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EVALUATION OF FACTORS AFFECTING RESERVOIR SEDIMENT DEPOSITION[1]

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ABSTRACT

A continuing need exists for more complete and realistic values for sediment yield from small watersheds in the loessial area. The designers of conservation structures also need a better evaluation of those parameters that affect sediment delivery to reservoirs. Good sites for reservoirs are a valuable natural resource. It is imperative that sound predictions of future reservoir sediment deposition be made to obtain most efficient use of reservoirs and sites.

Detailed field surveys were made of existing reservoirs in the loessial hills of western Iowa and northwestern Missouri to determine the rate of sediment accumulation. Additional data were secured to evaluate the variables associated with reservoir trap efficiency, with delivery of sediment to reservoir and with gross erosion from the contributing watershed area. Through the use of multiple regression techniques, the rate of sediment deposition in the reservoirs was expressed as a function of computed gross erosion and measured reservoir and watershed variables.

The results show that the amount of sediment deposited in the reservoir is highly correlated with the computed gross erosion. The remaining variation was explained as a function of variables defining the reservoir trap efficiency and watershed delivery ratio. A greater insight was obtained of the importance of land management and the interaction of reservoir and watershed variables as they affect reservoir sedimentation.

RÉSUMÉ

Évaluation des facteurs concernant la sédimentation de réservoirs

Il existe un besoin continu d'une évaluation plus complète et plus réaliste du débit d'alluvionnement de petits bassins hydrographiques des régions loessiales. Les auteurs de projets de structures de conservation ont besoin aussi d'une meilleure évaluation de ces paramètres qui concernent le débit de sédimentation aux réservoirs. De bons sites de réservoirs constituent une ressource naturelle de grande valeur. Il est essentiel que des prévisions valables de future sédimentation se fassent afin de réaliser l'emploi le plus efficace des réservoirs et sites disponibles.

Des études détaillées ont été faites des réservoirs dans la région vallonnée et loessiale que comprennent la partie de l'ouest de l'état d'Iowa et la partie nord-ouest de l'état de Missouri; études qui avaient pour but la détermination du débit de la sédimentation. On a obtenu des données supplémentaires afin d'évaluer les variables liés à l'efficacité des trappes de réservoir, au débit de la sédimentation au réservoir et à l'érosion totale du bassin hydrographique impliqué. A l'aide des techniques de régression multiple, le débit de sédimentation dans les réservoirs s'exprime comme fonction de l'érosion totale estimée et des variables de réservoir et de bassin hydrographique mesurés.

Les résultats indiquent que la somme du sédiment déposé dans les réservoirs se trouve en corrélation avec l'érosion totale estimée. La variation qui reste s'explique comme fonction des variables qui expriment le rapport entre l'efficacité des trappes de réservoir et le débit du bassin hydrographique. Un meilleur aperçu est obtenu de l'importance de l'exploitation de la terre et de l'action réciproque des variables de réservoir et de bassin hydrographique et de leur action sur la sédimentation de réservoir.

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INTRODUCTION

Recognition of the need to conserve soil and water resources in the United States has promoted the use of reservoirs for upland watershed protection and flood prevention. Associated with the use of reservoirs as a method of flood prevention is the loss of reservoir capacity due to the inflow and deposition of sediment. Reservoir sites are a valuable natural resource, and loss of reservoir capacity represents depletion of this resource.

The magnitude of the problem varies widely with physiographic areas and may vary rather markedly at different points within a given drainage basin. Sediment yields per unit drainage area in the Missouri River Basin loess hills of Iowa and Missouri are among the highest in the country because of the soil, topographical and climatological characteristics of the area. A combination of highly erosive loessial soils, steep topography, intensive cropping practices and high intensity rainfall contributes to the problem of reservoir sedimentation.

In developing sediment design criteria for erosion control, gully stabilization and flood prevention reservoirs in this area, Gottschalk and Brune (4) studied 30 small reservoirs. Drainage areas ranged from 0.038 to 41.8 square miles. Results of the study showed that the reservoirs were losing storage capacity at rates ranging from 1.2 to 33.9 percent annually. A storage capacity loss of 33.9 percent annually represents complete loss of usefulness in less than three years and the loss of a reservoir site as a natural resource.

Research workers in the field of erosion and sedimentation have developed empirical relationships to predict sheet and rill erosion from measureable topographic and climatic variables (4,9,13).

In addition, several studies have been conducted to determine sediment delivery ratio, the ratio of sediment yield at a point of measurement to the total erosion in the watershed upstream from this point. Maner (8) found a significant relationship between delivery ratio and drainage area in the Blackland Prairie area of Texas. However, Glymph (3), using data gathered by Gottschalk and Brune (4) in the Missouri River Basin loess hills, found that drainage area explained only 18 percent of the variation in delivery ratio. Roehl (10), in a study of sediment yields of 15 drainage areas in the South-eastern Piedmont region of the United States, found a highly significant relationship when delivery ratio was expressed as a function of net drainage area, weighted mean bifurcation ratio and relief-length ratio. Maner (8), in a study of the Red Hills area of Texas and Oklahoma found a highly significant relationship between delivery ratio and relief-length ratio.

Existing methods predict sediment yields to reservoirs in the Missouri Basin loess hills area with varying degrees of accuracy. As an example, predicted values varied from 0.4 to 5.4 times the actual amount deposited in the reservoirs included in this study. Evidently, factors that influence erosion, transportation and deposition of sediment in the reservoirs are not adequately described. As a result, reservoirs may be seriously over or under-designed in regard to sediment storage, thereby seriously limiting the intended function of the reservoir.

The Soil Conservation Service, United States Department of Agriculture, is actively engaged in the design and construction of watershed protection and flood prevention reservoirs. In view of the amount of design and construction work in the Missouri River Basin loess hills area, a study was initiated to improve the existing design criteria. The project was sponsored cooperatively by the Soil Conservation Service and Agricultural Research Service, U.S.D.A., and the Iowa Agricultural and Home Economics Experiment Station.

The study area is shown in figure 1. Each circle represents a reservoir site with a net drainage area varying in size from 0.086 to 2.65 square miles. The period of record varies from 5.7 to 39.8 years. Of the 22 reservoirs selected, 2 are in northwestern Missouri, the remaining 20 are in western Iowa. Physical characteristics considered as having significant effects on the processes of erosion, transportation and deposition were observed and measured on each watershed.

DATA COLLECTION

Reservoir Surveys

Detailed surveys were made on each of the reservoirs by a method described by Heinemann and Dvorak (6). Field determination of the emergency spillway contour and a selected lower contour provided horizontal control. In addition, a sufficient number of cross sections or ranges were surveyed to provide vertical control and to adequately define the reservoir topography. Bottom elevations along the ranges were determined by sounding. Where previous reservoir surveys were not available, a spud or a probe was used to determine the topography of the original reservoir bottom.

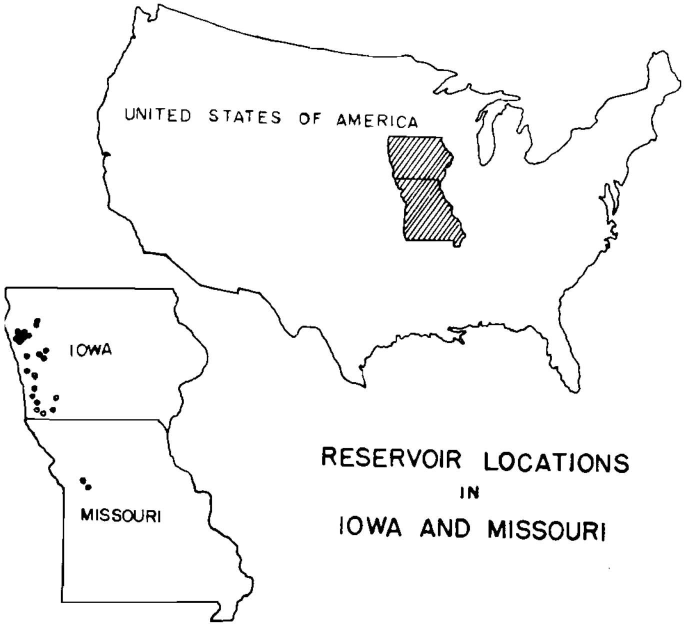

Fig. 1

Two-foot contour maps on a scale of 1:600 or 1:1,200 were prepared for each reservoir. Reservoir volumes were computed from these contour maps using the average contour area method described by Heinemann and Dvorak (6).

Since it was necessary to convert reservoir volumes to weight of sediment deposited, in-place sediment densities were determined. The equipment used for submerged deposits were the gamma density probe (5) and the volumetric sediment sampler (5). Only the volumetric samplers were used for exposed sediment deposits.

Watershed Surveys

A general survey of each drainage basin was also made. Field boundaries, fences, constructed terraces and incised channels, as well as other physical features of the particular basin, were plotted directly on aerial photographs of a scale of 1:7,920. Where marked changes in slope, vegetal cover and size and configuration of the drainageways were observed, elevations of these points were determined and locations plotted on the aerial photos. Maximum elevation on the watershed divide at the head of the main drainageway was also determined by survey. Cultural, management and conservation practices, land use and production level of the soils were obtained by personal interview with the land owners and operators. Soil type boundaries and dominant field slopes were obtained from soil survey maps of a scale of 1:15,840 prepared by the Soil Conservation Service.

DATA REDUCTION

Selection of Variables

The reservoir sediment prediction equations developed by Gottschalk and Brune (4), Stall and Bartelli (11) and Ackermann and Corinth (1) and the work of others described in the preceding paragraphs have been used as a guide in selecting variables. The following factors were considered as having measureable effects on reservoir sediment deposition.

Gross Erosion. In this study, gross erosion includes sheet and rill erosion and gully erosion. In the small drainage basins included in this study, sheet and rill erosion is the major source of reservoir sediment.

The universal soil loss equation (13) and the Musgrave equation (9) are commonly used to compute sheet and rill erosion. These equations were derived by empirical methods from small experimental plot data.

The universal soil loss equation is:

$$A = RKLSCP$$

where A is the average annual soil loss in tons per acre predicted by the equation,

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 (terracing, stripcropping, contouring).

In this study fields were subdivided, if necessary, so that measured slope lengths were representative of the field subdivision. Slope length for each soil type and slope group was measured from the highest elevation on a flow path to the lower boundary of the soil type or to a point where the flow path intersected a well defined drainageway. An average slope length for each soil type and slope group was determined from measurements along two or more flow paths in the field subdivision. An average LS factor was then determined by weighting the LS factors for the individual soil types and slope groups according to area.

The Musgrave equation is as follows:

$$E = I\frac{R'}{100}\left(\frac{S}{10}\right)^{1.35}\left(\frac{L}{72.6}\right)^{0.35}\left(\frac{P_{30}}{1.25}\right)^{1.75}$$

where E is the sheet and rill erosion in inches per year,

I is the erosion from continuous row crop from the given soil (adjusted to 1.25 inches rainfall) in inches per year,
R' is the cover factor (fallow or continuous row crop equals 100),
S is the degree of land slope in percent (with 10% as standard),
L is the length of land slope in feet (with 72.6 feet as standard), and
P_{30} is the maximum 30-minute rainfall amount, 2-year frequency, in inches (with 1.25 inches as standard).

The factor, I, was not available for the soils used in this study. The equation was modified by substituting the product 0.59 KR for I and by adding the practice factor P, both from the universal soil loss equation. The product KR is the soil loss from continuous fallow. Thus, multiplying the product KR by 0.59, the soil loss from continuous row crop is obtained which is comparable to the soil loss given by I. The term $[P_{30}/1.25]^{1.75}$ was dropped because rainfall is included in the R factor. Assuming the average volume-weight of the upland soils is 150 tons per acre-inch, the modified equation becomes:

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

where E' is the sheet and rill erosion in inches per year.

Measurement of slope length for use in the Musgrave equation involved the same subdivision of the fields and the same flow paths as used in the universal soil loss equation. However, the slope length, L, for each soil type and slope group is the distance from the upper boundary of the soil type and slope group to the lower boundary or to a well-defined drainageway within the soil type boundary. To investigate the relative merits of each method, each equation was used to compute sheet and rill erosion.

Gully erosion was estimated from field observations and from two flights of aerial photographs taken approximately five years apart. Gully erosion was added to the two values of sheet and rill erosion to give two values of gross erosion for each reservoir.

Reservoir Variables

1. Capacity-inflow ratio in acre feet per acre foot. Capacity is the reservoir volume at the emergency spillway elevation at the beginning of the period of record. Inflow is the mean annual runoff volume as determined from U.S. Geological Survey Circular 52.
2. Capacity-watershed ratio in acre feet per square mile of net drainage area. Capacity is defined in item 1 above. Net drainage area excludes the permanent pond area and the area of the watershed controlled by terraces.
3. Ratio of the reservoir capacity below the elevation of the principal spillway to the reservoir capacity at the elevation of the emergency spillway in acre feet per acre foot.
4. Flow area of the principal spillway conduit in square feet.
5. Reservoir shape factor in acres per acre. The shape factor is defined as the ratio of the reservoir area at the elevation of the emergency spillway to the area of a circle of the same perimeter.

Watershed Variables

1. Watershed shape factor in acres per acre. The shape factor is defined as the ratio of the watershed area to the area of a circle of the same perimeter.
2. Stream order as defined by Horton (7) and revised by Strahler (12). Starting at the upper reaches of the watershed, a first order stream is an unbranched tributary. Two first order streams must join to form a second order stream. Two second

order streams must join to form a third order stream, and so on. However, a first order stream joining a second order stream does not make a third order stream. Soil survey maps of a 1:15,840 scale prepared by the Soil Conservation Service were used in determining stream orders.

3. Average stream length in miles. The total length of streams of each order was measured from the soil survey maps. The average length of each order was then determined by dividing total length by the number of streams of that order. These averages were then summed to obtain an average length, L, for the entire drainage system.
4. Relief in feet. Relief, R, is defined as the elevation difference between the point of maximum elevation in the watershed at the head of the main drainage stream and the low point in the channel at the reservoir site at the time of construction. This elevation difference was determined by a field survey.
5. Bifurcation ratio. Bifurcation ratio is defined as the antilog of the slope of the line expressing the relationship of number of streams of a given order on the logarithmic ordinate versus the stream order number on the arithmetic abscissa.
6. Mean direct tributary area in acres. The total drainage area of first order streams outletting directly into the reservoir is summed. This sum is divided by the number of first order streams that outlet directly into the reservoir to give a mean tributary area for first order streams. This procedure is repeated for higher order streams that outlet directly into the reservoir. The mean direct tributary area is the sum of the mean tributary areas for each order divided by the highest order number of streams outletting directly into the reservoir.
7. Sediment trapping area in acres. Areas of sediment deposits upstream from roads and fences (across drainageways) were determined by field observation and plotted directly on the aerial photographs.
8. Direct tributary area to the reservoir in acres. This tributary area is the total area drained by first order streams outletting directly into the reservoir and was measured from soil survey maps.
9. Length of incised channels in miles. Incised channels are those cut sharply into the earth by flowing water. They are characterized by steep side banks regardless of the size or depth of the channel.
10. Length of non-incised channels in miles. Non-incised channels are those well defined drainageways where water collects and flows away, yet there is no incision into the earth.
11. Area of alluvial and colluvial soils in the drainage basin in acres. Areas of these soils were measured from the soil survey maps.
12. Total length of drainage in miles. The total length of streams of each order were summed to give total length of drainage.
13. Slope of the highest order stream above the principal spillway in feet per foot.

STATISTICAL ANALYSES

Multiple regression is frequently used when it is desired to express a dependent variable as a function of one or more independent variables. The form of the functional relationship derived by multiple regression is dependent upon the model used. In many cases where multiple regression is used, the "true" form of the functional relationship is not known. Therefore, the researcher usually tries different model assumptions or uses transformations of the data in arriving at a functional relationship between the dependent and independent variables.

In preliminary analyses a relatively high correlation, $r = 0.54$, was found between the weight of sediment deposited in the reservoir and the computed gross erosion. Therefore, by expressing the dependent variable as a ratio of the sediment deposited to the computed gross erosion, the selected independent variables would need to explain the variability associated with reservoir trap efficiency and delivery ratio (ratio of sediment delivered to the reservoir to gross erosion). The form of the model was

$$X_1 = a+bX_2+cX_3+\ldots+kX_n$$

where X_1 = Ratio of sediment deposited in the reservoir, P, to computed gross erosion, E, and $X_2, X_3, \ldots X_n$ = Dimensionless ratios of variables associated with trap efficiency and delivery ratio.

The selection of appropriate ratios for independent variables in the model was influenced by the criterion of keeping the ratios dimensionless. The selection of the most pertinent variables was facilitated by examining the relationship between reservoir deposition and the variables listed in the preceding pages.

The dimensionless ratios used as independent variables in the multiple regression analyses are as follows:

Reservoir variables

1. C/I, Capacity-inflow ratio, in acre feet per acre foot.
2. C/Wd, Capacity-watershed ratio divided by original maximum reservoir depth, d, in acre feet per square mile feet.
3. R_s, Reservoir shape factor, in acres per acre.
4. C_P/C, Ratio of original conservation pool capacity to total original reservoir capacity, in acre feet per acre foot.

Watershed variables

1. T, Ratio of mean direct tributary area to net drainage area, in acres per acre.
2. R/L, Relief-length ratio, in feet per foot.
3. C_n/L_t, Ratio of non-incised channel length to total length of drainage, in miles per mile.
4. S_w, Watershed shape factor, in acres per acre.
5. A_a/A, Ratio of area of alluvial and colluvial soils to net drainage area, in acres per acre.
6. S, Slope of the highest order stream above the principal spillway, in feet per foot.

RESULTS

Regression Analyses

Multiple regression analyses were run on 10 combinations of the 6 independent variables to determine the best combination for computing the dependent variable. Table 1 summarizes these multiple regression equations.

Equations 6 and 16 in table 1 have only one independent variable, C/Wd, capacity-watershed ratio divided by the original maximum reservoir depth. The coefficient of determination, R^2, is 0.47 and 0.37, respectively. This means that 47 percent and 37 percent of the variation in P/E can be explained by C/Wd.

Comparison of equations 6 and 16 with equations 1 and 11 shows that the independent variable C/Wd is a much better indicator of the variation in the dependent variable than C/I, the capacity-inflow ratio. R^2 for equations 6 and 16 are 0.47 and 0.37, respectively, as compared with 0.28 and 0.17.

Table 2 shows the 4 best equations of table 1. Where the 4 independent variables were used in combination, all regression coefficients were significant at the 90 percent

TABLE 1

Efficiency of regression equations

Equation[1] Number	Dependent Variable	Independent Variables	Coefficient of Determination, R^2	Degrees of Freedom	Standard Error of Estimate, S_e
1, (11)	P/E	C/I	0.28 (0.17)	20	0.25 (0.29)
2, (12)	P/E	C/I, T	0.31 (0.20)	19	0.25 (0.29)
3, (13)	P/E	C/I, T, R_s	0.39 (0.33)	18	0.24 (0.27)
4, (14)	P/E	C/I, T, R_s, S	0.46 (0.39)	17	0.24 (0.27)
5, (15)	P/E	C/I, T, R_s, S, R/L	0.47 (0.39)	16	0.24 (0.28)
6, (16)	P/E	C/Wd	0.47 (0.37)	20	0.22 (0.25)
7, (17)	P/E	C/Wd, T	0.52 (0.41)	19	0.21 (0.25)
8, (18)	P/E	C/Wd, T, R_s	0.70 (0.66)	18	0.17 (0.20)
9, (19)	P/E	C/Wd, T, R_s, S	0.76 (0.73)	17	0.16 (0.18)
10, (20)	P/E	C/Wd, T, R_s, S, R/L	0.79 (0.73)	16	0.15 (0.18)

[1] Gross erosion was computed using the universal soil loss equation and the Musgrave equation giving two values for the dependent variable. Numbers in parentheses indicate values for the statistics where gross erosion was calculated by the universal soil loss equation.

TABLE 2

Regression Equations

Equation	R^2	S_e
(9) $\frac{P}{E_m} = 0.494 + 0.072^{**}\left[\frac{C}{Wd}\right] - 1.041^{*}\,T - 1.258^{**}\,R_s + 10.255^{*}\,S$	0.76	0.16
(10) $\frac{P[^1]}{E_m} = 0.492 + 0.071^{**}\left[\frac{C}{Wd}\right] - 0.980^{*}\,T - 1.445^{**}\,R_s + 6.310\,S + 2.934\left[\frac{R}{L}\right]$	0.79	0.15
(19) $\frac{P}{E_u} = 0.515 + 0.076^{**}\left[\frac{C}{Wd}\right] - 1.102^{*}\,T - 1.562^{**}\,R_s + 10.688^{\dagger}\,S$	0.73	0.18
(20) $\frac{P[^2]}{E_u} = 0.515 + 0.075^{**}\left[\frac{C}{Wd}\right] - 1.070^{*}\,T - 1.662^{**}\,R_s + 8.579\,S + 1.568\left[\frac{R}{L}\right]$	0.73	0.18

[1] E_m is gross erosion with sheet and rill erosion computed by Musgrave's method.

[2] E_u is gross erosion with sheet and rill erosion computed by the universal soil loss equation.

* Significant at the 99% level.

** Significant at the 95% level.

† Significant at the 90% level.

level or greater. When relief-length ratio was included, slope of the mainstream became non-significant at the 80 percent level.

The simple correlation between relief-length ratio and slope of the mainstream is 0.60. It is believed that both variables are a measure of the same characteristic and when included together show a non-significant relationship.

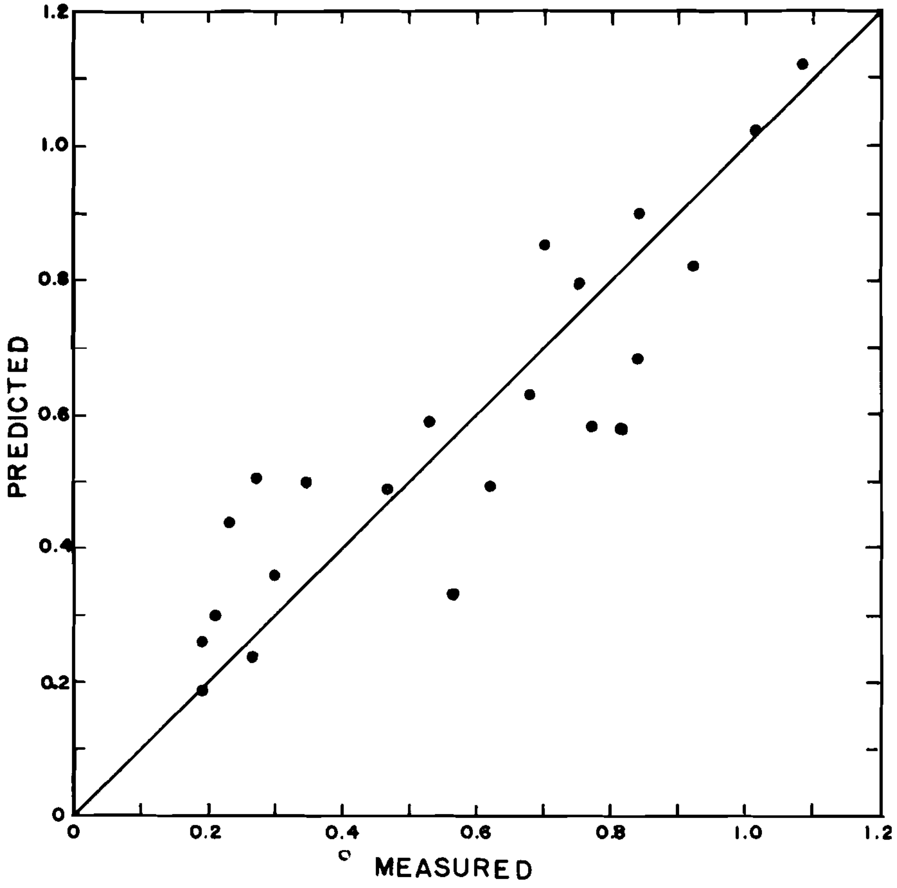

Fig. 2 – Relationship of predicted values of the dependent variable to measured values for equation 10.

The range in the independent variables listed in table 2 is as follows: C/I, 0.331 to 1.726 acre-feet per acre-foot; C/Wd, 4.41 to 18.24 acre-feet per square mile-feet; T, 0.180 to 0.500 acres per acre; R_s, 0.091 to 0.694 acres per acre; S, 0.0065 to 0.0363 feet per foot; and R/L, 0.012 to 0.118 feet per foot.

All four of the equations shown in table 2 are valid and can be used to compute the dependent variable. However, the equations using the Musgrave equation to calculate sheet and rill erosion consistently exhibit slightly better results. The universal soil loss equation was derived for field loss computations and was not developed for watershed application. Studies being planned will show if the application of the equation as used here is valid.

Using equation 10 and the actual field data, values for the dependent variable, the ratio of sediment deposition to computed gross erosion, were computed. These computed values were compared to observed values, and the points were plotted in figure 2. Deviations from the line of equal agreement are probably due to the effect of other independent variables not included in the final equation.

Summary

The study described in this paper involved the collection, reduction and analyses of data from 22 reservoirs and their associated drainage areas in the Missouri River Basin loess hills. Drainage area varied from 0.068 to 2.65 square miles. Period of record varied from 5.7 to 39.8 years.

Multiple regression techniques were used to evaluate the effect of gross erosion and watershed and reservoir variables on reservoir sediment deposition. Preliminary analyses showed a high correlation between sediment deposition and computed gross erosion. Final analyses were made by expressing the dependent variable, the ratio of reservoir sediment deposition to calculated gross erosion, as a linear function of 5 dimensionless watershed and reservoir variables. The 5 dimensionless variables are (1) capacity-watershed ratio divided by original maximum reservoir depth, (2) ratio of mean direct tributary area to net drainage area, (3) reservoir shape factor, (4) slope of the highest order stream above the principal spillway, and (5) relief-length ratio. These parameters were combined to account for about 80 percent of the variability in the dependent variable. It may be that other parameters investigated in this study were of such uniformity that they were not significant in the statistical analyses. In addition, other parameters may be more important in different physiographic areas.

The equations presented in this paper were developed specifically for use in the Missouri River Basin loess hills of Iowa and Missouri. They may not be applicable elsewhere. The limitations of the equations must be realized in that they should not be applied to reservoirs having values for independent variables which are greater or less than the values used here.

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