CHAPTER 3

SEDIMENT YIELD

Section I. Introduction

3-1. Purpose and Scope. This chapter presents guidance on the selection and application of procedures for calculating sediment yield. Procedures are identified; positive and negative attributes of methods are presented in terms of the type of project for which the yield is needed; and important checkpoints in the use of the methods are presented. The sequence in which the methods are presented indicates the reliability of results, from most reliable to least reliable. This chapter does not describe all calculations in detail.

3-2. Need for Sediment Yield Studies. Soil erosion or soil loss is not the same as sediment yield. Eroded soil may be redeposited a few inches from where it was dislodged, whereas sediment yield from a basin is that portion of the eroded soil which leaves the basin. Approximately one-sixth of all eroded soil reaches the ocean during the time of significance to engineering projects. The determination of sediment yield normally is not the end product of a sediment analysis for projects in the Corps of Engineers. Rather, it is an intermediate step in broader studies of sedimentation for reservoir projects, local flood protection channel projects, navigation projects, alternative future land use studies, and the other projects in which the Corps engages. In almost every case the real need is to forecast future conditions, and yet the material presented herein focuses on hindcasting a historical period. That is because land use, rainfall, and runoff are known for hindcasting; therefore, attention can be directed toward the application of the technique. However, in forecasting future yields, all these parameters must be estimated. Moreover, hindcasting is the required technique for "confirming" that the procedure will be valid for the proposed study area. Finally, two different levels of forecasts are needed: one is the long-term average to provide results for project life and maintenance and the other is sediment yield for single events. Specific requirements vary from one type of project to another as illustrated in the following subparagraphs.

a. Reservoirs. Each reservoir project needs a sediment yield analysis, and most yield studies to date have been performed to calculate reservoir storage depletion resulting from the deposition of sediment during the "project life." The project life for a flood control reservoir is different from that of a navigation reservoir. Since total yield is probably 90 percent suspended sediment, the primary field data needed for reservoir sedimentation forecasts are the suspended sediment discharges. Those needs will continue into the future as reservoir use studies, such as the reallocation of storage, the modification of operating rules, and the preparation of periodic sedimentation reports, update and reevaluate sediment yield. Suspended sediment sampling equipment was perfected to obtain such field data. The field data for headwater reaches of reservoirs, on the other hand, should include total sediment yield by particle size because that is where the sands and gravels will deposit. Calculating the behavior of these coarse particles requires a more detailed data collection and analysis program than just the suspended sediment concentration.

b. Local Flood Protection Channel Projects. Whereas reservoirs provide flood protection by modifying storage levees, diversions, and channelization are hydraulic means for reducing flood damages. Similarly, reservoir projects provide sediment storage, whereas sediment storage is typically not provided in channel projects except in special containments like debris basins. Consequently, problems resulting from sedimentation, both depositional and erosional, are noticed more frequently and earlier in the life of a channel project than they are at a reservoir. In addition, a reservoir acts as a sink, whereas a channel project creates both sinks and sources for sediment, and the most common problems are the deposition of sands and gravels or the erosion of sands and silts. So rather than total volume, sediment yield studies for channel projects must produce the volume of the bed material fractions. In most cases those are the particle sizes which are too large to be measured with suspended sediment samplers. Moreover, field samples of bed sediments must describe the sediment particle sizes "that will become the bed of the constructed project." Finally, sediment yield studies for a reservoir focus on the upstream watershed; whereas in channel projects they must also include the project area. A rigorous sediment yield forecast is required to produce such refinement.

c. Channel Projects for Navigation. Although the water-sediment behavior is similar to that in flood protection channels, the question being addressed is different. A flood project seeks to reduce the stage. A navigation project seeks to provide reliable water depth. The two are sometimes complementary and sometimes competitive requirements. The yield of sand is significant to both. Silt and clay are common materials dredged from navigation channels, whereas silts and clays are not common problems in flood channel studies, except in backwater and salinity areas. Another significant difference between the two channel uses is the resolution required to locate problem areas. Even one shallow crossing will obstruct navigation whereas that probably would not significantly change the stage of a flood.

d. Alternate Future Land Use Studies. Not only is future sediment yield important in project formulation but also it is important in land use planning even if no project is contemplated. The expanded flood plain management studies (XFPI's) have routinely identified areas of developing watersheds having high erosion potential and therefore significant sediment yield for receiving streams. Advance knowledge of yield potential can allow more intelligent land use decisions to be made. When a project is being considered, sediment studies should forecast a future condition without the project in place to establish how stream stability is changing through time as hydrology and sediment supply adjust to changes in land use, water chemistry, and other projects in the basin. As in hydrologic studies, a sediment investigation must establish the future conditions with project in place.

3-3. Field Reconnaissance. A reconnaissance of the stream should be conducted prior to adopting a method for calculating sediment yield because current methods do not aggregate erosion from the individual mechanisms eroding the sediment (i.e., sheet/rill erosion, gully erosion, bank caving, bed gradation, and tributary inflows). The field reconnaissance allows the engineer to determine the main sources of sediment entering the project. He should use that information to select the most appropriate method or methods for the sediment yield analysis. For example, the Universal Soil Loss Equation is not appropriate for a small watershed exhibiting severe bank caving or gully erosion because that equation was designed for sheet and rill erosion. Therefore, a field presence cannot be overemphasized when determining sediment yield. If sedimentation is critical to the recommended alternative, a rigorous sediment yield analysis is recommended early in the project planning process.

3-4. Methods for Determining Sediment Yield. The large variety of sediment yield methods can be placed into two broad categories: methods based on direct measurement and mathematical methods. Only those based on direct field measurements are considered a rigorous approach; mathematical methods are trend indicators at best.

Section II. Sediment Yield Methods Based on Direct Measurements

3-5. Introduction. This grouping of sediment yield methods is based on direct measurements of hydrologic, hydraulic, and sediment parameters in the study area. There are three major subcategories as follows: in-stream sampling, reservoir sedimentation investigations, and regional analysis.

3-6. In-stream Sampling. Instream sampling techniques are documented in [21] and [64]. This is the most reliable approach, and the several methods presented in the following subparagraphs are listed in the order of preference.

a. Published Long-Term Daily Discharge Records. The most accurate historical sediment discharge is that calculated from a long-term sediment gage record. The standard procedure used by the US Geological Survey is to plot the daily water discharge hydrograph and the daily sediment concentration graph, then integrate them as illustrated in item [46]. These records usually express sediment concentrations in milligrams per liter, and those units can be converted to tons per day with the following equation:

$$Qs = 0.0027 * Q * C * k \qquad (3\text{-}1)$$

where

Qs = sediment discharge, tons per day
0.0027 = convert cfs to tons/day/1000000 parts
Q = mean daily water discharge, cubic feet per second
C = mean daily sediment concentration, ppm
k = convert ppm to mg/l
k = 1 for concentrations less than 16000 ppm, otherwise See table 2 [46] or use the following equation.

$$k = \{10^{**}6 \;/\; [(10^{**}6)/(Cppm^{*}Sw) \;-\; 1 \;/\; Sw + 1 \;/\; Ss]\} \;/\; Cppm \qquad (3\text{-}2)$$

where

Ss = specific gravity of the sediment particles
Sw = specific gravity of the water

Usually, only the "measured load" is published; however, suspended samplers do not measure the lowest 0.3-0.4 feet of the water column. The sediment concentration in that "unmeasured zone" is usually estimated to be from 5 to 15 percent of the measured concentration, and that value is added to the suspended load to get the total. Before comparing sediment yield for one year to that for another, the period-of-record data should be examined for homogeneity. Adjustments for upstream reservoirs, the hydrologic record, land use changes, and farming practices may be necessary before the correlation between sediment yield and water yield can be established.

b. Period Yield Sediment Load Accumulation. This is the technique used by the USGS to calculate monthly and annual suspended sediment yield after the long-term mean daily values have been computed. Summations use the average daily sediment discharges, but they can be hourly for smaller streams. Reaches of river downstream of a major reservoir which receive little tributary contribution, or reaches of major rivers where the discharge is fairly constant for long periods of time, could have yearly sediment yield computed by summation of monthly or weekly loads. The engineer is responsible for determining the proper time interval to use.

c. Flow-Duration Sediment-Discharge Rating Curve Method. This is a simple integration of the flow duration curve with the sediment discharge rating curve at the outflow point from the basin. It is the most common method used in the Corps of Engineers because:

- both the flow duration curve and the sediment discharge rating curve are process-based and can be changed from the historical values needed for hindcasting to values needed for forecasting water and sediment runoff in the future;

- and these curves can be scoped to reflect specific components of the sediment runoff process (i.e., a sediment discharge rating curve can be calculated for sand and gravels when those are the types of sediment of most interest to project performance).

The sediment discharge rating curve is sometimes called a suspended sediment transport graph or a suspended sediment transport relationship. It is a relationship between water discharge and sediment discharge as illustrated by Figure 3-1. The flow duration curve of mean daily water discharges at that same gage is illustrated in Figure 3-2.

(1) Calculations. The computation of yield starts by establishing computation points along the flow-duration curve. Select either class intervals of Q or intervals along the "percent of time flow was equaled or exceeded" axis. In the example which follows, shown on Table 3-1, the latter approach was used. The percent exceedance is tabulated at each ordinate,

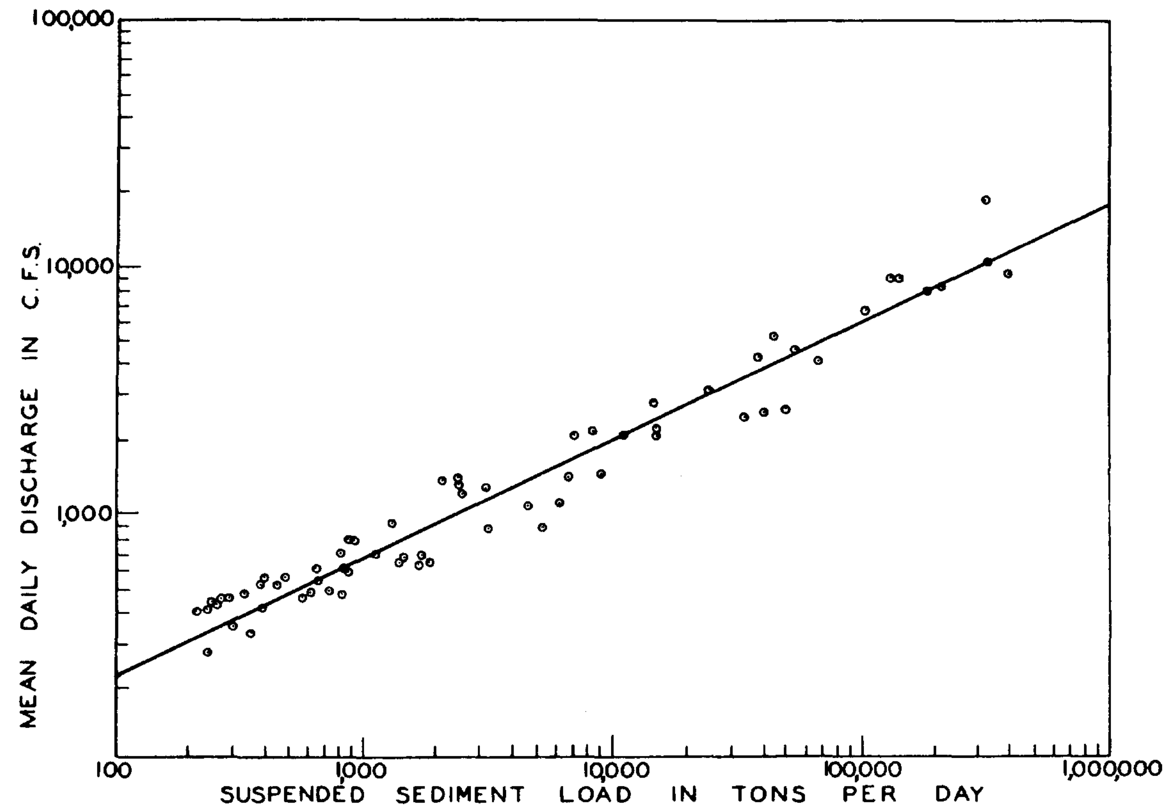

Figure 3-1. Sediment discharge rating curve, Elkhorn River, Waterloo, Nebraska

column 1, forming increments sufficiently small so the exceedance curve is approximated by straight line segments. The midpoint of each segment and its incremental time, in percent, are calculated in columns 2 and 3, respectively. Note, column 3 is referred to as having units of time because the units of the exceedance axis is time. The value of Q for the midpoint of each segment is recorded, column 4, and the sediment discharge for that Q is read from the sediment discharge curve and recorded in column 5. The daily average Q is calculated, column 6, by multiplying the water discharge by the time increment expressed as a decimal, column (4)x(3)/100, and summing all increments. The daily average sediment discharge is calculated similarly, by multiplying the suspended sediment load in column (5) by column (3)/100 and summing the column.

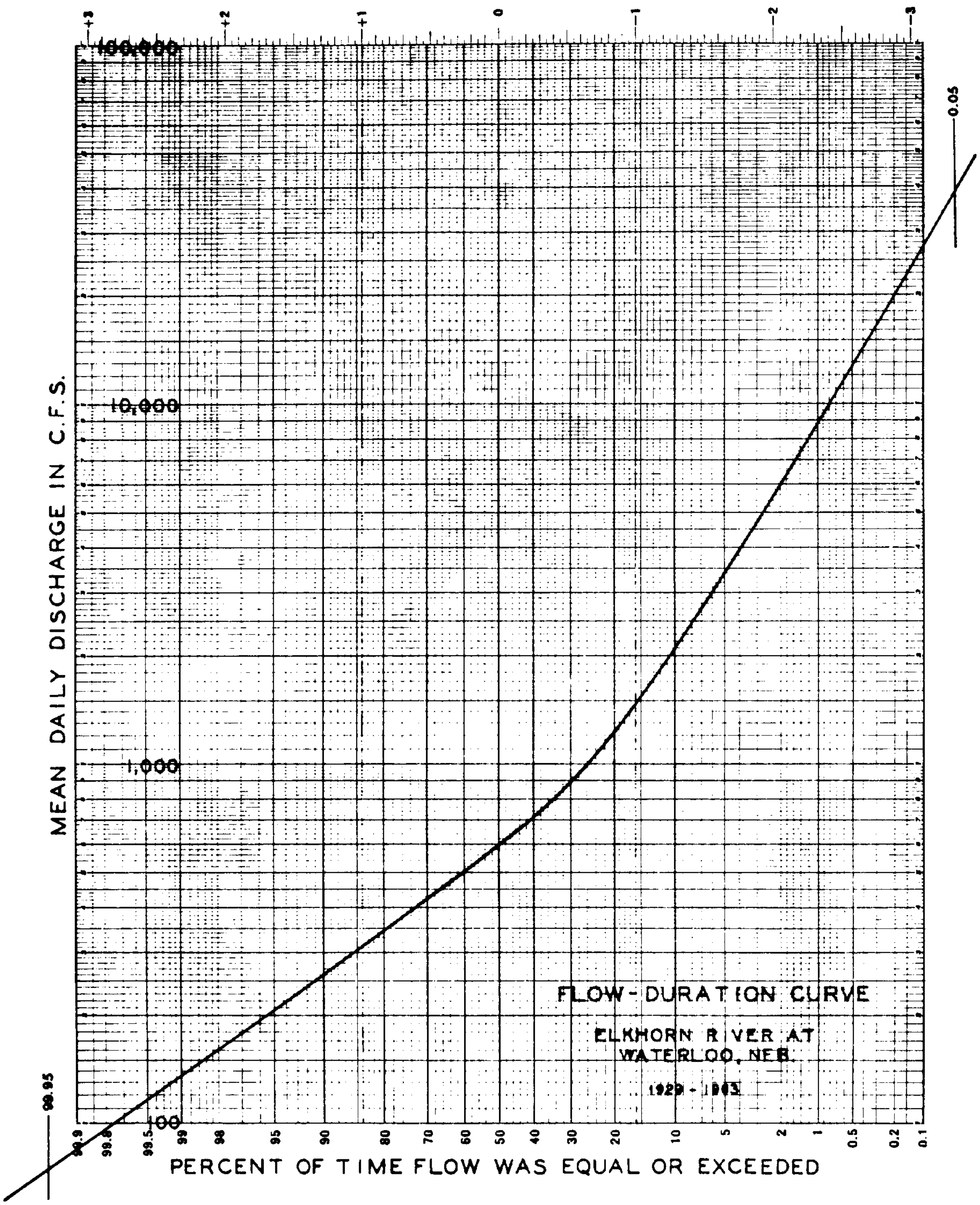

Figure 3-2. Flow duration curve, Elkhorn River, Waterloo, Nebraska

TABLE 3-1. Total Sediment Yield, Elkhorn River at Waterloo, Nebraska

Flow Duration in Percent Exceed-ence	Flow Duration in Percent Mid Ordinate	Flow Duration in Percent Incre-ment	Water Discharge Qw[1] (cfs)	Sediment Discharge Qs[2] (tons/day)	Daily Average Qw (cfs)	Daily Suspended Qs (tons/day)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0						
	0.05	0.1	37,000	4,500,000	37.0	4500
.1						
	0.3	0.4	15,000	680,000	60.0	2720
.5						
	1.0	1.0	9,000	230,000	90.0	2300
1.5						
	3.25	3.5	4,500	55,000	157.5	1925
5						
	10	10	2,100	11,000	210.0	1100
15						
	20	10	1,200	3,500	120.0	350
25						
	30	10	880	1,800	88.0	180
35						
	40	10	710	1,150	71.0	115
45						
	50	10	600	800	60.0	80
55						
	60	10	510	580	51.0	58
65						
	70	10	425	390	42.5	19
75						
	80	10	345	250	34.5	25
85						
	90	10	260	140	26.0	14
95						
	96.75	3.5	180	64	6.3	2
98.5						
	99.0	1.0	135	35	1.4	1
99.5						
	99.7	0.4	105	20	0.4	0
99.9						
	99.95	0.1	74	13	0.1	0
100					1055.7	13,409

Notes: [1] Stream Flow Record, 1929 to 1963
[2] Suspended Sediment Sampling Record, August 1948 to November 1950

The annual yield of water is the product of the mean daily value times 365 days per year times the conversion factor for acre-feet.

Annual Water Yield = 1055.7 x 365 x 1.98
= 762,950 acft/yr

The annual yield of suspended sediment is the product of the mean daily value times 365 days per year expressed in tons.

Annual Suspended Sediment Yield = 13,409 x 365
= 4,594,000 tons/yr

Assume the Unmeasured Sediment Discharge is 10% of the suspended discharge, 459,000 tons/yr, the resulting annual sediment yield is

Total sediment yield = 4,594,000 + 459,000
= 5,053,000 tons/yr

Total drainage area at the gage is 6,900 square miles of which the sediment contributing drainage area is 5,900 square miles.
The resulting annual unit sediment yield is

Unit sediment yield = 5,053,000 / 5900
= 856 tons/square mile

(2) Adjustments. Even when flow duration and sediment discharge curves are based on extensive field measurements, some adjustment may be necessary.

(a) The field data should be converted from instantaneous measurements of concentration into mean daily sediment discharges having units of tons per day. Values should be plotted versus mean daily water discharge on a log-log grid to form a suspended sediment discharge curve. To be considered as representative of long term conditions, samples should include a wide range of water discharges, flood sizes, land use changes and seasonal responses of the watershed.

(b) Estimates of the unmeasured load should be included to obtain the total sediment load as presented in the previous method.

(c) The flow duration curve is usually based on a longer record than that of the sediment discharge curve. Streams, particularly in arid regions, which transport the majority of sediment by one or two high-flow events each year may not have adequate discharge records in this range to estimate yield. In other cases new stations may not have experienced the flood flows. To fill in this crucial data may require some adjustment to the high-flow portion of the flow duration curve, statistically, to include extreme events which have been developed hydrologically. Another technique is to pattern the low-probability events after nearby gaged stations.

(d) The first step in forecasting future sediment yield is to estimate the future, sediment-discharge rating curve and the future flow-duration curve. Natural systems, i.e., climate and land form, are considered to be represented by historical records unless there is evidence to the contrary. Land use, on the other hand, is subject to man's activities and may change significantly during the life of a project. As a result both the flow duration curve and the sediment discharge relationship may require adjustment. Once the future relationships are established, the calculation of water and sediment yields follows the same procedure as described for historical conditions.

(3) Points of Caution About the Flow-Duration Sediment Discharge Rating Curve Method.

(a) The sediment discharge rating curve is plotted as water discharge(Q) versus sediment discharge(Qs) on a log-log grid. However, the amount of scatter in such plots shows that sediment discharge is not a simple function of water discharge. Consequently, the engineer should investigate and evaluate any regional and watershed characteristics which might contribute to that scatter. For example, plot the water discharge in cfs versus the sediment concentration in ppm to avoid the dependency from having Q on both axes of the sediment discharge rating curve. Test for homogeneity with respect to season of the year, systematic changes in land use, type of sediment load, and type of erosive mechanisms. Use a multiple correlation approach coupled with good engineering judgement to establish the dominant factors influencing historical concentrations. Predict how those factors might change in the future and how such changes will impact sediment concentrations and particle sizes. An excellent discussion of the application of seasonal separation, and other causes of scatter in sediment discharge records, is given by [42].

(b) Note that for channel studies the bed material load is the most important contribution of the entire sediment yield since it is the one which deposits first and controls the behavior of the channel.

(c) The amount of wash load in the sediment influences the amount of scatter in the data because the amount of wash load depends on its availability and not upon hydraulics of flow. Also, as the concentration of fines increases above 10,000 ppm, the transport rate of sands and gravels is increased significantly as shown by [2].

(d) Water temperature causes a significant variation in transport capacity of the bed material load. When coupled with seasonal changes in land use, separate warm and cold weather sediment discharge rating curves may be required to achieve acceptable accuracy in the calculated results.

(e) Separate samples according to "population" for later analysis. For example, land surface erosion caused by sheet and rill processes is strongly correlated with rainfall impact energy. Therefore, the correlation of in-stream sediment concentrations with water discharge from rainfall-runoff, which has different erosive mechanisms than the snow melt-runoff process, may show an improvement when compared with the correlation of the entire data set. Likewise, the artificial floods, such as the pond break-out which occurred on the avalanche formed by the May 1980 eruption of Mt. St. Helens, will contain yet another population of erosive mechanisms and data from such events should be analyzed separately from both snowmelt and rainfall-runoff events.

(f) It is usually necessary to extrapolate the sediment discharge rating curve to water discharges well above the range of measured data. Exercise great care when doing so. Give first consideration to extrapolating concentrations, rather than sediment discharges. Include lines of constant concentration along with the measured data, i.e., C = 1000, 10,000, 100,000 and 1,000,000 ppm. The maximum possible concentration is 1 million ppm, which is solid rock. Be careful not to extrapolate into embarrassment. As the final step, convert the relationship back to a sediment discharge rating curve using equation (3-1).

(g) Extrapolating the relationship for total concentration does not guarantee the proper behavior of individual size classes. Check each one before accepting the results.

(h) It is possible to measure as much variation in concentration from one event to another as occurs from one discharge to another within a single event. Developing a concentration curve for a single event analysis must accommodate such a possibility. Therefore, fit two lines through the data. One should be the curve of best fit and the other should be the 95 % exceedance curve. Test the sensitivity of the project to sediment discharge by using both curves as the inflowing load.

(i) This method is considered to give a reliable estimate of sediment yield, but where historical values are available from long term records the results of this method should be checked against those values and the sediment rating curve adjusted, within the scatter of data, as required to reproduce the historical value.

(j) The western regions of the United States, which undergo pronounced wet and dry seasons, may require separate sediment rating curves for early rainy season events from those for the balance of the rainy season. This is important because aeolian mechanisms are particularly active during the dry season which leaves an abundance of erodible sediment for the beginning of the next wet season. As that supply is exhausted by early precipitation events, the runoff can shift from one having a very high concentration of sediment to one having a supply controlled by runoff energy. These differences can be expressed by using seasonal sediment discharge and flow duration curves.

d. Flood Water Sampling. When no field measurements exist, and at least some are required to make dependable sediment yield estimates, a limited sediment sampling program is recommended early in the planning studies. Such short-record approaches are called flood water sampling.

(1) Calculations. Calculations are the same as described previously for the flow duration-sediment rating curve method.

(2) Adjustments. The same adjustments to flow and sediment concentration curves would be appropriate, but there is usually insufficient data to make them.

(3) Points of Caution About the Flood Water Sampling Method. The same points are appropriate that were discussed for the flow-duration sediment

discharge rating curve method. In addition, consider the following because the short record will not necessarily provide a representative sample.

(a) This yield should be regarded as less reliable than values determined by the flow-duration sediment discharge rating curve technique because the data may not be representative of the long-term sediment concentrations from the watershed. The absence of floods or the occurrence of one or two large events may biased the yield calculation.

(b) Since there is less confidence in yield estimates, sensitivity tests should be performed to evaluate the impact of shifts in the load curve on the alternative being analyzed. If doubling, or tripling, the sediment discharge does not greatly affect the alternative under study, additional sediment data may not be necessary.

(c) Since sediment discharge curves are often displayed as a straight line relationship logarithmically against discharge, and often with a slope of about 2, anticipation of that "rule-of-thumb" slope is comforting when working with a limited amount of measured data. However, in sand bed streams use sediment transport functions to curve-fit and extrapolate the sand discharge data. In gravel bed streams, sand behaves like wash load, but sediment transport functions are useful for curve fitting and extrapolating the gravel discharge.

(d) There is no rule of thumb, nor is there a transport function, for the amount of wash load in a stream. A correlation has been observed, at some locations, between the fraction of bed material present in the suspended sediment samples and the total concentration. If present, such a correlation allows the wash load to be extrapolated because the bed material discharge can be calculated using transport functions.

(e) Use a variety of methods when field data is inadequate. Always include sediment transport calculations for the sand and gravel loads. Consider using numerical models to fill in missing data by transposing existing records.

(f) Where a limited sampling program can be scheduled and funded prior to the start of detailed studies, this technique becomes quite valuable to supplement/modify the results of other methods. If a program was not possible during the feasibility report stage, one is strongly recommended for the design phase.

3-7. Reservoir Sedimentation Investigations. Many reservoirs across the United States, ranging from a few acres to thousands of square miles in drainage area, are periodically surveyed. The quantity of sediment deposited since the previous survey is calculated by subtraction. The results of these calculations are published in item [63], which is updated every 5 years. Storage changes and annual deposition in tons per square mile of drainage area are available. Since the volume of deposition is the sediment yield times the reservoir trap efficiency, sediment yield can be estimated provided a representative trap efficiency can be determined for the period between the surveys. This method for calculating sediment yield is considered by some agencies to give the best estimate, although the inflow record during the time period between reservoir surveys should be carefully analyzed. That is, droughts or large floods can greatly bias the estimate. It is not unusual to have a large percentage of the total deposition occur during one or two large flood events. To detect such occurrences, plot the annual sediment yield relationship as shown in Figure 3-3. Consider the following factors when using the reservoir sedimentation survey technique to estimate sediment yield:

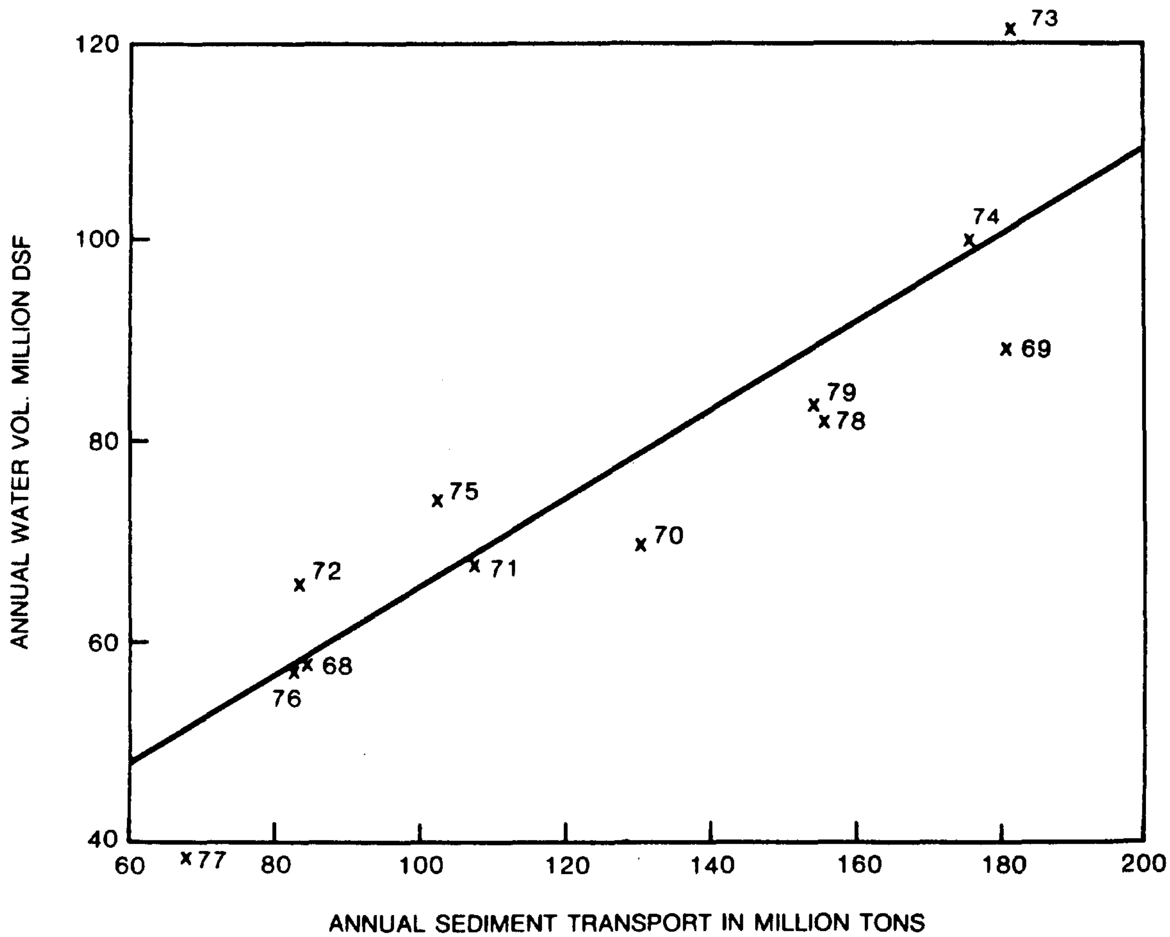

Figure 3-3. Sediment yield relationship

a. Trap Efficiency. Reservoir deposition is not synonymous with sediment yield. Some amount of inflowing sediment leaves the reservoir through the outlet and is not deposited within the pool. Although studies by Brune and others showed that reservoirs generally trap greater than 80 percent of the inflow, that should not be considered a rule-of-thumb. The reservoir trap efficiency must be determined and the measured deposit increased to account for that sediment passing through the reservoir. Trap efficiency is calculated by knowing the flow velocity through the reservoir and the gradation of the inflowing sediment load. Because flow velocities are difficult to estimate, Brune, item [10] proposed a surrogate means by which flow through time is related to the ratio of reservoir storage divided by average annual inflow. This relationship is widely used. Appendix F of this manual describes trap efficiency calculations in detail.

(1) Dry Detention Structures. The trap efficiency of a dry detention storage area would be expected to be less than that in a permanent pool reservoir. However, investigations of several small reservoirs, reported by Dendy item [16], have shown little difference in deposition between the two types of reservoirs. Trap efficiency relationships appear to apply equally well for both a permanent pool or dry reservoir, although the dry reservoirs in Dendy's study had only a 5-year maximum length of record. In calculating sediment yield for an existing dry detention structure, allow for some scouring and removal of previously deposited material during times of low to moderate in-channel flow through the reservoir area. Although no specific guidelines are available, Soil Conservation Service(SCS) techniques utilizing the Brune curves have incorporated a further adjustment for estimating yield from watersheds draining into dry detention areas. SCS employs a decrease in calculated sediment trap efficiency of 5 percent for streams that have incoming sediment consisting primarily of sand and a decrease of 10 percent for streams which carry predominantly fine material (silts and clays).

(2) Run of River Structures. Unlike dry detention or permanent pool reservoirs, run-of-river structures are not designed for flood storage but to maintain a minimum depth for navigation. Consequently deposition within the navigation pool is much less than within a flood-control reservoir, primarily occurring during normal flow periods. During flood periods, when the gates of the navigation dams are open and the river profile is about the same as the pre-project profile, some erosion of the previously deposited material may occur. Although primarily empirical, two techniques for estimating trap efficiency in a run-of-river pool are briefly described in Appendix C. It is more likely, however, that a computer model, such as HEC-6, would be needed to determine trap efficiency by calculating depositional changes in a navigation pool from year to year. Results from a period-of-record computer simulation could be used then to determine yield at the structure.

(3) Debris Basins. Debris basins are a special case of the dry reservoir designed to retain the coarsest sediments. The volume and rate of clean out are monitored, but it is extremely difficult to estimate total sediment inflow because trap efficiency typically changes drastically as the basin fills. Short circuits and high concentrations of fines are common; and trap efficiency is very sensitive to grain size. All of these complicate the use of debris basins in defining sediment yield from the watershed. The best approach is to process the system using a numerical model and calibrate the inflowing sediment discharge rating curve so the model reconstitutes the historical volume of sediment removed from the debris basin.

b. Sediment Size. The amount of sediment trapped by a reservoir or a debris basin depends on the flow velocity, flow depth, and sediment particle sizes. With the possible exception of dry detention areas or pondlike structures, it is reasonable to assume the trap efficiency of inflowing sands (particle sizes greater than 0.125 mm) to be 100 percent. Silts and clays are more difficult to settle, but pools with as small a ratio as 0.1 of reservoir capacity to average annual inflow settle 80-95 percent of all sediments.

c. Settling Velocity of Sediment Particles. Specific methods of computing settling velocities for sediment materials of various sizes and types are described in item [2] . This method is computerized in the CORPS system. The time required for sediment particles to settle out of the water column relative to the time required for flow to pass through the reservoir is a check against empirical trap efficiencies.

d. Consolidation of Deposition. Analysis of sediment yield from reservoir deposition requires a conversion of the deposited material from a volume per year basis to a weight per year basis. Deposited material in the pool contains varying amounts of water within its voids. This water volume changes with time as the deposition is consolidated. This consolidation must be considered in the yield calculation. Corps guidelines in developing these specific weights of deposited material are largely taken from item [2].

e. Contributing Drainage Area. The measured reservoir deposition must be adjusted for the actual contributing drainage area to obtain the correct sediment yield. The pool area should be deleted from the overall drainage area as should all other drainage areas controlled by reservoirs. In many parts of the country, portions of the watershed can be nondraining, with runoff going to potholes or sinkholes, or the soil may be primarily coarse material that allows little if any runoff. These areas may also be considered for deletion from the overall drainage area. Major changes in the upstream watershed between reservoir survey periods (extensive channelization, upstream reservoirs coming on-line, and other factors) should be accounted for during the development of unit sediment yield.

f. Erosion Mechanism. Relating sediment yield to drainage area assumes the primary erosion mechanisms are sheet and rill erosion. That may be true for silt and clay sediment, but the most likely erosion mechanisms for sands and gravels are gullying, bank erosion, and bed degradation. "Miles of channel having erodible bed and banks" is a better correlation parameter than drainage area for these mechanisms. Aerial photography is the best data source. In the more extreme cases, mass wasting mechanisms such as land slides or debris flows provides large volumes of all sizes of sediment.

3-8. <u>Transfer of In-Stream Data.</u> A wide variation in sediment discharge curves will be seen at different locations along a stream because minor changes in velocity will produce a significant change in the sediment transported. Therefore, transfer of sediment discharge rating curves from one point in a watershed to another point is discouraged. However, converting the discharge curve data to an annual sediment yield curve will usually result in a consistent relationship with drainage area, when land use, topography, and soils are similar. A plot of annual sediment transported against annual discharge can be used to estimate yield at different locations using the technique presented in the next paragraph.

3-9. <u>Transfer of Reservoir Deposition Data.</u> Sediment yield data calculated at a specific reservoir site can be transferred to the study watershed provided the topography, soils, and land use, particularly the percentage of both basins in agricultural usage are similar. If these similarities exist, transfer can be made by SCS techniques described in item [62] , or other criteria. SCS uses the following practices in transferring reservoir data east of the Rocky Mountains:

Direct transfer for study watersheds greater than 0.5 or less than 2.0 times the drainage area of the reservoir surveyed area.

No transfer for study watershed less than 0.1 or greater than 10.0 times the drainage area of the reservoir surveyed area.

Application of the following equation for study watersheds within these boundary limits:

$$Ye = Ym\ (Ae/Am)^{0.8} \qquad (3\text{-}3)$$

where

Ye = the total annual sediment yield estimated for the area under study, tons/year
Ym = the total annual sediment yield measured at the reservoir site, tons/year
Ae = the contributing drainage area for the site estimate
Am = the contributing drainage area for the reservoir measurement

These guides do not apply to mountainous areas which often show no consistent change in sediment yield for change in drainage area, or to streams where channel erosion may increase the sediment yield per unit area relationship with increasing drainage area.

3-10. Regional Analysis. Regional analyses have been performed for some areas of the United States and sediment yield is shown on maps, by graphs, or with equations based on definable parameters. However, regional methods should not be the only techniques used to calculate sediment yield. They are acceptable as preliminary procedures and are suggested as alternatives to support the other, more detailed, methods. In choosing a regional method always justify that their regression parameters include the erosive mechanisms that are predominant in your particular area of the region. That is, drainage area is an adequate parameter for land surface erosion, but it should not be correlated with stream bank erosion or even gullying. If these latter two are the predominate erosive mechanisms in your specific problem area of the region, avoid a regional equation that only includes drainage area. A few regional methods are:

a. Dendy and Bolton Method. This equation for sediment yield, developed by [17], has the widest potential application in the United States. Sediment yield from about 800 reservoirs throughout the continental United States was related to drainage area and mean annual runoff by the following two regression equations.

For watersheds having a mean annual water runoff equal to or less than 2 inches:

$$S = 1280 * (Q**0.46) * (1.43 - 0.26 \log A) \qquad (3\text{-}4)$$

For watersheds having a mean annual water runoff greater than 2 inches:

$$S = 1958 * [e**(0.055 * Q)] * (1.43 - 0.26 \log A) \qquad (3\text{-}5)$$

where

S = Unit sediment yield for the watershed, tons per square mile per year
Q = Mean annual water runoff for the watershed, inches
A = Watershed area, square miles
e = 2.73

Since these equations were developed from average values of grouped data, they are appropriate for general estimates. A better estimate can be expected for the larger, more varied watersheds than for smaller site specific areas. Do not use these equations for mountainous areas.

b. Pacific Southwest Interagency Committee (PSIAC) Method. The PSIAC method item [44] was developed for planning purposes and is applicable for basins in the western United States greater than 10 square miles. Sediment yield is directly proportional to the total of the numerical values assigned to nine different factors: land use, channel erosion/sediment transport, runoff, geology, topography, upland erosion, soils, ground cover, and climate. Numerical values range from 25 to -10 for each factor. Sediment yield can range from 0.15 acre-feet per square mile per year for watersheds with low PSIAC factor (20) to more than 3 acre-feet per square mile per year for large factors (100 or more). The PSIAC technique has compared well with actual watershed data and is one of the few methods which can estimate changed sediment yield caused by local land use management changes.

c. Tatum Method for Southern California. The Tatum method item [50] is used to calculate sediment yield and debris volumes for the arid, brush-covered, mountainous areas of southern California, see Appendix C. Calculations are made from nomographs using an equation with adjustment factors for size, shape, and slope of the drainage area, 3-hour precipitation, the portion of the drainage area burned, and the years occurring between the time of the burn and the time of the flood.

d. Transportation Research Board Method. Current guidance on the design of sediment-debris basins is given in [53]. Estimating sediment yield is one of the tasks in that design guidance.

e. Other Regional Studies. Several other regional approaches are available for estimating sediment yield. Appendix C describes methods by Mack item [40], Hill item [29], and Livesey item [39] . In addition, site specific studies, conducted by the Corps of Engineers, other Federal agencies, state agencies, universities, drainage districts, planning units, and other commissions and groups, may offer valuable sources of regional information for sediment yield. The engineer should perform a thorough literature search to determine what information may be available for the area under analysis.

f. Basin Specific Regionalization. Most of the regional criteria available for sediment yield are applicable over a wide area, and may not give an acceptable yield estimate for a specific watershed within the region. Consider applying the regional concepts described above to the specific watershed of the problem area. This type study could significantly improve the accuracy of yield calculations as compared to those obtained from the generalized criteria. Procedures for performing regional studies are described in item [22].

Section III. Mathematical Methods for Calculating Sediment Yield

3-11. General. The second major grouping of methods for calculating sediment yield are mathematical methods --the application of analytical techniques to calculate sediment yield from watershed, based on sediment and hydraulic parameters. The several techniques are placed into four categories: sediment transport functions, soil loss equations for small watersheds, bank/gully erosion, and watershed models. These methods were developed because sediment yields are needed at locations where there are no direct field measurement, and these methods can estimate sediment yield at a specific point without addressing the movement of sediment from point to point within the system. Most sediment yield studies utilize mathematical methods supplemented by whatever actual data are available. The results are not as reliable as the direct measurement methods presented in the previous section, and when sedimentation is a major project concern, a sampling station should be established in the project area to refine estimates made with the techniques presented in this section. Sole reliance on these mathematical methods to provide quantitative estimates of sediment yield would be unusual for a Corps analysis and would require careful justification in supporting the results. These methods are not listed in order of reliability.

3-12. Sediment Transport Functions. When sediment yield is needed for a site that has water discharge data but no sediment data, it is better to calculate a value using a calculated sediment discharge rating curve than to abort the effort altogether. A sediment transport function is the basis for the calculation. It can be used to calculate the bed material portion of the sediment discharge rating curve. Then the Flow-Duration Sediment-Discharge Rating Curve Method can be used to calculate the average annual yield of the bed material load. In channel studies this result will provide the most critical portion of the sediment load. That result is not adequate for reservoir studies, but it can be coupled with regional or mathematical techniques to calculate the wash load. Numerous sediment transport equations have been programed [66]. Please refer to reference [2] if more detail is needed. In addition, the HEC training document [26] describes a procedure for calculating the sediment discharge rating curve using the numerical sedimentation model HEC-6 [24]. That procedure differs from the application of a sediment transport function at a point in that HEC-6 integrates processes over several cross sections which describe a reach of the river and provides a continuity equation for sediment movement. Consequently, it will produce a more reliable result than comes from applying a sediment transport function at a single point.

3-13. Universal Soil Loss Equation (USLE). Soil loss equations, evolving since 1940, have been developed for use in small, rural upland watersheds. The USLE is one of the most recent and most widely used of these equations. It was developed to predict the long-term average soil loss from agricultural land. Rainfall simulators were used to create the erosive energy. Test were conducted on plots which were 72 feet long on uniform slopes. Surface erosion occurred in the form of rills; the quantity of eroded soil was measured at the outflow point and expressed as tons per acre per year. Consequently, the uses of the USLE are quite limited for Corps projects. Reconnaissance studies could find the USLE with a sediment delivery ratio appropriate for a preliminary estimate of sediment storage for a small reservoir where sediment is expected to come from the watershed and is not expected to be a significant problem. The pertinent parameters were assembled into the following regression equation by Wischmeier and Smith [68].

$$A = R*K*L*S*C*P \tag{3-6}$$

where

A = Soil loss per unit area per time period, tons per acre per year
R = Rainfall erosion index
K = Soil erodibility factor
L = Slope-length factor
S = Slope-steepness factor
C = Cover and management factor
P = Support practice factor

a. Calculations. A value is estimated for each of these variables using information gained through a field reconnaissance of the watershed to enter tables and nomographs provided in reference [68]. SCS personnel should be consulted to ensure that appropriate values have been selected. Guidance on adapting the equation to incorporate the effects of thaw, snowmelt, and irrigation on the area, on estimating erosion from construction sites; and on modification of the R-value to estimate sediment yield on a frequency basis through the 20-year recurrence interval event for individual hypothetical storms is presented in reference [68].

b. Points of Caution When Using the USLE. The following points are made to stress proper use of the USLE.

(1) Channel Projects. The USLE gives no information on gradation of the eroded sediment. Consequently, the equations would be of limited value in analyzing the effects of a channel project where sands and gravels are of primary interest.

(2) Construction Sites. The significance of selecting coefficients can be illustrated by looking at the soil erodibility factor, K. Published coefficients for crop land imply regular tillage of the soil, and that disturbs the natural armor layer which forms during rain events. The significance of this, the soil erodibility factor, K, for a construction site is not the same as published for crop land in the USLE manual. Soil in a construction area would be expected to exhibit similar erosion to agricultural land during the first rain event after the ground was disturbed, but successive rainfall events would erode that soil at a reduced rate because the construction site is not plowed regularly.

(3) Erosion Mechanisms. The channelization of surface water runoff due to construction may increase gully and channel erosion significantly, and the USLE would miss that altogether because it is formulated for sheet and rill erosion.

(4) Sediment Transport. There is no transport function in the USLE, and a watershed sediment delivery ratio must be applied to account for overland deposition. However, the validity of results is questionable when the USLE is applied to subareas in excess of a few square miles.

3-14. Sediment Delivery Ratio. With the addition of a sediment delivery ratio (SDR), the USLE can be extended to areas of several square miles. The SDR is a factor, ranging from 0 to 1, to multiply times the annual soil loss to obtain the annual sediment yield for the watershed. Sediment delivery ratios have been calculated for specific areas, but no generalized equations or techniques are yet available to universally determine a sediment delivery ratio. The SDR is proportional to drainage area, and the available data indicates the ratio may vary with the 0.2 power, in the form of:

$$(SDR2 / SDR1) = (A1 / A2)^{0.2} \tag{3-7}$$

where:

A1 = reference drainage area, square miles
A2 = desired drainage area, square miles
SDR1 = sediment delivery ratio for reference drainage area
SDR2 = desired sediment delivery ratio

Vanoni item [2] suggests using a reference drainage area of .001 and a SDR1 of 1.0 in this equation. Figure 3-4 illustrates sediment delivery ratio-drainage area relationships for different regions in the United States, and Figure 3-5 shows a generalized relationship drawn through a mass of data points from various regions. Any arbitrary sediment delivery ratio selected solely on the basis of drainage area could be in considerable error; other factors (soil moisture, channel density, land use, conservation treatment, soil type, rainfall intensity, topographic relief, and so forth) must also affect the SDR in some manner.

3-15. Modified Universal Soil Loss Equation (MUSLE). The Universal Soil Loss Equation was modified by Williams [69] with the resulting equation termed the Modified USLE (MUSLE). The MUSLE allows the estimation of soil losses for each precipitation event throughout the year, thereby becoming an event model

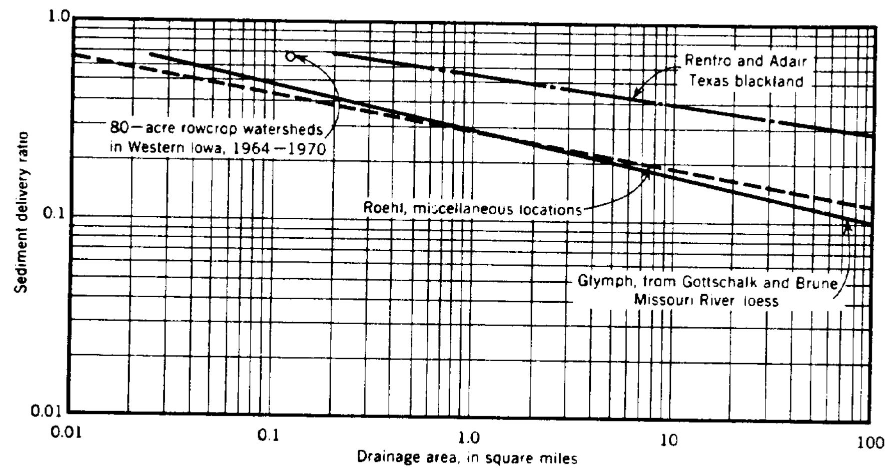

Figure 3-4. Sediment delivery ratios calculated for various watersheds (from item 2, Appendix A, courtesy of The American Society of Civil Engineers)

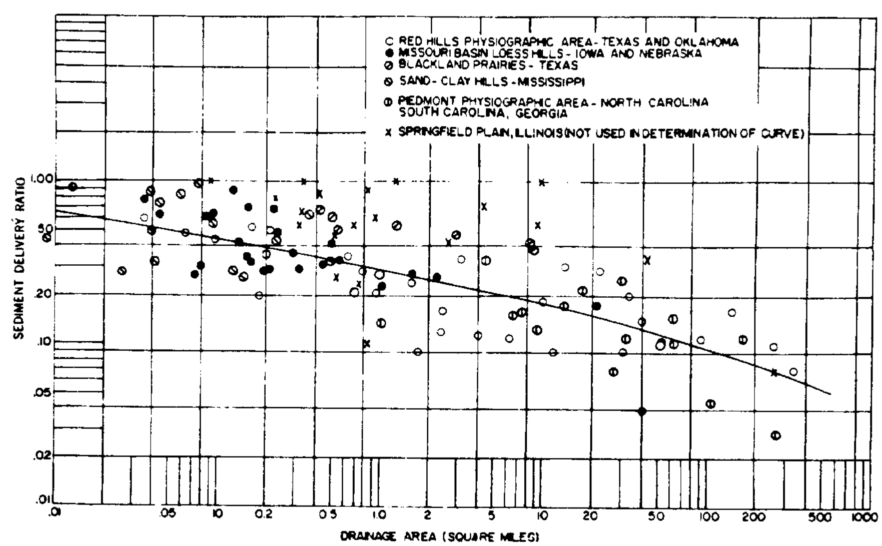

Figure 3-5. Example of scatter in the data (from item 2, Appendix A, courtesy of The American Society of Civil Engineers)

rather than an average annual runoff model. As an event model, the MUSLE and similar techniques have more application to Corps analyses. The full equation defining the MUSLE is:

$$Y = 95 * ([Q * qp]**0.56) *K*C*P*L*S \tag{3-8}$$

where

Y = Sediment yield from an individual storm through sheet and rill erosion only, tons
Q = Storm runoff volume in ac-ft
qp = Peak runoff rate in cubic feet per second
L*S = Slope length and gradient factor
K, C, P = as defined previously for the USLE

The MUSLE is simply the USLE with the rainfall erosion index replaced by the runoff rate term. Since erosion is computed for each event, a SDR is not necessary. The "Q" and "qp" terms would be obtained from the runoff hydrograph with "Q" used in estimating the amount of soil detachment and "qp" used in determining the volume of soil transported. The sediment yield for each event is summed to obtain each year's total with average annual sediment yield being the average of all the yearly values. Long-term simulation is normally required to obtain a representative estimate. While much additional information is gained from the use of the MUSLE and the necessity of determining an appropriate sediment delivery ratio is eliminated, this technique requires considerable data gathering and calibration effort to apply correctly. Reference [23] includes this method in the evaluation of potential deposition problems in a proposed flood control channel. The points of caution given for USLE apply to MUSLE also.

a. Runoff. A separate rainfall runoff model is needed to calculate flood volume and flood peak runoff rate. Calibration is usually against measured water volume, with at least 3 years of data normally needed.

b. Confirmation. Comparison and confirmation of sediment yield calculated with MUSLE should be made against that from other techniques. A report by Dyhouse item [18] describes a study in which sediment yield, which had been calculated by a method similar to the MUSLE, was calibrated using a flow-duration sediment transport integration.

3-16. Gully and Stream Bank Erosion. When the drainage basin exhibits extensive stream bank erosion and gullying, either on the primary stream or on tributaries to it, sediment yield determined by the following methods should be added to the sheet and rill erosion predicted by the soil loss equations.

a. Stream Bank Erosion. Soil losses through stream bank erosion and bank caving contribute significant quantities of the total sediment yield for most natural rivers. Estimates as high as 1,700 tons/year/mile of bank have been made at some locations. The causes are many and varied, and the prediction of future losses at specific locations is difficult. No generalized analytical procedures have yet been developed to formally calculate sediment yield or specific bank line losses from stream bank erosion. The most successful methods are based on aerial photography in which successive overflights can be used to overlay bank line movement with time. By measuring the surface area between successive bank lines and estimating bank heights from the field reconnaissance, quantities of sediment lost to erosion can be calculated between the surveys and average annual rates determined.

b. Gully Erosion. Soil loss from gullies is seldom sufficient to warrant inclusion in Corps studies because it makes up a very small percentage of the total sediment yield when the study area is more than 10 square miles. However, some parts of the country, such as much of the State of Mississippi, experience major sediment losses from gullying. When significant gully erosion is suspected, contact the local Soil Conservation Service office for their estimates. Items [45] and [60] should be reviewed.

c. Future Conditions. When the future includes watershed modifications such as reservoirs, channelization or land use change, do not accept historical bank caving or gullying quantities without justification. Based on knowledge of river morphology and the reaction of rivers to man's activities nation wide, an assessment of the likelyhood of changes in historical values should be made.

3-17. Computer Models of Watershed Sedimentation. Extensive research is under way on these methods. In concept, the computer is used to simulate water movement and the associated processes of sediment erosion, transportation and deposition, throughout the watershed. Most are hydrologic models with sediment runoff capability added through soil loss equations. They require substantial data but have the advantage of predicting the effects of future land use changes in considerable detail. The Corps STORM model is an example of a watershed model with a capability for calculating sediment yield. It has been generally applied to watersheds of 10 square miles or less, about the maximum area for application of soil loss equations. More sophisticated watershed models which attempt to address the actual mechanics of erosion and sediment movement are being developed and used, however, these models are largely applicable to basins of a few square miles or less in size. Given the usual lack of sediment data, yield estimates by watershed computer modeling may not be as reliable as the more simplified techniques.

Section IV. Urban Sediment Yield

3-18. Urban Sediment Yield. The analysis of sediment yield for urban areas or for a watershed undergoing urbanization introduces still more complexities into an already difficult problem. Measured yield data is essentially nonexistent for urban watersheds. As previously noted, yield varies dramatically as land use changes. Removal of vegetation and disturbing the soil preparatory to development can increase sediment runoff by orders of magnitude during the construction process. However, as the developed land is restabilized the attention that property owners give to their land and the large increase in impervious areas (roads, structures, parking lots) with the resulting decrease in land surface area exposed to the erosive effects of rainfall and runoff will reduce sediment yield from land surface erosion to smaller values than existed on the preurban land use, as illustrated in Figure 3-6. The usual hydrologic effects of urbanization, increased runoff and higher flow peaks, may somewhat offset this decrease from land surface erosion by increasing gully and channel erosion. All these factors are difficult to quantify.

3-19. Urban Yield Methods. Urban sediment yield methods are largely yet to be developed, however any of the methods previously described could be used. In practice, given the almost total lack of measured sediment data, yield methods have been limited to the various predictive techniques described in Section III. If discharge-duration data can be calculated for a prescribed land use, as by period-of-record hydrologic simulation, a transport equation can be calculated and integrated with that duration curve to estimate average annual sediment yield of the bed material load. A different land use would require a repetition of these steps after both the discharge-duration and sediment discharge curves have been modified to reflect the new land use condition. Mathematical modeling of the watershed's sediment runoff processes would normally be necessary to simulate flow duration data or to obtain sediment wash off information. Most soil erosion models have been developed for rural watersheds and rely on some variation of the USLE to calculate sediment runoff. Thus, parameter estimates in urban areas may reflect only the best judgment of the practicing engineer.

3-20. Adjustment Factors for Urbanization. Even with the problems involved with urban sedimentation analysis, proper evaluation for Corps work proposed in urban areas may still require an analysis of sediment yield under alternate land uses. The modification of a watershed's hydrology by urbanization has been much studied and can be analyzed by a variety of hydrologic models. The hydrologic effects of urbanization are generally shown as increased runoff volume from increased imperviousness factors and higher discharges from decreased overland and stream travel time. Most hydrologic models, however, do not simulate sediment runoff. Use of an appropriate sediment routing model under different land uses can at least allow qualitative estimates of the changes in sediment runoff, however subjective the selection of the various parameters might be. The summation of sediment runoff from individual events throughout the course of a year, along with summation of runoff water volume, will allow annual yield curves to be plotted. Figure 3-6 illustrates the calculated annual sediment yield for 20 years of water and sediment runoff simulation for two land use patterns using the HEC's STORM program item [25]. Average annual sediment yield can be found from summing and averaging the annual values. These yield curves can form the basis for adjusting a sediment discharge curve to reflect an alternative land use condition. Figure 3-7 shows the adjusted sediment discharge curve for a future land use pattern based on proportioning the "known" (existing land use) sediment discharge curve by the difference in the annual yield curves. Appendix C illustrates another method for estimating changes in sediment yield during urbanization. It is based on land use projections, available sediment yield data and urban runoff measurements.

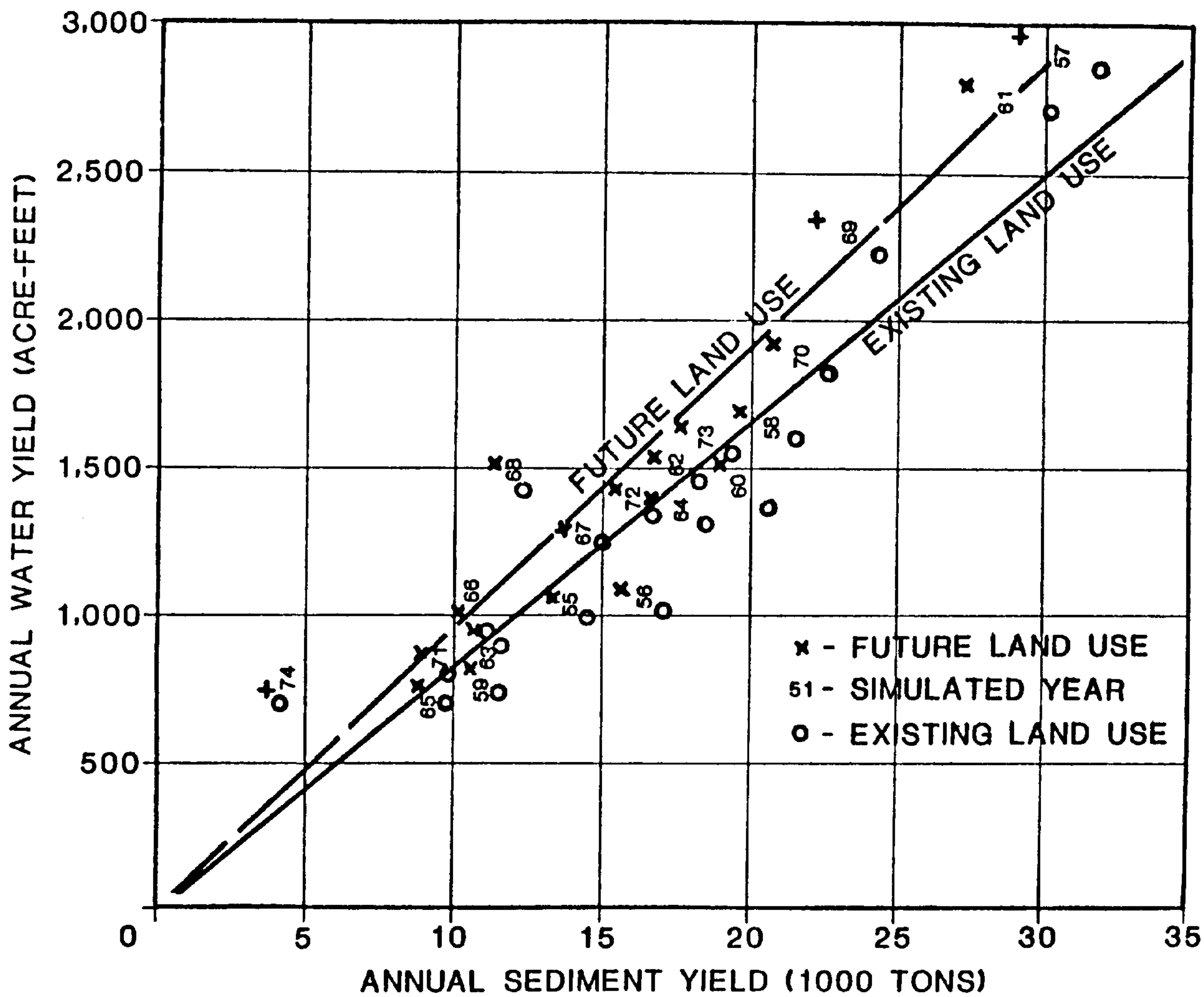

Figure 3-6. Effect of urbanization on sediment yield

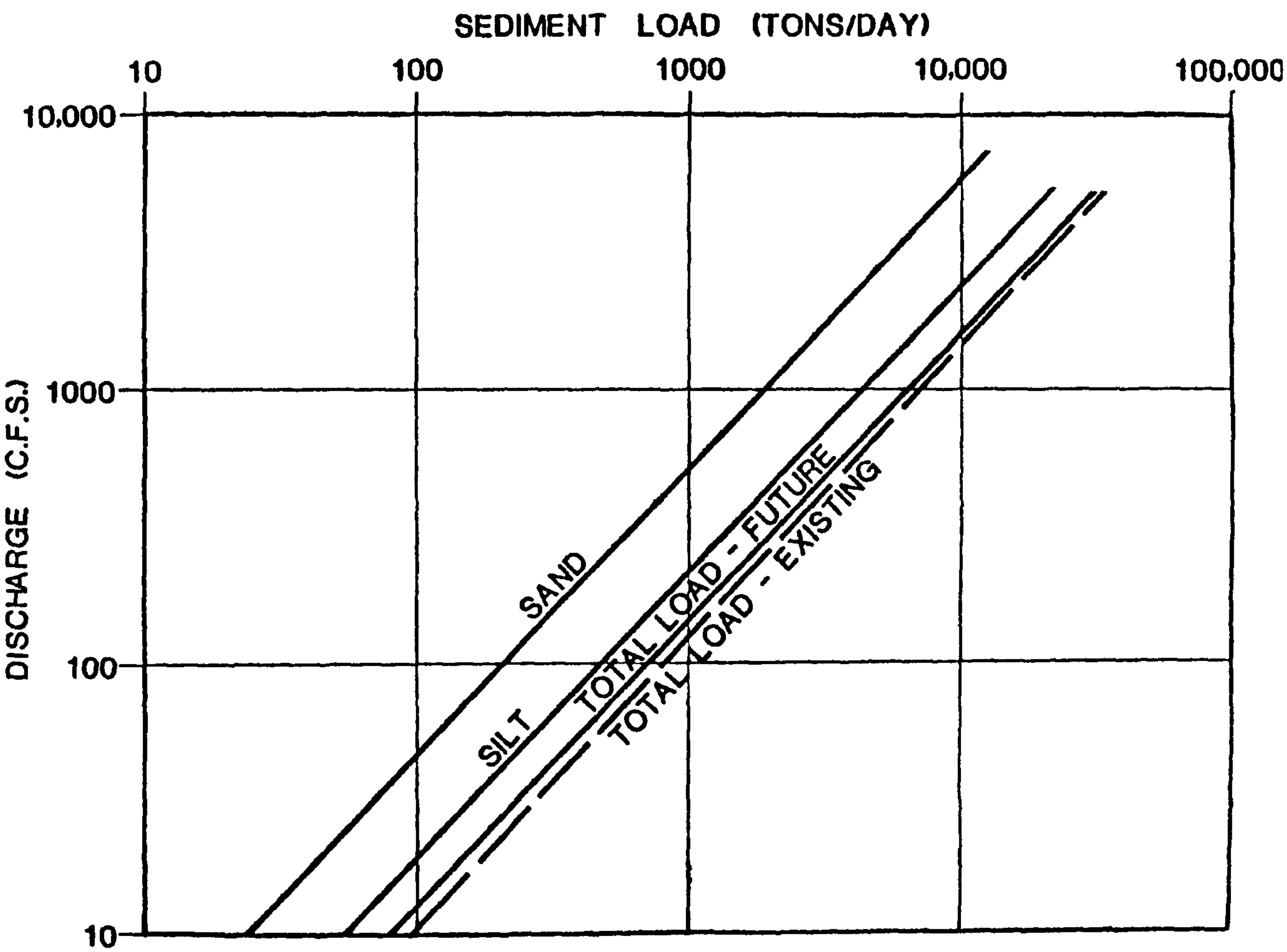

Figure 3-7. Sediment discharge adjusted for urbanization

Section V. Report Requirements

3-21. Topics to Report. Specific requirements necessary for every sediment report cannot be given, and reporting information necessary for sediment yield will be included with that requires for the entire sedimentation analysis. Information should include the level of effort used by the engineer to estimate sediment yield (qualitative vs. quantitative), references for techniques/technical data used, the method(s) used to calculate and check the adopted values for sediment yield throughout the study area. While additional reporting information is given in the following chapters, reviewers expect the following to be discussed or included:

a. Basin and study area map

b. Stream profile showing bed elevation versus river miles, hydraulic controls, structures, distributaries and tributary entry points

c. Land use map for study area

d. Soil type map for study area

e. Graph showing drainage area versus river mile

f. Graph showing average annual water yield versus river mile

g. Water yield

(1) average annual water yield by sub-basins including trends with time

(2) flow-duration curve (i.e. cumulative distribution function for water)

h. Water discharge hydrographs

(1) period of record

(2) single event (actual and/or hypothetical)

i. Water discharge versus sediment discharge rating curves, for the main stem as well as tributaries, showing measured data points

j. Sediment yield

(1) average annual sediment yield be sub-basin including trends with time

(2) fraction of average annual sediment yield carried by specific ranges of water discharge, Y versus Q-class interval (probability density function)

k. Graph of annual water yield versus annual sediment yield showing years (Figure 3-6)

l. Sediment yield for single events, actual and/or hypothetical

m. Sediment yield for clay, silt, sand, and gravel

n. sediment yield by grain size class (i.e., VFS, FS, MS, CS, VCS, etc.)

o. Sediment budget analysis for future conditions, with and without the proposed project