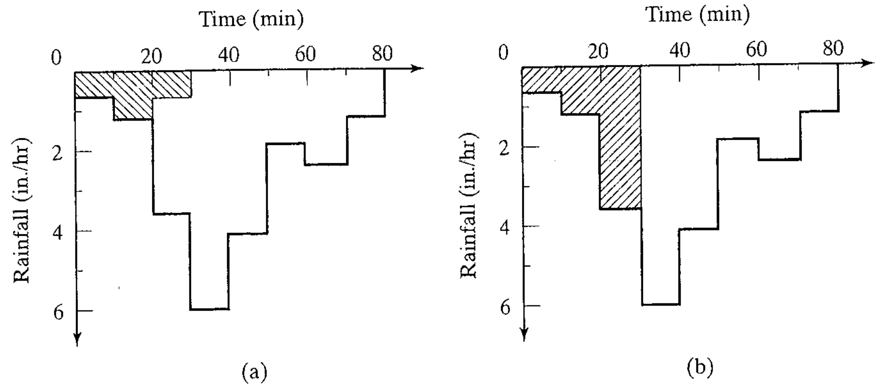

Figure 9.6 Separation of initial abstractions: (a) specific volume of 0.4 in. and (b) the specific time at start of direct runoff.

specification of the depth of the initial abstraction. Since only a few studies of this element of the runoff process have been made, it is difficult to justify a specific value. The specific-time method shown in Figure 9.6b can result in depths of initial abstraction that may be unusually high. Thus, both the specific-volume and specific-time methods have drawbacks. For this reason, initial abstraction is sometimes considered to be part of the losses and not a separate calculation.

EXERCISES

9.3.1 For the rainfall distribution shown in Figure 9.6(a), determine the proportion of the total rainfall that is initial abstraction if the initial abstraction is all of the rain that occurs prior to 35 min.

9.3.2 Estimate the time that rainfall excess begins if the intensity (in./hr) for the storm intervals (min) shown are

time	0–15	15–20	20–30	30–50	50–60	60–90	90–100	100–120
intensity	0.80	2.88	3.60	1.80	1.80	0.40	1.80	0.90

and the volume of initial abstraction is 0.7 in.

9.4 SEPARATION OF LOSSES USING INDEX METHODS

Losses reflect the ability of the watershed to retain water. At the beginning of a storm event that has been preceded by a period with no rainfall, the vegetation is dry, depressions are empty, and the upper layers of the soil structure have relatively low soil moisture. These watershed conditions represent the greatest potential for immediate storage of rainwater. Losses are usually thought to consist of water intercepted by vegetation (interception storage), water stored in small surface depressions (depression storage), and water that infiltrates into the soil (soil storage).

It is easy to become aware of interception storage. The interception of rain is evident from the dry area under the crown of a tree for the first few moments of a storm. The amount of interception storage could be measured using two raingages, with one located under the crown of the tree and another placed outside the range of influence of the tree. Such measurements have been taken at hydrologic research stations, and empirical formulas are available for estimating the interception storage as a function of the type and characteristics of the vegetation.

Depression storage, which is storage on the surface of the watershed in small depressions, depends on topography and landcover. Both depression and interception storage are depleted during the early part of a storm and thus are part of the initial abstraction if it is handled separately from other losses.

The primary component of losses is infiltration of rainwater into subsurface storage. In general, the available volume of subsurface storage is greatest at the start of rainfall and decreases over the duration of the storm. After a certain time, the infiltration capacity approaches a constant rate. Between storm events, percolation and evapotranspiration serve to decrease water stored in the soil structure. This process is referred to as *groundwater-storage recovery*. A number of methods have been proposed for estimating losses.

9.4.1 Phi-Index Method. To this point in the analysis process, the baseflow has been estimated and subtracted from the total runoff to determine the distribution of direct runoff. The depth of direct runoff is then computed. Also, the initial abstraction has been identified and separated from the measured rainfall hyetograph. From a conceptual standpoint, the remaining part of the rainfall hyetograph must be separated into losses and rainfall excess, such that the depth of rainfall excess equals the depth of direct runoff.

By definition, the phi index (ϕ) equals the average rainfall intensity above which the depth of rainfall excess equals the depth of direct runoff. Thus, the value of ϕ is adjusted such that the depths of rainfall excess and direct runoff are equal. The procedure for computing the phi index is as follows:

1. Compute the depths of rainfall (V_p) and direct runoff (V_d).
2. Make an initial estimate of the phi index:

$$\phi = \frac{V_p - V_d}{D}. \tag{9.9}$$

   In the preceding equation, D is the duration of rainfall (excluding that part separated as initial abstraction), and ϕ is an intensity, with a dimension of length per unit time such as inches per hour.

3. **a.** Compute the loss function, $L(t)$:

$$L(t) = \begin{cases} \phi & \text{if } \phi \leq P(t) \quad (9.10a) \\ P(t) & \text{if } \phi > P(t) \quad (9.10b) \end{cases}.$$

   In the preceding equation, $P(t)$ is the ordinate of the rainfall-intensity hyetograph at time t.

b. Compute the total depth of losses, V_L:

$$V_L = \sum L(t)^* \Delta t. \tag{9.11}$$

In the preceding equation, V_L is a depth, the summation is over all ordinates where losses occur, and Δt is the time interval, which may be a constant or a variable.

4. Compute $PE(t) = P(t) - L(t)$ for all ordinates in the rainfall hyetograph (excluding initial abstraction).

5. Compare V_L and $V_p - V_d$.

a. If $V_L = V_p - V_d$, go to Step 6

b. If $V_L < V_p - V_d$, compute the phi-index correction, $\Delta\phi$:

$$\Delta\phi = \frac{V_p - V_d - V_L}{D_1}. \tag{9.12}$$

In the preceding equation, D_1 is the time duration over which $PE(t)$ is greater than zero.

c. Adjust the phi index: $\phi_{\text{new}} = \phi_{\text{old}} + \Delta\phi$.

d. Return to Step 3.

6. Use the latest value of ϕ to define losses.

Example 9.3

Consider the rainfall hyetograph shown in Figure 9.7a. Assuming that the depth of direct runoff is 0.4 in., the value of ϕ must be set such that the depth of rainfall excess equals 0.4 in.; therefore, rainfall losses would equal 0.3 in. The value of ϕ is computed using Equation 9.9:

$$\phi = \frac{(0.7 - 0.4)\text{ in.}}{4\text{ hr}} = \frac{0.3\text{ in.}}{4\text{ hr}} = 0.075\text{ in./hr.}$$

Subtracting a loss of 0.075 in./hr from each ordinate of the hyetograph yields a time distribution of rainfall excess of (0.025, 0.175, 0.075, 0.125) in./hr. Converting these amounts to depths and summing yields a total depth of 0.4 in., which equals the depth of direct runoff. Thus, the computed value of ϕ is appropriate for this storm event.

Example 9.4

A rainfall hyetograph for a 70-min storm with a total depth of 3.5 in. is shown in Figure 9.7b. The depth of direct runoff is 1.90 in.; therefore, the depth of rainfall excess must be 1.9 in., and the depth of losses must be 1.6 in. One difference between this example and Example 9.3 is that the rainfall ordinates are not on a constant time interval; thus, the phi-index method can still be applied.

The depth of rainfall is

$$V_p = \frac{1}{60}[1(25) + 8(10) + 5(15) + 1.5(20)] = 3.5\text{ in.}$$

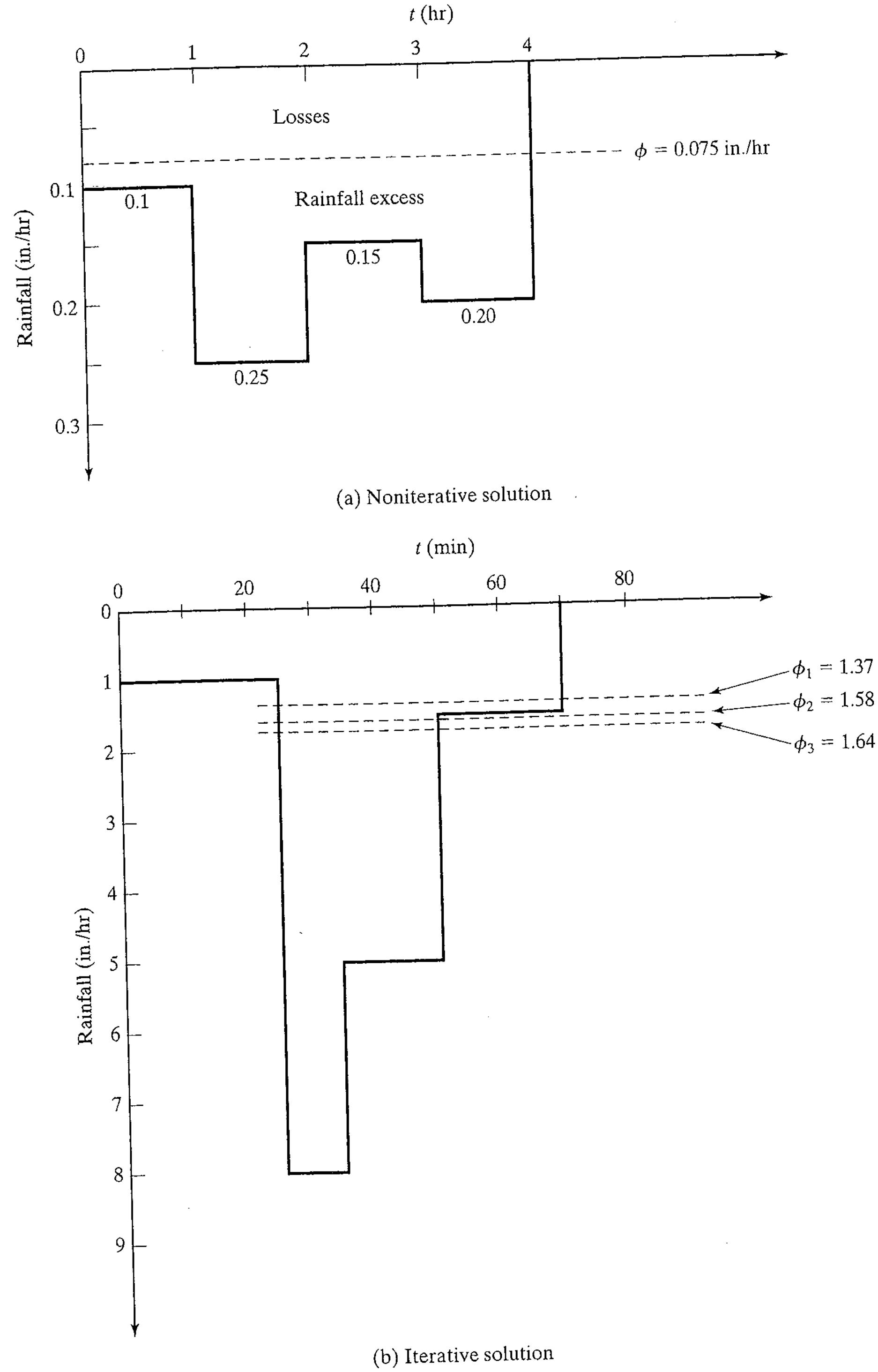

Figure 9.7 Separation of rainfall excess and losses using the phi-index method.

TABLE 9.3 Example 9.4: Calculation of Losses Using the Phi-Index Method

Time Period (min)	$i(t)$ (in./hr)	$L(t)$ (in./hr)	$V_L(t)$ (in.)	$L(t)$ (in./hr)	$V_L(t)$ (in.)	$L(t)$ (in./hr)	$V_L(t)$ (in.)	$i_e(t)$ (in./hr)	V_{pe} (in.)
0–25	1.0	1.00	0.417	1.00	0.417	1.00	0.417	0	0
25–35	8.0	1.37	0.228	1.58	0.263	1.64	0.273	6.36	1.06
35–50	5.0	1.37	0.342	1.58	0.395	1.64	0.410	3.36	0.84
50–70	1.5	1.37	0.457	1.50	0.500	1.50	0.500	0	0
			1.444		1.575		1.600		1.90

Using Equation 9.9, the initial estimate of ϕ is

$$\phi = \frac{V_p - V_d}{D} = \frac{3.5 - 1.9}{(70/60)} = 1.37 \text{ in./hr.}$$

Using Equation 9.10, the loss function is given in column 3 of Table 9.3, and the depths of losses are given in column 4. The total depth of losses is 1.44 in. Since this amount is less than the difference between V_p and V_d, the value of ϕ must be corrected using Equation 9.12:

$$\Delta\phi = \frac{V_p - V_d - V_L}{D_1} = \frac{3.5 - 1.9 - 1.44}{45/60} = 0.21 \text{ in./hr.}$$

$\phi_1 = 1.37$
$\phi_2 = 1.58$
$\phi_3 = 1.64$

A value for D_1 of 45 min is used because the initial value of ϕ is greater than $P(t)$ for the first 25 min. Thus, the adjusted ϕ is 1.37 + 0.21 = 1.58 in./hr, which is used to compute a revised loss function (column 5 of Table 9.3). The total loss is now 1.575 in., which is still less than the required depth of 1.6 in. Thus, Equation 9.12 is used to compute a new adjustment:

$$\Delta\phi = \frac{3.5 - 1.9 - 1.575}{25/60} = 0.06 \text{ in./hr.}$$

A duration D_1 of 25 min is used because now only the time period from 25 to 50 min has rainfall excess. The revised value of ϕ is 1.58 + 0.06 = 1.64 in./hr. The loss function for the revised ϕ value is given in column 7 of Table 9.3. Since the total loss is 1.6 in. (column 8), then the loss function of column 7 is the final value. The rainfall-excess intensity, $i_e(t)$, is computed (column 9) as the difference between the rainfall intensity (column 2) and the loss function of column 7. The depths of excess are given in column 10 with a total of 1.9 in., which equals the depth of direct runoff.

9.4.2 Constant-Percentage Method. The constant-percentage method assumes that losses are proportional to the rainfall intensity. Letting f be the fraction of rainfall that contributes to losses, then, assuming that depth of rainfall excess, P_e, equals the depth of direct runoff, Q_d, the value of f is given by

$$f = 1 - \frac{Q_d}{P}, \tag{9.13}$$

in which P is the total depth of rainfall.

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