ANALYSIS AND USE OF RESERVOIR SEDIMENTATION DATA

by L. C. Gottschalk *

## Introduction

Prior to 1934 about 40 reservoirs in the United States had been surveyed to determine rates of sedimentation. In that year the Soil Conservation Service began a nation-wide survey to evaluate the effects of accelerated soil erosion on reservoir sedimentation. To date detailed sedimentation surveys have been made on about 200 representative reservoirs and reconnaissance-type surveys on approximately 300 more. In addition, results from nearly 100 surveys made by other Federal, State, and local agencies are available. Thus, sedimentation data now exist on nearly 600 reservoirs in 36 States, more than 5 percent of the total number of larger reservoirs in the country.

## Factors Considered in Analysis of Data

Since the beginning of its program, the Soil Conservation Service has been concerned with analyzing these data: First, to obtain a better understanding of the basic factors controlling rates of sediment transportation and deposition; and, secondly, to develop procedures for useful application of the data to determine sedimentation damages and methods of control of sedimentation in existing and proposed reservoirs. Much work still remains to be done. Different methods of analysis are still being tested. From the results so far obtained, however, certain conclusions can be drawn. It is the purpose of this paper to point out the relative effects of some of the more important factors that need to be considered in the analysis and interpretation of reservoir sedimentation data and to outline briefly methods for applying the results.

The rate of silting of a reservoir depends upon its capacity, the quantity and nature of sediment delivered to it, and its ability to retain sediment. Some watersheds produce an abundance of sediment, while others of equal size do not. In some cases, sediment remains in suspension for long periods of time and is carried entirely through the reservoir and over the spillway. In others, it may be deposited almost immediately near the head of the reservoir. Some sediment deposits compact readily whereas others compact slowly. Reservoirs of equal size but of different use may trap sediment at different rates.

In analyzing reservoir sedimentation data, such factors as period of record, nature of reservoir operation, occurrence of density flows, watershed characteristics, capacity-watershed ratio of the reservoir, nature and specific weight of sediment, and precipitation and runoff should be considered. It is desirable, of course, to have long periods of records. Estimated long-term rates from sedimentation records of less than ten years generally are not dependable unless adequate inflow or precipitation records are available for making adjustments.

It is essential that the period of record be continuous. If gates in a dam have been kept open for long periods of time or if the dam has been breached so that considerable sediment has been sluiced out of the reservoir, the sediment that remains will not give a reliable measure of the total amount of sediment brought into the reservoir. Some operators make it a practice to open bottom sluices during periods of heavy sediment inflow. Plans are being made at present to develop operating schedules at some reservoirs to vent the maximum quantity of density flows in order to reduce the rate of sediment accumulation. Some operators draw down their reservoirs completely in attempts to desilt them. This not only sluices sediment from the reservoir but also increases the specific weight of remaining sediment by exposing it to aeration. Normal reservoir operation and seasonal draw-down cause minor redistribution and exposure of sediment to aeration. This, however, does not appreciably increase the density of sediment except in delta areas. The results of sedimentation surveys of reservoirs from which sediment has been partially removed by desilting practices or breaching of the dam are not comparable to results from surveys of reservoirs where no sediment has been removed other than by normal spillway losses, and cannot be considered on the same basis unless adjustment can be made for the quantity of sediment removed.

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Density flows have been observed in a number of reservoirs in the United States, particularly in the Southwest. It is suspected that they occur in many reservoirs. Usually they are not taken into account in analyses because of lack of quantitative data. In some reservoirs the amount of sediment transferred out by density flows may represent a significant proportion of the incoming load.

The quantity of sediment delivered to a reservoir depends on the rate of gross or absolute erosion in the watershed and the ability of the stream system to transport eroded material to the reservoir. The rate of gross erosion depends on climatic conditions, nature of the soils, slopes, topography, and land use. The ability of a stream system to transport eroded material to a reservoir depends on the hydrophysical conditions of its watershed. Not all of the material eroded from upland areas in a watershed is delivered to the reservoir. Part of it comes to rest at the base of slopes, on the stream flood plains, in upstream reservoirs, in stream channels, and as above-crest deposits within the reservoir area itself. In the analysis of reservoir sedimentation data only the net erosion, or quantity delivered to the reservoir, is considered. This is determined by measuring the volume of sediment in the reservoir and measuring or estimating the amount lost over the spillway. The annual net erosion is popularly referred to as the rate of sediment production.

In most of the analyses made by the Soil Conservation Service, the data are grouped according to a problem area. This is done in an effort to keep soil, slope, and topography, which are difficult to measure, more or less constant. Generally it has been found that on this basis the two measurable factors, net drainage area and land use, are the most important watershed factors affecting rates of sediment production.

The net drainage area is the sediment-contributing area. Excluded are areas above upstream reservoirs that intercept the sediment load and the main reservoir area, which does not contribute sediment to the reservoir.

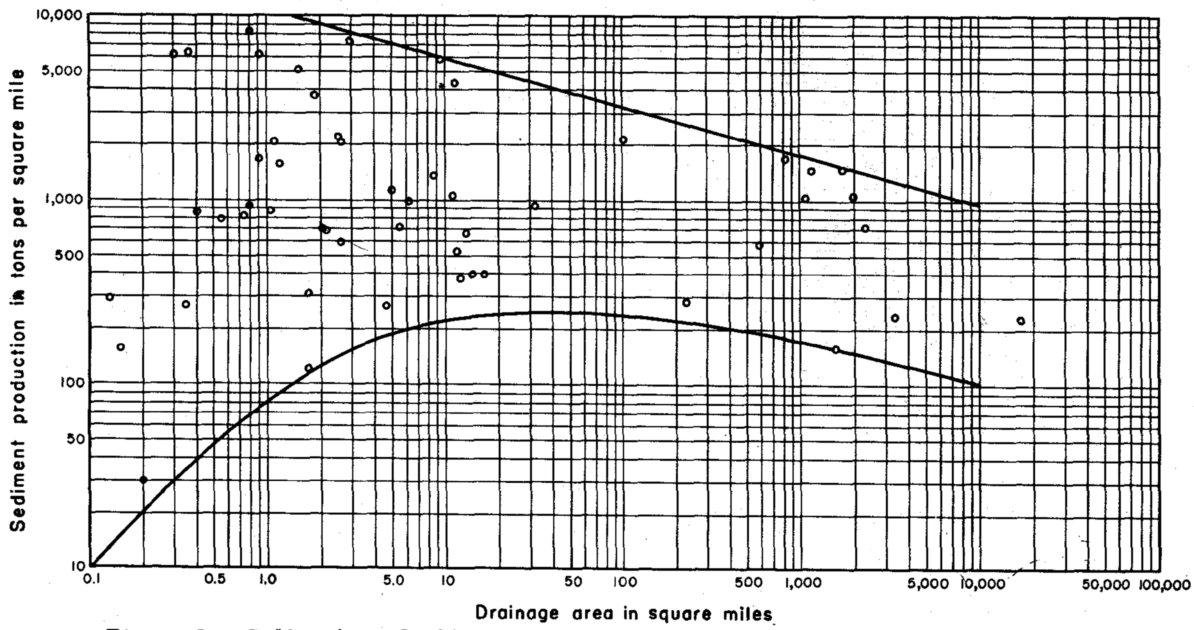

Figure 1.--Sediment-production rates in the Western Gulf Drainage Region.

Rates of sediment production per unit of area vary with the size of the net drainage area. As a general rule, the average rate of sediment production decreases as the size of the drainage area increases (See Figure 1). Also, the larger the watershed, the less is the variation between rates. The mean rate of sediment production decreases in much the same manner as runoff per unit of area decreases with increase in size of watershed. Also the larger the watershed, the greater the opportunity for deposition between the point of origin and the reservoir. Very high and very low rates of sediment production per unit area are found generally on very small watersheds. This is because a shorter distance of transportation gives lesser opportunity for deposition above the reservoir and because land use becomes increasingly important the smaller the watershed. A very small watershed may be entirely in forest or as much as 80 to nearly 100 percent in cultivation. The forested watersheds may produce extremely low rates of sediment production while the cultivated watersheds may produce extremely high rates. In larger watersheds land use tends toward greater uniformity with less variation between rates of sediment production.

Not much study has been given to the effects of land use on sediment production from areas larger than plot size. Effects of land use on rates of silting show up in reservoir sedimentation data but are often masked by other factors and have not yet been critically evaluated. In order to evaluate these effects, resurveys are needed on a number of reservoirs where land use adjustments have been made in the watersheds since the original sedimentation surveys were made.

The ratio between the capacity of a reservoir and the size of drainage area has an important bearing on the rate of silting of a reservoir. It is obvious that with a given sediment volume, a reservoir having twice the capacity of another will have only half the rate of capacity loss due to sedimentation. The smaller the capacity-watershed ratio, the greater the rate of silting, all other conditions being equal.

The capacity-watershed ratio also provides a clue to the trap efficiency of the reservoir. The trap efficiency, or effectiveness of a reservoir to retain sediment, has been found to be one of the most important factors involved in sedimentation.

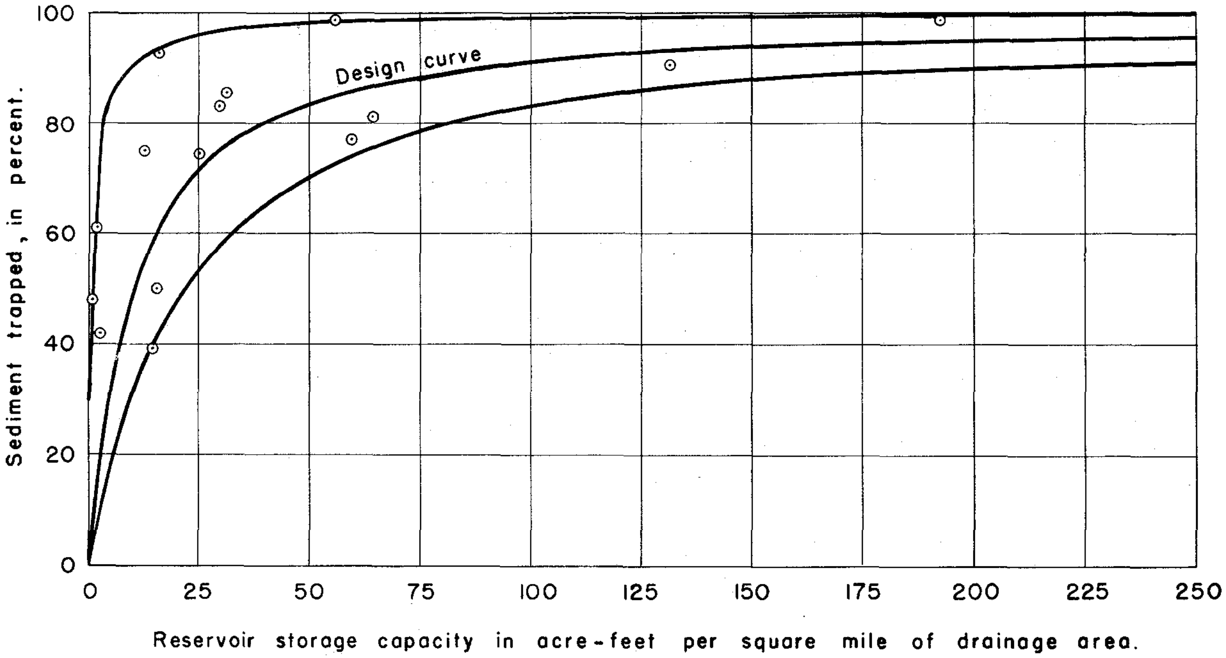


Figure 2.--Relation of reservoir trap efficiency to the capacity-watershed ratio.

By plotting all the measured soil-loss data in various watersheds against rate of silting of reservoirs in these same watersheds and by analyzing sediment-outflow records of various reservoirs, a general trap-efficiency curve has been developed which is useful for estimating the percentage of total sediment trapped in a reservoir, depending on its capacity-watershed ratio 1/. In general, a reservoir with a capacity-watershed ratio of 100 acre-feet or more per square mile will trap 96 percent or more of the incoming load. The trap efficiency gradually decreases in the range of 100 down to about 30 acre-feet per square mile, and from this point it diminishes rapidly to zero. On the average, a reservoir with only 30 acre-feet of storage per square mile will trap about 75 percent of the incoming load; one with 15 acre-feet per square mile will trap about 60 percent; and one with 5 acre-feet will trap only about 30 percent of the total incoming load.

The capacity-watershed ratio of a reservoir is used in place of capacity-inflow ratio because inflow data are usually available only for larger streams and major reservoirs. The assumption that the two are comparable is not strictly valid. For example, a reservoir in an arid or semi-arid region may have a low-capacity-watershed ratio yet not receive enough inflow in any one year to cause water to be discharged over the spillway. In contrast, the volume of mean annual

1/ See "References" at close of comments.

flow from a watershed of equal size in a humid area may be equivalent to 25 times that of a reservoir having the same capacity-watershed ratio. In the drier region 100 percent of the incoming sediment load is trapped, whereas in the humid area possibly only 70 percent is trapped.

Geology, topography, soil, and climatic conditions affect the nature as well as the quantity of sediment delivered to a reservoir. Where parent materials are shales or limestone, sand content of sediment is low. Where parent material is mainly sandstone, sand content may be high. Some igneous and metamorphic rocks produce fine sediment under some climatic conditions and coarse material under others. Sediments derived from Piedmont areas in the southeastern United States contain much clay and colloidal material. Sediments derived from loessal soils in the Midwest have a high silt content. The West Cross Timbers area of Texas, with sandy soils and poorly consolidated sandstone substrata, provides sediment with high sand content. Sand and silt settle out rapidly in reservoirs. Clay may settle out rapidly or be held in suspension for long periods because of the temperature or chemical nature of the water in which it is suspended. Its environmental origin has a definite bearing on the nature of the sediment transported to a reservoir, and the nature of the sediment has a direct bearing on the percentage of total load deposited in the reservoir and on the ultimate volume of deposited material.

The specific weight of sediment is an important factor in estimating the life of an existing reservoir and in estimating rates of sediment production which are generally expressed on a weight basis. Laboratory analyses have been made by the Soil Conservation Service to determine the specific weight of sediment in numerous reservoirs throughout the country. These analyses show variations in the dry weight of sediment ranging from 20 to 117 pounds per cubic foot, depending on the nature of the sediment and whether or not it had been exposed to aeration. Factors affecting the specific weight of sediment in a reservoir, including age, nature of sediment, and reservoir operation, have been discussed in detail by Lane and Koelzer 2/. In previous studies of the specific weight of sediment, sediment thickness as a factor has not been adequately evaluated because of lack of quantitative information. This is due mainly to lack of suitable equipment for taking undisturbed core samples of more than the upper two or three feet of sediment in a reservoir.

The relationship of the specific weight of sediment to depth is illustrated by an experiment conducted by the Soil Conservation Service at Greenville, S. Car., in 1939-1940. A measured quantity of sediment, about 2,700 grams, was allowed to settle in a $22\frac{1}{2}$-foot, transparent, calibrated, water-filled Lucite tube 6 inches in diameter. Each second or third day an equal portion was added and each successive layer separated from the preceding layer by a marker strata of fine sand. Over a period of 126 days, 36 separate layers of sediment were added to the tube, resulting in a total depth of sediment of nearly $13\frac{1}{2}$ feet. By knowing the approximate dry weight of each layer of sediment and measuring the volume occupied in the calibrated tube, the approximate specific weight of each layer could be determined. The relationship between specific weight and depth of sediment is shown in Figure 3. This relationship may be expressed by the empirical formula:

$$\rho = 22.05 + 1.09d + 0.00129e^{0.695d}$$

where $\rho$ = specific weight of sediment, in pounds per cubic foot
d = Depth of sediment, in feet
e = Base of natural logarithms.

If the vertical distribution of the specific weight of sediment in a reservoir is similar to that in a Lucite tube, then determinations of the average specific weight of sediment in a reservoir based on analyses of samples taken from the upper two or three feet are erroneous.

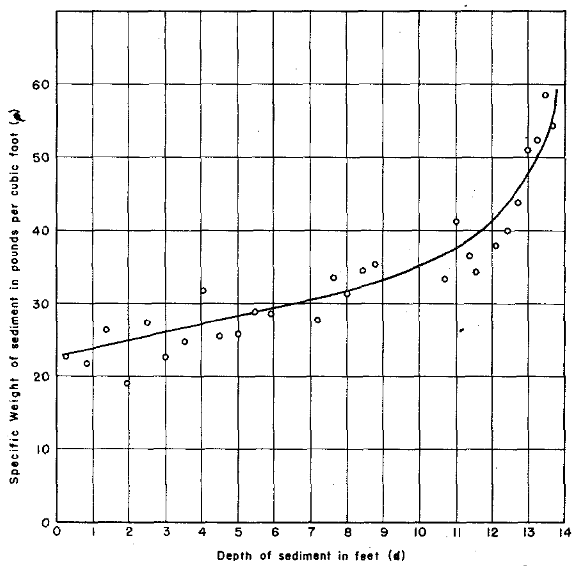


Fig. 3.--Relationship between specific weight and depth of sediment in 6-inch Lucite tube, Greenville, S. Car.

2/ See "References" at close of comments.

An analysis of reservoir sedimentation data, particularly where the period of record is short, should include an analysis of precipitation or discharge data to determine the adequacy of the sedimentation data for estimating long-term rates. If the period of record is short the results might be misleading, particularly if sedimentation occurred during a period when inflow was abnormal, either above or below average. Discharge records should be used when available. Accumulative-difference curves may be plotted to determine the position of the sedimentation record in relation to cyclic changes in discharge. Graphs showing departure of monthly discharge from the mean are helpful in estimating long-term rates since seasonal variations are readily apparent from these charts. Where discharge records are not available, it becomes necessary to use precipitation records instead. The use of either precipitation or discharge records for forecasting rates of sedimentation is only approximate, but they are helpful in extrapolating data from short records. Considerable work remains to be done in development and refinement of methods for adjusting short-term sedimentation records in terms of the longer runoff and precipitation records for a particular watershed or locale. Studies made to date indicate that sedimentation rates, in general, will be accelerated in the next 40 or 50 years.

## Presentation of Results of Analyses

When an analysis of a mass of complex reservoir sedimentation data is completed the results should be presented in some simple usable form for practical application. This may be in the form of curves, nomographs, charts, or formulas. Because of the lack of refinement of data and the numerous variable factors involved in sedimentation, it is difficult to develop single curves or formulas to adequately express sedimentation on a watershed or regional basis. Often envelope curves are drawn for this purpose. These show certain well-defined minimum and maximum expected rates for various watershed areas. From these the mean and design curves may be interpolated.

Attempts have been made from time to time to develop empirical formulas for expressing rates of silting of reservoirs on a watershed or regional basis. Reasoning indicates that the compound discount formula might be used to explain rates of sediment accumulation in reservoirs. Not enough work has yet been done, however, to evaluate the relative effects of such factors as density currents, capacity-watershed ratio, specific weight of sediment, and watershed characteristics in order to fit them into this type of formula.

Some progress has been made in analyzing sedimentation data by multiple-linear and curvilinear regressions. The use of multiple regression to estimate rates of sedimentation in a number of Government-owned stock-water ponds and reservoirs in a 327-square-mile area near Pierre, S. Dak., showed very good results 3/. In this study it was necessary to determine sedimentation damages to 43 Government-owned stock ponds. In the time allotted for field investigation, detailed sedimentation surveys could be made on only 18 ponds. A multiple regression was made to determine the function of various factors related directly or indirectly to sediment accumulation. Analysis of the results provided a formula which covered 93 percent of variability in sediment accumulation as expressed by the standard deviation. This formula was used for estimating the sedimentation damages to the other ponds in the area.

## Use of Reservoir Sedimentation Data

The results obtained from a sedimentation survey of a particular reservoir are used: (1) For determining the prevailing and probable future sedimentation damages to that reservoir, (2) for determining the most effective and economical control measures needed to reduce the rate of sedimentation of the reservoir, and (3) in combination with results from other reservoir sedimentation surveys and suspended-load measurements, for preparing regional indices of sediment production.

The measurement of the volume of sediment in a particular reservoir provides the basis for determining the rate of silting of that reservoir up to the date of survey. To project this rate into the future requires adjustment for changing trap efficiency and the specific weight of deposits. Progressive deposition of sediment reduces the trap efficiency of the reservoir until it approaches zero when the capacity of the reservoir is exhausted. On the other hand, progressive increase in thickness of superincumbent deposits increases the specific weight of underlying sediment, thus reducing the volume occupied by a given weight of sediment. More research on both trap efficiency and specific weight of sediment is needed to better enable us to approximate the expected rate of silting of an existing reservoir in say 10, 50, or 100 years. Heretofore it has been necessary to assume that trap efficiency and changing specific weight counter-balance each other and, consequently, the rate of silting progresses at a constant rate until the storage

3/ See "References" at close of comments.

capacity is depleted.

Maximum depletion of the storage capacity of a reservoir varies from one region to another in accordance with the relation of the original capacity to the channel volume required to carry the normal base flow of the stream through the reservoir reach. When the original capacity is reduced to this volume, no further net loss occurs and the capacity, in effect, is exhausted. Studies by the Soil Conservation Service indicate that the residual volume ranges from 1 or 2 percent to about 20 percent of the original capacity except for reservoirs of very low capacity-watershed ratio. Often a reservoir loses most or all of its usefulness long before maximum depletion of total storage occurs.

Although it is of interest to know the approximate date of maximum depletion of storage, it is more important, from the standpoint of evaluating sedimentation damages, to determine when sedimentation begins to encroach on the dependable storage capacity. The dependable storage capacity of a reservoir is that part of the usable capacity which is needed during periods of sustained low flow to offset consumption requirements and seepage and evaporation losses. Determination of the dependable storage capacity requires an analysis of runoff, evaporation, and seepage data as well as an analysis of water-consumption records. An economic study of damage by sedimentation to reservoirs in the Trinity River Basin in Texas 4/ showed that the dependable storage capacity of 23 reservoirs, built mostly for water-supply purposes, ranged from 38 to 85 percent of the total storage capacity.

Analysis of water-consumption records in many cities in the United States shows progressively increasing demands for water resulting from increase in area and population served and industrial expansion. To meet these demands a progressively increasing dependable storage capacity is required. When sedimentation reduces the capacity of a reservoir so that the dependable storage is not sufficient to supply primary services, then new sources must be developed to avert a serious water shortage. A recent analysis of water-consumption records at Decatur, Ill. 5/, for example, showed that, as of 1946, the dependable storage capacity of the water-supply reservoir for that city amounted to about 48 percent of the original storage capacity. At the 1936-1946 average rate of silting determined by a recent survey, loss of usable storage will become critical by 1956. After that date, the usable storage will become progressively less than the dependable storage required. If no sedimentation had occurred, the present lake would have been adequate to meet the needs of increased consumption until the year 2000. This type of analysis has been used to determine sedimentation damages to other water-supply reservoirs and to stock ponds and in principle can be applied to reservoirs designed for irrigation, power, and flood control storage as well.

The results of a sedimentation survey of a particular reservoir may be used for determining the control measures justified for reducing the rate of sedimentation of the reservoir. Reduction in the rate of sedimentation of certain types of reservoirs can be effected solely by conservation practices. In others, because of the rapid rate of silting and delay in installing conservation programs, by-pass channels, sluicing, dredging, etc., are required. In still others, where rates of silting are low, negligible benefits accrue, according to conventional economic thinking, from either conservation practices or other methods. The method of determining proper control measures has been discussed by C. B. Brown 6/ elswhere. It includes an analysis of the following conditions:

1. The rate, character, and sources of sediment production from the watershed.

2. The effect of capacity-watershed ratio on rate of silting.

3. The relative value of dam sites as determined by their abundance and demand for the services which their utilization can produce.

4. The economic pressure of the discount rate in computing benefits from sedimentation control.

5. The time required for application of soil conservation practices, the costs involved, and results to be expected from watershed treatment.

By proper analysis of data and using the criteria established by Brown, determination can be made of the proper type of measures to use for reduction in the rate of sedimentation of a reservoir.

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4/, 5/, 6/ See "References" at close of comments.

Regional indices of sediment-production rates useful for estimating sedimentation damages to reservoirs, canals, ditches, etc., can be developed by combining all known sedimentation data, including suspended-load measurements, from a particular watershed or region. The importance of reservoir sedimentation surveys for determining regional indices has not been fully realized. Where investigations are made specifically to determine regional indices, emphasis is placed on selecting reservoirs for survey which provide representative sampling of the principal variants within the region. Reservoir surveys have an advantage over suspended-load measurements in that sedimentation data covering longer periods of record can be obtained. The average period of record for reservoirs on which the Soil Conservation Service has made detailed sedimentation surveys is about 14 years. It is not possible to measure past rates of sediment production with current suspended-load measurements. Except on a very few of the larger streams in this country, suspended-load measurements usually cover only a few years of record.

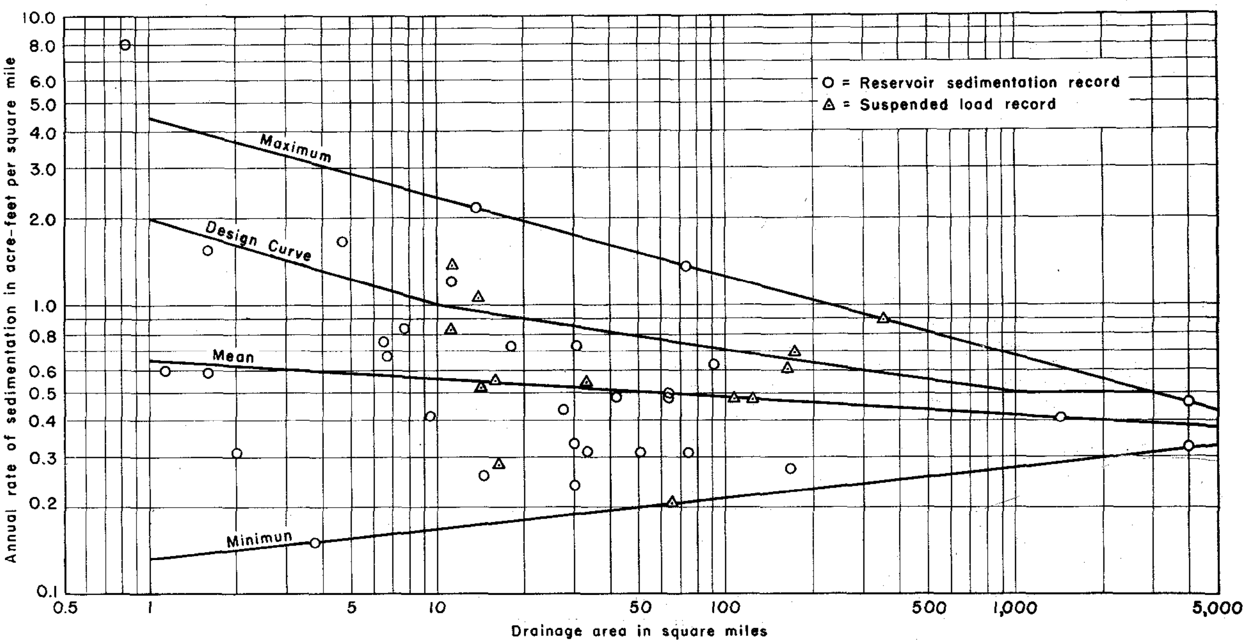


Fig. 4.--Relation of rate of sediment production to size of drainage area in the Southern Piedmont.

Indices of rates of sediment production are usually prepared in the form of envelope curves from which the minimum, maximum, and mean rates and the design curve can be determined (See Figure 4). Such curves have been widely used for estimating extent of sedimentation damage in existing and proposed reservoirs in connection with U. S. Department of Agriculture flood-control surveys. They have been supplied to other agencies and to private organizations for determining silting factors in connection with the design and maintenance of flood channels, drainage ditches, and other water-control developments.

## Conclusions

There is a definite need for additional reservoir sedimentation data in many parts of the country for determining rates of sediment production under different climatic, watershed, and reservoir conditions. Particularly there is a need for additional research on such factors as trap-efficiency, specific weight of sediment, and land use. By proper analysis, interpretation, and correlation of reservoir sedimentation data with other determinable information, rates of sedimentation can be predicted for existing and proposed reservoirs, the effects of such sedimentation on dependent developments evaluated, and the best methods of control determined.

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## DISCUSSION

M. G. BARCLAY.* Mr. Gottschalk has presented a very interesting and informative paper on the analysis and use of reservoir sedimentation data. He has emphasized the need for additional studies, particularly of such factors as trap efficiency, specific weight of sediment, and land use. These are points upon which we can readily agree.

Today, most engineers and conservationists recognize the probable effects and damages that will result from reservoir construction on sediment laden streams. Depletion of effective reservoir capacity by sediment deposition is the outstanding example recognized by both laymen and engineers. Failure to recognize the importance of sediment depletion in the design of reservoirs has resulted in the construction of many with uneconomical life spans. This has reduced the confidence of the general public in reservoir projects as effective and desirable flood control and water conservation measures.

Recognizing the importance of sedimentation, it is paramount that adequate basic data be obtained. As has been pointed out by Mr. Gottschalk, reservoir sedimentation datum is a basic step.

The effect of soil conservation and land management measures upon the reduction of sediment burden of streams has been demonstrated to date on only small watershed areas, but has not been definitely evaluated for larger watersheds. Reliable information on this project is needed so that effects of watershed treatment can be recognized in the design of reservoirs in the future.

Next to knowing how much sediment will accumulate in a reservoir, it is important to know where it will be deposited. It is important from the standpoint of location of recreational areas, and possible relocation of railroads and highways upstream from the reservoir. Also in irrigation and water supply projects, it is important to know if deposition of sediment in a reservoir is likely to change its area-capacity relationship over a period of years of operation. Since evaporation is a function of the surface area of a reservoir, it is essential to be able to anticipate such changes so that reliable forecasts of reservoir yields can be made.

It is only through intensive study of sediment deposition, based upon accurate surveys of reservoirs and upstream areas made at appropriate intervals, that such information can be obtained. In this connection, it is highly essential that accurate maps on an appropriately large scale be made of reservoir sites and upstream areas where sediment deposition may occur prior to or at the time of reservoir construction. Such surveys should be properly referenced by both vertical and horizontal control. Range lines at strategic points should also be established. Although considerable headway has been made in this direction, many reservoirs in the past were either improperly mapped or not mapped at all at the time of construction. This no doubt led to difficulty in obtaining reservoir sedimentation data, and has often resulted in such data being none too reliable.

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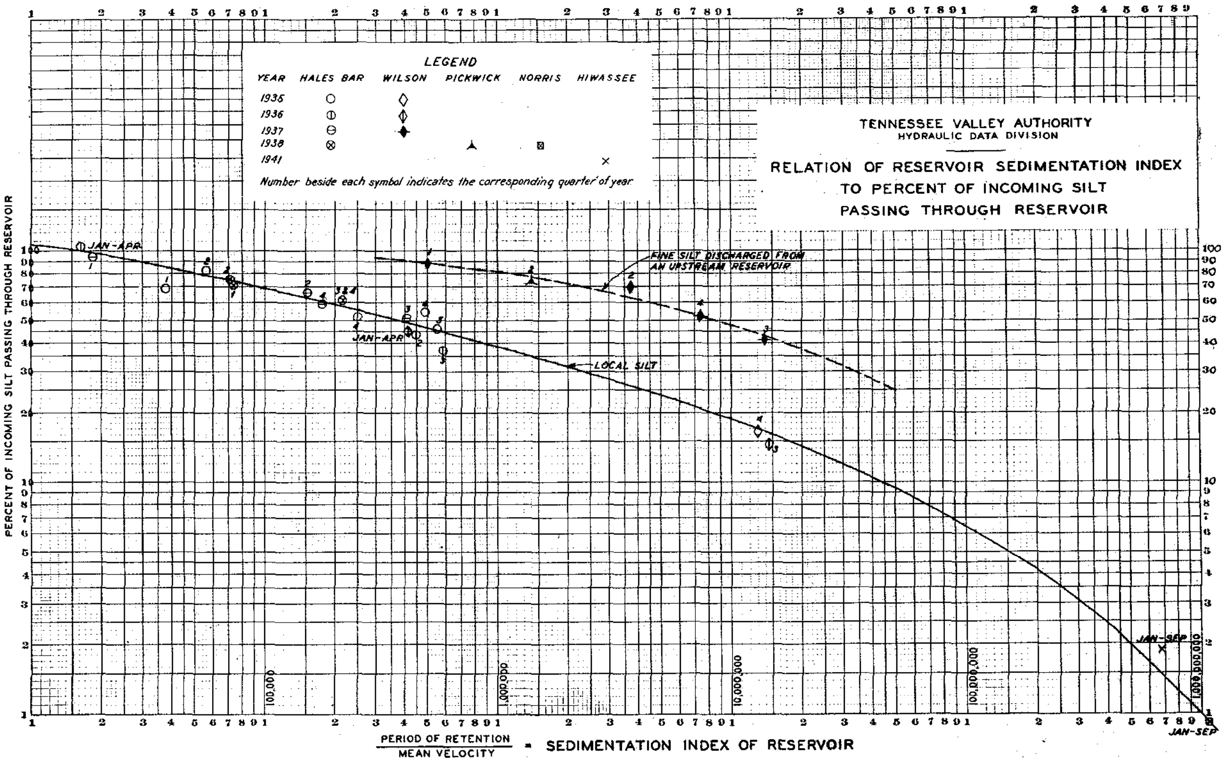
Since accurate basic data is fundamental, steps necessary for obtaining them should be recognized and carried out according to plan. This applies to reservoir sedimentation data as well as any others.

M. A. CHURCHILL.* A considerable portion of Mr. Gottschalk's excellent paper is concerned with the analysis and use of sedimentation data obtained from small reservoirs. As he has stated, stream flow data for these small reservoirs are, in many cases, not available. In such cases, Mr. Gottschalk has used the capacity-watershed ratio of a pool as an index to its trap efficiency in as much as the lack of flow data prevents the use of the capacity-inflow ratio for this purpose.

A somewhat different method of analyzing reservoir sedimentation data has been used by the Tennessee Valley Authority in arriving at a basis for estimating probable future rates of reservoir silting. The majority of Authority reservoirs are relatively large and stream-flow data are rather complete in each case. In an attempt to add to the value of Mr. Gottschalk's paper, the approach used by the Authority will be outlined briefly.

Two sizable reservoirs, Hales Bar and Wilson, were in existence on the Tennessee River for a number of years prior to the creation of the Authority in 1933. The trap efficiencies of these two pools under varying stream-flow conditions have been used as the principal basis for estimating trap efficiences of the other reservoirs in the Tennessee Valley. A certain amount of data on percentage depositions in several other relatively new reservoirs has also been included with the Hales Bar and Wilson information as supporting evidence.

It is apparent that the greater the period of retention in a given pool, and the lower the transit velocity and turbulence, the higher will be the percentage deposition of incoming sediment. The ratio of these two reservoir characteristics, period of retention to transit velocity, has been used by the Authority as a measure of the sedimentation efficiency of a reservoir. This ratio is termed the Sedimentation Index.

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It should be recognized that the Sedimentation Index of a pool is not the same as the capacity-inflow ratio but is this ratio divided by the mean velocity. The capacity-inflow ratio is nothing more or less than the period of retention. Regardless of the period of retention in a basin, if the velocity and resulting turbulence are too high, no sedimentation will take place.

Computed values of the Sedimentation Index for successive periods of time were limited against the measured percentage of incoming silt that passed through Hales Bar and Wilson reservoirs for a number of years, as shown by the lower of the two lines on the accompanying diagram. The upper line on the diagram applies to that portion of the total incoming silt load which is discharged from a main-river reservoir into the one next downstream. Any silt that passes one main-river dam is obviously finer grained that local silt from the same general area but which has not passed through a desilting basin. The TVA system of main-river reservoirs is unique in the respect that the nine pools, one immediately below another, form a chain of lakes some 650 miles in total length. In this system the desilting action of the upstream pools must be taken into account in estimating silting rates for the downstream reservoirs.

As a pool becomes filled with sediment, its Sedimentation Index value is reduced and a greater percent of the incoming load is passed on through. Thus a reservoir is filled with sediment at a continually decreasing rate, assuming that incoming silt loads and stream flows remain unchanged.

In view of the fact that inflows to the reservoir are included in the Sedimentation Index, there is no necessity for flows to be normal during the period when the suspended loads above and below the pools under study for the establishment of the relationship shown on the diagram are being determined.

The method of analysis outlined above has been used to estimate future silting rates for all TVA reservoirs.

The relationship shown between the Sedimentation Index and the percentage of incoming silt that will pass through a reservoir has been established for the relatively fine-grained sediment found in the Tennessee Valley. While the method of analysis is of course applicable to any reservoir, coarser or finer silt will result in a different relationship between the Sedimentation Index and the percentage of silt carried through a reservoir.

GAIL A. HATHAWAY.* Mr. Chairman, Mr. Churchill touched on a question that I feel is somewhat confusing when he mentioned that Mr. Gottschalk's very excellent paper concerned primarily small stock ponds. I would like to raise the question, when does a reservoir cease to be a reservoir and become a stock pond? I personally feel that perhaps the laws of sediment deposition in stock ponds and reservoirs may be somewhat different, and I think that question is something that the Inter-agency Sub-committee should establish a definition for, i.e., define a reservoir and define a stock pond and try to draw a line between the two. Do you care to comment on that, Mr. Gottschalk?

MR. GOTTSCHALK. I am sorry if I implied that all of our data are on stock ponds. Actually of the 600 reservoirs on which we have data not over 5 percent are stock ponds. We have made surveys on some very large reservoirs such as Elephant Butte, San Carlos, and a number of others. A stock pond is considered to be a special type of reservoir just as a water supply reservoir is a special type designed for a particular purpose. The laws of sediment deposition are the same for all types of reservoirs, including stock ponds, but the rates vary in accordance with method of operation and the relative effects of reservoir, watershed and climatic conditions as pointed out in my paper.

VICTOR H. JONES.** I would like to add a brief comment on this question of Mr. Hathaway's about the relationship between stock ponds and reservoirs. I think we can look at this problem as an extension of the curve, or the relationship of variability in sedimentation rates as shown on one of the diagrams that Mr. Gottschalk showed on the screen; namely, the one in which a greater

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variability of sedimentation range is shown for the smaller reservoirs. If we discount the important factor of capacity drainage-area relationship, assuming that may run uniformly in the smaller reservoirs, we should expect to find much greater variability on the same scale as we find greater quantities of sediment production from smaller unit drainages. We are moving up towards the head of the smaller drainage areas and should include more sediment which has moved a relatively short distance. In the larger reservoirs, where the capacity-drainage-area relationship is favorable, we generally find that the range of the sediment contribution annually per square mile of drainage runs from a fraction of unity up to possibly one or two acre-feet per square mile annually, which would be a fairly high rate. In the small reservoirs with a drainage area from a few acres up to a few hundred or thousand acres, we might expect to find, in some cases, four or five acre-feet of sediment contribution per square mile, or conversely, if the drainage area was under good control we would find a low rate. The main point I want to stress is that the smaller the reservoir and unit drainage area the greater variability we may expect. We may find under bad conditions very high rates, and under good conditions very low rates.