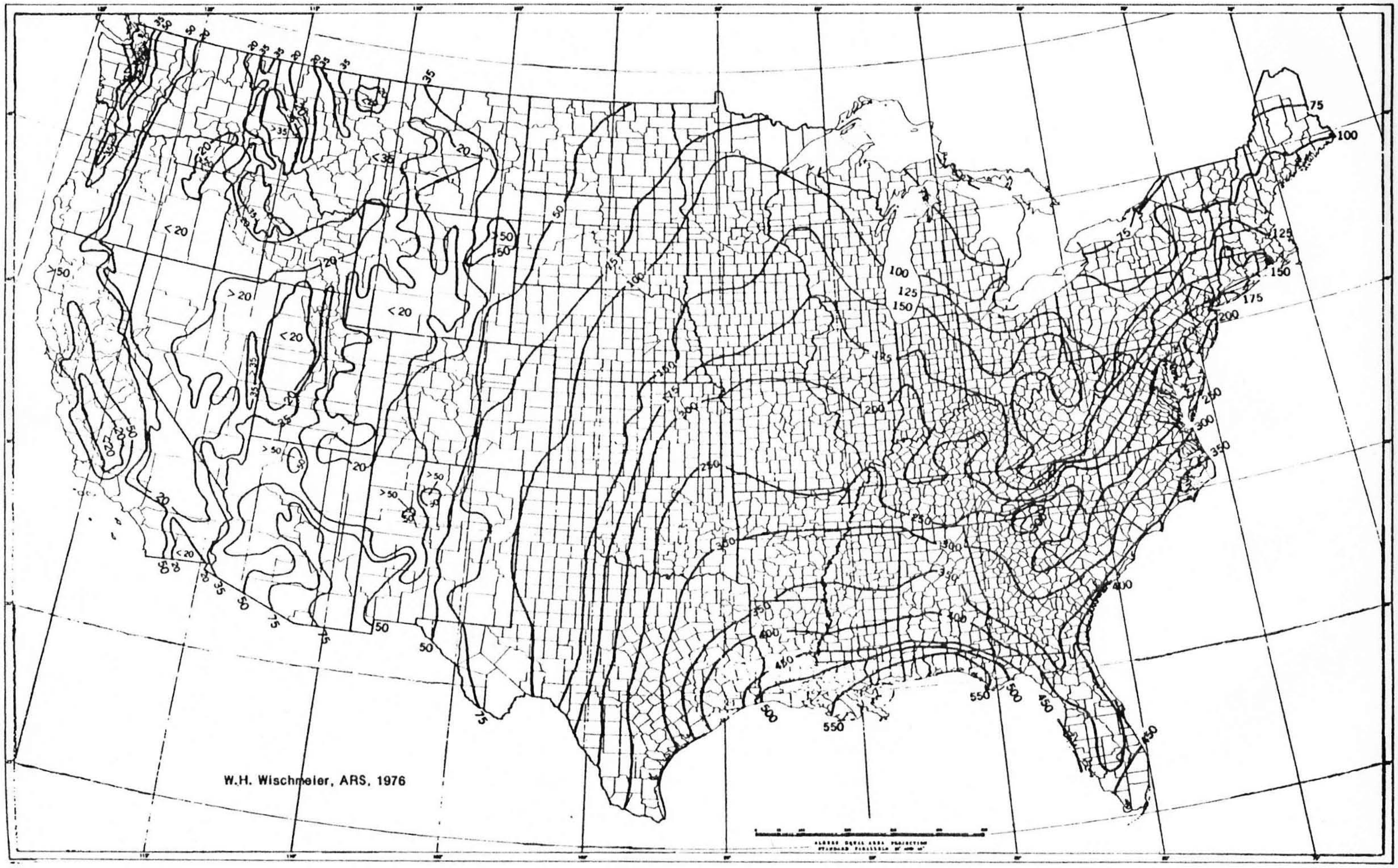


W.H. Wischmeier, ARS, 1976

Figure 15-2 Rainfall factor R in the universal soil loss equation [41].

TABLE 15-4 VALUES OF SOIL ERODIBILITY FACTOR *K* [43]

Soil Type	Source of Data	*K*
Dunkirk silt loam	Geneva, NY	0.69[1]
Keen silt loam	Zanesville, OH	0.48
Shelby loam	Bethany, MO	0.41
Lodi loam	Blacksbrug, VA	0.39
Fayette silt loam	LaCrosse, WI	0.38[1]
Cecil snady clay loam	Watkinsville, GA	0.36
Marshall silt loam	Clarinda, IO	0.33
Ida silt loam	Castana, IO	0.33
Mansic clay loam	Hays, KA	0.32
Hagerstown silty clay loam	State College, PA	0.31[1]
Austin clay	Temple, TX	0.29
Mexico silt loam	McCredie, MO	0.28
Honeoye silt loam	Marcellus, NY	0.28[1]
Cecil sandy loam	Clemson, SC	0.28[1]
Ontario loam	Geneva, NY	0.27[1]
Cecil clay loam	Watkinsville, GA	0.26
Boswell fine sandy loam	Tyler, TX	0.25
Cecil sand loam	Watkinsville, GA	0.23
Zaneis fine sandy loam	Guthrie, OK	0.22
Tifton loamy sand	Tifton, GA	0.10
Freehold loamy sand	Marlboro, NJ	0.08
Bath flaggy silt loam with surface stones greater than 2 in. removed	Arnot, NY	0.05[1]
Albia gravelly loam	Beemerville, NJ	0.03

[1] Evaluated from continuous fallow. All others were evaluated from row-crop data.

Use of the Universal Soil Loss Equation. The USLE computes upland erosion from small watersheds on an average annual basis. It includes the detachment and transport components, but it does not account for the deposition component. Therefore, the USLE cannot be used to compute sediment yield. For example, in a 1000-mi^2 drainage basin, only 5 percent of the soil loss computed by the USLE may appear as sediment yield at the basin outlet. The remaining 95 percent is redistributed on uplands or flood plains and does not constitute a net soil loss from the drainage basin.

Example 15-3.

Assume a 600-ac watershed above a proposed floodwater-retarding structure in Fountain County, Indiana. Compute the average annual soil loss by the universal soil loss equation for the following conditions: (1) cropland, 280 ac, contour strip-cropped, soil is Fayette silt loam, slopes are 8% and 200 ft long; (2) pasture, 170 ac, 50% canopy cover, 80% ground cover with grass, soil is Fayette silt loam, slopes are 8% and 200 ft long; and (3) forest, 150 ac, soil is Marshall silt loam, 30% tree canopy cover, slopes are 12% and 100 ft long.

1. From Fig. 15-2, $R = 185$. From Table 15-4, $K = 0.38$. From Fig. 15-3, $LS = 1.4$. The value of C for cropland is obtained from local sources; assume $C = 0.12$ for this

TABLE 15-5 VALUES OF CROP-MANAGEMENT FACTOR C FOR PERMANENT PASTURE, GRAZED FOREST LAND, RANGE AND IDLE LAND [41]

Vegetative Canopy		Cover That Contacts the Soil Surface						
			Percent Ground Cover					
Type and Height[2]	% Cover[3]	Type[4]	0	20	40	60	80	100
No appreciable canopy		G	0.45	0.20	0.10	0.042	0.013	0.003
		W	0.45	0.24	0.15	0.091	0.043	0.011
Tall grass, weeds or short brush with average drop fall of 20 in. or less	25	G	0.36	0.17	0.09	0.038	0.013	0.003
		W	0.36	0.20	0.13	0.083	0.041	0.011
	50	G	0.26	0.13	0.07	0.035	0.012	0.003
		W	0.26	0.16	0.11	0.076	0.039	0.011
	75	G	0.17	0.10	0.06	0.032	0.011	0.003
		W	0.17	0.12	0.09	0.068	0.038	0.011
Appreciable brush or bushes, with average drop fall height of 6.5 ft	25	G	0.40	0.18	0.09	0.040	0.013	0.003
		W	0.40	0.22	0.14	0.087	0.042	0.011
	50	G	0.34	0.16	0.08	0.038	0.012	0.003
		W	0.34	0.19	0.13	0.082	0.041	0.011
	75	G	0.28	0.14	0.08	0.036	0.012	0.003
		W	0.28	0.17	0.12	0.078	0.040	0.011
Trees, but no appreciable low brush. Average drop fall height of 13 ft	25	G	0.42	0.19	0.10	0.041	0.013	0.003
		W	0.42	0.23	0.14	0.089	0.042	0.011
	50	G	0.39	0.18	0.09	0.040	0.013	0.003
		W	0.39	0.21	0.14	0.087	0.042	0.011
	75	G	0.36	0.17	0.09	0.039	0.012	0.003
		W	0.36	0.20	0.13	0.084	0.041	0.011

[1] The listed C values require that the vegetation and mulch be randomly distributed over the entire area. For grazed forest land, multiply these values by 0.7.

[2] Canopy height is measured as the average fall height of water drops falling from canopy to ground. Canopy effect is inversely proportional to drop fall height and is negligible if fall height exceeds 33 ft.

[3] Portion of total area surface that would be hidden from view by canopy in a vertical projection.

[4] G: cover at surface is grass, grasslike plants, decaying compacted duff, or litter. W: cover at surface is mostly broadleaf herbaceous plants (weeds) or undecayed residues or both.

example. From Table 15-7, $P = 0.25$. Using Eq. 15-6: $A = 185 \times 0.38 \times 1.4 \times 0.12 \times 0.25 = 2.95$ tons/ac/y.

2. $R = 185$; $K = 0.38$; $LS = 1.4$. From Table 15-5, $C = 0.012$. No value of P has been established for pasture; therefore, $P = 1$. Using Eq. 15-6: $A = 185 \times 0.38 \times 1.4 \times 0.012 \times 1.0 = 1.18$ tons/ac/y.
3. $R = 185$. From Table 15-4, $K = 0.33$. From Fig. 15-3, $LS = 1.8$. From Table 15-6, $C = 0.006$. No value of P has been established for forest. Using Eq. 15-6: $A = 185 \times 0.33 \times 1.8 \times 0.006 \times 1.0 = 0.66$ tons/ac/y.

The total sheet and rill erosion from the 600-ac watershed is $(280 \times 2.95) + (170 \times 1.18) + (150 \times 0.66) = 1126$ tons/y.

TABLE 15-6 VALUES OF CROP-MANAGEMENT FACTOR *C* FOR UNDISTURBED FOREST LAND[1] [41]

Percentage of Area Covered by Canopy of Trees and Undergrowth	Percentage of Area Covered by Litter[2]	*C* Value[3]
100–75	100–90	0.0001–0.001
70–45	85–75	0.002–0.004
40–20	70–40	0.003–0.009

[1] Where litter cover is less than 40% or canopy cover is less than 20%, use Table 15-5. Also, use Table 15-5 when woodlands are being grazed, harvested, or burned.

[2] Percentage of area covered by litter is dominant. Interpolate on basis of litter, not canopy.

[3] The ranges in listed *C* values are caused by the ranges in the specified forest litter and canopy cover, and by variations in effective canopy height.

TABLE 15-7 VALUES OF EROSION-CONTROL-PRACTICE FACTOR *P* FOR CONTOURED-FARMED TERRACED FIELDS[1] [41]

	For Farm Planning		For Computing Sediment Yield[2]	
Land Slope (percent)	Contour Factor[3]	Strip-crop Factor	Graded Channels, Sod Outlets	Steep Backslope, Underground Outlets
1-2	0.60	0.30	0.12	0.05
3-8	0.50	0.25	0.10	0.05
9-12	0.60	0.30	0.12	0.05
13-16	0.70	0.35	0.14	0.05
17-20	0.80	0.40	0.16	0.06
21-25	0.90	0.45	0.18	0.06

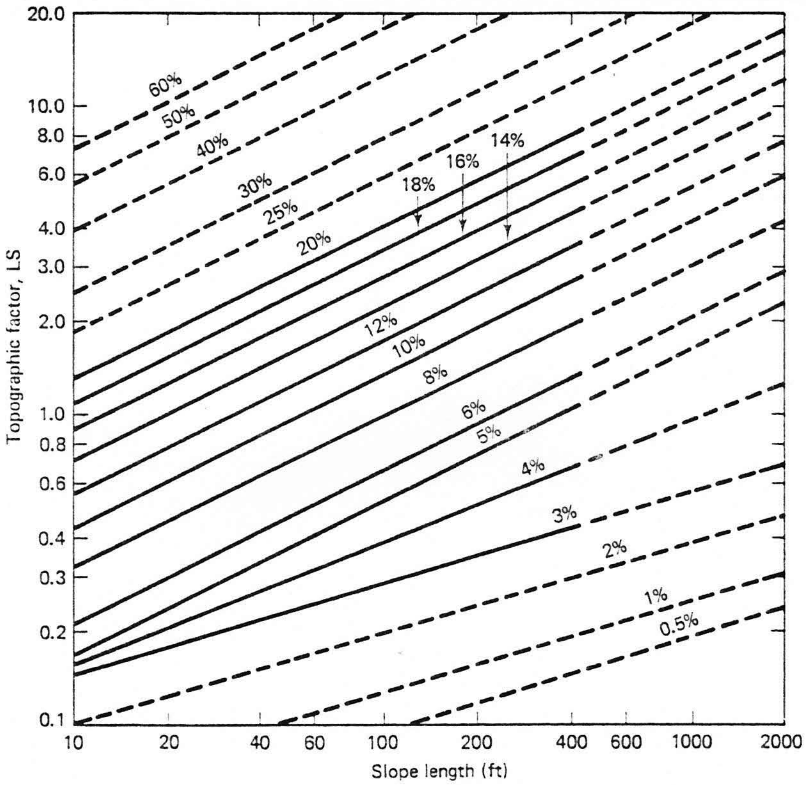
[1] Slope length is the horizontal terrace interval. The listed values are for contour farming. No additional contour factor is used in the computation.

[2] These values include entrapment efficiency and are used for control of offsite sediment within limits and for estimating the field's contribution to watershed sediment yield.

[3] Use these values for control of interterrace erosion within specified soil-loss tolerances.

Channel Erosion

Channel erosion includes gully erosion, streambank erosion, streambed degradation, floodplain scour, and other sources of sediment, excluding upland erosion. Gullies are incipient channels in process of development. Gully growth is usually accelerated by severe climatic events, improper land use, or changes in stream base levels. Most of the significant gully activity, in terms of the quantities of sediment produced and delivered to downstream locations, is found in regions of moderate to steep topography having thick soil mantles. The total sediment outflow from gullies is usually less than sheet and rill erosion [31].



*The dashed lines represent estimates for slope dimensions beyond the range of lengths and steepnesses for which data are available.

Figure 15-3 Topographic factor LS in the universal soil loss equation [41].

Streambank erosion and streambed degradation can be significant in certain cases. Changes in channel alignment and/or removal of natural vegetation from stream banks may cause increased bank erosion. Streambed degradation, typically downstream of reservoirs, can also constitute an additional source of sediment.

Methods for determining soil loss due to the various types of channel erosion include the following: (1) comparing aerial photographs taken at different times to assess the growth rate of channels, (2) performing river cross-sectional surveys to determine changes in cross-sectional area, (3) assembling historical data to determine the average age and growth rate of channels, and (4) performing field studies to evaluate the annual growth rate of channels.

Field surveys can often provide sufficient data to estimate streambank erosion as follows [41]:

$$S = HLR \tag{15-7}$$

in which S = annual volume of streambank erosion; H = average height of bank; L = length of eroded bank, each side of channel if both sides are eroding; and R = annual rate of bank recession (net rate if one side is eroding while the other is depositing).

Streambed degradation can be estimated as follows [41]:

$$S = WLD \tag{15-8}$$

in which S = annual volume of streambed degradation; W = average bottom width of degrading channel reach; L = length of degrading channel reach; and D = annual rate of streambed degradation.

Accelerated Erosion Due to Strip-mining and Construction Activities

Strip-mining and construction activities greatly accelerate erosion rates. For instance, Collier et al. [10] found that a watershed with 10.4 percent of its area strip-mined eroded 76 times more sediment than a similar undisturbed watershed. Wolman and Shick [45] found that sediment concentrations in streams draining construction areas ranged from 3000 to 150,000 ppm, compared to concentrations of 2000 ppm in comparable natural settings. These studies indicate that human-induced land disturbances have a substantial impact on sediment production. With a careful choice of factors, the USLE can be used to compute soil loss from disturbed lands.

Sediment Yield

In engineering applications, the quantity of sediment eroded at the sources is not as important as the quantity of sediment delivered to a downstream point, i.e., the sediment yield.

The sediment yield is calculated by multiplying the gross sediment production, which includes all types of erosion (sheet, rill, gully, and channel erosion) by a sediment-delivery ratio that varies in the range 0 to 1 (it can also be expressed as a percentage). Therefore, a calculation of sediment yield hinges upon an estimate of gross sediment production (from the various sources) and an appropriate sediment-delivery ratio.

Sediment-delivery Ratio

The sediment-delivery ratio (SDR) is largely a function of (1) sediment source, (2) proximity of sediment source to the fluvial transport system, (3) density and condition of the fluvial transport system, (4) sediment size and texture, and (5) catchment characteristics.

The sediment source has an influence on the delivery ratio. Not all sediments originating in sheet and rill erosion are likely to enter the fluvial transport system. However, sediments produced by channel erosion are generally closer to the transport system and are more likely to be delivered to downstream points. The proximity of the sediment source to the transport system is also an important variable in the estimation of SDR. The amounts of sediment delivered to downstream points will depend to a large extent on the ability of the fluvial transport system to entrain and hold on to the sediment particles. Silt and clay particles can be transported much more readily than sand particles; therefore, the delivery of silts and clays is more likely to occur than that of sands. Catchment characteristics also affect sediment-delivery ratios. High relief often indicates both a high erosion rate and a high SDR. High channel density is usually an indication of an efficient transport system and, consequently, of a high SDR.

Estimation of Sediment-delivery Ratios. The SDR is the ratio of sediment yield to gross sediment production. Sediment yield can be evaluated by one of several methods. At reservoir locations, estimates of sediment yield can be obtained by reservoir sedimentation surveys. Alternatively, sediment yield can be evaluated by direct measurement of sediment load at the point of interest. Estimates of gross sediment production from upland sources can be obtained using either the USLE formula or a regionally derived formula for sheet and rill erosion. When warranted, this estimate can be augmented by field estimates of gully and channel erosion.

In the absence of actual measurements, statistical analysis can be used to develop regional regression equations to predict SDRs. The simplest SDR prediction equation is that based solely on drainage area, as shown in Fig. 15-4. This figure shows that SDR varies approximately in inverse proportion to the $\frac{1}{5}$ power of the drainage area. Other sources, however, have quoted values of this power as low as $\frac{1}{8}$ [2]. The fact remains that the greater the drainage area, the smaller the catchment relief and the greater the chances for sediment deposition within the catchment. Consequently, the smaller the catchment's SDR. Rough estimates of SDR can be obtained from Fig. 15-4, but caution is recommended for more refined studies.

An example of the use of statistical analysis for the estimation of sediment-delivery ratios is given by Roehl [34]. Using data from the southeast Piedmont region of the United States, he developed the following predictive equation:

$$\mathrm{SDR} = 31{,}623(10A)^{-0.23}\left(\frac{L}{R}\right)^{-0.51} B^{-2.79} \qquad (15\text{-}9)$$

in which SDR = sediment-delivery ratio in percentage; A = drainage area in square miles; L/R = dimensionless ratio of catchment length-to-relief (length measured parallel to main drainageway, relief measured as the elevation difference between drainage divide and outlet); and B = weighted mean bifurcation ratio, defined as the the ratio of the number of streams in a given order to the number of streams in the next higher order. Values of SDR measured by Roehl in the Piedmont area were in the range 3.7 to 59.4 percent.

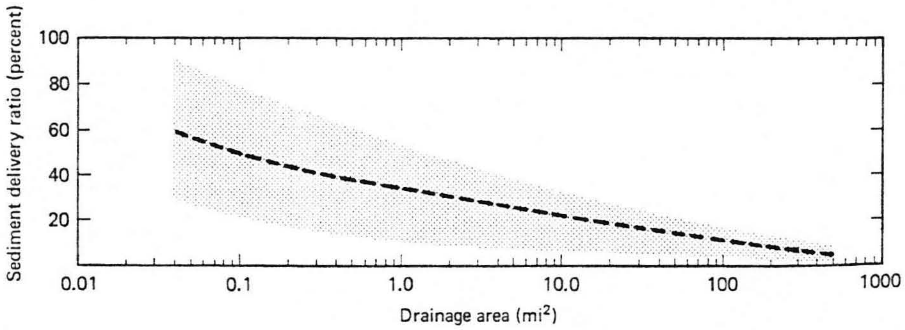


Figure 15-4 Relationship between sediment-delivery ratio and drainage area [41].

Empirical Formulas for Sediment Yield

As with the SDRs, statistical analysis can be used to develop regional equations for the prediction of sediment yield. A study by Dendy and Bolton [13] showed that sediment yield can be related to catchment area and mean annual runoff.

Sediment Yield versus Drainage Area. Dendy and Bolton studied sedimentation data from about 1500 reservoirs, ponds, and sediment detention basins. In developing their formulas, they used data from about 800 of these reservoirs with drainage areas greater than or equal to 1 mi^2. The smaller watersheds—those of drainage area less than 1 mi^2—were excluded because of their large variability of sediment yield, reflecting the diverse effects of soils, local terrain, vegetation, land use, and agricultural practices.

For drainage areas between 1 and 30,000 mi^2, Dendy and Bolton found that the annual sediment yield per unit area was inversely related to the 0.16 power of the drainage area:

$$\frac{S}{S_R} = \left(\frac{A}{A_R}\right)^{-0.16} \tag{15-10}$$

in which S = sediment yield in tons per square mile per year; S_R = reference sediment yield corresponding to a 1-mi^2 drainage area, equal to 1645 tons per year; A = drainage area in square miles; and A_R = reference drainage area (1 mi^2).

Sediment Yield versus Mean Annual Runoff. Dendy and Bolton studied sedimentation data from 505 reservoirs having mean annual runoff data. Annual sediment yield per unit area was shown to increase sharply as mean annual runoff Q increased from 0 to 2 in. Thereafter, for mean annual runoff from 2 to 50 in. annual sediment yield per unit area decreased exponentially. This led to the following equations.

For $Q < 2$ in.:

$$\frac{S}{S_R} = 1.07\,(Q/Q_R)^{0.46} \tag{15-11a}$$

For $Q \geq 2$ in.:

$$\frac{S}{S_R} = 1.19e^{-0.11(Q/Q_R)} \tag{15-11b}$$

in which Q_R = reference mean annual runoff, $Q_R = 2$ in.

Dendy and Bolton combined Eqs. 15-10 and 15-11 into a set of equations to express sediment yield in terms of drainage area and mean annual runoff.

For $Q < 2$ in.:

$$\frac{S}{S_R} = 1.07\left(\frac{Q}{Q_R}\right)^{0.46}\left[1.43 - 0.26 \log\left(\frac{A}{A_R}\right)\right] \tag{15-12a}$$

For $Q \geq 2$ in.:

$$\frac{S}{S_R} = 1.19e^{-0.11(Q/Q_R)}\left[1.43 - 0.26 \log\left(\frac{A}{A_R}\right)\right] \tag{15-12b}$$

For $S_R = 1645$ tons/mi^2/y, $Q_R = 2$ in., and $A_R = 1$ mi^2, Eq. 15-12 reduces to the following:

For $Q < 2$ in.:

$$S = 1280 Q^{0.46}(1.43 - 0.26 \log A) \tag{15-13a}$$

For $Q \geq 2$ in.:

$$S = 1965 e^{-0.055Q}(1.43 - 0.26 \log A) \tag{15-13b}$$

Equations 5-12 and 5-13 are based on average values of grouped data; therefore, they should be used with caution. In certain cases, local factors such as soils, geology, topography, land use, and vegetation may have a greater influence on sediment yield than either mean annual runoff or drainage area. Nevertheless, these equations provide a first approximation to the regional assessment of sediment yield for watershed planning purposes.

Example 15-4.

Calculate the sediment yield by the Dendy and Bolton formula for a 150-mi^2 watershed with 3.5 in. of mean annual runoff.

The application of Eq. 15-13b leads to:

$$S = 1965 \times e^{(-0.055 \times 3.5)}[1.43 - 0.26 \log (150)] = 1400 \text{ ton/mi}^2\text{/y}$$

Therefore, the sediment yield is 210,000 ton/y.

Other widely used sediment yield prediction formulas are the modified universal soil loss equation (MUSLE), developed by Williams [42], and the Flaxman formula [17]. Unlike the USLE, which is based on annual values, the MUSLE is intended for use with individual storms. The Flaxman formula was developed using data from the western United States and is therefore particularly applicable to that region.

15.3 SEDIMENT TRANSPORT

Sediment transport refers to the entrainment and movement of sediment by flowing water. An understanding of the principles of sediment transport is essential for the interpretation and solution of many hydraulic, hydrologic, and water resources engineering problems.

The study of sediment transport can be divided into (1) sediment transport mechanics, (2) sediment transport prediction, and (3) sediment routing. Sediment transport mechanics refers to the fundamental processes by which sediment is entrained and transported by flowing water. Sediment transport prediction refers to the methods and techniques to predict the equilibrium or steady rate of sediment transport in streams and rivers. The prediction of sediment transport is accomplished by means of a sediment transport formula. *Sediment routing* refers to the nonequilibrium or unsteady sediment transport processes, the net result of which is either the aggradation or degradation of stream and river beds.

The description of sediment transport is based on principles of fluid mechanics, river mechanics, and fluvial geomorphology. The energy and turbulence of the flow gives streams and rivers the capacity to entrain and transport sediment. The sediment being transported can originate in either (a) upland sources or (b) channel sources.

A significant feature of sediment transport is the entrainment and transport by the flow of the material constituting the channel bed. Thus, sediment transport serves not only as the means for the movement of sediment from upstream to downstream but also as the mechanism by which streams and rivers determine their own cross-sectional shapes and boundary roughness. While the transport of sediment is a fluid mechanics subject, the interaction between flowing stream and its boundary is a river mechanics subject.

Sediment Transport Mechanics

Sediment load or sediment discharge is the total amount of sediment transported by a stream or river past a given point, expressed in terms of weight per unit time. Based on the predominant mode of transport, sediment load can be classified into (a) bed load and (b) suspended load. *Bed load* is the fraction of sediment load that moves by saltation and rolling along the channel bed, primarily by action of bottom shear stresses caused by vertical velocity gradients. *Suspended load* is the fraction of sediment load that moves in suspension by the action of turbulence. Particles transported as bed load are coarser than particles transported as suspended load. However, the distinction between bed load and suspended load is not all-exclusive; some particles may move as bed load at one point, as suspended load at another, and vice versa.

Based on whether the particle sizes are represented in the channel bed, sediment load can be classified into (a) bed-material load and (b) fine-material load. *Bed-material load* is the fraction of sediment load whose particle sizes are significantly represented in the channel bed. Conversely, *fine-material load*—commonly referred to as wash load—is the fraction of sediment load whose particle sizes are not significantly represented in the channel bed. Stated in other terms, bed-material load is the coarser fraction of sediment load that may have originated in the channel bed and that may be subject to deposition under certain flow conditions. Wash load is the finer fraction of sediment load that has not originated in the channel bed and that is not likely to deposit. Wash load is then, *washed* through the reach, largely unaffected by the hydraulics of the flow.

The relationship between the two classifications of sediment load is shown in Fig. 15-5 [11]. This figure shows that the concepts of bed load and wash load are mutually exclusive. The middle overlap is the *suspended bed-material load,* i.e., the fraction of sediment load that moves in suspended mode and is composed of particle sizes that are represented in the channel bed.

Initiation of Motion. Water flowing over a streambed has a marked vertical velocity gradient near the streambed. This velocity gradient exerts a shear stress on the particles lying on the streambed, i.e., a bottom shear stress. For wide channels, the bottom shear stress can be approximated by the following formula [5]:

$$\tau_o = \gamma d S_o \qquad (15\text{-}14)$$

in which τ_o = bottom shear stress; γ = specific weight of water; d = flow depth; and S_o = equilibrium or energy slope of the channel flow.