

Module 2

The Science of Surface and Ground Water

Lesson

3

Rainfall Runoff
Relationships

Instructional Objectives

At the end of this lesson, the student shall learn

1. How hydrograph varies with the catchment characteristics
2. How hydrograph varies with the rainfall characteristics
3. What is Unit Hydrograph, its assumptions and limitations
4. Application of the Unit Hydrograph to find the Direct Runoff Hydrograph
5. What is S – Curve and its applications
6. Derivation of the Unit Hydrograph for gauged catchments
7. How to estimate Unit Hydrograph for ungauged catchments
8. Conceptual and Physically based catchment rainfall – runoff models

2.3.0 Introduction

Lesson 2.2 it was explained what a hydrograph is and that it indicates the response of water flow of a given catchment to a rainfall input. It consists of flow from different phases of runoff, like the overland flow, interflow and base flow. Methods to separate base flow from the total stream flow hydrograph to obtain the direct runoff hydrograph as well as infiltration loss from the total rainfall hyetograph to determine the effective rainfall have been discussed. In this lesson, a relationship between the direct runoff hydrograph of a catchment observed at a location (the catchment outlet) and the effective rainfall over the catchment causing the runoff are proposed to be dealt with.

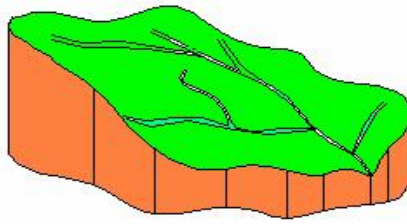
We start with discussing how the various aspects of a catchment's characteristics affects the shape of the hydrograph.

2.3.1 Hydrograph and the catchment's characteristics

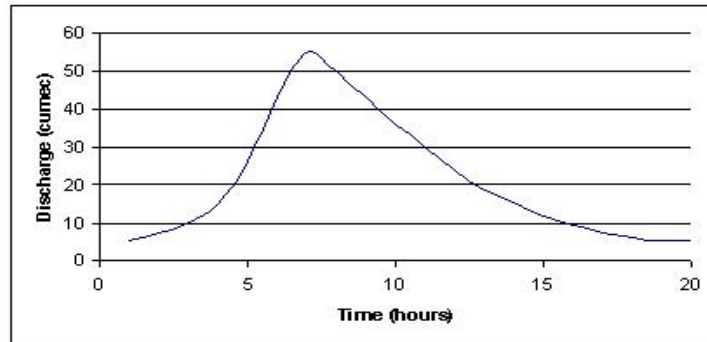
The shape of the hydrograph depends on the characteristics of the catchment. The major factors are listed below.

2.3.1.1 Shape of the catchment

A catchment that is shaped in the form of a pear, with the narrow end towards the upstream and the broader end nearer the catchment outlet (Figure 1a) shall have a hydrograph that is fast rising and has a rather concentrated high peak (Figure 1b).



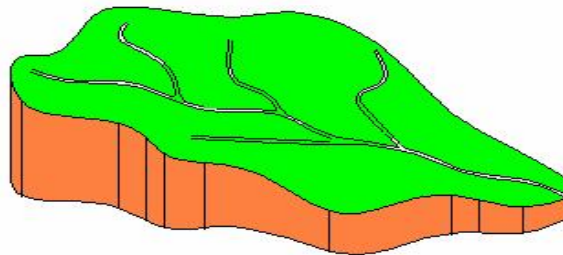
(a)



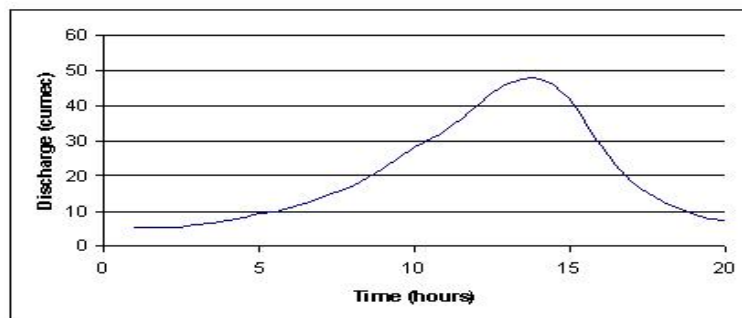
(b)

Figure 1. (a) Pear shaped catchment with narrow end towards upstream and blunt end towards outlet
(b) Corresponding hydrograph for a hypothetical rainfall

A catchment with the same area as in Figure 1 but shaped with its narrow end towards the outlet has a hydrograph that is slow rising and with a somewhat lower peak (Figure 2) for the same amount of rainfall.



(a)



(b)

FIGURE 2. (a) Catchment with narrow end towards outlet
(b) Corresponding hydrograph for a hypothetical rainfall

Though the volume of water that passes through the outlets of both the catchments is same (as areas and effective rainfall have been assumed same for both), the peak in case of the latter is **attenuated**.

2.3.1.2 Size of the catchment

Naturally, the volume of runoff expected for a given rainfall input would be proportional to the size of the catchment. But this apart, the response characteristics of large catchment (say, a large river basin) is found to be significantly different from a small catchment (like agricultural plot) due to the relative importance of the different phases of runoff (overland flow, inter flow, base flow, etc.) for these two catchments. Further, it can be shown from the mathematical calculations of surface runoff on two impervious catchments (like urban areas, where infiltration becomes negligible), that the non-linearity between rainfall and runoff becomes perceptible for smaller catchments.

2.3.1.3 Slope

Slope of the main stream cutting across the catchment and that of the valley sides or general land slope affects the shape of the hydrograph. Larger slopes generate more velocity than smaller slopes and hence can dispose off runoff faster. Hence, for smaller slopes, the balance between rainfall input and the runoff rate gets stored temporally over the area and is able to drain out gradually over time. Hence, for the same rainfall input to two catchments of the same area but with different slopes, the one with a steeper slope would generate a hydrograph with steeper rising and falling limits.

Here, two catchments are presented, both with the same area, but with different slopes. A similar amount of rainfall over the flatter catchment (Figure 3) produces a slow-rising moderated hydrograph than that produced by the steeper catchment (Figure 4).

2.3.2 Effect of rainfall intensity and duration on hydrograph

If the rainfall intensity is constant, then the rainfall duration determines in part the peak flow and time period of the surface runoff.

The concept of **Isochrones** might be helpful for explaining the effect of the duration of a uniform rainfall on the shape of hydrograph. Isochrones are imaginary lines across the catchment (see Figure 5) from where water particles traveling downward take the same time to reach the catchment outlet.

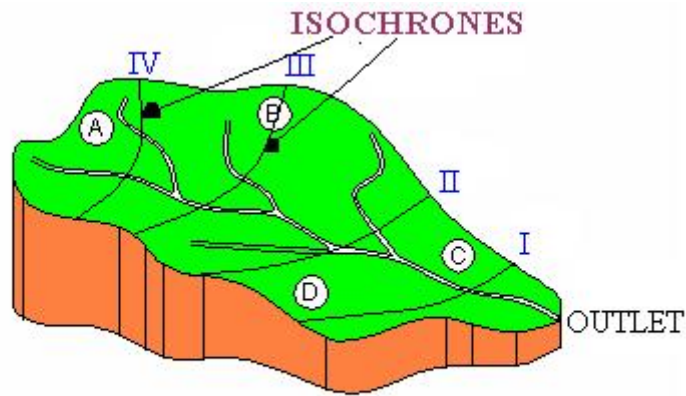


FIGURE 5. Typical isochrones over a catchment

If the rainfall event starts at time zero, then the hydrograph at the catchment outlet will go on rising and after a time ' Δt ', the flow from the isochrone I would have reached the catchment outlet. Thus, after a gap of time Δt , all the area A_1 contributes to the outflow hydrograph.

Continuing in this fashion, it can be concluded that after a lapse of time ' $4\Delta t$ ', all the catchment area would be contributing to the catchment outflow, provided the rain continues to fall for atleast up to a time $4\Delta t$. If rainfall continues further, then the hydrograph would not increase further and thus would reach a plateau.

2.3.3 Effect of spatial distribution of rainfall on hydrograph

The effect of spatial distribution of rainfall, that is, the distribution in space, may be explained with the catchment image showing the isochrones as in Figure 6. Assume that the regions between the isochrones receive different amounts of rainfall (shown by the different shades of blue in the figure).

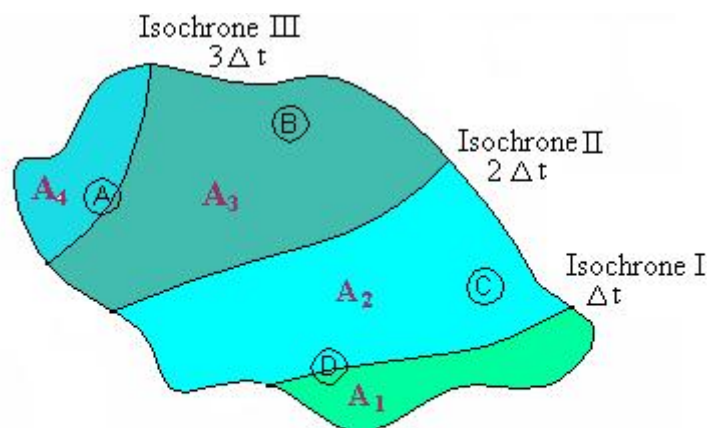


FIGURE 6. Areas of catchment subjected to different amounts of rainfall

If it is assumed now that only area A_1 receives rainfall but the other areas do not, then since this region is nearest to the catchment outlet, the resulting hydrograph immediately rises. If the rainfall continues for a time more than ' Δt ', then the hydrograph would reach a saturation equal to $r_e \cdot A_1$, where r_e is the intensity of the effective rainfall.

Assume now that a rainfall of constant intensity is falling only within area A_4 , which is farthest from the catchment outlet. Since the lower boundary of A_4 is the Isochrone III, there would be no resulting hydrograph till time ' $3\Delta t$ '.

If the rain continues beyond a time ' $4\Delta t$ ', then the hydrograph would reach a saturation level equal to $r_e \cdot A_4$ where r_e is the effective rainfall intensity.

2.3.4 Direction of storm movement

The direction of the storm movement with respect to the orientation of the catchments drainage network affects both the magnitude of peak flow and the duration of the hydrograph. The storm direction has the greatest effect on elongated catchments, where storms moving upstream tend to produce lower peaks and broader time base of surface runoff than storms that move downstream towards the catchment outlet. This is due to the fact that for an upstream moving storm, by the time the contribution from the upper catchment reaches the outlet, there is almost no contribution from the lower watershed.

2.3.5 Rainfall intensity

Increase in rainfall intensity increases the peak discharge and volume of runoff for a given infiltration rate. In the initial phases of the storm, when the soil is dry, a rainfall intensity less than infiltration rate produces no surface runoff. Gradually, as the rain progresses, the soil saturates and the infiltration rate reduces to a steady rate.

The relation between rainfall intensity and the discharge, strictly speaking, is not linear, which means that doubling the rainfall intensity does not produce a doubling of the hydrograph peak value. However, this phenomenon is more pronounced for small watersheds, such as an urban area. However in the catchment scale, due to the uncertainty of all the hydrological parameters, it might be assumed that the rainfall runoff relation follows a linear relationship. This assumption is made use of in the unit hydrograph concept, which is explained in the next section.

2.3.6 The Unit Hydrograph

The Unit Hydrograph (abbreviated as UH) of a drainage basin is defined as a hydrograph of direct runoff resulting from one unit of effective rainfall which is uniformly distributed over the basin at a uniform rate during the specified period of time known as unit time or unit duration. The unit quantity of effective rainfall is generally taken as 1mm or 1cm and the outflow hydrograph is expressed by the discharge ordinates. The unit duration may be 1 hour, 2 hour, 3 hours or so depending upon the size of the catchment and storm characteristics. However, the unit duration cannot be more than the time of concentration, which is the time that is taken by the water from the furthest point of the catchment to reach the outlet.

Figure 7 shows a typical unit hydrograph.

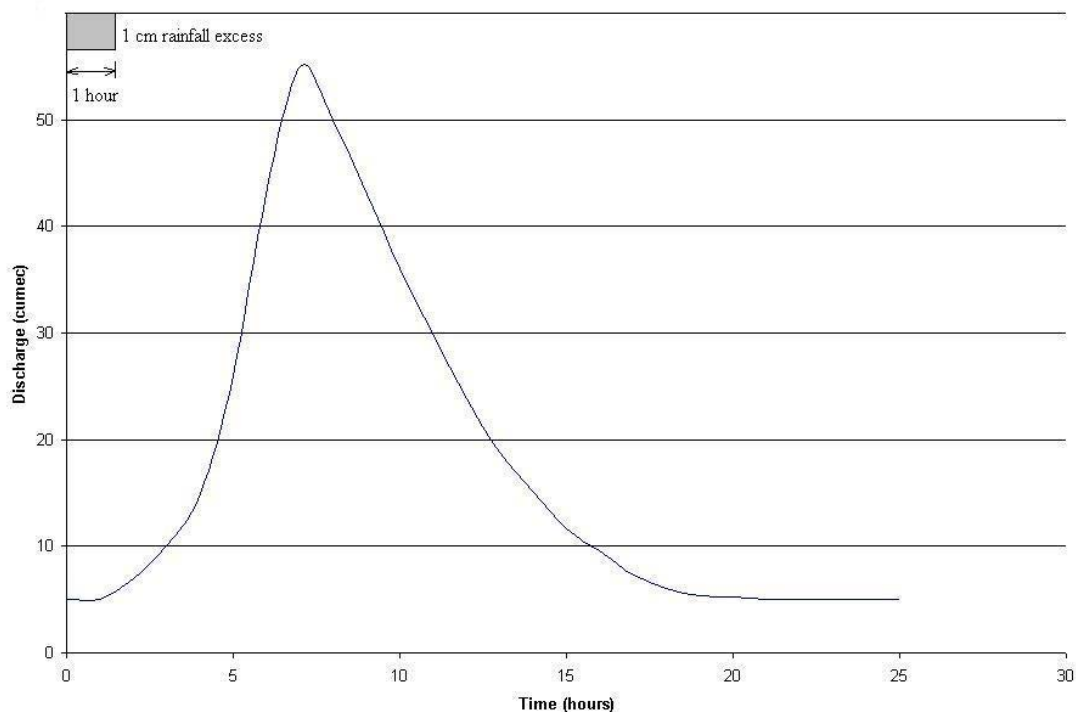


FIGURE 7. A typical unit hydrograph

2.3.6.1 Unit hydrograph assumptions

The following assumptions are made while using the unit hydrograph principle:

1. Effective rainfall should be uniformly distributed over the basin, that is, if there are 'N' rain gauges spread uniformly over the basin, then all the gauges should record almost same amount of rainfall during the specified time.
2. Effective rainfall is constant over the catchment during the unit time.

3. The direct runoff hydrograph for a given effective rainfall for a catchment is always the same irrespective of when it occurs. Hence, any previous rainfall event is not considered. This antecedent precipitation is otherwise important because of its effect on soil-infiltration rate, depression and detention storage, and hence, on the resultant hydrograph.

4. The ordinates of the unit hydrograph are directly proportional to the effective rainfall hyetograph ordinate. Hence, if a 6-h unit hydrograph due to 1 cm rainfall is given, then a 6-h hydrograph due to 2 cm rainfall would just mean doubling the unit hydrograph ordinates. Hence, the base of the resulting hydrograph (from the start or rise up to the time when discharge becomes zero) also remains the same.

2.3.6.2 Unit hydrograph limitations

Under the natural conditions of rainfall over drainage basins, the assumptions of the unit hydrograph cannot be satisfied perfectly. However, when the hydrologic data used in the unit hydrograph analysis are carefully selected so that they meet the assumptions closely, the results obtained by the unit hydrograph theory have been found acceptable for all practical purposes.

In theory, the principle of unit hydrograph is applicable to a basin of any size. However, in practice, to meet the basic assumption in the derivation of the unit hydrograph as closely as possible, it is essential to use storms which are uniformly distributed over the basin and producing rainfall excess at uniform rate. Such storms rarely occur over large areas. The size of the catchment is, therefore, limited although detention, valley storage, and infiltration all tend to minimize the effect of rainfall variability. The limit is generally considered to be about 5000 sq. km. beyond which the reliability of the unit hydrograph method diminishes. When the basin area exceeds this limit, it has to be divided into sub-basins and the unit hydrograph is developed for each sub-basin. The flood discharge at the basin outlet is then estimated by combining the sub-basin floods, using **flood routing** procedures.

Note:

Flood Routing: This term is used to denote the computation principles for estimating the values of flood discharge with time and in space, that is, along the length of a river. Details about flood routing procedures may be had from the following book:

M H Chaudhry (1993) Open channel hydraulics, Prentice Hall of India

2.3.7 Application of the unit hydrograph

Calculations of direct runoff hydrograph in catchment due to a given rainfall event (with recorded rainfall values), is easy if a unit hydrograph is readily available. Remember that a unit hydrograph is constructed for a unit rainfall falling for a certain T-hours, where T may be any conveniently chosen time duration. The effective rainfall hyetograph, for which the runoff is to be calculated using the unit hydrograph, is obtained by deducting initial and

infiltration losses from the recorded rainfall. This effective rainfall hyetograph is divided into blocks of T-hour duration. The runoff generated by the effective rainfall for each T-hour duration is then obtained and summed up to produce the runoff due to the total duration.

2.3.8 Direct runoff calculations using unit hydrograph

Assume that a 6-hour unit hydrograph (UH) of a catchment has been derived, whose ordinates are given in the following table and a corresponding graphical representation is shown in Figure 8.

Time (hours)	Discharge (m ³ /s)
0	0
6	5
12	15
18	50
24	120
30	201
36	173
42	130
48	97
54	66
60	40
66	21
72	9
78	3.5
84	2

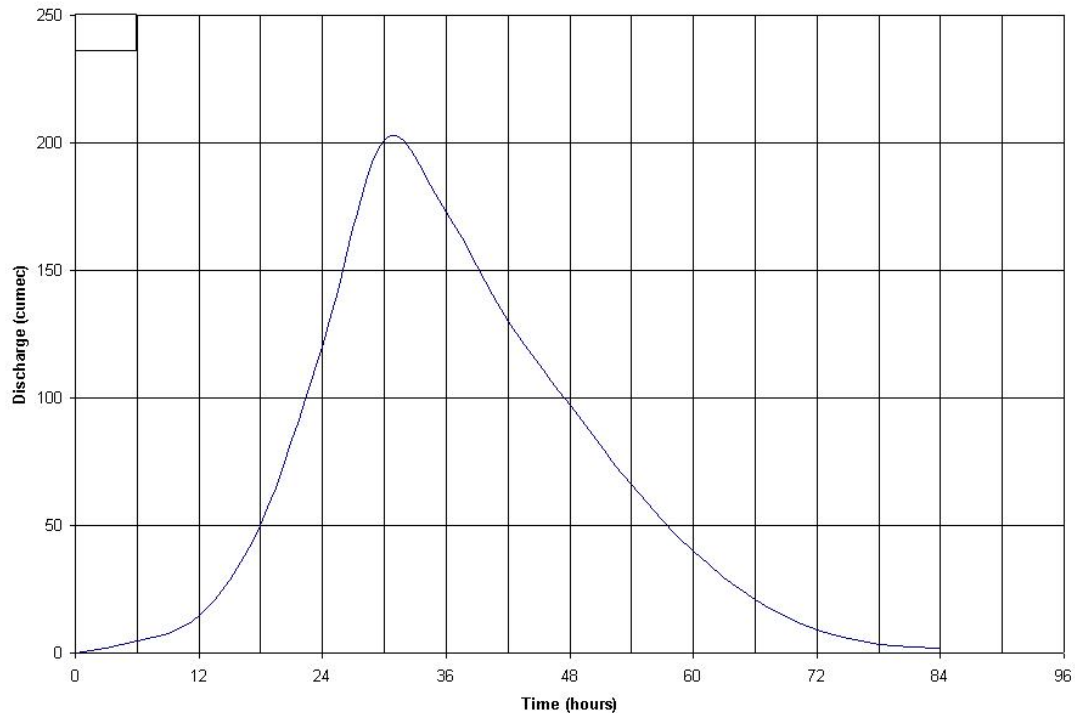


FIGURE 8. A 6-hour unit hydrograph

Assume further that the effective rainfall hyetograph (ERH) for a given storm on the region has been given as in the following table:

Time (hours)	Effective Rainfall (cm)
0	0
6	2
12	4
18	3

This means that in the first 6 hours, 2cm excess rainfall has been recorded, 4cm in the next 6 hours, and 3cm in the next.

The direct runoff hydrograph can then be calculated by the three separate hyetographs for the three excess rainfalls by multiplying the ordinates of the hydrograph by the corresponding rainfall amounts. Since the rainfalls of 2cm, 4cm and 3cm occur in successive 6-hour intervals, the derived DRH corresponding to each rainfall is delayed by 6 hours appropriately.

These have been shown in the figures indicated.

DRH for 2cm excess rainfall in 0-6 hours

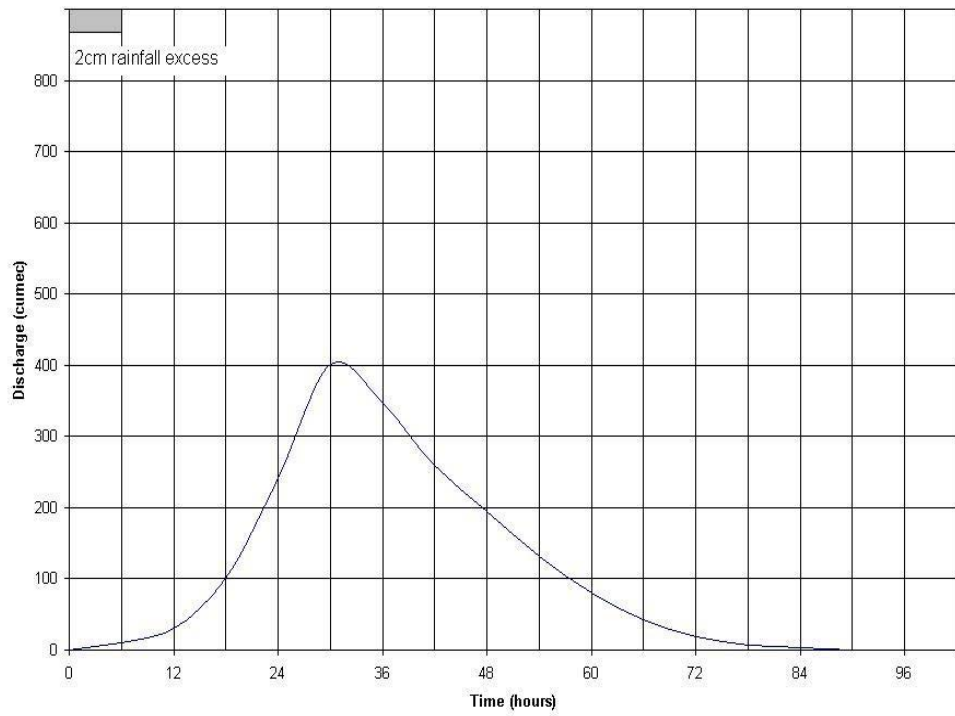


FIGURE 9. DRH corresponding to 2cm excess rainfall in 0 - 6 hours

DRH for 4cm excess rainfall in 6-12 hours

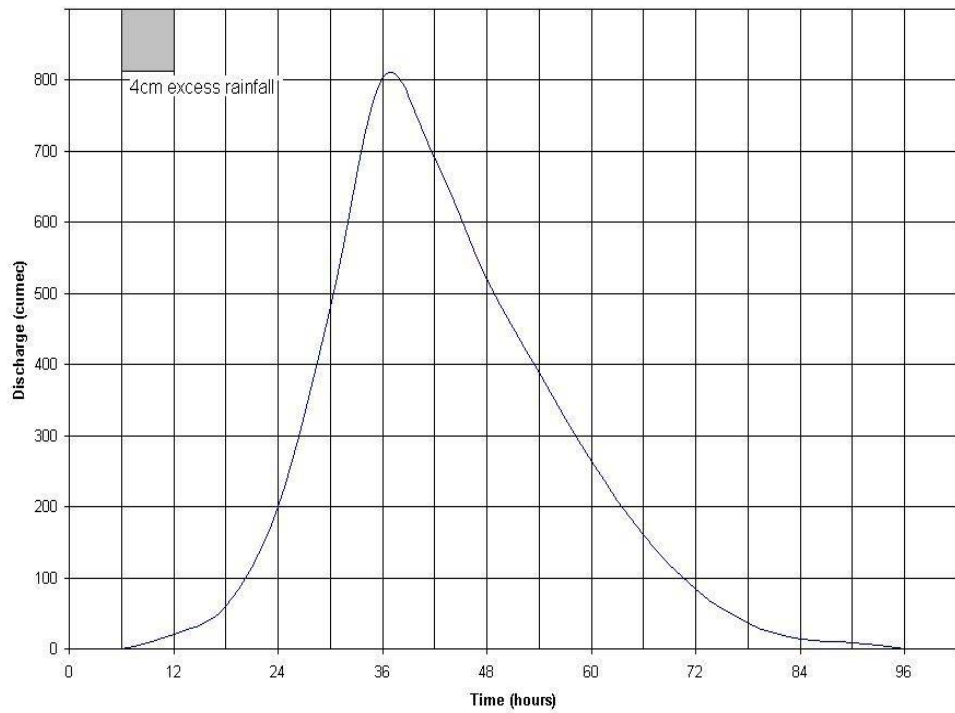


FIGURE 10. DRH corresponding to 4cm excess rainfall during 6 - 12 hours

DRH for 3cm excess rainfall in 12-18 hours

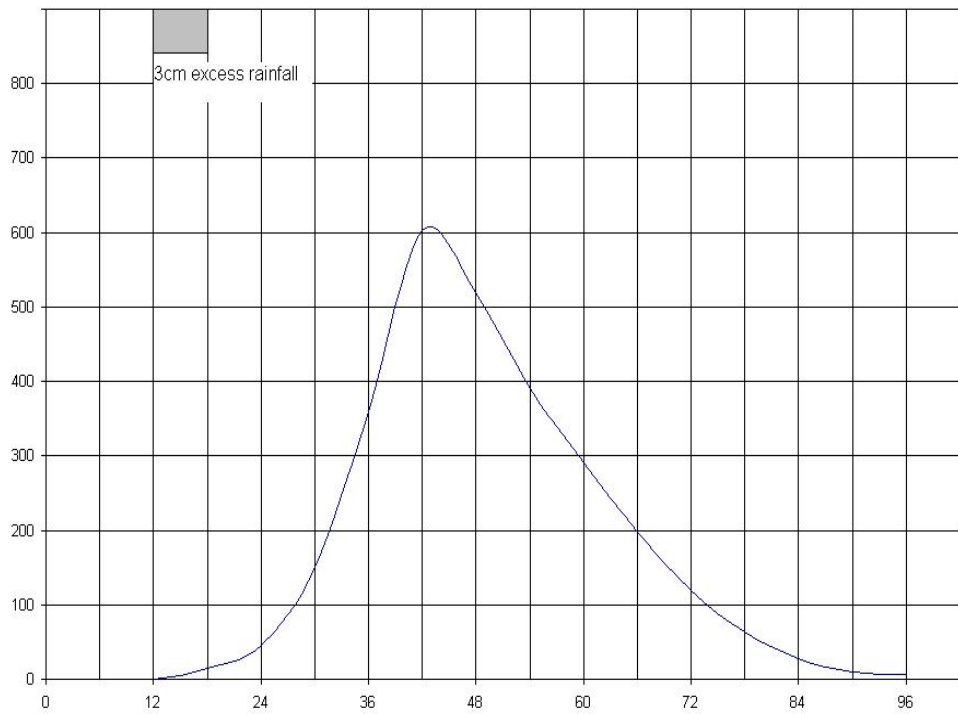


FIGURE 11. DRH corresponding to 3cm excess rainfall during 12 - 18 hours

The final hydrograph is found out by adding the three individual hydrographs, as shown in Figure 12.

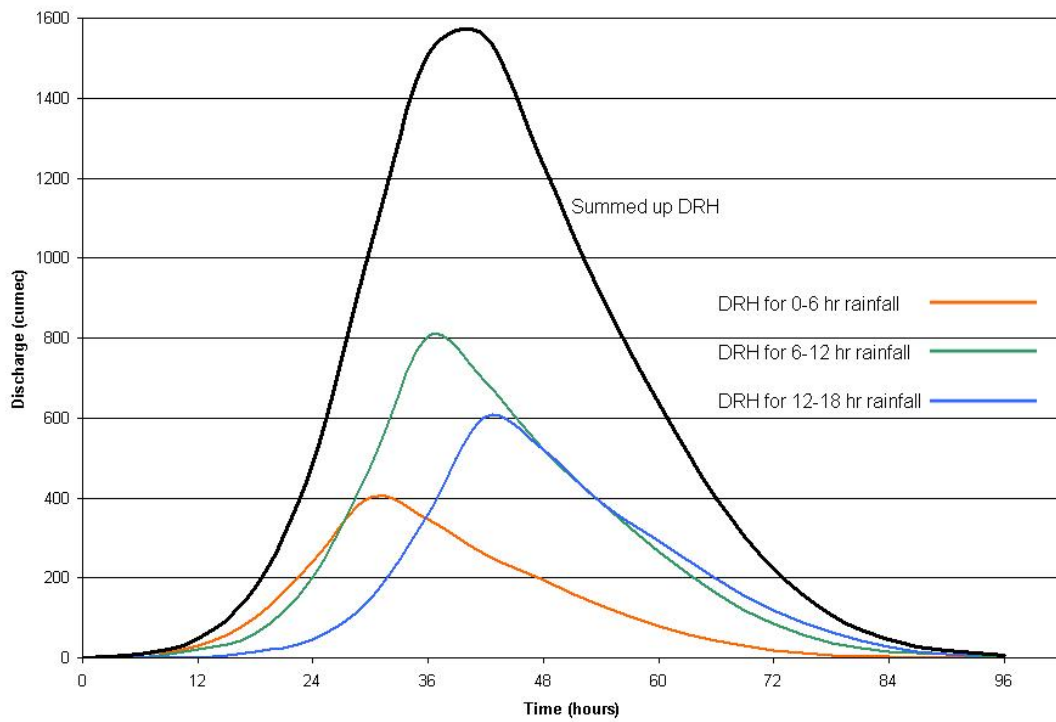


FIGURE 12. Final direct runoff hydrograph derived from summation of individual DRHs

The calculations to generate the direct runoff hydrograph (DRH) from a given UH and ERH can be conveniently done using a spreadsheet program, like the Microsoft XL.

A sample calculation for the example solved graphically is given in the following table. Note the 6 hour shift of the DRHs in the second and subsequent hours.

Time (hours)	Unit Hydrograph ordinates (m^3/s)	Direct runoff due to 2 cm excess rainfall in first 6 hours (m^3/s) (I)	Direct runoff due to 4 cm excess rainfall in second 6 hours (m^3/s) (II)	Direct runoff due to 3 cm excess rainfall in third 6 hours (m^3/s) (III)	Direct runoff Hydrograph (m^3/s) (I)+(II)+(III)
0	0	0	0	0	0
6	5	10	0	0	10
12	15	30	20	0	50
18	50	100	60	15	175
24	120	240	200	45	485
30	201	402	480	150	1032
36	173	346	804	360	1510
42	130	260	692	603	1555
48	97	194	520	519	1233
54	66	132	388	390	910
60	40	80	264	291	635
66	21	42	160	198	400
72	9	18	84	120	222
78	3.5	7	36	63	106
84	2	4	14	27	45
90		0	8	10.5	18.5
96		0	0	6	6

The last column in the above table gives the ordinates of the DRH produced by the ERH. If the base flow is known or estimated (Lesson 2.2), then this should be added to the DRH to obtain the 6-hourly ordinates of the flood hydrograph.

2.3.9 The S – curve

This is a concept of the application of a hypothetical storm of 1 cm ERH of infinite duration spread over the entire catchment uniformly. This may be done by shifting the UH by the T-duration for a large number of periods. The

resulting hydrograph (a typical one is shown in Figure 13) is called the S – hydrograph, or the S – curve due to the summation of an infinite series of T – hour unit hydrographs spaced T – hour apart. For the example of the UH given in the earlier section, the table below provides the necessary calculations.

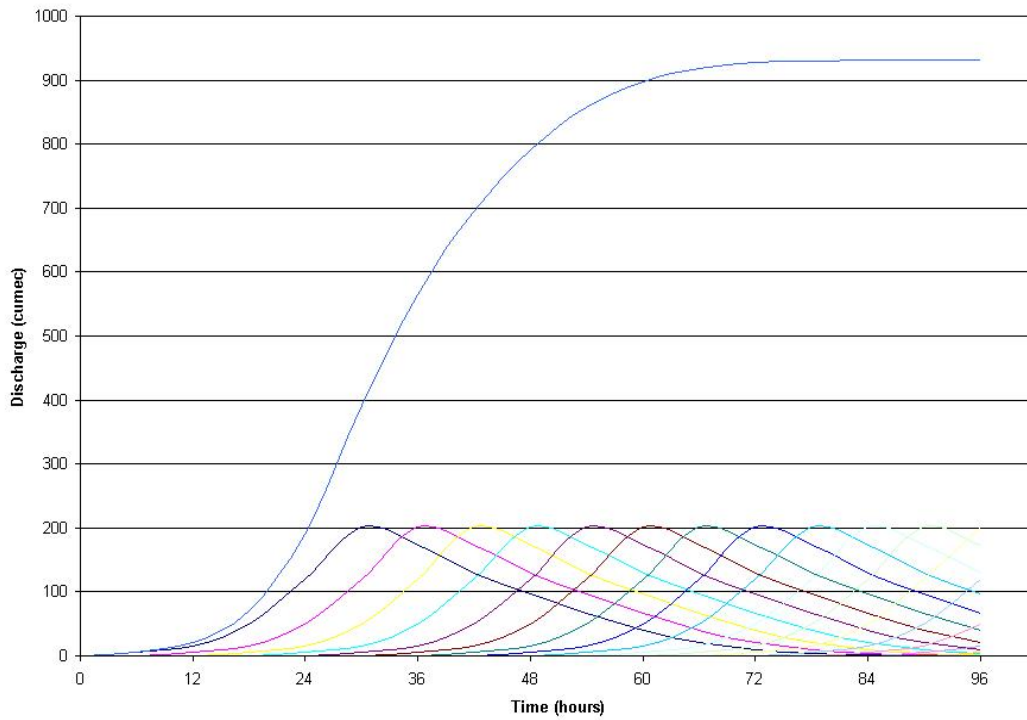


FIGURE 13. S - Curve, or Summed up Unit Hydrographs

Time (hr)	UH Ord-Nates	UH Ord-nates shifted by 6 hr	UH Ord-nates shifted by 12 hr	UH Ord-nates shifted by 18 hr	UH Ord-nates shifted by 24 hr	...	...	...	...	...	...	...	...	...	...	...	Sum of all the UH ord-nates
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
12	15	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20
18	50	15	5	0	0	0	0	0	0	0	0	0	0	0	0	0	70
24	120	50	15	5	0	0	0	0	0	0	0	0	0	0	0	0	190
30	201	120	50	15	5	0	0	0	0	0	0	0	0	0	0	0	391
36	173	201	120	50	15	5	0	0	0	0	0	0	0	0	0	0	564
42	130	173	201	120	50	15	5	0	0	0	0	0	0	0	0	0	694
48	97	130	173	201	120	50	15	5	0	0	0	0	0	0	0	0	791
54	66	97	130	173	201	120	50	15	5	0	0	0	0	0	0	0	857
60	40	66	97	130	173	201	120	50	15	5	0	0	0	0	0	0	897
66	21	40	66	97	130	173	201	120	50	15	5	0	0	0	0	0	918
72	9	21	40	66	97	130	173	201	120	50	15	5	0	0	0	0	927
78	3.5	9	21	40	66	97	130	173	201	120	50	15	5	0	0	0	930.5
84	2	3.5	9	21	40	66	97	130	173	201	120	50	15	5	0	0	932.5
90	0	2	3.5	9	21	40	66	97	130	173	201	120	50	15	5	0	932.5
96	0	0	2	3.5	9	21	40	66	97	130	173	201	120	50	15	5	932.5

The average intensity of the effective rainfall producing the S – curve is $1/T$ (mm/h) and the equilibrium discharge is given as $(\frac{A}{T} \times 10^4) m^3 / h$ where, A is the area of the catchment in Km^2 and T is the unit hydrograph duration in hours.

2.3.10 Application of the S – curve

Though the **S – curve** is a theoretical concept, it is an effective tool to derive a **t – hour** UH from a **T – hour** UH, when **t** is smaller than T or **t** is larger than T but not an exact multiple of T. In case **t** is a multiple of T, the corresponding UH can be obtained without the aid of a S – hydrograph by summing up the required number of UH, lagged behind by consecutive T – hours.

For all other cases shift the original S – hydrograph as derived for the T – hour UH by **t** hours to obtain a lagged S- hydrograph. Subtract the ordinates of the second curve from the first to obtain the **t – hour** graph. Next, scale the ordinates of the discharge hydrograph by a factor t/T , to obtain the actual **t – hour** UH which would result due to a total 1 cm of rainfall over the catchment. This is illustrated by the S-curve derived in the previous section.

Recall that the S-curve was obtained from a 6-hour UH. Let us derive the UH for a 3-hour duration. Since we do not know the ordinates of the S-curve at every 3-hour interval, we interpolate and write them in a tabular form as given in the table below:

Time	S-curve ordinates as derived from 6-hr UH (I)	S-curve ordinates as derived from 6-hr UH but with interpolated values (II)	S-curve ordinates as derived from 6-hr UH lagged by 3 hrs. (III)	Difference of the two S-curves (II) – (III) (IV)	3-hr UH ordinates Col. (IV) divided by (3hr/6hr) = (IV)*2
(hours)	(m^3/s)	(m^3/s)	(m^3/s)	(m^3/s)	(m^3/s)
0	0	0		0	
3		2.5	0	2.5	
6	5	5	2.5	2.5	
9		12.5	5	7.5	
12	20	20	12.5	7.5	
15		45	20	25	
18	70	70	45	25	
21		130	70	60	
24	190	190	130	60	
27		290.5	190	100.5	
30	391	391	290.5	100.5	

33		477.5	391	86.5	
36	564	564	477.5	86.5	
39		629	564	65	
42	694	694	629	65	
45		742.5	694	48.5	
48	791	791	742.5	48.5	
51		824	791	33	
54	857	857	824	33	
57		877	857	20	
60	897	897	877	20	
63		907.5	897	10.5	
66	918	918	907.5	10.5	
69		922.5	918	4.5	
72	927	927	922.5	4.5	
75		928.75	927	1.75	
78	930.5	930.5	928.75	1.75	
81		931.35	930.5	0.85	
84	932.5	932.5	931.35	1.15	
87		932.5	932.5	0	
90	932.5	932.5	932.5	0	
93		932.5	932.5	0	
96	932.5	932.5	932.5	0	

2.3.11 Derivation of unit hydrograph

An observed flood hydrograph at a streamflow gauging station could be a hydrograph resulting from an isolated intense short – duration storm of nearly uniform distribution in time and space, or it could be due to a complex rainfall event of varying intensities. In the former case, the observed hydrograph would mostly be single peaked whereas for the latter, the hydrograph could be multi peaked depending on the variation in the rainfall intensities. For the purpose of this course, we shall only consider rainfall to be more or less uniformly distributed in time and space for the purpose of demonstrating the derivation of unit hydrograph. The procedure may be broadly divided into the following steps:

1. Obtain as many rainfall records as possible for the study area to ensure that the amount and distribution of rainfall over the watershed is accurately known. Only those storms which are isolated events and with uniform spatial and temporal distribution are selected along with the observed hydrograph at the watershed outlet point.
2. Storms meeting the following criteria are generally preferred and selected out of the uniform storms data collected in Step 1.
3. Storms with rainfall duration of around 20 to 30 % of **basin lag**,
4. Storms having rainfall excess between 1 cm and 4.5 cm.

5. From the observed total flood hydrograph for each storm separate the base flow (discussed in lecture 2.2) and plot the direct runoff hydrograph.
6. Measure the total volume of water that has passed the flow measuring point by finding the area under the DRH curve. Since area of the watershed under consideration is known, calculate the average uniform rainfall depth that produced the DRH by dividing the volume of flow (step 3) by the catchment area. This gives the effective rainfall (ER) corresponding to the storm. This procedure has to be repeated for each selected storm to obtain the respective ERs.
7. Express the hydrograph ordinate for each storm at T – hour is the duration of rainfall even. Divide each ordinate of the hydrograph by the respective storm ER to obtain the UH corresponding to each storm.
8. All UHs obtained from different storm events should be brought to the same duration by the S – curve method.
9. The final UH of specific duration is obtained by averaging the ordinates of the different UH obtained from step 6.

2.3.12 Unit hydrograph for ungauged catchments

For catchments with insufficient rainfall or corresponding concurrent runoff data, it is necessary to develop synthetic unit hydrograph. These are unit hydrographs constructed from basin characteristics. A number of methods like that of Snyder's had been used for the derivation of the Synthetic hydrographs. However, the present recommendations of the Central Water Commission discourage the use of the Snyder's method.

Instead, the Commission recommends the use of the Flood Estimation Reports brought out for the various **sub-zones** in deriving the unit hydrograph for the region. These sub-zones have been demarcated on the basis of similar hydro – meteorological conditions and a list of the basins may be found. The design flood is estimated by application of the design storm rainfall to the synthetic hydrograph developed by the methods outlined in the reports.

2.3.13 Catchment modelling

With the availability of personal computer high processing speed within easy reach of all, it is natural that efforts have been directed towards numerical modeling the catchment dynamics and its simulation. It is not possible to outline each model in detail, but the general concept followed is to represent each physical process by a conceptual mathematical model which can be represented by an equivalent differential or ordinary equation. These

equations are solved by changing the equations to solvable form and writing algorithms in suitable computer language. However, the user of the programs generally input data through a **Graphical User Interface** (GUI) since there is a lot of spatial information to be included like land-use, land-cover, soil property, etc. Now a day, this information interaction between the user and the computer is through **Geographic Information System** (GIS) software. Once the information is processed, the output results are also displayed graphically. A list of notable conceptual models may be found in the following websites:

- <http://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6656/cr6656.pdf>
- www.hydrocomp.com/simoverview.html
- http://www.ems-i.com/gmshelp/numerical_models/modflow/modflow_conceptual_model/the_conceptual_model_approach.htm

2.3.14 Examples of catchment models

Though many of these models are sold commercially, there are quite a few developed by academic institutions and government agencies worldwide which are free and can be downloaded for non – commercial purposes through the internet. A few examples are given below.

- US Army corps of Engineers' **HEC-HMS** and **HEC-GeoHMS**
- US Army corps of Engineers' **GRASS**
- US Army corps of Engineers' **TOPMODEL**

Water resources section of the Department of Civil Engineering, IIT Kharagpur has developed a watershed simulation model based on deterministic theory. A copy of the same may be made available on request for educational purposes.

2.3.15 Important terms

1. Linearity: A linear relation between rainfall and runoff from a catchment suggests that variations in rainfall over a catchment is related to the variations in runoff from the outlet of the catchment by a linear function.

2. Basin lag: Basin lag is the time between the peak flow and the centroid of rainfall.

3. Graphical User Interface (GUI): An interface that represents programs, files, and options with graphical images is called GUI. These images can include icons, menus, and dialog boxes. The user selects and activates these options by pointing and clicking with a mouse or with the keyboard. A

particular GUI item (for example, a scroll bar) works the same way in all applications.

4. Geographic Information System (GIS): A system, usually computer based, for the input, storage, retrieval, analysis and display of interpreted geographic data. The database is typically composed of map-like spatial representations, often called coverages or layers. These layers may involve a three dimensional matrix of time, location, and attribute or activity. A GIS may include digital line graph (DLG) data, Digital Elevation Models (DEM), geographic names, land-use characterizations, land ownership, land cover, registered satellite and/or areal photography along with any other associated or derived geographic data.

5. HEC-HMS: The Hydrologic Modeling System (HEC-HMS) is designed to simulate the precipitation-runoff processes of dendritic watershed systems. It is designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems. This includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff. Hydrographs produced by the program are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation.

6. HEC-GeoHMS: The Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) is a public-domain software package for use with the ArcView Geographic Information System. GeoHMS uses ArcView and Spatial Analyst to develop a number of hydrologic modeling inputs. Analyzing the digital terrain information, HEC-GeoHMS transforms the drainage paths and watershed boundaries into a hydrologic data structure that represents the watershed response to precipitation. In addition to the hydrologic data structure, capabilities include the development of grid-based data for linear quasi-distributed runoff transformation (ModClark), HEC-HMS basin model, physical watershed and stream characteristics, and background map file.

7. GRASS: GRASS is an integrated set of programs designed to provide digitizing, image processing, map production, and geographic information system capabilities to its users. GRASS is open software with freely available source code written in C.

8 Topmodel: TOPMODEL predicts catchment water discharge and spatial soil water saturation pattern based on precipitation and evapotranspiration time series and topographic information.

References

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- Mutreja, K N (1995) Applied Hydrology, Tata Mc Graw Hill