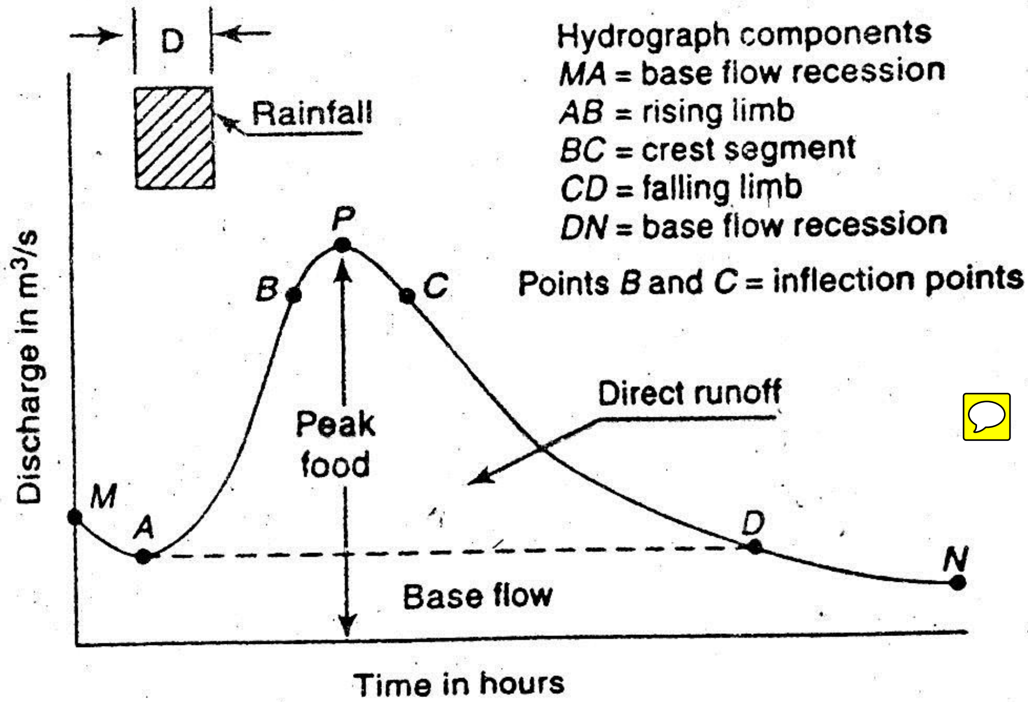



Fig. 6.1 Elements of a Flood Hydrograph

## 6.4 BASE FLOW SEPARATION

In many hydrograph analyses a relationship between the surface-flow hydrograph and the effective rainfall (i.e. rainfall minus losses) is sought to be established. The surface-flow hydrograph is obtained from the total storm hydrograph by separating the quick-response flow from the slow'response runoff. It is usual to consider the interflow as a part of the surface flow in view of its quick response. Thus only the base flow is to be deducted from the total storm hydrograph to obtain the surface flow hydrograph.

There are three methods of base-flow separation that are in common use.

### METHODS OF BASE-FLOW SEPARATION

*METHOD I—STRAIGHT-LINE METHOD* In this method the separation of the base flow is achieved by joining with a straight line the beginning of the surface runoff to a point on the recession limb representing the end of the direct runoff. In Fig. 6.5 point $A$ represents the beginning of the direct runoff and it is usually easy to identify in view of the sharp change in the runoff rate at that point.

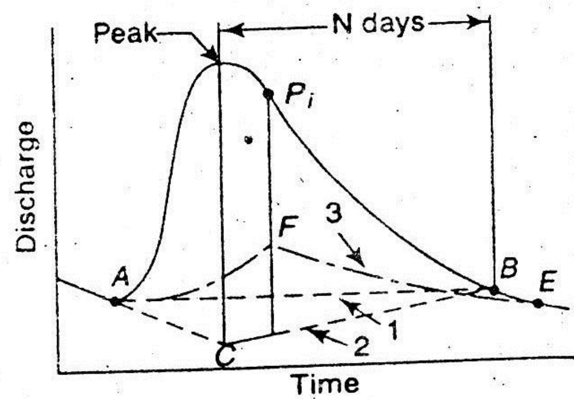


Fig. 6.5 Base Flow Seperation Methods

Point $B$, marking the end of the direct runoff is rather difficult to locate exactly. An empirical equation for the time interval $N$ (days) from the peak to the point $B$ is

$$N = 0.83A^{0.2} \tag{6.4}$$

where $A$ = drainage area in km$^2$ and $N$ is in days. Points $A$ and $B$ are joined by a straight line to demarcate to the base flow and surface runoff. It should be realised that the value of $N$ obtained as above is only approximate and the position of $B$ should be decided by considering a number of hydrographs for the catchment. This method of base-flow separation is the simplest of all the three methods.

*METHOD 2* In this method the base flow curve existing prior to the commencement of the surface runoff is extended till it intersects the ordinate drawn at the peak (point $C$ in Fig. 6.5). This point is joined to point $B$ by a straight line. Segment $AC$ and $CB$ demarcate the base flow and surface runoff. This is probably the most widely used base-flow separation procedure.

*METHOD 3* In this method the base flow recession curve after the depletion of flood water is extended backwards till it intersects the ordinate at the point of inf tion (line *EF* in Fig. 6.5). Points *A* and *F* are joined by an arbitrary smooth curve. method of base-flow separation is realistic in situations where the groundwater coi butions are significant and reach the stream quickly.

It is seen that all the three methods of base-flow separation are rather arbitrary. selection of anyone of them depends upon the local practice and successful pre tions achieved in the past. The surface runoff hydrograph obtained after the base- separation is also known as *direct runoff hydrograph* (DRH).

## 6.5 EFFECTIVE RAINFALL (ER)

*Effective rainfall* (also known as *Excess rainfall*) (ER) is that part of the rainfall becomes direct runoff at the outlet of the watershed. It is thus the total rainfall given duration from which abstractions such as infiltration and initial losses are tracted. As such, ER could be defined as that rainfall that is neither retained o land surface nor infiltrated into the soil.

For purposes of correlating DRH with the rainfall which produced the flow, the hyetograph of the rainfall is also pruned by deducting the losses. Figure 6.6 shows the hyetograph of a storm. The initial loss and infiltration losses are subtracted from it. The resulting hyetograph is known as *effective rainfall hyetograph* (ERH). It is also known as *excess rainfall hyetograph*.

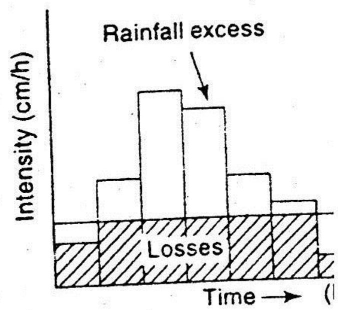



**Fig. 6.6** Effective Rai Hyetograph (E

Both DRH and ERH represent the same total quantity but in different units. Since ERH is usually in cm/h plotted against time, the area of ERH multiplied by the catchment area gives the total volume of direct runoff which same as the area of DRH. The initial loss and infiltration losses are estimated ba the available data of the catchment.

**EXAMPLE 6.2** *Rainfall of magnitude 3.8 cm and 2.8 cm occurring on two cons 4-h durations on a catchment of area 27 km² produced the following hydrograph at the outlet of the catchment. Estimate the rainfall excess and $\phi$ index.*

| Time from start of rainfall (h) | –6 | 0 | 6 | 12 | 18 | 24 | 30 | 36 | 42 | 48 | 54 | 60 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Observed flow ($m^3/s$) | 6 | 5 | 13 | 26 | 21 | 16 | 12 | 9 | 7 | 5 | 5 | 4.5 |

*SOLUTION:* The hydrograph is plotted to scale (Fig. 6.7). It is seen that th hydrograph has a base-flow component. For using the simple straight-line method flow separation, by eg. (6.4)

$$N = 0.83 \times (27)^{0.2} = 1.6 \text{ days} = 38.5 \text{ h}$$

However, by inspection, DRH starts at $t = 0$, has the peak at $t = 12$ h and ends at (which gives a value of $N = 48 - 12 = 36$ h). As $N = 36$ h appears to be more sati

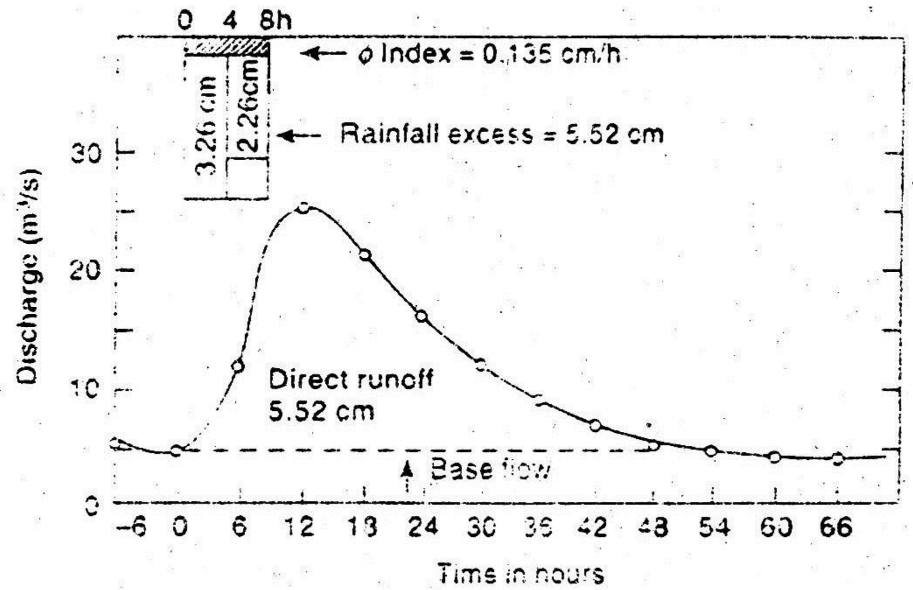



Fig. 6.7 Base Flow Separation – Example 6.2

than $N = 38.5$ h. in the present case DRH is assumed to exist from $t = 0$ to 48 h. A straight line base flow separation gives a constant value of 5 m³/s for the base flow.

$$\text{Area of DRH} = (6 \times 60 \times 60)\left[\frac{1}{2}(8) + \frac{1}{2}(8+21) + \frac{1}{2}(21+16) + \frac{1}{2}(16+11) + \frac{1}{2}(11+7) + \frac{1}{2}(7+4) + \frac{1}{2}(4+2) + \frac{1}{2}(2)\right]$$

$$= 3600 \times 6 \times (8 + 21 + 16 + 11 + 7 + 4 + 2) = 1.4904 \times 10^6 \text{ m}^3$$

= Total direct runoff due to storm

$$\text{Runoff depth} = \frac{\text{runoff volume}}{\text{catchment area}} = \frac{1.4904 \times 10^6}{27 \times 10^6} = 0.0552 \text{ m}$$

= 5.52 cm = rainfall excess

Total rainfall = 3.8 + 2.8 = 6.6 cm

Duration = 8 h

$$\phi \text{ index} = \frac{6.6 - 5.52}{8} = 0.135 \text{ cm/h}$$

## 6.6 UNIT HYDROGRAPH

The problem of predicting the flood hydrograph resulting from a known storm in catchment has received considerable attention. A large number of methods are pr posed to solve this problem and of them probably the most popular and widely us method is the *unit-hydrograph method*. This method was first suggested by Sherm in 1932 and has undergone many refinements since then.

A *unit hydrograph* is defined as the hydrograph of direct runoff resulting from o unit depth (1 cm) of rainfall excess occurring uniformly over the basin and at a ur form rate for a specified duration (D hours). The term unit here refers to a unit dep of rainfall excess which is usually taken as 1 cm. The duration, being a very importa characteristic, is used as a prefix to a specific unit hydrograph. Thus one has a 6-h u hydrograph, 12-h unit hydrograph, etc. and in general a *D-h* unit hydrograph applic ble to a given catchment.

**EXAMPLE 6.4** *Given below are the ordinates of a 6-h unit hydrograph for a catchment. Calculate the ordinates of the DRH due to a rainfall excess of 3.5 cm occurring in 6 h.*

| Time (h) | 0 | 3 | 6 | 9 | 12 | 15 | 18 | 24 | 30 | 36 | 42 | 48 | 54 | 60 | 69 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UH ordinate ($m^3/s$) | 0 | 25 | 50 | 85 | 125 | 160 | 185 | 160 | 110 | 60 | 36 | 25 | 16 | 8 | 0 |

SOLUTION: The desired ordinates of the DRH are obtained by multiplying the ordinates of the unit hydrograph by a factor of 3.5 as in Table 6.3. The resulting DRH as also the unit hydrograph are shown in Fig. 6.10 (a). Note that the time base of DRH is not changed and remains the same as that of the unit hydrograph. The intervals of coordinates of the unit hydrograph (shown in column 1) are not in any way related to the duration of the rainfall excess and can be any convenient value.

**Table 6.3** Calculation of DRH Due to 3.5 ER—Example 6.4

| Time (h) | Ordinate of 6-h unit hydrograph ($m^3/s$) | Ordinate of 3.5 cm DRH ($m^3/s$) |
|---|---|---|
| 1 | 2 | 3 |
| 0 | 0 | 0 |
| 3 | 25 | 87.5 |
| 6 | 50 | 175.0 |
| 9 | 85 | 297.5 |
| 12 | 125 | 437.5 |
| 15 | 160 | 560.0 |
| 18 | 185 | 647.5 |
| 24 | 160 | 560.0 |
| 30 | 110 | 385.0 |
| 36 | 60 | 210.0 |
| 42 | 36 | 126.0 |
| 48 | 25 | 87.5 |
| 54 | 16 | 56.0 |
| 60 | 8 | 28.0 |
| 69 | 0 | 0 |

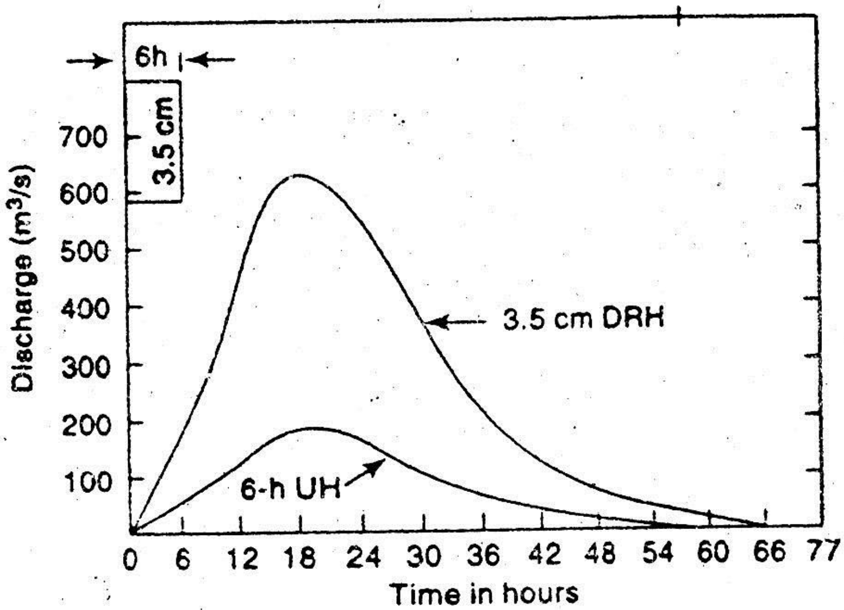



**Fig. 6.10(a)** 3.5 cm DRH derived from 6-h Unit Hydrograph — Example 6.4

**Example 6.5** *Two storms each of 6-h duration and having rainfall excess values of 3.0 and 2.0 cm respectively occur successively. The 2-cm ER rain follows the 3-cm rain. The 6-h unit hydrograph for the catchment is the same as given in Example 6.4. Calculate the resulting DRH.*

*Solution:* First, the DRHs due to 3.0 and 2.0 cm ER are calculated, as in Example 6.3 by multiplying the ordinates of the unit hydrograph by 3 and 2 respectively. Noting that the 2-cm DRH occurs after the 3-cm DRH, the ordinates of the 2-cm DRH are lagged by 6 hrs as shown in column 4 of Table 6.4. Columns 3 and 4 give the proper sequence of the two DRHs. Using the method of superposition, the ordinates of the resulting DRH are obtained by combining the ordinates of the 3- and 2-cm DRHs at any instant. By this process the ordinates of the 5 cm DRH are obtained in column 5. Figure 6.10(b) shows the component 3- and 2-cm DRHs as well as the composite 5-cm DRH obtained by the method of superposition.

**Table 6.4** Calculation of DRH by method of Superposition—Example 6.5

| Time (h) | Ordinate of 6-h UH ($m^3/s$) | Ordinate of 3-cm DRH (col. 2) × 3 | Ordinate of 2-cm DRH (col. 2 lagged by 6 h) × 2 | Ordinate of 5-cm DRH (col. 3 + col. 4) ($m^3/s$) | Remarks |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 |
| 0 | 0 | 0 | 0 | 0 | |
| 3 | 25 | 75 | 0 | 75 | |
| 6 | 50 | 150 | 0 | 150 | |
| 9 | 85 | 255 | 50 | 305 | |
| 12 | 125 | 375 | 100 | 475 | |
| 15 | 160 | 480 | 170 | 650 | |
| 18 | 185 | 555 | 250 | 805 | |

(*Contd.*)

| | | | | | |
|---|---|---|---|---|---|
| (21) | (172.5) | (517.5) | (320) | (837.5) | Interpolated value |
| 24 | 160 | 480 | 370 | 850 | |
| 30 | 110 | 330 | 320 | 650 | |
| 36 | 60 | 180 | 220 | 400 | |
| 42 | 36 | 108 | 120 | 228 | |
| 48 | 25 | 75 | 72 | 147 | |
| 54 | 16 | 48 | 50 | 98 | |
| 60 | 8 | 24 | 32 | 56 | |
| (66) | (2.7) | (8.1) | (16) | (24.1) | Interpolate value |
| 69 | 0 | 0 | (10.6) | (10.6) | Interpolate value |
| 75 | 0 | 0 | 0 | 0 | |

*Note:* 1. The entries in col. 4 are shifted by 6 h in time relative to col. 2.
2. Due to unequal time interval of ordinates a few entries have to be interpolated complete the table. These interpolated values are shown in parentheses.

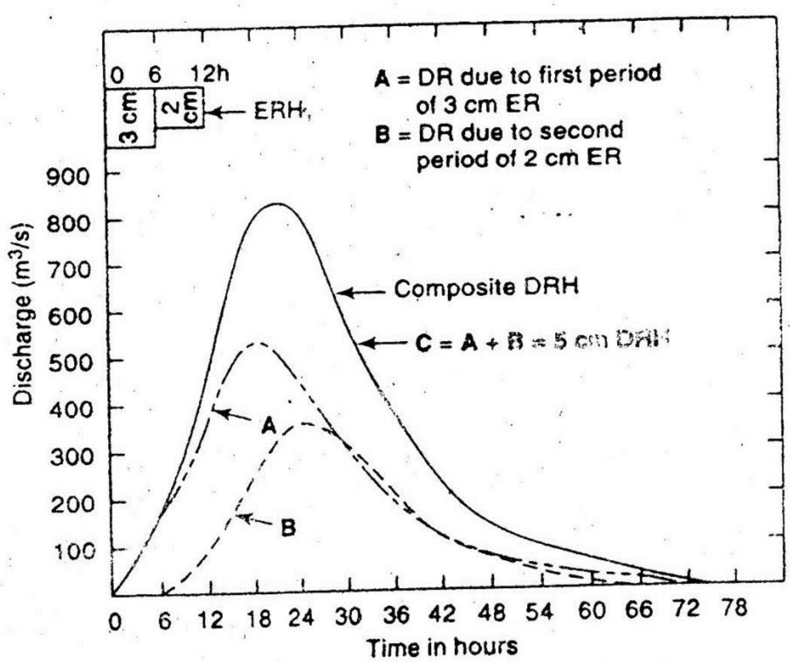



**Fig. 6.10(b)** Principle of Superposition—Example 6.5

## 6.8 UNIT HYDROGRAPHS OF DIFFERENT DURATIONS

Ideally, unit hydrographs are derived from simple isolated storms and if the dura of the various storms do not differ very much, say within a band of ± 20% *D*, would all be grouped under one average duration of *D*-h. If in practical applicat unit hydrographs of different durations are needed they are best derived from data. Lack of adequate data normally precludes development of unit hydrographs ering a wide range of durations for a given catchment. Under such conditions a *D* unit hydrograph is used to develop unit hydrographs of differing durations *nD*. methods are available for this purpose.

- Method of superposition
- The *S*-curve

These are discussed below.

### METHOD OF SUPERPOSITION

If a *D*-h unit hydrograph is available, and it is desired to develop a unit hydrograp *nD* h, where *n* is an integer, it is easily accomplished by superposing *n* unit hydrogr with each graph separated from the previous on by *D*-h. Figure 6.15 shows three unit hydrographs *A*, *B* and *C*. Curve *B* begins 4 h after *A* and *C* begins 4-h, aft Thus the combination of these three curves is a DRH of 3 cm due to an ER of duration. If the ordinates of this DRH are now divided by 3, one obtains a 12-h hydrograph. The calculations are easy if performed in a tabular form (Table 6.7)

**EXAMPLE 6.9** *Given the ordinates of a 4-h unit hydrograph as below derive the nates of a 12-h unit hydrograph for the same catchment.*

| Time (h) | 0 | 4 | 8 | 12 | 16 | 20 | 24 | 28 | 32 | 36 | 40 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ordinate of 4-h UH | 0 | 20 | 80 | 130 | 150 | 130 | 90 | 52 | 27 | 15 | 5 |

*SOLUTION:* The calculations are performed in a tabular form in Table 6.7. In this

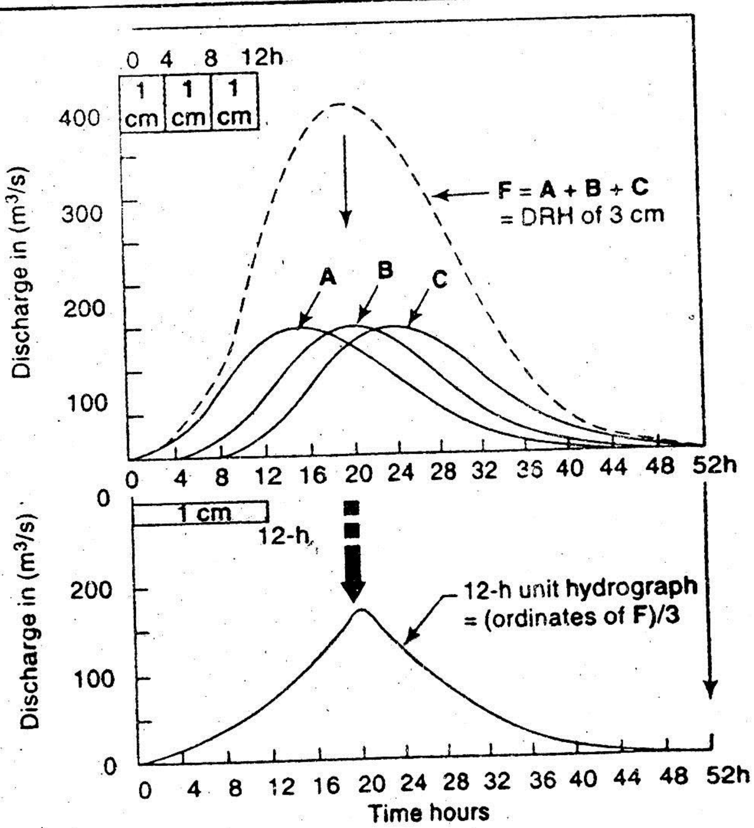
Column 3 = ordinates of 4-h UH lagged by 4-h
Column 4 = ordinates of 4-h UH lagged by 8-h
Column 5 = ordinates of DRH representing 3 cm ER in 12-h
Column 6 = ordinates of 12-h UH = (Column 5)/3

The 12-h unit hydrograph is shown in Fig. 6.15.

### THE S-CURVE

If it is desired to develop a unit hydrograph of duration *mD*, where *m* is a fraction method of superposition cannot be used. A different technique known as the *S*-c method is adopted in such cases, and this method is applicable for rational values ble 6.7 Calculation of a 12-h Unit Hydrograph from a 4-H Unit Hydrograph—Example 6.9

| Time (h) | Ordinates of 4-h UH ($m^3$/s) *A* | *B* Lagged by 4-h | *C* Lagged by 8-h | DRH of 3 cm in 12-h ($m^3$/s) (Col. 2+3+4) | Ordinate of 12-h UH ($m^3$/s) (Col. 5)/3 |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 |
| 0 | 0 | — | — | 0 | 0 |
| 4 | 20 | 0 | — | 20 | 6.7 |
| 8 | 80 | 20 | 0 | 100 | 33.3 |
| 12 | 130 | 80 | 20 | 230 | 76.7 |
| 16 | 150 | 130 | 80 | 360 | 120.0 |
| 20 | 130 | 150 | 130 | 410 | 136.7 |
| 24 | 90 | 130 | 150 | 370 | 123.3 |
| 28 | 52 | 90 | 130 | 272 | 90.7 |
| 32 | 27 | 52 | 90 | 169 | 56.3 |
| 36 | 15 | 27 | 52 | 94 | 31.3 |
| 40 | 5 | 15 | 27 | 47 | 15.7 |
| 44 | 0 | 5 | 15 | 20 | 6.7 |
| 48 | | 0 | 5 | 5 | 1.7 |
| 52 | | | 0 | 0 | 0 |




ig. 6.15 Construction of a 12-h Unit Hydrograph from a 4-h Unit Hydrograph—Example 6.9

The *S-curve*, also known as *S-hydrograph* is a hydrograph produced by a continuous effective rainfall at a constant rate for an infinite period. It is a curve obtained by summation of an infinite series of *D*-h unit hydrographs spaced *D*-h apart. Figure 6.15 shows such a series of *D*-h hydrograph arranged with their starting points *D*-h apart. At any given time the ordinates of the various curves occurring at that time coordinate are summed up to obtain ordinates of the S-curve. A smooth curve through these ordinates result in an S-shaped curve called S-curve.

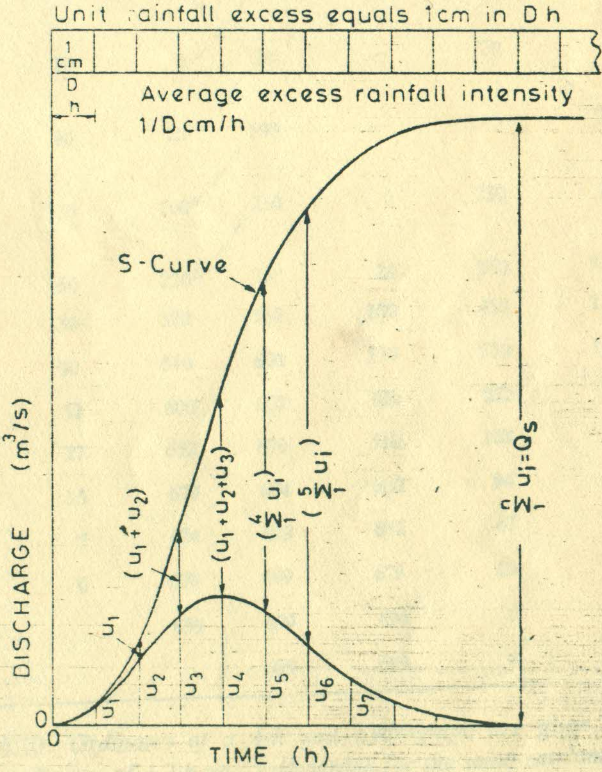



**Fig. 6.15** *S*-curve

This *S*-curve is due to a *D*-h unit hydrograph. It has an initial steep portion and reaches a maximum equilibrium discharge at a time equal to the time base of the first unit hydrograph. The average intensity of ER producing the S-curve is $1/D$ cm/h and the equilibrium discharge,

$$Q_s = \left(\frac{A}{D} \times 10^4\right) \text{m}^3/\text{h},$$

where $A$ = area of the catchment in km² and $D$ = duration in hours of ER of the unit hydrograph used in deriving the S-curve. Alternatively

$$Q_s = 2.778 \; \frac{A}{D} \; \text{m}^3/\text{s} \qquad (6.7)$$

where $A$ is in km$^2$ and $D$ is in h. The quantity $Q_s$ represents the maximum rate at which an ER intensity of $1/D$ cm/h can drain out of a catchment of area $A$. In actual construction of an S-curve, it is found that the curve oscillates in the top portion at around the equilibrium value due to magnification and accumulation of small errors in the hydrograph. When it occurs, an average smooth curve is drawn such that it reaches a value $Q_s$ at the time base of the unit hydrograph.

Consider two $D$-h S-curves $A$ and $B$ displaced by $T$ h (Fig. 6.16). If the ordinates of $B$ are subtracted from that of $A$, the resulting curve is a DRH produced by a rainfall excess of duration $T$ h and magnitude $\left(\frac{1}{D} \times T\right)$ cm. Hence if the ordinate differences of $A$ and $B$, i.e. $(S_A - S_B)$ are divided by $T/D$, the resulting ordinates denote a hydrograph due to an ER of 1 cm and of duration $T$ h, i.e. a $T$-h unit hydrograph. The derivation of a $T$-h unit hydrograph as above can be achieved either by graphical means or by arithmetic computations in a tabular form as indicated in Example 6.9.

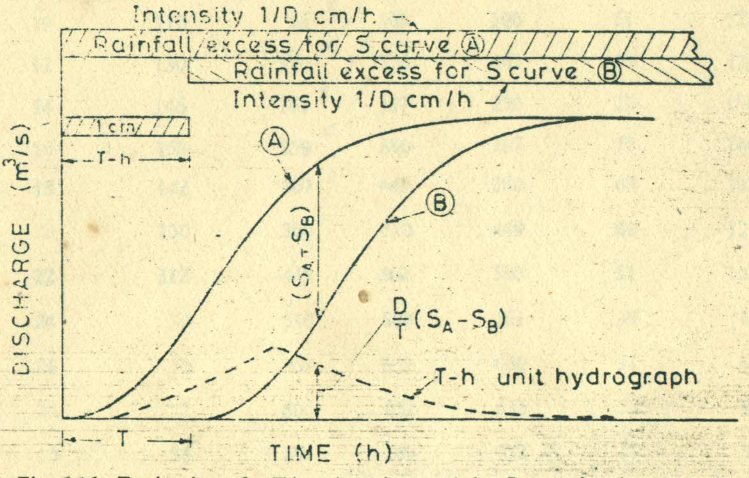



**Fig. 6.16** **Derivation of a *T*-h unit hydrograph by *S*-curve lagging method**

EXAMPLE 6.9 *Solve Example 6.8 by the S-curve method.*

The computations are shown in Table 6.7. Column 2 shows the ordinates of the 4-h unit hydrograph. Column 3 gives the S-curve additions and column 4 the S-curve ordinates. The sequence of additions are shown by arrows. At $t = 4$ h, ordinate of the 4-h UH = ordinate of the S-curve. This value becomes the S-curve addition at $t = 2 \times 4 = 8$ h. At this $t = 8$ h, the ordinate of UH (80) + S-curve addition (20) = S-curve ordinate (100). The S-curve addition at $t = 3 \times 4 = 12$ h is 100, and so on. Column 5 shows the S-curve lagged by 12 h. Column 6 gives the subtraction of lagged S-curve (column 5) from the S-curve (column 4). Ordinates shown in column 6 are divided by $T/D = 12/4 = 3$ to obtain the ordinates of the 12-h unit hydrograph shown in column 7.

TABLE 6.7 DETERMINATION OF A 12-h UNIT HYDROGRAPH BY S-CURVE METHOD—*Example 6.9*

| Time (h) | Ordinate of 4-h UH ($m^3/s$) | S-curve addition ($m^3/s$) | S-curve ordinate ($m^3/s$) (Col. 2 + Col. 3) | S-curve lagged by 12 h ($m^3/s$) | (Col. 4 — Col. 5) | Col. 6 / (12/4) = 12-h UH ordinates ($m^3/s$) |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 0 | 0 | — | 0 | — | 0 | 0 |
| 4 | 20 | 0 | 20 | — | 20 | 6.7 |
| 8 | 80 | 20 | 100 | — | 100 | 33.3 |
| 12 | 130 | 100 | 230 | 0 | 230 | 76.7 |
| 16 | 150 | 230 | 380 | 20 | 360 | 120.0 |
| 20 | 130 | 380 | 510 | 100 | 410 | 136.7 |
| 24 | 90 | 510 | 600 | 230 | 370 | 123.3 |
| 28 | 52 | 600 | 652 | 380 | 272 | 90.7 |
| 32 | 27 | 652 | 679 | 510 | 169 | 56.3 |
| 36 | 15 | 679 | 694 | 600 | 94 | 31.3 |
| 40 | 5 | 694 | 699 | 652 | 47 | 15.7 |
| 44 | 0 | 699 | 699 | 679 | 20 | 6.7 |
| 48 | | 699 | 699 | 694 | 5 | 1.7 |
| 54 | | | 699 | 699 | 0 | 0 |

EXAMPLE 6.10 *Ordinates of a 4-h unit hydrograph are given. Using this derive the ordinates of a 2-h unit hydrograph for the same catchment.*

| Time (h) | 0 | 4 | 8 | 12 | 16 | 20 | 24 | 28 | 32 | 36 | 40 | 44 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ordinate of 4-h UH ($m^3/s$) | 0 | 20 | 80 | 130 | 150 | 130 | 90 | 52 | 27 | 15 | 5 | 0 |

In this case the time interval of the ordinates of the given unit hydrograph should be at least 2 h. As the given ordinates are at 4-h intervals, the unit-hydrograph is plotted and its ordinates at 2-h intervals determined. The ordinates are shown in column 2 of Table 6.8. The S-curve additions and S-curve ordinates are shown in columns 3 and 4 respectively. First, the S-curve ordinates corresponding to the time intervals equal to successive

TABLE 6.8 DETERMINATION OF 2-h UNIT HYDROGRAPH FROM A 4-h UNIT HYDROGRAPH —*Example 6.10*

| Time (h) | Ordinate of 4-h UH ($m^3/s$) | S-curve addition ($m^3/s$) | S-curve ordinate Col. (2) +(3) ($m^3/s$) | S-curve Lagged by 2 (h) | Col. (4) −(5) | 2-h UH ordinate $\frac{\text{Col. (6)}}{(2/4)}$ ($m^3/s$) |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 0 | 0 | — | 0 | — | 0 | 0 |
| 2 | 8 | | 8 | 0 | 8 | 16 |
| 4 | 20 | 0 | 20 | 8 | 12 | 24 |
| 6 | 43 | 8 | 51 | 20 | 31 | 62 |
| 8 | 80 | 20 | 100 | 51 | 49 | 98 |
| 10 | 110 | 51 | 161 | 100 | 61 | 122 |
| 12 | 130 | 100 | 230 | 161 | 69 | 138 |
| 14 | 146 | 161 | 307 | 230 | 77 | 154 |
| 16 | 150 | 230 | 380 | 307 | 73 | 146 |
| 18 | 142 | 307 | 449 | 380 | 69 | 138 |
| 20 | 130 | 380 | 510 | 449 | 61 | 122 |
| 22 | 112 | 449 | 561 | 510 | 51 | 102 |
| 24 | 90 | 510 | 600 | 561 | 39 | 78 |
| 26 | 70 | 561 | 631 | 600 | 31 | 62 |
| 28 | 52 | 600 | 652 | 631 | 21 | 42 |
| 30 | 38 | 631 | 669 | 652 | 17 | 34 |
| 32 | 27 | 652 | 679 | 669 | 10 | 20 |
| 34 | 20 | 669 | 689 | 679 | 10 | (20)15 |
| 36 | 15 | 679 | 694 | 689 | 5 | (10)10 |
| 38 | 10 | 689 | 699 | 694 | 5 | (10)6 |
| 40 | 5 | 694 | 699 | 699 | (0) | (0)3 |
| 42 | 2 | 699 | 701 | 699 | (2) | (4)0 |
| 44 | 0 | 699 | 699 | 701 | (−2) | (−4)0 |

Final adjusted values are given in col. 7.

Unadjusted values are given in parentheses.

durations of the given unit hydrograph (in this case at 0, 4, 8, 12,...h) are determined by following the method of Example 6.8. Next, the ordinates at intermediate intervals (viz. at $t$ = 2, 6, 10, 14...h) are determined by having another series of S-curve additions. The sequence of these are shown by distinctive arrows in Table 6.8. To obtain a 2-h unit hydrograph the *S*-curve is lagged by 2 h (column 5) and this is subtracted from column 4 and the results listed in column 6. The ordinates in column 6 are now divided by $T/D = 2/4 = 0.5$, to obtain the required 2-h unit hydrograph ordinates, shown in column 7.

The errors in interpolation of unit hydrograph ordinates often result in oscillation of S-curve at the equilibrium value. This results in the derived *T*-h unit hydrograph having an abnormal sequence of discharges (sometimes even negative values) at the tail end. This is adjusted by fairing the S-curve and also the resulting *T*-h unit-hydrograph by smooth curves. For example, in the present example the 2-h unit hydrograph ordinates at time > 36-h are rather abnormal. These values are shown in parentheses. The adjusted values are entered in column 7.

## 6.9 USE AND LIMITATIONS OF UNIT HYDROGRAPH

As the unit hydrographs establish a relationship between the ERH and DRH for a catchment, they are of immense value in the study of the hydrology of a catchment. They are of great use in (i) the development of flood hydrographs for extreme rainfall magnitudes for use in the design of hydraulic structures, (ii) extention of flood-flow records based on rainfall records and (iii) development of flood forecasting and warning systems based on rainfall.

Unit hydrographs assume uniform distribution of rainfall over the catchment. Also, the intensity is assumed constant for the duration of the rainfall excess. In practice, these two conditions are never strictly satisfied. Nonuniform areal distribution and variation in intensity within a storm are very common. Under such conditions unit hydrographs can still be used if the areal distribution is consistent between different storms. However, the size of the catchment imposes an upper limit on the applicability of the unit hydrograph. This is because in very large basins the centre of the storm can vary from storm to storm and each can give different DRHs under otherwise identical situations. It is generally felt that about 5000 $km^2$ is the upper limit for unit-hydrograph use. Flood hydrographs in very large basins can be studied by dividing them into a number of smaller subbasins and developing DRHs by the unit-hydrograph method. These DRHs can then be routed through their respective channels to obtain the composite DRH at the basin outlet.

There is a lower limit also for the application of unit hydrographs. This limit is usually taken as about 200 ha. At this level of area, a number of