4 Estimating Peak Runoff Rates

J. Boonstra[1]

4.1 Introduction

When designing a drainage project, we have to know the peak runoff rate, for designing the cross-sections of main drainage canals, culverts, and siphons or the capacity of pumping stations. The source of peak runoff is sometimes water from drainage basins surrounding the project area, or it can be water from the project area itself. The source of peak runoff can also be melting snow, possibly in combination with high rainfall. Because this source of peak runoff occurs very locally, we shall not discuss it here. Anyone wanting more information on this subject should refer to the literature (e.g. Chow 1964).

The magnitude of the peak runoff rate is related to the frequency of occurrence; the higher the peak runoff rate, the less frequently it will occur. In drainage projects, the design return period usually ranges from 5 to 25 years.

In this chapter, we shall discuss the rainfall frequency approach. It involves performing a statistical analysis of the recorded rainfall data and then making an estimate of the design return period. Using certain rainfall-runoff relationships, we then convert this design rainfall into a design runoff; the runoff is thus considered indirectly.

4.2 Rainfall Phenomena

The amount of rain that falls in a certain period is expressed as a depth (in mm) to which it would cover a horizontal plane. Rainfall depth is considered a statistical variate, because it differs according to the season of the year, the duration of the observation period, and the area under study.

Rainfall analysis for drainage design can be restricted to that part of the year when excess rainfall may cause damage. If the drainage problem is one of surface drainage for crop protection, the growing season may be the critical period. If the problem is that of surface drainage for erosion control, the off-season may be critical because of the erosion hazard on bare soils. If the problem is one of accommodating peak runoff, the whole hydrological year may be critical.

Rainfall intensity is expressed as a depth per unit of time. This unit can be an hour, a day, a month, or a year. The type of problem will decide which unit of time to select for analysis. For surface drainage, the critical duration is often of the order of some days, depending on the storage capacity of the system and the discharge intensity of the drainage area. For erosion control and the accommodation of peak runoff in small drainage basins, the storage capacities will be small and information on hourly rainfalls may be required.

Rainfall is measured at certain points. It is likely that the rainfall in the vicinity

[1] International Institute for Land Reclamation and Improvement

of a measurement point will be approximately the same, but farther away from the point this will not be true. Point rainfall can be considerably higher than areal rainfall, depending on the duration of the rainfall and the size of the area. The shorter the duration and the larger the area, the smaller the areal rainfall will be with respect to the point rainfall. So, information on areal rainfall is often also required.

To be able to estimate the design rainfall, we need depth-frequency curves of daily rainfall data or depth-duration-frequency curves that are representative of the area under study. This implies that we have to analyze the depth-area and depth-frequency of the recorded rainfall data.

4.2.1 Depth-Area Analysis of Rainfall

The analysis of rainfall is understood here to mean the analysis of area averages of point rainfalls. Usually, one of the following three methods is employed (Figure 4.1):

- The arithmetic mean of rainfall depths recorded at measuring stations located inside the area under consideration;

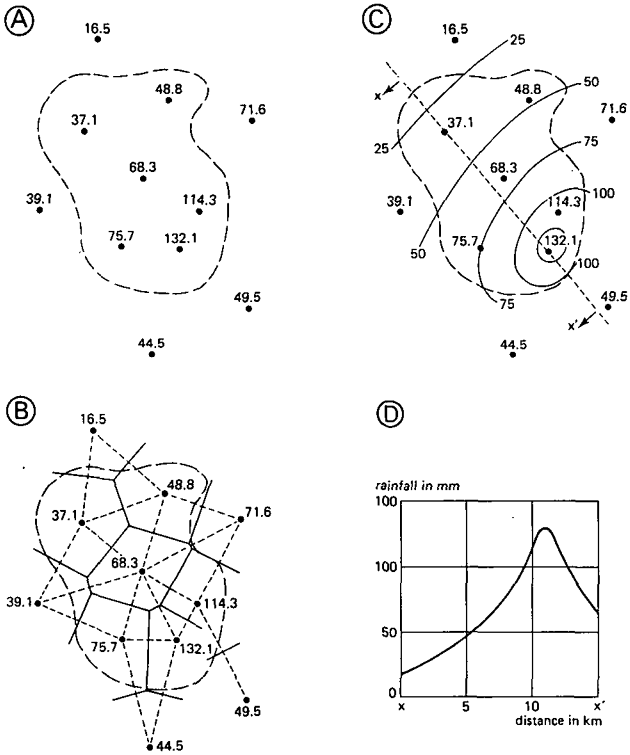

Figure 4.1 Methods of computing areal rainfall: (A) Arithmetic mean method; (B) Thiessen method; (C) Isohyetal method; and (D) Section X-X′ of Figure 4.1.C

- The weighted mean of rainfall depths at stations both inside the area and in its immediate surroundings, the weight being determined by polygons constructed according to the Thiessen method;
- The weighted mean of average rainfall depths between isopluvial lines, the weight being the area enclosed by the isopluvials.

An advantage of the arithmetic mean is its simplicity. The method can only be used in a relatively flat area, where no irregular changes occur in isopluvial spacing and where the stations are evenly distributed, thus being equally representative of the area. With this method, the areal rainfall is calculated as follows

$$\frac{37.1 + 48.8 + 68.3 + 114.3 + 75.7 + 132.1}{6} = 79.4 \text{ mm}$$

The Thiessen method assumes that the rainfall recorded at a station is representative of the area half-way to the stations adjoining it. Each station is connected to its adjacent stations by straight lines, the perpendicular bisectors of which form a pattern of polygons. The area for which each station is representative is the area of its polygon, and this area is used as a weight factor for its rainfall. To get the weighted average rainfall, we have to divide the sum of the products of station areas and rainfalls by the total area covered by all stations. With this method, the areal rainfall is calculated as follows:

Rainfall (mm)	Area (km^2)	Area (%)	Weighted rainfall (mm)
16.5	18	1	0.2
37.1	311	19	7.0
48.8	282	17	8.3
68.3	311	19	13.0
39.1	52	3	1.2
75.7	238	15	11.4
132.1	212	13	17.2
114.3	194	12	13.7
Total	1618	99	72.0

The Thiessen method can be used when the stations are not evenly distributed over the area. As the method is rather rigid, however, excluding as it does possible additional information on local meteorological conditions, its use is restricted to relatively flat areas.

When the rainfall is unevenly distributed over the area (e.g. because of differences in topography), the isohyetal method can be applied. This method consists of drawing lines of equal rainfall depth, isopluvials or isohyets, by interpolation between observed rainfall depths at stations. Any additional information available can be used to adjust the interpolation. With this method, the areal rainfall is calculated as follows:

Isohyet (mm)	Rainfall between isohyets (mm)	Area (km^2)	Area (%)	Weighted rainfall (mm)
125	129.5	33	2	2.6
100	112.5	199	12	13.5
75	87.5	300	19	16.6
50	62.5	507	31	19.4
25	37.5	499	31	11.6
<25	23.0	80	5	1.2
	Total	1618	100	64.9

From the weighted mean of average rainfalls between two isohyets, the weight being the area enclosed between the isohyets, the areal rainfall is calculated. The reliability of the method depends on the accuracy with which the isopluvials can be drawn.

These methods can be applied when rainfall stations are situated within the study area and in its intermediate surroundings. If there is only one rainfall station in or nearby the study area, we can convert the single station data to areal rainfall data by using empirical relationships established from dense networks elsewhere. Many countries have such depth-area-duration curves available, which can be used in case of a single rainfall station.

Figure 4.2 shows an example of depth-area-duration curves. The average areal rainfall is shown as a percentage of the point rainfall. A different relationship is seen for each duration, with steeper gradients for the shorter durations. These relationships are also influenced by other variables such as return period and total rainfall depth; the effect of these variables on the areal rainfall, however, is often obscured.

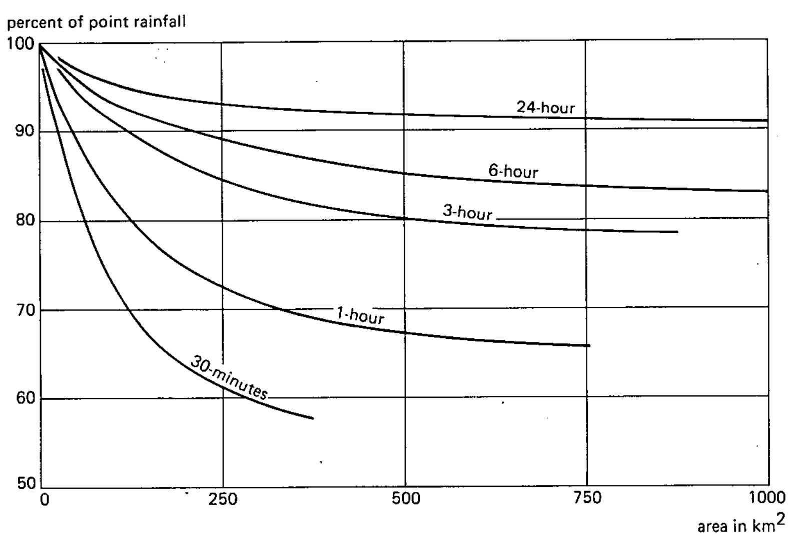

Figure 4.2 Example of depth-area-duration curves (after U.S. Weather Bureau 1958)

Finally, it should be noted that while the curves of Figure 4.2 indicate a reduction for all sizes of area, point rainfalls are often used without reduction for areas up to 25 km^2.

4.2.2 Frequency Analysis of Rainfall

Basically, rainfall is measured with two types of gauges: non-recording gauges and recording gauges.

In non-recording gauges (or pluviometers), the rainfall is measured by periodical readings of the rain that has accumulated in them. This is generally done every 24 hours, which implies that the distribution of rainfall within the interval of observation remains unknown.

Recording gauges (or pluviographs) give continuous readings of the rain being caught in them. They enable the rainfall depth over any period to be read and are a prerequisite if short-duration rainfalls are to be determined.

Anyone wanting more information on rainfall gauges, including networks, should refer to the literature (e.g. Gray 1973).

On the basis of daily rainfall data, depth-frequency curves can be constructed for successive n-day total rainfalls. (These calculation procedures are discussed in Chapter 6.) Depth-duration-frequency curves that provide information on periods longer than one day are usually sufficient for calculating the design capacity of surface drainage systems.

Depth-duration-frequency curves are often required for durations of less than one day. In such cases, continuous records of rainfall should be available. Sometimes rainfall intensity is used instead of rainfall depth. Figure 4.3 gives an example of an intensity-duration-frequency curve. The two types of curves that provide information

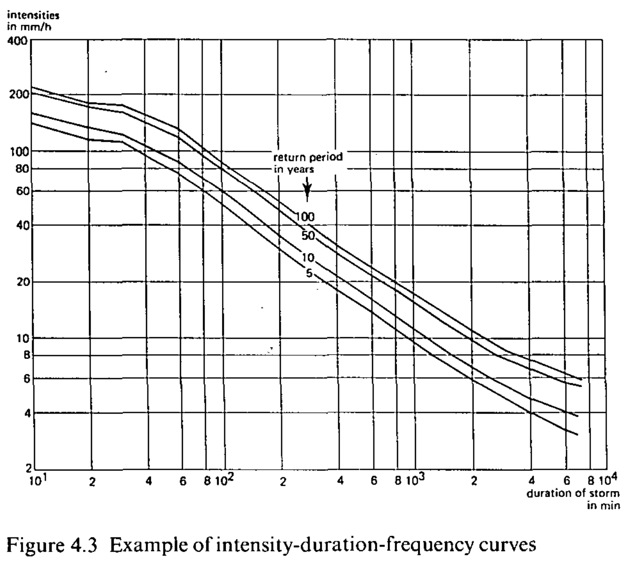

Figure 4.3 Example of intensity-duration-frequency curves

Table 4.1 Ratio of rainfall depth to 2-year 1-hour rainfall depth for different durations and return periods

Rainfall duration	Return period in years				
	2	5	10	25	50
5 min	0.28	0.39	0.48	0.57	0.65
10 min	0.43	0.61	0.73	0.88	1.01
15 min	0.54	0.76	0.91	1.11	1.25
30 min	0.78	1.05	1.35	1.57	1.79
1 h	1	1.35	1.65	2.00	2.25
2 h	1.40	1.89	2.34	2.80	3.15
3 h	1.50	2.02	2.47	3.00	3.37
4 h	1.60	2.16	2.64	3.20	3.60
6 h	1.65	2.25	2.70	3.30	3.70
24 h	2.40	3.25	3.95	4.80	5.40

on any rainfall duration are the basis on which to determine the design rainfall for estimates of peak runoff rates of small areas.

When continuous records of rainfall are not available, the relationships between long and very short duration maximum intensities derived from other sites can be used. Many such relationships exist; they have in common that they plot as straight lines on log-log paper.

Another approach is to use generalized ratios of maximum rainfall of certain durations with certain return periods to 2-year, 1-hour rainfall. Table 4.1 gives an example of such relationships; they give fairly good estimates for countries as different as the U.S.A., Tunisia, Indonesia (Java), and The Netherlands. It will be clear that using these kinds of relationships for arbitrarily chosen areas can yield appreciable errors in the design rainfall.

It should be noted that available rainfall records that are representative of an area often encompass too short a period for a reliable frequency analysis. If no information such as that in Table 4.1 is available, the following procedure can be used. The rainfall data of the station with the short period of records is compared with the corresponding data of a station with a sufficiently long period of records. This is done with a regression analysis as is discussed in Chapter 6. The results of the frequency analysis made for the station with the long period of records can then be converted to frequency data representative of the area under study.

4.3 Runoff Phenomena

4.3.1 Runoff Cycle

The runoff cycle, which is a part of the hydrological cycle, is shown in Figure 4.4. Part of the rainfall will be temporarily stored on the vegetation; this interception will eventually evaporate or reach the soil as stem flow. Rainfall actually reaching the

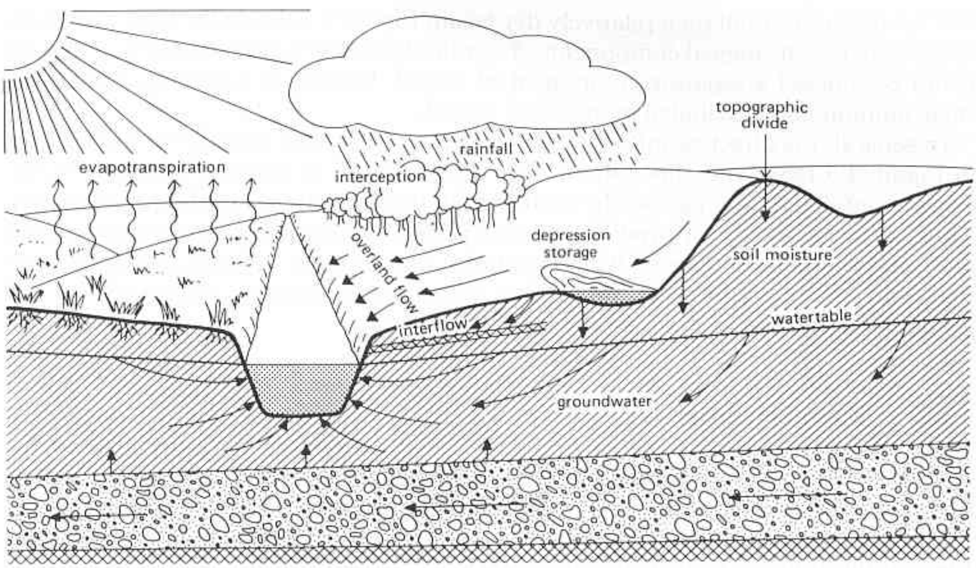

Figure 4.4 Schematization of the runoff cycle

soil may infiltrate into it and part of it will merely become soil moisture, only to be lost again by transpiration or evaporation.

The soil moisture excess will percolate to the watertable and replenish the groundwater system. The groundwater system is slow to respond to the additional supply of infiltrating rain water. When this water is finally discharged into the channel system, it makes up the groundwater runoff, or base flow. Although its contribution to peak runoff is generally small, groundwater runoff in some areas represents the greater part of the annual runoff and is the only source of stream flow during protracted dry spells.

For short high-intensity rainfalls or for prolonged periods of medium-intensity rainfall, the rainfall rate can exceed the soil's maximum infiltration rate. The surplus rainfall will then build up in topographic depressions, from which it will infiltrate or evaporate when the rainfall ceases. If the topographic depressions fill up and begin to overflow, overland flow starts and this water reaches the channel system via rivulets and rills. In areas with deep, highly permeable soils, overland flow may not occur at all, even after rainfalls of the highest intensities. Peak runoff rates are then exclusively attributable to groundwater runoff.

There are thus two main paths by which rainfall water moves to the channel system: over the soil surface and through the groundwater system. Short circuits, however, must also be expected to occur. Water that has already infiltrated into the soil may move over a shallow layer of low permeability, to be forced out again at a lower point of the slope where it changes into overland flow; this process is called interflow. On the other hand, water moving over the soil surface may still become groundwater if it enters an area with a high infiltration capacity, where it infiltrates into the soil.

Overland flow and interflow together make up the direct runoff, which moves swiftly through the drainage basin to the outlet. This direct runoff, together with the groundwater runoff, yields the total runoff from a drainage basin.

For a constant rainfall on a relatively dry basin, Figure 4.5 shows the time variations of the above hydrological components. The rain that falls on the channel system itself is not considered a separate component of runoff, because it is usually a relatively small amount and is included in the direct runoff.

In general, the direct runoff is the major cause of the peak runoff; the shaded area in Figure 4.5 represents this volume. The direct runoff, in its turn, is caused by the excess rainfall (i.e. that part of the total rainfall that contributes to the direct runoff). Thus, as far as the direct runoff is concerned, the difference between excess rainfall and total rainfall are 'losses', which comprise interception, depression storage, and that part of the infiltrated water that either evaporates or percolates to the groundwater system.

4.3.2 Runoff Hydrograph

A drainage basin is the entire area drained by a stream in such a way that all streamflow originating in the area is discharged through a single outlet. The topographic divide that encloses the drainage basin designates the area in which overland flow will move towards the drainage system and ultimately become runoff at the outlet. Topographic maps or aerial photographs are used to determine the actual size of a drainage basin.

According to Chow (1964), the main characteristics of a basin are:
- Geometric factors (e.g. size, shape, slope, and stream density);
- Physical factors: land use and cover, surface infiltration conditions, soil type, geological conditions (e.g. permeability and capacity of the groundwater system), topographic conditions (e.g. the presence of lakes and swamps), artificial drainage;
- Channel characteristics (e.g. size and shape of cross-section, slope, roughness, length).

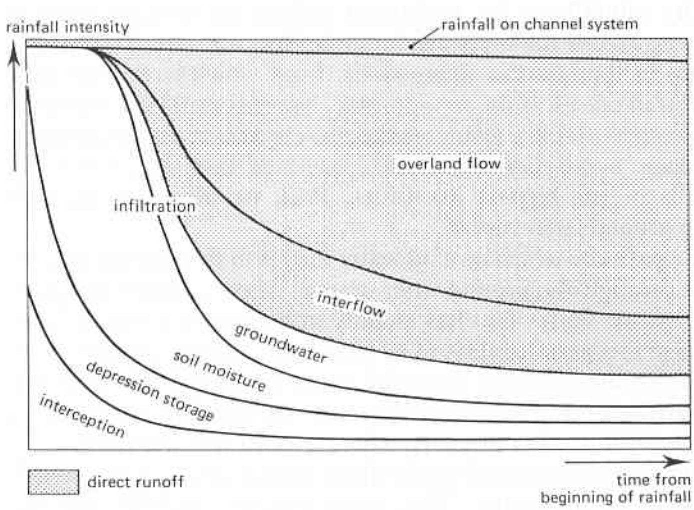

Figure 4.5 Distribution of the total rainfall with time over the various components of the runoff cycle

A graph showing the total runoff at the outlet of a drainage basin with time is called a hydrograph. The hydrograph includes the integrated contributions from overland flow, interflow, and groundwater flow, defining the complexities of the basin characteristics by a single empirical curve.

A typical hydrograph produced by a concentrated high-intensity rainfall is a single-peak skew distribution curve (Figure 4.6). If multiple peaks appear in a hydrograph, they may indicate abrupt variations in rainfall intensity, a succession of high-intensity rainfalls, or other causes.

All single-peaked hydrographs follow the same general pattern (Figure 4.6). This pattern shows a period of rise, culminating in a peak runoff rate, followed by a period of decreasing runoff. Three principal parts can be distinguished:

- A rising limb from Point A, which represents the beginning of direct runoff, to Point B, the first inflection point; its geometry depends on the duration and intensity distribution of the rainfall, the antecedent moisture condition in the drainage basin, and the shape of the basin;
- A crest segment from the first Inflection Point B to the second Inflection Point D, including the peak of the total runoff hydrograph, Point C. The peak runoff represents the highest concentration of the runoff. It usually occurs at a certain time after the rainfall has ceased; this time depends on the areal distribution of the rainfall and its duration;
- A recession limb from Point D onwards. Point D is commonly assumed to mark the cessation of overland flow and interflow at the outlet of the drainage basin. The recession limb represents the withdrawal of water from storage: surface storage, channel storage, and groundwater storage.

The drainage basin, with all its specific characteristics, can thus be regarded as the 'intermediate agent' that turns rainfall on the basin into runoff at the outlet.

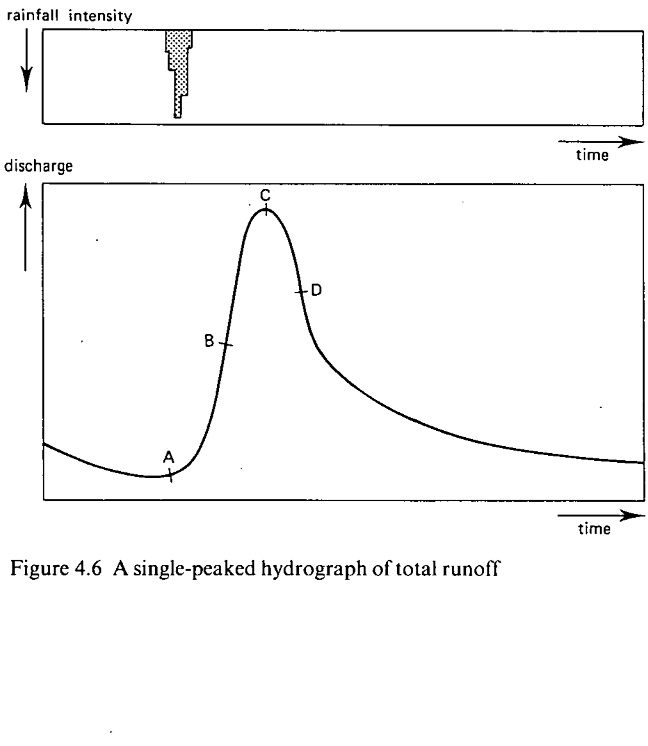

Figure 4.6 A single-peaked hydrograph of total runoff

4.3.3 Direct Runoff Hydrograph

Any hydrograph of total runoff can be considered a hydrograph of direct runoff, superimposed on a hydrograph of groundwater runoff. Methods of estimating peak runoff rates, which are based on the volume of direct runoff, have been developed. It is thus logical to attempt to separate the total runoff hydrograph into two parts, so that the phenomenon of direct runoff can be analyzed independently.

Let us consider a single-peaked hydrograph of total runoff as shown in Figure 4.7A. The sharp departure at Point A designates the arrival of direct runoff at the point of measurement. The start of direct runoff can usually be determined from a visual inspection of the hydrograph of total runoff.

Locating the end of the direct runoff is less straightforward, but we make use of the fact that the recession limb of a hydrograph of total runoff represents the depletion of water from different storages, as was mentioned in the previous section. When

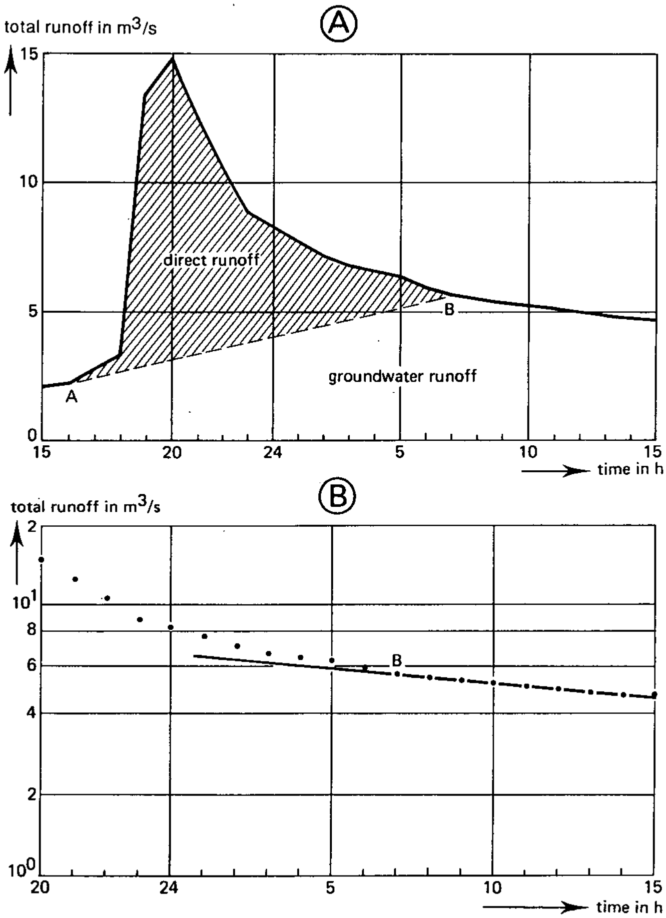

Figure 4.7 Observed hydrograph of total runoff: (A) Separation into direct runoff and groundwater runoff; and (B) Recession limb of hydrograph of total runoff with groundwater depletion curve (straight line)