USE OF GABIONS IN SMALL HYDRAULIC WORKS

SECTION 2

INVESTIGATION ON BASIN GEOMORPHOLOGY AND HYDROLOGY

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An extensive analysis of runoff calculation procedures does not fall within the scope of this manual, yet it will be useful to provide a general description of the hydrologic methods used to estimate a basin's runoff features. This section also illustrates the main procedures used to evaluate watershed features and methereologic data, required in the application of hydrologic methods.

When projecting a hydraulic work it is necessary to know the ***runoff features*** of the concerned watershed (e.g. runoff coefficient, annual flow rate and maximal runoff rate). Unless the basin has already been gauged, these runoff characteristics will be unknown, in which case we will have to refer to data collected on similar gauged basins in order to determine the runoff characteristics of the watershed. Runoff features depend on several ***basin characteristics*** (e.g. basin shape, watershed relief and drainage pattern) and on local rainfall characteristics. The soil's nature in the drainage area will also affect the watershed's reaction in the event of a rainstorm.

In hydrology, there are several ways to classify watersheds on the basis of the above mentioned characteristics. These ***hydrologic methods*** of classification are based on wide-ranging investigations done on several gauged watersheds. On the basis of data collected during runoff events in gauged basins, we can establish the relation between runoff features and various watershed characteristics (e.g. basin shape and surface, soil features...). For these classification methods to be applied, various kinds of data on basin characteristics and rainfall features should be available beforehand. This chapter provides a general description of the watershed features required in the application of these classification methods. Some of the principal hydrologic methods used for estimating runoff features (***rational, IUH, U.S. S.C.S. and Orstom***) will also be briefly described.

In this section:

- ***definition and delineation of a watershed;***
- ***morphological features required to classify watersheds;***
- ***soil features inquiries;***
- ***rainfall features required for hydraulic work design;***
- ***hydrologic methods;***
- ***erosion and solid transportation;***
- ***evaporation.***

2.1 – WATERSHED DEFINITION AND DELINEATION

The concept of watershed is basic to all hydraulic work design. In fact, a hydraulic structure is always positioned in a watershed outlet. With respect to the outlet, the ***watershed*** is defined as *all the land area that sheds water to the outlet during a rainstorm*. A line called ***water divide*** or ***watershed boundary*** delimits this area, joining all its outermost points. The water divide also demarcates the separation between two different watersheds: rain falling on one side of this line sheds to the outlet of one watershed and, conversely, rain falling on the other side sheds to the outlet of the other watershed, as shown in figure 2.1.

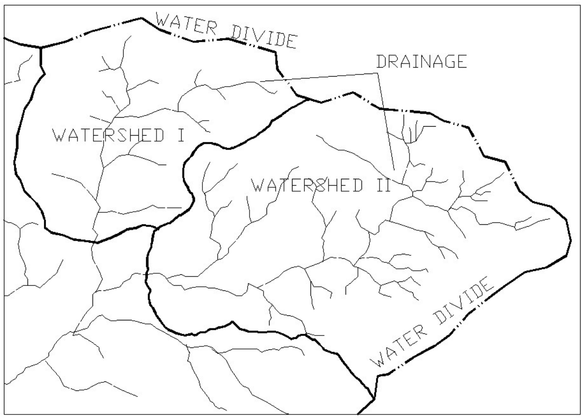
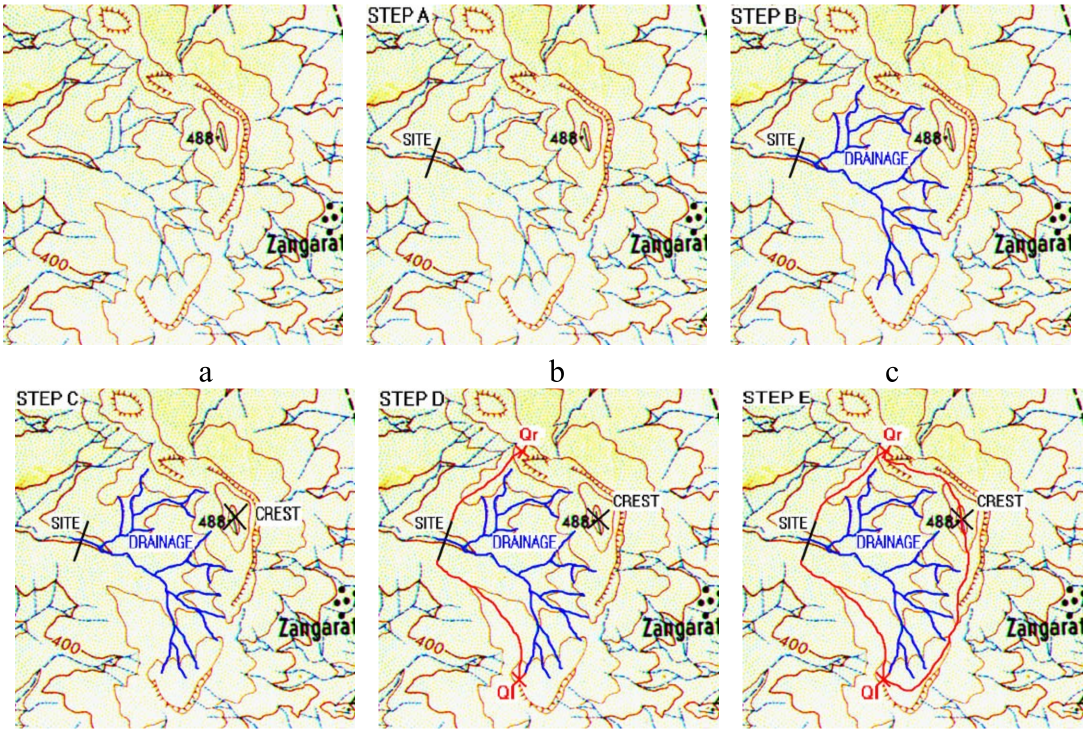


Fig. 2.1 - Watershed representation

The preliminary phase of ***watershed delineation*** consists in drawing the water divide. For doing so, we will require a topographic map of the area. Aerial photos with a proper stereoscopic device can also be used. The different steps to draw the water divide on a topographic map are mentioned below (see figure 2.2)

b – mark the site selected for the hydraulic work (this point will be the ***watershed outlet***),
c – draw all the drainage channels which flow to the outlet,
d – mark the crest of the mountains and hills which separate the chosen watershed from the surrounding area,
e – draw two lines, perpendicular to the elevation contour lines (along the maximal slope direction), connecting the extremes of the outlet point with the two upper points (Qr, Ql),
f – from one of these points, for example Qr, draw the water divide which should join all the marked crest-points as far as the second upper point Ql. This line will mark the minimal slope direction.

The contour obtained with the lines drawn in point e and f represent the water divide.



d e f

Fig. 2.2 - Watershed delineation

If a Digital Elevation Model of the concerned area already exists, a proper GIS tool will allow us to draw the watershed boundary automatically.

2.2 – INVESTIGATION ON BASIN MORPHOLOGY

Once the concerned watershed has been delimited, the basin's morphology should be analysed in order to determine further important basin's parameters, such as :

- ***shape,***
- ***relief***,
- ***drainage pattern***.

The main parameters used to characterise the basin's morphology are briefly described below.

BASIN SHAPE

The basin's reaction to a rainstorm depends, inter alia, from its shape. In fact, it can be noticed easily that the two different watersheds shown in figure 2.3, other things being equal (such as surface, vegetative cover, soils characteristics and basin relief), should not have the same reaction time. We can expect the runoff of the longest watershed to be more diluted than the other.

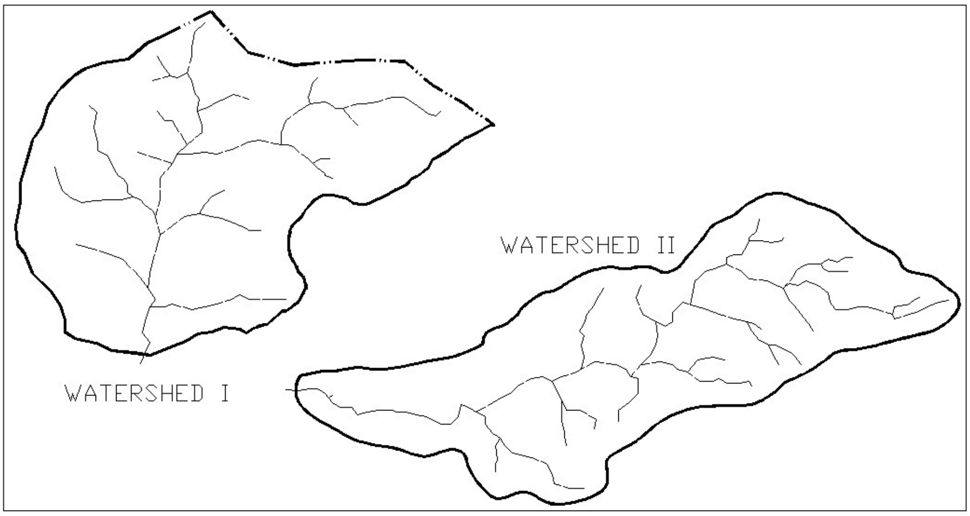


Fig. 2.3 - Two different shapes for watershed

Several parameters have been introduced to represent watershed shape. The most commonly used is the ***circularity ratio*** (Fc), also called ***Gravelius index*** (Icomp), given by:

$Fc = 0.28 \times P \times S^{0.5}$

where P and S are respectively the perimeter and the area of the watershed.

J Basin Shape

Basin shape is not usually used directly in hydrologic design methods; however, parameters that reflect basin shape are used occasionally and have a conceptual basis, so a few words about it are in order. Watersheds have an infinite variety of shapes, and the shape supposedly reflects the way that runoff will "bunch up" at the outlet. A circular watershed would result in runoff from various parts of the watershed reaching the outlet at the same time. An elliptical watershed having the outlet at one end of the major axis and having the same area as the circular watershed would cause the runoff to be spread out over time, thus producing a smaller flood level than that of the circular watershed. The importance of watershed shape will be more apparent after the concept of a time-area diagram is introduced and discussed. A number of watershed parameters have been developed to reflect basin shape. The following are a few typical parameters:

1. *Length to the center of area* (L_{ca}): the distance in miles measured along the main channel from the basin outlet to the point on the main channel opposite the center of mass.
2. *Shape factor* (L_l):

$$L_l = (LL_{ca})^{0.3} \qquad (3\text{-}1)$$

where L is the length of the watershed in miles.

3. *Circularity ratio* (F_c):

$$F_c = \frac{P}{(4\pi A)^{0.5}} \qquad (3\text{-}2)$$

where P and A are the perimeter (feet) and area (ft^2) of the watershed, respectively.

4. *Circularity ratio* (R_c):

$$R_c = \frac{A}{A_0} \qquad (3\text{-}3)$$

where A_0 is the area of a circle having a perimeter equal to the perimeter of the basin.

5. *Elongation ratio* (R_e):

$$R_e = \frac{2}{L_m}\left(\frac{A}{\pi}\right)^{0.5} \qquad (3\text{-}4)$$

where L_m is the maximum length of the basin parallel to the principal drainage lines.

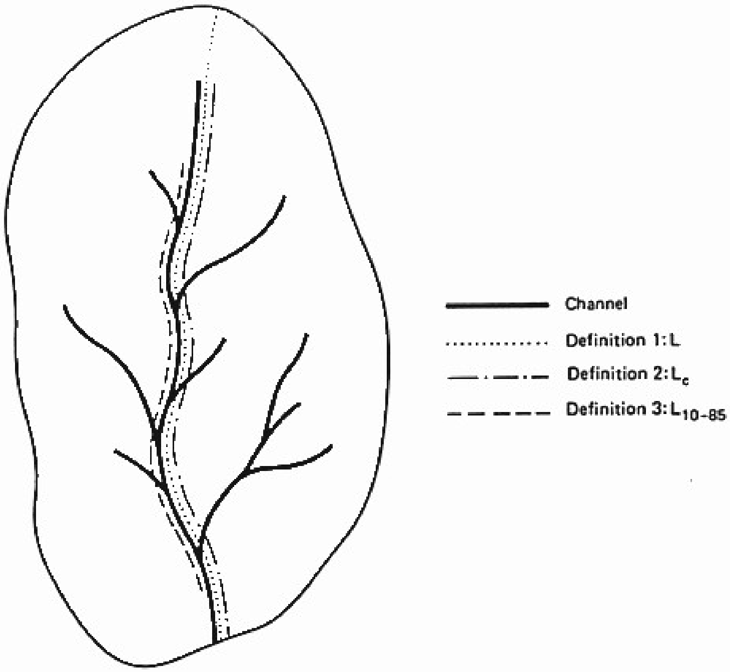


Fig. 3-5 Delineation of watershed length.

WATERSHED RELIEF

The runoff speed, overland and in drainage channels, depends to a great extent upon channel and land slope. Therefore, a number of parameters have been developed to signal variations in watershed relief.

The ***channel slope*** represents the slope of the watershed's main drainage channel, and can be expressed by the following relation:

$$S = \Delta E / L$$

where ΔE is the difference in elevation between the upper end of the channel and the outlet, and L is the length of the channel flowing between these two points.

With regards to the watershed slope it will be necessary to introduce the notion of ***hypsometric curve***, which represents the relationship between elevation and watershed surface at different elevation levels. The hypsometric curve is generally plotted as shown in figure 2.4 with the elevation on the ordinate axis and the related surface on the abscissae axis. This curve can also be represented in dimensionless form by plotting the cumulative fractions rather than the real values.

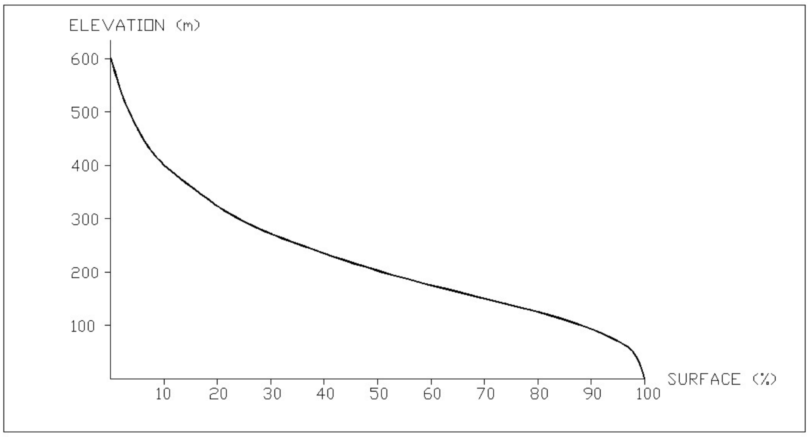


Fig. 2.4 - Hypsometric curve

An important parameter of the Orstom classification method is the ***slope global index*** (Ig) which comprises shape, surface and relief of the watershed.

DRAINAGE PATTERN

In a rainstorm event, the reaction time of a basin also depends on the extension of the drainage axis. Generally, the rain falling in the basin will travel some time overland before reaching the drainage channel. The flow's speed is usually inferior overland than in a channel. In a basin with a thick drainage pattern, the rainwater will normally have to travel a short distance overland before flowing quickly into the drainage channel. Consequently, the basin's reaction time will be shorter than in the case of a basin characterised by a scattered drainage pattern.

Several parameters have been introduced by Horton to represent the drainage pattern. The most important among them is ***drainage density***, i.e. the ratio of the total length of the drainage axis to the watershed surface.

The drainage pattern is also an important indicator of soil features. A thick drainage pattern generally corresponds to an impervious soil, whereas a pervious soil is characterised by a scattered drainage as shown in figure 2.5 (a,b).

In arid and semi-arid regions, in conjunction with large watersheds, we commonly find the phenomenon of ***endorheism***. The latter refers to portions of drainage that do not reach the watershed outlet, as shown in figure 2.5 (c). In this case, the runoff will gather in a depression to form a pond. Alternatively, it may infiltrate into the subsoil.

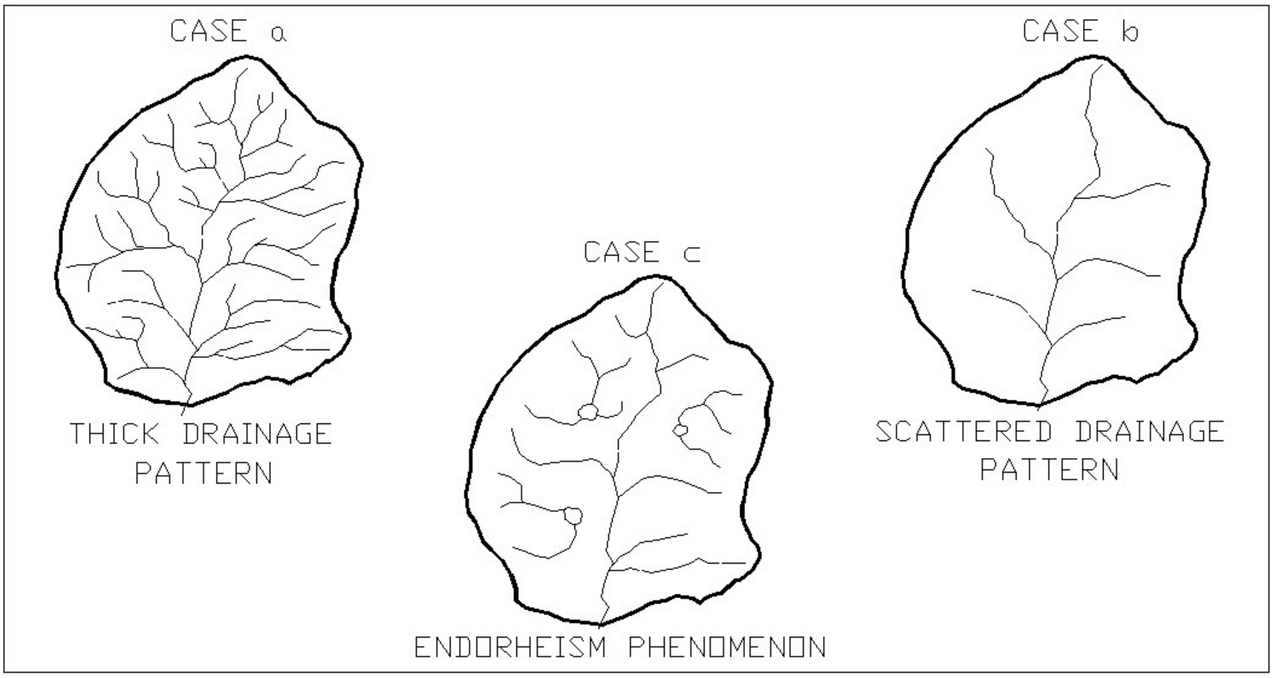


Fig. 2.5 (a,b,c) - Three watersheds with different drainage pattern

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Horton's method for drainage pattern classification

Descriptors of the Drainage Pattern

The velocity of water flowing in a channel is usually greater than the velocity of overland flow. Therefore, the travel time of runoff for a watershed in which the overland flow length is relatively small compared with the channel flow length would be small relative to the travel time for a watershed with a relatively long overland flow length. Thus the speed with which the runoff gets to the channel can affect the travel time of runoff. As will be shown in a following section, the travel time is an important input to many hydrologic design models. Thus the drainage pattern is another indicator of the flow characteristics of storm runoff. A number of parameters have been developed to represent the drainage pattern.

Horton's Laws

Horton developed a set of "laws" that are indicators of the geomorphological characteristics of watersheds. The stream order is a measure of the degree of stream branching with a watershed. Each length of stream is indicated by its order (i.e., first order, second order, etc.). A first-order stream is an unbranched tributary, and a second-order stream is a tributary formed by two or more first-order streams. A third-order stream is formed by two or more second-order streams, and in general, an nth-order stream is a tributary formed by two or more streams of order (n - l) th and streams of lower order. For a watershed, the principal order is defined as the order of the principal channel (i.e., the order of the tributary passing through the watershed outlet). The ordering of streams with a hypothetical watershed is shown in Fig. 3-9. For this case, the watershed has a principal order of 4. The concept of stream order is used to compute other indicators of drainage character. The bifurcation ratio (R_b) is defined as the ratio of the number of streams of any order to the number of streams of the next-lower order. Values of R_b typically range from 2 to 4. Figure 3-10 shows the same watershed as in Fig. 3-9, but the streams of each order have been specifically delineated. Figure 3-l0a shows that there are 17 first-order streams, with Fig. 3-l0b to d indicating 6, 2, and 1 streams of orders 2, 3, and 4, respectively. This yields bifurcation ratios of 2.83, 3.0, and 2.0 for stream orders 1 to 2, 2 to 3, and 3 to 4, respectively, and an average value of 2.6.

Law of Stream Numbers. Horton also proposed the law of stream numbers, which relates the number of streams of order i (Ni) to the bifurcation ratio and the principal order (k):

$$Ni = Rb^{k-1} \quad (3\text{-}10)$$

For a watershed with a bifurcation ratio of 2.6 and a fourth-order principal stream, Eq. 3-10 becomes

$$Ni = 2.64^{4-1} \quad (3\text{-}11)$$

Thus the law of stream numbers would predict 18, 7, and 3 streams of order 1, 2, and 3, respectively; these agree closely with the 17, 6, and 2 streams for the watershed of Fig. 3.9 and 3.10.

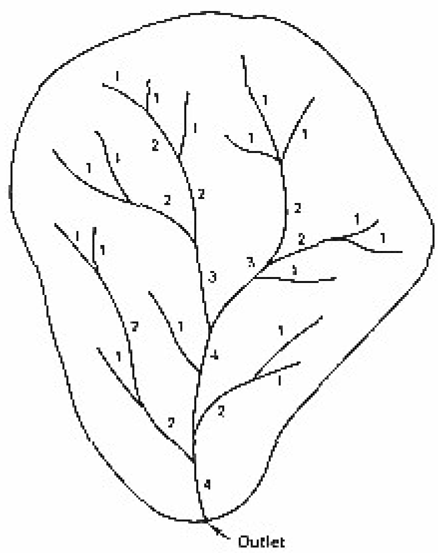


Fig. 3-9 Ordering of stream of watershed having a principal order of 4.

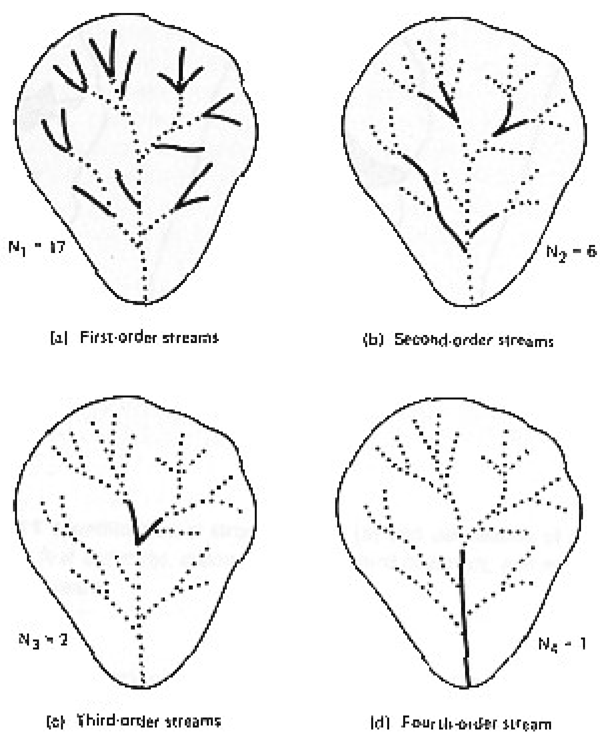


Fig. 3-10 Stream-order separation for estimating the bifurcation ratio.

Law of Stream Lengths. The law of stream lengths relates the average length of streams of order i (Li) to the stream length ratio (r_l) and the average length of first-order streams (L_1):

$$Li = L_1 \, r_l^{\,i-1} \qquad (3\text{-}12)$$

where the stream length ratio is defined as the average length of streams of any order to the average length of streams of the next-lower order.

Law of Stream Areas. The law of stream areas is similar to the law of stream lengths. Specifically, the law relates the mean tributary area of streams of order i (Ai) to the mean drainage area of first-order basins (A_1) and the stream area ratio (r_a):

$$Ai = A_1 \, r_a^{\,i-1} \qquad (3\text{-}13)$$

where the stream area ratio is the average basin area of streams of one order to the average area of basins of the next-lower order. The similarity in Eqs. 3-12 and 3-13 reflects the high correlation that exists between watershed length and area.

Law of Stream Slopes. The law of stream slopes relates the average slope of streams of order i (Si) to the average slope of first-order streams (S_1) and the stream slope ratio (r_s):

$$Si = S_1 \, r_s^{\,i-1} \qquad (3\text{-}14)$$

where the stream slope ratio is the average slope of streams of order j to the average slope of streams of the next-higher order, j + 1.

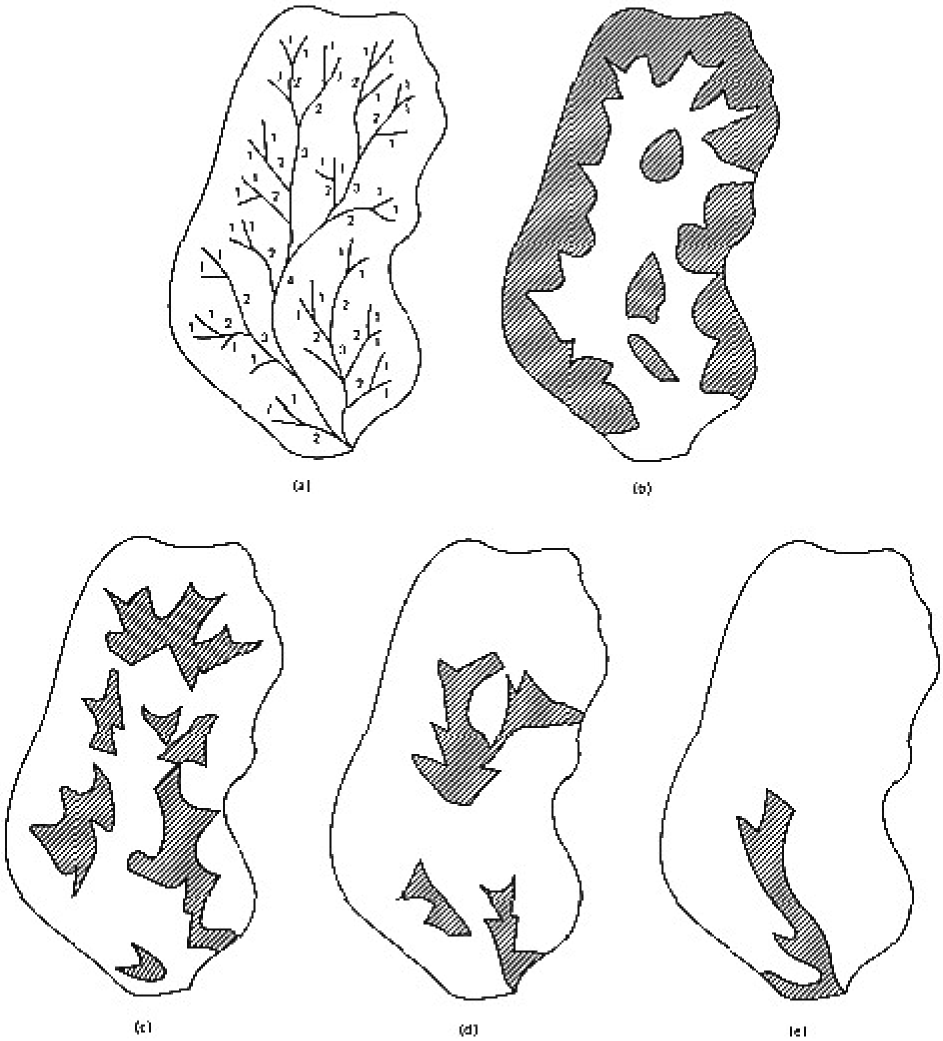


Fig. 3-11 Identification of stream orders (a) and delineation of stream areas for first order (b), second order (c), third order (d), and fourth order (e) streams.

2.3 – SOILS CHARACTERISTICS

Texture*, *structure and moisture
Vegetation cover
Rodier's classification
U.S. Soil Conservation Service

The characteristics of a watershed's soil are crucial toward the determination of runoff features because they influence the rainfall's infiltration rates. The principal soil features influencing the infiltration rate are ***texture***, ***structure*** and ***moisture***. Texture refers to the relative fractions of mineral particles of different size classes present in a soil. In particular, the percentage of clay in the soil significantly influences the soil's infiltration rate. The tendency of soil particles to aggregate into lumps and clods determines the soil's structure. The soil's structure varies according to its texture, organic contents, and minerals present in it.

The ***vegetation cover*** also affects the soil's retention volume, and consequently alters the runoff features. The vegetation generally absorbs the first portion of rainfall and, if the basin presents a thick vegetative cover, the amount of water retained can represent an important percentage of the total rainfall volume. The presence of vegetation also favours the infiltration of rainfall through the roots. The stems of grass and shrubs hinder the overland flow and consequently retard the runoff.

Rodier proposed a qualitative classification of soils into six classes on the basis of their infiltration rate. ***Rodier's classification*** concerns both soil's features and vegetative cover.

The ***U.S. Soil Conservation Service*** proposed a very detailed classification of soils according to three main criteria:

- hydrologic soil group,
- land use,
- treatment class.

The classification by hydrologic soil group concerns the texture and the structure of the soil. Lands are also classified according to their utilisation into four main classes:

- fully developed urban areas,
- developing urban areas,
- cultivated agricultural land,
- non-cultivated agricultural land.

Each class is subdivided into several subclasses. Agricultural lands are also characterised by the cultivation methods applied, in line with local agricultural practices (e.g. straight row, conservation tillage, contour ploughing and terraces).

The application of one of the above mentioned classification methods will be greatly simplified if a soil survey report for the concerned area already exists. Otherwise aerial photos or satellite images will be required in order to decompose the watershed in homogeneous zones according to soil type, utilisation, and vegetative cover. After a preliminary interpretation of aerial photographs or satellite images, the ensuing findings should be double-checked through a soil survey.

2.4 – RAINFALL DATA

Annual average rainfall
Design flood
Depth-duration-frequency curve
Thiessen method for computation of areal rainfall
Point to areal rainfall

Two are the principal rainfall features that should be taken into account before moving on to hydraulic works design. The first one concerns the ***annual average rainfall***. In fact, it is fundamental to know the rainfall's variability throughout the years, and its distribution within a single year, in order to estimate the storage volume, in case of a retention dam, or to calculate the hydraulic characteristics of the outlet, in case of a diversion weir.

The second feature concerns the evaluation of the ***characteristics of a rainstorm*** with a determinate ***return period***. The return period is the average time interval between single occurrences of a particular event, in this case a rainstorm. The rainstorm's characteristics will be used to determine the design flood.

All the rainfall features required should be deduced from precipitation data collected in ***regional meteorological stations***. If these data do not exist for the concerned area, it is possible to estimate rainfall features on the basis of data collected in the stations of neighbouring regions with characteristics, such as altitude and exposure, similar to those found in the area under consideration.

For a complete description of the methods used to collect and to process rainfall data the reader should refer to specific works on this subject. A brief description of the principal rainfall features required to design hydraulic works is provided below.

Before projecting a hydraulic work it is always necessary to decide about its '***life expectancy'***, that is, the average period a structure is expected to 'live' before any important damage (generally caused by extraordinary floods) occurs. Then, the ***design flood*** should be calculated as a function of a rainstorm characterised by the selected return period (life expectancy). The spillway should be dimensioned so as to evacuate this flood. The methods used to calculate the design flood, as a function of watershed and rainfall features, are described in the next paragraph.

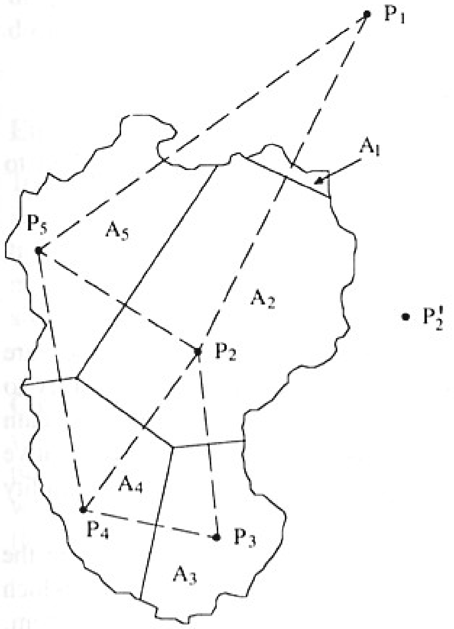
The ***depth-duration-frequency curve*** describes the relationship between depth and duration of rainfall, with a fixed return period. It can be easily derived from the analysis of rainfall data, and it is also largely used in runoff computations. The depth-duration-frequency curve is given by:

$$h = a \times t^{b}$$

where h and t represent, respectively, the depth and the duration of rainfall, and a, b are two coefficients calculated with a suitable statistical method (e.g. Gumbel) and are a function of the return period. A precondition for the application of these statistical methods is the availability of precipitation data, such as rainfall depth and duration, for several (at least 15) years.

In order to estimate watershed's runoff features it is fundamental to know the rainfall's depth relative to a specified duration, as will be described in the next paragraph.

Thiessen method for computation of areal rainfall



Station	Observed rainfall (mm or in)	Area (km^2 or mi^2)	Weighted rainfall (mm or in)
P_1	10.0	0.22	2.2
P_2	20.0	4.02	80.4
P_3	30.0	1.35	40.5
P_4	40.0	1.60	64.0
P_5	50.0	1.95	97.5
		9.14	284.6

Average rainfall = 284.6/9.14 = 31.1 mm or in

FIGURE 3.4.3(*b*)
Computation of areal average rainfall by the Thiessen method.

Point to areal rainfall

Frequency analysis of precipitation over an area has not been as well developed as has analysis of point precipitation. In the absence of information on the true probability distribution of areal precipitation, point precipitation estimates are usually extended to develop an average precipitation depth over an area. The areal estimate may be either storm-centered or location-fixed. For the location-fixed case, one accounts for the fact that precipitation stations are sometimes near the storm center, sometimes on the outer edges, and sometimes in between the two. An averaging process results in location-fixed depth-area curves relating areal precipitation to point measurements. Fig. l4.1.3 provides curves for calculating areal depths as percentage of point precipitation values (world Meteorological Organisation).

Depth area relationship for various durations, such as those shown in Fig. 14.1.3, are derived by a depth-area-duration analysis, in which isohyetal maps are prepared for each duration from the tabulation of maximum n-hour rainfalls recorded in a densely gaged area. The area contained within each isohyets on these maps is determined and a graph of average precipitation depth vs. area is plotted for each duration.

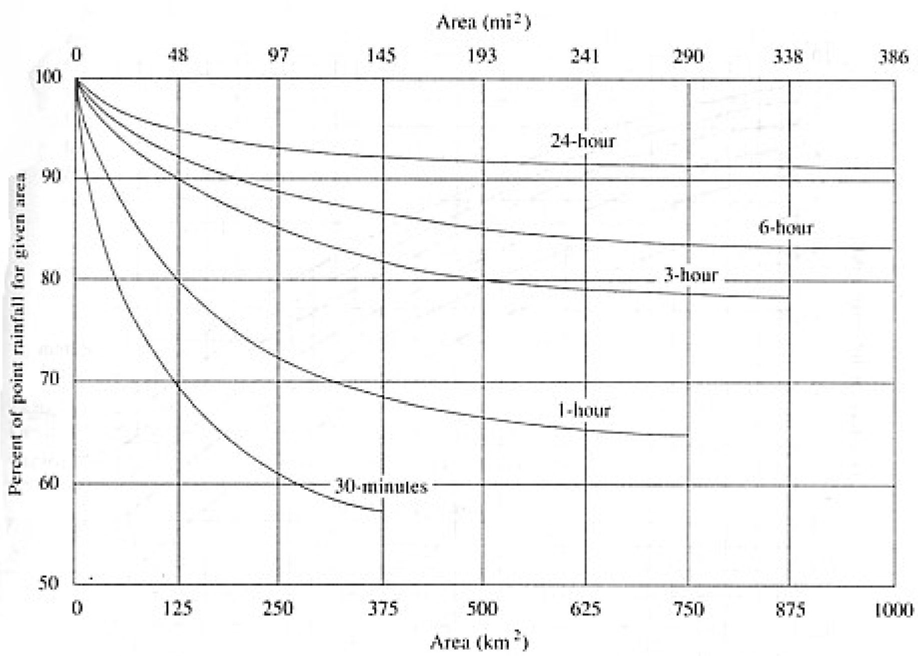


FIGURE 14.1.3
Depth-area curves for reducing point rainfall to obtain areal average values. (*Source*: World Meteorological Organization, 1983; originally published in Technical Paper 29, U. S. Weather Bureau, 1958.)

The Orstom, on the basis of rainfall data collected throughout several years, prepared some geographic charts of West Africa with isolines for daily and annual rainfall depth with a ten year return period.

All the methods used for estimating rainfall's depth provide a local peak value. But, especially in arid and semi-arid regions, rainstorms are not uniformly distributed on the watershed. Several existing relations allow us to estimate the value of rainfall data adapted to a particular watershed. The Orstom, for example, proposed the following formula:

$Pm_{10} = A \times P_{10}$

whereby:
P_{10}: *daily rainfall depth with a ten year return period,*
Pm_{10}: *rainfall depth adapted to the drainage area,*
A : *coefficient of abatement dependent on the watershed area and the mean annual rainfall depth.*

2.5 – HYDROLOGIC INVESTIGATION

Classification of hydrologic models
Calculation of rainfall infiltration
Time-area method
Discharge hydrograph
Synthetic formulae (Rodier, Rational,
Regional statistical methods
Impoundment's routing

Some hydraulic works used for water supply, such as retention dams or diversion weirs, necessitate a separate calculation of their features, such as retention volume or weir height, as a function of the annual runoff characteristics. For these specific calculations the reader should refer to specialised publications. The main purpose of this paragraph is to describe the principal methods used to calculate the design flood in order to dimension the spillway. The ***design flood*** can be determined as a function of watershed and rainfall features. The calculation of the spillway's characteristics, such as height and width, really is the most delicate step of the design of all hydraulic works.

The methods used to evaluate runoff characteristics vary consistently between large and small watersheds. In fact, in small watersheds, the runoff is mainly dependent upon the actual rainstorm. On the contrary, in large watersheds, runoff characteristics are also related to previous rainstorms. Some hydrologic procedures for evaluating runoff characteristics in small watersheds are described below.

Classification of hydrologic models

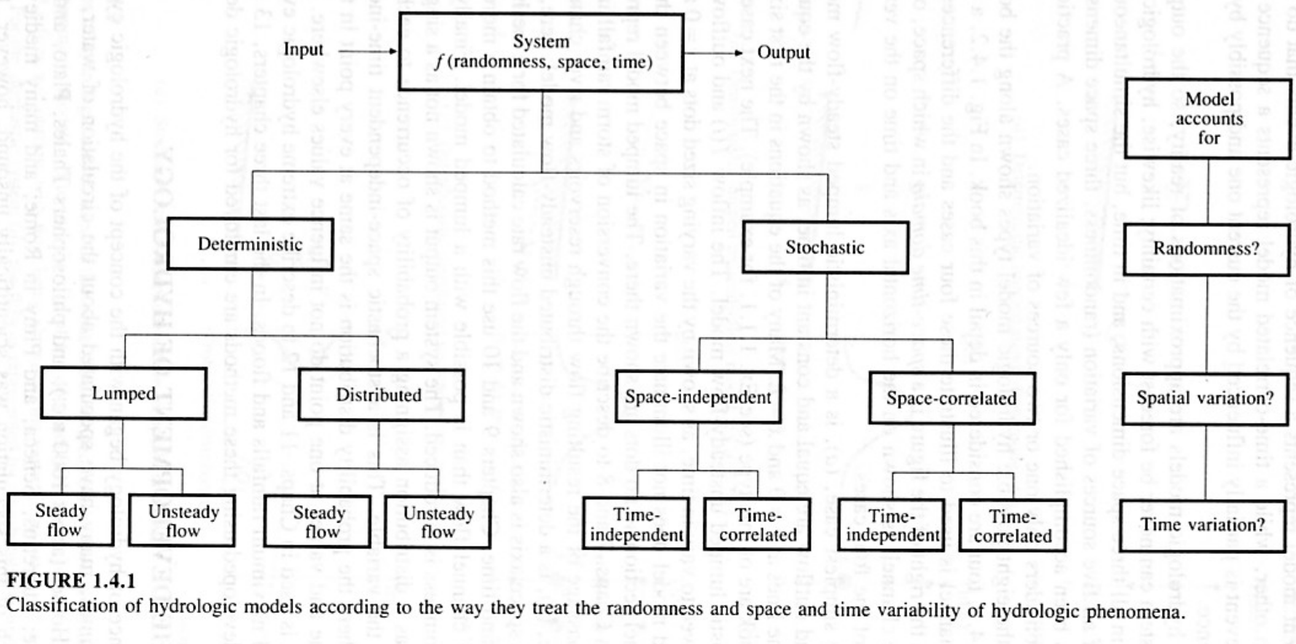


FIGURE 1.4.1
Classification of hydrologic models according to the way they treat the randomness and space and time variability of hydrologic phenomena.

Calculation of rainfall infiltration

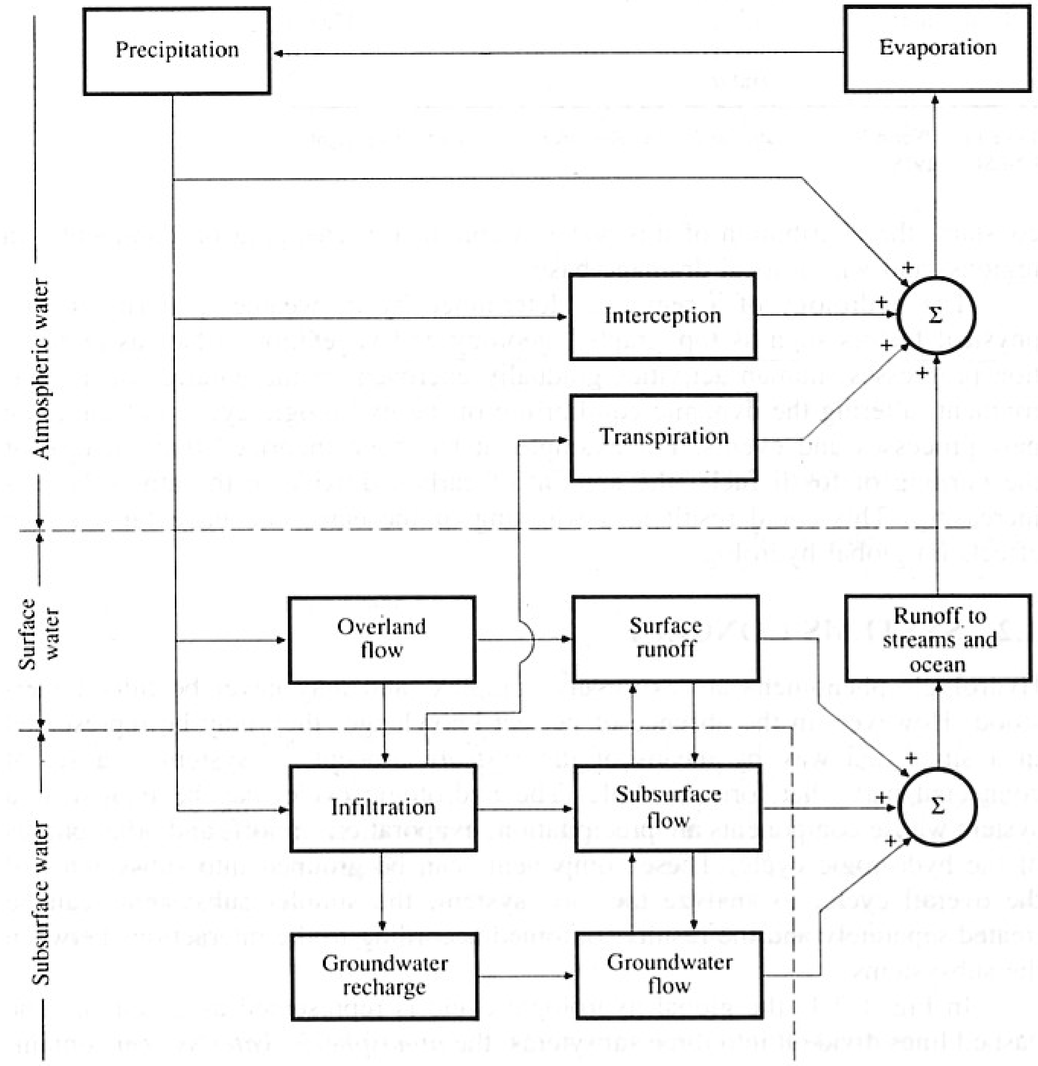


FIGURE 1.2.1
Block-diagram representation of the global hydrologic system.

Precipitation on the pervious surfaces is subject to losses. The following alternative models are to account for the cumulative losses:

The initial and constant-rate loss model;
The deficit and constant-rate model;
The SCS curve number (CN) loss model (composite or gridded); and
The Green and Ampt loss model.

Time-area method

Once net rainfall has been determined for a watershed, it then be comes a central problem of engineering hydrology to convert net rainfall into direct surface runoff. The resulting hydrograph is basically built up from contributions of overland flow and channel flow arriving at different times from all points in the watershed. The relative times of travel of overland and channel flow are related to the size of the watershed; overland flow time is more significant in a small watershed whereas time of travel in the channel predominates in a large watershed.
An interesting way to understand how rainfall excess is converted into a hydrograph is to use the concept of the time-area histogram. This method assumes that the outflow hydrograph results from pure translation of direct runoff to the outlet, ignoring any storage effects in the watershed. If a rainfall of uniform intensity is distributed over the watershed area, water first flows from areas immediately adjacent to the outlet, and the percentage of total area contributing increases progressively in time. For example, in Fig. 2.6 the surface runoff from area A_1(reaches the outlet first, followed by contributions from A_2, A_3, and A_4, in that order.

One can deduce

$$Q_n = R_1 A_1 + R_2 A_2 + R_3 A_3 + R_4 A_4$$

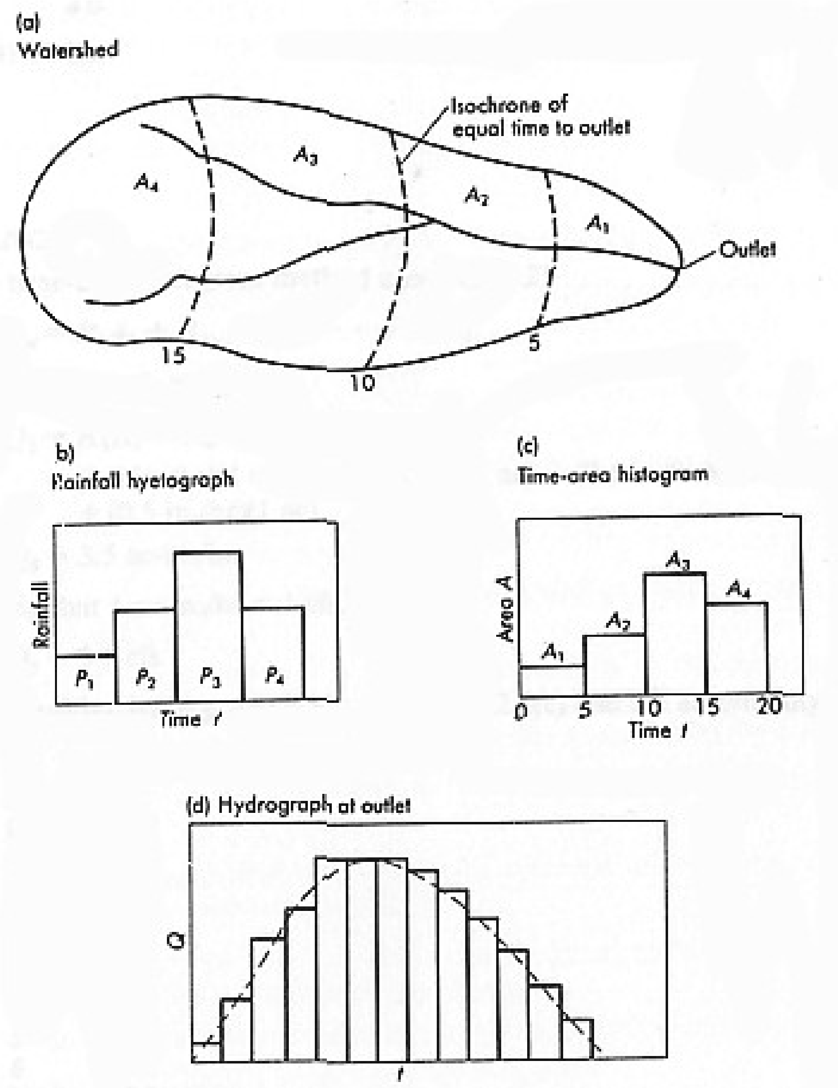
where

Q_n = hydrograph ordinate at time n (m^3/s),
R_i = excess rainfall ordinate at time i (m/s),
A_j= time-area histogram ordinate at time j (m^2).

(Note that the number of hyetograph ordinates need not be equal to the number of histogram ordinates.)

Runoffs from storm period R_1 on A_3, R_2 on A_2 and R_3 on A_1 arrive at the outlet simultaneously to produce Q_3. The total hydrograph is developed by evaluating Q_1, Q_2, Q_3, ..., Q_n.

The time-area concept provides useful insight into the surface runoff phenomena, but its application is limited because of the difficulty of constructing isochronal lines and because the hydrograph must be further adjusted or routed to represent storage effects in the watershed (see Example 2.2). A more general concept in actual practice is the theory of the unit hydrograph, still recognized as one of the most important contributions to hydrology related to surface runoff prediction. This theory, combined with infiltration methods and flood routing in stream channels and reservoirs, is sufficient to handle input rainfall variability and storage effects in small and large watersheds. It should be noted that the time-area method is a special case oft he unit hydrograph approach.



Discharge hydrograph

When the rain rushes into a watershed, the runoff volume can be calculated as shown in the following expression:

V = C x S x h

whereby:

C: runoff coefficient, expressed by the ratio of the volume of runoff and the volume of rainfall,

S: watershed surface,
h: rainfall depth.

Before extrapolating the ***peak rate*** from the runoff volume, it will be helpful to introduce the concept of ***discharge hydrograph***. A hydrograph is a graph representing discharge rate versus time in the outlet of the watershed. A rainstorm hydrograph is generally represented as shown in figure 2.6.

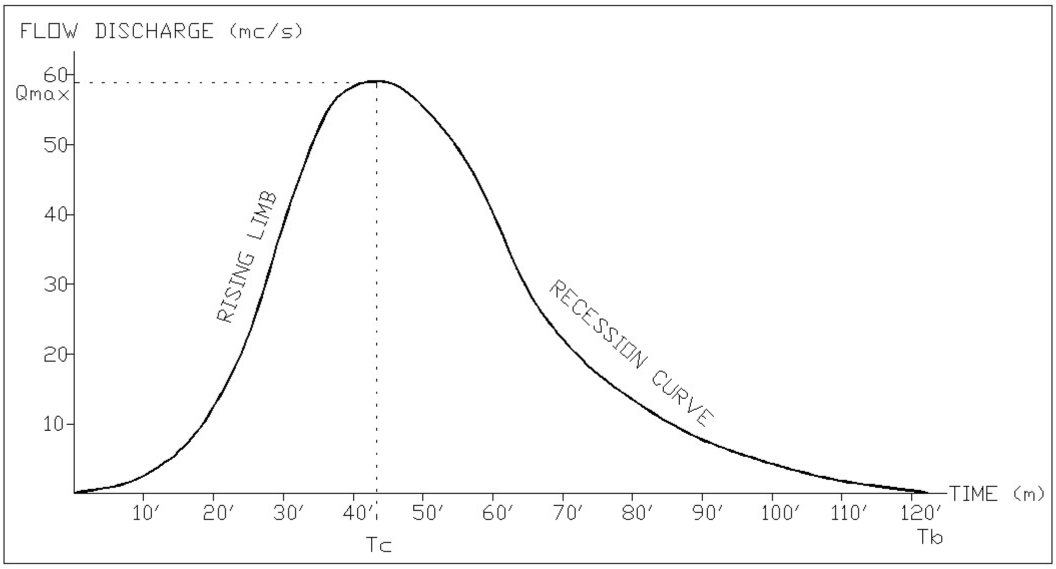


Fig. 2.6 - Discharge hydrograph - rising limb, recession curve

whereby:
q_{max} : maximum discharge rate
t_c : time of concentration,
t_b : base time.

The runoff volume is represented by the surface comprised between the hydrograph and the abscissa's axis. Now, with reference to the concept of hydrograph, a time parameter is needed to quantify the discharge rate of the runoff volume. For this purpose, the most widely used parameter is the ***time of concentration*** (t_c). It is defined as the time necessary for a raindrop to flow from the farthest point in the basin to the outlet.

From the definition of concentration time, it follows that the whole watershed will contribute to the runoff in the outlet, only with rainstorm duration equal to the concentration time. In this case the runoff discharge rate will assume the maximum value and even if the rainfall continues, the discharge rate will tend to be constant. This is only a schematic but effective description of the natural phenomenon of runoff formation. The key hypothesis underpinning the theory described above is that rainstorms be uniformly distributed on the watershed and constant in time.

The concept of concentration time is fundamental in hydraulic works design. In fact, for calculating the spillway's features, it is always necessary to refer to a rainstorm with duration equal to the concentration time of the watershed.

Several existing expressions will allow us to compute the concentration time. To use these formulae, we should dispose of a number of watershed features, such as watershed surface, a parameter to represent basin slope and, sometimes, another parameter to describe basin roughness. ***Rodier's formula*** for calculating concentration time, used for small watersheds, is:

$t_c = a \times (S - b)^{0.5} + c$

where a, b and c are coefficients which depend from the global slope index and from the permeability class of the watershed.

In some hydraulic works, runoff detention can play a determinant role in altering the concentration time. For example, in the case of a detention dam, the concentration time of the system composed by watershed and dam together can be doubled or tripled with respect to the original value of the watershed alone. The rise in concentration time is a function of the impoundment's topography and of the characteristics of the outlet system. It will be necessary to refer to the new value of the concentration time before calculating the design flood.

The principal methods used in the determination of the design flood refer to concentration time, or to another time parameter such as the base time, that is, the total runoff duration. In the ***rational method*** for example, the following relation expresses the maximum discharge rate:

$q_{max} = C \times i_p \times S$ ***(rational method)***

where i_p is the rainfall intensity referred to the time of concentration and derived from the intensity-duration-frequency curve

$i_p = a \times t_c^{\ k}$

this relationship can be obtained directly from the depth-duration-frequency curve, with $k = b - 1$. C is the runoff coefficient, its values are a function of land use, soil group and watershed slope.

For the calculation of a design flood with a ten-year return period, Rodier proposed the following formula:

$Q_{10} = (A \times P_{10} \times Kr_{10} \times \alpha_{10} \times S) / t_b$ ***(Rodier's formula)***

whereby:

A : coefficient of abatement,
P_{10} : rainfall's depth for a daily rainstorm,
Kr_{10} : runoff coefficient,
α_{10} : peak coefficient,
S : watershed surface,
t_b : base time.

The values of P_{10}, Kr_{10} and α_{10} refer to a ten-year return period. All the coefficients of Rodier's formula can be extrapolated from graphs obtained by processing runoff data collected on similar basins.

The ***U.S. S.C.S.*** proposed the most detailed among all the hydrologic methods used for estimating runoff characteristics. This method is based on a very detailed land classification system, briefly mentioned above, in the third paragraph. An index, called ***curve number*** (CN), is associated with each land category. This index can be corrected in function of previous rainstorms (***AMC = antecedent moisture condition***). The capacity of a particular type of land to provoke runoff when interested by a rainstorm depends only from its curve number. In fact, there is a relationship between rainfall's depth, curve number and runoff 's depth.

The S.C.S. also proposed a procedure to evaluate the runoff hydrograph and, consequently, the design flood. When a digital model for soil group, land use and treatment of the drainage area is available, the S.C.S. method is the best suited of all the hydrologic methods mentioned above to elaborate computations of runoff characteristics.

Further hydrologic methods largely used for calculating the discharge hydrograph are based on the theory of Instantaneous Unit Hydrograph (IUH) proposed by Sherman. These methods are characterised by different formulation of the parameters of IUH, the mostly common are: Nash, Clark and Snyder.

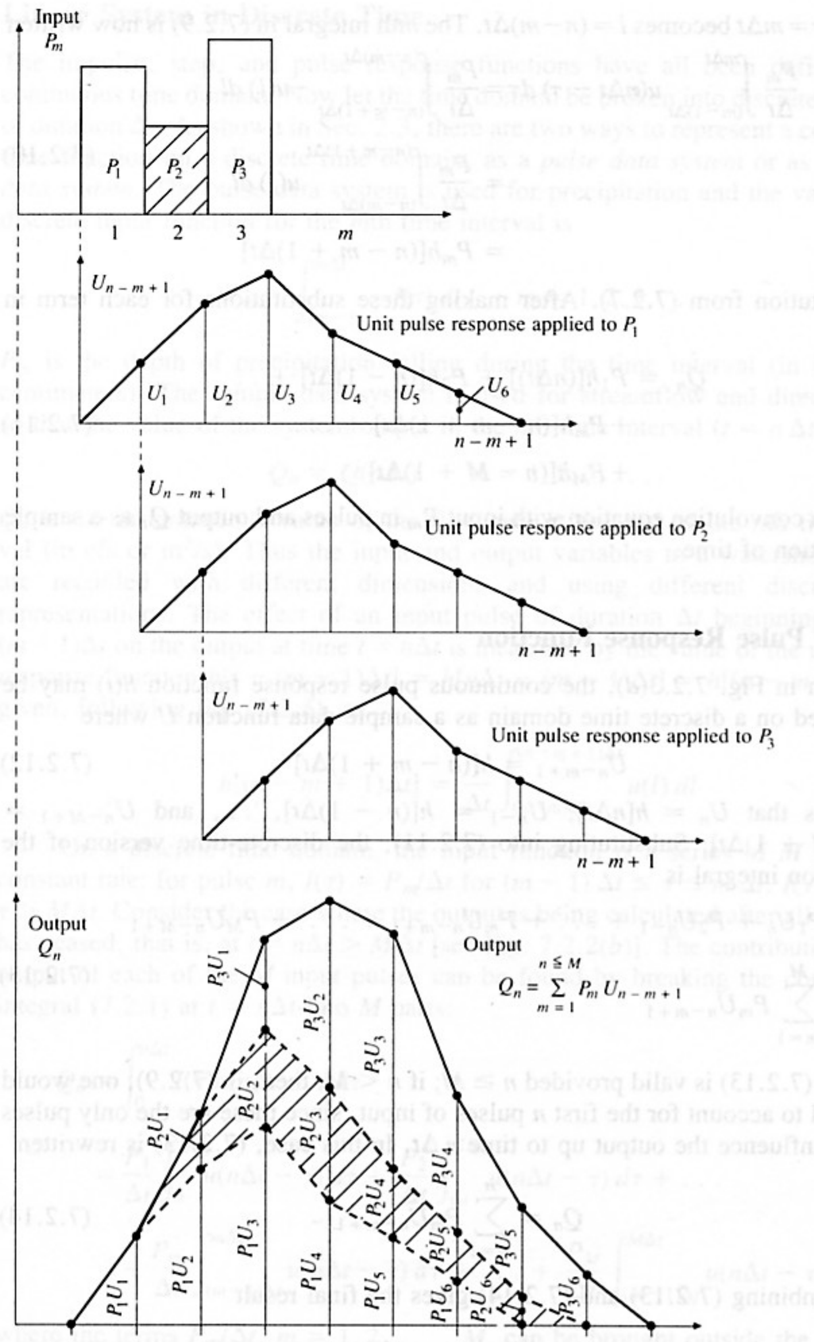


FIGURE 7.2.5
Application of the discrete convolution equation to the output from a linear system.

The three hydrologic methods described above (rational, Rodier and S.C.S.) can be used for both small and medium watersheds. However, hydrologic features should be homogeneous in the drainage area, otherwise local natural phenomena of retention or infiltration could significantly affect runoff characteristics. In this case, these methods can give rise to miscalculations. Therefore, it is fundamental to adopt other hydrologic methods characterised by greater detail in the description of the phenomenon of runoff formation. These methods decompose watersheds in several sub-basins. The runoff features of single sub-basins can be determined using the simple methods described above (rational, Rodier and S.C.S.). Then a routing procedure should be used to calculate the runoff hydrograph at the outlet. The routing method includes also a schematic description of the main drainage axis with detention and infiltration area.

Regional statistical methods

On the contrary, the regional analysis methods entirely leave out all schematic descriptions of the physic phenomenon of runoff formation. They are based only on the statistical elaboration of runoff data collected in the region. Introducing some watershed features, such as drainage area, shape and slope, with these methods it is possible to extrapolate some runoff features, principally the design flood.

The CIEH proposed a statistical method for calculating the design flood with a ten-year return period given by the following relation:

$$Q_{10} = a \times S^s \times P_{an}^p \times I_g^i \times Kr_{10}^k \times D_d^d$$

whereby:

- Q_{10} *: maximum flow rate,*
- S *: watershed surface,*
- P_{an} *: mean annual rainfall's depth,*
- I_g *: global slope index,*
- Kr_{10} *: runoff coefficient,*
- D_d *: drainage density,*
- *a, s, p, i, k and d : coefficients calculated with a method of multiple linear regression.*

Rodier and the CIEH proposed specific expressions to convert, if necessary, the calculated value of design flood from a ten year return period to a different return period.

Utilising one of the hydrologic methods described above, it is always possible to estimate the design flood of the concerned watershed's outlet. But, especially in case of the design of important hydraulic structures, it will be preferable to verify the value obtained for the design flood. The verification can be performed in two principal ways.

The first way consists in estimating the maximum discharge rate that can flow in the outlet as a function of the characteristics of the streambed (e.g. longitudinal slope, roughness, and water's depth – cross section area curve). The maximum discharge rate should then be compared to the design flood values estimated with a hydrologic method.

For the construction of important hydraulic works, it will be useful to previously install a station for measuring the discharge rate in the outlet of the watershed. The discharge rates thus achieved, together with the relative rainfall depths, should then be compared to the results obtained through the application of the hydrologic method used for estimating the design flood.

Impoundment's routing

The movement of a flood wave down a channel or through a reservoir and the associated change in timing or attenuation of the wave constitute an important topic in floodplain hydrology. It is essential to understand the theoretical and practical aspects of flood routing to predict the temporal and spatial variations of a flood wave through a river reach or reservoir. Flood routing methods can also be used to predict the outflow hydrograph from a watershed subjected to a known amount of precipitation. The storage routing concept is most easily understood by referring to Fig. 4.1.

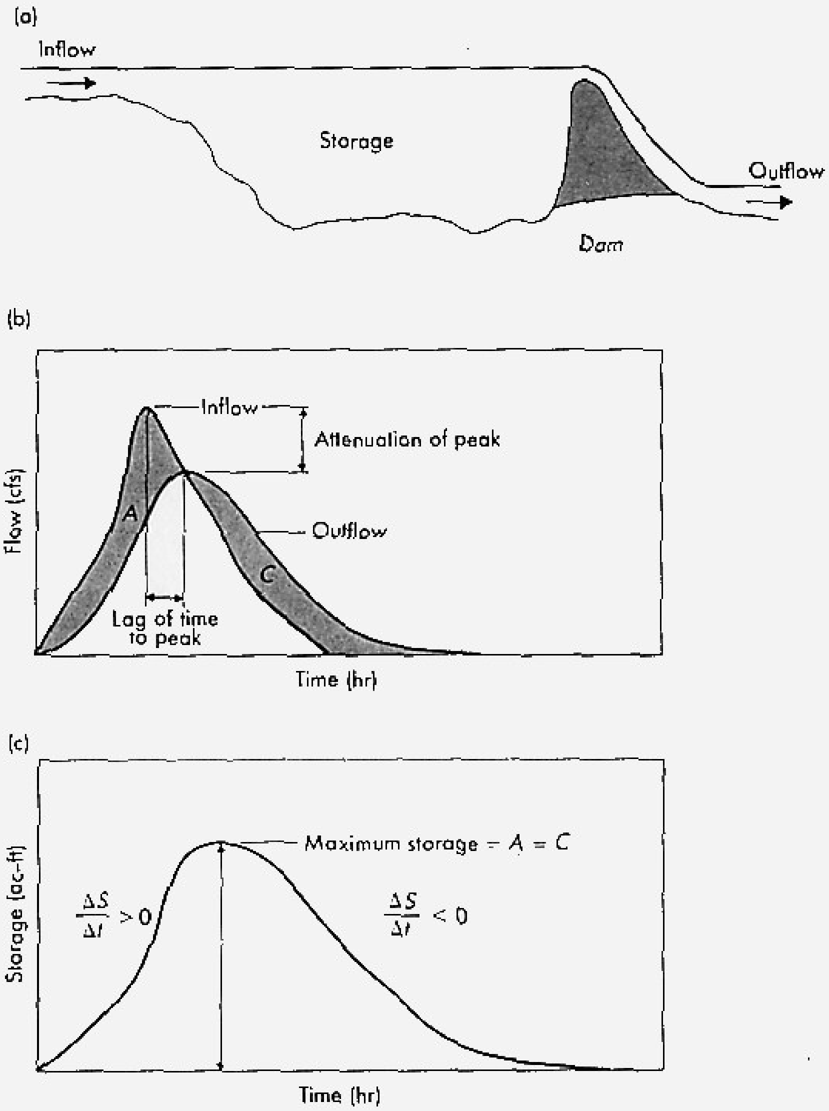


FIGURE 4.1

Reservoir concepts. ***(a) Reservoir storage.*** **(b) Inflow to and outflow from the reservoir. (c) Storage in the reservoir.**

Inflow and outflow hydrographs for a small level-surface reservoir have been plotted on the same graph. Area A represents the volume of water that fills available storage up to time t_1. Inflow exceeds outflow and the reservoir is filling. At time t_1, inflow and outflow are equal and the maximum storage is reached. For times exceeding t_1, outflow exceeds inflow and the reservoir empties. Area represents the volume of water that flows out of the reservoir and must equal area A if the reservoir begins and ends at the same level. The peak of the outflow from a reservoir should intersect the inflow hydrograph as shown in Fig. 4.1 because outflow is uniquely determined by reservoir storage or level.

2.6 – EROSION AND SOLID TRANSPORTATION

Production of sediment in the drainage area
Solid transportation in the drainage axis

The ***production of sediment*** is dependent on soil group-type, land use and agrarian practices in the watershed; it is most often measured in ton / ha / year. The production of sediment is generally provoked by artificial or natural erosion phenomena, such as local agricultural practices or the erosive effects of rainwater. Several methods have been developed to estimate the annual volume of sediment produced in a watershed.

The second aspect concerns the ***capacity*** of minor and major streams to ***transport*** to the outlet the volume of sediment produced in the watershed. Several formulae can be used to calculate the solid transportation characteristics within reach of a stream. Some stream features, such as cross section, longitudinal slope and flow rate, should be known in advance for the computation of solid transportation characteristics. These formulae are all based on ***Shield's theory***, and they allow us to calculate both the volume and the particles' size of solid transportation.

An excessive solid transportation can strongly reduce the storage volume of a retention dam. If possible, in this case, it will be preferable to change site altogether. Otherwise, it will be necessary to diminish the solid transportation with several ***debris dams*** upstream the site.

We can chose among several methods to measure the solid transportation rate in a streambed, with the utilisation of proper sampling devices. However, it is difficult to obtain precise measurements, as usually solid transportation phenomena take place in conjunction with severe floods. Under such circumstances, ordinary solid transportation sampling devices cannot be used.

2.7 – EVAPORATION

Evaporation is caused by solar irradiation and it can also be influenced by wind conditions and by local humidity rates. Water losses caused by evaporation in a watershed can be divided in two different kinds:

- losses in surface water,
- losses in ground water.

To evaluate water losses caused by evaporation in an impoundment, it will be useful to collect evaporation data from standardised basins (BAC). There are several methods to adapt these data so as to achieve the average daily evaporation rates of other impoundments.

Due attention should be paid to evaporation losses from the impoundment in projecting a retention dam. Especially in arid and semi-arid regions, evaporation losses represent a very important percentage of the total storage volume.

Also the roots of trees and plants absorb water from the soil. Several existing formulae can be used to evaluate potential evaporation losses as a function of regional meteorological features.