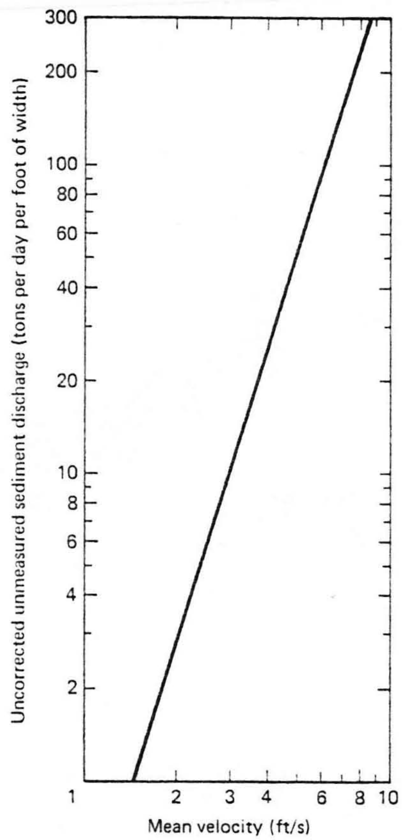

Figure 15-11 Uncorrected unmeasured sediment discharge versus mean velocity in Colby 1957 method [7].

in which q_s = bed-material discharge in tons per day per foot; q = water discharge in cubic feet per second per foot; C_m = measured concentration of suspended bed-material discharge in milligrams per liter; and 0.0027 is the conversion factor for the indicated units. Table 15-8 shows a factor to convert concentration in parts per million to milligrams per liter.

Example 15-8.

Given mean flow depth $d = 10$ ft, mean channel width $b = 300$ ft, mean velocity $v = 3$ fps, measured concentration of suspended bed material discharge $C_m = 100$ ppm, calculate the total bed material discharge by the Colby 1957 method.

From Fig. 15-11, the uncorrected unmeasured sediment discharge is $q_u' = 10$ ton/d/ft. From Fig. 15-12, the relative concentration of suspended sands is $C_r = 380$ ppm. The availability ratio is $100/380 = 0.26$. From Fig. 15-13, the correction factor is $C = 0.6$. Therefore, $q_u = 6$ ton/d/ft. The water discharge per unit width is $q = vd = 3 \times 10 = 30$ ft^3/s/ft. From Eq. 15-23, the sediment discharge per unit width is $q_s = (0.0027 \times 100 \times 30) + 6 = 14.1$ ton/d/ft. Therefore, the bed-material discharge by the Colby 1957 method is $Q_s = q_s b = 14.1 \times 300 = 4230$ ton/d.

Colby's 1964 Method. In 1964, Colby published a method to calculate discharge of sands (i.e., bed-material discharge) in sand-bed streams and rivers . The

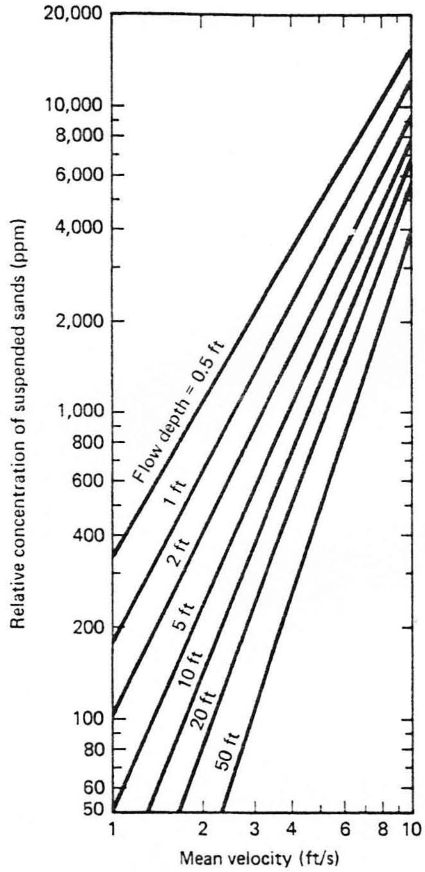

Figure 15-12 Relative concentration of suspended sands versus mean velocity and flow depth in Colby 1957 method [7].

development of the method was guided by the Einstein bed-load function and supported by large amounts of laboratory and field data. The method has been shown to provide a reasonably good prediction of sediment transport rates, particularly for sand-size particles.

The following data are needed in an application of the Colby 1964 method: (1) mean flow depth d, (2) mean channel width b, (3) mean velocity v, (4) water temperature, (5) concentration of fine-material load (i.e., wash load), and (6) median bed-material size. The procedure is as follows [8]:

1. Use Fig. 15-14 to determine the uncorrected discharge of sands q_u (in tons per day per foot of width) as a function of mean velocity, flow depth, and sediment size.
2. For water temperature of 60°F, negligible wash load concentration (less than 1000 ppm), and sediment size in the range 0.2 to 0.3 mm, no further calculations are required, and q_u is the discharge of sands q_s.
3. For conditions other than the preceding, use Fig. 15-15 to obtain the correction factor k_1 as a function of flow depth and water temperature, k_2 as a function of

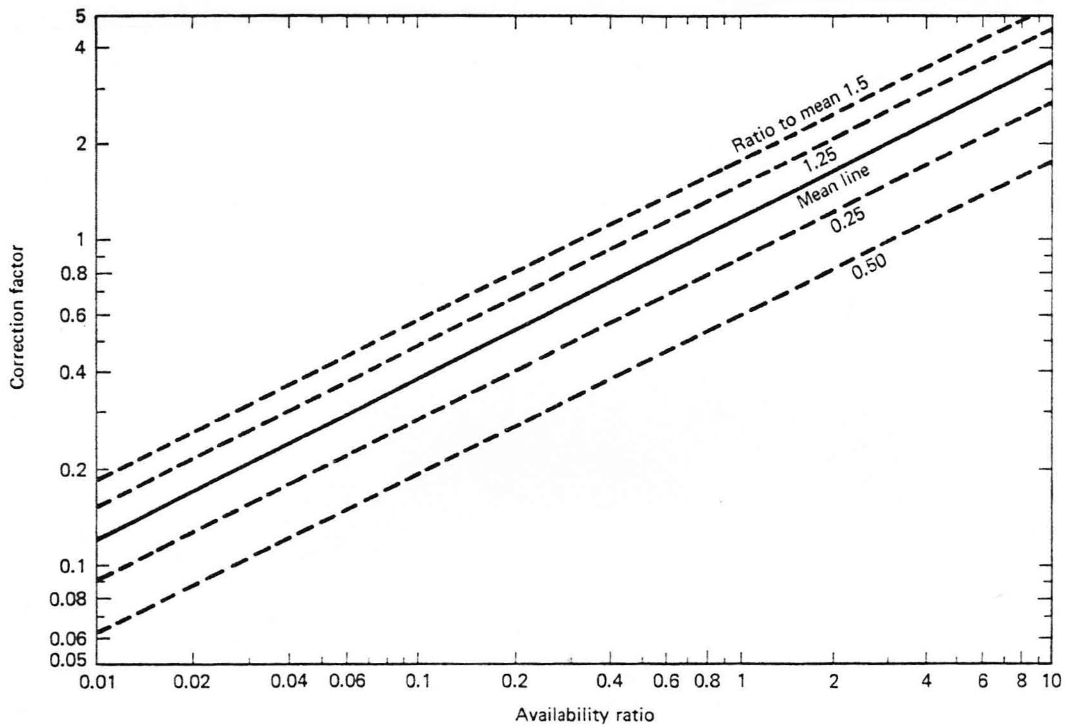

Figure 15-13 Correction factor versus availability ratio in Colby 1957 method [7].

flow depth and concentration of fine-material load, and k_3 as a function of median size of bed material.

4. The discharge of sands is given by the following formula:

$$q_s = [1 + (k_1 k_2 - 1)k_3]q_u \tag{15-24}$$

in which q_s discharge of sands in tons per day per foot.

Example 15-9.

Given mean flow depth $d = 1$ ft, mean channel width $b = 30$ ft, mean velocity $v = 2$ fps, water temperature 50°F, wash-load concentration $C_w = 10{,}000$ ppm, and median bed-material size $d_{50} = 0.1$ mm. Calculate the discharge of sands by the Colby 1964 method.

From Fig. 15-14, $q_u = 9.3$ ton/d/ft. From Fig. 15-15, $k_1 = 1.15$, $k_2 = 1.20$, $k_3 = 0.6$. From Eq. 15-24, $q_s = [1 + (1.15 \times 1.20 - 1) \times 0.6] \times 9.3 = 11.4$ ton/d/ft. Therefore, the discharge of sands is $Q_s = 11.4 \times 30 = 342$ ton/d.

Other Methods for the Calculation of Sediment Discharge. Many other methods have been proposed for the calculation of sediment discharge. Notable among them are the methods of Ackers and White [1], Engelund and Hansen [16], Toffaleti [39], and Yang [46]. The various procedures vary in complexity and range of applicability. For details on these and other sediment transport formulas, see [2, 4, 25, 38].

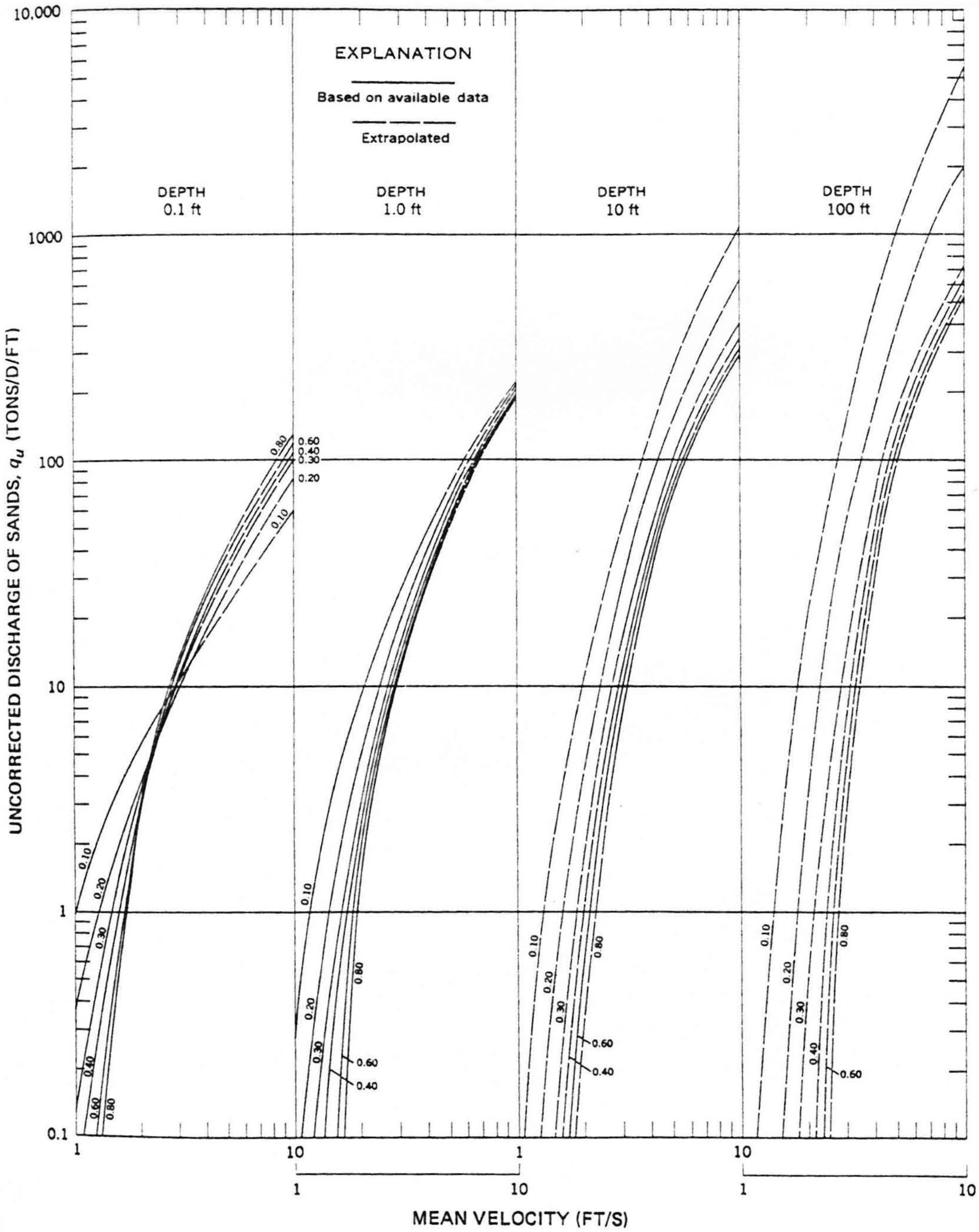

Figure 15-14 Discharge of sands versus mean velocity, flow depth and sediment size in Colby 1964 method [9].

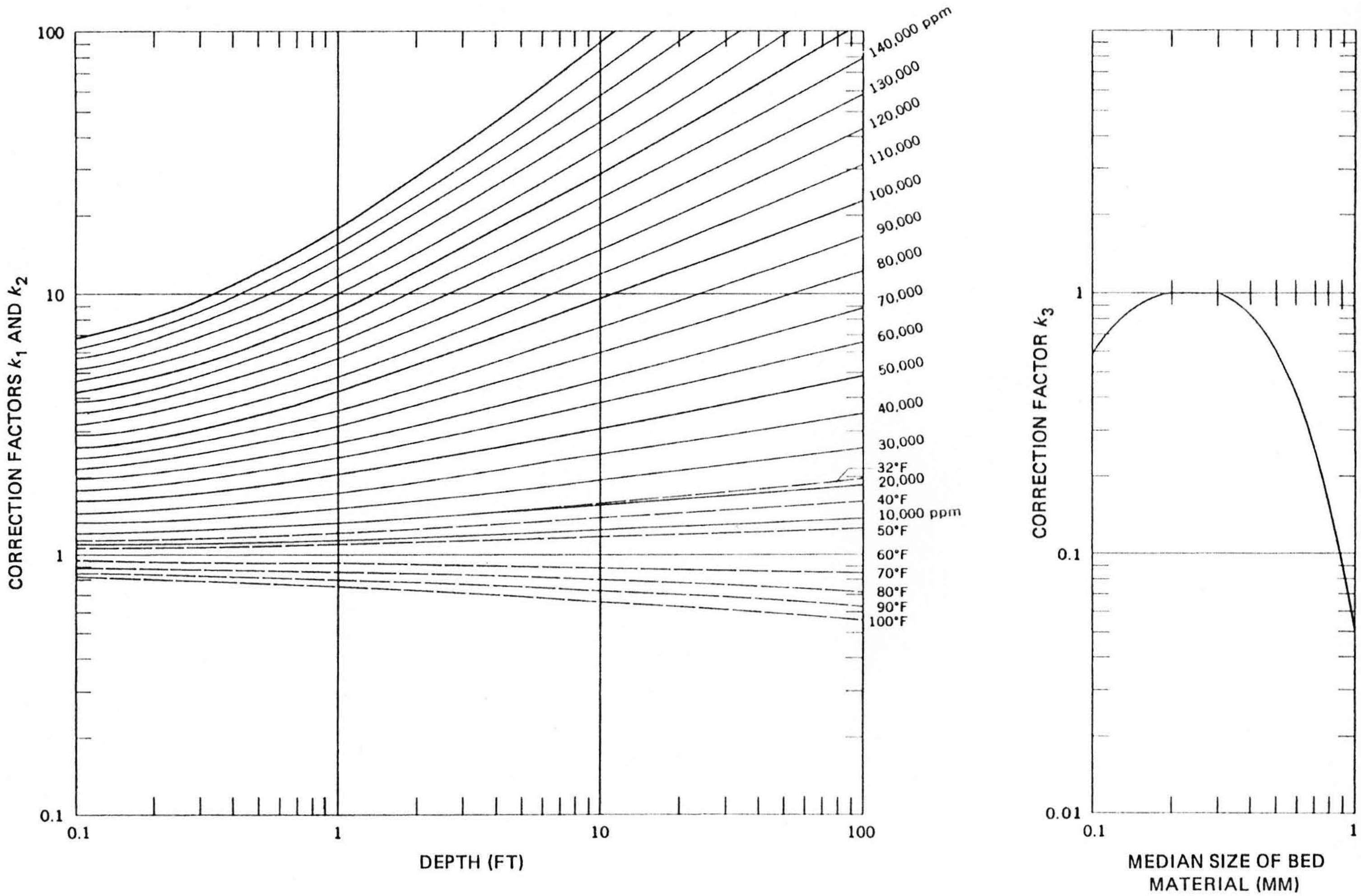

Figure 15-15 Correction factors for water temperature (k_1), fine-material-load concentration (k_2), and median size of bed material (k_3), in Colby 1964 method [9].

Sediment Rating Curves

A useful curve in sediment analysis is the sediment rating curve, defined as the relationship between water discharge and sediment discharge at a given gaging site. For a given water discharge, the sediment rating curve allows the estimation of sediment discharge, assuming steady equilibrium flow conditions.

The sediment rating curve is an xy plot showing water discharge in the abscissas and sediment discharge in the ordinates. This plot is obtained either by the simultaneous measurement of water and sediment discharge or, alternatively, by the use of sediment transport formulas. For low-water discharges, the sediment rating curve usually plots as a straight line on logarithmic paper, showing an increase of sediment concentration with water discharge. However, for high water discharges, the sediment rating curve has a tendency to curve slightly downward, approaching a line of equal sediment concentration (i.e., a line having a 45° slope in the xy plane) [2].

Like the single-valued stage-discharge rating, the single-valued sediment rating curve is strictly valid only for steady equilibrium flow conditions. For strongly unsteady flows, the existence of loops in both water and sediment rating curves has been demonstrated [2]. These loops are complex in nature and are likely to vary from flood to flood. In practice, loops in water and sediment rating are commonly disregarded.

Sediment Routing

The calculation of sediment yield is lumped, i.e., it does not provide a measure of the spatial or temporal variability of sediment production within the catchment. Sediment transport formulas are invariably based on the assumption of steady equilibrium flow. *Sediment routing,* on the other hand, refers to the distributed and unsteady calculation of sediment production, transport and deposition in catchments, streams, rivers, reservoirs, and estuaries.

Of necessity, sediment routing involves a large number of calculations and therefore is ideally suited for use with a computer. Sediment routing should be used—in addition to sediment yield and sediment transport evaluations—in cases where the description of spatial and temporal variations of sediment production, transport, and deposition is warranted. Sediment routing methods are particularly useful in the detailed analysis of sediment transport and deposition in rivers and reservoirs. For example, the computer model HEC-6, "Scour and Deposition in Rivers and Reservoirs," is a sediment routing model developed by the U.S. Army Corps of Engineers [21]. Several other sediment routing models have been developed in the last two decades; see, for instance, [4] and [25].

15.4 SEDIMENT DEPOSITION IN RESERVOIRS

The concepts of sediment yield and sediment transport are essential to the study of sediment deposition in reservoirs. Sediment is first produced at upland and channel sources and then transported downstream by the action of flowing water. If the flowing water is temporarily detained, as in the case of an instream reservoir, its ability to continue to entrain sediment is substantially impaired, and deposition takes place.

Sediment deposition occurs in the vicinity of reservoirs, typically as shown in Fig. 15-16 [20]. First, deposition of the coarser-size fractions takes place near the entrance to the reservoir. As water continues to flow into the reservoir and over the dam, the delta continues to grow in the direction of the dam until it eventually fills the entire reservoir volume. The process is quite slow but relentless. Typically, reservoirs may take 50 to 100 y to fill, and in some instances, up to 500 y or more.

The rate of sediment deposition in reservoirs is a matter of considerable economic and practical interest. Since reservoirs are key features of hydroelectric and water-resource development projects, the question of the design life of a reservoir is appropriate, given that most reservoirs will eventually fill with sediment. In an extreme example, the filling can occur in a single storm event, as in the case of a small sediment-retention basin located in a semiarid or arid region. On the other hand, the reservoir can take hundreds of years to fill, as in the case of a large reservoir located in a predominantly humid or subhumid environment.

Reservoir Trap Efficiency

The difference between incoming and outgoing sediment is the sediment deposited in the reservoir. The incoming sediment can be quantified by the sediment yield, i.e., the total sediment load entering the reservoir. The outgoing sediment can be quantified by the *trap efficiency*. Trap efficiency refers to the ability of the reservoir to entrap sediment being transported by the flowing water. It is defined as the ratio of trapped sediment to incoming sediment, in percentage, and is a function of (1) the ratio of reservoir volume to mean annual runoff volume and (2) the sediment characteristics.

The following procedure is used to determine trap efficiency [41]:

1. Determine the reservoir capacity C in cubic hectometers or acre-feet.

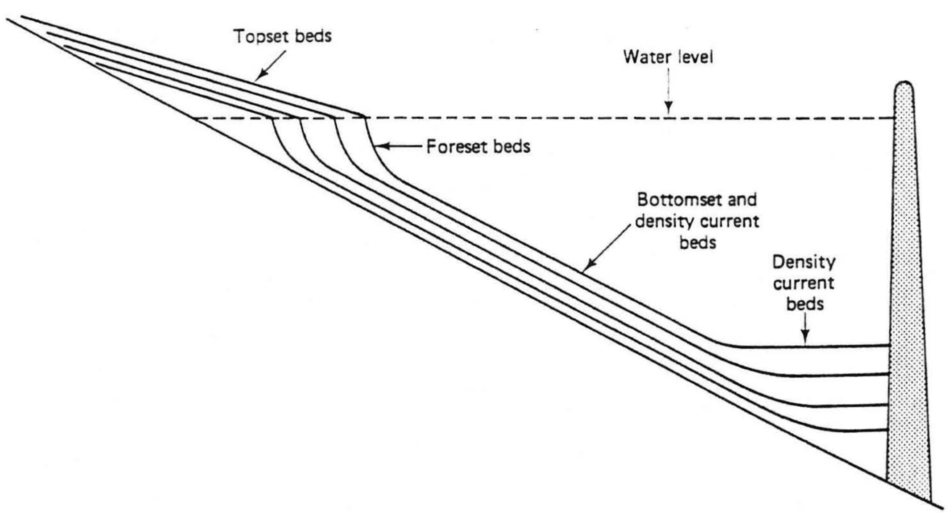

Figure 15-16 Longitudinal sedimentation patterns in a reservoir operating at constant water level [20].

2. Determine the mean annual (runoff volume) inflow I to the reservoir, in cubic hectometers or acre-feet.
3. Use Fig. 15-17 to determine the percentage trap efficiency as a function of the ratio C/I for any of three sediment characteristics. Estimate the texture of the incoming sediment by a study of sediment sources and/or sediment transport by size fractions. The upper curve of Fig. 15-17 is applicable to coarse sands or flocculated sediments; the middle curve, to sediments consisting of a wide range of particle sizes; and the lower curve, to fine silts and clays.

Reservoir Design Life

The design life of a reservoir is the period required for the reservoir to fulfill its intended purpose. For instance, structures designed by the Soil Conservation Service for watershed protection and flood prevention programs have a design life of 50 to 100 y. Due to reservoir sedimentation, provisions are made to guarantee the full-design reservoir water-storage capacity for the planned design life. This may entail either (1) cleaning out reservoir sediment deposits at predetermined intervals during the life of the structure or, as is more often the case, (2) providing a reservoir storage capacity large enough to store all the accumulated sediment deposits without encroachment on the designed water-storage volume. Typically, calculations of sediment-filling rates and sediment accumulation are part of the design of reservoir-storage projects.

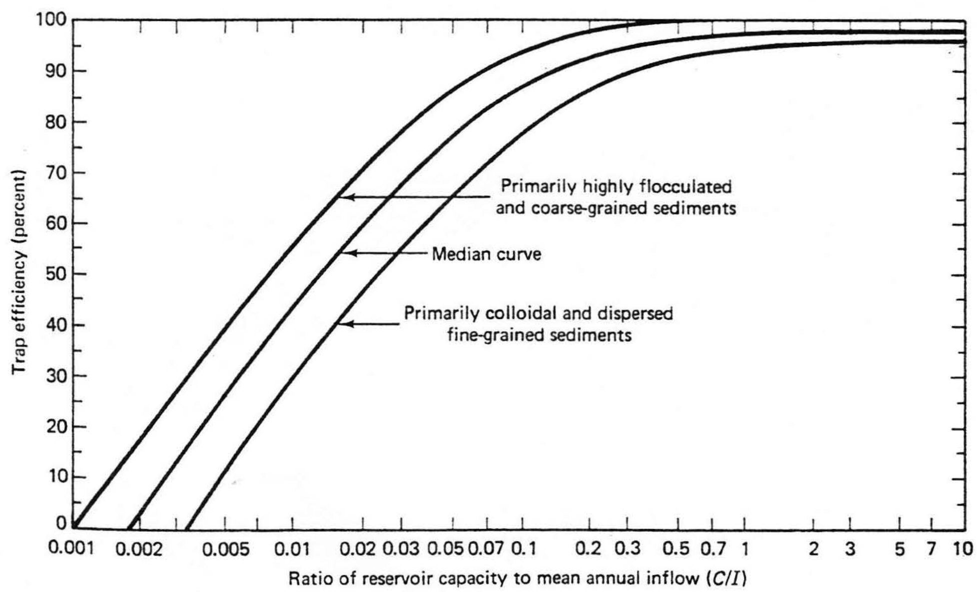

Figure 15-17 Trap efficiency of reservoirs versus capacity-inflow (C/I) ratio [41].

Distribution of Sediment Deposits

The distribution of sediment deposits may be such as to materially affect the operation and maintenance of the dam and reservoir. The amount and types of sediment deposits vary with the nature of the sediment itself, the shape of the reservoir, the topography of the reservoir floor, the nature of the approach channel, detention time, and purpose of the reservoir. The coarser sediment sizes are the first to deposit in the vicinity of the reservoir entrance. Finer sediment sizes are able to travel longer distances inside the reservoir and deposit at locations close to the dam. However, very fine sediments are usually uniformly distributed in the reservoir bed.

Sediment-retention, or Debris, Basins

Sediment-retention basins, or debris basins, are small reservoirs located in upland areas with the specific purpose of trapping sediment and debris before they are able to reach the main fluvial network system. *Debris* is a general term used to describe the assortment of cobbles, boulders, branches, and other vegetative material that may clog channels and hydraulic structures, causing them to reach a critical design condition prematurely and often resulting in structural failure.

Debris basins are placed upstream of channels or reservoirs with the specific purpose of temporary detainment of debris. Debris basins are usually small and designed to be cleaned out from time to time. Some basins are sized to fill up during one or two major storms. Others may have a 50- or 100-y design life. Project costs and site conditions determine the size of debris basins.

Sediment-yield determinations for debris basin design should include both short-term and long-term analyses. The long-term sediment yield is determined from the appropriate sediment rating curve. For infrequent storms, however, sediment concentrations may exceed long-term averages by a factor of 2 or 3 [40].

Example 15-10.

A planned reservoir has a total capacity of 10 hm^3 and a contributing catchment area of 250 km^2. Mean annual runoff at the site is 400 mm, annual sediment yield is 1000 metric tons/km^2, and the specific weight of sediment deposits is estimated at 12,000 N/m^3. A sediment source study has confirmed that the sediments are primarily fine-grained. Calculate the time that it will take for the reservoir to fill up with sediments.

The calculations are shown in Table 15-9. Because of decreased reservoir capacity as it fills with sediment, an interval of storage equal to $\Delta V = 2$ hm^3 is chosen for this example. Column 2 shows the loss of reservoir capacity, and Col. 3 shows the accumulated sediment deposits. The mean annual inflow to the reservoir is 400 mm $\times$ 250 km^2 $= 100$ hm^3. Column 4 shows the capacity-inflow ratios at the end of each interval, and Col. 5 shows the average capacity-inflow ratios per interval. Column 6 shows the trap efficiencies T_i obtained from Fig. 15-17 using the curve for fine-grained sediments (lower curve). The annual sediment inflow I_s is:

$$I_s = \frac{1000\ \text{ton/km}^2\text{/y} \times 1000\ \text{kg/ton} \times 250\ \text{km}^2 \times 9.81\ \text{N/kg}}{12{,}000\ \text{N/m}^3 \times 10^6\ \text{m}^3\text{/hm}^3} \qquad (15\text{-}25)$$

$$I_s = 0.204\ \text{hm}^3\text{/y}$$

TABLE 15-9 SEDIMENT ACCUMULATION IN RESERVOIRS: EXAMPLE 15-10

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Interval i	Reservoir capacity C (hm^3)	Accumulated volume (hm^3)	C/I ratio	Average C/I in interval	Trap efficiency T_i (%)	Number of years to fill (y)
0	10	0	0.10			
1	8	2	0.08	0.09	77	13
2	6	4	0.06	0.07	72	14
3	4	6	0.04	0.05	66	15
4	2	8	0.02	0.03	55	18
5	0	10	0.00	0.01	30	33
Total						93

The number of years to fill each ΔV interval is $\Delta V/[I_s(T_i/100)]$, shown in Col. 7. The sum of Col. 7 is the total number of years required to fill up the reservoir: 93 y.

15.5 SEDIMENT MEASUREMENT TECHNIQUES

The measurement of fluvial sediments is often necessary to complement sediment yield and sediment transport studies. The accuracy of the measurement, however, is dependent not only on the equipment and techniques but also on the application of basic principles of sediment transport.

As sediment enters a stream or river, it separates itself into bed-material load and wash load. In turn, the bed-material load is transported as either bed load or suspended load. The suspended bed-material load plus the wash load constitutes the total suspended-sediment load of the stream or river.

The term *sampled suspended-sediment discharge* is used to describe the fraction of suspended-sediment load that can be sampled with available equipment. Generally, it excludes the *unsampled suspended-sediment discharge*, i.e., the fraction of suspended-sediment load that is carried too close to the stream bed to be effectively sampled. The suspended-sediment discharge is the sum of sampled and unsampled suspended-sediment discharges.

Sediment-sampling Equipment

Sediment-sampling equipment can be classified as the following:

1. Suspended-sediment samplers, which measure suspended-sediment concentration
2. Bed-load samplers, which measure bed load
3. Bed-material samplers, which sample the sediment in the top layer of the stream bed