# Evaluating Sedimentation Prediction Techniques in Western Iowa

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THE amount and location of sediment deposits derived from eroded soil needs to be known for the efficient design of today's soil and water management facilities. For example, sediment deposition in reservoirs reduces the useful life of the reservoir and affects the quality of the impounded water. Agencies actively engaged in designing and constructing reservoirs must plan to use valuable storage to accommodate the sediment accumulations.

A number of techniques have been developed to explain the three component parts of the sedimentation processes. But which ones should the designer use in western Iowa? Most techniques are empirical and require considerable judgment on the part of the designer. It is the purpose of this paper to review and evaluate the various techniques currently available to predict values for the three component parts – gross erosion, sediment transport, and deposition in western Iowa. This evaluation is made with field data.

Farnham (2)[*] made a study of 24 reservoirs located in the loess soil resource area of western Iowa and northwestern Missouri to determine the volume and density of the sediment. The locations of the reservoir sites are shown in Fig. 1. The original reservoir capacities at the principal spillway varied from 3.78 acre feet to 447.63 acre feet and the drainage areas varied from 0.068 to 2.65 sq. mi. Additional data were secured to describe the land management, soil type, geometry of drainageways and area of the watersheds contributing runoff to the reservoirs. There was no active gullying in twenty-two of the 24 watersheds. Thus sheet and rill erosion was the major source of the sediment. Existing techniques then were used to compute predicted values of the various components involved in the sedimentation cycle. The predicted values were compared with Farnham's data which were obtained in the field. This constitutes an evaluation of these methods for use in western Iowa.

## EXISTING TECHNIQUES

The component parts of the sedimentation process may be classified as follows: gross erosion including sheet and rill erosion, gully and streamback erosion and other sources of sediment; sediment transport or delivery from point of detachment to ultimate deposition, and the actual deposition which, in the case of reservoirs, involves reservoir trap efficiency.

Most field procedures used to predict sediment volumes in reservoirs require that gross erosion be determined for each watershed. Most sheet and rill erosion equations have been developed from small plot data, and methods of extending the equations to describe erosion from a large watershed complex need further development. Some equations for predicting gullying have been derived, but universal methods of obtaining that part of gross erosion to be added to sheet and rill erosion have not been established. Gross erosion is adjusted to reflect the losses in transportation or delivery to a specified point in the watershed. A common technique is to use a delivery ratio, which is a ratio of the amount of sediment delivered to a point to the total erosion in the watershed above that point.

In the design of reservoirs, the amount of sediment delivered to the site is adjusted by the reservoir-trap efficiency to determine the amount of sediment that will be deposited in the reservoir. For reservoir design, equations have been developed which include variables as indexes of delivery ratio and trap efficiency (4), (8). When using these equations, individual values of delivery ratio and trap efficiency are not determined.

In this paper, methods of predicting sheet and rill erosion, delivery ratio and trap efficiency are compared. Sediment-yield values obtained from prediction equations that use indexes of delivery ratio and trap efficiency are also compared with values from field surveys.

## SHEET AND RILL EROSION

Several equations have been developed to express the average yearly amounts of sheet and rill erosion from uplands. These equations have been based on data giving measured rates of erosion from controlled plots, and the extension of the equations to predict sheet and rill erosion from a watershed complex has not been completely verified.

For this paper, three soil erosion equations were used to compute sheet and rill erosion: the universal soil loss equation developed by the Agricultural Research Service (9), the modified Musgrave (2a) equation developed from the original equation of Musgrave (7) which in subsequent discussion will be called the modified Musgrave equation, and the method developed by Gottschalk and Brune (4), commonly referred to as TP-97. These methods are as follows:

### Universal

$$A = RKLSCP$$

where $A$ is the average annual soil loss in tons per acre. $R$ is the rainfall factor, $K$ is the soil erodibility factor in tons per acre per year, $LS$ is the length and steepness of slope factor, $C$ is the cropping and management factor, and, $P$ is the supporting conservation practice factor.

### Musgrave (Modified)

$$E' = 0.59\frac{(KR)}{150}P'\frac{R'}{100}\left[\frac{S}{10}\right]^{1.35}\left[\frac{L}{72.6}\right]^{0.35}$$

where $E'$ is the average soil loss in inches per year, $KR$ is the product of the soil erodibility factor and the rainfall factor from the universal equation, $P'$ is the supporting conservation practice factor from the Universal equation, $R'$ is the cover factor (fallow or continuous row crop equal 100), $S$ is the degree of land slope in percent (with 10 percent as a base), $L$ is the length of land slope in feet (with 72.6 ft as a base), and 150 and 0.59 are constants for tons per acre-inch of soil and for the cropping factor for continuous row crop (Universal), respectively.

### TP-97

In this method, the average slope and average slope length are determined for the area in row crops and small grain. The predominant crop rotation also is determined. Tabulated values for soil losses from straight-row cultivation, contoured but not terraced, and contoured and terraced cropland are used to determine sheet and rill erosion from the cultivated cropland. These values are then adjusted for both

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[*] Numbers in parentheses refer to the appended references.

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the proportion of the watershed in clean-tilled row crops and the predominant rotation. Sheet and rill erosion losses from other sources are estimated at 350 tons per square mile per year.

In comparing the three methods for computing soil loss, the predicted sheet and rill erosion was first computed from the drainage areas above the 24 reservoirs. In making this comparison, it must be stressed that the correct value of sheet and rill erosion from the drainage area above any one of the reservoirs is not known. Therefore, any techniques of comparison used must of necessity compare the relative merits of the three methods.

When applying the three methods to any one drainage area, the results showed that the deviations between computed values were generally consistent and followed the ratio of the means. The means of 24 values computed by the Universal, Musgrave (modified) and the TP-97 methods were 44,930, 39,920 and 91,240 tons, respectively. This shows that values from the Musgrave (modified) method are comparable to the values from the Universal method while the values from the TP-97 method are approximately twice those from the Universal method.

Farnham (2a) developed a prediction equation for the amount of sediment deposited in a reservoir by using gross erosion as one of the variables. However, sheet and rill erosion constituted the entire amount of gross erosion in 22 of the 24 samples. Since a multiple regression technique was used, one test of the three methods was the use of the different values of gross eroion (while other variables remained constant) to develop prediction equations. The resulting prediction equations were then evaluated on the basis of the following statistics: coefficient of determination, $R^2$; standard error of estimate, $S_e$, and coefficient of variation $(S_e/\bar{y})$, $C_v$. The results are shown in Table 1.

The results show that both the Universal and Musgrave (modified) equations give comparable values of $R^2$, but the standard error of estimate is less for the Musgrave (modified) equation. However, since the magnitude of the computed values of sheet and rill erosion is smallest for the Musgrave (modified) equation and no absolute comparison is available, a more descriptive statistic is the coefficient of variation, $C_v$. This coefficient was determined by expressing the standard error of estimate as a percentage of the mean of the dependent variable (ratio of reservoir deposition to gross erosion). The Musgrave (Modified) equation has the lowest $C_v$ and $S_e$, but the highest $R^2$, which shows it was the best estimator of sheet and rill erosion on the 24 drainage basins studied. If values from both Musgrave (modified) equation has the regressed on the Universal, the similarity between the Musgrave (modified) and Universal is shown by an $R^2$ value of 0.93, whereas an $R^2$ of only 0.47 is obtained when TP-97 is regresed on the Universal. The Universal equation is relatively new, and research is under way to apply it for use on watersheds.

TABLE 1. COMPARISON OF STATISTICS FOR THREE METHODS OF COMPUTING SHEET AND RILL EROSION

| Method of computing sheet and rill erosion | $R^2$ | $S_e$ | $C_v$ |
|---|---|---|---|
| Musgrave (modified) | 0.79 | 0.15 | 0.26 |
| Universal | 0.73 | 0.18 | 0.35 |
| TP-97 | 0.53 | 0.19 | 0.63 |

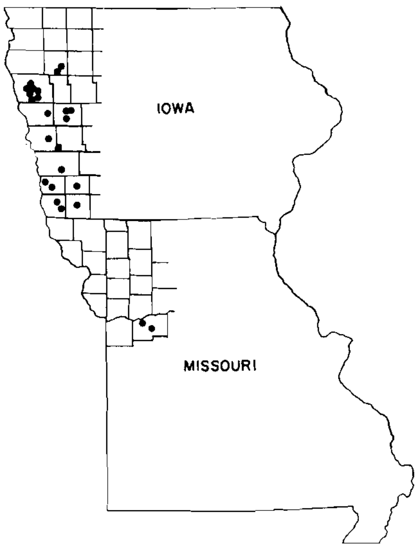

**FIG. 1 Location of reservoir sites.**

## Delivery Ratio

The use of delivery-ratio curves which show the percentage of total soil eroded that is delivered to a specified point, has been considered a significant step in many design procedures. Delivery ratio curves that have been developed from the loess soil area data are shown in Fig. 2. Curve A from Glymph (3) and curve B from Mule Creek watershed in southwestern Iowa (unpublished SCS report) are both shown in relation to the data from Farnham's study (2). The plotted points for delivery ratio were obtained by dividing the measured reservoir deposition by a trap efficiency of 97 percent, estimated from Brune's curves (1). Sheet and rill erosion was computed by the Musgrave (modified) equation.

For curve A, Glymph reported the correlation coefficient to be 0.426 and a standard error of 0.220 log units. A relationship for the plotted points in Fig. 2 was not derived because visual observation shows a low $R^2$ and a high standard error of estimate to be imminent. Curve B for Mule Creek was fitted by least squares but no statistics on the goodness of fit were reported.

Although the studies of Maner and Barnes (6) in the blacklands of Texas indicated a good relationship between delivery ratio and drainage area, the obvious conclusion from the western Iowa data presented in Fig. 2 is that drainage area and delivery ratio are poorly correlated. This probably results from poor reservoir trap efficiency values. Also, the sediment delivered is influenced by variables other than drainage area alone.

## Reservoir Trap Efficiency

The volume of sediment storage provided in the design of a reservoir is influenced by the value of trap efficiency used. All methods relating to reservoir design either specify a design value for trap efficiency or include variables that influence trap efficiency in a mathematical relationship to determine sediment storage required. With the exception of Brune's study (1), little data are available on accurate measurements of all sediment amounts needed to compute the trap efficiency. Brune related the reservoir trap efficiency to the capacity-inflow ratio. The results are presented with a median curve and envelope curves for normal ponded reservoirs. The difference in values of the trap efficiency between envelope curves ranges from 30 percent at low capacity-inflow ratios to 5 percent at large values of capacity-inflow.

In subsequent studies, Gottschalk (5) showed measured trap efficiencies for 18 reservoirs to fall on or below Brune's median curve. Gottschalk reported that the drainage areas of the 18 reservoirs ranged from 0.23 to 106 sq mi. The majority were under 5.0 sq mi. Thirty-two of the 41 reservoirs used in Brune's study had drainage areas larger than 100 sq mi. Therefore, research results reported to date tend to support Brune's curves for use on smaller watersheds than those from which they were derived. However, for small drainage areas, Brune's curves tend to give narrow ranges for trap efficiency. For the 24 reservoirs reported by Farnham, the estimated value as determined from the median curve ranged from 95 to 97 percent.

The data collected by Farnham did not permit the reservoir trap efficiencies to be computed. However, during the development of the prediction equations discussed under sheet and rill erosion, interesting correlations were found. The estimated trap efficiency (after Brune) was correlated with both capacity-inflow ratio and the capacity-watershed area ratio divided by maximum reservoir depth. The latter ratio then became a dimensionless term. The correlation between the estimated trap efficiency and the capacity-inflow ratio was 0.31, whereas it was 0.61 between

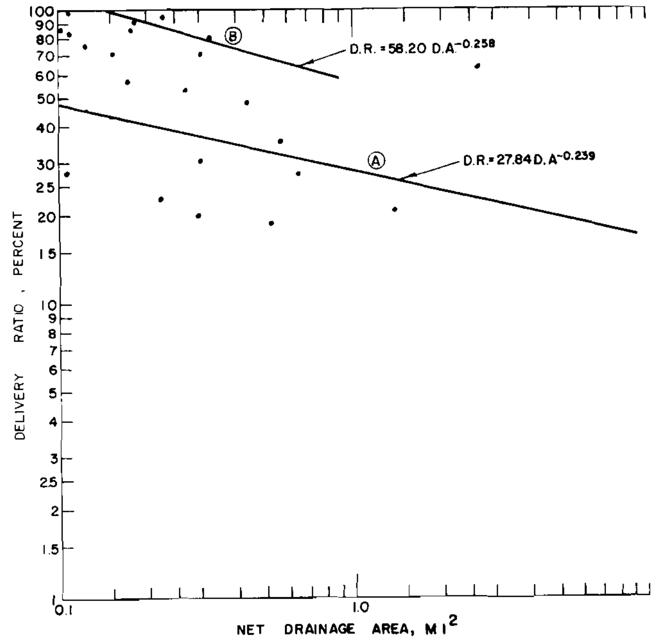

**FIG. 2 Comparison of computed delivery ratio with curves developed from data from eastern Nebraska and western Iowa.**

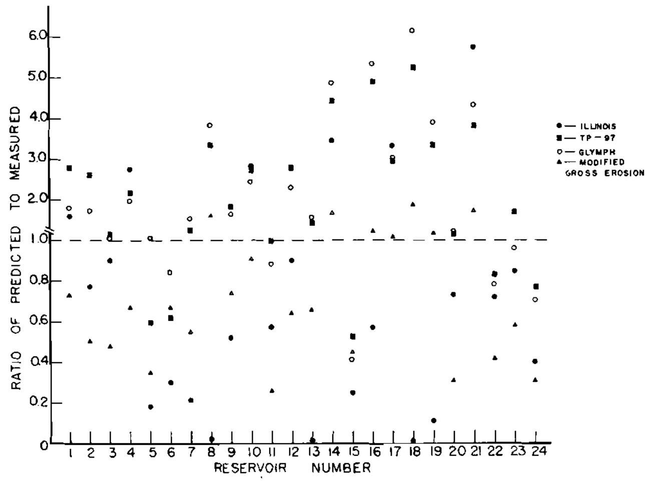

**FIG. 3 Comparison of measured reservoir sedimentation with that predicted by four existing methods.**

the trap efficiency and the dimensionless capacity-watershed term. These results suggest that capacity-inflow may not be the most indicative estimator of trap efficiency for reservoirs in the loess soil area. Another source of error in the capacity-inflow ratio may arise from the value of the inflow used. Inflow volumes were taken from USGS circular 52 which gives gaging data on much larger drainage basins than those investigated in Farnham's study.

## SEDIMENT YIELD

The everpresent need for more and better sediment-yield data has stimulated research on this problem. A review of the literature shows that many relationships derived from data from a given physiographic area are available for design purposes.

The validity of any derived relationship may be assessed by using one or both of the following tests. It is a general practice to substitute values of the original independent variables in the derived relationship to obtain predicted values. A standard error of estimate is then computed which measures the reliability of the derived relationship. The lower the standard error of estimate, the closer the predicted values will be to the observed values of the sample observations. It is a more severe test of a relationship to predict values of a desired factor from data that were not included in its derivation. In the discussion to follow, four relationships for sediment yield or for deposition of sediment in a reservoir are tested.

The data collected by Farnham (2) were substituted into each relationship and the resulting predicted value of sediment deposited was compared with the measured quantity. Three of the relationships were developed for the loess soil area along the Missouri River basin and the other was developed for a deep loess soil in west-central Illinois. The relationships that were compared are as follows:

**Method 1** This method was developed by Gottschalk and Brune (4) for estimating sediment yields for use in the design of small detention reservoirs in the Missouri basin loess hills of western Iowa. In subsequent discussion it will be called TP-97. Statistical analysis of the data indicated that total sediment accumulation in the reservoirs could be expressed best by the equation:

$$\text{Log } S = 0.7664 \log 100W + 0.7867 \log T + 1.0545 \log E + 0.3701 \log C_T/W - 2.9127$$

where

$S$ = total sediment accumulation in the reservoir, in tons
$W$ = net watershed area, in square miles
$T$ = age of the reservoir, in years
$C_T/W$ = capacity-watershed ratio of combined flood and conservation storage, in acre-feet per square mile of drainage area
and $E$ = rate of gross erosion, in tons per square mile per year.

**Method 2** This method was developed by Glymph, Heinemann and Kohler (3) for estimating the annual sediment yield from watersheds in eastern Nebraska. In the discussion that follows it will be called the Glymph equation.

Statistical analysis of the data indicated the following formula for estimating annual sediment yield:

$$\text{Log } S = 1.0078 \log E + 0.6460 \log 10N - 0.1354 \log 100W - 1.4130$$

where

$S$ = sediment yield, in tons per square mile per year
$E$ = gross erosion, in tons per square mile per year
$N$ = number of rainfall events, average annual number of events equal to or exceeding one inch per day during the growing season April 1 to October 15, and
$W$ = net drainage area, square miles.

The variable $E$ in this equation was computed after the method of Gottschalk and Brune (4). The variable S was adjusted for trap efficiency to compare it with the measured amounts of sediment deposited in the reservoirs.

**Method 3** This method was developed by Stall and Bartelli (8) for reservoirs within the deep loess soils of the Springfield Plain physiographic area in west-central Illinois. In subsequent discussion this method will be called the Illinois equation.

The most accurate equation developed in the Illinois study was the following:

$$P = 3.9 + 0.25S + 0.74A + 12.2E + 26.9I - 1.16C - 8.21 \log D$$

where

$P$ = sediment deposition, in tons per acre
$A$ = age, in years
$S$ = mean slope of third order streams, in feet per mile

$E$ = gross erosion, in tons per acre per year

$I$ = capacity-inflow ratio, where the original capacity is computed at emergency spillway elevation and the inflow is the mean annual inflow for the area

$C$ = density of non-incised channels, in feet per acre, and

$D$ = mean direct tributary drainage area, in acres.

The sheet and rill portion of gross erosion, $E$, was computed by the Musgrave (modified) method described under sheet and rill erosion.

**Method 4** This method does not consist of a single relationship credited to a given person. It is a procedure whereby gross erosion is adjusted for watershed delivery ratio and reservoir trap efficiency to give a predicted amount of sediment deposited in the reservoir. A delivery ratio curve developed and reported by Glymph (3) was used. The estimated trap efficiency was determined by the method of Brune (1) and the sheet and rill erosion was computed by the Musgrave (modified) method. This fourth method will be referred to as the modified gross erosion method.

The base for comparing and determining the adequacy of the four previously developed methods was the measured sediment deposits determined by Farnham (2) in a study of 24 reservoirs. Since Farnham's study involved reservoirs in the loess soil area along the Missouri River valley, only those methods which had been derived from data from similar soil types were used for comparison.

The predicted amount of sediment was calculated by each of the four methods for the 24 reservoirs used in Farnham's study. The comparison was made by computing the ratio of the predicted value to the measured value. A value of the ratio less than 1 shows that for a given reservoir a method underpredicted the actual deposition while a value greater than 1 shows an overprediction. On the average, two of the methods overpredicted and two underpredicted. The average deviations (predicted minus measured) were computed and found to be −6,097 tons, + 9,233 tons, + 6,663 tons and −11,730 tons for the Illinois, Glymph, TP-97 and modified gross erosion methods, respectively. Fig. 3 shows a random scatter of the values of the ratio computed by the four methods. About 40 percent of the plotted points lie in a band where the actual deposition was predicted within ± 50 percent. No individual method could be designated as being superior; none were adequate to predict accurately the measured deposition in the 24 reservoirs. Since all methods include sheet and rill erosion as a variable, the method by which it is calculated influences the final result more than any other variable.

The above comparisons show the inherent empiricism in the previously developed methods. In all methods where statistics showed the goodness of fit of a particular method to the original data, a reasonable fit was obtained. Empiricism in any method should not be criticized if the method survives tests which define its applicability. Further research and different techniques of analysis are needed to obtain an absolute explanation.

## Discussion and Conclusions

Present design criteria for estimating required sediment storage in reservoirs may be classified in one of two broad categories. One category includes methods where the total expected gross erosion in the drainage basin is computed and modified by a delivery ratio and trap efficiency. The other category includes mathematical relationships that have incorporated reservoir, watershed and hydrologic variables to explain and predict reservoir sedimentation.

Methods which may be included in both categories were evaluated for the loess soil area in the Missouri River basin. The base for comparison was the measured sediment in 24 reservoirs included in a study by Farnham.

The reliability of estimation of the components (delivery ratio, trap efficiency, etc.) in the first category was investigated. The results show that computed delivery ratios were in poor agreement with previously derived delivery-ratio curves for the loess soil region. The data in Fig. 2 suggest no relationship between delivery ratio and drainage area. The results also show that the estimated trap efficiency was poorly correlated with the capacity-inflow ratio.

The various methods of computing sheet and rill erosion were compared by determining their relative efficiency in the analyses of the reservoir data for development of sediment prediction equations. Of three equations compared, the universal soil loss equation and the Musgrave (modified) equation gave comparable results, but the Musgrave equation was the most efficient.

Three mathematical relationships were also used to compute estimated sediment deposition in the reservoirs. The estimated values were then compared with the measured amounts of sediment in the reservoirs. The reliability of the prediction by the three equations varied from sample to sample, but two of the three equations overestimated the amounts of deposition. The average deviation (predicted minus measured) for any one equation varied for 40 percent of the measured mean to 28 percent of the measured mean.

Although the results of the analyses of the individual components of delivery ratio and trap efficiency did not follow expected trends, delivery ratio and trap efficiency were used to modify gross erosion to give a predicted sediment deposition. The predicted deposition by this method was also compared with the measured deposition, and it was found to give poorer agreement than the three mathmatical relationships.

It may be concluded from the results of the comparisons in this paper that the methods tested for predicting sediment deposits in reservoirs are empirical. The factor that contributed the most variability in the various methods was the estimation of sheet and rill erosion. The soil loss equations were developed from research data and represent the best estimates of sheet and rill erosion. However, when used on a watershed complex, the range of their applicability may be exceeded. Until research provids a method of accurately estimating gross erosion, which includes improving estimates of critical sediment sources other than sheet and rill erosion and a search for significant geomorphic factors in causing deposition as colluvium and alluvium, prediction techniques for sediment storage in reservoirs will continue to be empirical in nature. There is no assurance that a technique developed in one land resource area will apply to another. This paper shows wide discrepancy between methods applied in the same land resource area.

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