank number will be 1 for the 1987 as it has first place first and rank 2 will be for the year 1995 because this event was taken place after first event. Accordingly, plotting positions for years 1987 and 1995 will be as below.

Using Weibul's method,

$$p_{\%} = \frac{m}{N+1} x100$$

in which, $p_{\%}$ is the plotting position(percent); m is the rank number and N is the length of record. Accordingly,

(i) Plotting position of the rainfall depth 25cm for the year 1987- For this case, m=1 and N=75. Substituting these values in above formula and solving, we have,

$$p_{\%} = \frac{1}{75+1} x100 = 1.25\%$$ **Ans.**

Return period (T) is the inverse of plotting position. For this case it is $T = \frac{1}{1.25/_{100}}$ =80 years.

(i) Plotting position of the rainfall depth 25cm for the year 1996- For this case, m=2 and N=75. Substituting these values in above formula and solving, we have,

$$p_{\%} = \frac{2}{75+1} x100 = 2.50\%$$ **Ans.**

For this case return period (T) is $= \frac{1}{2.5/_{100}}$ =40 years.

Problem (7)- *Determine the length of rainfall record, if return period of highest rainfall of 75 cm is 25 years.*

Solution- Using Weibul's method,

$$p_{\%} = \frac{m}{N+1} x100$$

In this formula, plotting position ($p_{\%}$) is equal to $\frac{1}{T}$, i.e. $\frac{1}{25} x100 = 4.0\%$. Substituting the value of m =1 and plotting position **(** $p_{\%}$) as 4.0% and solving, we have,

$$4.0 = \frac{1}{N+1} x100$$

$$N = \frac{100}{4} - 1$$

$$= 24\ years$$ **Ans.**

Suggested Reference

19. Watershed Hydrology- R. Suresh
20. Soil & Water Conservation Engineering- R. Suresh
21. Hydrology and Soil Conservation – G. Das
22. Engineering Hydrology – K. Subramanya

Lecture-7
Rainfall Abstractions and Initial Loss

Initial Loss of Rainwater

In course of rainfall occurrence there is significant water loss from various sources such as interception, evaporation, transpiration, infiltration, depression storage. In result the overland flow and runoff yield against rainfall gets reduce. These loses are referred as initial loss. The prediction of initial rainwater loss is very important for determining the runoff and hydrograph derivation.

Interception- It is the amount of rainwater loss due to abstractions from initially dry surfaces of the objects lying on the ground surface. The objects may be the live vegetations e.g. herbs, shrubs & trees and any dry surfaces like building etc. From a tree the interception is mainly from the canopy, is called canopy interception (Fig-)

Intercepted rainwater is lost due to evaporation is called interception loss. The extent of interception loss depends on a host of factors such as types and characteristics of vegetations, rainfall, temperature, season of the year, wind velocity etc, mainly. Average interception loss from few forest cover and crops is presented in following table.

S. No	Vegetation	Average Interception loss (of total rainfall)
1.	Forest	
	Coniferous forests	15-35%
	broad-leaved forests	9-25%
	natural grasses	14-19%
2.	Crops	
	Oats	about 7%
	corn	about 16%
	clover	about 40%

Interception losses generally occur during the first part of a precipitation event and the interception loss rate trends toward zero rather quickly (Figure 1). Interception losses are described by the following equation (Horton reprinted by Viessman 1996):

$$L_i = S + K.E.t$$

in which L_i is the total volume of water intercepted, S is the interception storage, K is the ratio of the surface area of the leaves to the area of the entire canopy, E is the rate of evaporation during rainfall and t is the time. This equation assumes that the rainfall is enough to satisfy the storage capacity of vegetation. Horton equation suggests that the total interception is dependent on the duration of rainfall as longer duration rainfall event allows more evaporation from the canopy. Brooks (2003) also suggested following formula for predicting interception loss,

$$L_i = P_g - T_h - S_f$$

in which L_i is the canopy interception loss, P_g is the gross precipitation, T_h is the through fall and S_f is the stem flow. The intensity of the storm also plays a role in canopy interception (Viessman 1996); however, there is debate as to whether intensity increases or decreases interception storage in canopy (Keim 2003).

Interception is mainly at two levels depending on features of vegetation, given as under,

1. Primary interception, and
2. Secondary Interception

Primary Interception takes place from the vegetations of uniform canopy like crops etc where secondary interception is from the vegetations having more that one level canopy such as found n the forest covers. In forest the tall tress constitutes primary level of interception. And the vegetative layer existing below the tall tree canopy is the secondary canopy, which intercepts the rainwater falling from the upper canopy, called secondary interception and loss of it is as secondary interception.

Through fall – It is the process of falling of rainwater through the sp[aces of plant canopy. Through fall is affected by the factors such as plant leaf and stem density, type of precipitation, rainfall intensity and duration of the rainfall event. Through fall may be bys direct falling of rain water or dropping of intercepted water through tips of the leaf. The measurement of through fall can be carried out by putting a bucket below the tree canopy.

Stem flow – In course of rainfall a part of rainwater is also absorbed by the branches and stem of the tree. If rainfall is continued, then after some time the absorbed water starts flow through the branches and joins to the soil surface through stem, is called stem flow. By this process a part of rain water is also absorbed by the surfaces of tree branches and stem, which is lost due to evaporation. The characteristics of tree branches and stem affect the rate of stem flow. A tree with rough surface of branches /stem involves high level of stem flow loss.

Depression storage- Depressions are the small size low pockets lying on the ground surface. Such appearances are very common in undulating lands. Presence of depressions on the ground surface cause significant level of water retention in them, known as depression storage. It also constitutes a kind of rainwater loss because the retained water is lost due to infiltration and evaporation actions. Depression storage affects the rainfall- runoff relationship of the area. Linsley (1982) suggested following formula for predicting the volume of retained in depression storage at any time during a rainfall event

$$V = S_d(1 - e^{kP_e})$$

In which V is the volume of water retained in depression storage, S_d is the maximum storage capacity of, P_e is the rainfall excess and k is a constant equal to $1/S_d$. As per various research studies the level of depression storage for different land covers are presented in following table,

Land cover	**Depression storage (inch)**	**Reference**
Impervious, 1% slope, flat roofs, parking lots, roads	0.0625 – 0.125	Tholin and Kiefer(1960)
Impervious, 2.5% slope and sloped roofs	0.05	Viessman (1996)
Turf grass	0.25	Tholin and Kiefer(1960)
Open fields	0.40*	Urban Drainage and Flood Control District (2008)
Wooded Areas	0.40*	Urban Drainage and Flood Control District (20080

*These values include interception losses by vegetation

Infiltration

It is defined as the entry of water into the soil by crossing the imaginary boundary between soil and atmosphere. Infiltration is treated as one of the most important factors making rainwater loss from the total. Runoff generating potential of area/ soil is very much affected by infiltration rate. A sandy soil belt involves very less potential for runoff yield to that of the heavy soil belt, because of the reason that the infiltration rate is quite high of sandy soil as compared to the heavy soil. The rate of water soaking by the soil is called as infiltration rate and its maximum rate is termed as infiltration capacity.

Infiltration rate, Initial Infiltration rate and Basic Infiltration rate

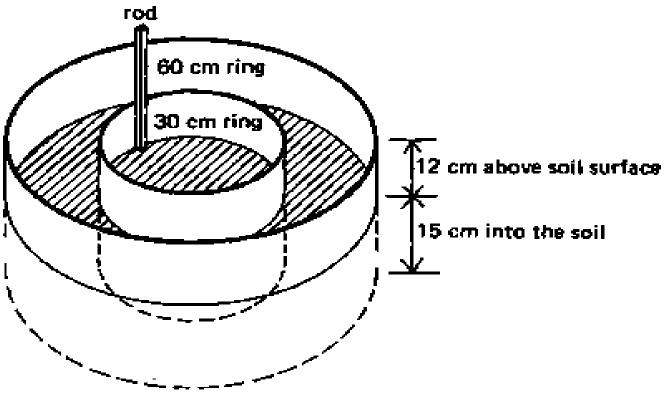
The velocity or speed at which water enters into the soil is called infiltration rate. It is usually measured by the depth (in mm) of the water layer that can enter the soil in one hour. For example an infiltration rate of 15 mm/h reveals that a 15 mm water depth standing on soil surface will infiltrate into the soil in one hour time. Initially, infiltration rate is very high and becomes slower as time proceeds. This is because of the reason that at beginning there is sufficient space or reservoirs are there for storing water in the soil media and likely to get reduce because of filling of water content in them with time advancement. In dry soil, the water infiltrates rapidly called initial infiltration rate. As more water replaces the air in the pores, the water from the soil surface infiltrates more slowly and eventually reaches a steady rate, called the basic infiltration rate. Basic infiltration rate of various soils are narrated as under,

Soil type	Basic infiltration rate (mm/h)
sand	less than 30
sandy loam	20 - 30
loam	10 - 20
clay loam	5 - 10
clay	1 - 5

Infiltration rate depends on host of factors such as soil texture (size of soil particles) and soil structure (arrangement of soil particle), soil depth, land topography, water- table position, vegetations and climatic factors, mainly.

Field Test for Infiltration Measurement

The most common method to measure the infiltration rate is by using the Double Ring Infiltrometer. The diameter of inner ring is 30 cm and of outer rings 60 cm. View of double ring infiltrometer is shown in Fig-. Experimental procedure is described as under.



Procedure

Different steps followed are numerated as under,

Step (1) Insert the inner ring (30cm dia.) into the soil at least for 15 cm depth by using hammer.

Care should be taken that there should not be any kind of damage in the ring. Normally for this purpose a wooden plate is placed at the top of ring and hammering is done on that.. The side of ring must be in vertical position. After it, insert the measuring rod in the area of inner ring for taking observations about depth of water entered into the soil

Step 2: Also, insert the outer ring (60cm dia.) ring into the soil for 15cm depth to create a protection bund or buffer area around inner ring.

Step 3: Pouring water into both the rings for the depth of 70-100 mm. The pounding water should be done quickly. The water in outer area of inner ring or within the two rings prevents the lateral movement of water from the infiltrometer.

Step 4: Record the time when test begins, and note the water level on the measuring rod. Initially the observations should be taken at lesser time intervals.

Step 5: After lapse of 1-2 minutes, record the drop in water level in the inner ring area. It is noted from measuring rod. And Add water to bring the water level at original level. Also, maintain the water level outside the ring similar to the inside. Take the readings frequently (e.g. every 1-2 minutes) at the beginning, but extend the interval as the time goes on (e.g. every 20-30 minutes) and rate of water level drop also becomes slow.

Step 6: Continue the test until the rate of water level drop becomes constant.

It is suggested that at a given site at least two infiltration tests should be carried out to have a correct result.

Water Year: It starts from Ist June to 31st May during the year.

Suggested Reference

23. Watershed Hydrology- R. Suresh
24. Soil & Water Conservation Engineering- R. Suresh
25. Hydrology and Soil Conservation – G. Das
26. Engineering Hydrology – K. Subramanya

Lecture-8

Runoff and Its Computation

Runoff Definition and Occurrence

Runoff is defined as the flow of excess rainwater through a channel, gully, river or any fluvial path. The overland flow is the main input for generating runoff. On watershed scale, the rainwater after getting satisfied with the initial losses such as, abstractions, evapotranspiration, infiltration etc the remaining rainfall water is called excess rainfall or effective rainfall, is converted into a head of water on the ground surface, which attains motion due to land slope. In result the standing water starts moving down the slope. This phenomenon is called overland flow. As soon as the overland flow joins any flow path like channel etc, the runoff takes place. Since, this flow is through channel; therefore, runoff is also called channel flow. The length of overland flow is limited to a very short distance, normally maximum up to 150 m.

Runoff Classification

It is classified as

1. Direct runoff, and
2. Indirect runoff

Direct Runoff - It is the surface runoff, takes place on the ground surface through the streams / channels etc. Since, it takes place very soon after start of rainfall event; therefore, it is called as the direct runoff. Direct runoff is also known as surface runoff.

The *interflow,* in which the infiltrated rainwater joins to the stream flow in terms of influent flow, soon after start of rainfall, is also the part of surface or direct turnoff. The reason behind this is that the time gap between rainfall occurrence and interflow is very less, say as few minutes. The interflow always takes place above the main ground water- table.

Indirect Runoff- This type of runoff takes place below the ground surface. In the course of occurrence of rainfall a part of rain water which is infiltrated into the soil media moves downward and joins to the water –table. The joined rainwater starts moving or flow along with ground water to the other places in forward direction, called indirect runoff. Since, this runoff takes place below the ground surface; therefore, it is also called sub-surface runoff. Sometimes, it is also known as the *delayed runoff* because of the reason that there is very large gap between occurrence of rainfall and formation of runoff say for example 1- year or more.

Factors Affecting Runoff

Conceptually, in runoff formation the rainfall is an input and watershed is the system on which rainfall take place, and runoff is the output. It means that the parameters associated to the rainfall (climate) and watershed affect the runoff yield. Broadly, the list of factors affecting the runoff are listed in following table-

S. No	Parameters	Factors affecting
1.	Climatic	
1.1	Rainfall	
1.1.1		Intensity
1.1.2		Duration
1.1.3		Direction
	Temperature	
1.3	Wind velocity	
1.4	Humidity	

2.	Watershed	
2.1	Physiographic factors	
2.1.1		Size
2.1.2		Shape
2.1.3		Slope
2.1.4		Form factor
2.1.5		Compactness factor
2.1.6		Drainage density
2.1.7		Stream frequency
2.1.8		Channel slope
2.1.9		Channel length
2.1.10		Channel size
2.2	Soil	
2.2.1		Type
2.2.2		Depth
2.2.3		Slope
2.3	Land use	

Form Factor-It is defined as the ratio of average width to the axial length of the watershed. Axial length of watershed is the distance between outlet and the remotest point of the watershed. Width is determined by dividing the area of watershed by its axial length.

Compactness factor- It is the ratio of watershed perimeter to the circumference of a circle which area is equal to the area of watershed. It is given by

$$\boldsymbol{Compactness\ factor} = \frac{\boldsymbol{Watershed\ Perimeter}}{\text{Circumference of a circle which area is equal to the area of watershed}} = \frac{\boldsymbol{P}}{\boldsymbol{2\pi A}}$$

In which, P is the perimeter and A is the area of watershed.

Problem (1)- *Determine form factor of an elongated watershed, which axial length is 15000m and average width as 750m.*

Solution- The formula of form factor is given, below.

$$F_f = \frac{Average\ width\ of\ watershed}{Axial\ length\ of\ watershed}$$

in which, average width and axial length of watershed is given as 15000 and 750m, respectively.

Substituting these values in above equation and solving, we have,

$$F_f = \frac{750}{1350} = \mathbf{0.55}\ \textbf{Ans.}$$

Problem (2)- *Determine compactness factor of an elongated watershed, which perimeter is 2500m and area is 1.5sqkm.*

Solution- The formula of compactness factor is given, below.

$$C_f = \frac{Perimeter\ \ of\ watershed}{Circumferance\ of\ circle\ whose\ area\ is\ equal\ to\ area\ of\ watershed}$$

in which, perimeter of watershed is given as 2500m and circumference of circle is determined as below.

$$\pi r^2 = 1.5x1000x1000m2$$

r = 691m

Circumference of circle = 2 πr

= 2x3.14x 691 m

= 4339.48m

Therefore,

$$= \frac{2500}{4339.48}$$

= 0.576 **Ans.**

Stream Classification

Manly, streams are classified as under,

1. Perennial stream,
2. Intermittent stream, and
3. Ephemeral stream

Perennial stream carries runoff flow throughout the year. In off-season, i.e. summer season the flow of water is contributed by ground water. Resulted hydrograph is extended for the entire year duration. *Intermittent streams* do not have continuous flowing water year-round and are not relatively permanent. Water flowing water period is limited during wet season (winter-spring) but are normally dry during hot summer months.

The water flow in *Ephemeral streams* is confined with the occurrence of rainfall. Comparatively, these streams have less flow than the intermittent stream. Typically these are shallow and have very less flowing periods.

Effective Rainfall Hyetograph: ERH is the plot of rainfall intensity and time after deducting the Phi – index. It is plotted in the form of bar diagramme. The area of ERH is the depth of effective rainfall. The time duration of ERH is the duration ER.

Direct Runoff: It is the runoff directly formed due to rainfall. In other words, the runoff excluding base flow is the direct runoff. It can be presented in terms of volume and rate both. The depth of effective rainfall multiplied by area of watershed is the direct runoff volume. The depth of effective rainfall is the area of ERH.

Relationship between ER and DR: In terms of depth both are same. However, the volume of direct runoff is the product of ER and area of watershed. In other words, area of ERH multiplied with the area of watershed casts the volume of direct runoff.

Runoff Computation

There are host of method and empirical formulae for computing the runoff from a watershed, few important amongst them are listed as under,

1. Rational method,
2. SCS method
3. Cooks method
4. Infiltration Indices method
5. Hydrograph method
6. Empirical formulae

Rational Method

This method computes the peak runoff of small watershed**.** Peak runoff is required for design of hydraulic structures such as culverts, bridges, drop structures, and others**.** The rational method is appropriate for estimating peak discharge for small drainage areas of up to about 80 hectares with no significant flood storage. The method provides the designer with a peak discharge value, but does not provide a time series of flow nor flow volume. This method follows the hypothesis that,

1. Runoff is directly proportional to the area of watershed , and
2. Directly proportional to the rainfall intensity
3. Rainfall intensity must be for the duration equal to time of concentration of watershed.

Accordingly, if the area of watershed is A (-) and rainfall intensity for the time equal to time of concentration of watershed is I then, the equation of peak runoff (Q_p) is given as under,

$$Q_p = CIA$$

Time of Concentration- The time of concentration (Tc) of watershed is defined as the time required for movement of rainwater from remotest point to the outlet of watershed. If rainfall duration is equal to or greater than the TOC then from entire watershed area the excess rainwater or runoff is started to generate, which cumulatively comes to the watershed outlet. The cumulative runoff joining to the watershed outlet is at highest level, called peak runoff. Fig- shows the view of formation of peak runoff depending on rainfall duration and TOC. In contrast when rainfall duration does not coincide to the TOC the runoff yield at outlet is not at peak level. The following formula given by Kirpitch (1940) can be used for determining the TOC of watershed.

$$T_c = 0.02L^{0.77}.S^{-0.385}$$

In which T_c is the time of concentration (minute); L is the longest length of water course (m) and s is the average slope of water course (m/m).

The above formula is revised by Haan etal (1982) by including the component of overland flow. They reported that the Rational Method does not compute well when size of watershed is less than 5sqkm area. Such watersheds are dominated by overland flow rather channel flow or the runoff. In this condition after incorporating the effect of overland flow the revised formula for TOC is mentioned as under,

$$T_c = 0.02L^{0.77}.S^{-0.385} + \left(\frac{2L_0}{S_0}n^{0.5}\right)^{0.467}$$

In which, Lo is the length of overland flow (m) and n is the Manning's roughness coefficient and s0 is the slope of overland flow path (m/m). The value of Manning's roughness coefficients are given in following table,

Table- Manning's roughness coefficient (n)

S.No	Surface condition	n
1.	Smooth and impervious surface	0.02
2.	Smooth and bare surface	0.10
3	Cultivated new crops	0.20
4	Pasture or average grassed surface	0.40
5.	Forest area with dense grass cover	0.80

Rainfall Intensity- It is the ratio of rainfall depth and duration of rainfall event. As per this definition the computed rainfall intensity does not fit for rational method. The rainfall duration must be taken as the TOC of watershed. Accordingly, the rainfall intensity is presented as the ratio of rainfall depth to the TOC. Sometimes, for design of hydraulic structures such as the drop structure or grassed waterways etc the design runoff for a given return period or rainfall frequency is required. For such cases the formula for rainfall intensity – return period is given by the following expression.

$$i = \frac{KT^a}{(t+b)^d}$$

in which, i is the rainfall intensity (cm/h) for given return period (T, year) and t is the TOC (h) and K ,a ,b and d are the regional constants. Solve problem (3) of lecture-6 illustrates the computation procedure.

Runoff Coefficient- It is the fraction of total rainfall converted into runoff. In other terms it is the ratio of Runoff depth and total rainfall depth. Its value is dimensionless varies from 0 to maximum 1 in which 0 is for soils having very high rate of infiltration, i.e. there is no excess rainwater available for generating runoff from the surface. The value of runoff coefficient for sandy soil may be approaching 1.0 at the beginning of rainfall occurrence when total rain water is likely to get infiltrated into the soil. And the value of runoff coefficient as 1.0 which is maximum may be for concrete or any hard formation in which the infiltration of rainwater is about to zero. However, the runoff coefficient for use in rational method is cited in Table- 1

Table-1. Runoff coefficient

S. No	Land use and topography		Soil Type		
			Sandy loam	Clay and silt loam	Tight clay
1.0	Cultivated land	Flat	0.30	0.50	0.60
		Rolling	0.40	0.60	0.70

		Hilling	0.52	0.70	0.82
2.0	Pasture land	Flat	0.10	0.30	0.40
		Rolling	0.16	0.36	0.55
		Hilling	0.22	0.42	0.60
3.0	Forest land	Flat	0.10	0.30	0.40
		Hilling	0.30	0.50	0.60
4.0	Populated land	Flat	0.40	0.55	0.65
		Rolling	0.50	0.65	0.80

Normally, there is a large variation in soil types , slope gradient, vegetations in the watershed. Because of this reasion the selction of single runoff coefficnt value is not accurate. In this condition the coideraion of weighted runoff coeffcient is most appropriate, which should be interms of soil types , types of vegations an slope gradient , if so. The formual for detrmining the weighted runoff coefcient is mentioned as under,

$$C_w = \frac{C_1A_1+C_2A_2+C_3A_3+\cdots C_nA_n}{A}$$

In which, C_w is the weighted runoff coefficient, A is the total land area and C_1 … C_n are runoff coefficient for the area A_1 ….A_n .

Assumptions and Limitations

Assumptions counted under rational method are as follows,

- Applicable when TOC of watershed is at least equal to or greater than the duration of peak rainfall intensity.
- The calculated runoff is directly proportional to the rainfall intensity.
- Rainfall intensity is uniform throughout the duration of the storm.
- The frequency of occurrence for the peak discharge is the same as the frequency of the rainfall producing that event.
- Rainfall is distributed uniformly over the drainage area.
- The minimum duration to be used for computation of rainfall intensity is 10 minutes. If the time of concentration computed for the drainage area is less than 10 minutes, then 10 minutes should be adopted for rainfall intensity computations.
- The rational method does not count for storage in the drainage area. Available storage is assumed to be filled.

Problem (3)- *For a watershed of varying land use systems, soils and topography, determine the weighted runoff coefficient. The requisite details are outlined as under:*

Landuse/topography	*Agricultural lands/ topography is flat/ soil sandy*	*Grassland/ rolling topography/ soil is sandy*	*Residential lands/ topography is flat/ soil is tight clay or hard soil.*
Area (ha)	*250*	*175*	*25*

Solution- The formula for weighted runoff coefficient is given as under:

$$C_w = \frac{C_1A_1+C_2A_2+C_3A_3}{A_1+A_2+A_3}$$

The values of runoff coefficient for respective land use systems, soil types and topographic conditions are taken from the given values, which may obtained from any book of watershed hydrology. The obtained values of runoff coefficients are tabulated as under:

Land use/topography	Agricultural lands/ topography is flat/ soil sandy	Grassland/ rolling topography/ soil is sandy	Residential lands/ topography is flat/ soil is tight clay or hard soil.
Area (ha)	250	175	25
Runoff coefficient	0.30	0.16	0.40

Substituting these values in above equation and solving, we have,

$$C_w = \frac{250x0.30+175x0.16+25x0.40}{250+175+25}$$

$$= \frac{75+28+10}{450}$$

$= 0.251$ **Ans.**

Problem (4)- *Determine time of concentration of watershed, if*

- *(i) Length of longest water course =1500m*
- *(ii) Average longitudinal slope of water course=2.5%.*
- *(iii) Length of overland flow=125m*
- *(iv) Slope of overland flow path =0.02.*

Take Manning's roughness coefficient as 0.15.

Solution- In problem the occurrence of overland flow has been mentioned. For this condition the time of concentration is computed by considering the overland flow phenomenon. Formula is outlined as under:

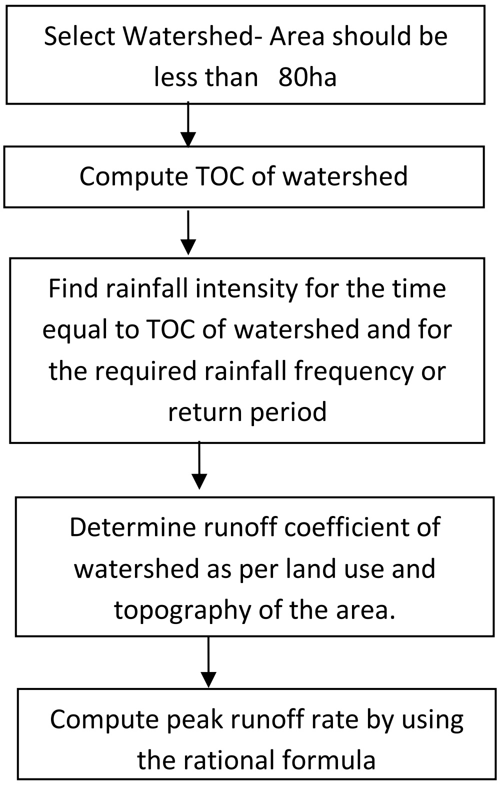
$$T_c = 0.02L^{0.77}.S^{-0.385} + \left[\frac{2L_0\sqrt{n}}{S_0}\right]^{0.467}$$

in which, L is the length of longest water course (1500m); S is the longitudinal slope of water course (2.5/100); L_0 is the length of overland flow path(125m) and S_0 is the slope of flow path of overland flow (0.02). Substituting these values in above equation and solving, we have,

$$T_c = 0.02x1500^{0.77}.(0.025)^{-0.385} + \left[\frac{2x125\sqrt{0.15}}{0.02}\right]^{0.467}$$

= 75.69 minutes **Ans.**

Computation Steps- Various steps involved in computation of peak runoff using rational method are as follows,



Solve problem (5) illustrates the computation procedure.

Problem (5)- *For a watershed of varying land use systems, soils and topography, determine the weighted runoff coefficient,TOC peak runoff rate. The requisite details are outlined as under:*

Landuse/topography	*Agricultural lands/ topography is flat/ soil sandy*	*Grassland/ rolling topography/ soil is sandy*	*Residential lands/ topography is flat/ soil is tight clay or hard soil.*
Area (ha)	*250*	*175*	*25*

- *(i) Length of longest water course =1500m*

(ii) Average longitudinal slope of water course=2.5%.
(iii) Length of overland flow=125m
(iv) Slope of overland flow path =0.02.
(v) Rainfall depth =5.0cm
(v) Take Manning's roughness coefficient as 0.15

Solution

Stepwise computations are described as under,

(1)Computation of weighted runoff coefficient- The formula for weighted runoff coefficient is given as under:

$$C_w = \frac{C_1A_1+C_2A_2+C_3A_3}{A_1+A_2+A_3}$$

The values of runoff coefficient for respective land use systems, soil types and topographic conditions are taken from the given values, which may obtained from any book of watershed hydrology. The obtained values of runoff coefficients are tabulated as under:

Land use/topography	Agricultural lands/ topography is flat/ soil sandy	Grassland/ rolling topography/ soil is sandy	Residential lands/ topography is flat/ soil is tight clay or hard soil.
Area (ha)	250	175	25
Runoff coefficient	0.30	0.16	0.40

Substituting these values in above equation and solving, we have,

$$C_w = \frac{250x0.30+175x0.16+25x0.40}{250+175+25}$$
$$= \frac{75+28+10}{450}$$
$$= 0.251$$

(2) Computation of Time of Concentration (TOC)- In problem the occurrence of overland flow is mentioned. For this condition the time of concentration is computed by considering the overland flow phenomenon. Formula is outlined as under:

$$T_c = 0.02L^{0.77}.S^{-0.385} + \left[\frac{2L_0\sqrt{n}}{S_0}\right]^{0.467}$$

in which, L is the length of longest water course (1500m); S is the longitudinal slope of water course (2.5/100); L_0 is the length of overland flow path(125m) and S_0 is the slope of flow path of overland flow (0.02). Substituting these values in above equation and solving, we have,

$$T_c = 0.02x1500^{0.77}.(0.025)^{-0.385} + \left[\frac{2x125\sqrt{0.15}}{0.02}\right]^{0.467}$$

= 75.69 minutes

(3) Computation of peak runoff – Formula for peak runoff is given as under,

$$Q_p = \frac{1}{3.6}CIA$$

Substituting the value of C,I and A in the formula and after solving , we have

$$Q_p = \frac{1}{3.6}0.251\ x\ \frac{50}{75.69}x\ 4.5$$
$$= \mathbf{0.21m^3/s}\ \textbf{Ans}$$

Suggested Reference

27. Watershed Hydrology- R. Suresh
28. Soil & Water Conservation Engineering- R. Suresh
29. Hydrology and Soil Conservation – G. Das
30. Engineering Hydrology – K. Subramanya

Lecture -9

SCS method of Runoff Computation

This method was originally established by the Soil Conservation Services (USA) in the year 1954 for estimation of runoff based on rainfall depth from agricultural fields. However, it is now used as the method for computing peak runoff rates and volumes for Urban Hydrology.

It calculates the runoff on the basis of retention capacity of soil, which is predicted by wetness status (Antecedent Moisture Conditions [AMC]) and physical features of watershed. Method assumes that prior to formation of runoff the possible initial losses such as interception, infiltration etc are fully satisfied by the rainfall. The Initial loss (Ia) is taken as 0.2S, in which S is the retention capacity of the soil. Retention capacity of soil is the function of Curve Number (CN).

Derivation of SCS Equation

In deriving the SCS runoff equation the ratio of cumulative infiltration of rainwater (F) to the watershed storage (S) to be equal to the ratio of actual direct runoff to effective rainfall (total rainfall minus initial abstraction, given as

$$\frac{F}{S} = \frac{Q}{P-I} \qquad \text{...(1)}$$

in which F, S, Q and I are in dimension of depth. The amount of infiltrated rainwater after runoff begins can be expressed as:

$$F = (P-I) - Q \qquad \text{...(2)}$$

By substituting F in equation ( ) Equation (1) and solving the Q is given as under,

$$Q = \frac{(P-02.S)^2}{P+0.8S}$$, when P is greater or equal to Ia

In this equation the value of initial loss (Ia) is takes 0.2S.

The value of S for a given characteristics of watershed or land area considered for computation of the runoff, is function of curve number (CN). The relationship between CN and S is given as under,

$$CN = \frac{2540}{25.4 + S}$$

in which, S is the retention capacity of the soil (cm). The value of CN is obtained from the table.. against given hydrologic soil group, land use, treatment and hydrologic condition of the area or the watershed .

Curve Number- The curve number is based on the hydrologic soil group, land use, treatment and hydrologic condition of the watershed or area concern. The description of hydrologic soil group is as under,

Group A— Various features are as follows,

- Soils in this group have low runoff potential when thoroughly wet.
- Water is transmitted freely through the soil.
- Soils typically have less than 10% clay and more than 90% sand or gravel and have gravel or sand textures. The soils having loamy sand, sandy loam, loam or silt loam textures may also be kept under this group, provided they are well aggregated, of low bulk density, or contain greater than 35% rock fragments.
- The saturated hydraulic conductivity of soil layers exceeds 40.0 micrometers per second.
- The depth to the water table is greater than 60cm. Also, the soils deeper than 100 cm to an impermeable layer may be kept in group A if saturated hydraulic conductivity of all soil layers within 100cm of the surface is more than 10 micrometers per second.

Group B- This group soil have following characteristics,

- Soils have moderately low runoff potential when thoroughly wet.
- Water transmission through soil is unimpeded.
- Soils typically have clay between 10 and 20%, sand 50 to 90% and have loamy sand or sandy loam textures. The soils having loamy sand, sandy loam, loam or silt loam textures may also

be kept under this group, provided they are well aggregated, of low bulk density, or contain greater than 35% rock fragments

- The saturated hydraulic conductivity in the least transmissive layer between the surface and 50cm varies from 10.0 to 40.0 micrometers per second.
- The depth to water table is greater than 60cm.
- Soils deeper than 100cm to the impermeable layer or water table are also in group B if the saturated hydraulic conductivity of all soil layers within 100cm of the surface is more than 4.0 micrometers per second but less than 10.0 micrometers per second.

Group C: The features are under,

- Of this hydrologic group the Soils have moderately high runoff potential when thoroughly wet.
- Water transmission is little bit restricted. Clay varies between 20 and 40% and sand is less than 50%. Soils also have loam, silt loam, sandy clay loam, clay loam, and silty clay loam textures. Few soils having clay, silty clay, or sandy clay textures may also kept in this group, provided they are well aggregated, of low bulk density, or contain greater than 35% rock fragments.
- Saturated hydraulic conductivity of least transmissive layer between the surface and 50cm varies between 1.0 micrometers per second and 10.0 micrometers per second.
- The depth of impermeable layer is more than 50cm.
- The depth to the water table is greater than 60 cm.
- The soils deeper than 100cm to a restriction or water table are also kept under this group, provided the saturated hydraulic conductivity of all soil layers within 100cm of the surface is greater than 0.40 micrometers per second but less than 4.0 micrometers per second.

Group D: The important features are as follows,

- Soils have high runoff potential when thoroughly wet.
- Water movement is restricted or very restricted.
- Soils typically have more than 40% clay; less than 50% sand, and texture is clayey. In some areas, they also have high shrinking potential.
- The soils with depth to water impermeable layer less than 50cm
- All the soils with water table within 60cm of the surface also fall in this group.
- The soils with a water impermeable layer at the depth between 50 and 100cm, the saturated hydraulic conductivity of least transmissive soil layer is less than or equal to 1.0 micrometers per second.
- The soils deeper than 100cm to a restriction or water table, the saturated hydraulic conductivity of all soil layers within 100cm of the surface is less than or equal to 0.40 micrometers per second.

Antecedent Moisture Condition (AMC)- It denotes the preceding relative moisture of pervious surfaces prior to the rainfall event, also referred as Antecedent Runoff Condition (ARC). AMC is classified into three classes, i.e.

AMC- I- Antecedent Moisture is low when there has been little preceding rainfall

AMC-II: Average moisture condition. For modeling purposes, the watersheds to be at AMC- II, is considered.

AMC-III: High moisture condition, when there has been considerable preceding rainfall prior to the rainfall event.

The criteria for deciding the level of AMC of watershed is presented in following table.

Antecedent Moisture condition	Description	Growing season (5-day antecedent rainfall)	Dormant season (5-day antecedent rainfall, inch)
AMC-I (dry)	An optimum condition of watershed soil, where soil are	Less than 35mm	Less than 12mm

	dry but not to the wilting point, and when satisfactory ploughing or cultivation takes place		
AMC-II (average)	Average case of moisture status	35 to 53mm	12 to 28mm
AMC-III (wet)	When a heavy rainfall or light rainfall and low temperature have occurred during 5-days previous to a given rainfall event.	More than 53mm	More than 28mm

The computed value of runoff, so, is applicable for AMC-II, i.e. for average soil moisture condition of land area. However, for runoff computation for AMC-I and III the CN values are modified for respective AMC and used for determining the value of S. The CN formulae for AMC-I and AMC-III are given as under,

$$CN(I) = \frac{4.2CN(II)}{10 - 0.058\ CN(II)}$$

$$CN(III) = \frac{23CN(II)}{10 + 0.13\ CN(II)}$$

Also, at watershed scale, where there is large possibility of variation in occurrence of hydrologic soil groups, soil condition and treatment / conservation practices followed, The weighted CN is calculated for accurate estimation of runoff.

Soil Cover Condition- The followings are the criteria for deciding Poor, fair and good cover conditions,

Grass or pasture covers

- Poor- <50% ground cover or heavily grazed with no mulch
- Fair: 50-75% ground cover and not heavily grazed
- Good: >75% ground cover and light or only occasionally grazed.

Other than pasture and grass cover

- Poor: <50% ground cover
- Fair: 50-75% ground cover
- Good: >75% ground cover.

Conservation treatment – These are mainly the development of crop residue cover, straight row cropping, contouring, terracing.

Table- Curve number for Agricultural lands

Cultivated agricultural lands						
Cover description			Curve numbers for hydrologic soil group			
Cover type	Treatment	Hydrologic condition	A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86

	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T + R	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T + R	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

[A] Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.

Other Agricultural Lands					
Cover description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic condition	A	B	C	D
Pasture, grassland, or range—continuous forage for grazing.[A]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay.	—	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element.[B]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30[C]	48	65	73
Woods—grass combination (orchard or tree farm).[D]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods.[E]	Poor	45	66	77	83

	Fair	36	60	73	79
	Good	30	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

[C] Actual curve number is less than 30; use CN = 30 for runoff computation.

[D] CN's shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.

[E] Poor: Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning; Fair: Woods are grazed but not burned, and some forest litter covers the soil; Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

Arid and semiarid rangelands					
Cover description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic conditions	A[B]	B	C	D
Herbaceuous—mixture of grass, weeds, and low-growing brush, with brush the minor element	Poor	—	80	87	93
	Fair	—	71	81	89
	Good	—	62	74	85
Oak-aspen—mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush	Poor	—	66	74	79
	Fair	—	48	57	63
	Good	—	30	41	48
Pinyon-juniper—pinyon, juniper, or both; grass understory	Poor	—	75	85	89
	Fair	—	58	73	80
	Good	—	41	61	71
Sagebrush with grass understory	Poor	—	67	80	85
	Fair	—	51	63	70
	Good	—	35	47	55
Desert shrub—major plants include saltbush, greasewood, creosote bush, black brush, bursage, Palo Verde, mesquite, and cactus.	Poor	63	77	85	88
	Fair	55	72	81	86
	Good	49	68	79	84

[A] Poor: <30% ground cover (litter, grass, and brush over story); Fair: 30 to 70% ground cover; Good: >70% ground cover.

[B] Curve numbers for group A have been developed only for desert shrub.

Problem (1)- *A watershed involves varying conservation measures and hydrologic soil groups. Determine its weighted CN for predicting runoff. The details are given as under:*

Land use	*Conservation treatments*	*Hydrologic condition*	*Hydrologic soil group*	*Area, ha*
Fallow-row cropping	*Straight row*	*Good*	*B*	*50*
Small grain crops	*Contoured condition*	*Poor*	*C*	*150*
Pasture land	*Contoured condition*	*Poor*	*D*	*75*
Wood land	*-*	*Fair*	*A*	*100*

Also, determine the retention capacity and extent of initial loss from the rainfall.

Solution- On the basis of land use system, conservation treatments followed, hydrologic condition and hydrologic soil groups of watershed the value of CN are taken from table for respective land segments. They are summarized in following table.

Land use	Conservation treatments	Hydrologic condition	Hydrologic soil group	Area, ha	CN

Fallow-row cropping	Straight row	Good	B	50	78
Small grain crops	Contoured condition	Poor	C	150	74
Pasture land	Contoured condition	Poor	D	75	88
Wood land	-	Fair	A	100	36

Therefore, weighted CN,

$$CN_w = \frac{CN_1A_1+CN_2A_2+CN_3A_3+CN_4A_4}{A}$$

Substituting values in above formula, and solving, we have,

$$CN_w = \frac{78x50+74x150+88x75+36x100}{276}$$

$$= \frac{3900+11100+6600+3600}{276}$$

$$= 91.30$$ **Ans.**

Retention capacity- Using the following formula,

$$CN = \frac{2540}{(25.4+S)}$$

Substituting the value of CN and solving for S, we have,

$$91.3 = \frac{2540}{(25.4+S)}$$

S= 2.42cm **Ans.**

Initial loss- It is given by following formula,

Ia= 0.2S
= 0.2x2.42cm
= 0.484cm **Ans.**

Problem (2)- *Determine the runoff depth in response to a given rainfall of 15cm from the watershed of 500ha area. Take level of initial abstraction as 1.5cm.*

Solution- Using CN method for computing runoff,

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)}$$

in which, Q is the runoff depth; P is the depth of rainfall (15.0cm) and S is the retention capacity of soil. Retention capacity (S) is given by the following formula.

$$1.5 = 0.2S$$

or S =1.5/0.2 =7.5cm

Substituting the values of P and S in above equation and solving, we have,

$$Q = \frac{(15-0.2x7.5)^2}{(15+0.8x7.5)}$$

$$= \frac{182.25}{21}$$

$$= 8.68cm$$ **Ans.**

Problem (3)-*Determine the runoff (m^3/s) from the watershed of 500ha area, which longest water course length is 1000 m and its longitudinal slope is 0.3m/m. The other details are as below,*

(i) Weighted CN of watershed is 80.
(ii) Depth of rainfall is 12.0cm.

Solution- Using the following formula for runoff,

$$Q_p = \frac{0.0208AQ}{T_p}$$

In this formula, the values of Q (depth) and Tp (hour) are unknown. These are determined as under:

Runoff depth - Using SCS method, i.e.

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)}$$

in which, P is the depth rainfall of a given rainfall event (12cm) and S is the retention capacity of watershed. The value of S is determined by using following formula,

$$CN = \frac{2540}{(25.4+S)}$$

The CN is given as 80. Substituting this in above formula, and solving for S, we have,

$$80 = \frac{2540}{(25.4+S)}$$

S = 6.35cm

Therefore, $Q = \frac{(P-0.2S)^2}{(P+0.8S)}$

$$Q = \frac{(12-0.2x6.35)^2}{(12+0.8x6.35)} = \frac{115.13}{17.08} = 6.74cm$$

Time to peak is given by the following formula,

$$T_p = 0.6T_c + \sqrt{T_c}$$

In this formula, the value of Tc is not known, which is determined as below,

$$T_c = 0.01947L^{0.77}.S^{-0.385}$$

Sustituing the value of L and S is above formula and solving for T_c , we have,

$$T_c = 0.01947x1000^{0.77}x0.3^{-0.385}$$

= 6.15minutes or 0.1025 h.

Therefore, time to peak (Tp) is equal to

$$T_p = 0.6x0.1025 + \sqrt{0.1025}$$

=0.381 hour

Substituting the values of different parameters in formula $Q_p = \frac{0.0208AQ}{T_p}$ and solving for Q_p

$Q_p = \frac{0.0208x500x6.74}{0.381} = 183.98$ m3/s **Ans.**

Assignment- Derive the SCS equitation used for computing runoff.

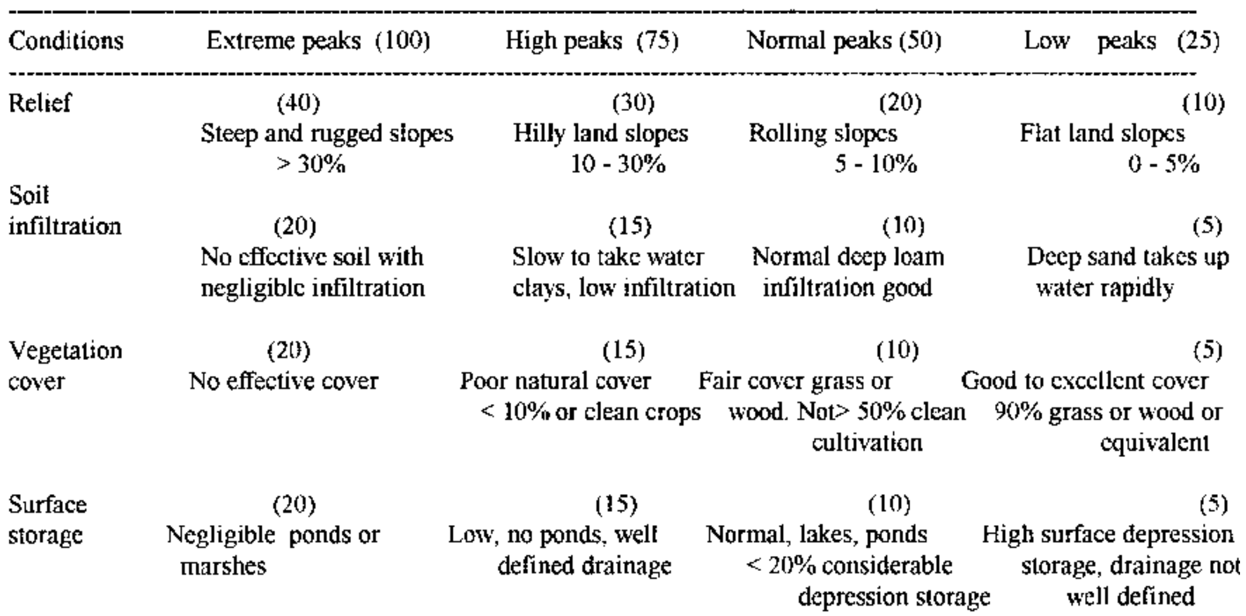
Suggested Reference

31. Watershed Hydrology- R. Suresh
32. Soil & Water Conservation Engineering- R. Suresh
33. Hydrology and Soil Conservation – G. Das
34. Engineering Hydrology – K. Subramanya

Lecture -10

Cooks Method of Runoff Computation

The method was developed by United States Department of Soil Conservation Services. This is a simple method and more generalized, but involves similar approach to the estimation of peak runoff to the Rational Method. In Cooks method the runoff approximation is carried out based on four different characteristics of watershed, namely (i) Relief, (ii) Infiltration rate, (iii) Vegetal cover, and (iv) Surface depression. Numerical values for above four characteristics are assigned in respect of extreme, high, normal and low runoff, given in following table (developed by USDA.



Conditions	Extreme peaks (100)	High peaks (75)	Normal peaks (50)	Low peaks (25)
Relief	(40) Steep and rugged slopes > 30%	(30) Hilly land slopes 10 - 30%	(20) Rolling slopes 5 - 10%	(10) Flat land slopes 0 - 5%
Soil infiltration	(20) No effective soil with negligible infiltration	(15) Slow to take water clays, low infiltration	(10) Normal deep loam infiltration good	(5) Deep sand takes up water rapidly
Vegetation cover	(20) No effective cover	(15) Poor natural cover < 10% or clean crops	(10) Fair cover grass or wood. Not> 50% clean cultivation	(5) Good to excellent cover 90% grass or wood or equivalent
Surface storage	(20) Negligible ponds or marshes	(15) Low, no ponds, well defined drainage	(10) Normal, lakes, ponds < 20% considerable depression storage	(5) High surface depression storage, drainage not well defined

Calculation Steps- These are as below,

Step 1: Evaluate the degree of watershed characteristics in respect of relief, Infiltration rate, vegetal cover and surface storage by comparing with similar conditions.

Step 2: Assign numerical value (W) to each of the characteristics with the help of Table value.

Step 3: Find sum of numerical values assigned to all the characteristics, i.e.

$$\Sigma W = R+I+V+D$$

in which R is for relief , I for Infiltration rate , V for vegetal cover and D for surface depression.

Step 4: Determine runoff rate against ΣW using runoff curve (valid for specified geographical region and 10 year recurrence interval)

Step 5: Compute adjusted runoff rate for desired recurrence interval and watershed location by using the following formula

$$Q_{peak} = prfs$$

Where,

Q_{Peak} = Peak runoff for specified geographical location and recurrence interval (m3/s)
P = Uncorrected runoff obtained from step -4
R = Geographic rainfall factor (Fig)
F = Recurrence interval factor and (Table-)
S = Shape factor (Table-)

Table – Shape factor for using in Cooks method

Length /width	Watershed area (ha)				
	20	40	80	200	240
1	1.0	1.0	1.0	1.0	1.00
1-1-1.5	0.92	0.92	0.91	0.90	0.90
2	0.88	0.87	0.86	0.84	0.83
2-2-2.5	0.85	0.84	0.82	0.80	0.78
3	0.81	0.80	0.78	0.76	0.74
4	0.76	0.72	0.70	0.68	0.66
5	0.74	0.70	0.68	0.66	0.64
6	0.72	0.68	0.66	0.64	0.62
7	068	0.66	0.64	0.61	0.59

Table- Rainfall frequency factor for different zones of India

S.No	Zones	Rainfall Return period (year)	Frequency factor (F)
1	I	10	1.0
		25	1.2
		50	1.4
2	II	10	1.0
		25	1.3
		50	1.5
3	III	10	1.0
		25	1.3
		50	1.6
4	IV	10	1.0
		25	1.2
		50	1.3

Infiltration Indices method

Infiltration of rainwater into the soil media plays a significant effect on surface runoff formation. Although, in case of sub- surface runoff formation its effect is beneficial because infiltrated rainwater ultimately joins to the water- table via percolation. Infiltration rate varies with the soil types, land use practices and so many other factors related to soil and climate.

In surface runoff formation the Infiltration creates loss of rainwater in result the net amount of rainwater available for runoff becomes less. In nutshell

Runoff = Total rainfall – losses (Infiltration and other losses)

The relationship between rainfall – Infiltration and runoff is p[resented by the Fig-.

Infiltration Index- It is defined as the average infiltration rate during rainfall when rainfall intensity exceeds the infiltration rate. The following infiltration indices are used for computing the infiltration rate,

1. $\emptyset - Index$
2. W- Index

$\emptyset - Index$ - It is the loss of rainwater above which the volume of rainfall is equal to the volume of runoff. It is shown in Fig-. It is determined from the rainfall hyetograph with the edge of the resulting runoff volume. In other words the $\emptyset - Index$ is the amount of water loss from the rainfall, transforming into ER or the direct runoff. The ERH is derived by deducting the value of $\emptyset - \text{index}$ from the rainfall hyetograph, as shown in Fig-. The area of ERH multiplied by the area of rainfall contributing catchment is the volume of direct or surface runoff.

Solve problem – explains the computation procedure.

W- Index- It is refined form of $\emptyset - Index$. In W- index the surface storage and retention are included. The following formula can be used for its computation,

$$W - Index = \frac{P - R - Ia}{t_e}$$

In which, P is the total rainfall (cm), R is the total runoff (cm); Ia is the initial losses(cm) and t_e is the duration of rainfall excess.

Solve problem (1)Illustrates the computation of runoff using infiltration index.

Problem (1)- Determine ϕ- index based on the following data.

Time(minute)	0	20	40	60	80	100	120	140
Rainfall rate (cm/s)	0	1.5	2.5	4.0	7.0	3.5	3.0	1.0

Take the runoff depth as 4.5cm.

Solution- ϕ- index is the average loss of rain water. Accordingly, the runoff is equal to total rainfall depth -ϕ- index, expressed in following form,

$$Runoff = \sum(I - \emptyset).t$$

Accordingly,

$$4.5 = \frac{20}{60}[(1.5 - \phi) + (2.5 - \phi) + (4.0 - \phi) + (7.0 - \phi) + (3.5 - \phi) + (3.0 - \phi) + (1.0 - \phi)]$$

$$= \frac{20}{60}[22.5 - 7\phi]$$

$\phi = 1.286\text{cm/h}$ **Ans.**

Problem (2)- *Determine W-index based on following data. Take infiltration capacity of soil is 4.5cm/h.*

Time(minute)	*0*	*20*	*40*	*60*	*80*	*100*	*120*	*140*
Rainfall intensity (cm/s)	*0*	*2.5*	*4.5*	*5.0*	*7.0*	*5.5*	*3.0*	*1.0*

Solution- W- index is the average rate of water loss during rainfall event when rainfall intensity exceeds the infiltration capacity, presented by the following relationship,

$$W - index = \frac{F}{t_r}$$

in which, F is the total rain water loss due to infiltration during rainfall and t_r is the time during which rainfall intensity exceeds the infiltration capacity. Computation is shown in following table.

Time interval, minute	Rainfall intensity, cm/h	Infiltration capacity ,cm/h	Water loss due to infiltration, cm	Time during which rainfall exceeds the infiltration capacity, minutes
0	0.0	4.5	$=\frac{140}{60}x4.5$ $= 10.5cm$	-
20	2.5			-
40	4.5			
60	5.0			
80	7.0			
100	5.5			
120	3.0			-
140	1.0			-
	28.5			80

Therefore, $W - \ index = \frac{10.5}{80}$

$$= 7.88cm/h$$ **Ans.**

Problem (3)- *Determine W- index based on following data base,*

- *(i) Depth of rainfall=13.5cm*
- *(ii) Depth of runoff yield =7.0cm*
- *(iii) Duration of rainfall excess=4.5hour*
- *(iv) Depth of initial loss=1.350cm.*

Solution- The relationship for W- index is given as below,

$$W - index = \frac{P - Q - I_a}{t_r}$$

in which, P is the depth of rainfall (13.5cm); Q is the runoff depth (7.0cm) ; I_a is the initial loss (1.350cm) and t_r is the duration of rainfall excess (4.5hour). Substituting the value of P in above formula and solving, we have,

$$W - index = \frac{13.5 - 7.0 - 1.350}{4.5}$$

= 1.14cm/h **Ans.**

Hydrograph Method

In common terms, hydrograph is a graph presenting the relationship between discharge and corresponding time (Fig-). However in broad sense the graph showing the stage, velocity, or other properties of water flow with respect to time is also called hydrograph. A hydrograph plotted between flow stage and time, is called stage hydrograph. The stage hydrograph is used in the form of a stream gage record.

Hydrograph shows the time distribution of runoff at stream gauging point of watershed. Hydrograph reflects the complex characteristics of the watershed. The duration or time of runoff flow is about to a constant for a particular watershed, regardless of the peak flow from a specific storm, assuming constant storm duration.

With the help of hydrograph the runoff can be computed in following way,

1. **Runoff volume-** The runoff volume formed by a given rainfall event occurred in the watershed is determined by calculating the area of hydrograph (DRH) resulted from the said rainfall event. In contrast, in case of perennial stream hydrograph, it is determined by deducting the contribution of base flow from the hydrograph and computing the area of new hydrograph called DRH.
2. **Runoff rate –** At any time instant the rate of runoff can be directly read from the hydrograph. In addition, the time of peak runoff occurrence and what is the extent of peak runoff can also be directly read from the hydrograph.
3. **Duration of Runoff:** A hydrograph also provides the information about total time of runoff flow at the outlet of watershed due to a given rainfall event.

Empirical Formulae

Empirical formulae are developed for a specific condition and area based on the gauged data. These formulae have limitations about their use unless they are validated for the new condition or watershed. There have been developed several well recognized empirical formulae developed by different researchers for different regions /watersheds in India and foreign countries for computing the runoff rate. Few important amongst them are described as under,

Runoff coefficient method: Runoff coefficient is the fraction of rainfall depth converted into runoff presented as C. This fraction is presented in terms of the coefficient. This varies from place to place or one watershed to another because of variations in watershed characteristics, soil, vegetations etc. The value of runoff coefficient varies from 0 to maximum 1.0. The value of C as 0 is for highly coarse textured soils in which total rainwater is likely to get infiltrated. In contrast the C as little less than 1.0 is for those soils which have very less rainwater loss due to infiltration. Normally, the hard soils (impervious) are the example of it. Although, there is loss of water, but very small, is counted negligible. The runoff computing formula can be presented in following form,

$$R = k.P$$

in which R is the runoff (depth), k is the coefficient (dimensionless) and P is the rainfall (depth). The value of k is given in following table.

Table- Runoff coefficient (k)

S. No	Area	K
1.	Urban area covered by (i) Buildings (ii) Garden apartment	 0.30 0.5
2.	Commercial and industrial areas	0.9
3.	Forest area	0.5 to 0.2

Regression Formula: Chow (1964) listed several regression equations as empirical formulae for computing the runoff on the basis of area of drainage basin. The form of equation is given a sunder,

$$Q = CA^n$$

in which Q is the runoff (m3/s), C & n are the empirical constant and A is the area of drainage basin (sqKm).

Dicken Formula- It is an regression equation model for predicting the runoff. Originally it was developed for design of bridge. This formula hold good for central and north India. The equation is given as under,

$$Q = CA^{0.75}$$

In this formula the value of C varies 2.80 to 5.60 for plain regions and 14 to 28 for mountainous regions.

Problem (4)-*Using Dicken's formula compute the runoff of small watershed dominated by residential establishments, if area of watershed is 100sqkm falling within 25km periphery from sea. Take the value of constant relating the runoff as 2.80.*

Solution- Dickens's formula for runoff is given as under

$$Q = CA^{3/4}$$

in which, Q is the runoff (m3/s); C is the constant (2.80) and A is the area of watershed (100sqkm). Therefore,

$$Q = 2.8x100^{0.75}$$

$$= 88.54 \text{ m}^3\text{/s}$$ **Ans.**

Ryve's formula: It is basically modified form of Dickens' formula, useful for south Indian coastal areas lying within periphery of 25 km from the sea. Formula is given as under,

$$Q = CA^{2/3}$$

In this formula the value of C is taken as 6.8 for flat tracts and 42.40 for western ghat areas.

Problem (5)- *Using Ryve's formula compute the rate of flood flow from a catchment located at the distance of 60Km from sea coast in south India. The size of catchments is 75sqkm. Also, compute the flood flow for the catchments located at the distance between 80 to 2400km from sea coast and near the hill. The size of both catchments is 100sq km.*

Solution- The Ryve's formula for flood flow is given as under.

$$Q = CA^{2/3}$$

in which, the value of coefficient (C) for the given catchment located at the distance of 60 km from the sea coast in South India, is taken as 6.8. Therefore,

$$Q = 6.8x75^{\frac{2}{3}}$$

$$= 122.69 \text{ m}^3\text{/s}$$ **Ans.**

For the catchment located at the distance between 80 and 2400km from sea coast the value of coefficient (C) is taken as 8.3. Therefore,

$$Q = 8.3x100^{\frac{2}{3}}$$

$$= 181.60 \text{ m}^3\text{/s}$$ **Ans.**

Similarly, for the catchment located near the hill, the value of coefficient (C) is taken maximum 40. Therefore,

$$Q = 40x100^{\frac{2}{3}}$$

$$= 875.10 \text{ m}^3\text{/s}$$ **Ans.**

Inglis formula: C.C. Inglis (1940) developed following two empirical formulae for two different areas, given as under,

1. For ghat areas $R = 0.85P - 30.5$
2. For non- ghat areas $R = \frac{P-17.8}{254}$

In which R is the runoff depth (cm) and P is the depth of rainfall (cm)

Problem (6)- *Determine the flood flow rate form the catchment located in Maharashtra. The area of catchment is about 125sqkm. Use Inglis formula.*

Solution- The Inglis formula for computing flood flow rate is given as under.

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

in which, A is the area of catchment (125sqkm). Therefore,

$$Q = \frac{124}{\sqrt{125+10.4}}$$

$$= 10.65 \text{ m}^3\text{/s}$$ **Ans.**

Khosla formula: This formula was developed by considering the temperature in addition to precipitation. The formula is given as under,

$$R = P - \frac{T - 32}{3.74}$$

in which, R is the runoff and p is the precipitation and T is the average temperature of the are in ^{0}F

Suggested Reference

35. Watershed Hydrology- R. Suresh
36. Soil & Water Conservation Engineering- R. Suresh
37. Hydrology and Soil Conservation – G. Das
38. Engineering Hydrology – K. Subramanya

Lecture-11

Hydrograph

In common terms, hydrograph is a graph presenting the relationship between discharge and corresponding time. However in broad sense the graph showing the stage, velocity, or other properties of water flow with respect to time is also called hydrograph. A hydrograph plotted between flow stage and time, is called stage hydrograph. The stage hydrograph is used in the form of a stream gage record.

Hydrograph shows the time distribution of runoff at stream gauging point of watershed. Hydrograph reflects the complex characteristics of the watershed. The duration or time of runoff flow is about to a constant for a particular watershed, regardless of the peak flow from a specific storm, assuming constant storm duration.

Characteristics Region- Hydrograph is in the form of a continuous loop of smooth curve, which starts at origin point of runoff formation and rises up with increase in runoff with advancement of time, attains peak which continues till rainfall ends, thereafter starts decline and terminates to the point where runoff stops. It is shown in Fig-.1.

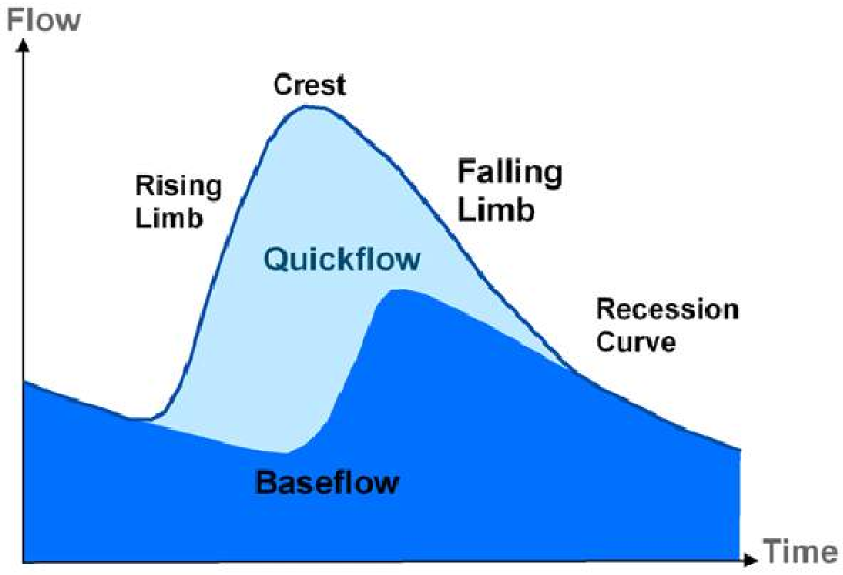


Figure-1.0 View of hydrograph

Hydrograph included following three characteristics regions,

1. Rising limb,
2. Crest or peak , and
3. Falling limb.

Rising limb- It represents the region of increase in runoff with respect to enhancement of rainfall duration over the watershed surface. The plotted curve attains very steep slope. Because of this reason some times, this region is also called concentration curve. The watershed and rainfall characteristics both in combine form affect this region.

Crest or peak- This region of hydrograph includes peak of runoff formed from the watershed due to a given rainfall event. Extent of this region is for a very short time extended from the point of inflections on rising limb and to a similar point towards falling limb. This segment is also affected by watershed and rainfall characteristics both in combine form. A hydrograph with single peak is called single peak hydrograph. Sometimes, due to variation in rainfall intensity and complicity of watershed shape, the runoff bears more than one peak, and accordingly the plotted hydrograph contains more than none peak. Such hydrographs are called complex hydrograph. Normally, for study purposes of the single peak hydrographs are commonly used. Because of this reason the selection of rainfall event or runoff data should be done by considering this fact into account.

Falling limb- It starts from the point of inflection at falling limb to the end of runoff yield. The point of inflection represents the point when rainfall event has been stopped. The flow of runoff at out let is only the stored rainwater in the stream courses or watershed surface. The rate of runoff flow depends to large extent on the channel characteristics. Comparatively, this region is largest amongst all.

Factors Affecting Hydrograph Shape

Since, the hydrograph is associated to the runoff yield from the watershed for a given rainfall event; therefore, the factors responsible to affect the shape of hydrograph are related to the rainfall and watershed, both in combine form. However, the factors affecting are listed as under,

S. No	Particular	Factors
1.0	Rainfall	
1.1		Rainfall intensity
1.2		Rainfall depth
1.3		Rainfall duration
1.4		Rainfall direction
1.5		Rainfall distribution
2.0	Watershed Physiography	
2.1		Size
2.2		Shape
2.3		Slope
2.4		Drainage density
2.5		Stream frequency
		Slope of the stream

The shape of hydrograph is formed by the base width and peak runoff. Base with of hydrograph is the sum of duration of rising limb, crest segment and falling limb. Majorly, the duration of falling limb contributes more time to the base width, because of the reason that the withdrawal of stored water from the watershed surface and channel storage takes grater time. Also, the rainfall occurrence close to the outlet and at the farthest distance from outlet, affects the duration of recession or falling limb.

As per hydrograph shape is concerned, it may be conical or bell/sluggish. A hydrograph with wide base width and less peak runoff will be in bell shape or sluggish. In contrast, a hydrograph having very less base width and very high peak runoff involves conical shape.

Sometimes, the hydrograph shape is also found complex, i. e, there appears more than one peak, which because of variations in rainfall intensity and skewed shape of watershed.

Depth and Duration of Effective Rainfall

In computation of direct runoff/direct runoff hydrograph or the unit hydrograph the information on effective rainfall is required. The area of contributing watershed multiplied by the depth of ER is the volume of direct runoff. The depth of ER is calculated with the help of effective rainfall hyetograph (ERH) which is obtained by deducting the value of $\emptyset\ index$ from the hyetograph. Area of ERH denotes to the depth of effective rainfall. The duration of ER is also determined from the ERH, which is determined by counting those time periods for which rainfall is still remained after deducting the $\emptyset\ index$, from the hyetograph. It is shown in Fig-2.0

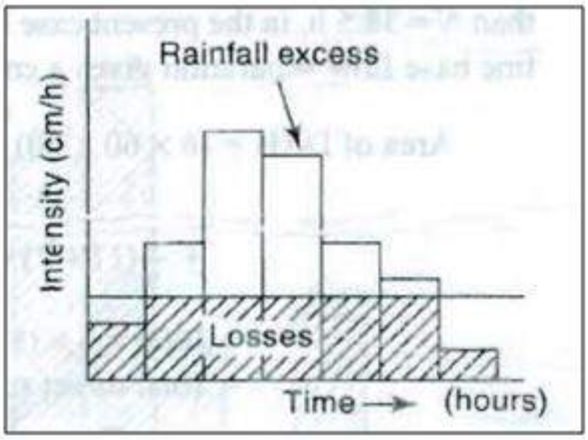


Figure-2.0

Direct Runoff Hydrograph

The hydrograph resulted from direct runoff is called direct runoff hydrograph (DRH). It is also derived with the help of runoff hydrograph of perennial stream by deducting the base flow contribution. Area of DRH is the volume of direct runoff. The hydrograph derived from the runoff data of intermittent and ephemeral streams are the DRH as there is no contribution of base flow in runoff observations. The procedures for base flow separation are described as under,

Base flow Separation

In hydrograph analyses the separation of base flow is required to determine the contribution of direct runoff out of the total runoff against a given rainfall event occurred in the watershed, presented by the hydrograph of perennial streams/rivers. In other words, for deriving the unit hydrograph from the annual runoff hydrograph the separation of base flow is done. The annual runoff hydrograph includes the base flow and direct runoff, both. The base flow is the off-season water flow through the stream or river, which is mainly due to contribution of ground water. The ground water contribution to a river or stream makes it to carry the water flow throughout the year. Such stream or rivers are called perennial stream/river. And the generated hydrograph is stretched for the year period.

Method: There are several methods have been devised for separating the base flow from the annual hydrograph, the important amongst them are described as under,

Straight line method: In this method the beginning point of surface/direct runoff and the point representing the end of direct runoff on recession limb are joined together by a straight line for separating the base flow as shown in Fig-. The area below the straight line represents the contribution of base flow from the total runoff. In Fig the Point A is the beginning of direct runoff off and B is the end of direct runoff. The beginning of direct runoff is usually identified in the view of a sharp change in the runoff rate at the point or time concern. In contrast the exact location of end point B is difficult. However, the following empirical formula can be used for locating the end point of direct runoff,

$$N = 0.83A^{0.2}$$

in which N is the days from the peak towards recession limb of hydrograph and A is drainage area in (km^2). This method of base-flow separation is the simplest of all the three methods.

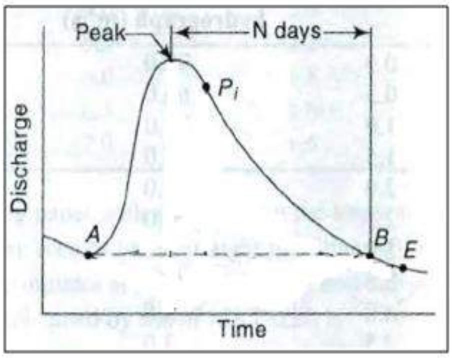


Fig-

Method -2: In this method the base flow separation is carried out by extending the base flow curve existing prior to the commencement of the surface runoff to intersect the ordinate drawn at the peak (Fig.). Intersected point (C) is joined to the point B by a straight line. B is the end point located at N days from the peak. The area below the segment AC and CB demarcates the base flow and above to the surface runoff. This is most widely used base-flow separation method.

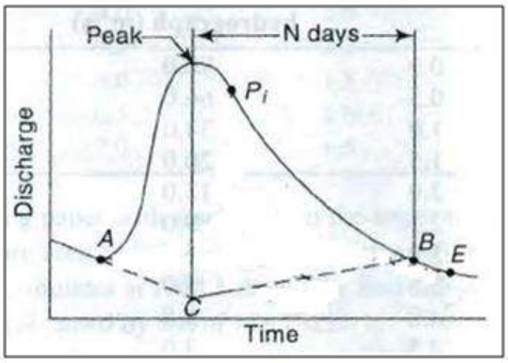


Fig.

Method- 3: In this method for separating the base flow the base flow recession curve after depletion of runoff is extended backward till to intersect the ordinate at the point of inflection, shown in Fig. In figure the arbitrary curves AF and EF are the base flow demarcating curves. This method is considered to be realistic when groundwater contribution is significant and reaches the nearby stream quickly.

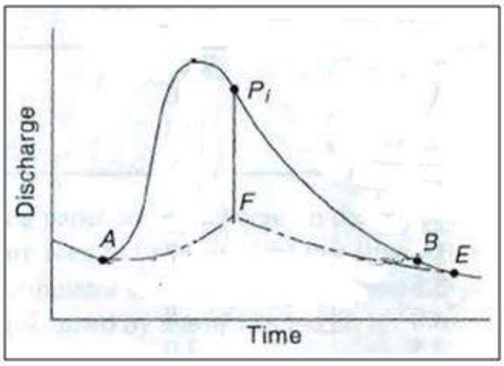


Fig.. Method 3

Problem (1)- *At the outlet of a watershed of 500ha area the initial discharge (runoff) is recorded as 250m*^{3}*/h. At lapse of 1.5 hours determine followings:*

(i) Rate of surface runoff.
(ii) Interflow rate, and
(iii) Rate of base flow.

Take the values of recession constants for surface runoff , inter flow and base flow 0.15, 0.55 and 0.85, respectively.

Solution- Using following formula for recession flow,

$$Q_t = Q_0 K_r^{-t}$$

in which , $Q_t$is the discharge at time t; Q_0 is the initial discharge (25m^3/s) and K_r is the recession constant. Accordingly,

(i) Surface runoff - it is given as under,

$$Q_t = 250x0.15^{-1.5}$$

$= 4303.31$ m^3/s **Ans.**

(ii) Inter flow- It is given below.

$$Q_t = 250x0.55^{-1.5}$$

$= 612.90$ m^3/h **Ans.**

(iii) Base flow- It is as below.

$$Q_t = 250x\ 0.85^{-1.5}$$

$= 319.01$ m^3/h **Ans.**

Problem (2)-*Determine the value of recession constant for interflow, if rate of initial discharge is 120m^3/h and discharge after 2.0 hour is 250m^3/h.*

Solution- It is computed by using the following formula,

$$Q_t = Q_0 K_r^{-t}$$

in which, Q_t is the discharge at time t (250m^3/h); Q_0 is the discharge at initial (120m^3/h) and t is the elapsed time (2.0hour). Substituting these values in above formula and solving, we have,

$$250 = 120K_r^{-2}$$

Therefore, $K_r^{-2} = \frac{250}{120} = 2.083$

$Kr =$ 0.69 **Ans.**

Problem (3)- *The record of time vs discharge data against a given rainfall event of gauged watershed denotes the peak runoff taken place after 8 hours from start of runoff. The area of watershed is 50sqkm. Determine the end time of runoff from watershed.*

Solution- The relationship predicting the end time of runoff from watershed, is given as under:

$$N = 0.83A^{0.2}$$

in which , N is the days after peak runoff and A is the area of watershed(sqkm) is given 100sqkm. Substituting the value of A in above formula and solving, we have,

$N = 0.83x50^{0.2} = 1.8days$ **Ans.**

The end time of runoff 1.8days is from the peak runoff.

Lecture-12

Unit Hydrograph

The unit hydrograph of a given watershed is derived with the help of DRH. Unit hydrograph is the DRH of unit depth of effective rainfall. The depth of ER is determined by the effective rainfall hyetograph. Area of ERH is the depth of ER, and its duration denotes to the duration of ER. A unit hydrograph is designated for a given duration of ER.

Definition: It is a typical hydrograph of direct runoff generated from unit depth (1cm) of effective rainfall falling at a uniform rate over the entire drainage basin and is uniformly distributed during a specific duration.

Assumptions:

The main assumptions followed for driving unit hydrograph are as follows

(i) Effective rainfall is uniformly distributed over the entire drainage basin and within its specified duration. The rainfall events of small duration generally produce an intense and nearly uniform effective rainfall. The produced hydrograph is of single peak with short time base. Such a storm is termed as “unit storm”, is selected for unit hydrograph development.

(ii) The effective rainfalls of equal (unit) duration will produce the DRHs having same or constant time base.

(iii) The ordinate of direct runoff hydrograph is directly proportional to the depth of ER. This is assumption is called as principle of linearity or superposition.

(iv) The DRH of a given effective rainfall will remain invariable irrespective of its time of occurrence. This assumption is called principle of time invariance.

Limitations:

These are as below,

(i) Unit hydrograph development is valid and suitable for small watersheds, in which the uniformly distribution of effective is possible to a large scale within storm duration. The limiting size of the drainage basin is considered to be 5000 sqkm. However, in the condition when area of drainage basin exceeds the limit, the large area is sub-divided into smaller units (sub- watersheds) and unit hydrograph for each of them is developed. The runoff at the watershed outlet can then be determined by combining the runoff of sub- watershed using flood routing technique.

(ii) The derivation of unit hydrograph is only feasible for the rainfall events having precipitation in the form of rainfall.

(iii) (iii) Also, for the watershed covered to a large extent by the snow cover the development of unit hydrograph for runoff estimation is not found suitable.

(iv) (iv)Also, for the watersheds having significant change in land cover or physical characteristics w.r.t. seasons, development of man-made structures, conditions of flow etc the unit hydrograph theory, i.e. the principle of time invariance is not satisfied, and thus, the development of unit hydrograph is not found realistic.

(v) It is commonly observed that no two rainfall events have same pattern, temporally and spatially, both; and it is not practicable to derive separate unit hydrograph for each time-intensity pattern. Therefore, in addition to limiting drainage basin area up to 5000 sqkm, if storms of shorter duration say for 33 to 25% of peak times are selected, the runoff pattern does not vary drastically.

(vi) The principle of linearity assumption of unit hydrograph is also not valid because of the reason that there is a large variation in the quantity of direct or surface runoff formation, even the level of peak runoff due to the rainfall event of short and large durations for the same watershed.

Derivation Procedure

It is described under following steps,

1. Select the rainfall event producing sufficient runoff at the outlet with well defined peak. Normally, single peak rainfall events are selected for derivation of unit hydrograph to analyse the rainfall- runoff relationship using hydrograph approach.
2. Using the gauged data (time vs runoff) plot the hydrograph. In case of perennial stream used as the outlet for recording the data and hydrograph is prepared using the said data, the obtained hydrograph includes the base flow. On the other hand, in case of intermittent and ephemeral streams there is no contribution of based flow in the recorded data, and the plotted hydrograph is the DRH.
3. Separate the contribution of base flow from the hydrograph derived by using the perennial stream flow data. It should be done by using a most suitable method so that there should be least chances of error in estimation of direct runoff or derivation of unit hydrograph.
4. Find the ordinates of DRH for each time segment of the hydrograph. It is done by deducting the base flow from the respective time segment.
5. Plot the ordinates of DRH determined in step -4. The obtained hydrograph is the direct runoff hydrograph.
6. Compute the depth of ER based on the derived DRH in step-5. It is carried out by using the following formula,

$$ER = \frac{Area\ of\ DRH}{Area\ of\ watershed}$$

7. If the computed ER is the unit depth (1cm) the derived DRH in step-5 is the unit hydrograph, otherwise, it is DRH only.
8. If ER is not unit depth, compute the ordinates of UHG by dividing the ordinates of DRH of respective time segment with the determined depth of ER in step-6. This is done as per the assumption “Principle of linearity”.
9. Plot the ordinates of UHG obtained in step -8. This is the UHG for the given ER duration.
10. Check the sketched unit hydrograph, whether it represents the depth of ER as unit depth or not. If not, then correction or adjustment in UHG sketch is required.

Solve problem (1) showed the derivation of unit hydrograph.

Problem (1)- *Determine followings,*

(i)Depth of effective rainfall,
(ii) Duration of effective rainfall, and
(iii)Volume of direct runoff

The mass curve of rainfall event is given below.

Time since start of rainfall, h	*0*	*2*	*4*	*6*	*8*	*10*	*12*	*14*	*16*
Cumulative rainfall, cm	*0*	*0.90*	*3.25*	*4.50*	*6.50*	*10.0*	*12.0*	*12.25*	*13.50*

(Consider ϕ- index 1.10cm/h and area of watershed as 500ha).

Solution- Computation is presented in following table.

Time , hour	Cumulative rainfall, cm	Depth of rainfall, cm	Intensity of rainfall, cm/h	Effective rainfall intensity, cm/h*	Depth of ER, cm**	Duration of ER, hour
0	0.0	0.0	0.00	-	-	-
2	0.90	0.90	0.45	-	-	-
4	3.25	2.35	1.175	0.075	0.150	
6	6.50	3.25	1.625	0.525	1.050	
8	9.50	3.00	1.500	0.400	0.800	
10	12.0	2.50	1.25	0.150	0.300	
12	15.0	3.00	1.50	0.400	0.800	

14	17.25	2.25	1.125	0.025	0.050	
16	19.25	2.00	1.00	-	-	-
					3.150cm	**10.0h**

* - Difference of rainfall intensity and ϕ- index.

**- Product of effective rainfall intensity and respective duration.

Volume of direct runoff- It is equal to the product of depth of ER and area of watershed, given as under,

Volume of D. Runoff= 3.15x500ha.cm = 1575 ha.cm

Result is summarized below:

(i) Depth of ER= 3.15cm
(ii) Duration of ER=10.0hour
(iii) Volume of DR=1575ha.cm

Problem (2)- *On a specific date during monsoon season the measured time vs runoff data at the outlet of watershed is given below. Determine the ordinates of unit hydrograph. Take the area of watershed as 50sqkm and uniform base flow @ 10.50m^3/s.*

Time, h	*0.0*	*2.0*	*4.0*	*6.0*	*8.0*	*10.0*	*12.0*	*14.0*	*16.0*	*18.0*	*20.0*
Runoff, m^3/s	*0.00*	*13.50*	*25.00*	*57.5*	*80.0*	*140.5*	*127.0*	*55.5*	*35.50*	*22.50*	*10.50*

Solution- Computation is presented in following table.

Time (hour)	Discharge rate (m^3/s)	Base flow (m^3/s)	Direct runoff (m^3/s)	OUHG, m^3/s*
0.0	0.00	10.50	0.00	0.00
2	13.50	10.50	3.00	0.03
4	25.00	10.50	14.50	2.20
6	57.50	10.50	47.00	7.12
8	80.00	10.50	69.50	10.53
10	140.50	10.50	130.00	19.70
12	127.00	10.50	116.50	17.65
14	55.50	10.50	45.00	6.82
16	35.50	10.50	25.00	3.79
18	22.50	10.50	12.00	1.82
20	10.50	10.50	0.00	0.00

(*- Direct runoff / ER)

$$Depth\ of\ ER\ = \frac{Volume\ of\ direct\ runoff}{Area\ of\ watershed}$$

$$Volume\ of\ Direct\ runoff$$

$$= 2x60x60\left[\frac{1}{2}(0+3)+\frac{1}{2}(3+14.5)+\frac{1}{2}(14.5+47.00)+\frac{1}{2}(47.0+69.50)\right.$$
$$+\frac{1}{2}(69.50+130.0)+\frac{1}{2}(130.0+116.5)+\frac{1}{2}(116.5+45.0)+\frac{1}{2}(45.0+25.0)$$
$$\left.+\frac{1}{2}(25+12.0)+\frac{1}{2}(12.0+0)\right]$$
$$= 7200(1.5+8.75+30.75+58.25+99.75+123.25+80.75+35.0+18.50+6.0)$$
$$= 3.33x10^6 \text{ m}^3\text{/s}$$

$$Depth\ of\ ER\ = \frac{3.33x10^6}{50x10^6} = 0.066m$$

$S = 6.6cm$ **Ans**

Lecture -13

Unit Hydrograph for Different Durations

Originally, a unit hydrograph derived for a given watershed is of fixed duration of ER depending on the rainfall event. ER duration affects the yield of direct runoff from a watershed due to a given rainfall, and accordingly the nature of UHG also. Because of this reason, sometimes, the requirement of UHG for different ER durations is required for hydrological analysis of a watershed. A unit hydrograph may be

1. in the multiple of given duration of ER of UHG, and
2. of any ER duration.

Case – 1: When ER duration is in multiple of given ER duration.

Superposition method

In this case the given UHG is superimposed lagged by the given ER duration to (n-1) times in which n is the multiple numbers. And the time segment -wise ordinates are added together. The obtained ordinates present the ordinate of DRH, which is divided by the number of superimposition/ lagging. Example-- illustrates the procedure.

Case-2: For any ER duration

The derivation of UHG for any ER duration, i.e. when desired ER duration is not in term of multiple of original ER duration of UHG cannot be done by the method of superimposition. For this purpose the S-curve method is followed to derive the UHG. The S- curve approach is described as under,

S-Curve

It is also called summation curve, as it is obtained after summation of infinite number of D-h UHGs lagged by D-hour. Its shape is in English word "S" therefore it is named as the S-curve. This is used as a method to derive the UHG of any ER duration using a given ER duration UHG. The ordinate of S – curve at time segment is the sum of all the ordinates of D-hour falling at the time segment, shown in Fig. In derivation of S-curve there are few important points to follow, mentioned as under,

1. Attains maximum equilibrium discharge at the time of base width of Ist UHG.
2. S-curve ordinate at any time segment is given by

   $$Q_s = \sum_{i=1}^{n} U_i$$

   In which Q_s is the total ordinate of S-curve at time segment i and U_i is the ordinate of UHG at time segment i.
3. Average intensity of ER of S-curve is given as $I_{av} = \frac{1}{D}$ cm/h.
4. The equilibrium discharge is $Q_{eq} = 2.778\frac{A}{D}$ m^3/h, in which A is the area of watershed (sqkm) and D is the duration of ER (hour).
5. At the top around equilibrium discharge the s curve is observed to be in oscillating form, which is mainly due to magnification and accumulation of errors in hydrograph formation. However, it is rectified by sketching a curve passing through an average value, keeping in view that the maximum equilibrium discharge must attain at the base of UHG.
6. If two D-h s- hydrographs say A and B are lagged by T-h then difference of the ordinates of both the S- hydrographs results DRH of the excess rainfall for T-h duration. And magnitude of ER will be equal to (1/D).T cm, in which 1/D is the rainfall intensity.
7. The difference of ordinates of two S- curves divided by rainfall excess, i.e. T/D computes the ordinate of UHG of T-h duration.

Solve problem (1) illustrates the procedure under S-curve methods.

Problem (1)- *Followings are the ordinates of DRH of 3.0cm ER of 6h duration. Determine the ordinates of unit hydrograph of 12h duration.*

Time, h	*0.0*	*6.0*	*12.0*	*18.0*	*24.0*	*30.0*	*36.0*	*42.0*	*48.0*	*54.0*	*60.0*
Ordinates of , m^3/s	*0.00*	*12.00*	*27.00*	*36.0*	*57.0*	*90.0*	*120.0*	*66.0*	*24.00*	*6.00*	*0.00*

Solution- Computation is presented in following table.

Time, h	DRH,m^3/s	OUHG,m^3/s	UHG Ordinate's lagged by 6-h	OUHG of 12-h,m^3/s (Col.3+Col.4)/2
(1)	(2)	(3)	(4)	
0	0.00	0.00	-	0.0
6	12.0	4.00	0.00	2.0
12	27.0	9.00	4.00	6.5
18	36.0	12.0	9.00	10.5
24	57.0	19.0	12.0	15.5
30	90.0	30.0	19.0	24.5
36	120.0	40.0	30.0	35.0
42	66.0	22.0	40.0	31.0
48	24.0	8.0	22.0	15.0
54	6.0	2.0	8.0	5.0
60	0.0	0.0	2.0	1.0
			0.0	0.0

Problem (2)- *Determine the ordinates of DRH, if three successive rainstorms producing 5-h effective rainfall of 2.0,3.0 and 5.0cm, respectively taken place in the same watershed. The time interval between three effective rainfalls is 5-h. The ordinates of 5-h UHG are given as under.*

Time, h	*0.0*	*5.0*	*10.0*	*15.0*	*20.0*	*25.0*	*30.0*	*35.0*	*40.0*	*45.0*	*50.0*
OUHG, m^3/s	*0.00*	*3.50*	*15.00*	*27.5*	*40.0*	*50.5*	*77.0*	*55.5*	*35.50*	*12.50*	*0.00*

Solution- Computation is presented in following table.

Time (hour)	OUHG (m^3/s)	Ordinates of DRH due to 2.0cm ER	Ordinates of DRH due to 3.0cm ER lagged by 5-h	Ordinates of DRH due to 5.0cm ER lagged by 5-h	Ordinates of DRH
0.0	0.00	0.0	-	-	0.00
5	3.50	7.0	0.0	-	7.0
10	15.00	30.0	45.0	0.0	75.0
15	27.50	55.0	82.5	17.5	155.0
20	40.00	80.0	120.0	75.0	275.0
25	50.50	101.0	151.5	137.5	390.0
30	77.00	154.0	231.0	200.0	585.0
35	55.50	111.0	151.5	252.5	515.0
40	35.50	71.0	106.5	385.0	562.5
45	12.50	25.0	37.5	277.5	340.0
50	0.00	0.00	0.00	177.5	177.5
			0.00	62.5	62.50
				0.0	0.0

Average Unit Hydrograph

The UHG derived for a given watershed are not identical because of temporal and spatial variation in rainfall pattern. In this condition the UHG derived for different rainfall events are averaged. It is carried out based on the following information related to derived UHG,

1. Average time to peak
2. Average peak discharge, and
3. Average base width.

View of averaging of UHG is shown in Fig.

Suggested Reference

39. Watershed Hydrology- R. Suresh
40. Soil & Water Conservation Engineering- R. Suresh
41. Hydrology and Soil Conservation – G. Das
42. Engineering Hydrology – K. Subramanya

Lecture-14

Synthetic Unit Hydrograph

It is an artificial unit hydrograph derived for un-gauged watershed, developed by Snyder (1938). Because of this reason sometimes this hydrograph is also known as Snyder Unit Hydrograph. An un-gauged watershed which is located at very remote areas does not have the record of rainfall- runoff for the rainfall events taken place, there. The concept of SIUHG was firstly developed by The SIUHG is derived on the basis of watershed morphology and rainfall – runoff data of Morpho-hydrologically identical watershed located in the adjoining to the un- gauged watershed. For this purpose the empirical formulae relating the watershed characteristics and requisite parameters of UHG are used. The associated formulae for computing SIUGHG parameters are described as under

1. **Basin lag (t_p) -** It is defined as the time between mid-point of rainfall excess to the peak of UHG (Fig. 27.1). The computing formula based on basin characteristics is given as,

$$t_p = C_t - (LL_{ca})^{0.3}$$

where t_p is the basin lag (hour), L is the basin length measured along the water course from the basin divide to the gauging station (km), L_{ca} is the distance along the main water course from the gauging station to a point opposite to the watershed centroid (km), C_t is a regional constant representing watershed slope and storage effects taken as 1.3 to 1.65.

2. **Standard duration of effective rainfall (t_r)-** It is given by the following formula,

$$t_r = \frac{t_p}{5.5}$$

3. **Peak discharge (m^3/s) unit hydrograph (Q_{ps})-** For the standard duration (t_r) it is given as

$$Q_{ps} = \frac{2.78.A\,.C_p}{t_p}$$

where, A is the catchment area (km^2) and C_p is the regional constant taken as 0.56-0.69. This equation follows the assumption that the peak discharge is proportional to the average discharge

$$\left(\frac{1\ cm \times catchmentarea}{durationofrainfallexcess}\right).$$

4. **Non-standard rainfall duration (t_R):** Snyder also suggested to use a non – standard duration of ER (t_R) for deriving SIUHG at the place of standard duration. In this condition the basin lag is also like to change. The modified basin lag (t'_p) for non- standard duration of ER is as below,

$$t'_p = t_p + \frac{t_R + t_r}{4}$$

$$= \frac{21}{22}t_p + \frac{t_R}{4}$$

5. **Peak discharge (m^3/s) for a non-standard ER of duration** – It is given as below,

$$Q_p = \frac{2.78.A.C_p}{t'_p}$$

6. **Time base of a unit hydrograph (T_b)** - It is given by Snyder as

$$T_b = 3 + \frac{t'_p}{8} \text{ days}$$

$$= (72 + 3.t'_p)hour$$

Base time is taken as the next larger integer value divisible by t_R, i.e. T_b is about five times the time-to-peak.

In order to sketch the SIUHG properly and smoothly the U. S. Corps of Engineers have suggested the widths of unit hydrographs at 50 and 75% of the peak. The computing formulae are as under,

$$W_{50} = \frac{5.87}{q^{1.08}}\ hour$$

and $$W_{75} = \frac{W_{50}}{1.75}\ hour$$

where W_{50} is the width of UHG at 50% peak discharge, W_{75} is the width of UHG in h at 75% peak discharge and $q = Q_p/A$ is the peak discharge per unit catchment area ($m^3/s/km^2$)
Solve problem (1) showed the procedure for determining the SIUHG.

Problem (1)- In order to derive synthetic unit hydrograph determine the peak discharge of watershed. Take time to peak 7.5 hours. Also, assume the following values:

(i) Regional constant =0.56
(ii) Area of watershed =300sqkm.

Solution- Snyder, suggested following formula for predicting peak discharge,

$$Q_p = \frac{2.78C_p.A}{t_r}$$

in which, C_p is the regional constant (0.56); A is the area of watershed (300sqkm) and t_r is the duration of ER. The formula for duration of ER is given as under,

$$t_r = \frac{t_p}{5.5}$$

$$t_r = \frac{7.5}{5.5} = hour$$

in which, t_r is the duration of effective rainfall and t_p is the basin lag of watershed (12.5hours). Substituting these values in above formula, and solving, we have,

$$t_r = \frac{12.5}{5.5} = 2.27\ hour$$

Therefore, $Q_p = \frac{2.78x\ 0.56x300}{2.27} = 205.74$ m^3/s **Ans.**

Problem (2)- Determine the time base of synthetic unit hydrograph of 6 hour ER duration for an un-gauged watershed of 300 sqkm area.

Solution- The formula for time base of SIUH is given below,

$$t_b = 3 + \frac{t_p}{3}\ \text{days}$$

The time to peak is given by the following formula,

$$t_r = \frac{t_p}{5.5}$$

Accordingly, $t_p = 5.5x6.0 = 33\ hours.$

Therefore,

$$t_b = 72 + 3t_p$$
$$= 72 + 3x33$$
$$= 171\ hours.$$ **Ans.**

Problem (3)- Calculate the width of Synthetic Unit Hydrograph at 50 and 75% of the peak flow. The peak discharge of watershed is 30m^3/s and area of watershed is 300sqkm.

Solution- The formula for determining the width of SIUH at 50% peak is given as under:

$$W_{50} = \frac{5.87}{q^{1.08}}$$

in which, q is the discharge per unit area, given as 30/300=0.10m/s. Substituting this value in above formula, and solving, we have,

$$W_{50} = \frac{5.87}{0.1^{1.08}} = 70.58\ hours$$ **Ans.**

Similarly, the formula for determining the width of SIUH at 75% peak is given as under:

$$W_{75} = \frac{W_{50}}{1.75}$$

Substituting the value of W_{50} in above formula, and solving, we have,

$$W_{75} = \frac{W_{50}}{1.75} = \frac{70.58}{1.75} = 40.331\ \text{hours.}$$ **Ans.**

Dimensionless Unit Hydrograph

It is a kind of SIUHG, developed by the Soil Conservation Services in the 1972. In this UHG the ordinate is expressed by the ratio of discharge (Q) to peak discharge (Qpk) and abscissa by the ratio of time (t) to time of rise of unit hydrograph (tpk). View of DUHG is shown in Figure-. By using this method the unit hydrograph can be easily developed for a given peak discharge and lag time. It involves following formulae,

1. **Duration of ER**- It is given as,

$$t_r = 1..33t_c$$

2. **Peak discharge** (Q$_{pk}$)**-** It is by the following formula,

$$Q_{pk} = \frac{5.36.A}{t_{pk}}$$

in which tpk is the time to peak and A is the area of watershed

Time to peak, t_{pk} is given as

$$t_{pk} = \left(t_{pR} + \frac{t_R}{2}\right)$$

3. As per definition

$$\left(\frac{Q}{Qpk}\right) = 1 \text{ , when } \frac{t}{t_{pk}} = 1$$

The coordinates, i.e., (Q/Qp) Vs (t/tp) data generated by the SCS is presented in table-

Table- Average coordinates of DUHG

t/t$_{pk}$	Q/Q$_{pk}$	t/t$_{pk}$	Q/Q$_{pk}$
0.00	0.00	2.75	0.105
0.25	0.12	3.00	0.075
0.50	0.43	3.25	0.053
0.75	0.83	3.50	0.036
1.00	1.00	3.75	0.026
1.25	0.88	4.00	0.018
1.50	0.66	4.25	0.012
1.75	0.45	4.50	0.009
2.00	0.32	4.75	0.006
2.25	0.22	5.00	0.004
2.50	0.15		

The derivation procedure is explained in example-

Distribution Graph

The distribution graph introduced by Bernard (1935) is treated as special type of UNHG. In distribution graph the ordinates are expressed in the form of percentage of total runoff in successive uniform time interval of D-h. The successive percentage applies to the volumes of rainfall excess in each unit storm period, resulting into an equal number of overlapping hydrographs. The DRH is obtained by adding the coinciding ordinates of distribution graph, i.e. in t4e same way as in case of UHG. Distribution graph is presented in stepped from (fig). Note that the ordinates plotted at D-h intervals and the total area under the distribution graph adds up to 100%. Distribution graphs are useful in comparing the runoff characteristics of different catchments. The discharge ordinates for successive unit time intervals are shown as under,

P1	P2	P3	P4	P5	P6	P7	P8
U1P1	U2P1	U3P1	U4P1	U5P1			
	U1P2	U2P2	U3P2	U4P2	U5P2		
		U1P3	U2P3	U3P3	U4P3	U5P3	
			U1P4	U2P4	U3P4	U4P4	U5P4
				U1P5	U2P5	U3P5	U4P5
					U1P6	U2P6	U3P6
Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8

P1 …..P8 are the volume of rainfall excess in successive unit storm periods; U1…U5 are the percentage of distribution graph and Q1 …Q8 are the discharge of successive time intervals.

Same is expressed as under. Same is also mentioned as under,

Q1= U1P1

Q2=U2P1+ U1P2
Q3= U3P1+ U2P2+ U1P3
Q4= U4P1+ U3P2+ U2P3+ U1P4
Q5=U5P1+ U4P2+ U3P3+ U2P4+ U1P5
Q6= U5P2+ U4P3+ U3P4+ U2P5+ U1P6
Q7= U5P3+ U4P4+ U3P5+ U2P6
Q8= U5P4+ U4P5+ U3P6

Suggested Reference

43. Watershed Hydrology- R. Suresh
44. Soil & Water Conservation Engineering- R. Suresh
45. Hydrology and Soil Conservation – G. Das
46. Engineering Hydrology – K. Subramanya

Lecture-15

Stream Flow Measurement

The stream flow measurement is also known as stream gauging, is a technique used to measure the discharge passing through a stream/channel per unit time. The height (depth) of water flow in the stream channel is known as flow stage or gage height, can be used to determine the stream flow discharge. The flow measurement is important in various aspects related to watershed study. Few important points about significance of stream flow measurements are mentioned s under,

Importance: Stream gauging for the following purposes,

1. The design of water supplies, dams and other engineering works;
2. Monitoring the sustainability of water allocation and water management;
3. Implementing water restrictions;
4. Flood mitigation and drainage;
5. Monitoring climate change and drought; and
6. Assessment of changes in water yields resulting from altered land use.

Gauging Station

The place where the stream flow measurement is carried out is called gauging point or gauging station. The gauging station must be in permanent nature, i.e. the site characteristics should remain unchanged for a long period to time. Such sites are called permanent control. A gauging site in permanent nature makes the data validity for a long period of time, and also the validity of relationship developed between gauge and stream discharge sustained to a greater span of time. In order to have an accurate data, a gauging station must have following features,

1. Towards u/s and d/s sides there should be a straight reach of stream section.
2. The siltation and vegetative growth must be restricted.
3. Confluent of stream flow should not be there.
4. The soil at the site should be impervious or hard in nature.
5. Site should be easily accessible.
6. Must be connected with road.

Measurement of Flow Stage

Stream gauging can be done by measuring the stage height and velocity at a series of points in a cross-section of a stream or by constructing a flume or weir and recording stage height. Stage height can be measured using a ruler, or a pressure transducer or stilling well connected to a data logger. In addition it is frequently done by means of following devices,

1. Staff gauge
2. Chain , tape, wire gauge
3. Electric tape gage
4. Pressure transmitter gauge
5. Crest stage indicator
6. Automatic stage recorder

Staff gauge- It is a graduate scale made of durable materials with low expansion characteristics due to heat effect. For measurement of flow stage it is placed in the water flow by fastening with the wall, pier or any other structure. The level of water flow is directly read from the gauge. Sometime, the fluctuation of water level is very high. In this condition several gauges are installed at different sections and points of the stream. However, it should always be kept in view that across the gauge there must be minimum disturbances.

Electric Tape gauge- It consists of an electrical circuit equipped with galvanometer etc. For measurement the tape is lowered to the water flow. On contact of tape with water level there is deflection in the needle. The reading on the tape is read directly. As compared to staff gauge this provides better measurement.

Pressure Transmitter Gauge- This a kind of electronic device used for measuring the flow stage. This measures the flow stage in terms of pressure with respect to the water flow stage. It consists of a cylinder through which water is allowed to a flexible diaphragm. In result water suppresses the diaphragm. The developed suppression is transmitted to the dial via transmitter. Reading is indicated on dial.

Crest Stage Indicator- It is used for measuring peak stage of floods. It consists of a pipe placed in vertical position with open and screened bottom and top is vented. Inside pipe a wooden staff gauge is placed, which is kept in position with the help of a cap. Powered cock is placed at the top of the pipe. On passing of flood water through indicator the cock is lifted up and at the crest it clings to the graduated staff.

Automatic Stage Recorder- There are many commonly used automatic stage recorders available in the market for measuring the water flow stage in the river system. Few very common amongst them are Float – gauge recorder, Bubble gauge, Tensiometric recorders etc. These devices record the observations, automatically.

Flow Velocity Measurement

In stream flow velocity measurement, it is always kept in view that the flow velocity also varies within the cross-section of flow stream. Close to stream banks there is greater friction and hence velocity of flow is slow. Therefore, to overcome this effect it is necessary to take velocity measurements along the entire flow width of stream. The following methods are used for measuring velocity water flow through stream/ rives system,

1. Float method
    a. Surface float ,and
    b. Sub- surface float
2. Velocity rod method
3. Current meter method
    a. Pigmy type
    b. Propeller type
    c. Price type

Float Method- In this method the flow velocity is measured by placing a float on the water surface, and time taken by the float to cover a pre-decided distance is noted. The distance covered divided by the elapsed time, yields the velocity of stream flow. Floats are made of wooden or any other materials which are less in weight and have good characteristics of floating. Floats are of two types, i.e., surface float and sub- surface float.

Surface floats are used when a high degree of accuracy is measurement is not required, and also when costly device is possible to use. Surface floats are 7 to 15cm in diameter and light in weight. In stream gauging the mean velocity of flow is considered for computing the runoff rate. These measure the velocity of flow at the top of water surface, which does not represent the mean value of flow velocity. Therefore, mean flow velocity is required to have, which is determined by the formula $V_m = 0.85V_s$. In which V_m is the mean flow velocity and V_s is the velocity of surface float. Surface floats are normally used for the flow depth up to 4.5m.

Sub- surface floats are in the form of double or twin floats. In double float system the one float is kept at the top of water surface called surface float, and other is below the water surface is called sub-surface float. The sub-surface float is made of hollow metal in spherical shape and is attached with the surface float by means of thin cord of known length. The length of cord is decided on the basis of flow depth. However, the sub-surface float should always 0.2d (d is the flow depth) above the steam bed, which is adjusted with the help of cord length. The main purpose of sub- surface float is to keep the surface float is position against high wind velocity and water current.

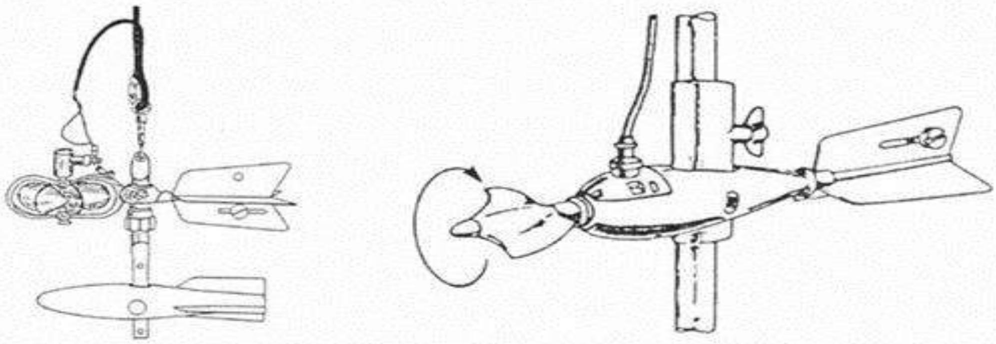
In twin float, both the floats are in spherical shape, made of hollow metal. Upper float is partially submerged in the water while other is completely into the flow, called sub-surface float. The function of sub-surface float is to keep the surface float is position against high wave and wind velocity. The lower or sub-surface float is adjusted / maintained at the depth of 0.6d (d is the depth of flow) from the top of water surface. The measured velocity is taken as the mean value.

Current Meter Method- Stream water velocity is measured using a current meter. A current meter consists of a propeller or a horizontal wheel with small, cone-shaped cups mounted on it. When current meter is placed into the water flow, the mounted cups fill with water and turn the wheel. The number of rotations of the propeller or wheel-cup mechanism correspond the velocity of water flowing through the stream. In order to have accurate measurement the current meter is lowered to the depth 0.6d (d is the flow depth). The measured flow velocity at this depth is considered as mean flow velocity in the stream. The lowering of meter is done by using hanging rod, which provides easiness in measurement of velocity at a particular flow depth. On the basis of observations on number of revolutions the velocity of water flow through stream section is calculated by using the following formula,

$$V = aN + b$$

in which, V is the stream flow velocity (m/s) a and b are the constant and N is the number of revolutions per second. The value of constant a and b are available with the current meter, which is determined by calibration of current meter.

FIGURE 21
Two types of current meter



(a) cup type

(b) propeller type

PLATE 23 Measuring streamflow with a current meter in Botswana
(FAO Photo Library)

Problem (1). *In order to determine the discharge of a particular stream the velocity of flow was measured by using the current meter. The current meter was placed at top of water surface and at the depth of 75 cm below the top of water surface. The number of revolutions per second recorded at the top of water surface and 75cm below the top of water surface are 100 and 75, respectively. Determine the mean flow velocity of the stream. Take the value of constant a and b as 0.45 and 0.05, respectively.*

Solution-

Given that,

(i)Number of revolutions at the top of water surface =100/per second

(ii) Number of revolutions at 75cm below the top of water surface =75/per second

Using the following formula for flow velocity, using the current meter

$$\mathrm{V = aN + b}$$

in which, *a* and *b* are the constant given as 0.45 & 0.05, respectively and N is the number of revolutions per second. Substituting these values in above formula, and solving, we have,

(i)At top of water surface-

$$\mathrm{V} = 0.45\mathrm{x}100 + 0.05$$
$$= 45.05\text{m/s}$$

(ii) At 75cm depth below the top of water surface-

$$\mathrm{V} = 0.45\mathrm{x}75 + 0.05$$
$$= 33.8\text{m/s}$$

Mean flow velocity = (45.0 +33.8)/2= **39.43m/s Ans**

Problem (2). *In a moderate stream the Price type current meter was used for measuring the flow velocity. The observations recorded at the depths of 0.2 and 0.8time of flow depth are 100 and 75rps, respectively. Find the average flow velocity. Take the value of constants of current meter as a =0.65 and b=0.30.*

Solution-

Given that,

(i)Number of revolutions at 0.2 of flow depth =100/per second

(ii) Number of revolutions at 0.8 of flow depth =75/per second

The stream flow velocity using current meter is computed by using the following formula,

$$V = aN + b$$

in which, *a* and *b* are the constant given as 0.65 & 0.30, respectively and N is the number of revolutions per second (100). In moderate streams the mean flow velocity is determined by taking the measurements at 0.2d (d is the flow depth) and 0.8d from the top of flow surface, by using the following formula,

$$\bar{V} = \frac{V_{0.2d}+V_{0.8d}}{2}$$

Substituting these values in above formula, and solving, we have

(i) $V_{0.2d} = 0.65\mathrm{x}100 + 0.30$ =65.30m/s

and

(ii) $V_{0.8d} = 0.65\mathrm{x}75 + 0.30$ =49.05m/s

Therefore,

$$\bar{V} = \frac{65.3+49.05}{2}$$
$$= \mathbf{57.17}\textbf{m/s Ans.}$$

Suggested Reference

47. Watershed Hydrology- R. Suresh
48. Soil & Water Conservation Engineering- R. Suresh
49. Hydrology and Soil Conservation – G. Das
50. Engineering Hydrology – K. Subramanya

Lecture- 16

Manning's formula

Sometimes, because of various reasons the measurement of flow velocity is not possible in field. In this condition the empirical formulae are the alternative for determining the stream flow velocity. The Manning's formula is one the most versatile formulae, is used for computing the flow velocity. Manning's formula computes the velocity of flow on the basis of channel characteristics mainly the roughness, mean hydraulic radius and longitudinal slope of the stream. The formula is described as under,

$$V = \frac{1.49 R^{0.66} S^{0.5}}{n}$$

in which V is the stream flow velocity; R is the mean hydraulic radius, S is the longitudinal slope of stream (m/m) and n is the Manning's roughness coefficient. The value of Manning's roughness coefficient is given in following table.

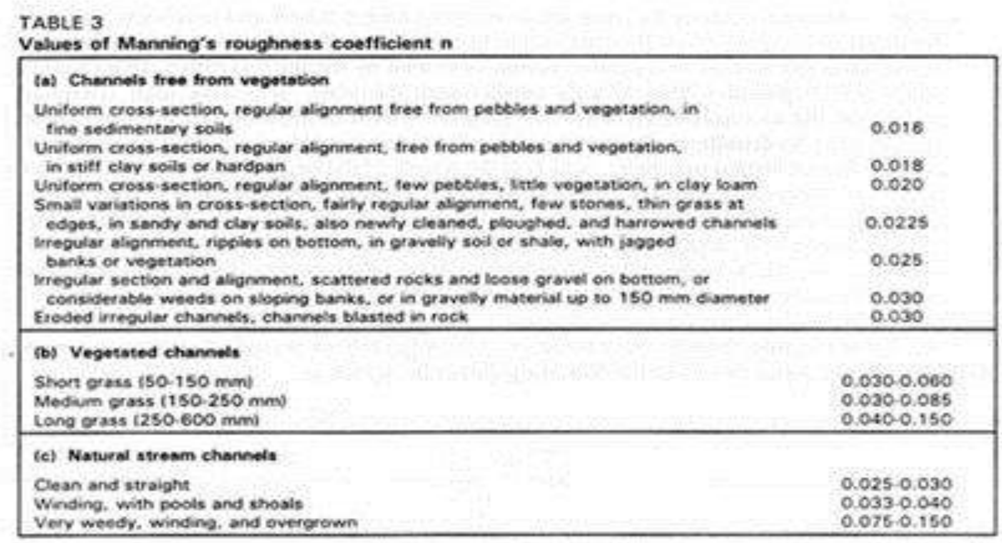
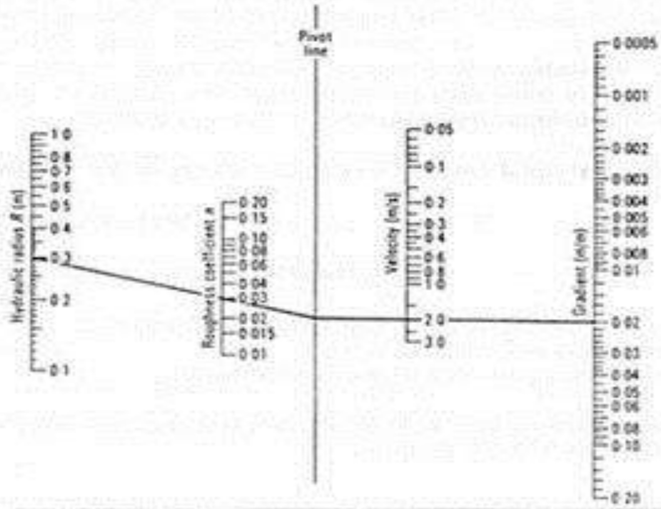


TABLE 3
Values of Manning's roughness coefficient n

(a) Channels free from vegetation	
Uniform cross-section, regular alignment free from pebbles and vegetation, in fine sedimentary soils	0.016
Uniform cross-section, regular alignment, free from pebbles and vegetation, in stiff clay soils or hardpan	0.018
Uniform cross-section, regular alignment, few pebbles, little vegetation, in clay loam	0.020
Small variations in cross-section, fairly regular alignment, few stones, thin grass at edges, in sandy and clay soils, also newly cleaned, ploughed, and harrowed channels	0.0225
Irregular alignment, ripples on bottom, in gravelly soil or shale, with jagged banks or vegetation	0.025
Irregular section and alignment, scattered rocks and loose gravel on bottom, or considerable weeds on sloping banks, or in gravelly material up to 150 mm diameter	0.030
Eroded irregular channels, channels blasted in rock	0.030
(b) Vegetated channels	
Short grass (50-150 mm)	0.030-0.060
Medium grass (150-250 mm)	0.030-0.085
Long grass (250-600 mm)	0.040-0.150
(c) Natural stream channels	
Clean and straight	0.025-0.030
Winding, with pools and shoals	0.033-0.040
Very weedy, winding, and overgrown	0.075-0.150

FIGURE 25
Nomograph for solving Manning's formula. If any 3 variables are known, the 4th can be found

Example: Given R = 0.3 m, n = 0.03, gradient = 2% or 0.02 m per m, find velocity V.
Solution: Join R = 0.3 and n = 0.03 and project to pivot line. Join the point on pivot line to gradient = 0.02. Intersection of the velocity scale gives V = 2.0 m/s.



Area- Velocity Method

The stream or river discharge is the volume of water flowing through a cross-section in a unit of time, is usually expressed as m^3 /s. It is calculated as the product of average velocity of stream flow and flow cross-sectional area. These two are affected by the flow depth, river alignment, gradient and roughness of the bed. The velocity of stream flow is computed by using the Manning equation. Although, the Manning's formula is developed for the condition of uniform flow in open channel; however, it also yields an adequate estimate for non-uniform flow which is normally takes place in natural channels. The Manning equation is given as under,

$$V = \frac{R^{2/3}S^{1/2}}{n}$$

$$Q = A.V$$

$$Q = A.\frac{1}{n}R^{2/3}.S^{1/2}$$

Where, Q is the discharge (m3/s), A is the cross-sectional area of flow (m$^{2)}$,R is the hydraulic radius (m) is equal to A/P (P is the wetted perimeter, m), S is the slope of stream bed n is the roughness coefficient.

More accurate values for discharge can be obtained by using permanent gauging station, established on a straight reach of river where there is a stable relationship between stage (water level) and discharge. The relationship between flow stage and discharge is called S-D relationship. With the help of this relationship, only stage data is required to find the value of corresponding discharge against given flow stage.

Problem (1)- *Determine discharge rate of stream flow by using Two –Point Method, if the velocity of stream flow at the points of 20 and 80% depths of flow from top of water surface is 2.5 and 1.75m/s, respectively; and average depth of flow is about 5.0m.*

Solution-

Given that,

(i) Stream flow velocity at 20% of depth of flow from top of water surface= 2.5m/s
(ii) Stream flow velocity at 80% of depth of flow from top of water surface= 1.75m/s
(iii) Average depth of flow = 5.0m

Using following formula for determining the stream flow discharge rate,

$$Q = d.V_m$$

in which, d is the average flow depth (5.0m) and V_m is the mean velocity of stream flow is given as (2.5+1.75)/2=2.125m/s. Substituting these values in above formula and solving , we have,

$Q = 5.0x\ 2.125 = \mathbf{10.625}$**m^3/s per unit width of stream flow. Ans.**

Problem (2)- *Determine the discharge rate of stream flow by using two-point method. The requisite data is as follows,*

Distance from one end of the stream, m		*0*	*1.5*	*3.0*	*3.5*	*4.0*	*4.5*	*5.0*
Flow depth, m		*0.0*	*1.75*	*2.25*	*3.75*	*2.10*	*1.5*	*0.75*
Flow velocity, m/s	*0.2d*	*0.0*	*2.60*	*2.25*	*2.10*	*2.35*	*2.70*	*3.45*
	0.6d	*0.0*	*1.75*	*1.60*	*1.45*	*1.47*	*2.62*	*3.00*
	0.8d	*0.0*	*1.35*	*1.20*	*1.15*	*1.10*	*1.40*	*2.75*

Also, calculate the stream flow rate by using three- point method.

Solution-

(i) Two- point method- Using fowling formula,

$$Q = A.V_m$$

in which A is the area of stream flow is equal to *b.d* (b is the breadth of flow and d is the flow depth) and V$_m$ is the mean velocity of flow. Considering unit width of flow, the area A is equal to depth of flow (d). Accordingly, $= d.V_m$. Computation is shown below,

Distance from one end of the stream, m	*0.0*	*1.5*	*3.0*	*3.5*	*4.0*	*4.5*	*5.0*	*Total*
Flow depth, m	*0.0*	*1.75*	*2.25*	*3.75*	*2.10*	*1.5*	*0.75*	

$\bar{V} = \frac{V_{0.2d} + V_{0.8d}}{2}$	*0.0*	*1.975*	*1.725*	*1.625*	*1.725*	*2.05*	*3.100*	
Discharge rate,m³/s/m width $(Q = A.V_m)$	*0.0*	*3.456*	*3.881*	*6.094*	*3.623*	*3.075*	*2.325*	*22.454*

Total discharge =22.454m³/s/unit flow width **Ans.**

(ii) Three – point method- In this method, the same procedure is followed as in case of Two –point method, except the mean flow velocity is determined by taking the average of flow velocity measured at three different depths of stream flow, i.e. $\bar{V} = \frac{V_{0.2d}+V_{0.6d}+V_{0.8d}}{3}$. Computation is presented as under,

Distance from one end of the stream, m	*0.0*	*1.5*	*3.0*	*3.5*	*4.0*	*4.5*	*5.0*	*Total*
Flow depth, m	*0.0*	*1.75*	*2.25*	*3.75*	*2.10*	*1.50*	*0.75*	
$\bar{V} = \frac{V_{0.2d}+V_{0.6d}+V_{0.8d}}{3}$	*0.0*	*1.900*	*1.683*	*1.566*	*1.64*	*2.24*	*3.066*	
Discharge rate,m³/s/m width $(Q = A.V_m)$	*0.0*	*3.325*	*3.787*	*5.873*	*3.444*	*3.360*	*2.300*	*22.089*

Total discharge =22.089m³/s/unit flow width **Ans.**

Suggested Reference

51. Watershed Hydrology- R. Suresh
52. Soil & Water Conservation Engineering- R. Suresh
53. Hydrology and Soil Conservation – G. Das
54. Engineering Hydrology – K. Subramanya

Lecture- 17

Problem (3)- *In order to determine the flow rate of a given natural stream the entire width of flow has been divided into various segments. The details are given as under,*

Distance from one end of the stream, m	*0*	*5*	*10*	*15*	*20*
Depth of flow, m	*0*	*3.0*	*5.25*	*4.75*	*2.25*

Determine the area of each segment of flow.

Solution- Computation is presented in following table.

Distance from one end of the stream, m	Width of segment ,m	Flow depth, m	Area,m^2
0	0	0	0.0
3	3.0	3.0	9.0
10	5.0	5.25	26.25
16	6.5	4.75	30.88
21	5.5	2.25	12.37

Dilution method: This is also called salt concentration method. In dilution technique of stream flow determination the salts are injected into the river flow and on the basis of salt concentration available in the flow at d/s stream side , concentration of salt already existing in the original flow and rate of injection of salt in the flow the stream discharge of determined. The Sodium chloride (common salt) is a *good tracer* for dilution gauging. In general a salt/chemical to be used for stream gauging should have following properties,

(a) Chemically conservative', i.e., does not adsorb ('chemically bind') onto river sediments,

(b) Should be highly soluble in the water.

(c) Should be relatively non-toxic.

(d) Should not get loss due to evaporation effect.

(e) Easily measureable in the field indirectly with a conductivity meter, and

(f) Cheap and readily available.

However, for a large rivers the alternative tracers that can be traced at ppb (part per billion) levels are normally used, e.g., the fluorescent Rhodamine WT.

Basically this method follows following equation,

$$(Q+q)C_2 = Q.C_1 + Q.C_0$$

in which the left hand side component , i.e. $(Q+q)C_2)$ denotes total d/s flow *x* mixed concentration and right hand side component $(Q.C_1)$ to the rate of traced input and component $(Q.C_0)$ to u/s flow x back ground flow concentration. In equation the *Q* is the river discharge at u/s side to be determined; *q* is the rate of tracer discharge; C_2 is the mixed downstream concentration, C_1 is the concentration of tracer to be added in the river flow, and C_0 is the background tracer concentration in the river (may be zero).

In this method, two approaches namely the 'constant injection method' and the 'integration or gulp injection method' is followed. The discharge computing relationship under *constant injection method* is mentioned, below,

$$Q = q\frac{(C_1 - C_2)}{(C_2 - C_0)}$$

In constant injection method a known tracer concentration ($C1$) is trickled into the stream flow at a fixed rate (*q)* by using a device called 'Mariotte device'. At a d/s point, the background concentration (C_0) is measured, followed by the concentration mixed with the tracer (C_2).

In second method, i.e. the *Integration or Gulp method* a known volume and concentration of a tracer (VC_1) into the river as a single 'slug'. Thereafter the d/s mixed concentration in flow is measured (C_2) and the background concentration (C_0) is subtracted. The area of the curve drawn between C_2-C_0 versus time (t) estimates the stream flow rate, expressed by the following relationship,

$$Q = \frac{VC_1}{\int_{t1}^{t2} (C_2 - C_0) dt}$$

Hydraulic Structures for Measuring Stream Flow

Apart from above- mentioned methods to determine the stream flow rate, the hydraulic structures are also used for the purpose of stream gauging. In this case the structures are constructed in the stream/river section. Through which the flow is allowed and data is recorded in terms of depth of flow. This method is found suitable for measuring small runoff flow rate. The weirs and flumes are very commonly used structures for stream gauging.

Weirs- These are the notch of regular form, are constructed with the help of wooden materials, metal sheets, concrete etc. in the stream section across the flow at the pre-selected place. An opening gate is provided at the top of the weir to allow the flow from the stream. The sharp crested and broad crested weirs are used for the purpose. In order to have an accurate measurement of stream flow rate using the weir, the followings are the essential requirements,

1. The weirs should have sharp crest and sharp sides.
2. Stream reach should be straight and uniform at the construction point.
3. The effect of back water flow should be negligible.
4. The depth of flow over weir crest should be measured at the distance of 4 times the flow depth from the weir towards u/s side.
5. Weir crest should be fixed at the height 2 times the depth of flow from the stream bed.
6. The water falling from the weir toward d/s side should in free flow nature.

The sharp crested weirs are normally preferred for the stream flow free from silts and debris contents. The sharp crested weirs are again classified as

Rectangular weir – It has level crest and vertical sides. The formula for discharge calculation for this weir is given as under,

$$Q = 0.0184L.H^{3/2}$$

In which, Q is the discharge rate, L is the crest length and H is the depth of flow over the crest.

Trapezoidal Weir- It is also known as Cippoleti weir. It has level top and sloppy sides in the ratio of 1:4 (H: V). The discharge computing formula for this weir is given as under,

$$Q = 0.0186L.H^{3/2}$$

Triangular weir- This is also called V-notch. The angle between two sides is kept to the tune of 45, 90 and 120 degree. However, the V notch with 90 degree angle is commonly used. The following formula is used for computing the discharge rate,

$$Q = 0.0138H^{2.48}$$

Flume- It is also used for measuring the small flow rate, constructed to the shape of stream section, in the stream. Flow computation is based on the specific energy and critical flow concept. Specific energy of flow at any section is the sum of all the energies with reference to the stream bed, as mentioned below,

$$E = h + \frac{V^{2}}{2g}$$

In which, E is the specific energy, h is the depth of flow V is the velocity of flow and g is the acceleration due to gravity. The venturi and meter flumes are commonly used for stream gauging.

The meter flume follows following formula for computing the flow rate,

$$Q = 1.7C.b.H^{1.5}$$

Where, Q is the flow rate; C is the constant depends on the relative proportion of flume dimension, b is the width of flume and H is the total head , i.e. the sum of flow depth over the crest and head due to velocity of flow.

The venturi flume is the meter flume. Discharge is determined by measuring the difference of water flow heads at entrance and throat points of the flume. The discharge computing formula is mentioned as under,

$$Q = \frac{C.a_1 a_2 \sqrt{2g(h_1 - h_2)}}{\sqrt{a_1.a_2}}$$

in which ,Q is the flow rate; C is the constant, depends on the relative proportion of the flume dimension; a1 , a2 are the cross sectional area at entrance and throat points of the flume, respectively; h1 , h2 are the depth of flow at entrance and throat points of the flume, respectively.

Suggested Reference

55. Watershed Hydrology- R. Suresh
56. Soil & Water Conservation Engineering- R. Suresh
57. Hydrology and Soil Conservation – G. Das
58. Engineering Hydrology – K. Subramanya

Lecture-18

Stream – Discharge Relationship

This relationship is treated as one of the tools for predicting the steam flow rate against a given flow stage. It is developed on the basis of stream discharge vs flow stage data collected from the gauging station of a given river or stream system. The accuracy in estimation depends very much on the accuracy of the data used and nature of gauging station. In general it is very essential to establish a permanent type control station for collecting the data and developing the relationship. The permanent type gauging station assures the collected data to be valid for a greater time length unless there is some drastic change occurs at gauging station. Although, it can also be developed on the basis of the data collected from the temporary control point or the station, but the validity of relationship is always in risk.

The stage – discharge curve or relationship is developed by plotting the stream discharge and corresponding flow stage on log-log paper (Fig-). The curve obtained so is called stage-discharge rating curve. It is also known as G-Q relationship is shown in Figure-1.0. This curve facilitates to determine the steam discharge against given flow stage. Mathematically, G-Q relationship is presented as under,

$$Q = C_r(G - a)^{\beta}$$

In which Q is the stream discharge, G is the flow stage; C_r and β are the constants of rating curve and a is the constant which is the gauge height corresponding to zero discharge.

This equation is in non- linear form, which can be linearize by taking log of the above equation, given as under,

$$\log Q = \beta.\log(G - a) + \log C_r$$

Or

$$Y = \beta logX + b$$

This is the expression of straight line for G-Q relationship, in which Y= log Q is the dependent variable; X = log (G-a) is as independent variable and β & b are the constant. The value of β and b are expressed as under,

$$\beta = \frac{N(\sum X.Y) - (\sum X)(\sum Y)}{N(\sum X^2) - (\sum Y^2)}$$

$$b = \frac{\sum Y - \beta(\sum X)}{N}$$

And correlation coefficient (r) is given as

$$r = \frac{N(\sum X.Y) - (\sum X)(\sum Y)}{\sqrt{N(\sum X^2) - (\sum X)^2}\sqrt{N(\sum Y^2)(\sum Y)^2}}$$

The value of r between 0.6 and 1 is considered as a good correlation. The r=1 shows perfect correlation.

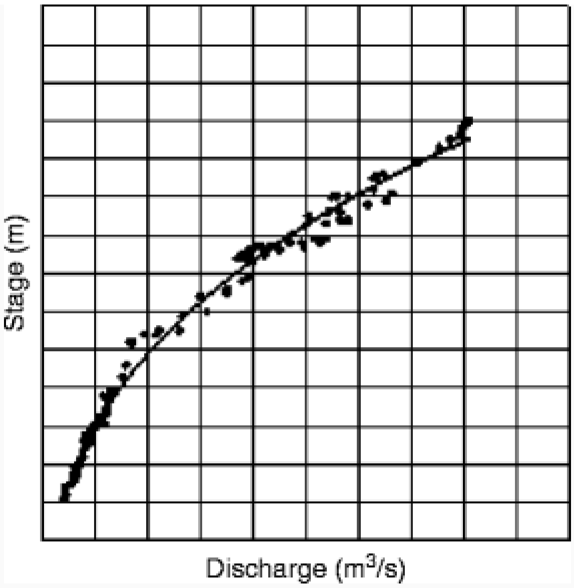


Figure- 1.0. G-Q relationship

Procedures to Determine the Value of Factor a in G-Q Relationship

In G-Q relationship the factor *a* represents the gauge height corresponding to zero discharge rate of stream. Its measurement in field is not possible, but can determined by using following techniques,

Method-1: The following steps are followed,

1. Plot a best fit curve between Q and G on normal graph paper.
2. Extrapolate the curve by eye judgement and fined the value of a corresponding to zero discharge.
3. considering the determined value of a in step (2) plot the curve between Q and (G-a) on log paper. If plotting yields straight line the determined value of a in step (2) is considered to be correct. Otherwise take another value of a in the neighbour of the previous value and again plot the curve between Q and (G-a) on log paper till to achieve a straight line.

Method-2:

It follows the following steps,

1. Plot the curve between Q and G on arithmetic graph paper and draw a best fit curve.
2. Select any three points on the curve A,B and C in such a way that their discharge values are in geometric progression., i.e.
$$\frac{Q_A}{Q_B} = \frac{Q_B}{Q_C}$$
3. Draw a vertical line from the points A and B and also draw horizontal lines from points B and C to intersect the vertical lines.
4. Draw a straight line by joining the points E to D and extend forward.
5. Also draw a straight line from the points B to A and extend forward.
6. The two lines EF and BF where joins, represents the value of a. This method assumes that the lower segment of G-Q curve is parabolic in shape.
(Procedure is shown in Fig-)

Method-3

Procedure is described as under,

1. Plot the curve between Q and G on arithmetic graph paper and draw a smooth curve.
2. Select three discharge Q_1,Q_2 and Q_3 in such a way that they are in geometric progression., i.e.

$$\frac{Q_1}{Q_2} = \frac{Q_3}{Q_4} \qquad \text{… (1)}$$

3. Determine the value of G_1, G_2 and G_3 corresponding to Q_1, Q_2 and Q_3, respectively from the plotted curve.
4. Express the G_1, G_2 and G_3 in following form,

$$\frac{(G_1-a)}{(G_2-a)} = \frac{(G_2-a)}{(G_3-a)} \qquad \text{…(2)}$$

5. Solve the equation (2) and determine the value of a.

Hydrometry Station

This is meant for taking the measurements on discharge flowing through the river system. WMO has recommended the norms of establishment of hydrometric stations, detailed as under,

1. For flat , temperate ,mediterrean and tropical zones the number of station varies as per
   a. Minimum density-1000 to 2500sqkm/station
   b. Tolerable density under difficult condition-3000 to 10000sqkm/station.
2. For mountainous region on temperate , mediterrean and tropical zone it varies as under,
   a. Minimum density-300 to 1000sqkm/station
   b. Tolerable density under difficult condition-1000 to 5000sqkm/station.
3. For arid and polar regions the minimum density should be 5000 to 20000sqKm/ station.

Problem(1) - *Derive the G-Q relationship for the stream of perennial nature. The gauge versus discharge data of gauging station is given below,*

Gauge reading (m)	*5.0*	*5.05*	*5.10*	*5.15*	*5.20*	*5.25*	*5.30*	*5.35*	*5.40*
Discharge (m^3/s)	*30.0*	*33.25*	*35.0*	*37.70*	*40.00*	*42.15*	*43.05*	*45.10*	*47.40*
Gauge reading (m)	*5.45*	*5.50*	*5.55*	*5.60*	*5.65*	*5.70*	*5.75*	*6.80*	*5.85*
Discharge (m^3/s)	*50.05*	*52.15*	*54.35*	*56.20*	*58.30*	*61.50*	*65.00*	*68.45*	*70.25*

Also, find the discharge rate at 10m gauge height by using the derived G-Q relationship. Take the value of a as 4.80m.

Solution- Taking the G-Q relationship, i.e. $Q = C_r(G-a)^{\beta}$ is a non- linear relationship. In order to derive the relationship based on the given data set, the constants, involved in above equation is determined. The procedure is described below

Taking log of the equation,

$$\mathrm{logQ = logC_r + \beta log(G-a)}$$

This is the linear form of G-Q relationship, i.e.,$\mathrm{y\ = mx\ + c}$, in which $\mathrm{Y = logQ}$; $\mathrm{m = \beta}$; $\mathrm{x = log(G-a)}$and $\mathrm{c = logC_r}$. The values of constants β and $\mathrm{C_r}$ are determined as under,

$$\beta = \frac{N(\sum x.y)-(\sum x)(\sum y)}{N(\sum x^2)-(\sum x)^2}\text{ ; and}$$

$$C = \frac{\sum y-\beta\sum x}{N}$$

$$C_r = Antilog\ C$$

The requisite computations are presented as under,

Gauge reading, (G)	Discharge (Q) ,m^3/s	$(G-a)$	$x = log(G-a)$	x^2	$y\ = \ logQ$	y^2	$x.y$

m							
5.00	30.00	0.20	0.6989	0.4884	1.4771	2.1818	1.0323
5.05	33.25	0.25	0.6020	0.3624	1.5219	2.3162	0.9162
5.10	35.00	0.30	0.5228	0.2733	1.5440	2.3839	0.8072
5.15	37.70	0.35	0.4559	0.2078	1.5763	2.4847	0.7186
5.20	40.00	0.40	0.3979	0.1583	1.6020	2.5664	0.6374
5.25	42.15	0.45	0.3467	0.1202	1.6248	2.6400	0.5633
5.30	43.05	0.50	0.3010	0.0906	1.6339	2.6696	0.4918
5.35	45.10	0.55	0.2596	0.0673	1.6542	2.7364	0.4294
5.40	47.40	0.60	0.2218	0.0491	1.6757	2.8080	0.3717
5.45	50.05	0.65	0.1870	0.0349	1.6994	2.8880	0.3178
5.50	52.14	0.70	0.1549	0.0239	1.7171	2.9484	0.2660
5.55	54.35	0.75	0.1249	0.0156	1.7352	3.0109	0.2188
5.60	56.20	0.80	0.0969	0.0093	1.7497	3.0614	0.1695
5.65	58.30	0.85	0.0861	0.0074	1.7657	3.1177	0.1520
5.70	61.50	0.90	0.0457	0.0020	1.7889	3.2001	0.0817
5.75	65.00	0.95	0.0222	0.0005	1.8129	3.2866	0.0402
5.80	68.45	1.00	0.0000	0.0000	1.8353	3.3683	0.0000
5.85	70.25	1.05	0.0211	0.0004	1.8466	3.4100	0.0389
			4.5454	**1.9114**	**30.2607**	**51.0784**	**7.2528**

Accordingly, the value of constants are computed as follows,

$$\beta = \frac{N(\sum x.y) - (\sum x)(\sum y)}{N(\sum x^2) - (\sum x)^2}$$

Substituting the values of associated parameters in above formula for determining the value of β

$$\beta = \frac{18(7.2528 - 4.5454x30.2607)}{18(1.9114) - 4.5454^2} \quad = \frac{-2345.29}{13.7446}$$

$$= -170.63$$

And C_r is determined as under,

$$C = \frac{30.2607 + 170.63x4.5454}{18} = 44.77$$

Therefore, $C_r = Antilog\ 44.77$ =

Substituting the value of β and C_r in above formula, we have $\boldsymbol{Q = C_r(G - a)^{-170.63}}$ **Ans.**

Suggested Reference

59. Watershed Hydrology- R. Suresh
60. Soil & Water Conservation Engineering- R. Suresh
61. Hydrology and Soil Conservation – G. Das
62. Engineering Hydrology – K. Subramanya

Lecture- 19

Stream Flow and Reservoir Routing

Definitions

Flood routing is variously defined as follows:

- **Routing, flood-**The procedure that determines the timing and magnitude of a flood wave at a point on a stream from the known or assumed data at one or more points upstream (Chow 1964).
- **Routing, flow-**A mathematical procedure that predicts the changing magnitude, speed, and shape of a flood wave as a function of time at one or more points along a watercourse (Maidment 1993).
- **Routing, stream channel-** Mathematical relations that calculate outflow from a stream channel once inflow, lateral contributions, and channel characteristics are known (Ponce 1989). These definitions relate to flood routing in streams and rivers.
- **Routing, reservoir-** This procedure derives the outflow hydrograph from a reservoir from the inflow hydrograph into the reservoir with consideration of elevation, storage, and discharge characteristics of the reservoir and spillways. The conservation of mass equation is solved with the assumption that outflow discharge and volume of storage are directly related.

Basic Equations

The continuity equation is used in stream flow/flood routing, which states that the difference in the rate of inflow and outflow is equal to the rate of change in storage. Mathematically, it is expressed as under,

$$I - O = \frac{dS}{dt}$$

in which, I and O are the inflow and out flow rates, respectively and $\frac{dS}{dt}$ is the rate of change in storage. For a small routing time Δt the continuity equation is presented as under,

$$\left(\frac{I_1 + I_2}{2}\right)\Delta t - \left(\frac{O_1 + O_2}{2}\right)\Delta t = S_2 - S_1$$

The Δt should be very small so that the segment of hydrograph at the beginning and end of it should be a straight line. Differential form of continuity equation is given as under,

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

In which Q is the discharge rate, T is the top width of flow and y is the flow depth. This equation holds good for unsteady state condition provided the lateral flow should not be there.

Channel Flow Routing

In stream flow routing the outflow hydrograph is predicted with the help of known inflow hydrograph of a gauged station located at u/s side. In steam flow routing the following information are derived,

1. Attenuation , and
2. Time lag

Attenuation is the difference in the peaks of known inflow hydrograph and computed out flow hydrograph. It provides the information about the rising or lowering in rate of peak flow at d/s stream side , which could be utilized for flood forecasting. If attenuation is +ve, i.e. increasing over the u/s peak flow rate then there is possibility of occurrence of flood at d/s side, provided the capacity of stream section is not sufficient to accommodate the increased peak flow rate.

Time lag is difference in the time to peak of the known inflow hydrograph and computed out flow hydrograph. It is required to have the information about time of occurrence of peak flow rate at d/s side, which is utilized for providing the information about time of flood occurrence towards d/s side of the stream.

Stream Flow Routing Method

There are several techniques available for computing the stream flow routing. The most commonly used method is the Muskingum method. The name Muskingum was derived from the name of a watershed "Muskingum", for which this technique was developed.

This method considers the total storage of the stream or channel as the sum of two types of storages, i. e. 1. Prism storage and 2. Wedge storage.

Prism storage- It refers to that storage of the channel/stream flow which lies below an imaginary line drawn parallel to the channel/stream bed. This storage is the function of outflow, only, presented as under,

$$S_p = f(O)$$

In which S_p is the prism storage and O is the out flow of the stream.

Wedge storage- It is that part of channel storage which lies above the imaginary line drawn up to the top water surface. Wedge storage is the function of difference in inflow and out flow rates of the stream. It becomes less during falling stage, taken as –ve storage, while increased during rising stage, taken as +ve storage. Wedge storage is expressed as under,

$$S_w = f(I)$$

In this way, total channel storage (S)

$$S = S_p + S_w$$

Simplified form of this equation is as below,

$$S = K[xI^m + (1 - x)O^m]$$

In which, *K* is the storage constant (time) , *x* is the weighing factor , *I* and *O* are the inflow and outflow rates, respectively and *m* is the exponent; its value depends on type the channel. For natural channel the value of m is taken as 1.0 and for rectangular channel it is 0.6.

Since, Muskingum method is developed for natural channel; therefore using the value of m as 1.0, the above equation is reduced to

$$S = K[xI + (1 - x)O]$$

The value of K is normally very close to the travel time of channel reach. The value of weighing factor x varies from 0 to 0.3 (dimensionless) for natural channel. For linear channels the value of x is taken as 0. Accordingly, the storage equation (eq….) is given as,

$$S = KO$$

Problem (1)- *Calculate prism storage, wedge storage and total storage in a natural stream, if*

(i) Inflow rate is 25m³/s.
(ii) Outflow is 15m³/s
(iii) Storage constant is 0.45 day.
(iv) Weighing factor is 0.35.

Solution- The expressions for prism and wedge storage are outlined as under:

Prism storage- It is given as

$$S_p = K(1 - x)O^m$$

in which, K=0.45day;x = 0.35 and O is 15m³/s are given. For natural streams the value exponent m is taken as 1. Substituting these values in above formula and solving for S_p, we have,

$$S_p = 0.45(1 - 0.35)15^1$$

$= \mathbf{4.39}$ **m³. Ans.**

Similarly, wedge storage is given by the following expression.

$$S_w = K(xI^m)$$

in which, K = 0.45day; x = 0.35 and I= 25m³/s are given. For natural streams the value exponent m is taken as 1. Substituting these values in above formula and solving for S_w, we have,

$S_w = 0.45(0.35x\ 25^1) = \mathbf{3.94}$**m**^{3} Ans

Determining K and x

In equation – the values of x and K are unknown. These are determined by the following method summarized in the steps, given below,

1. Collect the inflow and outflow data for the channel, concern.
2. Compute the value of S for each time period on the basis of given inflow and outflow data.
3. Take an arbitrary value of x within the given range, i.e. 0 to 0.3.
4. Calculate the values of $[xI + (1 - x)O]$ for each time interval.
5. Plot the curve between S and $[xI + (1 - x)O]$ on a simple graph paper. If the obtained curve is straight line the selected value of x is assumed to be correct; otherwise, another x value is selected and process is repeated to obtain a straight line.
6. Find the value of K, which is the inverse slope of straight line, obtained in step (5).

Suggested Reference

63. Watershed Hydrology- R. Suresh
64. Soil & Water Conservation Engineering- R. Suresh
65. Hydrology and Soil Conservation – G. Das
66. Engineering Hydrology – K. Subramanya

Lecture-20

Routing Procedure

Muskingum method follows following steps for computing the steam/ channel flow routing,

1. Collect the time vs inflow data of the natural channel which routing is to be computed.
2. Determine the value of storage constant K and weighing factor x for the given channel.
3. Calculate the ordinate of outflow hydrograph, based on the given inflow data, K and x values. The ordinate of out flow hydrograph using in Muskingum method is computed by using the following formula,

$$O_2 = C_0 I_2 + C_1 I_1 + C_2 O_1$$

In which, O_2 is the ordinate of out flow hydrograph (out flow); I_1 and I_2 are the inflow rates at the beginning and end of the routing time Δt ,O_1 is the outflow rate at the beginning of routing time Δt , which is taken as the I_1 and C_0, C_1 & C_2 are the constants, computed by using the following formula,

$$C_0 = \frac{Kx + 0.5\Delta t}{K - Kx + 0.5\Delta t};\ C_1 = \frac{-Kx + 0.5\Delta t}{K - Kx + 0.5\Delta t}\ \text{and}\ C_2 = \frac{K - Kx - 0.5\Delta t}{K - Kx + 0.5\Delta t}$$

Condition, C0 +C1+ C2 =1

Example- shows the computation procedure.

Problem (1)-*Find the outflow against following observations by using Muskingum equation of channel routing,*

Time , hour	*0*	*6*
Inflow,m³/s	*30*	*40*

Take the value of storage constant (S) 12.0 hours and weighing factor (x) as 0.25.

Solution- Muskingum equation is given by the formula,

$$O_2 = C_0 I_2 + C_1 I_1 + C_2 O_1$$

in which, C_0, C_1 and C_2 are the constant; I_1 , I_2 and I_3 are the inflow rates; O_1 and O_2 are the outflow rates. The values of C_0, C_1 and C_2 are computed as under,

$$C_0 = \frac{K.x + 0.5\Delta t}{K - K.x + 0.5\Delta t};\ C_1 = \frac{-K.x + 0.5\Delta t}{K - K.x + 0.5\Delta t};\ \text{and}\ C_2 = \frac{K - K.x - 0.5\Delta t}{K - K.x + 0.5\Delta t}$$

Substituting the value of associated parameters in above equations and solving, we have,

$$C_0 = \frac{12x0.25 + 0.5x6}{12 - 12x0.25 + 0.5x6} = \frac{6.0}{12} = 0.50$$

$$C_1 = \frac{-12x0.25 + 0.5x6}{12 - 12\ x\ 0.25 + 0.5x6} = \frac{0}{12} = 0.0$$

$$C_2 = \frac{12 - 12x0.25 - 0.5x6}{12 - 12x0.25 + 0.5x\ 6} = \frac{6}{12} = 0.50$$

(Checking, $C_0 + C_1 + C_2 = 1.0$)

Substituting the values of $C_0, C_1 and\ C_2$ in above formula and solving,

$$O_2 = 0.5I_2 + 0xI_1 + 0.5O_1$$

$$O_2 = 0.5I_2 + 0.5O_1$$

Time , h	Inflow,m³/s	0.5 I_2	0.5O_1	$O_2 = 0.5I_2 + 0.5O_1$
	(1)	(2)	(3)	Col(1)+Col(2)+Col(3)
0	30	-	-	30 (at beginning the outflow is taken same to the inflow rate)
6	40	20	15	35

Thus, the computed outflow is obtained as **35.0m³/s Ans.**

Reservoir Routing

In Reservoir routing the effect of a flood wave entering a reservoir is studied. Knowing the volume-elevation characteristic of the reservoir and the outflow-elevation relationship for the spillways and other outlet structures in the reservoir, the effect of a flood wave entering the reservoir is studied to predict the variations of reservoir elevation and outflow discharge with time. This form of reservoir routing is essential (i) in the design of the capacity of spillways and other reservoir outlet structures, and (ii) in the location and sizing of the capacity of reservoirs to meet specific requirements.

Modified Pul's Method

Basic Equation $\left(\frac{I_1+I_2}{2}\right)\Delta t - \left(\frac{O_1+O_2}{2}\right)\Delta t = S_2 - S_1$

At the starting of flood routing, the initial storage and outflow discharges are known. Accordingly re-arranging this equation as under,

$$\left(\frac{I_1+I_2}{2}\right)\Delta t - \left(S_1 - \frac{O_1\Delta t}{2}\right)\Delta t = \left(S_2 + \frac{O_2\Delta t}{2}\right)$$

This method requires construction of only two curves, i.e.

(i) Storage (S) Curve, and

(ii) $S + \frac{O\Delta_t}{2}$ curve.

Routing is performed under following steps

Step (1) Using inflow hydrograph obtain the volume of water entering the reservoir in time intervalΔt, i.e., compute average inflow $\left(\frac{I_1+I_2}{2}\right)\Delta t$.

Step (2) From S curve obtain initial outflow and compute $\left(S_1 - \frac{O_1\Delta t}{2}\right)$.

Step (3) Add average inflow $\left(\frac{I_1+I_2}{2}\right)\Delta t$ and $\left(S_1 - \frac{O_1\Delta t}{2}\right)$ to find $\left(S_2 + \frac{O_2\Delta t}{2}\right)$

Step (4) Calculate the value of O_2 by using computed values $\left(S_2 + \frac{O_2\Delta t}{2}\right)$ from the $S + \frac{O\Delta_t}{2}$ curve

Step (5) Repeat the entire procedure to complete the routing.

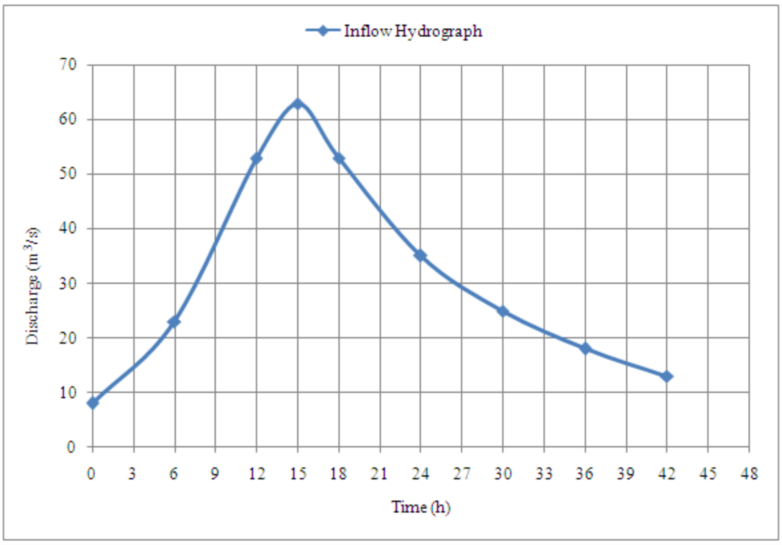
Problme (2). A small reservoir has the following storage elevation relationship

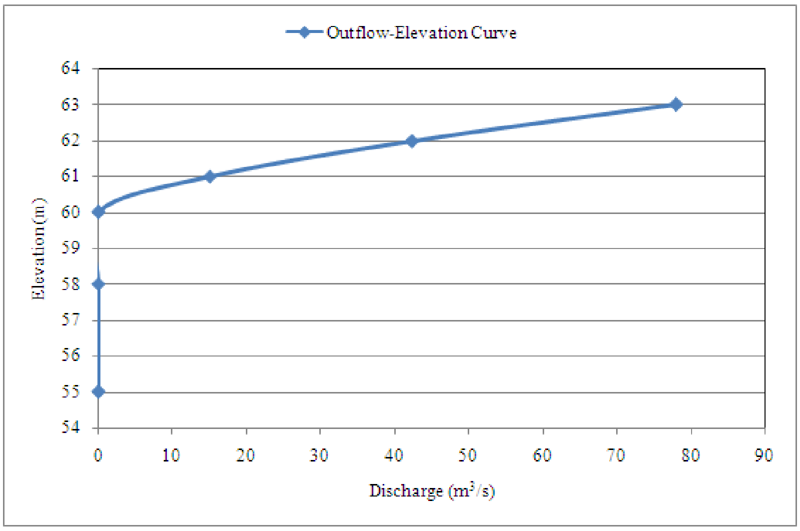
Elevation (m)	55.00	58.00	60.00	61.00	62.00	63.00
Storage (10^3 m^3)	250	650	1000	1250	1500	1800

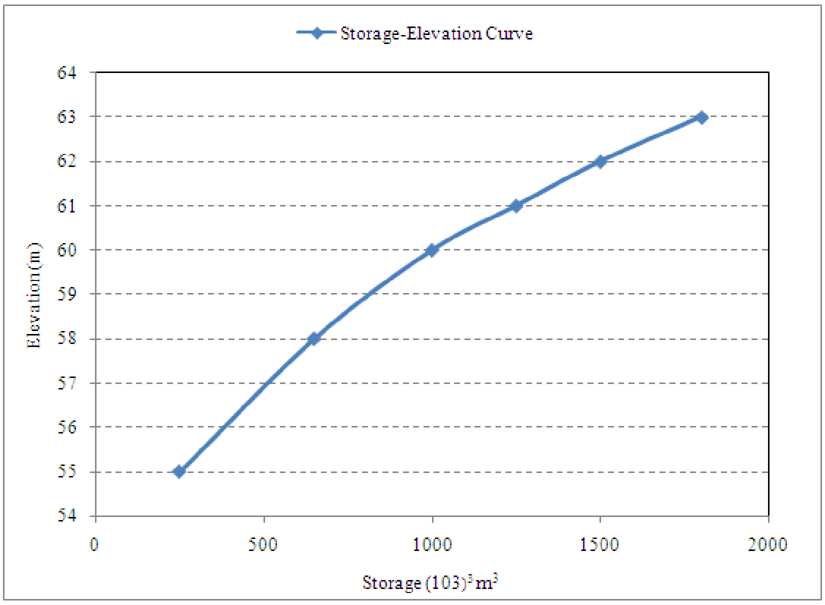
A spillway provided with its crest at elevation 60.00 m has the discharge relationship. $Q = 15H^{3/2}$, where H = head of water over the spillway crest.When the reservoir elevation is at 58.00 m a flood as given below enters the reservoir. Route the flood and determine the maximum reservoir elevation, peak outflow and attenuation of the flood peak using Modified Pul's method.

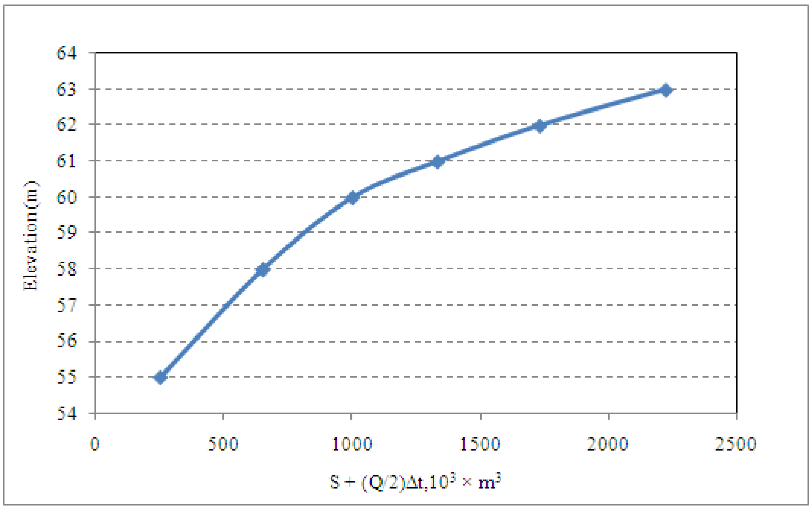
Time (h)	0	6	12	15	18	24	30	36	42
Inflow (m^3/s)	8	23	53	63	53	35	25	18	13

Solution


Inflow Hydrograph
Discharge (m^3/s)
70
60
50
40
30
20
10
0
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
48
Time (h)


Outflow-Elevation Curve
Elevation (m)
64
63
62
61
60
59
58
57
56
55
54
0
10
20
30
40
50
60
70
80
90
Discharge (m^3/s)


Storage-Elevation Curve
Elevation (m)
64
63
62
61
60
59
58
57
56
55
54
0
500
1000
1500
2000
Storage (103)^3 m^3



Routing period	I_1(m^3/s)	I_2(m^3/s)	$\left(\frac{I_1+I_2}{2}\right) \times 10^3\,\mathrm{m}^3$	Q_1(m^3/s)	$S_1 - \frac{Q_1}{2}\Delta t \times 10^3\,\mathrm{m}^3$	$S_2 + \frac{Q_2}{2}\Delta t \times 10^3\,\mathrm{m}^3$	Q_2(m^3/s)	Elevation at beginning (m)	Elevation at end (m)
0-3	8	14.5	121.5	0	650	771.5	0	58	58.6
3-6	14.5	23	202.5	0	771.5	974	0	58.6	59.8
6-9	23	38.5	332.1	0	974	1306.1	13	59.8	60.8
9-12	38.5	53	494.1	13	1165.7	1659.8	39	60.8	61.9
12-15	53	63	626.4	39	1238.6	1865	52.5	61.9	62.4
15-18	63	53	626.4	52.5	1298	1924.4	57	62.4	62.5
18-21	53	43	518.4	57	1308.8	1827.2	50.5	62.5	62.3
21-24	43	35	421.2	50.5	1281.8	1703	42	62.3	62
24-27	35	29	345.6	42	1249.4	1595	35	62	61.8
27-30	29	25	291.6	35	1217	1508.6	29	61.8	61.6
30-33	25	22	253.8	29	1195.4	1449.2	24	61.6	61.4
33-36	22	18	216	24	1190	1406	20.5	61.4	61.2
36-39	18	15	178.2	20.5	1184.6	1362.8	17	61.2	61.05
39-42	15	13	151.2	17	1179.2	1330.4	14	61.05	60.9

Suggested Reference

67. Watershed Hydrology- R. Suresh
68. Soil & Water Conservation Engineering- R. Suresh
69. Hydrology and Soil Conservation – G. Das
70. Engineering Hydrology – K. Subramanya