Sediment yield-runoff-drainage area relationships in the United States

F. E. DENDY and G. C. BOLTON

ABSTRACT—We related watershed sediment yields, as determined from sediment deposits in about 800 reservoirs, to drainage area size and mean annual runoff. We found that average sediment yields per unit of net drainage area were inversely proportional to the 0.16 power of drainage area. Average sediment yields increased sharply to about 1,860 tons per square mile of drainage area as runoff increased from 0 to about 2 inches and then decreased as runoff increased from 2 to about 50 inches.

MANY variables influence sediment yield from a drainage basin. They include climate, drainage area, soils, geology, topography, vegetation, and land use (*1*, *2*, *7*, *8*). The effect of any of these variables may vary greatly from one geographic location to another, and the relative importance of controlling factors often varies within a given land resource area.

Previous studies indicate that sediment yield per unit area generally decreases as drainage area increases (*3*, *10*). As drainage area increases, average land slopes usually decrease; and there is less probability of an intense rainstorm over the entire basin. Both phenomena tend to decrease sediment yield per unit area.

Data compiled by Langbein and Schumm (*9*) showed that sediment yield per unit area increased as effective preciptation increased, peaked at 12 inches, and decreased as precipitation exceeded 12 inches. In arid regions, sparse precipitation and low runoff are the limiting factors. As precipitation increases, density of vegetation also increases, resulting in less erosion. In areas with adequate and evenly distributed precipitation, vegetation thus becomes the limiting factor.

Our study attempted to evaluate in a general way the effect of drainage area size and mean annual runoff on sediment yield in the contiguous United States, as revealed by sediment deposition rates in reservoirs. Such a study, although limited in scope, may provide some insight into the relative importance of these two factors on regional sediment yields.

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Reservoir Sedimentation Data

The U. S. Department of Agriculture summarized sedimentation data from about 1,500 reservoirs, ponds, and debris basins (*6*). We used the data from about 800 of these water bodies with drainage areas of one square mile or more. We excluded the smaller drainage basins because of highly variable sediment yields. Soils, local terrain, vegetation, land use, and agricultural practices greatly influence erosion in small drainage areas, and variability in sediment yield is normally much greater than in large basins, even in the same geographic area.

The reservoirs we selected for this study are distributed throughout the United States. Figure 1 shows their location in the river basins established by the U. S. Inter-Agency Committee on Water Resources (*11*).

The accuracy of the sedimentation surveys varied, ranging from reconnaissance-type measurements of sediment deposits to detailed surveys consisting of closely spaced cross-sections or contours. We made no attempt to classify the surveys according to accuracy.

We translated runoff data to inches per year per unit area and sediment deposition data to acre-feet or tons per year per square mile of net drainage area. We defined net drainage area as the sediment-contributing area and normally excluded areas above upstream reservoirs or other structures that were effective sediment traps. Our net drainage areas were only rough approximations for many of the larger reservoirs because drainage areas above many small upstream structures were not always excluded. We converted sediment deposits given in acre-feet only to tons by assuming a deposit density of 60 pounds per cubic foot, the approximate average of reported densities. Periods of record ranged from 2 years to more than 50 years.

We assumed that reservoir sediment deposition rates equaled watershed sediment yield (trap efficiency equaled unity). Actual sediment yields undoubtedly were slightly higher because most reservoirs do not trap all inflowing sediment. However, the error is probably less than 15 percent in most cases. Sediment trap efficiency studies have shown that most reservoirs with capacities equal to or greater than 0.1 of the average annual inflow normally trap 85 percent or more of the incoming sediment (*4*, *5*).

Sediment Yield vs. Drainage Area

We first ranked the data by drainage area size, then assembled them into logarithmic groups. We subdivided each log cycle into 10 groups so that each group represented 0.1 of the log scale length. This provided a fairly uniform distribution of the reservoirs within each log cycle. We then computed arithmetic averages of drainage area and sediment yield for each group.

Table 1 gives the average values of sediment yield, drainage area, and runoff for the grouped data. The number of reservoirs in each group varied from 60 with drainage areas between 2 and 2.5 square miles to two with areas of 25,000 to 30,000 square miles. Within each group, particularly those with small drainage areas, sediment yields often varied greatly, reflecting differences in climate, soils, geology, land use, vegetation, topography, and other factors.

There is some opportunity for bias in the data. Average sediment yields determined from a relatively small number of reservoirs for some drainage area size categories may not truly represent the size category. And while almost every section of the country is represented, the heaviest concentrations of reservoirs are in Texas, Oklahoma, and California.

Figure 2 shows the general relationship between net drainage area (A) and sediment yield (S). The plotted points are average values. We assumed a linear relationship and fitted the curve by the least squares method. On the average, sediment yield is inversely proportional to the 0.16 power of drainage area for drainage areas between 1 and 30,000 square miles.

Symbolically, the equation is:

$$\frac{S}{S_R} = \left(\frac{A}{A_R}\right)^{-0.16} \qquad [1]$$

where S is the sediment yield (tons/mi^2/yr.), S_R is a reference sediment yield value equal to 1,645 tons per square mile per year, A is the net drainage area (mi^2), and A_R is a reference drainage area equal to 1 square mile.

The intercept value of a curve fitted to a log-log plot of net drainage area versus sediment yield is 1,645 tons per square mile. Thus, 1,645 tons per square mile and 1 square mile were used as reference values.

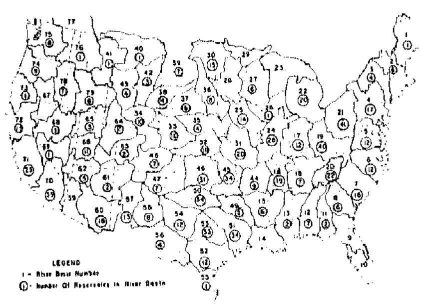

Figure 1. Location of reservoirs.

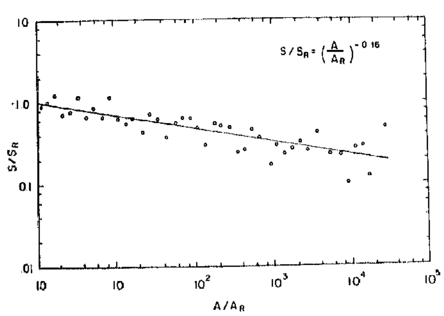

Figure 2. Sediment yield-drainage area relationship.

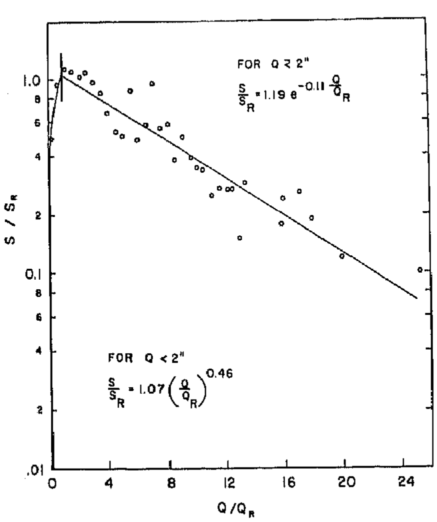

Figure 3. Sediment yield-runoff relationship.

Sediment Yield vs. Runoff

Mean annual runoff (Q) was available for 505 reservoirs. We assembled these data into class groups by 1-inch runoff increments, and computed mean runoff and sediment yield values for each group (Figure 3). Sediment yield increased sharply to about 1,860 tons per square mile per year as runoff increased from 0 to about 2 inches. As runoff increased from 2 to about 50 inches, sediment yield decreased exponentially.

Because sediment yield must approach zero as runoff approaches zero, a curve through the plotted points must begin at the origin. The abrupt change in slope of a curve through the data points at Q equals 2 inches precluded the development of a continuous function that would adequately define this relationship. Thus, we derived dual equations for when Q was less than 2 inches (175 reservoirs) and when Q was greater than 2 inches (330 reservoirs):

For Q less than 2 inches:

$$\frac{S}{S_R} = 1.07 \left(\frac{Q}{Q_R}\right)^{0.46} \qquad [2]$$

For Q equal to or greater than 2 inches:

$$\frac{S}{S_R} = 1.19\ e^{(-0.11\ Q/Q_R)} \qquad [3]$$

where Q is the mean annual runoff (in) and Q_R is a reference value equal to 2 inches.

We determined the combined influence of runoff and drainage area on sediment yield by using equations 2 and 3 to compute the sediment yield for each drainage basin. Then we determined the ratio of observed sediment yield (S_o) to computed sediment yield (S_c) for each basin. We assembled these data into class groups by drainage area size, as previously defined, and determined average drainage area and S_o/S_c values for each group (Figure 4).

Although poorly correlated, S_o/S_c generally decreases as drainage area increases. Therefore, some adjustment for drainage area size is needed. Assuming a semilogarithmic relationship (Figure 4), the equation for a best fit curve is:

$$S_o/S_c = 1.43 - 0.26 \text{ Log } (A/A_R) \qquad [4]$$

The runoff-sediment yield relationships, equations 2 and 3, adjusted for

Table 1. Summary of reservoir sedimentation data.

Number of Reservoirs	*Average Net Drainage Area (mi^2)*	*Average Sediment Yield (t/mi^2/yr)*	*Average Runoff*[a] *(in/yr)*
45	1.11	1502	2.75
39	1.39	1617	3.82
46	1.74	1983	4.10
60	2.25	1144	2.61
45	2.86	1265	3.60
40	3.58	1901	5.12
44	4.48	1081	3.08
33	5.62	1357	5.28
25	7.12	1090	5.75
28	8.96	1888	2.75
37	11.2	1033	3.52
27	14.2	904	4.93
23	17.8	1031	3.50
19	22.9	700	3.09
20	28.5	1157	6.59
16	35.5	1004	3.15
20	44.4	619	5.55
21	57.2	905	3.87
18	71.2	1053	2.68
13	89.8	1060	7.63
15	110	782	6.37
7	140	501	10.04
16	180	902	7.25
11	219	831	9.85
14	277	805	10.26
12	363	399	5.16
13	445	431	8.08
5	554	769	6.70
9	689	599	8.78
5	947	283	6.38
15	1,115	492	6.81
14	1,468	368	8.99
10	1,724	426	10.60
10	2,196	518	5.59
10	2,834	419	12.98
3	3,697	692	1.13
4	5,714	378	1.28
4	7,396	393	6.75
3	9,149	159	8.03
2	11,283	465	1.45
3	13,935	477	3.20
3	17,728	205	.83
2	27,395	812	1.25

[a]Runoff data were not available for all reservoirs in each drainage area size category. Runoff values given are average values for reservoirs with runoff data.

drainage area, become:

For runoff less than 2 inches:

$$\frac{S}{S_R} = 1.07 \left(\frac{Q}{Q_R}\right)^{0.46} \times (1.43 - 0.26 \text{ Log } (A/A_R)) \quad [5]$$

For runoff equal to or greater than 2 inches:

$$\frac{S}{S_R} = 1.19 \, e^{(-0.11 \, Q/Q_R)} \times [1.43 - 0.26 \text{ Log } (A/A_R)] \quad [6]$$

Using equations 5 and 6, we computed sediment yields for each of the 505 drainage basins and assembled the data by 1-inch runoff intervals as before. We then determined the average values of computed and observed sediment yields for each interval (Figure 5). The scatter of points about the line of equal values indicates a relatively high degree of correlation ($r^2 = 0.75$), between observed and computed sediment yield. However, the relationships defined by equations 5 and 6 are based on average values of grouped data. Use of these equations to predict sediment yield for a specific location would be unwise because of the wide variability caused by local factors not considered in the equations' development.

Summary and Conclusions

We used sediment deposition data from more than 500 reservoirs to develop relationships between sediment yield, drainage-area size, and mean annual runoff. On the average, sediment yield per unit area was inversely proportional to the 0.16 power of net drainage area for drainage areas between 1 and 30,000 square miles. Sediment yield per unit area increased quite rapidly to about 1,860 tons per square mile per year as runoff increased from 0 to about 2 inches. It then decreased as runoff increased from 2 to about 50 inches.

We developed equations 5 and 6 to relate mean sediment yield to mean annual runoff and drainage-area size. While these equations explained 75 percent of the variation in average sediment yield, we should emphasize that they were derived from average values of grouped data. Use of the equations to predict sediment yield for individual drainage basins would be unwise. Local factors, including soils, geology, topography, land use, and vegetation, may influence sediment yield much more than either

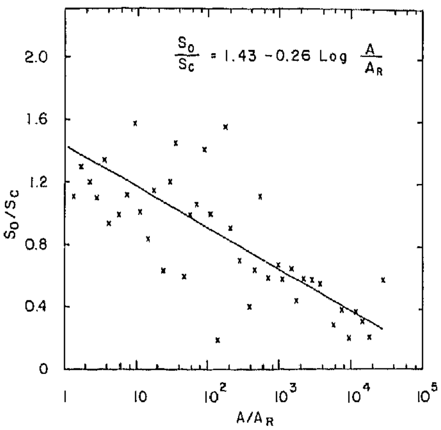

Figure 4. Variation in computed sediment yield as related to drainage area.

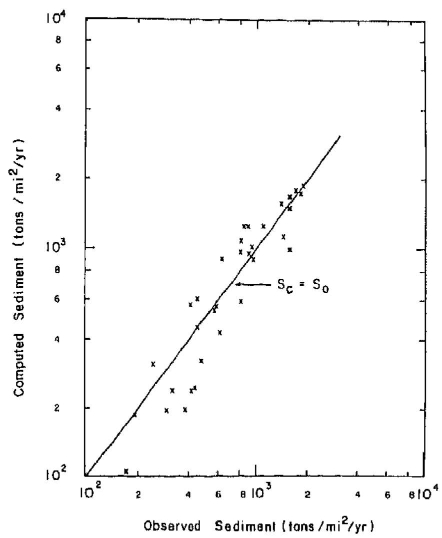

Figure 5. Observed versus computed sediment yield.

runoff or drainage area. Actual sediment yields from individual drainage basins may vary 10-fold or even 100-fold from computed yields.

The equations express the general relationships between sediment yield, runoff, and drainage area. They may provide a quick, rough approximation of mean sediment yields on a regional basis for preliminary watershed planning. Because we derived the equations from average values, computed sediment yields normally would be low for highly erosive areas and high for well stabilized drainage basins with high plant density.

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Important dates to remember

February 6-10
31st Annual Meeting, National Association of Conservation Districts
Atlanta, Georgia
Contact: NACD, 1025 Vermont Avenue, N.W., Washington, D. C. 20005

February 14-18
Annual Meeting, Society of Range Management
Portland, Oregon
Contact: SRM, 2120 S. Birch, Denver, Colorado 80222

February 20-26
143rd Annual Meeting, American Association for the Advancement of Science
Denver, Colorado
Contact: AAAS, 1776 Massachusetts Ave., N.W., Washington, D. C. 20036