

Basics of Surface Water Hydrology

Sharad K Jain

Scientist G

National Institute of Hydrology

Roorkee 247667, India

s_k_jain@yahoo.com

The term 'watershed' or 'catchment' represents an area falling between ridges that separate water flowing to different river basins. Ridges of a catchment divide and direct water to a particular river or water body. Thus the two terms, watershed and catchment, convey the same meaning; the use of term watershed is more common in North America, and in the UK and the commonwealth countries the term 'catchment' is more common. Another term that is used synonymously is 'drainage basin' but the term 'basin' is commonly used for a large catchment. A watershed or a catchment is the basic geographical unit within which the hydrological processes take place and are studied by hydrologists. However, groundwater may flow across the boundaries of a catchment.

A catchment can be exoreic which means that its water outflows to a major ocean. Examples include the Mississippi River basin and the Amazon River basin. We also have endorheic basins whose water does not flow to an ocean. These are found mostly in arid areas and the main river may end up in a desert or marsh, etc. Examples of such basins are the Luni River basin in India and the Okavango River basin in Africa.

1.0 Delineation of Catchments

In earlier times and still in many cases, delineation of catchment areas was performed manually by the use of topographic maps showing contours. Beginning from the specified outlet of the catchment, look around and mark the high hills which can be identified by small close contours. Then, a curve is drawn by moving the pen in the upstream direction such that the curve cuts the contour lines at right angles. Fig. 1 shows a contour map and the catchment boundaries drawn on it. Point X in the lower left corner is the catchment outlet.

A Digital Elevation Model (DEM) is a 3-dimensional representation of the earth surface. Commonly data required for preparing a DEM is acquired by remote sensing. These days the common sources of DEM data are Shuttle Radar Topography Mission (SRTM), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Cartosat satellites from India, etc. DEM data from SRTM, ASTER and many other sources are freely available but they have coarse resolutions. Higher resolution DEM data can be purchased commercially. For most hydrological applications, public domain data suffice.

Commonly used Geographical Information Systems (GIS) software packages, such as the ArcGIS (developed by Environmental Systems Research Institute or ESRI, USA) and the Geographical Resources Analysis Support System (GRASS) system, have tools to automatically demarcate the catchment area. To do this, depressions are to be removed from the DEM. A depression is formed when a group of raster cells in a DEM is completely surrounded by cells of higher elevations. The catchment delineation algorithm is trapped in depressions, since it cannot identify a flow direction out of the depression. Hence, it is necessary to remove the depressions before using the DEM for catchment delineation. There are many ways of doing this, e.g., by increasing the elevation of the cells forming a depression such that there is a flow direction for water to move out. GIS software, such as ArcGIS, have built-in tools ('Spatial Analysis Toolbox' → 'Hydrology toolset' → 'Watershed') to remove depressions. In addition to catchment delineation, GIS software can also delineate

the river channel network from the DEM data products.

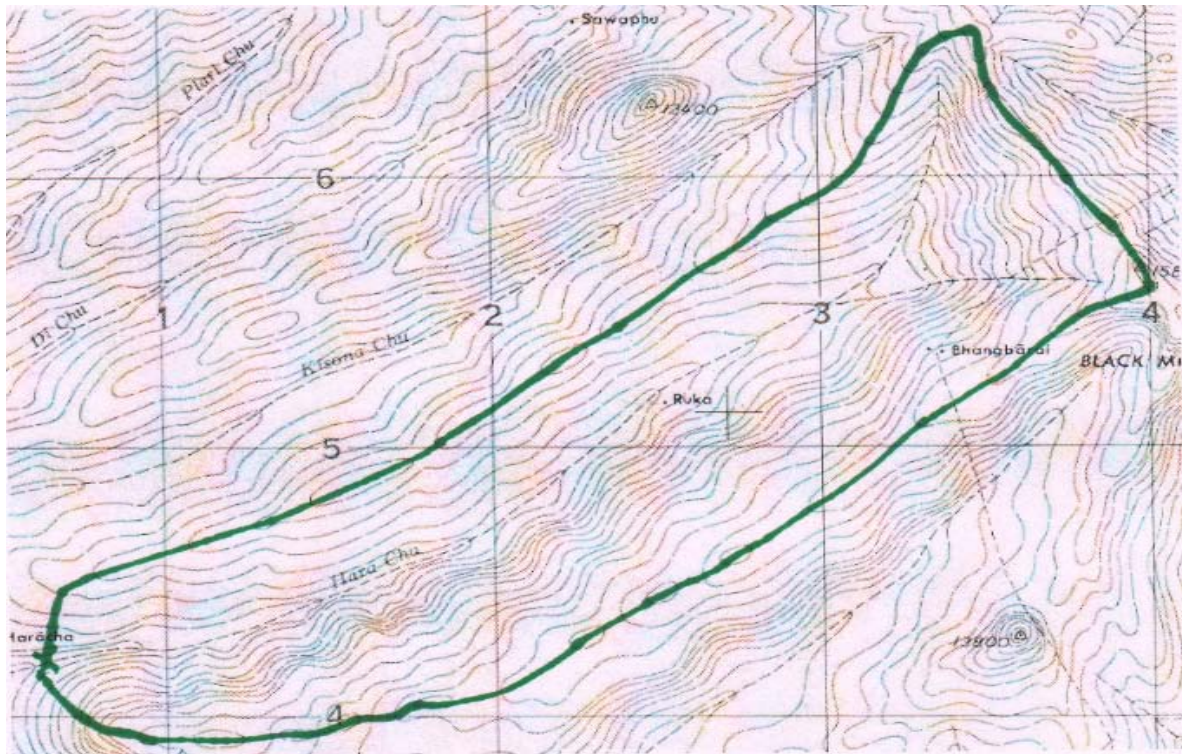


Fig. 1 Contour map of a small area and the catchment delineated. Outlet is at X in the lower left corner.

1.1 Channel Networks

The network of river channels in a catchment is formed by geological and geomorphic processes. There is a dynamic equilibrium between the forces of moving water that try to form catchment surface and channel network and those resisting the erosion. The shape and size of a river cross-section influences flow in it which also influences the cross-section. The shape and dimensions of a cross-section of a river keep changing with distance, topography and geology. The properties of cross-sections are used by hydrologists in hydrologic modeling and prediction and by ecologists for evaluation of habitat conditions for aquatic flora and fauna.

Water, sediment, and pollutants enter the channels from the nearby areas and move downstream in the channels. As the speed of movement of water and sediment in the channel network is faster compared to overland, a denser stream network would result in quicker movement of water, sediment, and pollutants to the outlet. Important characteristics of channel reaches are gradient (slope) and plan geometry. The gradient of a river may be steep (say, 1:100), mild (say 1:1000), or flat (say 1:10,000). The categories of planforms include meanders (tortuous, serpentine, confined and shifting), islands and braided.

Ordering of river channel networks is important in studies dealing with their evolution and watershed response. One of the earliest schemes for ordering of river channel networks was developed by Horton in 1945 and was modified by Strahler (1952). According to the Strahler system, the smallest headwater streams are called first-order streams (Figure 2). The first-order streams have no tributaries. When two streams of the same order join, a new stream of one order high is created but no higher order stream is created when a stream is

joined by a lower order stream. When two first-order streams join, a second-order stream is created; where two second-order streams join a third-order stream is created; and so on. But when a second-order stream joins a third-order stream, the resultant stream is also of third-order. The highest order river in the world is Amazon which has 12-order segment at the mouth. Fig. 2 shows a stream network of third order and numbering as per the Horton-Strahler scheme.

Horton's law of stream numbers states that there exists a geometric relationship between the number of streams of a given order N_i and the corresponding order, i . The parameter of this geometric relationship is the Bifurcation Ratio (R_B) which is the ratio of the number of stream segments of a given order N_n to the number of segments of the next highest order N_{n+1} :

$$R_B = \frac{N_n}{N_{n+1}} \quad \dots(1)$$

A higher value of bifurcation ratio indicates more streams implying a faster response of the catchment. Typically R_B varies between 2 and 5.

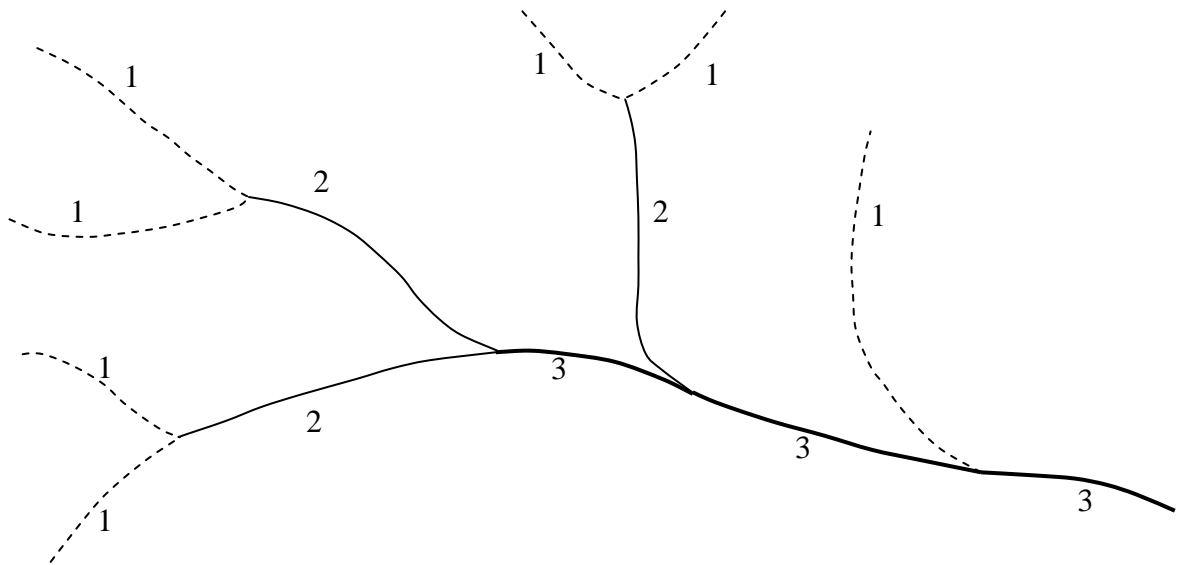


Fig. 2 A stream network of third order and numbering as per the Horton- Strahler scheme.

Horton's law of stream lengths states that there is a geometric relation between the average length of streams of a given order ($n+1$) and of the order n . The stream length ratio R_L is computed as

$$R_L = \frac{L_{n+1}}{L_n} \quad \dots \quad (2)$$

where L_n and L_{n+1} are the average stream lengths of streams of order n and $n+1$, respectively.

Schumm (1956) proposed the law of drainage areas and defined the drainage area ratio R_A as

$$R_A = \frac{A_{n+1}}{A_n} \quad (3)$$

where A_n and A_{n+1} are the average drainage areas of streams of order n and ($n+1$), respectively.

To compute the three ratios, the values of N_i , L_i , and A_i are plotted against stream order on a semi-log graph and the slopes of these lines are R_B , R_L , and R_A , respectively.

Another useful parameter is the drainage density which is the ratio of the total length

of all streams (of all orders) in a catchment to its area:

$$D = \frac{\sum_{i=1}^n L_i}{A} \quad (4)$$

Sometimes difficulties are faced in the determination of drainage network. First, in many instances catchments contain artificial channels, such as storm water channels, waterways, and drains along highways. These channels are often difficult to locate in maps and are difficult to include in the stream order hierarchy in the natural drainage networks. Maps with scales of 1:50,000 to 1:24,000 are typically used in this analysis.

Example 1: Use the drainage network laws to determine the bifurcation ratio, stream length ratio, and drainage area ratios for a 730-ha fourth-order watershed. The drainage network characteristics are summarized in Table 1.

Solution: Values of R_B , R_L , and R_A for each set of successive stream orders can be obtained using the information in Table 1 and Equation 1, 2, and 3 respectively. For example, R_B for the ratio of stream orders 1 and 2 would simply be 80 divided by 14 or 5.7, respectively. However, what we need to obtain are values of R_B , R_L , and R_A that are representative of the whole network. First, we obtain natural logarithms of the N_n , L_n , and A_n values in Table 1.

Table 1: Drainage Network Characteristics for Example 1 and Natural Logarithms of Selected Drainage Network Characteristics

Stream Order n	Number of Streams N_n	Average Stream Length L_n (m)	Average Drainage Area A_n , (ha)	$\ln(N_n)$	$\ln(L_n)$ (m)	$\ln(A_n)$ (ha)
1	80	400	5	4.38	5.99	1.61
2	14	1100	27	2.64	7.00	3.29
3	4	3000	140	1.39	8.01	4.94
4	1	8000	730	0.00	8.99	6.59

We now need to plot the set of N_n , L_n , and A_n values against stream order on a semi-log graph and fit a straight line to each set of values. The slope of the line drawn through the set of N_n value will be b_1 , and the slopes of the lines drawn through the sets of L_n , and A_n values will be b_2 and b_3 , respectively. From the plots, b_1 and b_2 and b_3 are 1.46, 1.0, and 1.66, respectively. Then, by obtaining the antilogarithm (e^{b_1} , e^{b_2} , and e^{b_3} , respectively) of each of these values, we find that R_B , R_L and R_A are 4.3, 2.7, and 5.3, respectively.

Hence, the bifurcation ratio R_B is 4.3, the stream length ratio R_L is 2.7, and the drainage area ratio R_A is 5.3.

2.0 Catchment Response Mechanisms

All the water that is carried out of a catchment by rivers is known as runoff. This water moves by many different routes on the surface of a catchment (overland flow), or below the surface (interflow or groundwater flow), or the river channel. Streamflow is the discharge or flow rate of water along a river, commonly expressed in m^3/s (cumec) or litre per second. Runoff may be expressed in volume units (m^3) or as depth (mm, cm or m). Streamflow is composed of overland flow, baseflow and interflow. Some rivers are perennial and have flow throughout a year while some are ephemeral which remain dry during certain periods.

Geomorphology is the study of earth's features or landscapes. Morphology of a watershed keeps on evolving due to natural and human-induced causes albeit over very long time horizons. Water is an important natural agent behind the changes. The following

discussion is drawn from books on catchment hydrology.

Overland flow frequently occurs as a saturation excess mechanism. All other things remaining the same in a rain storm, soil tends to saturate first where the antecedent soil moisture deficit is the smallest. This situation occurs in valley bottom areas where slopes from opposite hills converge and gradually decline towards the stream. Saturation rapidly occurs in those areas where soils are thin or have low permeability. As the rains continue, the areas of saturated soil expand and contract when rainfall stops. In addition to contribution to runoff from rainfall, surface runoff from such a saturated area may also be due to the return flow of subsurface water. Since this concept recognizes that the catchment area that contributes to runoff keeps changing, it is called “dynamic contributing area” concept.

A similar concept may be applicable in areas whose responses are controlled by subsurface flows. When saturation starts to build up at the base of soil over a relatively impermeable bedrock, water will start to flow downslope. The connectivity of saturation in the subsurface is, however, important initially. It may be necessary to satisfy some initial bedrock depression storage before there is a consistent flow downslope. The dominant flow pathways may be localized, at least initially, related to variations in the form of bedrock surface. In the catchments whose soils are deep and have high infiltration capacities, responses may be dominated by subsurface stormflow. In the catchments where secondary permeability is present through joints and fractures, it can provide flow pathways and storage that help maintain baseflow over longer periods of time.

Traditionally, it has been usual to differentiate between different conceptualizations of catchment response based on the dominance of one set of processes over another. An example is the Hortonian model in which runoff is generated by an infiltration excess mechanism all over the hillslope. Many forested catchments have deep soils with high infiltration capacities. Response of these catchments during storms is often controlled by sub-surface processes and surface runoff is restricted mainly to the channels.

Betson (1964) hypothesized that only a part of a catchment is likely to produce runoff in any storm. Since infiltration capacities decrease with increasing soil moisture and the downslope flow of water on hillslopes tends to result in wetter soils at the bottom of hillslopes, the area of surface runoff would tend to start near the channel and expand upslope. This partial area model allowed for a generalization of the Horton conceptualization. It is now realized that the variation in overland flow velocities and the heterogeneities of soil characteristics and infiltration rates are important in controlling partial area responses. If runoff generated on one part of a slope flows onto an area of higher infiltration capacity further downslope it will infiltrate (the run-on process). When the high intensity rainfall producing the overland flow is of short duration, it is also likely that water will infiltrate before it reaches the nearest channel.

Consider a simple case where the rain falls at a uniform rate on a catchment which is flat and impervious. There is no loss of water due to evaporation and infiltration. Initially, a thin layer of water is formed on the catchment surface (detention storage). The hydrograph at the outlet begins to rise almost immediately as the rain begins. The discharge at the outlet gradually rises till it attains a plateau and thereafter it continues at a rate which is equal to the rainfall intensity and catchment area. When the rain stops, the discharge begins to fall exponentially and stops after sometime. The detention storage will also be gradually emptied after the rain stops. If the rain stops before the discharge attains a plateau, the discharge will begin to fall from that point.

Now consider a small natural catchment which has some vegetation. When rain begins at time $t = 0$, some rain is intercepted by the vegetation, resulting in interception loss. Of the remaining rain which hits the ground surface, some part infiltrates into soil and some part fills up small depressions on the surface. After the interception, depression and

infiltration requirements are satisfied by the falling rain, runoff starts. The interception process begins with rainfall but lasts for a short time because the interception demand is generally very small compared to typical rates of rainfall. The remaining rainfall is used to satisfy soil infiltration demands. Typically these demands are higher than the rate of application of rainfall or irrigation and thus initially there may be no water left for runoff. As the infiltration capacity falls with time, if the rain continues, some water will be available for runoff generation. Note that if the rain stops before time t_1 when runoff is expected to commence, there will be no runoff from the storm. Thus, the antecedent conditions (the conditions in the catchment in terms of soil moisture etc. before storm begins) have an important role in the production of runoff. At the places where the application rate of water (rain or irrigation etc.) is more than the infiltration capacity of the soil, infiltration excess overland flow will be generated. This process is also known as Hortonian flow. Since the soil property may change widely even in a small catchment, the Hortonian infiltration excess overland flow generation may have a large variation in space. In a natural catchment, only a portion will be contributing to the overland flow at a given time and this concept is known as partial area infiltration excess overland flow.

Another process responsible for overland flow generation is saturation excess overland flow which occurs when the soil zone is completely saturated. As a result, even if rain is falling at a small rate, overland flow is generated because the soil has no capacity to absorb any more water. Saturation excess flow may also occur when the surface soil has very low permeability due to which saturation occurs at the catchment rapidly. During a storm the area of saturated soil expands and contract, depending upon the rainfall intensity, and this phenomenon is known as dynamic contributing area concept. Note that soil profile at a place may also be saturated due to flow coming from upstream area (on the surface or under the surface) in addition to rainfall. The partial area concept suggested by Betson (1964) is a generalization of the Horton concept.

It is also noted that sometimes there are pathways below the surface due to rock fractures or macro pores etc. which allow water to move through the soil rapidly. At times, these results in large flow contribution to the river through sub-surface pathways and this is known as sub-surface storm flow.

3.0 Factors affecting Runoff from a Catchment

Runoff from a catchment depends upon a number of factors. Major factors are discussed next.

3.1 Topography and Orientation

Topography of a catchment which has evolved over millions of years due to geomorphological processes plays an important role in runoff generation. In conjunction with other factors, topography also determines the flow pathways, storages, and types and density of vegetation. These ultimately influence catchment water and sediment yield. In catchment with steep slopes, water stays on the surface for a shorter time, the opportunity for infiltration is less and runoff is more if all other things are the same. Steep sloped catchments also have a shorter time of concentration. The average slope of river is an important parameter in some empirical methods to determine the time of concentration. If the catchment hillslopes are steep, water swiftly moves over the land, whereas in relatively flat catchments, more water infiltrates and runoff moves slowly. The same behavior is expected for the river network.

The aspect or orientation of the catchments is important particularly in the case of snow and glacier fed streams. North facing hillslopes receive less sunshine in the northern hemisphere and this results in more melt water to the streams and also more ET. Further, the orientation of the valley with respect to wind and storm direction also influences hydrologic

processes in a catchment. Some models explicitly account for the topography of catchment through topography-based indices. For example, the TOPMODEL (Bevan and Kirkby, 1979) uses a topographical index as a measure of flow accumulation at a given point on the catchment surface. It was first defined as a wetness index:

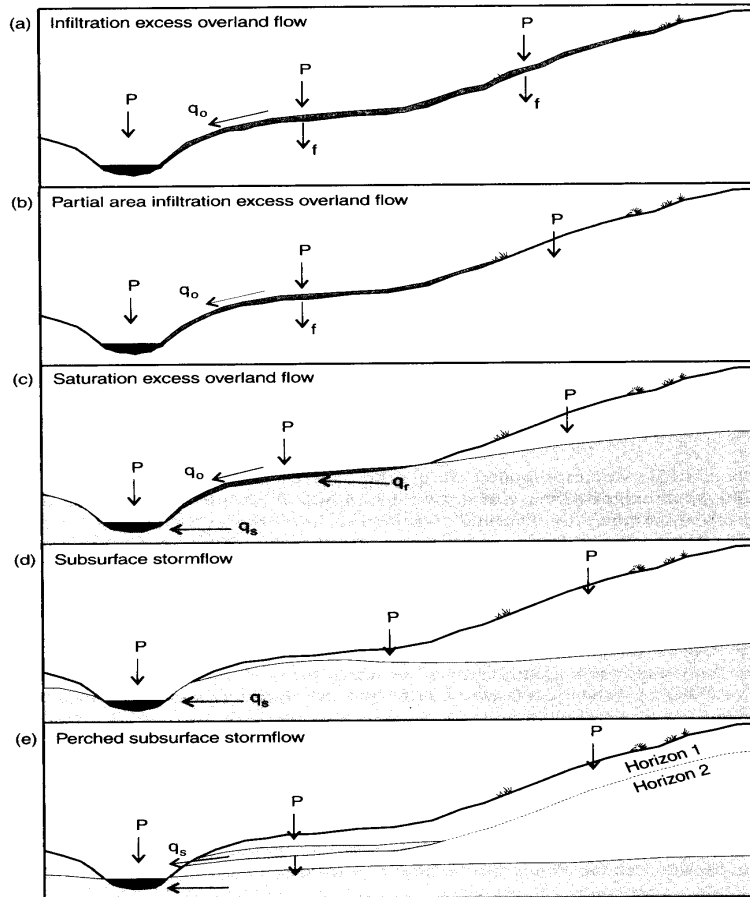


Figure 3: Various hillslope runoff mechanisms (Source: Beven 2001).

$$\lambda = \ln \frac{\alpha}{\tan \beta} \quad (5)$$

where λ is the topographical wetness index, α is the local upslope area draining through a certain point per unit contour length and $\tan \beta$ is the local slope in radians. Topographical index controls the flow accumulation and soil moisture.

3.2 Size and Shape

The size of a catchment naturally determines the magnitude of runoff generated due to several reasons. Usually the amount of water received by precipitation increases with size. The rational formula relates peak discharge from a catchment directly with area. However, in a large catchment, rainfall may have large variations and if the average rainfall decreases as we move downstream, the runoff per unit of catchment area may actually decrease. For example, in Krishna River basin in India, the head waters region receives very high rainfall which gradually decreases in the downstream direction. As a result, the runoff generated per

unit area decreases with the increase in the catchment area. The time base of the hydrograph typically increases with catchment size.

The shape of the watershed controls the synchronization of flow from various parts to the outlet. Catchments with circular or fan shape produce runoff at higher rates compared to those which are elongated because runoff from different locations will reach the outlet at nearly the same time. Hydrographs from circular catchments will have sharper peaks and shorter time base. Elongated catchments produce hydrographs with smaller peaks and longer time base. The shape of river valleys also affects the flow velocity and hence the time to peak.

3.3 Soil and Geology

Soil properties chiefly influence runoff in two ways. Infiltration of water depends upon soil properties and thickness. The soils which are highly permeable will permit higher infiltration and less runoff. The depth of soil profile determines the soil moisture storage capacity. Deeper soils will absorb more water before attaining saturation compared to shallow soils. The properties of soils in a catchment also determine the type of vegetation and crops grown. Land use and vegetation impact catchment response. More vegetation will produce more resistance to overland flow and more infiltration (partly due to plant roots).

Whereas the geographical features, such as mountains and continents, have evolved over long time horizons, small-scale features, such as gullies and drainage channels, form over shorter time scales. Weathering, erosion and deposition are the main processes involved. The main processes that control short-term changes are weathering, erosion, transport, and deposition. Fluvial geomorphology is the study of the formation of rivers and how they respond to anthropogenic and climate induced changes.

Geological properties, such as types of rocks, fractures, and faults, also affect the occurrence and movement of sub-surface water. Some rock types permit easy storage and movement of water and such basins are rich in groundwater occurrence. The chemical composition of rocks also determines the quality of ground water as many minerals may get dissolved when water passes through these rocks.

4.0 Elements of the Hydrograph

A streamflow hydrograph is a graph of the time distribution of water discharge at a location. The graph is plotted with discharge on the ordinate and time on the abscissa. A hydrograph for a given storm reflects the influence of all the physical characteristics of the drainage basin and, to some extent, also reflects the characteristics of the storm causing the hydrograph. A hydrograph can be considered a thumbprint of the drainage basin. The actual shape of a hydrograph is determined by the rate at which water is transmitted from the various parts of the drainage basin to the outlet. Most of this water is carried by the channels, but some water flows overland directly to the outlet. Two drainage basins will not produce identical hydrographs for the same storm. Similarly, no two storms produce identical hydrographs from the same basin.

A number of conceptual models are available to describe runoff generation in different catchments or at different locations in the same catchment but at different times. Based on the path taken by water, streamflow may be divided into surface flow, interflow, and base flow. Fig. 4 shows the components of a typical hydrograph.

The streamflow hydrograph rises from the beginning of wet season and with increasing catchment area at the gauging site for two reasons: a) as we move downstream in a basin, the area contributing to flow increases and so does the amount of river flow; and b) the accumulative rainfall increase as the wet season (or storm) progresses and also the river flow. When the wet or rain season is over, we enter the falling limb of the hydrograph and flow

begins to gradually recede. Hydrograph in figure 4 corresponds to uniform rainfall and stationary storm. If rainfall is not uniform, hydrograph will have kinks. If storm is moving, the hydrograph shape might be different depending upon the direction of storm movement.

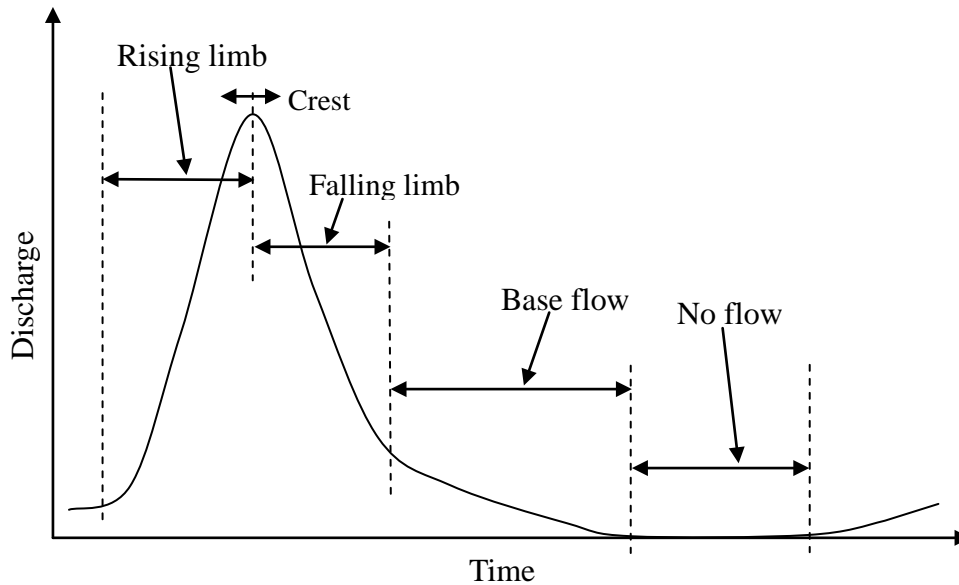


Fig. 4 Components of a streamflow hydrograph.

Rising Limb

As surface runoff reaches the river, the water level in it begins to rise. As rain continues, more and more surface runoff reaches the river from larger areas, flow and water level continues to rise. After a certain time when rain stops or its intensity or areal coverage decreases, lesser amount of water reaches the channel and the discharge and water level begins to fall. The rising portion of the hydrograph is called the rising limb.

Crest

The time interval bracketing the highest discharge near the peak of the hydrograph is called the crest. In the case of a sharp peak, the crest will be of short duration, while for a flat peak, the crest segment covers a fairly long time interval. The crest represents a subjective zone of nearly equal highest discharges. The greatest discharge within the crest is the peak discharge, which is of primary interest in hydrologic design.

Recession Limb

Recession limb is the portion of the hydrograph after the crest segment. It is also known as the falling limb or the recession curve. The recession limb represents decreasing discharge as water drains out from the catchment storage after rainfall stops. The slope of the recession limb indicates the rate at which water is drained from the basin. The lower part of the recession after the inflexion point, which has a much lower slope, is believed to represent groundwater contribution because here water is withdrawn more slowly.

Streamflow recession can be expressed by an exponential decay:

$$Q_t = Q_0 K_r^t \quad (6)$$

where Q_0 is the initial discharge at any time, Q_t is the discharge at time interval t later, and K_r is the recession or depletion constant r dependent upon the unit of time and is less than unity.

4.1 Hydrograph Time Characteristics

Some critical characteristics and the shape of a hydrograph can be expressed in terms of a few time parameters.

Time to Peak: The time to peak of a hydrograph is the time elapsed from the beginning of the rising limb to the peak discharge. This time depends on the drainage-basin characteristics, such as shape (elongated, circular, any other), distance from the most upstream point to the outlet, drainage density, channel slope and roughness, and soil characteristics. Time to peak somewhat depends upon the distribution of rainfall over the basin. For a given amount of runoff, a longer time to peak has a lower peak discharge than a shorter time to peak.

Time of Concentration: It is the time required for a drop of water which falls on the most remote part of the catchment to reach the outlet. If a rainfall of sufficient intensity continues for the time of concentration then the entire drainage basin would be contributing to the hydrograph at this time and the discharge will be the maximum that can occur from a given storm intensity over the catchment. Assuming that the rainfall is uniform over the entire catchment, the discharge increases as water from progressively farther distances arrives at the outlet. At and after the time of concentration, the discharge becomes constant since the entire basin is contributing to the flow.

One of the most commonly used formulas to compute the time of concentration was developed by Kirpich (1940):

$$t_c = 0.0078 (L/S^{0.5})^{0.77} \quad (7)$$

where t_c is the time of concentration in minutes, L is the length of travel in feet from the most remote point on the drainage basin along the drainage channel to the basin outlet, and S is the slope in feet per foot (it can be determined by the difference in elevation of the most remote point and that of the outlet divided by L). The equation assumes uniform rainfall over the catchment.

5.0 Components of Streamflow

Figure 2 shows a streamflow hydrograph and its components. The two main components of runoff are: (a) direct runoff and (b) baseflow. The direct runoff is divided into surface runoff and quick interflow, whereas the baseflow is divided into delayed interflow and groundwater runoff. The division into quick and delayed interflows is essentially arbitrary. The total runoff corresponds to a given storm event and its volume is determined by including in the streamflow hydrograph all runoff between the baseflow discharge occurring prior to the storm up to the same baseflow discharge after the storm. Verification of the pathways of water movement can be accomplished by isotopic techniques or by employing a process-based hydrologic model.

Surface Runoff

Surface runoff or overland flow is that water which travels over the ground surface to a drainage channel. Most surface runoff flows to first-order channels because they collectively drain the greatest area of the drainage basin. Surface runoff also includes that precipitation that falls directly on water flowing in the channel. Sheet flow usually occurs from an

impervious surface such as a paved parking lot, but can only occur on a natural drainage basin when rainfall intensity uniformly exceeds the infiltration capacity. This condition does not frequently happen. Variations in the distribution of soil type and of rainfall over a drainage basin usually result in limited sheet flow. Surface runoff is believed to be the principal contributor to the peak discharge from a storm event. Because this water runs off over the surface to the channel, it is the first to reach the channel and, hence, forms the rising limb and peak of the hydrograph.

As the catchment area at a gauging site increases, the slope of rising limb of the surface runoff hydrograph becomes flatter; typically discharge is a power function of area.

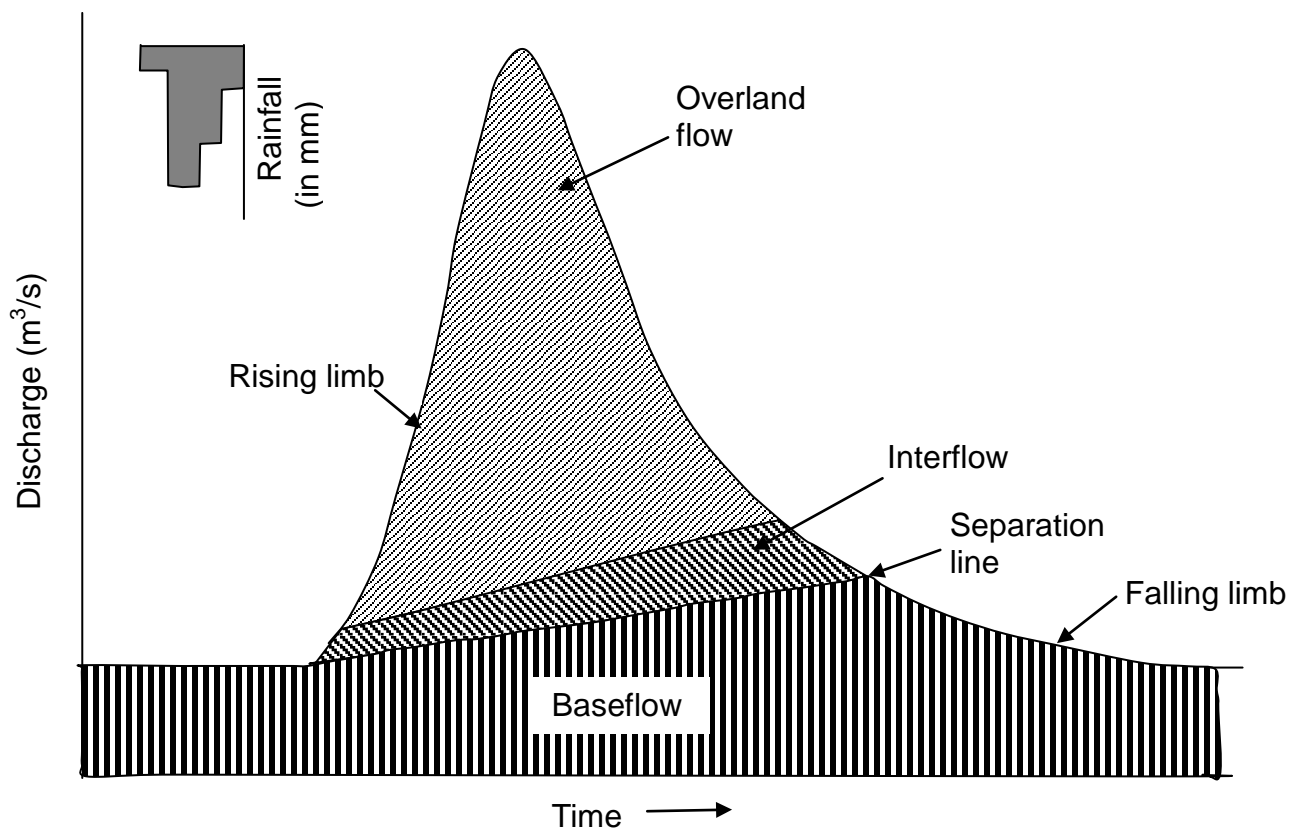


Figure 5: A typical streamflow hydrograph.

Interflow

Interflow, also called subsurface storm flow, is that surface water that infiltrates the surface layer and moves laterally beneath the surface to a channel. Interflow can occur on forest floors, where the leaves, needles, and other debris cover the ground. Interflow might occur in shallow soils filled and loosened by tree roots, rock debris covering the ground surface, or surface soils loosened by any cause. During interflow, the movement of water is subject to greater flow resistance than surface runoff. As a result, interflow does not move as rapidly as surface runoff. Accordingly, interflow does not add to the peak discharge, but reaches the outlet after the peak discharge has passed.

Direct Runoff

Direct runoff is usually considered to be the sum of surface runoff and interflow. Direct runoff is frequently equated with surface runoff. These two flow components move more

rapidly than groundwater flow and for this reason are often lumped together for hydrologic purposes. Such lumping is reasonable for certain purposes because it is logical to believe that some interflow near the outlet will arrive at that point before surface runoff from farther up the basin.

6.0 Baseflow

Flow in a perennial stream prior to a storm is from baseflow. During a storm event, the baseflow is augmented by infiltration. Drainage basins with highly permeable, thick soils usually have a high groundwater-flow component and relatively small direct-flow component, whereas basins with heavy-clay, low-infiltration soil have a small or zero groundwater component and a high direct-runoff component. A portion of the groundwater-flow component occurs from water infiltrating the banks of the channel during high-water flows.

ASCE (1996) defined base flow (or groundwater flow, fair weather flow) as the runoff that has reached the stream or river by passing first through the underlying aquifer, rather than by flowing directly on the ground surface. Hence, base flow is that part of river flow that is gradually entering the river from groundwater storage. Baseflow is also called as the groundwater flow, low flow, and fair weather flow.

Perennial streams depend on base flow for discharge between runoff producing events. The presence of base flow around the year indicates humid climate and a shallow water table that is hydraulically connected with the stream. Base flow is absent in (semi)arid climates and areas of deep groundwater. Contribution of base flow to streamflow depends upon the hydro-geology of the aquifers. Sources, such as lakes, marshes, snow, and river banks may also supply water for base flow. At a given time, more than one source may be supporting base flow. The movement of groundwater in the lateral direction is slower than vertical, since the hydraulic gradient for lateral movement is smaller. The supply of water from the aquifer to the river continues as long as there is adequate gradient.

As water moves to the stream from higher elevations, the hydraulic gradient decreases and lesser water will travel to the stream with time, unless there is additional infiltration to the aquifer. The gradual reduction of baseflow is called baseflow recession. Many different forms of base flow recession curves have been proposed. Among these, the most common is the exponential recession:

$$Q_t = Q_0 k_r^t \quad (8)$$

where Q_0 is the flow at time $t = 0$; Q_t is the flow at time t ; and parameter k_r is known as the recession constant. It is a dimensionless quantity which depends upon the unit of time selected. It lies in the interval $[0,1]$ and is normally greater than 0.7. Horton (1933) suggested a non-linear recession equation, known as the Horton's double exponential:

$$Q_t = Q_0 \exp(-a_2 t^m) \quad (9)$$

where a_2 and m are constants.

To determine the recession constant k_r , one can plot Q_{t-1} versus Q_t on a simple graph. This plot will result in a straight line passing through the origin whose slope will be k_r .

The master baseflow recession curve is a composite recession curve which represents the mean recession behavior. Of course, the information about the recession variability is lost in the process. This curve can be constructed by observing discharge at a number of time intervals encompassing the entire dry-weather period. These are then plotted against time on

a semilog paper, and a best-fit straight line is drawn through the plotted points. The resulting curve is the master baseflow recession curve.

Baseflow Separation

Baseflow separation is the process of separating surface runoff from baseflow. Even though such separation is somewhat arbitrary and subjective, it is useful in many analyses. Several techniques have been developed to perform base flow separation. The area method of base flow separation is based upon a nonlinear relation between time and area:

$$N = b A^{0.2} \quad (10)$$

where A is the drainage-basin area in km^2 ; b is a coefficient, equal to 0.8; and N is the time in days from the hydrograph peak. This equation is not suitable for smaller watersheds. It generally gives a longer time base. For example, if $A = 1000 \text{ km}^2$, then $N = 3.18$ days, i.e., if rainfall occurs for 6 hours, its effect will be felt for more than 3 days.

It is convenient to draw a separation line directly from the chosen groundwater discharge on the receding limb to the point under the hydrograph peak. Although this linear separation does not represent the true boundary between direct runoff and groundwater runoff, the error may be acceptable in most cases.

The three-component separation involves separating surface runoff, interflow, and base flow. A method, developed by Barnes (1940) is illustrated in Fig. 6. First, streamflow recession is plotted on a semi-logarithmic paper. In Fig. 6, the groundwater recession plots approximately as a straight line, with $K_r = 0.992$. By extending this straight line under the hydrograph to the point directly under the point of inflection E and to B on line AB , points B and J are connected arbitrarily by a straight line. The area under the hydrograph above BJH is considered to be direct flow and that area below BJH is considered to be groundwater flow. The direct runoff is replotted and a straight line IL with $K_r = 0.966$ is fitted and extended to point I directly under the inflection point E and to the beginning point M . The line MIL divides the replotted hydrograph into surface runoff on the top and interflow below.

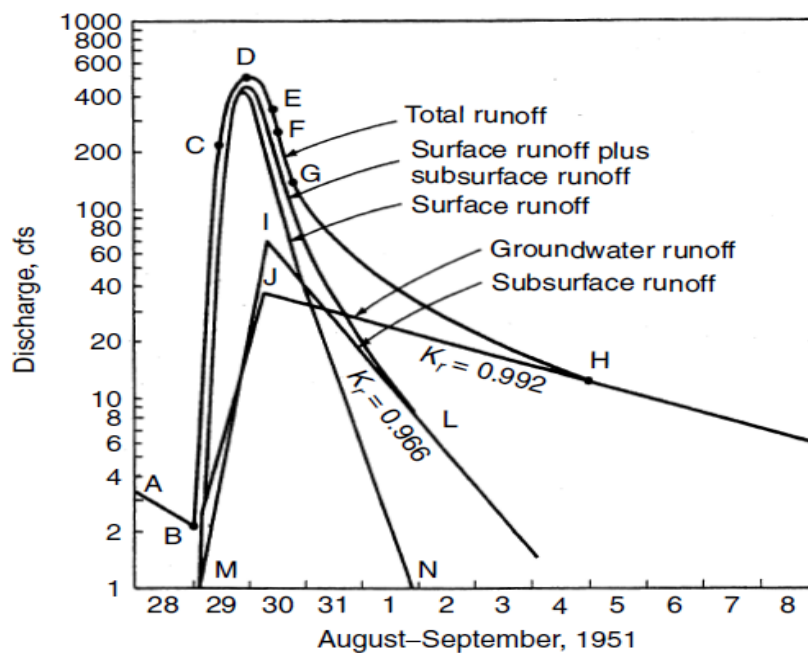


Fig. 6 Three-component hydrograph separation.

The method developed by Singh and Stall (1971) is also followed by many engineers. Digital filters and chemical and isotope tracers provide another means to separate hydrograph in components.

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