

SECTION 3. SEDIMENT YIELD AND SOURCES

Role of Large Events in Average Soil Loss--	
A. T. Hjelmfelt, Jr., L. A. Kramer and R. G. Spomer.....	3-1
Sediment Redistribution by Raindrop Impact--	
M. J. M. Römken and J. Y. Wang.....	3-10
Sediment Yield from Small and Medium Watersheds--	
C. D. Clarke and P. G. Waldo.....	3-19
Ephemeral Gully Erosion--	
J. M. Laflen, D. A. Watson and T. G. Franti.....	3-29
Drainage Density versus Runoff and Sediment Yield--	
P. B. Allen.....	3-38
Sediment Yield Methods Used in the Corps of Engineers--	
Gary R. Dyhouse.....	3-45
Sediment Storage and Delivery - Eastern Colorado--	
K. L. Clarkin, M. D. Harvey, A. Elkin and S. C. McIntyre.....	3-54
Sediment Yield and Runoff after Timber Harvest--	
Vito A. Ciliberti, Jr.....	3-64
River Sediment Budget--	
Edward F. Sing.....	3-73
Sediment Concentration and Channel Morphology--	
Richard J. Janda and David F. Meyer.....	3-83
Landform Modifications at a Nuclear-Waste Burial Site--	
J. R. Gray.....	3-93
Sediment Yield of Three Drainage Basins in Guam--	
Patricia Shade.....	3-103
Hydropower Impacts on Erosion and Sedimentation--	
Walter M. Linder and Tsong C. Wei.....	3-112
Erosion and Sediment Yield from Flatlands--	
C. E. Murphree and C. K. Mutchler.....	3-122
Sagebrush Rangeland Erosion and Sediment Yield--	
Clifton W. Johnson and Nancy D. Gordon.....	3-132
Sediment Yield from a Gully--	
Norman H. Welch.....	3-142
Ephemeral Gullies as Sources of Sediment--	
C. R. Thorne, Lyle W. Zevenbergen, E. H. Grissinger and J. B. Murphey.....	3-152
Sediment in Mugu Lagoon, Ventura County, California--	
Lyle J. Steffen.....	3-162

SECTION 3
SEDIMENT YIELD AND SOURCES

ROLE OF LARGE EVENTS IN AVERAGE SOIL LOSS

By A. T. Hjelmfelt, Jr., Hydraulic Engineer; L. A. Kramer, Agricultural Engineer, USDA-ARS, Columbia, Missouri; and R. G. Spomer, Agricultural Engineer, USDA-ARS, Council Bluffs, Iowa

ABSTRACT

Long-term records of soil loss from plots and sediment yield from fields cropped to corn were evaluated to assess the significance of large events in establishing average annual sediment production. At Kingdom City, Missouri, the thirty-seven year average annual soil loss was 8 Mg ha^{-1} . Only nine of those thirty-seven years showed soil loss greater than average. On an individual event basis, four percent of the events accounted for fifty percent of the total soil loss. At Treynor, Iowa, the eighteen-year average sediment yield was 26 Mg ha^{-1} . Only four years exhibited sediment yield greater than the average. Three percent of the events accounted for more than fifty percent of the total erosion.

The results indicate that erosion modeling cannot be aimed to adequately describe average events, but must properly treat the extremes.

INTRODUCTION

Erosion field studies are often carried out over relatively short time periods, ten years or less. The results of such studies may be biased by the occurrence or absence of very large soil loss events. Similarly, numerical studies that simulate long-term soil loss may give misleading results if infrequent, large events are not properly modeled.

The importance of large soil loss events has been noted previously by Wischmeier (1962), and by Piest (1965). Wischmeier, in a study of plot data, noted that three-fourths of the soil loss resulted from an average of four storms per year. Piest studied soil loss from watersheds ranging in size between 40 and 40,000 ha. He found that between 3 and 46 percent of the suspended sediment yield was caused by storms with return period greater than two years. Unfortunately, the record lengths available to Piest were quite short; one record was of twelve years and the rest of seven years or less.

In this paper we consider soil loss from plots in Missouri and sediment yield from fields in Iowa, all of which were cropped to corn. Thirty-seven years of plot data and eighteen years of field data are considered. We confirm, in general, the findings of Wischmeier and Piest.

STUDY SITES

This study was made using data collected on plots located near Kingdom City, Missouri, and a field located at Treynor, Iowa. In both cases, only data for continuous corn cropping using conventional tillage was used. Both sites are managed by the USDA, Agricultural Research Service.

The test facility at Kingdom City, Missouri, consists of plots measuring 27.4 m by 3.2 m. The soil is classified as Mexico silt loam, a member of the fine, montmorillonitic, mesic Udollic Ochraqualfs. The soil is derived from loess, but a high content of colloidal material in the claypan subsoil that occurs 300 to 600 mm below the surface retards percolation of water. Slopes of the plots range from 3 to 3.5 percent.

Total runoff volume is measured in tanks located at the outlet of each plot. The volume of water captured is measured, samples for sediment and chemical analyses are taken, and the tanks emptied and cleaned to prepare for the next event. To accomplish this, it is necessary to have several daylight hours without rainfall. An event, then, consists of all rainfall and soil loss that occurred between opportunities for tank cleaning. Additional information concerning the Kingdom City site is given by Burwell and Kramer (1983).

The facility at Treynor, Iowa, consists of four field-size watersheds. Only Watershed 2 was selected for this study. The watershed has an area of 33.5 ha with slopes at the ridges and valleys of about four percent, and a maximum side slope of 14 percent. The soils are representative of the deep loess soils adjacent to the Missouri river valley in Iowa, Kansas, Missouri, and Nebraska. These silt loam soils are typic Hapludolls, typic Udorthents, and cumulic Hapludolls. All of these soils are fine silty, mixed mesics and have moderate to moderately rapid permeability. The watershed has been continuously cropped to corn using conventional tillage on field contours.

Runoff is measured using a broadcrested triangular weir. Samples for sediment and chemical analyses are taken using a pumping sampler. An event is defined by the rainfall-runoff record. Thus, an event begins with a rainstorm that produces runoff and ends when the hydrograph indicates return to base flow. Additional information concerning the Treynor site is given in Spomer et al. (1981).

EXPERIMENTAL RESULTS

The long-term average annual soil loss and sediment yield for the sites are 7.7 Mg ha^{-1} for Kingdom City and 22.6 Mg ha^{-1} for Treynor. The long-term average is not indicative of the actual annual soil loss or sediment yield as shown in Figs. 1 and 2. At Kingdom City (Fig. 1), only nine of the thirty-seven years, less than one-fourth, had an annual soil loss greater than the 37-year average. Short-term, say ten-year studies of soil loss would produce very different results depending upon which study period is selected. Similar results were found at Treynor, Iowa, (Fig. 2) where, in only four of the seventeen years, again less than one-fourth, was the annual sediment yield greater than the average annual value.

In order to investigate the influence of individual events, an arbitrary large soil loss threshold was selected. At Kingdom City the selected threshold of 2 Mg ha^{-1} was exceeded in only 37 events. These events have a recurrence interval of approximately one year or greater. At Treynor, Iowa, a sediment yield threshold of 4 Mg ha^{-1} is exceeded for a recurrence interval of approximately one-half year or greater. These threshold definitions were used to subdivide the bars representing annual soil loss for each year, in Figs. 1 and 2, into components attributable to the large and small events.

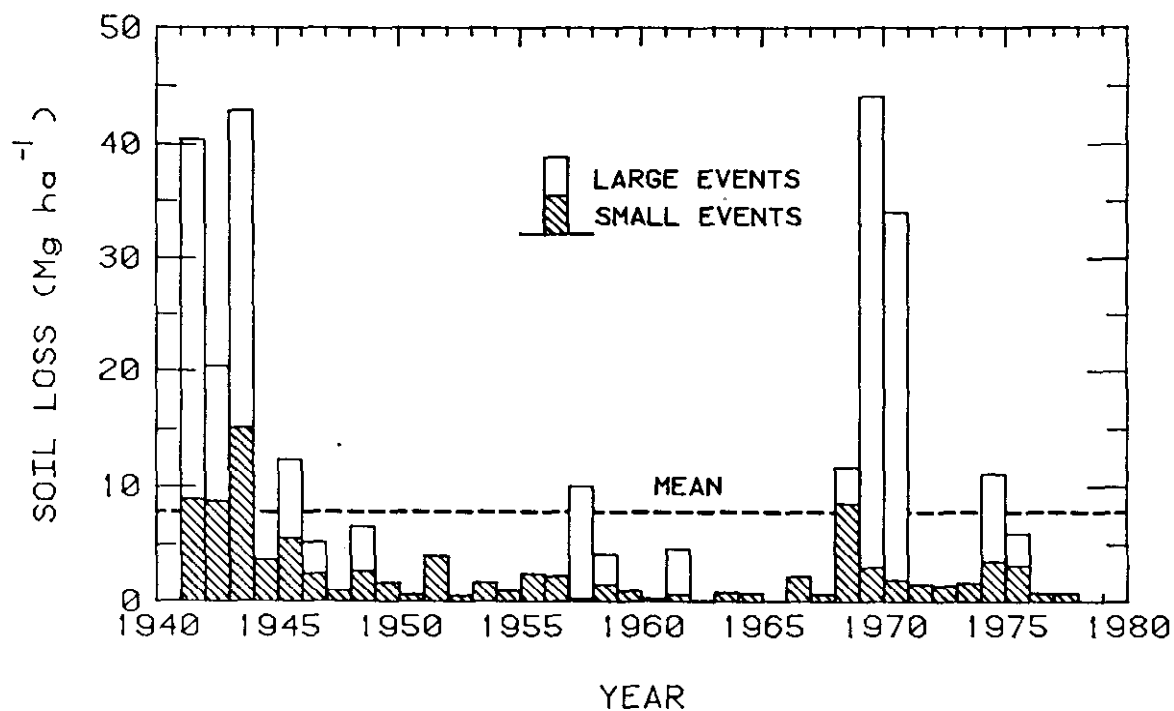


Fig. 1. Measured annual soil loss at Kingdom City, Mo.

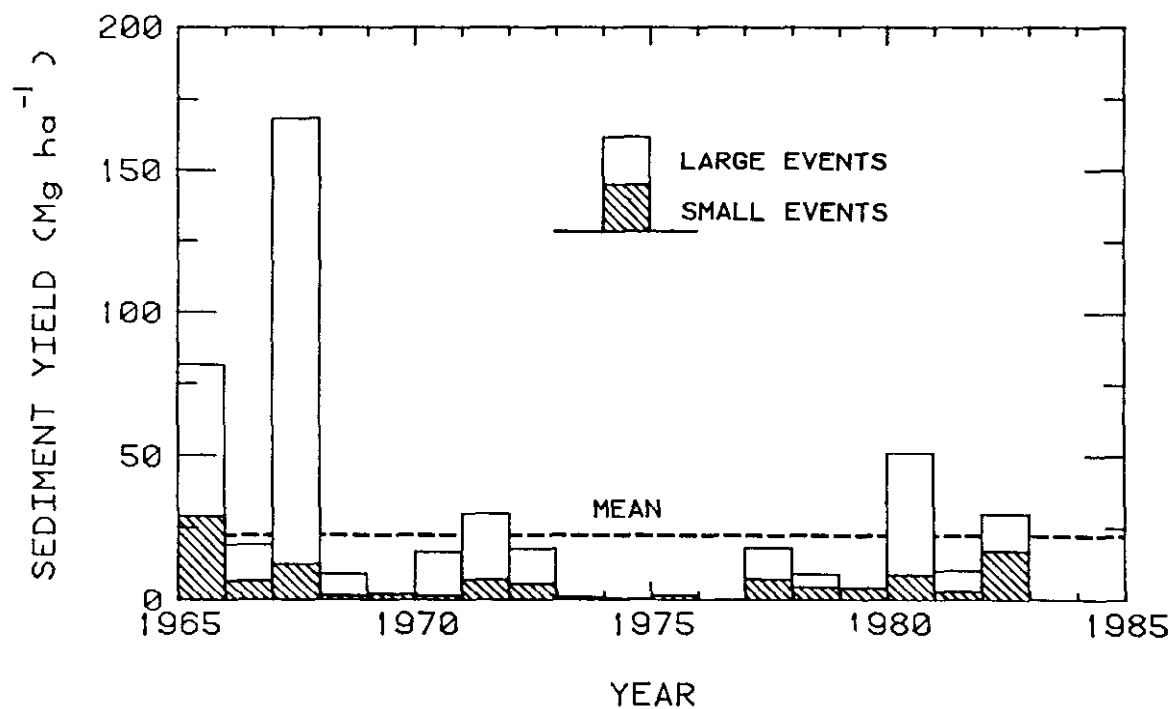


Fig. 2. Measured annual sediment yield at Treynor, Ia.

Details of the large events are given in Table 1 for Kingdom City, Missouri, and in Table 2 for Treynor, Iowa. For completeness, rainfall, volume of runoff, erosivity and, for the Treynor, Iowa, field studies, peak discharges are tabulated along with the soil loss. Peak discharge was not measured on the erosion plots at Kingdom City. The erosivity was determined using total kinetic energy and the maximum thirty-minute rainfall intensity for the event.

Note the seasonal censoring of the soil loss and sediment yield data that results from considering only those events exceeding the threshold. The large soil loss and sediment yield events occurred primarily during May and June except for one August event at Treynor and one October event at Kingdom City. The magnitudes of these rainfall amounts and of the other rainfall and runoff characteristics for these autumn events were much larger than for spring events that produced similar soil loss.

To display the effects of the individual large events, they were ordered from largest to smallest and the cumulative sum of either the soil loss or sediment yield for all events with losses equal or larger than the soil loss of the selected event was determined. The results for both locations are shown in Fig. 3. The large events account for 65 percent of the total 37-year soil loss at Kingdom City and 75 percent of the 18-year sediment yield at Treynor. The total number of rainfall events that caused soil loss during the periods of record was 513 in 37 years at Kingdom City and 357 in 18 years at Treynor. Note that at Kingdom City, the seven largest events account for 25 percent of the total soil loss. The twenty largest events account for more than half of the total. At Treynor, Iowa, the three largest events account for more than 25 percent of the total sediment yield. The thirteen largest events account for more than half of the total.

The two curves on Fig. 3 collapse to nearly the same line if the two largest events at Treynor are omitted from the sequence. The largest event at Treynor was caused by a rainstorm that contained increments of rainfall that exceeded the 100-year intensities for this location. Thus, it may be reasonable to consider the largest sediment yield value to be an outlier of the 18-year record. This suggests that the frequency distribution is similar for both locations.

A partial duration series for the large soil loss events at Kingdom City is given in Fig. 4. The plotting positions were determined using $n_r = m/N$, where m is the order number of the soil loss event and N is the number of years of record. A semilogarithmic plot was used as is often suggested for partial flood series. A least squares fit of a straight line to these data results in

$$SL = 1.99 - 3.56 \ln(n_r) \quad (1)$$

with $r^2 = 0.973$. Although this fits the large events reasonably well, it predicts the event with zero soil loss to occur with an average frequency of 1.75 events/year. The records, however, show that there is an average of 14.5 soil loss events/year. Thus, the distribution is not adequate for describing the numerous small events.

It may prove easier to simulate soil loss from large events than to attempt to simulate soil loss from all events. In this case it is necessary to determine the average annual soil loss from the partial duration series. Following the methods used to determine average annual flood damage, the average annual soil loss can be estimated as the area under the soil loss-frequency curve. This can be determined using the integral

$$SL = \int_{n_1}^{n_2} (SL) dn_r = \int_0^{1.75} (1.990 - 3.565 \ln(n_r)) dn_r \quad (2)$$

where the lower limit is the recurrence interval for the largest possible event, and the upper limit is the recurrence interval for events with zero soil loss. The result is

$$SL = 6.23 \text{ Mg ha}^{-1}$$

This is low compared to the measured average of 7.7 Mg ha^{-1} , suggesting that improper representation of the small storms by Eq. 1 neglected an average of 1.48 Mg ha^{-1} per year.

SUMMARY

The large events, those that occur with an average return interval of once each year or less often, produced more than half of the total soil loss and sediment yield. The remainder of the soil loss and sediment yield was distributed among the numerous small events, of which there were an average of 14.5 each year at Kingdom City and 18.8 at Treynor. The large events tend to be grouped in a single wet year or in a sequence of wet years. A partial duration soil loss series can be used to estimate average annual soil loss, but the result may be low due to the large number of events with very small soil loss.

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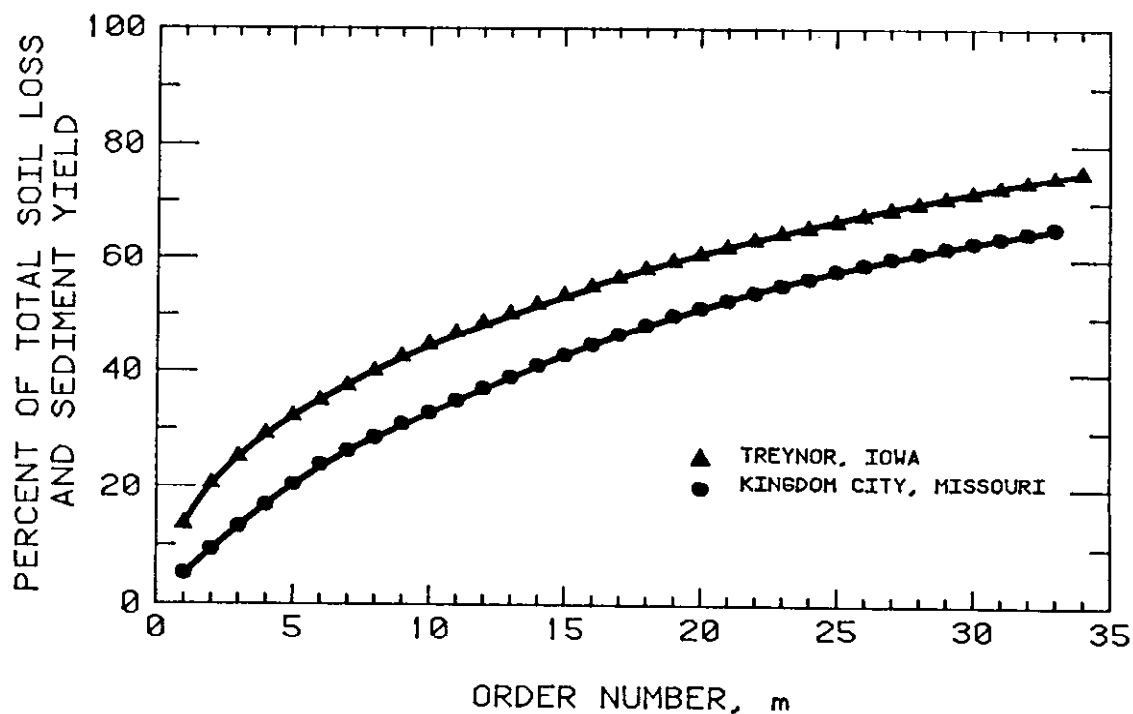


Fig. 3. Partial cumulative distribution for soil loss at Kingdom City, Mo., and sediment yield at Treynor, Ia.

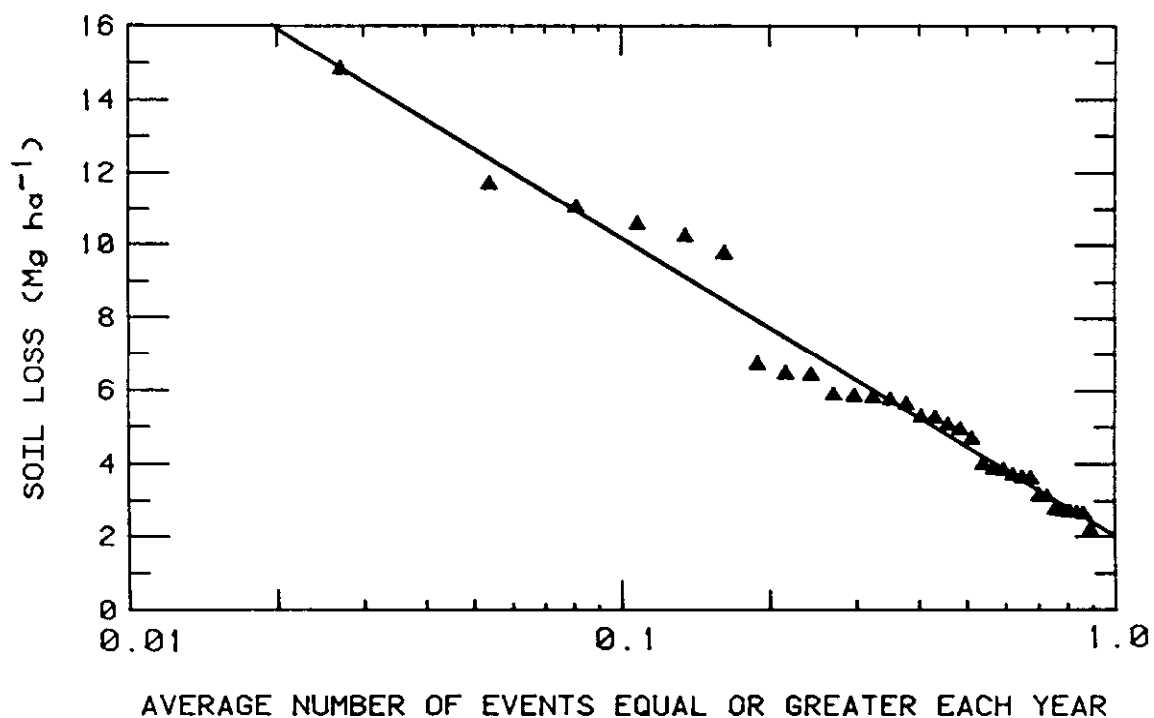


Fig. 4. Partial duration series for soil loss events at Kingdom City, Mo.

Table 1. Characteristics of large soil loss events at Kingdom City, Mo.

Year	Date	Rain (mm)	Erosivity (MJ mm ha ⁻¹ h ⁻¹)	Q (mm)	SL (Mg ha ⁻¹)
1941	April 18	117.1	938	64.0	10.28
	July 2-3	97.8	581	65.0	10.62
	July 10	49.8	186	30.7	4.70
	Oct. 3	216.7	3022	165.4	5.91
1942	June 7	45.5	637	14.0	3.65
	June 9	50.0	496	24.4	2.76
	June 25-26	107.2	840	52.6	5.29
1943	May 14-20	148.8	918	103.6	11.74
	June 3	41.4	357	13.7	4.97
	June 4-8	74.2	452	51.3	11.09
1945	June 5	89.2	936	63.0	6.76
1947	Mar. 31-Apr. 1	42.2	239	31.8	2.69
1948	May 1	45.2	618	9.1	3.85
1957	June 29-30	108.2	701	52.8	9.79
1958	June 13	59.7	369	17.3	2.67
1961	June 30-July 2	112.8	1711	32.0	4.01
1968	May 22	79.2	456	24.9	3.14
1969	May 30-June 1	97.5	1116	46.0	5.08
	June 14	61.0	441	40.1	3.63
	June 22	48.8	297	35.1	6.50
	June 23	27.4	226	21.3	5.89
	June 28	27.7	371	14.7	3.72
	June 30	45.7	265	31.5	5.85
	July 2	31.2	159	24.4	3.88
	July 5-7	51.6	294	28.4	6.47
1970	May 14	83.3	491	50.5	5.78
	May 22-25	44.5	359	19.3	5.67
	May 29-June 4	76.2	398	32.5	2.64
	June 12-16	128.8	2130	78.0	14.85
	June 20	33.8	516	16.0	3.16
1974	May 29-30	62.0	605	30.2	5.31
	June 8-9	19.6	102	12.4	2.22
1975	June 16-17	81.3	950	27.2	2.71

Table 2. Characteristics of large sediment yield events at Treynor, Iowa

Year	Date	Rain (mm)	Erosivity (MJ mm ha ⁻¹ h ⁻¹)	Q (mm)	Qp (mm/hr)	SL (Mg ha ⁻¹)
1965	May 17-18	21.3	190	3.0	9.1	4.82
	May 21	19.6	174	5.8	15.2	5.57
	May 22	16.5	142	9.6	43.5	12.71
	May 24	16.8	101	6.3	20.4	4.76
	June 6	17.8	107	9.1	29.2	4.60
	June 28-29	31.8	541	17.2	46.3	12.01
	June 29	33.0	448	16.2	47.8	8.17
1966	June 5	21.8	195	3.0	11.9	4.90
	June 26	26.4	294	10.1	46.6	7.68
1967	June 4-5	92.5	1541	42.4	43.2	32.92
	June 7	41.9	1022	25.6	105.3	22.40
	June 9	10.7	60	7.6	32.0	5.87
	June 9-10	34.8	438	31.7	86.4	18.21
	June 11-12	21.6	91	11.6	30.7	4.52
	June 14	22.6	187	12.4	55.4	6.90
	June 20	145.0	5213	95.5	123.5	65.17
1968	June 13-14	24.6	341	7.1	28.6	7.68
1970	May 12	35.1	571	9.9	26.2	10.42
	Aug. 2	48.8	1753	17.7	85.8	4.60
1971	May 10	17.0	130	7.6	33.8	4.25
	May 10	22.9	166	11.9	20.7	4.25
	May 18	27.9	298	18.5	65.1	14.20
1972	May 5	15.7	135	7.3	36.8	12.09
1977	May 4	17.8	180	8.3	28.0	4.17
	May 8	26.9	405	10.9	44.1	6.63
1978	May 19	28.4	381	5.0	25.6	4.68
1980	June 1	17.0	185	5.8	22.8	5.79
	June 1	20.6	204	9.6	32.3	4.84
	June 4	30.7	357	13.4	35.6	6.03
	June 12	29.2	531	10.9	39.9	8.41
	June 15	21.1	271	8.6	63.0	9.87
	June 15	12.4	90	8.3	49.3	7.28
1981	June 2	24.9	349	6.1	21.9	7.28
1982	June 14	34.3	603	12.7	45.9	12.42

Fig. 1. Measured annual soil loss at Kingdom City, Mo.

Fig. 2. Measured annual sediment yield at Treynor, Ia.

Fig. 3. Partial cumulative distribution for soil loss at Kingdom City, Mo., and sediment yield at Treynor, Ia.

Fig. 4. Partial duration series for soil loss events at Kingdom City, Mo.

Table 1. Characteristics of large soil loss events at Kingdom City, Mo.

Table 2. Characteristics of large sediment yield events at Treynor, Ia.

SEDIMENT REDISTRIBUTION BY RAINDROP IMPACT

By M. J. M. Römken, Soil Physicist/ Agr. Engineer, and J. Y. Wang, Physicist,
USDA-ARS, USDA National Sedimentation Laboratory, Oxford, Mississippi

ABSTRACT

Sediment redistribution by rainfall is discussed in relation to changes in roughness following the application of several consecutive rainstorms. An overview of different roughness parameters is given and their values are computed and compared for a number of transects. Different microrelief measuring devices are discussed. Changes in roughness are described in terms of an exponential decaying function of the cumulative rainfall.

INTRODUCTION

Soil loss during rainfall from upland areas is either estimated from soil erosion prediction equations or is measured at runoff gaging stations in downslope drainage channels or at discharge points on the field. Considerable soil movement that is not accounted for by these estimation procedures, however, may take place within a field. The need to improve our understanding of soil erosion processes and predictions requires more detailed, preferably mathematical, descriptions and evaluations of soil redistribution within an area. This paper summarizes recent progress in evaluating soil redistribution and movement using measured changes in surface elevations following the application of rain. The discussion uses variations in a recently proposed surface roughness parameter (Römken and Wang, 1984) to quantify soil redistribution.

SOIL REDISTRIBUTION PROCESSES

Sediment movement on upland areas may result from several processes or activities. These are: (1) soil particle detachment, transport and deposition by impacting raindrops, thin-film flow and concentrated flow, (2) changes in soil bulk density due to consolidation or loosening by implements or to climatological factors, such as wetting or drying, and (3) biological activities within soils. All of these processes or activities alter the surface elevations of upland areas. The most important processes during and following rainfall are soil detachment and redistribution by impacting raindrops and surface runoff, the sloughing of wet soil, and soil consolidation by drying. An analysis of the relative contributions of these processes to soil redistribution has been limited by measuring techniques incapable of detecting minute changes in surface elevation, and by analytical techniques incapable of relating the measured changes in surface elevation to the various component processes. Field observations have indicated that substantial changes in the matrix of recently tilled soil take place during a storm event as manifested by a change in surface roughness and nonuniformity in soil settling. As will be shown, soil movement or changes in surface elevation during the early part of a rainstorm on loosely tilled soil is the combined result of soil particle translocations by the erosive agents of rainfall and runoff and the settling of bulk soil from wetting. During this stage of the storm, consolidation is the dominating influence. Additional

soil settling takes place during drying due to a contracting matrix. Once soil is consolidated, changes in soil profile elevations are primarily due to erosion by rainfall and surface flow.

ROUGHNESS PARAMETERS

Descriptions of surface roughness and its changes have been complicated by the requirement of expressing a complex, seemingly random, distribution of surface elevations into a single variable. Although various indices have been proposed, their usefulness as descriptors of surface roughness has been limited by their nonuniqueness. That is, a given value of any one of these indices may result from different surface configurations. Nevertheless, a quantitative description of surfaces in terms of a number of parameters, expressing the distributive properties of the elevations and the degree of randomness, could be helpful in evaluating other properties of interest such as surface storage and soil erodibility.

The earliest mathematical expression of soil surface roughness was by Kuipers (1957), who defined roughness as

$$R_k = 100 \log(\sigma) \quad [1]$$

where σ is the standard deviation of the elevation readings of a grid system. Burwell et al. (1963) and Allmaras et al. (1966) introduced and used the concept of random roughness which was defined as the standard error of the logarithmic values of the measured elevations. Unfortunately, criteria or tests for spatial independence were not indicated in these studies. The validity of applying these definitions to real situations ultimately depends upon conformance with the requirement of spatial independence in the elevation of adjacent grid points and with the requirement of randomness. The latter requirement cannot be addressed until spatial independence is assured. Recently, Römken and Wang (1984) proposed a roughness parameter

$$R_r = A \times F \quad [2]$$

where A is the microrelief index, which is the area per unit of transect length between the actual soil surface and the regression line of best fit (Römken and Wang, 1985a), and F is the peak frequency factor or the number of peaks per unit transect length. This expression integrates the contribution of all elevations to roughness. Figure 1 shows the effects of changes in surface elevation and peak frequency on surface roughness for three idealized models. The parameter R_r reflects the effect of peak height and frequency on surface roughness. Perhaps, a more unique representation of surface roughness may be given by the integral of the power spectrum:

$$R_p = \int a(f) df \quad [3]$$

where f is the frequency and $a(f)$ is spectrum function or the amplitude given as a function of the frequency. Figure 2 shows the relationship between R_p and A^2 , where A is defined as in equation [2] for a number of parallel, but

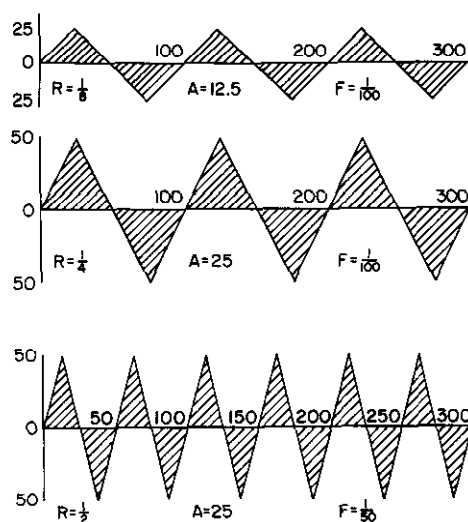


Figure 1. Schematic representation of the surface roughness parameter for three 1-dimensional geometric models.

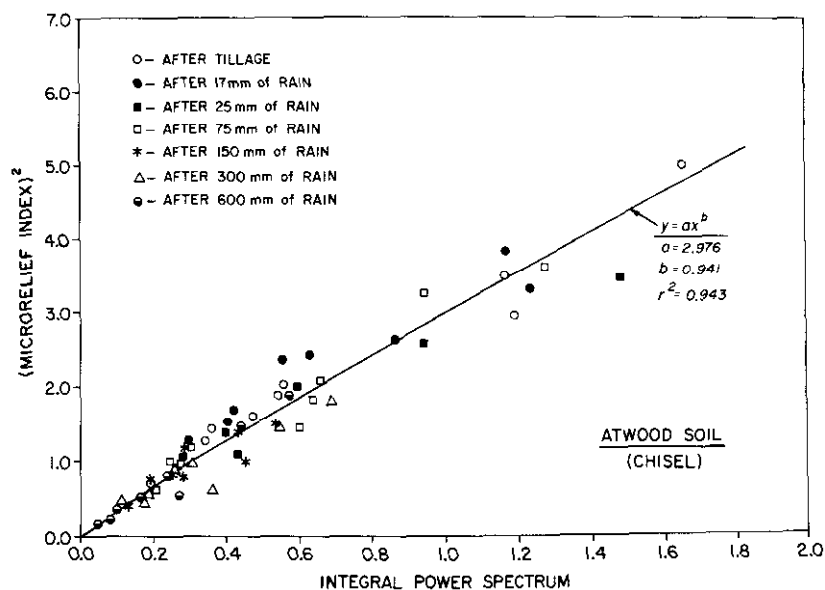


Figure 2. Relationship between the integral of the power spectrum (Equation [3]) and the quadratic term of the microrelief index A (Equation [2]) for several transects following different applications of rain.

spatially independent transects taken on a chiseled plot (Römkens and Wang, 1985b). The quadratic form of A in Figure 2 was chosen to agree with its conceptual equivalence $a(f)$. Both terms represent an amplitude. A represents an "average", single-valued amplitude, whereas $a(f)$ is the amplitude for each frequency f . Table 1 summarizes the various roughness indices for a number of transects on a chiseled plot following 75 mm of rain. The values show considerable variability between transects for each index and high correlation coefficients between indices.

ROUGHNESS MEASURING DEVICES

Several types of devices for evaluating soil surface roughness, often called microrelief meters, have been developed. Although photogrammetry principles could be employed, most roughness measuring devices are microrelief meters, which are based on contact measurements with one or more probes touching the soil surface. The most advanced microrelief meters of this type are those by Podmore and Huggins (1981) with one probe and by Radke et al. (1981) with a multitude of probes. These meters are highly automated, accurate, rapid, and have a high rate of point measurements. However, their usefulness in soil erosion research may be limited due to probe penetration into soft soil or clod breakdown upon probe contact. To avoid these complications, Römkens et al. (1985) designed a noncontact profile meter. Its principle of operation is based on sensing the soil surface at close range (15-20 mm) with an optical probe, which scans the soil surface in predetermined transects. This profile meter is less accurate than contact probe type meters because of hysteresis effects. Recently, a laser-microrelief meter was developed capable of profiling 2.5-m long transects at a high data acquisition rate (>25 points per second) and density (> 1 set of coordinates per mm), with an elevation accuracy of at least 0.25 mm¹. This profile meter, shown in Figure 3, permits detailed observations and facilitates an in-depth analysis of soil redistribution following rainfall. An example of part of a laser-beam-measured transect is given in Figure 4. The data points, obtained in a forward (Transect I) and backward (Transect II) direction, indicate a high degree of reproducibility.

ROUGHNESS MEASUREMENTS AND SOIL REDISTRIBUTION

Measurements of surface elevations have focused on the evaluations of total porosity (Burwell et al., 1963; Allmaras et al., 1966), surface storage (Mitchell and Jones, 1976; Onstad, 1983) and soil erosion (Dexter, 1977; Römkens and Wang, 1985b). Dexter (1977) observed a linear decrease in the variance, σ^2 , of the measured surface elevations with cumulative rainfall energy, E , following the incidence of four natural rainstorms of different rainstorm energy rates and intensities. His relationship

$$\sigma^2 = A - B E \quad [4]$$

varied for different tillage systems. The results showed appreciable differences between the observed and predicted values according to equation

¹Unpublished data M. J. M. Römkens, USDA National Sedimentation Laboratory, Oxford, MS.

Table 1. Roughness indices for spatially independent transects on a chiseled Atwood soil following 75 mm of rain.

Transect	Roughness Parameters		
	R_k (Equation [1])	R_r (Equation [2])	R_p (Equation [3])
1	13.40	0.264	0.292
2	10.39	0.346	0.254
3	6.58	0.287	0.213
4	7.17	0.279	0.219
5	20.30	0.368	0.401
6	33.85	0.428	0.749
7	29.36	0.376	0.609
8	38.88	0.478	0.944
9	48.37	0.599	1.462
10	26.57	0.377	0.536
11	41.29	0.455	1.055
Average	25.11	0.387	0.612
St. Deviation	14.60	0.099	0.405
Coeff. of Var.	58.2	25.6	66.2

Correlation coefficients: $r(R_r \text{ vs } R_k) = 0.932$; $r(R_r \text{ vs } R_p) = 0.963$; $r(R_k \text{ vs } R_p) = 0.964$.

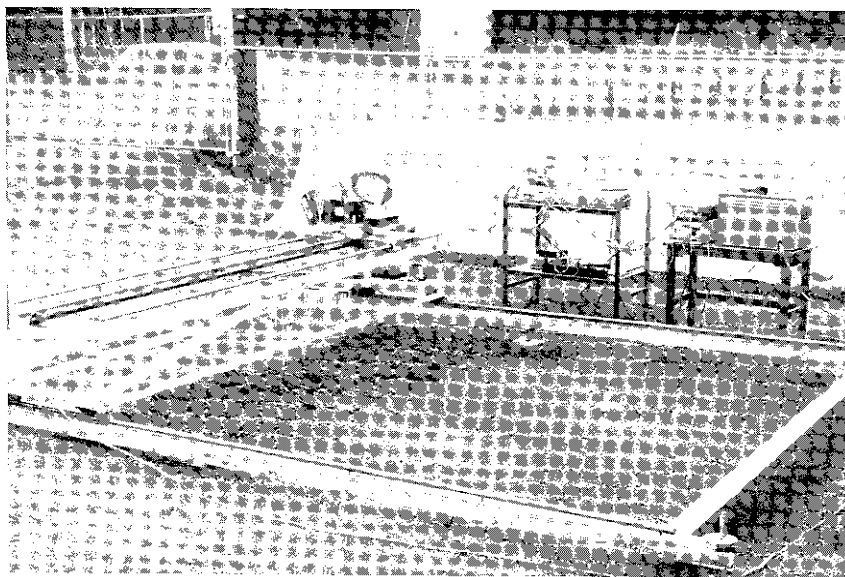


Figure 3. A laser-microrelief meter for measuring surface roughness.

[4]. These differences were presumably variations due to the selection of transects on different parts of the plot surface following each storm. A similar study by Römken and Wang (1985b), in which surface roughness estimates were based on spatially independent transects, indicated that surface roughness could be described as a function of the cumulative rainfall, r , according to either of two relationships:

$$R_r = a + b \cdot \exp(-c \cdot r) \quad [5a]$$

$$R_r = \frac{1}{d + e \cdot r} \quad [5b]$$

where a , b , c , d , and e are constants. Equation [5a] was obtained for an Atwood soil (Römken and Wang, 1985b) and equation [5b] for Cascilla soil (Römken and Wang, 1985a).

Surface roughness values, R_r , were computed following the application of each of a number of simulated rainstorms of increasing duration, having a constant rainfall intensity and energy rate. Figure 5 shows relationship [5a] for different tillage practices. The rapid decrease in roughness during the early part of this study ($0 < r < 150\text{mm}$) may primarily be attributed to (1) the breakdown and sloughing of soil clods upon wetting during a rainstorm and (2) the consolidation of loosely tilled soil during the drying phase following rainfall. Of course, some soil redistribution by raindrop impact takes place during this stage of the process, but the relative contribution to changes in soil elevation at a given location is primarily the result of consolidation effects by sloughing and matric changes by drying. On the other hand, soil redistribution by raindrop impact and splash dominates changes in surface elevation during the latter part of the storm ($r > 150\text{mm}$). Although both relationships [5] indicate a gradual decrease in surface roughness for $r > 150\text{mm}$, the actual data points following 3, 6, and 12 hours of rainfall suggest slightly larger soil redistribution rates than those indicated by equation [5a]. However, the number of observations are too limited for definitive conclusions. These elevation measurements were obtained with a noncontact microrelief meter (Römken et al., 1985) with limited elevation accuracy (2-3 mm). It is anticipated that similar measurements with the laser-microrelief meter will yield more detailed and accurate information relative to the size, location and distribution of sediment source and deposition areas.

RESEARCH NEEDS AND PLANS

Recent developments in the application of laser mensuration techniques to soil surface measurements have substantially improved our capabilities of studying soil redistribution processes on upland areas. Of particular interest is the ability to identify and quantify areas of sediment sources and deposition. This type of information provides a better basis for describing and quantifying soil erosion and sediment movement on upland areas, improving prediction models, and ultimately developing process based soil management techniques. Several specific research areas come to mind:

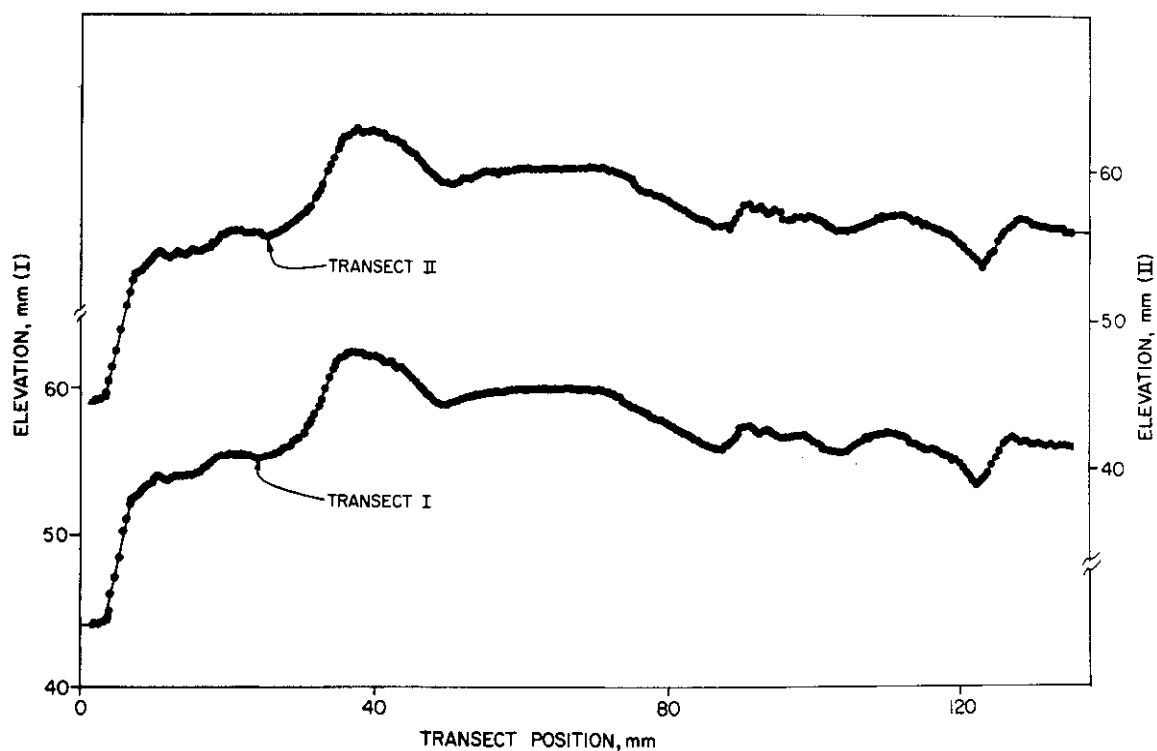


Figure 4. Measured surface elevations in forward and backward direction with the laser-microrelief meter.

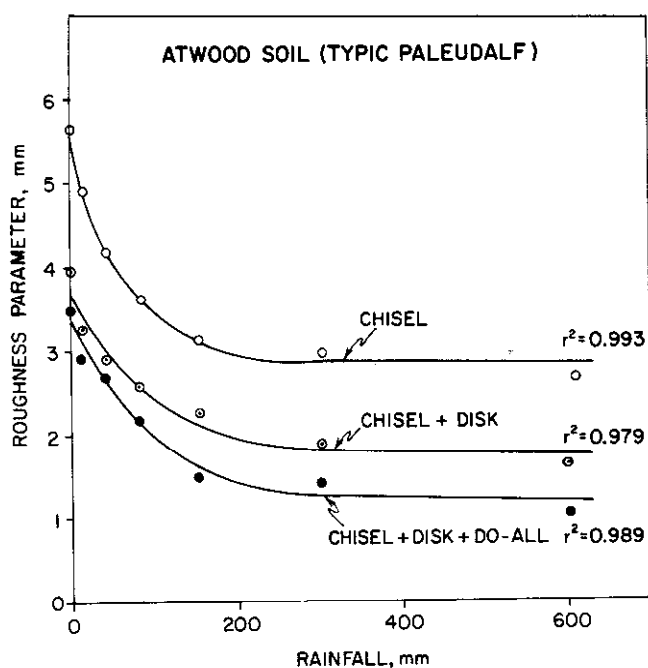


Figure 5. The relationship between the roughness parameter R_r and the cumulative rainfall r .

1. The effect of soil and antecedent soil surface conditions on changes in the soil surface by different erosion processes, e.g. rainfall and surface flow. Studies of this type provide a better insight into the effect of soil type and soil properties on soil erodibilities by different erosion mechanisms. They also permit differentiation between soil erosion factors which are intrinsic in nature and those that are man-induced by management practices.
2. The influence of different rainstorm and surface flow characteristics and regimes on soil detachment, transport and deposition. Variations in storm and flow regimes invariably affect soil erosion processes differently. Detailed and refined studies of changes in surface elevations and configuration will greatly improve our insight and ability to quantify soil erosion and sediment movement for different storm and flow regimes. Very little attention has been given to this aspect of soil erosion processes.
3. The relationship between surface storage and surface roughness, both of the periodic and non-periodic type. Such relationship, if present, will greatly complement existing knowledge in surface hydrology. Of particular interest will be how soil erosion rates and surface storage functions are affected by frequency and amplitude of surface elevations.
4. The effect of surface roughness on runoff velocity. Roughness modifies slope gradients and hence flow velocities. A relationship is needed to relate roughness to the reduction in the effective gradient.

Of specific interest in future work will be a further examination of the integral of the power spectrum as a measure of surface roughness and the power spectrum as an indicator of surface water storage and soil erosion rates.

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SEDIMENT YIELD FROM SMALL AND MEDIUM WATERSHEDS

By C. D. Clarke, geologist, Soil Conservation Service (SCS), Washington, D.C.; and P. G. Waldo, geologist, Soil Conservation Service, Fort Worth, Texas.

ABSTRACT

Hillside slope morphology and surface roughness affect the transport efficiency of overland flow. The slope configuration method quantifies the effects of downslope changes and predicts average annual erosion and sediment yield to low order channels within fields. A modification of the complex slope version of the Universal Soil Loss Equation (USLE) estimates sheet and rill erosion. Transport efficiency, or Sediment Delivery Ratio (SDR), is computed from representative overland profiles. The method predicts sediment yields from sheet and rill erosion in small watersheds (less than 10 mi²).

Sediment transport efficiency in medium-sized (0.1 to 1,000 mi²) watersheds depends both on hillside morphology and on characteristics of the stream channel system. Methods for estimating channel transport efficiency vary, depending on data available and the degree of accuracy desired. Direct methods require stream gage or reservoir survey data. The accounting method uses field and photogrammetric mapping techniques to identify and quantify the effects of sediment traps or sinks. A predictive method depends on the relationship established between SDR and drainage area. The methods apply to a variety of small and medium-sized watersheds.

SMALL AND MEDIUM WATERSHEDS

This study classifies watersheds as small, medium, and large, based on geomorphic characteristics that influence sediment transport efficiency (Waldo, 1983; 1985a). In the humid eastern United States, small watersheds tend to vary up to about 10 sq mi in size. Medium watersheds range from about 0.1 to 1,000 sq mi, and large watersheds (Waldo, 1986) are greater than 100 sq mi. The boundaries between the three size classes overlap because characteristics which control sediment transport efficiency vary both within and between regions. Variables such as climate, relief, lithology, sediment load, landform, land use, vegetation, tectonic activity, and geomorphic history influence the efficiency of a given channel network to transport sediment.

Hillside morphology and surficial roughness characteristics control the efficiency of small watersheds to deliver eroded sediments to their mouths. The sediment yield to the mouth of a small watershed approximately equals the amount of sediment delivered from the hillsides to the main channel, assuming the channel is in dynamic equilibrium as defined by Hack (1960), Leopold et al. (1964), and Schumm et al. (1984). The main channel occupies a narrow valley with very little alluvial floodplain. Channel sinuosity approaches a value of 1.0, especially when observed at a map scale of 1:24,000 or smaller.

Sediment yield from a medium watershed depends both on hillside morphology and the efficiency of the principal channels to transport sediment. Sediment discharge at the mouth of a medium watershed is proportional, but not equal, to gross erosion, assuming dynamic equilibrium in the channels. Significant

alluvial deposits occur in the lower reaches, and sinuosity values of the principal channels significantly exceed 1.0.

THRESHOLD DRAINAGE AREA

The distinction between small and medium watersheds within a given geomorphic region implies the existence of a unique drainage area, or narrow range of areas, which marks the division between these two classes. This definitive value of drainage area is referred to here as the threshold drainage area. The existence of a threshold drainage area will be examined by three approaches in this paper: hydrologic considerations (Leopold et al., 1964), stream order analysis (Horton, 1945; Leopold et al., 1964; Waldo, 1985b), and field identification.

In developing their hydrologic arguments, Leopold et al. (1964) noted that discharges of a particular recurrence interval correlate as power functions to drainage areas above the points of measurement. They found that the values of the exponents in the resulting equations varied within narrow limits throughout humid regions of the United States. The exponent m (mean annual flow) averages about 1.0, and b (bankfull discharge) about 0.75. Specifically,

$$q_m = k_m A^m$$

$$q_b = k_b A^b$$

where A = drainage area, sq mi; q_m = mean annual discharge, cfs; q_b = bankfull discharge, cfs; and k_m and k_b constants which vary between geomorphic regions. Leopold et al. (1964) attribute the difference between the exponents to loss of water to floodplain storage during flood stages.

If the threshold drainage area indeed exists in nature, then the above discussion applies to medium and large watersheds. The threshold area represents the size of watershed at which significant friction loss to overbank flow commences. Watersheds smaller than the threshold possess no appreciable floodplain area. Assuming that such relatively small watersheds have ephemeral flow, the channel form will be adjusted to the average runoff event if in dynamic equilibrium. Since flow endures for relatively short periods, bankfull discharge approximately equals mean annual discharge, excluding periods of no flow. Therefore,

$$\frac{q_b}{q_m} = \frac{k_b}{k_m A} = 1.0$$

which defines a hypothetical condition of no friction loss to floodplains.

Rearranging terms,

$$A^b/A^m = k_m/k_b$$

$$A^{(b-m)} = k_m/k_b$$

and
$$A_t = (k_m/k_b)^{1/(b-m)}$$

where A_t = threshold drainage area in sq. mi.

Stream order analysis consists of the systematic study of the hierarchical order among the constituent channels of the drainage network (Horton, 1945; Leopold et al., 1964; Schumm et al., 1984; Waldo, 1985b). Mean values of drainage area, channel length and gradient, valley length and gradient, and other parameters are correlated to stream order number, and define the stream order laws. Characteristics descriptive of the threshold drainage area, such as sinuosity, ratio of valley bottom width to channel top width at the watershed mouth, and presence of floodplain or alluvial fan deposits, may be correlated to stream order during the analysis. It is therefore possible to estimate the drainage area of the threshold watershed by the stream order laws.

Field identification consists of following selected channels downstream until encountering a recognizable sediment sink or trap. The drainage area above this point is determined. Several such determinations define the mean and range of values of the threshold drainage area. Features that serve as sediment traps include upper ends of alluvial fans and floodplains, ponds, swamps, restrictive culverts and bridges, embankments, kettles, sinkholes, log jams, and beaver dams. Pronounced downstream decreases in channel gradient and changes from straight to sinuous planforms are other indicators of long-term sediment storage. Aerial photographs, topographic, and surficial geologic maps of sufficient resolution assist in the field identification of threshold drainage areas.

The above techniques were applied to the Raccoon Creek Watershed, a medium watershed of about 52 sq mi in Marion County, southern Illinois. The table below reports the results of the threshold drainage area determinations, in sq mi.

method	minimum	mean	maximum
hydrologic	- -	1.1	- -
stream order analysis	0.2	0.7	0.85
field identification	0.02	0.16	0.23

The hydrologic determination relied on equations presented in Fitzgerald et al. (1983) relating mean annual and the 7-day, 10-year-high flows to drainage area in the nearby Kaskaskia River basin. Manipulations of these equations and those in Curtis (1977) to represent more frequent flood events produce results which differ little from the 1.1 sq mi value. The value exceeds those determined by the other methods, because the hydrologic method accounts only for friction losses to the floodplain during flood stages. It does not accommodate friction losses to the channel bed and banks, or to sediment entrained in the flow.

Stream order analysis provides a measure of threshold drainage area for conditions relatively unmodified by man. Natural watersheds can generally be divided into zones of active incision, sediment transportation, and deposition (Schumm et al., 1984). The greater number of low order channels tends to concentrate in the zone of incision (Waldo, 1985b). The stream order technique identifies the lower order tributaries most efficient at sediment production, and it may be verified by geomorphic mapping of the watershed zones.

Agricultural activities have extensively modified the drainage characteristics of Raccoon Creek watershed. Numerous ponds and farm and county road crossings obstruct the small, formerly erosional channels. Disruption of the natural ground cover on cropland dramatically increases sediment loads. Therefore, the field identification method provides the best estimate of the threshold drainage area existing at the present time.

SEDIMENT YIELD FROM SMALL WATERSHEDS

The overland transport and deposition of sediment is highly dependent on the slope characteristics which influence the velocity of surface runoff. Slope angle, roughness, and depth of flow are the principal factors influencing the velocity of overland flow. For simplicity, the slope configuration method depends on the assumption that depth of overland flow for a given runoff event remains constant along a given slope profile. Slope and roughness remain as the influencing variables. Boyce (1981) used cover (C) and support practice (P) factors of the USLE (Wischmeier and Smith, 1978) to represent roughness in his procedure known as CELLS. The C and P factors were chosen in this procedure also. The concept employed in both CELLS and this method assumes that a downslope reduction in slope angle, C value, or P value is accompanied by a proportionate reduction in transport capacity, and that deposition is inversely proportional to the transport capacity.

The procedure evaluates cumulative changes along overland flow paths (profiles) which are selected to represent geomorphic zones or watershed subareas. The amount of sediment influenced by a downslope reduction in a transport factor value is proportional to the length of profile and the erosion rate(s) upslope from the point where deposition occurs.

The effect of landform is governed by downslope changes in slope gradient. A slope with no change in gradient or increasing gradient is considered to have no deposition resulting from slope characteristics. The effects of roughness irregularities are expressed by the ratio of downslope C and P values to upslope C and P values. Increases or no changes in these values in the downslope direction would indicate no deposition resulting from roughness characteristics, and the ratios are interpreted to have a value of 1.0.

Downslope changes in gradient and roughness are collectively referred to as transport efficiencies, expressed as the ratios P_d/P_u , C_d/C_u , S_d/S_u at points where values of these ratios are less than 1.0. The subscripts d and u indicate slope segments immediately downslope and immediately upslope from deposition points, respectively.

Watershed subareas or zones should be mapped according to sets of geologic, geomorphic, land use, and land management characteristics. Consideration should be given to soils, slope steepness and length, positions of gradient change on the landscape, concavity, convexity, and patterns of land use, management, and treatment. Some watersheds do not require zoning because of the uniformity of physical and cultural characteristics. In many cases, surficial geology forms the basis for zoning, because it is manifested in the soils, slope morphology, and land uses.

Sample profiles are selected to represent each zone. Level surveys along each profile are performed. If the sets of topographic and cover characteristics of the zone are consistent, one or two profiles are sufficient. The profiles are to be aligned in the direction of overland flow and therefore will be perpendicular to contour lines and usually will not be straight lines in map view. Each profile begins at the point where overland runoff commences and ends where it enters a well defined concentrated flow path.

Points where reductions in slope gradient, C, or P occur (Fig. 1) are referred to as "deposition points." Essential data for application of the procedure are steepness of slope, C, P, total profile length(s), and the segment and slope lengths for each segment on the profile(s) (Fig. 2). Slope length, slope gradient, and C and P values are determined in accordance with Agriculture Handbook 537 (Wischmeier and Smith, 1978). A "P" factor value of 1.0 is used for contour farming without terraces.

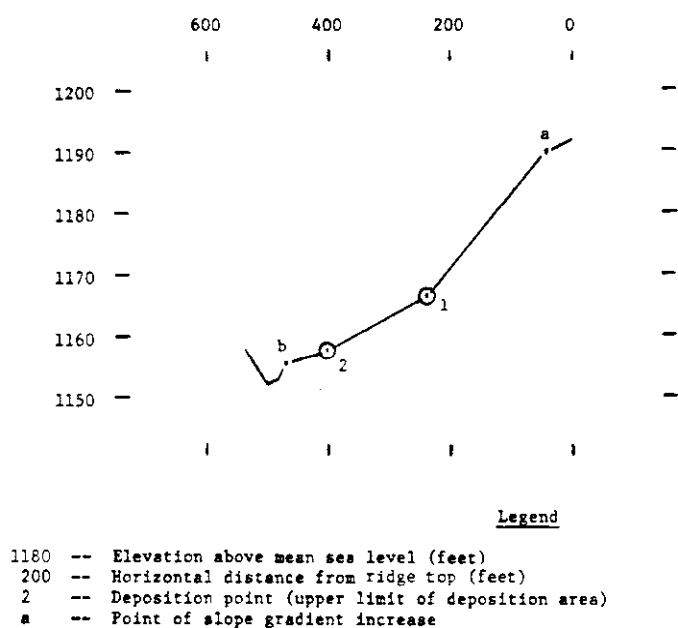


Fig. 1. Representative profile of hillside slope in Treynor Research Watershed No. 1 near Treynor, Iowa. Data provided by Agricultural Research Service, Council Bluffs, Iowa (R. G. Spomer, personal communication, 1982).

(1) Profile Point on Fig. 1	(2) Upslope Segment Length in feet (l_u)	(3) Cumulative Slope Length in feet	(4) Segment Length as a Proportion of Total Profile Length $\left(\frac{l_u}{l_t}\right)$	(5) Seg. Slope Angle, λ	Universal Soil Loss Equation				
					(6) * LS	(7) C	(8) P	(9) ** RK	(10) *** Soil Loss in tons/ ac./yr (A_i)
a	45	45	.10	4	0.3	0.3	1.0	51	4.6
1	190	235	.42	14	3.4	0.3	1.0	51	52.0
2	150	385	.33	6	1.3	0.3	1.0	51	19.9
b	<u>70</u>	455	<u>.15</u>	3	0.5	0.3	1.0	51	<u>7.7</u>
$l_t = 455$					1.00			**** $A_w = 30.0$	

Fig. 2. Data necessary to sediment delivery ratio determination for the profile in Fig. 1. Data provided by the Agricultural Research Service, Council Bluffs, Iowa (R. G. Spomer, personal communication). * LS values determined after Wischmeier and Smith (1978) using cumulative slope length in column (3) and segment slope angle in column (5). ** Rainfall factor (R) = 160 and soil erodibility factor (K) = 0.32 for Treynor No. 1 Watershed, therefore RK = 51. *** Column (10) values = (6) x (7) x (8) x (9). **** A_w , the weighted average annual soil loss for the total profile, consists of the sum of the products of the values in columns (4) and (10).

The following equation is used to estimate average annual sediment delivery ratio for each sample subwatershed by the slope configuration method.

$$SDR_t = \frac{\sum_{i=1}^n \left(A_i \times \frac{l_{ui}}{l_t} \times SDR_i \right)}{A_w}$$

where

SDR_t = average annual sediment delivery ratio (total profile)

A_w = weighted average annual soil loss for total profile, tons/acre/year
(Fig. 2)

A_i = soil loss rate for a given slope segment, tons/acre/year

l_{ui} = segment length along the profile occurring upslope from a given point,
ft

l_t = total length of profile, ft

SDR_i = sediment delivery ratio for length of profile occurring upslope from a
given point

SDR for each segment is the product of transport efficiencies at all
deposition points occurring between the segment and a channel.

For example, the SDR for point a on Fig. 1 is computed as

$$SDR_a = \frac{S_{d1}}{S_{u1}} \times \frac{S_{d2}}{S_{u2}} = \frac{6}{14} \times \frac{3}{6} = 0.21$$

Changes in P which are not associated with changes in support practices are ignored. For example, this procedure does not recognize a reduction in P caused only by a change in slope gradient, because such changes are accounted for by

S_d/S_u ratios. Term l_u/l_t indicates the proportion of the profile length influenced by a downslope reduction in slope steepness, C factor, or P factor.

The total sediment delivery ratio, SDR_t , for the profile in Fig. 1 is computed as

$$SDR_t = \frac{(4.6 \times 0.1 \times 0.21) + (52.0 \times 0.42 \times 0.21) + (19.9 \times 0.33 \times 0.5) + (7.7 \times 0.15 \times 1.0)}{30} \\ = 9.1/30 = 0.30$$

The numerator is the rate of sediment yield at the downslope end of the profile, and the denominator is the weighted average annual soil loss rate (Fig. 2).

Sediment yields from sheet and rill erosion in small watersheds may be predicted from the weighted average of representative profiles. Some studies in the midwestern United States have successfully employed this technique (Davenport, 1983; 1984; SCS, 1983a).

SEDIMENT YIELDS FROM MEDIUM WATERSHEDS

Computing sediment yields from hillsides to the lower order channels constitutes the first step in estimating sediment yields from medium watersheds (Clarke, 1983). The results are then multiplied by a routing factor to accommodate transport inefficiencies in the principal channels. The channel routing factor may be determined by either the direct, the accounting, or the predictive method.

The direct method requires measurements of sediment discharged to the watershed mouth in addition to estimates of sediment yields from the hillsides. Reservoir sediment surveys or stream gages with sediment discharge data provide the necessary results. The routing factor is computed by dividing the measured sediment yield by the predicted yield to the lower order channels. The routing factor may be applied to other watersheds of similar stream order number, climate, geomorphology, and land use. If sufficient data from reservoir surveys or stream gages exist within a given geomorphic region, the data may be extrapolated to other watersheds by statistical methods of correlation and regression analysis.

The accounting method relies upon the field identification of sediment sinks. The trap efficiencies of features such as natural and man-made impoundments, swamps, floodplains, sinkholes, and kettles are estimated by existing techniques (SCS, 1975; 1983b). Subtracting the amount of sediment trapped in the sinks from the total yield predicted to the lower order channels (Clarke, 1983) determines the sediment yield to the mouth of the watershed. The channel routing factor may then be computed, and applied to similar watersheds.

Predictive methods provide a channel routing factor with little inconvenience to the user. Although several approaches are possible, the one presented here depends on the well established relationship between sediment delivery ratio and drainage area (SCS, 1973; 1983b; Waldo, 1983; 1985a). The channel routing factor is considered as a function of both threshold and total drainage area, and the mean curve drawn through the SDR versus drainage area data (see Fig. 6-2, SCS, 1983b) is recomputed as a family of curves for various values of threshold area (Fig. 3).

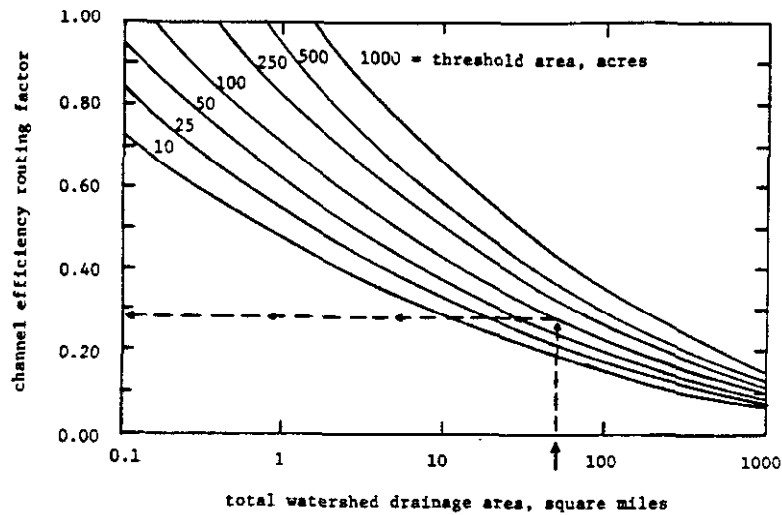


Fig. 3. Channel efficiency routing factor as a function of total watershed drainage area and mean threshold drainage area within the watershed. Dashed lines indicate determination of the channel efficiency routing factor for the 52 sq mi Raccoon Creek watershed in southern Illinois, assuming a threshold drainage area of 100 ac (0.16 sq mi).

The table below summarizes determinations of the channel routing factor for the Raccoon Creek watershed in southern Illinois.

method	channel routing factor
direct	0.25
accounting	0.30
predictive (Fig. 3)	0.28

Data used in the direct method were obtained from field determinations (SCS, 1983a) of sediment yields to lower order channels (Clarke, 1983), and reservoir sediment surveys (Illinois State Water Survey, 1979). J. Wallace (personal communication, 1983) of SCS provided data used in the accounting method.

DISCUSSION

The slope configuration method (Clarke, 1983) accounts for the effects of hillside morphology and surficial roughness distribution on sheet and rill erosion as computed by the USLE (Wischmeier and Smith, 1978). The method identifies zones of deposition on the hillside, and predicts sediment yield from sheet and rill erosion to low order channels.

Other applications include ranking hillsides according to their relative contribution to watershed sediment yields. The most significant contributors may be selected for conservation treatment in order to reduce the downstream effects of sediment derived from sheet and rill erosion. The effects of proposed treatment measures may be estimated by applying the equation to the predicted hillside configuration and roughness distribution.

The method predicts sediment yields from sheet and rill erosion in small watersheds. These predictions provide information for designing sediment

storage requirements of practices such as farm ponds, terraces, and debris basins. The method estimates the effectiveness of vegetative filter strips in reducing the sediment yields from small watersheds.

A potential application of the slope configuration method consists of simulating the mass transfer of soil on sloping cropland. Denudation rates may be approximated for the various hillside segments, and related to the soil profile. Crop productivity may then be associated with zones of present and past rates of erosion and deposition.

The direct, accounting, and predictive methods provide estimates of the trap efficiency of principal channels in medium watersheds. The direct method appears to be the most accurate but requires particular types of data that are frequently unavailable. The accounting method requires time for field reconnaissance and mapping, the amount depending on the degree of sophistication desired. The predictive method provides relatively quick answers but is subject to uncertainty.

Both the accounting and predictive methods may be applied to several subwatersheds within a larger watershed with little increase in the amount of time or field effort. The direct method is not readily amenable to this, unless an adequate data base exists within the geomorphic region of interest.

The use of a channel routing factor in combination with the slope configuration method (Clarke, 1983) permits the estimation of sediment yields from medium watersheds. The results may be used in designing sediment storage requirements of reservoirs. The methods apply to subwatersheds within the drainage area of interest and delineate the relative contribution of each subwatershed to the total yield. Therefore, the methods may be applied to problems such as quantifying the downstream effects of sediment derived from sheet and rill erosion and identifying critical sediment sources for conservation treatment.

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EPHEMERAL GULLY EROSION

By J. M. Laflen, Agricultural Engineer, U. S. Department of Agriculture, Agricultural Research Service, Ames, Iowa; D.A. Watson, Assistant Professor, Agricultural Engineering Department, Iowa State University, Ames, Iowa; and T. G. Franti, Graduate Research Assistant, Agricultural Engineering Department, Iowa State University, Ames, Iowa.

ABSTRACT

Ephemeral gully erosion is a form of erosion caused by concentrated flow in small channels that are routinely destroyed by tillage. Erosion in these channels is not predicted by the Universal Soil Loss Equation and is not accounted for in current soil loss assessment programs. Ephemeral gully erosion can be very significant, and its magnitude depends on many factors. Ephemeral gully erosion can exceed 25% of the erosion predicted by the Universal Soil Loss Equation, and, because it is a flow related phenomena, tends to be much greater in areas where surface runoff is great. While our ability to predict erosion in ephemeral gullies has not been adequately tested, a few theoretical and empirical approaches have been advanced. Two critical needs for improving predictions of ephemeral gully erosion rates are better values for the process coefficients for a range of soil conditions and a better understanding of the erosive process itself. There is an array of practices available that may be used on most cropland to control the formation of, and the erosion in, ephemeral gullies.

INTRODUCTION

Ephemeral gully erosion is a sediment source that is presently not accounted for in estimating soil erosion occurring on a watershed. Estimates of soil erosion on a field are presently made using the Universal Soil Loss Equation (Wischmeier and Smith, 1978) for sheet and rill erosion, but these estimates do not include the soil loss associated with erosion within the small channels that carry excess rainfall from watersheds. These small channels, when eroding, are called ephemeral gullies. The failure to include soil erosion within these channels can lead to significant underestimates of soil erosion's severity. Also, when estimates of gross soil erosion are used to develop sediment delivery ratios, and the soil loss estimates do not include the contribution of ephemeral gully erosion, sediment delivery ratios can be seriously overestimated.

The objectives of this paper are to describe the characteristics of ephemeral gullies, to evaluate the available data indicating the severity of ephemeral gully erosion, to describe the process of erosion in ephemeral gullies, and to discuss measures for controlling ephemeral gully growth.

CHARACTERISTICS OF EPHEMERAL GULLIES

"Ephemeral" is something that is transient, lasting only a short time. An ephemeral gully is a landscape feature that lasts only a short time—a small channel (usually in a natural drainageway) in a farm field that carries surface runoff and is eroded most years. These channels are filled with soil and effectively obliterated by conventional tillage. Consequently, to be considered ephemeral gullies, the channels must be shallow enough to be crossed with farm equipment during normal farming operations. Hence, they are ephemeral in the sense that they are identifiable for only a short time. While ephemeral gullies usually occur in or near areas subject to tillage, they can also be found in vegetated areas where they tend to remain unnoticed for some time after they form. Obviously, the field identification of ephemeral gullies is somewhat subjective.

In Table 1 are given a set of comparative characteristics of ephemeral gully erosion, sheet and rill erosion, and classical gully erosion. Most of these were identified by Foster et al (1984). While ephemeral gullies do reform in the same places year after year and may eventually lead to gullies that cannot be crossed with farm equipment and thereby become a permanent feature of the landscape, the primary distinguishing feature of ephemeral gullies is their temporary nature.

The Universal Soil Loss Equation does not predict this type of erosion because ephemeral gully erosion is caused by flowing water only, and does not have a component due to raindrop impact. Erosion in an ephemeral gully is due to detachment of channel material by flowing water, sloughing of channel sides and by a headcutting process, none of which are included specifically in the Universal Soil Loss Equation. While the rill component of the sheet and rill erosion predicted by the Universal Soil Loss Equation is in some cases very similar to erosion in an ephemeral gully, the flow rates, headcutting and bank sloughing in an ephemeral gully do not occur in rill erosion.

SIGNIFICANCE OF EPHEMERAL GULLY EROSION

There is considerable work underway to determine the extent and severity of ephemeral gully erosion. Almost every farm field has a number of channels to carry excess runoff to field outlets. The steeper the slope and the greater the runoff to be transported, the greater the potential for erosion in these small channels.

The magnitude of the energy losses associated with surface runoff can be compared to the energy losses when rainfall strikes the soil surface. Rainfall energy is used to detach and transport sediment and to compact the soil surface. Runoff energy is used to overcome friction and to detach and transport sediment. The kinetic energy of rainfall is usually considerably greater than the energy loss in surface runoff on a field, depending on the slope of the land surface, and the fraction of rainfall that becomes surface runoff. However, the energy of rainfall is dissipated over an entire field, while the energy loss in concentrated flow channels occurs in a very small area. The energy loss per unit of area impacted can be as high in an ephemeral gully as it is in rainfall.

Table 1. Characteristics of different types of erosion

Sheet And Rill Erosion	Ephemeral Gully Erosion	Gully Erosion
Occurs on smooth side slopes above drainage-ways.	Occurs along shallow drain-aways upstream from incised channels or gullies.	Generally occur in well defined drainageways.
May be of any size but are usually smaller than concentrated flow channels,	May be of any size but are usually larger than rills and smaller than permanent gullies.	Usually larger than concentrated flow channels and rills.
Flow pattern develops many small disconnected parallel channels which end at concentrated flow channels, terrace channels, or in depositional areas.	Usually forms a dendritic pattern along water courses beginning where overland flows, including rills, converge. Flow patterns influenced by tillage, rows terraces, man made features.	Dendritic pattern along natural water courses. May occur in non-dendritic patterns in road ditches, terrace or diversion channels, etc.
Rill cross-sections usually are narrow relative to depth.	Cross-sections usually are wide relative to depth. Sidewalls not well defined.	Cross-sections usually narrow relative to depth. Sidewalls are steep.
	Headcuts not readily visible; do not become prominent because of tillage.	Headcut prominent. Eroding channel advances upstream.
Rills normally removed by tillage, usually do not reoccur in the same place.	Temporary feature, usually removed by tillage; reoccur in same place.	Not removed by tillage.
Soil removed in thin layers or shallow channels. Soil profile becomes thinner over entire slope.	Soil removed along narrow flow path, to tillage depth if untilled layer is resistant to erosion, or deeper if untilled layer is less resistant.	Soil may erode to depth of profile, and can erode into soft bedrock.
Low erosion rates not readily visible.	Area may or may not be visibly eroding.	Erosion readily visible.
Detachment and transport by raindrops and flowing water.	Detachment and transport by flowing water only.	Detachment by flowing water and slumping of unstable banks; transport by flowing water.

Table 2. Data on soil erosion in ephemeral gullies.

Location	Estimated Annual Sheet and Rill Erosion*	Measured Ephemeral Gully Erosion	Ratio Ephemeral	Comments
	t/ha	t/ha	Sheet-Rill	
Pottawattamie county, Iowa	74.6	18.2	0.25	SCS unpublished survey data. Loess soil. Slopes 3-11%. 8 ha.
Boone county, Iowa	19.3	4.7	0.24	SCS unpublished survey data. Glacial till soil. Slopes 2%. 4 ha.
Wiregrass, Alabama	13.4	19.7	1.47	SCS Data(Miller, 1982) Soil from hydrologic group A.
Wiregrass, Alabama	35.9	35.9	1.00	SCS data(Miller, 1982) Soil from hydrologic group B.
Treynor, Iowa	3.8**	2.0	0.53	Spomer and Hjelmfelt (1985). Conservation tillage, cont. corn on contour. Loess soil. Steep slopes. 43 ha.
Treynor, Iowa	59.6***	17.0	0.29	Spomer and Hjelmfelt (1985). Conventional tillage, cont. corn on contour. Loess soil. Steep slopes. 24 ha.

*Estimated using the Universal Soil Loss Equation(Wischmeier and Smith, 1978)

**Estimated soil loss is the average sediment yield 1972-1983 divided by a
delivery ratio of .53(Spomer and Mahurin, 1984).

***Estimated soil loss is the average sediment yield 1964-1983 divided by a
delivery ratio of .53(Spomer and Mahurin, 1984).

Much of the available soil loss data from ephemeral gully erosion studies is given in table 2. Data are very limited, but there is a major effort underway to collect information that will provide a perspective on the national significance of the problem. The data available seems to indicate that ephemeral gully erosion is a major source of eroded sediment.

Spomer and Hjelmfelt(1985) reported soil loss measurements for a research watershed near Treynor, Iowa. The site was similar to the Pottawattamie county site, on a deep loess soil with an appreciable slope. While there is a considerable body of data from the Treynor, Iowa site, measurements of ephemeral gully erosion were made only in 1984. Spomer and Hjelmfelt (1985) indicated that more ephemeral gully erosion occurred in 1984 than is usual; sheet and rill erosion was judged to have been near to or above average. Their results would indicate that ephemeral gully erosion is from 25 to 50% of the average measured long term erosion. Spomer and Hjelmfelt also reported that surface runoff was about 14% of annual precipitation for the conventionally tilled watershed and only about 4% of precipitation for the conservation tilled watershed for the 1972-83 period.

The Boone County site in Iowa has a much flatter slope than the Pottawattamie County site. The soils at the two sites also differ appreciably. Yet, the ratio of ephemeral gully erosion to estimates of average annual soil erosion are quite similar for both Iowa sites. This could be a coincidence, or it could be because the sites are in similar climatic regions and grew similar crops. Runoff volumes, expressed as a fraction of rainfall, would be expected to be somewhat greater than those reported by Spomer and Hjelmfelt(1985).

Compared with the Iowa sites, the Alabama sites show a much higher ratio of ephemeral gully erosion to soil erosion estimated using the Universal Soil Loss Equation. While the data for all sites are very limited, one would expect the ratio to be higher in regions where runoff is a greater proportion of rainfall. In Alabama, surface runoff is usually much greater, in terms of percentage of precipitation, than it is in Iowa. For example, Murphree and Mutchler(1981) reported surface runoff of about 40% of precipitation for a flatland watershed in Mississippi and McGregor and Greer(1982) reported runoff percentages of about 30% for a conventionally tilled plot in Mississippi.

The very limited amount of field data available indicates that soil erosion in ephemeral gullies is a substantial fraction of that expected from sheet and rill erosion. A failure to include this component of soil loss in many studies aimed at estimating sediment delivery ratios could well lead to substantial overestimates of this ratio. Furthermore, neglect of this component of erosion may also lead to serious underestimates of the sediment storage needs of reservoirs, underestimates of the maintenance needs of reservoirs, and overestimates of the life of reservoirs.

Ephemeral gullies are also important because they are channels where significant landscape changes begin. As soil is removed year after year from an ephemeral channel and nearby areas, a well-defined drainageway tends to develop. Over time, fields may be visibly dissected by these drainageways. In fields with shallow surface soils, removal of the fertile surface soil in drainageways can expose subsoils, restricting the use and productivity of these fields. Significant costs may be incurred for reshaping and patching damaged drainageways and for maintaining the productive capacity of less fertile subsoils.

CONTROLLING EPHEMERAL GULLIES

Ephemeral gullies can be very effectively controlled by controlling surface runoff. The principle that must be followed is to regulate runoff so that critical shear values in a channel are not exceeded. This is accomplished by constructing channels that have a high enough critical shear value so as to insure that shear of the flowing water remains below the critical shear value, or by controlling runoff rates so that critical shear values are not exceeded. Usually, some combination of practices that satisfy the above principle is used.

A general comment frequently heard with regard to ephemeral gullies is that they occur where grassed waterways should be located. Grassed waterways, because of their high component of friction have considerable energy loss along the channel, leaving little energy for the detachment of sediment. Also, the existence of permanent vegetation with little disturbance of the channel results in very high critical shear values. In many cases, a properly designed and maintained set of grassed waterways will completely eliminate the development of ephemeral gullies. Where ephemeral gullies exist, some minor shaping may be required prior to establishment of the waterway. A set of well designed grassed waterways will perform satisfactorily as long as they are maintained properly. Maintenance may involve clipping, shaping, and care when operating tillage and spraying equipment nearby.

Stable earthen channel design techniques can also be used in conjunction with standard conservation practices to control the formation of ephemeral channels. The tractive force method (Schwab et al, 1981) is used to design channels such that the critical tractive force of the channel is not exceeded. Typically, this is accomplished on cultivated fields by the use of terraces, diversions, and sediment and water control basins. In these cases the volume of water in a channel is limited by controlling watershed size. Also, channel slope may be reduced.

Other conservation technologies can also be used to control ephemeral gullies. Farming on the contour, providing slopes and slope lengths are not excessive, will reduce ephemeral gullying. Ridge tillage methods when used on the contour are extremely effective, if the ridges do not overtop and if all runoff is discharged into a properly designed set of channels. However, if this is not the case, very severe gullying can occur because of the discharge of large volumes of water into a single channel.

Practices that reduce surface runoff can be expected to reduce ephemeral gullying. Generally, practices that reduce sheet and rill erosion will also reduce surface runoff, but to a much lesser extent. Conservation tillage, a farming practice that leaves crop residue on the soil surface for erosion protection, can reduce surface runoff by preventing sealing of the soil surface and by having a rougher soil surface, promoting ponding of runoff on the soil surface. Practices that leave the soil surface virtually undisturbed, such as no-till, can also reduce ephemeral gullying by leaving the soil surface at a higher density which will increase the critical tractive force, the threshold that must be exceeded before erosion can occur.

Land use changes, such as a lowered intensity of cultivation, are important strategies for controlling ephemeral gullies. The use of crop rotations that include grass and small grains will reduce runoff volumes and peak rates.

Also, the use of strip cropping, a practice where alternate strips on the contour are farmed to different crops in a small grain-grass-row crop rotation, will reduce runoff volumes and peak rates.

On some fields, ephemeral gullies occur only in certain areas such as field ends, or areas that have soils with physical or chemical problems, or areas that have steep slopes or excessive slope lengths. These areas may require special treatment such as removal from crop production and the use of permanent vegetation, or the use of structures on a small portion of a field.

On nearly every field, ephemeral gullies can be controlled through the use of some conservation practice. A considerable array of practices are available from which to select that practice most suitable for a particular farmer, soil, climate, and topography. But unfortunately, most practices either remove valuable land from production, decrease the intensity of cropping, or result in structures or waterways that affect the farming operations.

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DRAINAGE DENSITY VERSUS RUNOFF AND SEDIMENT YIELD

By Paul B. Allen, Hydraulic Engineer, USDA, ARS, Water Quality and Watershed Research Laboratory, Durant, Oklahoma

ABSTRACT

Runoff and sediment yields were correlated to watershed drainage densities derived by various procedures for 17 watersheds in the U. S. Southern Plains. The best correlations, $r^2=0.88$ for runoff and $r^2=0.83$ for sediment yield, resulted with drainage densities determined with a remote sensing technique using aerial photography. The procedure used to determine drainage density is described in detail because drainage density is affected by the scale of the base map or aerial photo, the magnification of the viewing instrument, and the definition for an initial channel. These relationships, proven only for U.S. Southern Plains watersheds, will be useful for prediction purposes if similar correlations are found for other areas.

INTRODUCTION

Strahler (1958) lists and defines 37 geomorphological properties of landforms that have been introduced to characterize drainage basins and their hydrologic response. He divided the properties into three groups: those derived from the channel networks and basin outlines, those requiring areal measurements, and those involving elevation differences. Few of these properties have been proven useful in predicting the hydrologic performance of watersheds.

This paper takes one geomorphological characteristic, drainage density, and relates it to runoff and sediment yield. Although the conceptual role of runoff in the development of channel networks as described by Horton (1945) is well accepted, reports on the use of drainage density to predict water yield are few and sometimes contradictory. Carlston (1963) reported that the base flow rate and mean annual flow rate of streams in central and eastern U.S. are functions of drainage density. Dingman (1978), however, found no detectable correlation between drainage density and mean flow for streams in New England.

The remote sensing technique for obtaining the drainage density values used in this report is described in detail because these values will vary with the scale of the base map or aerial photo, the type and magnification of the map viewing instrument, and the definition of a beginning stream channel.

PROCEDURE

Drainage densities were determined for a group of USDA experimental watersheds in the Southern Plains (figure 1). Runoff and sediment yield data were available for 11 to 15 year periods for these watersheds (Table 1). The topography in this area is gently to sharply rolling with a maximum relief for the larger watersheds of about 120 m. The percentage of alluvial land in the watersheds is minor; the small watersheds 1 through 8 have no alluvium and the others have a maximum of 15 percent. The texture of the upland soils ranges from silty clay loam to fine sand. The predominant land use in all the watersheds is rangeland (Table 1). The percentage of cultivated land is generally small, although one watershed has 37 percent. Average annual rainfall ranges from 70 cm for the watersheds on the west to 85 cm for those on the east.

Table 1. Pertinent data for the watersheds

No.	Watershed Name	Drainage Area (ha)	Land Use ¹ (%)			Drainage Density (km/km ²)			Hydrologic Data		
			Range ²	Cult.	Misc. ³	Peren. & Ephem.	Peren. Only	Incl. Micro-Chan.	Data for Yrs.	Avg. Annual Runoff (cm)	Avg. Ann. Sediment Yield (tonnes/ha)
1	---	7.2	100	0	0	0.00	0.00	0.00	63 - 75	0.17	0.03
2	---	9.8	100	0	0	0.00	0.00	0.73	63 - 75	0.42	0.75
3	---	10.5	100	0	0	0.00	0.00	0.39	63 - 75	0.16	0.00
4	---	7.3	100	0	0	0.00	0.00	1.46	63 - 75	0.29	0.04
5	---	9.6	100	0	0	0.00	0.00	1.59	68 - 77	4.13	0.06
6	---	11.0	100	0	0	0.00	0.00	1.85	68 - 77	4.43	0.34 ⁴
7	---	7.8	100	0	0	0.00	0.00	7.85	68 - 77	13.57	5.82 ⁴
8	---	7.5	100	0	0	0.00	0.00	12.22	68 - 77	13.67	8.72 ⁴
9	Big Dry Cr.	1961.	100	0	0	1.50	0.32	3.55	65 - 72	5.55	1.05 ⁴
10	Salt Cr.	6164.	51	7	12	1.81	0.00	2.92	67 - 77	5.31	1.41 ⁵
11	Tonkawa Cr.	6734.	72	9	9	1.59	0.10	1.93	63 - 77	2.61	0.40
12	Winter Cr.	8624.	82	8	10	1.57	0.04	4.38	64 - 77	8.00	3.36
13	East Bitter Cr.	9090.	84	9	7	2.12	0.93	5.10	64 - 77	7.53	4.79 ⁴
14	Delaware Cr.	10390.	71	14	15	1.38	0.00	1.41	64 - 77	2.20	0.58
15	West Bitter Cr.	16150	63	29	8	1.50	0.50	3.73	63 - 77	5.88	2.84 ⁴
16	Sugar Cr.	53340.	53	25	22	1.53	0.24	1.93	64 - 73	2.39	3.54
17	L. Washita R.	53800.	66	17	17	1.89	0.20	2.16	64 - 77	4.67	3.52 ⁴

¹ 1967 Land use survey

² Includes timber pasture

³ Dense timber, farmsteads, streams, impoundments, roads, rock outcrops, and urban areas

⁴ Sediment data missing for one year

⁵ Sediment data missing for four years

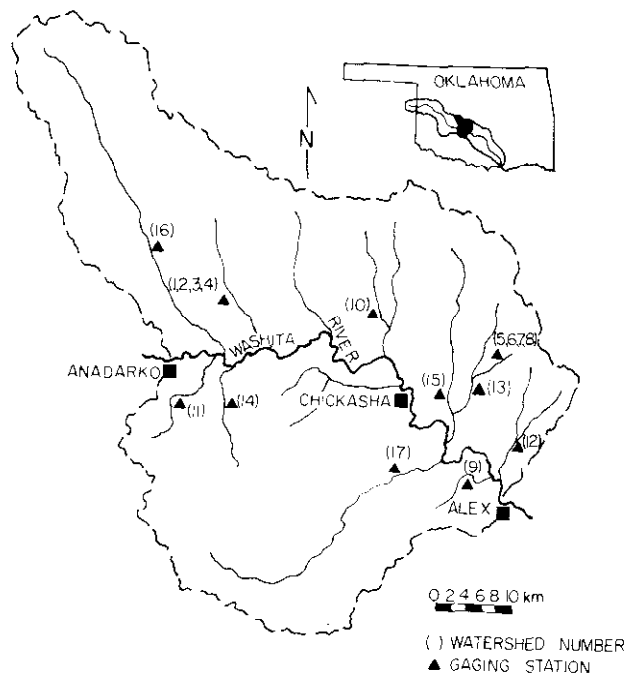


Figure 1. Location of watersheds.

Horton (1945) defined drainage density as the total of all channel lengths in an area divided by the area, using a common measurement unit for both. He suggested using U.S. Geological Survey topographic maps to determine channel lengths, including both perennial and intermittent streams. Drainage densities were determined for the 17 watersheds using Horton's method. For those watersheds with drainage areas less than about 2000 hectares, drainage densities were determined from the channel data from the entire watershed. To save time on larger watersheds drainage densities were determined for roughly 20 percent of the drainage area. The 20 percent consisted of several 2.59 km² (one square mile) areas selected across the watershed on an approximate grid. Drainage densities were calculated as follows and are listed in Table 1.

$$\text{Drainage density} = \frac{\sum L}{A}$$

where $\sum L$ = the total channel length in km, and
 A = the drainage area in km²

Since the data were readily obtained, drainage densities were also determined using only the perennial drainage (Table 1). Since about half the watersheds had zero drainage density and initial plots of runoff and sediment yield vs. drainage density had no visible relationship, another procedure to determine drainage density was sought. Since observation of aerial photos and the watersheds themselves showed that watersheds with high runoff and sediment yield also were high in gullying and microchannels, the following drainage density procedure was devised to include the microdrainage.

Aerial photos with a 1:20,000 scale, taken by the U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service, were used as the

base maps. Photos from the 1966 flight were selected because this flight was made during the hydrologic data collection period. A Hilger and Watts model SB180 mirror stereoscope¹ equipped with X4 magnification binocular eyepieces was used. While viewing a stereo pair of photos the channel system was drawn in ink on a transparency placed over one of the photos.

The small watersheds, numbers 1 through 8, were used to determine the optimum beginning channel size that would give the best drainage density-runoff correlation. They were ideal for this purpose because their small size facilitated multiple trials and they varied widely in channel density and runoff. This showed that all watercourses that appear sharply incised with the stereoscope should be measured, as well as the lengths of barren areas above gullies. The smallest watercourse visible through the stereoscope was about 0.2 m wide. For the upper reaches of watersheds with very good rangeland cover, channels sometimes consisted of a series of non-connected cascading pools. Such channels were measured as if they were continuous. Cattle trails were not included in the channel system unless they had become a watercourse. Also nonfunctioning channels were not included.

Nonfunctioning channels were probably formed between the 1920s and mid-1940s when the rangeland was generally overgrazed and cultivated, causing greater runoff than that of the present time. Rhoades et al. (1975), for example, reported that runoff in this area is about four times greater for rangeland with poor cover than for rangeland with good cover. Nonfunctioning channels have a rounded appearance, vegetation completely covers the channel bottom, and the channel vegetation is similar to the adjacent rangeland vegetation.

When the foregoing channel identification techniques were applied to the larger watersheds, additional guidelines were needed for ambiguous situations. Some of these guidelines were based on logic to fit the presumed increasing drainage density - increasing runoff relation; others were arbitrary for the sake of measurement consistency. For example, man-made changes to the watersheds such as terraces, diversions, and all farm ponds were not counted as channels and were ignored. If included, terraces and diversions would increase the drainage density; whereas, it is generally believed that these features reduce the amount of runoff. Where hillslope channel had been interrupted by a terrace system, the original channel location was approximated and used. Road ditches were not included except where they coincided with a natural channel.

On some watersheds, watercourses were sometimes discontinuous, such as where gullies eroded midway up hillslopes with no connections to the channel below. Discontinuity also occurred on some watersheds with sandy soils when the channel, through deposition, lost its identity and thus became a nonfunctioning channel. For both types of discontinuity, upstream channels were ignored if their aggregate length was less than the length of the intervening non-channelized area. The upstream channels were included in the channel system when their length exceeded the nonchannelized length. For both of these criteria, the nonchannelized portion was not included as part of the channel system. Total channel, gully, and microchannel lengths were measured on the

¹Trade names are used for information only and do not constitute endorsement by the U.S. Department of Agriculture.

transparencies with a map measure and drainage densities were calculated as before (Table 1). The same equation used to calculate drainage density by the other procedures was used for this procedure.

FINDINGS

Simple linear regression analyses were used to relate runoff and sediment yield to the drainage densities. There were virtually no correlations between runoff and sediment yield vs. drainage density derived from perennial and ephemeral channel data, $r^2=0.005$ and $r^2=0.018$, respectively (Table 2). The correlations were still very poor using drainage densities derived from perennial channels only, $r^2=0.026$ for runoff and $r^2=0.080$ for sediment yield (Table 2).

Table 2. Results of linear regression analysis

Correlation r^2	Equation ¹
Drainage density from perennial & ephemeral streams	
0.055	$Q = 0.334D + 4.471$
0.018	$S = 0.390D + 1.850$
Drainage density from perennial streams	
0.026	$Q = 2.69D + 4.395$
0.080	$S = 2.81D + 1.806$
Drainage density from aerial photogrammetry	
0.884	$Q = 1.280D + 0.726$
0.831	$S = 0.747D - 0.164$

¹ Q = Watershed runoff in cm, D = Drainage density in km/km², and S = Sediment yield in tonnes/ha.

Runoff and sediment yields, however, were highly related to drainage density determined from aerial photogrammetry that included the gullies and micro-channels in the channel network. Figure 2 shows a plot of the runoff vs. drainage density data that had an r^2 of 0.884. Figure 3 shows a plot of the sediment vs. drainage density data that had an r^2 of 0.831.

Two complimentary processes may explain why runoff increased as the latter drainage density increased. First, in this area where all soils have similar erosivity values, higher-than-average runoff (and the resulting higher erosional stresses at the soil surface) will produce more rills, gullies, and channels. Secondly, a watershed with a well developed channel system will be more efficient in conveying runoff to the watershed outlet. Where channel densities are high, overland flow distances are reduced; consequently infiltration losses are also reduced.

The runoff-drainage density relation did not apply to alluvial cultivated land. Data from 7 small alluvial watersheds, shown as crosses in figures 2 and 3, plotted generally left of the regression curve. The alluvial land in these watersheds is very flat and the low-velocity runoff has little erosive

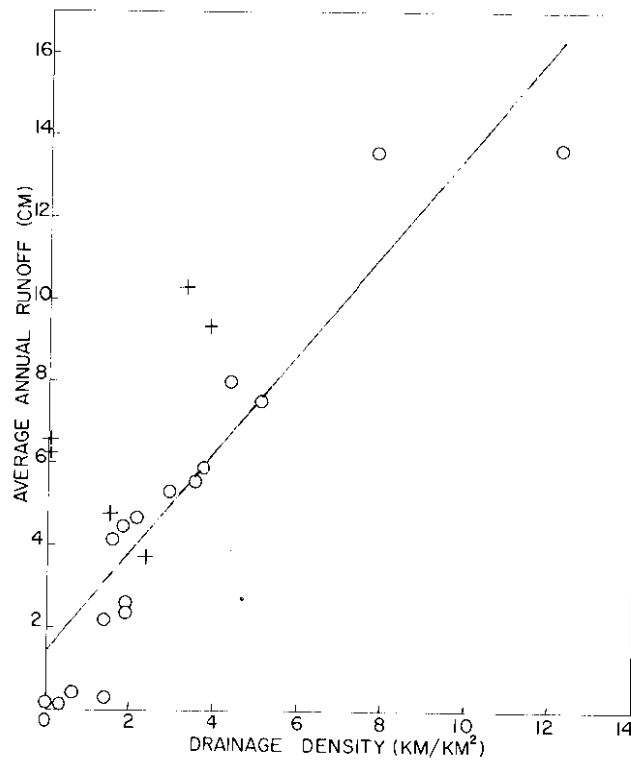


Figure 2. The relation of runoff to drainage density.

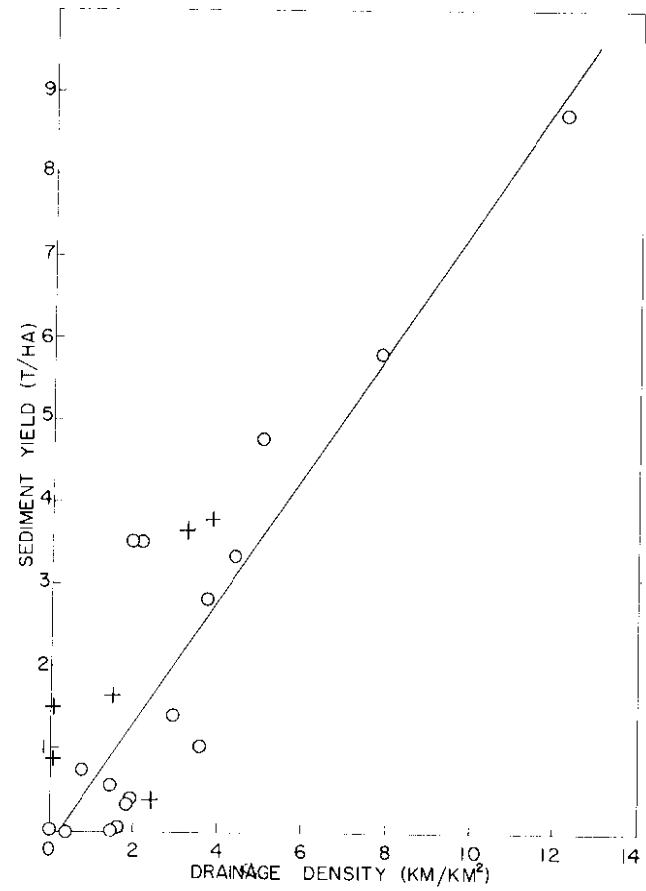


Figure 3. The relation of sediment yield to drainage density.

force to create channels. Cultivation of the alluvium further compounded the problem. Drainage on the cultivated alluvium was man-made and controlled by the farm operator. Some alluvial watersheds appeared to be overdrained, whereas others had no drainage. Since about half the watersheds used in correlation analysis had no alluvium and the remainder had less than 15 percent, the alluvial land effect was probably small.

CONCLUSIONS

Average annual runoff was highly correlated ($r^2=0.88$) with drainage density that included microchannels for a group of watersheds in the Southern Plains of the United States. The relation appears sufficient to use as a runoff prediction tool for the area. Further investigations are needed to determine if similar relations exist for other areas.

The correlation of sediment yield to drainage density ($r^2=0.83$) was less than the correlation of runoff to drainage density. Even so, the sediment relation might still be considered for a prediction tool because it is simple and easily applied and because other watershed sediment prediction procedures are notorious for their prediction inaccuracy.

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SEDIMENT YIELD METHODS USED IN THE CORPS OF ENGINEERS

by Gary R. Dyhouse, Chief, Hydrologic Engineering Section, St. Louis District, Corps of Engineers, 210 N. Tucker Blvd., St. Louis, MO 63101

ABSTRACT

The primary methods employed by the Corps of Engineers to compute sediment yield have changed but slightly over the past decade. The use of sediment load curves, either measured or developed predictively, integrated with discharge-duration curves predominates. The development and application of hydrologic and sediment transport models has allowed this technique to be used for studies with essentially no sediment or discharge data. Reservoir deposition measurements are used primarily as a comparison with the sediment load curve method, or to transfer yield information to ungaged areas. Soil loss equations and other empirical techniques see limited application by the Corps; being used mainly to estimate yield for reconnaissance level reports, to estimate sediment-impact of an alternative, or to develop a watershed sediment budget.

INTRODUCTION

In 1986 the Corps of Engineers (COE) will release a total revision of the original Engineer Manual 1110-2-4000, Reservoir Sedimentation Investigation Program, (1961). The revised manual is expected to guide and assist Corps personnel in conducting sediment studies through the rest of this century. One of the chapters, dealing with the subject of "sediment yield" and prepared by this writer, describes the potential methods of yield calculation for Corps reports. This paper is a condensation of that chapter, supplemented by considerable discussions with Corps personnel from around the country as to the sediment yield methods used by different Corps Districts. It is also intended to update an excellent paper by Livesay (1972) on the same subject. Past COE efforts in sediment yield have largely been influenced by reservoir storage requirements and the previous version of the EM dealt exclusively with reservoir analysis. For the foreseeable future, reservoir deposition studies are expected to be a progressively smaller feature of COE sediment work. The majority of COE flood control studies now evaluate non-reservoir solutions, particularly channel modifications. Sediment yield analyses must be a part of the studies leading to the design recommendations for levees, channels, and other flood control modifications, and for evaluation of land use changes. Many methods have been used by the Corps of Engineers to estimate sediment yield. However, all the methods can be placed in two broad categories---either based on direct field measurement of sediment data or on indirect, or predictive, techniques.

MEASUREMENT-BASED SEDIMENT YIELD METHODS

This grouping of sediment yield techniques is based on actual measured data available in the study area and is the most widely used yield method in the COE. There are three major sub-categories within this grouping---instream sampling, reservoir deposition studies, and regional analysis.

Instream Sampling. Techniques associated with sediment sampling are considered by the COE to give the most accurate yield estimate. Long-term sediment gage records are occasionally available from which annual average sediment yield is drawn. Reliance on published sediment data records alone requires at least 10 years of data; however, at least 30 years would be desired to give reasonably dependable yield estimates. Unfortunately this much data is available in quantity for few rivers outside of the Great Plains. Even when lengthy records do exist, the period-of-record data may not be homogeneous. Adjustments for upstream reservoirs, land use changes, and farming practices have been necessary.

Average Annual Yield (Load Curve-Duration Integration). Where sediment concentrations are regularly sampled and many measurements exist, the data can be plotted against water discharge, giving a suspended sediment rating or load curve. Numerous measurements of sediment concentrations, including flood events, are needed to fully define the relationship. Estimates of bed load are added for the total sediment load. Corps Districts have used sediment sampling periods as short as 3 years when a wide range of sediment discharges have been sampled and long-record, discharge-duration data existed. This technique is the most widely used within the COE to calculate yield. An excellent discussion of this technique, including seasonal separation and other problems encountered, is given by Miller (1951), with sample calculations shown by Livesay (1972).

Flood Water Sampling. When no measured data exist and at least some is required for sediment yield estimates, a limited sediment sampling program has been established prior to the start of planning and engineering studies. Since sediment load curves are usually displayed as a straight-line relationship logarithmically against discharge, often with a "rule-of-thumb" slope of 2, a limited amount of sediment samples for high in-bank and flood flows may be sufficient to approximate the sediment rating curve. Short record sediment load data is recognized as rough at best and much less desirable to use than the previous technique. When using this method, sensitivity tests are performed to evaluate the additional uncertainty in the load curve on the alternative being analyzed. If a doubling or tripling of the load for all discharges does not greatly affect the alternate under study, additional sediment data may not be necessary. This technique gives low estimates of sediment yield if the unmeasured bed load is not included. If previously ungaged, the site hydrology recorded during the sampling period should be scrutinized. The absence of floods or the occurrence of one or two large events can result in biased estimates of yield. Where a limited sampling program can be scheduled and funded prior to the start of detailed COE studies, this technique has been quite valuable to supplement/modify the results of other methods.

Reservoir Sedimentation Surveys. Many reservoirs across the United States, ranging in drainage area from a few acres to thousands of square miles are periodically surveyed to determine the quantity of sediment deposited over time and the corresponding loss of reservoir storage. The main source of reservoir sedimentation information is the USDA-ARS Publication 1362 (1975),

updated about every 5 years, showing storage changes and annual reservoir deposition in tons/square mile of drainage area. Information is obtained for structures in or near the study watershed, transferred to the location under study and adjusted as necessary. This technique is used by various Corps Districts to estimate sediment yield at ungaged sites. The hydrology during the measurement period is important as deposition is directly related to the runoff volume during the period. Droughts or large floods can greatly bias the estimate. Use of reservoir sedimentation surveys to determine sediment yield does require the recognition and evaluation of two important factors: first, reservoir deposition is not synonymous with sediment yield. Some amount of inflowing sediment leaves the reservoir through the outlet and this additional sediment must be included in the calculation of watershed yield. Second, upstream drainage area must be analyzed for non-contributing areas, such as land draining to upstream reservoirs, ponds and lakes, potholed areas, sand hills contributing negligible runoff, etc. These areas would then be deleted from the total area where yield is to be calculated.

Debris Basins. The design of debris basins by the COE requires special procedures to calculate sediment yield. Most of the COE effort is still performed by the Los Angeles District with the Tatum method (1963). The method was developed specifically for the San Gabriel Mountains of southern California, but may be applicable to similar regions of the United States. Yield is predicted by nomographs and 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 between the time of the burn and the time of the flood. The limited debris basin design done by other Corps Districts relies on empirical methods or on the recent guidance of the Transportation Research Board (1980).

Regional Criteria. Regional analyses (using data from sediment load stations and reservoir deposition surveys to develop sediment yield prediction equations or nomographs for an entire basin or region) are used by essentially all Corps Districts. Measured yield is regionalized by maps, graphs or equations to predict sediment yield based on definable parameters for a study area. A regional method usually serves as a preliminary procedure to estimate sediment yield or to supplement/calibrate other more detailed techniques.

Dendy and Bolton. Although not yet widely used by the COE, the work of Dendy and Bolton (1976) has potential application throughout the United States. Sediment yield from about 800 U.S. reservoirs is related to drainage area and mean annual runoff. Prediction equations are based on mean annual runoff being more or less than 2 inches. Although these equations were developed from over 800 reservoir sites throughout the United States, they were derived from average values of grouped data; therefore, total reliance on these equations to predict sediment yield in any one location would be dangerous. Soils, slopes, vegetation, and land use will influence sediment yield at a specific site and must be included in detailed yield studies.

Pacific Southwest Inter-Agency Committee Method. The PSIAC Method (1968) 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. These factors are: 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 ac-ft/sq mi/yr for watersheds with low PSIAC factor (20) to more than 3 ac-ft/sq mi/yr 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 yield caused by local land use management changes. Corps Districts have successfully applied this technique on studies in the southwestern United States, although the resulting sediment yield estimates are extremely sensitive to parameter selection.

Other Regional Studies. Numerous other methods for estimating sediment yield are available, all based on regional analyses of stream and reservoir data. Methods developed by Mack (1970), Hill (1965), Flaxman (1972), Livesey (1972), and many others to predict yield for different sections of the United States are routinely applied for qualitative estimates for potential projects or land use modifications. A thorough literature search for sedimentation information in any area has often paid unexpected dividends, as the USDA-SCS, USGS, other Federal, State, and local agencies have frequently studied particular basins and regions in some detail, providing data and information on sediment runoff. A computerized literature search for sediment information for a basin or region should be mandatory.

PREDICTIVE-BASED SEDIMENT YIELD METHODS

The second major grouping of sediment yield techniques employed by the Corps can be categorized as predictive, or an application of analytic models to infer sediment yield for a watershed. While the "best" or most-accurate techniques are based on field measurements, seldom does sufficient information exist for sole reliance on direct field measurement. The majority of Corps sediment yield studies utilize predictive methods, supplemented by whatever actual data is available. Most predictive methods can be grouped into two areas---sediment transport functions (used with discharge-duration curves) and soil loss equations. Both methods can estimate sediment yield at a specific point, generally without addressing the movement of sediment from point-to-point within the system. Continuing research work has resulted in several models to simulate sediment erosion and movement, although most of these models are only applicable to very small drainage areas. These evolving watershed sediment routing models have not yet been employed to any extent by the COE.

Sediment Transport Functions. As described previously, the integration of flow duration and sediment load curves gives average annual sediment yield and is the preferred technique within the Corps. However, there are relatively few sediment sampling stations available from which to derive sediment load curves, as compared to the many gages supplying discharge information. Therefore, when Corps studies require yield estimates (particularly for a large stream), discharge information is typically available near the study site but suspended sediment information is not. Thus, the lack of sediment

load information is the main difficulty in the application of this technique. Numerous equations have been derived to define a water and sediment discharge relationship. However, a great variance in derived load curves is typical, depending on the equation used, and no one equation can best describe the load curve for all possible streams. As measured sediment load data is a luxury which is infrequently available, typical Corps practice includes the derivation of the load curve by either the selection of an equation and direct calculation, or by applying the Corps' HEC-6 program to estimate a load curve, using very short time steps and assuming the existing reach is not in a rapid state of aggradation or degradation.

Sediment Transport Equations. The Waterways Experiment Station computer library (CORPS) has several inter-active programs available to solve various transport equations. Equations in the library include: Colby, Toffaletti, Einstein, Yang, etc. For user-furnished input (discharge, depth, velocity, D50, etc.), calculation of the transport potential by the specified equation will be solved interactively and displayed at the user's terminal.

HEC-6 Calculation. Derivation of the sediment load curve may also be obtained directly through hydraulic modeling of the stream reach under study. Surveyed cross-sections through the reach and bed and bank samples, to determine a sediment gradation curve of the active bed, are needed to derive a load curve with the HEC-6 program, or equivalent. Sediment transport capacity is calculated directly for time-steps measured in minutes and for the existing geometry and active bed gradation used. The Hydrologic Engineering Center (HEC) Trng. Document No. 13 (1981) describes this technique in detail.

Upland Erosion Methods. Soil loss equations, to define sediment yield from fields, gullies and small watersheds, have been used to predict sediment yield since first described by Musgrave (1947), however Corps utilization of these techniques is not common. Use of soil loss equations by the Corps has been limited to providing qualitative estimates of erosion potential from urbanizing watersheds and sediment contributions to receiving streams, and for developing sediment budgets for reconnaissance or feasibility level studies.

Modified Universal Soil Loss Equation. Gross erosion losses with sediment delivery ratios allow estimates of annual soil losses to be made. Since only a single annual value is obtained and applicable drainage areas are quite small, the Universal Soil Loss Equation is not used by the COE. Sediment runoff during a single event is of interest, however, and even hourly soil erosion losses throughout a specific event can be required, particularly in evaluating stream water quality. To estimate these short-interval soil losses for small watersheds, the Corps has used the Modified USLE (MUSLE), Williams and Berndt, (1977). The MUSLE allows the estimation of soil losses for each precipitation event throughout the year, thereby becoming an event model rather than an average annual runoff model. As an event model, the MUSLE and similar techniques have somewhat more application to Corps analyses. Long-term simulation is normally required to obtain a suitable sediment yield 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 correctly apply. A rainfall runoff model must be utilized with, as a minimum, daily rainfall, average monthly evaporation values, and measured average annual runoff. Calibration is usually against measured water volume, with at least 3 years of data normally needed. Comparison and confirmation of sediment yield calculated through soil loss equations should be made against other techniques, where feasible. A variation of technique is employed in HEC's STORM program (1977). A study by Dyhouse and Williams (1980) describes a method of calibrating the sediment yield derived using STORM with a sediment transport-discharge duration integration to predict surface runoff of sediments. Other equations and techniques have also been used to develop sediment budgets for a watershed and to assist in estimating potential scour-deposition problems for alternative flood control modifications. Total yield for each of several hypothetical flood events has been estimated qualitatively by the HEC using techniques described by Wishmeier and Smith (1978). Yield for each event is then proportioned into clay, silt, and sand loads, based on gradation of the bed and bank soil samples. For most local protection projects, the sand load is of most interest since it may deposit in a modified channel, while the clays and silts would remain in suspension and pass through the reach. Tons/event and tons/year of sand deposition have been successfully estimated for reconnaissance level studies with these techniques. HEC Special Project Memo No. 82-4 (1982) illustrates the use of these qualitative techniques.

Streambank Erosion. Soil losses through streambank erosion and bank caving contribute greatly to the sediment yield totals for most major river basins. The causes of streambank erosion are many and varied, and the prediction of future losses at specific locations has been difficult. No generalized analytical procedures have yet been developed to formally calculate sediment yield or specific bank line losses from streambank erosion. The few COE attempts at streambank erosion studies have concentrated on measuring bankline changes over time from aerial photographs or from maps and projecting losses based on past hydrologic occurrences, measured bank losses, and judgment. Where future analysis would include watershed modifications such as reservoirs and channelization, past changes could be of little assistance in estimating future yield. The Corps generally relies on hydraulic modeling of the channel to adequately address changes in geometry through a reach.

Watershed Mathematical Models. Recent developments in sediment analysis have concentrated on mathematical computer modeling of the sediment runoff process, in varying levels of sophistication. Many of these models are hydrologic, with sediment runoff capability added through soil loss equations; such as the Corps STORM model. STORM, like most watershed models, 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 also largely applicable to basins of a few square miles or less in size. While mathematical modeling may be considered a more rigorous approach to sediment

yield, significant input data for these models are necessary. Given the usual lack of sediment data, yield estimates by watershed computer modeling may not be any more quantitative than more simplified techniques. Consequently, no serious attempt at modeling the mechanics of watershed sediment movement has yet been made by the Corps.

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. Yield varies dramatically as land use changes. Removal of ground cover, trees and vegetation preparatory to development can increase sediment runoff by orders of magnitude during the construction process. However, as the land is developed and re-stabilized, the great increase in impervious areas (roads, structures, parking lots) results in less land surface area exposed to the erosive effects of rainfall and runoff. Consequently, sediment yield by land surface erosion is less for a fully-developed urban area than yield from the pre-urban land use. The usual hydrologic effects of urbanization may somewhat counterbalance this yield decrease from land surface areas. Increased runoff from impervious areas with higher peak flows may result in increased gullying and/or streambank erosion. All these factors are difficult to meaningfully quantify.

Urban Yield Methods. Theoretically, all of the various methods previously described could be used to calculate sediment yield for urban areas. In reality, given the almost total lack of measured sediment data, COE yield methods have been limited to various predictive techniques. If discharge-duration data can be synthesized for a given land use with period-of-record hydrologic simulation, a transport equation has been calculated and integrated with the duration curve to estimate average annual sediment yield. A different land use would require a repetition of this method with both the discharge-duration and sediment load curves modified to reflect the new land use condition. Mathematical modeling of the watershed's sediment runoff processes would normally be necessary to develop flow duration data or to obtain sediment washoff information. Most sediment models have been developed for rural watersheds primarily, relying on soil loss equations to calculate sediment runoff. Thus, parameter estimates in urban areas reflect only the best judgment of the practicing engineer. Urban sediment yield methods are largely yet to be developed.

Adjustment Factors for Urbanization. Even with the problems involved with urban sedimentation analysis, proper evaluation for Corps work proposed in urban areas has required 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. Use of an appropriate mathematical sediment routing model under different land uses allows 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 the summation of runoff water volume, allows annual yield curves to be plotted. Average annual sediment yield can be found from summing and

averaging the annual values. These yield curves have formed the basis for adjusting the sediment load curve to reflect an alternative land use condition. Livesay (1972) also proposed a method for estimating changes in sediment yield during urbanization, based on land use projections and available sediment yield and urban runoff measurements. Reservoir sediment storage for several small detention sites in the Omaha, Nebraska area were designed with this technique. Several years of deposition data have been obtained since these structures were built, but the data has not yet been analyzed. This method may be the only urban sediment analysis with prototype data for confirmation/modification of the original procedure.

FUTURE NEEDS

Many areas of COE sediment yield analysis require further effort, with the following judged most important by the writer:

Training. As increasing emphasis has been placed on sedimentation analyses in the Corps, a need for additional training has become apparent. Many Corps Districts have no one who is knowledgeable in sediment, and must rely on outside experts. Only five years ago, it was estimated that no more than 6-8 people in the entire COE were involved with riverine sedimentation studies on a full-time basis, EC 1110-2-232 (1980). Consequently, expanded sediment training has been offered at both the Waterways Experiment Station and the Hydrologic Engineering Center. Additional guidance and information concerning the need for sediment assessments has also been forthcoming from the Washington level. Corps hydraulic engineers are becoming at least moderately aware of sediment effects and the need for proper evaluation during feasibility and design reports.

Urban Data. The lack of data makes COE urban sediment studies largely qualitative in nature. Collection of sediment data in urban areas would allow calibration of models and improve the qualitative aspects of the urban sediment study. Today's funding restrictions make the acquisition of significant urban sediment data questionable, however.

Single Event Yield. No adequate procedures exist to quantitatively estimate yield from a single event. Most COE flood control projects are sized to safely pass a given frequency event; i.e., the 100-year recurrence interval flood. Sediment runoff and the amount of deposition or scour during the design event are needed to ensure the project functions as intended. Future research in this area is anticipated and greatly needed.

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SEDIMENT STORAGE AND DELIVERY - EASTERN COLORADO

By K. L. Clarkin, graduate student; M. D. Harvey, Associate Professor, Dept. of Earth Resources, Colorado State University, Ft. Collins; A. Elkin, State Geologist, Soil Conservation Service, Denver, Colorado; and S. C. McIntyre, Scientist, Agricultural Research Service, Durant, Oklahoma

ABSTRACT

Differences in sediment delivery ratio at four small reservoirs in the Kiowa Creek watershed are related to basin storage capacity, measured as percent of total basin area in depositional sites. Storage capacity depends both on topography and the degree of integration of the incised channel network. In semi-arid areas, drainage network continuity, and therefore area available to store sediment, may change over time as a basin undergoes a cycle of high sediment production, storage and flushing.

Post-European settlement sediment budgets were developed for the four watersheds for the periods before and after dam construction. They indicate that delivery ratios have remained approximately constant in three basins where relative sediment storage area was not greatly affected by gullying. Delivery appears to have increased where channel incision reduced available storage area. The budgets also suggest that the USLE may significantly overestimate rates of soil loss from uncultivated slopes in Eastern Colorado.

INTRODUCTION

Many studies have documented both temporal changes and spatial variability of sediment delivery on widely different scales (eg. Trimble and Lund, 1982; Piest et al., 1975). Delivery variations through time in one basin can occur when an episode of high sediment production due to land use changes or climatic factors overloads the drainage system (Bergstrom, 1982; Trimble, 1981). Storage and later remobilization of this sediment may result in a changing relationship between erosion and sediment yield. Differences in average delivery ratio between basins with similar land use and precipitation have been related to relief ratio (Maner, 1958), drainage area (Roehl, 1962), channel slope (Williams and Berndt, 1972) and to conveyance efficiency of channels (Hadley and Shown, 1976).

The purpose of the present study was to define the factors responsible for the large observed difference in delivery between two basins in Eastern Colorado. This difference may be explainable by a measure of basin sediment storage capacity. Because this characteristic is related not only to topography, but also to the nature of the drainage network, it may change over time.

Both watersheds are adjusting to the destabilization of their sediment regimes which followed European settlement. Construction of sediment budgets for these basins permits estimation of the effects of this destabilization on sediment storage and delivery over time.

DESCRIPTION OF STUDY AREA

The two major watersheds studied, B9 and K41 (Figure 1), are drained by ephemeral streams that are tributaries to Kiowa Creek near its headwaters on the Platte-Arkansas Divide. The area's climate is semi-arid: average annual precipitation at the National Weather Service station just east of K41 dam is 17.1 inches based on a 23-year record. Weather on the Divide is renowned for its variability and intensity; droughts, dust storms, blizzards and 'gully-washers' have historically made upland dryland farming an uncertain undertaking and localized intense summer thunderstorms have subjected the area to severe flood damage.

Kiowa Creek itself responded to farming and overgrazing by changing from a narrow channel meandering 'almost aimlessly through the meadows' (Carnahan, 1949) to a 'sand-choked, mud-baked land hog', as it was described in 1961 (Jones, 1961). Farming and ranching began in the late 1860's, and floods and gullying began to occur extensively in the 1920's (Carnahan, 1949). The worst flood on record, on Memorial Day 1935, so devastated the valley that the upper Kiowa Creek drainage basin became the site of an SCS pilot watershed-protection project, one of those authorized by the USDA Appropriation Act of 1954. Among other measures, 60 floodwater-retarding dams were built around 1955, including K41 and B9.

B9 dam, with a drainage area of 415 acres, was built with a sediment pool of 14 acre-feet, but in 29 years, only 0.93 acre-foot of sediment has actually been delivered to the dam. Two smaller dams (B9a and B9u) are upstream of the main structure; one, a stockwater pond, was built in 1952, and the other was constructed around 1936, apparently as a gully plug by the CCC. Together these upstream dams control about one-third of the entire watershed. In this basin the resistant Castle Rock Conglomerate overlies the more erodible Dawson Arkose. Topographically the watershed is composed of broad divide areas (5 to 8% slopes), steep slopes of 32 to 34% where the conglomerate outcrops, and wide valley bottoms. Some of the upland areas are still farmed for permanent hay and small grains; the rest of the watershed has a sparse to moderate forest cover and is grazed about half the year.

In the K41 basin, the Castle Rock Conglomerate is absent and the steepest slopes are about 14%, without the sharp slope breaks found in the B9 watershed at the Castle Rock-Dawson contact. The 208-acre watershed was farmed and grazed through the early 1960's, but was developed as part of a subdivision in 1972, when most of its area was reseeded. Gullying was apparently initiated by the severe 1935 Memorial Day storm (Carl R. Guy, local rancher, pers. comm.), and by 1955 the main channel was incised to a depth of 2 to 4 ft. for about half the length of the basin. Erosion of its tributaries occurred primarily after the dam was built in 1955. Several of the tributaries are graded to the main channel, but others are ungraded and have built small fans at its former floodplain level. K41 dam was constructed with a sediment pool of 1.5 acre-feet, but it has received 5.05 acre-feet in 29 years. Maps of the two basins, traced from aerial photos, are shown in Figures 2 and 3.

Both watersheds have stored sediment in swales, valley bottoms and fans, and in some areas in the B9 basin sediment is found on the slopes at the base of the conglomerate outcrop. This sediment is easily distinguishable from the darker, better-structured buried soils. Early descriptions of the lush

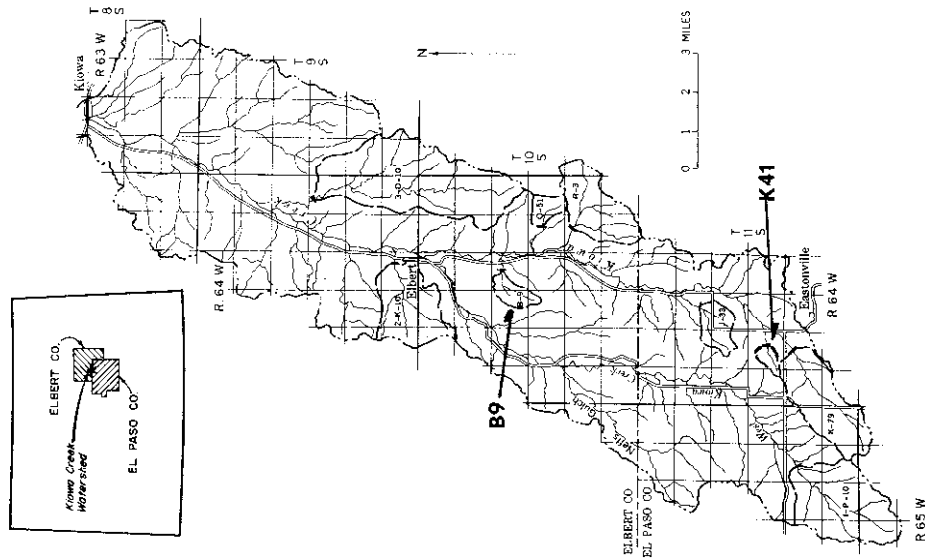


Fig. 1. Location map (base map from Mundorff, 1964).

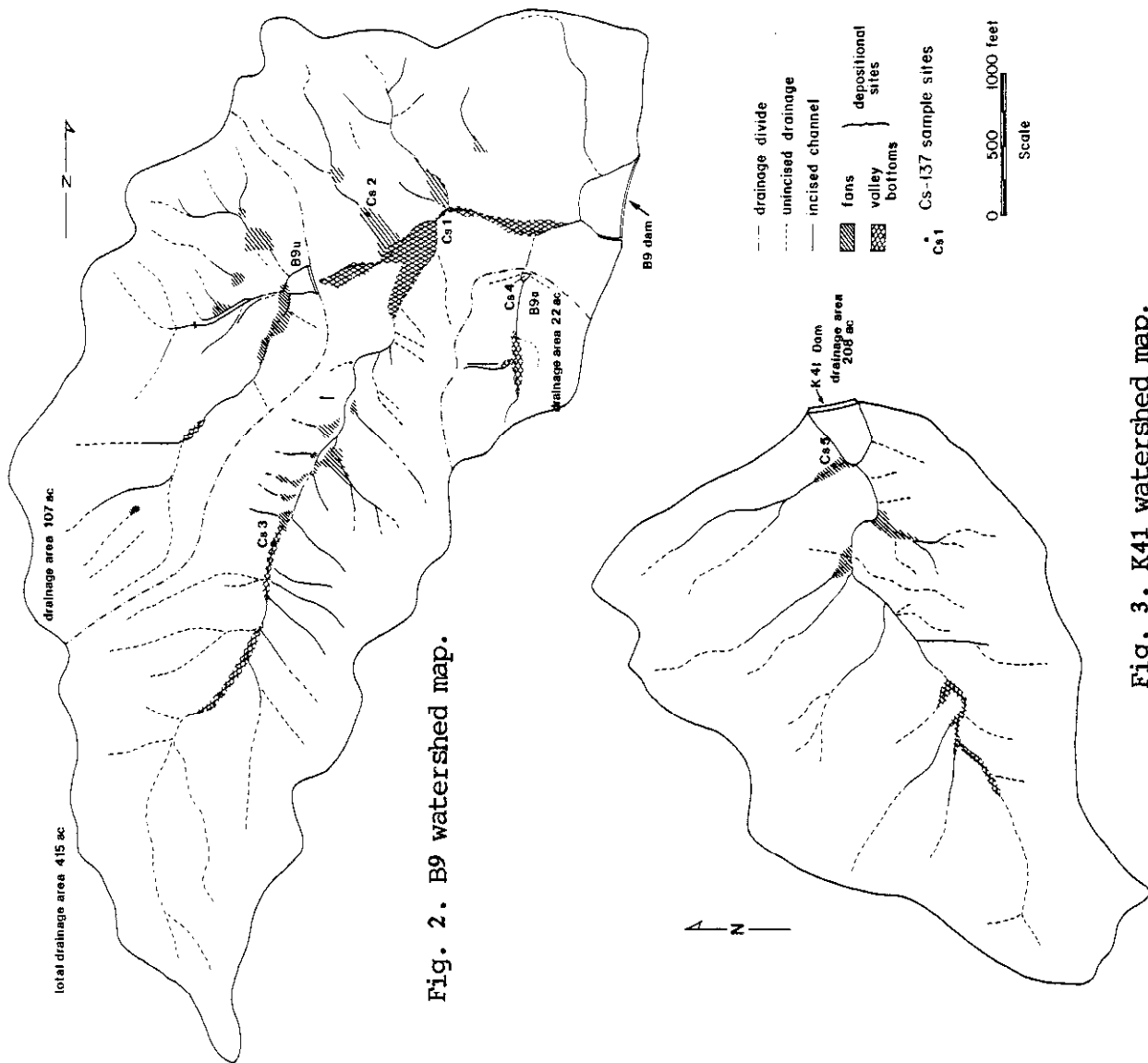


Fig. 2. B9 watershed map.

Fig. 3. K41 watershed map.

meadows, pine forests and clear streams in the area suggest that the land surface was relatively stable when the first settlers arrived in the mid-1860's, and it is reasonable to assume these buried soils represent the surface at that time (Carnahan, 1949; Pierce, 1866). Buried tin cans and well-preserved tree stumps also support the hypothesis that this sediment has been deposited since then. Some sediments, originally deposited in swales and valley bottoms and on fans, have been remobilized by gullies which formed later in those locations. However, where the gullies are discontinuous, at least some of those sediments, along with newly eroded materials, have been redeposited in secondary, perhaps even tertiary, depositional sites.

METHODS

The sediment budgets developed for these basins include sheet/rill and gully erosion as sediment sources, sediment stored in the basins, and sediment delivered to the reservoirs. The budgets cover the entire historical period, from 1865 to the present, the assumed period of accelerated erosion and sedimentation. The drainage areas of the two dams upstream of B9 were treated as independent sediment-yielding units, and their sediment contributions were added to those of the areas draining directly to B9 dam.

Gully volumes were surveyed in the field and their volume changes since dam construction were estimated using the sequence of aerial photos available for the area. The USLE (Wischmeier and Smith, 1978) was used to estimate current and historical rates of sheet and rill erosion, based on field measurements of slope gradient, length, and current cover conditions, and on historical information on land use. Soil erodibility (K) factors given by the Soil Surveys (USDA-Soil Conservation Service, 1975, 1977) and long-term average rainfall and runoff (R) values (USDA-Soil Conservation Service, 1982) were used. We recognize that the application of the USLE on this scale, and on uncultivated and in some cases rocky and very irregular slopes, is able to provide only a very gross estimate of potential soil loss; however, it was the best practicable method of estimating sheet and rill erosion and the results are comparable with values expected for this area.

Sediment accumulation behind the dams was measured by a resurvey of the reservoir area in the case of B9 - the only one with a baseline survey - and by augering or probing the sediment at the other three reservoirs. The volume estimate for K41 was refined by observations made during the sediment excavations which were necessary to restore the dam's capacity. Dam trap efficiencies and sediment densities were estimated. The estimates of sediment density were based on several measurements of sediment in two reservoirs. In-situ soil densities were measured at several locations in both watersheds, and average values were used both for soils and sediments stored upstream of the reservoirs. Average sediment densities and estimated reservoir trap efficiencies are shown in Table 1.

Volumes of material stored in the basins were measured by field surveys and auger probes along transects taken across valleys, fans and other depositional sites. Depths of sediment ranged from a few inches to more than 7 feet; average depths in valley bottoms and swales were on the order of 1 to 2 feet. Sediment depths in fans and colluvial deposits at the base of slopes can only be described as highly variable. Sediment profiles at five locations (Figs. 2

and 3) were sampled in 2-inch increments and analysed for Cs-137 concentrations to provide an estimate of basin storage rates before and after 1954. Although these are point data and cannot be extrapolated to estimate storage rates over the entire basins, they do give a point of reference which can be used to corroborate the sediment budgets.

Measurements of area and relief were made from 1:24,000 USGS topographic maps. Channels were mapped in the field on 1:7920 scale enlarged aerial photos for determination of drainage densities. The basin morphometric characteristics are presented in Table 1.

Table 1 Basin-average erosion and sedimentation rates (tons/acre/year) and morphometric data

	B9a		B9u		B9 (1)		K41	
	1870-1936	1937-1984	1870-1951	1952-1984	1870-1955	1956-1984	1865-1955	1956-1984
EROSION								
Sheet/rill	0.78	0.57	0.77	1.63	0.80	0.89	1.01	0.59
Total gully	0.14	0.004	0.72	0.20	1.34	1.19	0.42	2.30
Total net erosion (2)	0.92	0.57	1.42	1.83	2.07	2.08	1.24	2.89
Observed basin storage	0.17		0.49		1.17		0.21	
Sediment Yield (3)		0.25		0.45		0.20		1.91
SDR		45%		24%		9.5%		66%
Trap Efficiency	90%		90%		100%		80%	
Res. Sed/Soil Density (pcf)	90/96.7		75/96.7		80/96.7		84/95.5	
Basin Area (mi ²)	0.03		0.17		0.45		0.33	
Relief Ratio	0.074		0.060		0.033		0.033	
Drainage Density (mi/mi ²)	9.76		14.96		13.37		11.35	
Main Channel Slope (4)	0.08		0.05		0.03		0.03	
% Area in Dep'l Sites	3.6		6.7		20.2		2.3	

(1) Excluding areas tributary to dams B9a and B9u.

(2) Where sediment was deposited and remobilized by gullying during a single period, the rate of remobilization was subtracted from the total gully erosion rate, to avoid double-counting. For this reason, total net erosion shown is sometimes less than the sum of sheet/rill and total gully erosion.

(3) Adjusted for trap efficiency and sediment density to in-situ soil equivalent weight.

(4) Determined by the method of Williams and Berndt (1972).

RESULTS AND DISCUSSION

Watershed Morphology and Sediment Delivery. Area- and time-averaged erosion and sedimentation rates are shown in Table 1 for the periods before and after dam construction in each of the four basins. Calculated sheet and rill erosion rates for specific subareas ranged from 0.01 t/ac/yr for managed range-land on 3% slopes to 7.7 t/ac/yr for wheat/fallow farming on 6% slopes without conservation practices. The averaged rates reflect different combinations of area and length of time cultivated, and vary by only a small amount. Gully erosion rates, on the other hand, range from essentially zero to 2.3 t/ac/yr. The large differences in the relative importance of gullying as a source of sediment are not reflected in delivery differences. In the B9 basin, for example, gullying accounts for more than half the total erosion and yet

delivery to the dam is only 9.5%. This can be compared to B9u, where gullying over the life of the dam constituted about one-tenth of the total, but where delivery was much higher, 24%. Although delivery is normally expected to be high where channel erosion is important as a sediment source, these results reflect the nature of the incised drainage system, which is not integrated in the B9 basin. As seen in Figure 2, discontinuous gullies alternate with thickly vegetated depositional areas along the length of the basin. K41, which has the highest delivery ratio, also has the highest proportion of erosion due to gullying. In this watershed, however, several tributaries are graded to the main channel, which in turn is continuously incised. Thus there is less opportunity for sediment storage in the drainage system than at B9.

The watershed morphologic data shown in Table 1 and the plots of delivery ratio versus drainage area and relief ratio in Figures 4 and 5 indicate that the differences in delivery among these basins are not well-explained by these characteristics. The trends identified in previous work (Maner, 1958; Roehl, 1962; Williams and Berndt, 1972) are generally followed by the three B9 sub-basins; that is, delivery decreases with increasing drainage area, and increases with average main channel slope and relief ratio. However, in this small data set, K41 is in every case an outlier. With average slopes similar to those of the main B9 basin, its delivery ratio is almost 7 times higher, and it is 2.5 times higher than that of B9u which has half its drainage area. The one characteristic that correlates with the observed delivery variations among all four watersheds (Figure 6) is the fraction of the total basin area occupied by depositional areas: valley bottoms, swales, fans and valley side slopes at the base of much steeper slopes. Definition and measurement of this variable would require care in the case of a basin where actual sites of deposition were unknown. Some field reconnaissance would be needed to identify the types of depositional sites in order to recognize and measure them on aerial photos. A similar observation was made by Hadley and Schumm (1961) in their study of the Cheyenne River Basin in Wyoming. They noted that the percent of the basin area graded to channels versus that graded to terraces and floodplains was associated with delivery.

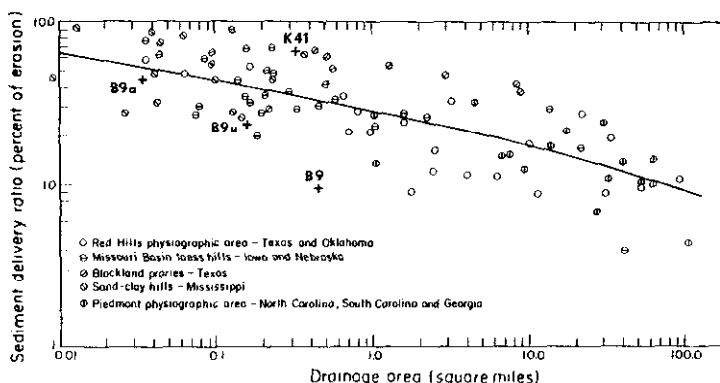


Fig. 4. Roehl's (1962) plot of drainage area versus SDR with K41 and B9 data (post-dam period).

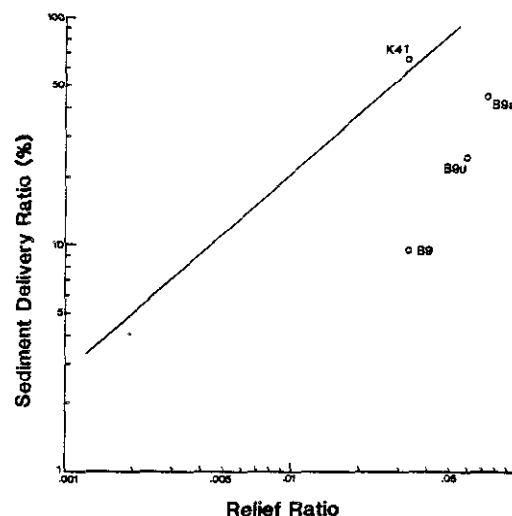
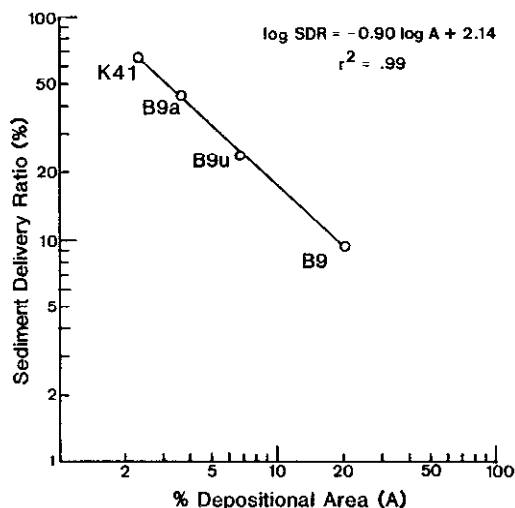


Fig. 5. K41 and B9 data (post-dam period) on SDR vs. relief ratio plot from SCS Tech. Guide 12 (USDA-SCS, 1976).

The relationship shown in Figure 6 is not presented as a universally applicable predictive tool, but rather as an indication that this basin characteristic merits consideration as one among several factors that influence delivery. The three B9 sub-basins are topographically different from K41 in that they have sharp slope breaks at the base of the conglomerate slopes, whereas K41 shows graded convex-concave slope shapes. The two distinct lithologies create in this case a topography with a higher sediment storage capacity than would be expected from average watershed slope or area. A similar observation was made by Hadley and Schumm (1961).

Fig. 6. SDR (post-dam period) versus % basin area in depositional sites.



Changes in Storage and Delivery over Time. Even with the Cs-137 data on pre- and post-1954 depths of sediment deposition in several storage sites upstream of the reservoirs it is not possible to precisely define delivery or sediment yield prior to dam construction. However, two scenarios can be formulated based on different assumptions concerning storage and delivery. Budget scenario A, in Table 2, is based on the assumption that the field surveys of recognizable storage sites successfully estimated the total volume of sediment stored in the basins. The difference between estimated erosion and measured sediment yield is the volume of eroded material stored in the basin over the dam lifetime. This volume was subtracted from the total measured volume of stored sediment, and the remainder ascribed to deposition prior to the dam.

The pre-dam delivery ratios resulting from this scenario are in every case unrealistically high, especially in comparison to those estimated for the dam lifetimes. The only factor that might account for such differences is the effect of the 1935 storm when 12 to 24 inches of rain fell in one day. Another severe storm of unknown magnitude occurred in 1868. However, there have also been severe storms since 1955. In 1965, 4.5 inches fell at B9 (Mitchell et al., 1967) and 6.4 inches at K41 in about 6 hours. In a localized thunderstorm in 1957, 4.5 inches of rain fell in 45 minutes in the watershed adjacent to K41, and although some uncertainty exists with respect to its areal extent, it is likely that at least 2 to 3 inches fell over K41 watershed (Mundorff, 1964). Both of these storms are thought to have exceeded the intensity of the 100-yr frequency storm. Given also the increase in transport efficiency due to the progressively incising drainage network at K41, it is highly improbable that the average delivery ratio has decreased in this basin.

Table 2 Budget scenarios for periods before and after dam construction
(acre-feet)

	B9a		B9u		B9 (1)		K41	
	1870-1936	1937-1984	1870-1951	1952-1984	1870-1955	1956-1984	1865-1955	1956-1984
SCENARIO A (2)								
Net erosion	0.65	0.28	5.92	3.07	30.10	8.16	11.25	8.38
Measured volume of basin storage	0.20		2.88		18.34		2.57	
Basin yield at damsite	0.60	0.13	5.26	0.75	18.35	0.77	11.14	5.55
Net increase in basin storage (3)	0.05	0.15	0.66	2.22	11.75	6.59	0.11	2.46
SDR	92%	45%	88%	24%	61%	9.5%	99%	66%
SCENARIO B (4)								
Calculated net increase in basin storage (5)	0.36	0.15	4.41	2.23	22.73	6.59	2.65	2.46
Basin yield at damsite	0.29	0.13	1.51	0.75	3.27	0.77	8.60	5.55

(1) Sediment yields from basins B9a and B9u were added into the B9 budget.

(2) Scenario A assumes field measurement successfully estimated total volume of sediment stored upstream of dams.

(3) For dam lifetimes, sediment remobilized by gullies was subtracted from (erosion - delivery), to avoid double-counting.

(4) Scenario B assumes constant delivery ratios through time.

(5) Total erosion * (1-SDR), adjusted for sediments deposited and remobilized during a single time period.

This analysis then leads to the conclusion that the original assumption is untenable; that is, much of the material estimated from the USLE as 'soil loss' has evidently remained on slopes, rather than being delivered to the surveyed storage sites. The discrepancy cannot be ascribed merely to deposition at the base of concave slopes unless this process has been slow enough for the added materials to be incorporated into the existing organic matter-rich A horizons. In this regard, it is worth noting that both basins have slopes of relatively high roughness: K41, under native conditions and currently, has a very good grass cover over most of its area, and the conglomerate slopes at B9 are extremely irregular, with many rock outcrops, stones, trees and patches of duff where soil could be trapped.

The second way of handling the available data to estimate storage rate changes between the pre- and post-dam periods is to assume that the delivery ratios estimated for the dam lifetimes are constant long-term average values for each basin. In scenario B, Table 2, these delivery ratios were applied to estimated erosion prior to dam construction to calculate the volume of material which, under this assumption, must have been stored during that period. The measured volumes of stored sediment range from 40-57% of the total volumes calculated in this manner. As the relative importance of gully-ing as a sediment source increases among the basins, the ratio of measured to calculated sediment storage also increases. This may indicate that the total erosion estimate increases in accuracy as sheet and rill erosion become less important. This possibility again leads to the conclusion that the USLE may significantly overestimate rates of soil loss due to sheet and rill erosion on range and forest lands in this area.

This suggestion obviously arouses uncertainty with regard to the attempt to quantify the sediment budgets. Nevertheless, since the USLE was used in a standard and consistent manner, the results should be comparable to those from other locations. Relative differences among the basins in this study are real.

The Cs-137 profiles from the B9 basin showed that about 25% (12 to 40%) of the total sediment depth at two sites (#1 and 2, Fig. 2) in the main valley was deposited since 1954. Further upstream at site 3, the entire 2.5 ft. of sediment were deposited before 1954. These data tend to support the assumption of constant delivery ratios (Scenario B), under which 23 to 34% of the total calculated sediment would have been stored after the dams were built. In reservoir B9a, approximately 32% of the sediment in the sampled profile was deposited since 1954. Taking this as an indicator of the volume of sediment delivered during the periods 1937-54 and 1955-84, the delivery ratios for these periods are 48% and 44%, respectively. This also argues against large changes in average sediment delivery ratio over time.

The sampled profile in the K41 basin showed that 15% of the sediment depth on one of the small fans was deposited after 1954. Because the drainage network in this basin has undergone incision since 1955, with a consequent loss of sediment storage area, Fig. 6 was used to estimate pre-1955 delivery ratios based on the depositional area which existed before major degradation occurred. The resulting delivery ratio is 44%, significantly lower than the current 66%. This would imply a net change in storage of 5.5 acre-feet for the pre-dam period, and it would mean that about 30% of the total was stored after 1955. This is more consistent with the Cs-137 results than either Scenario A or B and is the best estimate of delivery changes over time in the K41 watershed.

CONCLUSIONS

The results of this study illustrate the fact that delivery ratios estimated from empirical relationships with drainage area or channel or watershed slope can result in gross over- or underdesign of reservoir sediment pools. They also point out the importance of considering basin storage capacity and drainage network continuity, especially in areas drained by ephemeral streams. Percent of total basin area in depositional sites is a morphologic variable which can be used to account for these characteristics.

Watershed sediment budgets in conjunction with results from Cs-137 profiles in stored sediments suggest that long-term average delivery ratios have increased in the K41 basin, where drainage network degradation and concurrent loss of storage capacity have occurred since 1955. In the B9 subbasins, where loss of basin storage capacity has been negligible, delivery ratios appear to have remained approximately constant. The budget scenarios suggest that the USLE may significantly overestimate the amount of sheet-eroded material actually transported off slopes to valley bottoms, swales and other storage sites on range and forest lands in Eastern Colorado.

The study leaves unanswered the question of the sensitivity of sediment delivery to the occurrence of severe storms in semi-arid, ephemeral stream drainages. Because delivery depends strongly on channel network continuity, drainage network response to heavy storms merits further research,

particularly with regard to the potential integration of previously discontinuous gullies.

ACKNOWLEDGEMENTS

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SEDIMENT YIELD AND RUNOFF AFTER TIMBER HARVEST

**By Vito A. Ciliberti, Jr., Soils and Water Scientist
Bureau of Land Management, Missoula, Montana, July 1985**

ABSTRACT

Timber management activities in a hard (metamorphosed) sedimentary rock basin from 1978 to 1982 resulted in eight percent of the basin being in "Equivalent Clearcut Status" (i.e., that portion of vegetation removal, per unit area, which responds hydrologically the same as one acre of clearcut).

Annual sediment production of 1.4 to 4.5 tons/sq mi/year approximates the 5.2 tons/sq mi/year provided by the FS model "Guide for Predicting Sediment Yields From Forested Watersheds" (USDA, Forest Service 1981). Calculated annual runoff, based on the Vegetation Manipulation Guidelines (USDA, Forest Service 1973) using average annual isohyetal precipitation data is within 5.5 percent of measured runoff.

These data indicate that sediment production rates and annual runoff have not been altered from natural conditions as defined by the models.

INTRODUCTION

Natural erosional processes which operate to supply sediment to mountain streams can be altered by management activities in forested mountain watersheds. In some instances the effects are small, while in other cases there can be significant impacts. Road construction, yarding, slash disposal, site preparation, and streamside management can accelerate erosional processes (Beschta 1981).

The purpose of this paper is to validate two models which describe the effects of timber management on water yield and sediment production using data collected in the Chamberlain Creek watershed.

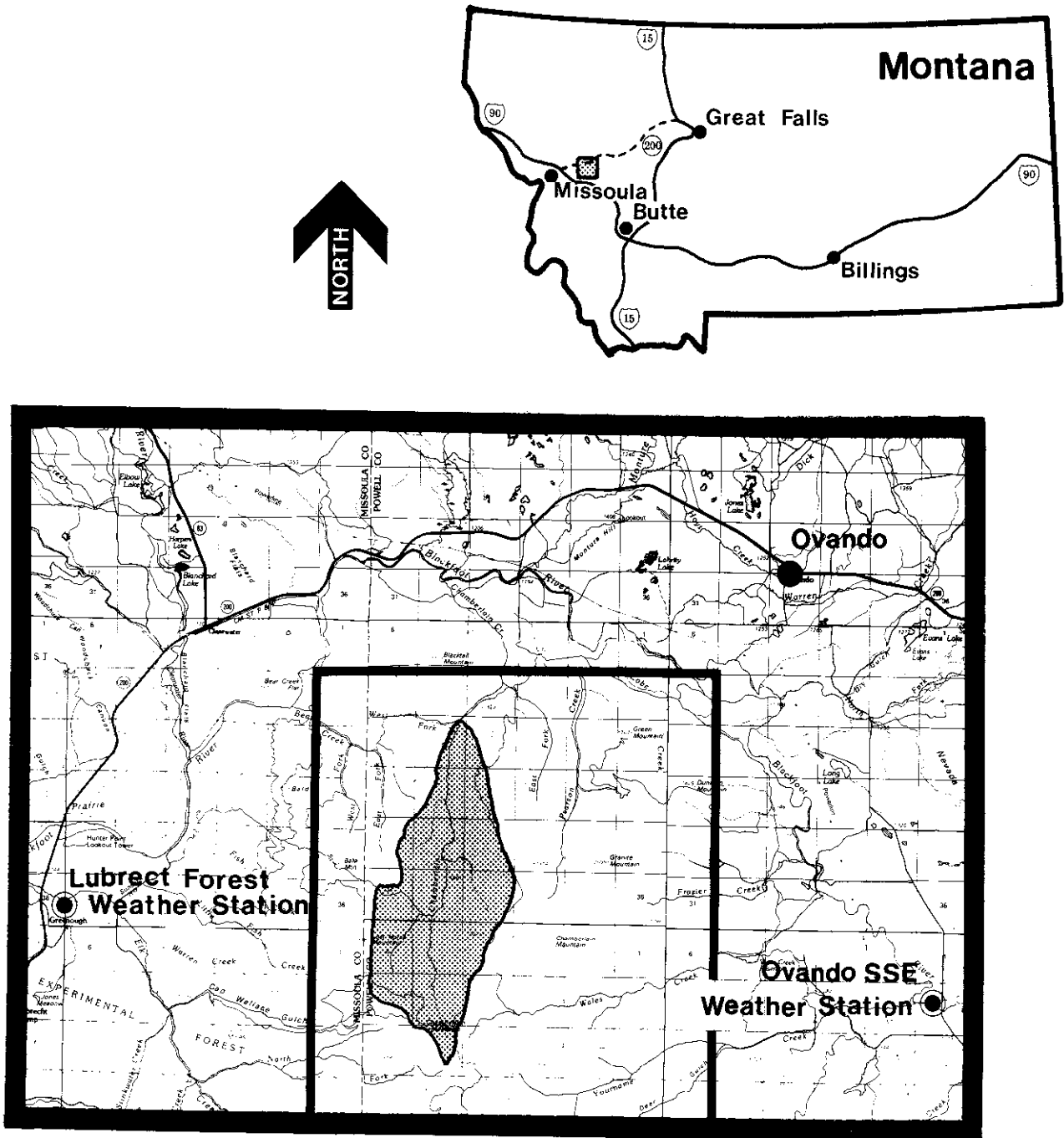
Chamberlain Creek is a north flowing stream about nine miles long. That portion of the drainage south of the north section line of T. 14 N., R. 13 W., Section 17, P.M.M., comprises the analysis area. Basin area above this point is approximately 10.2 square miles (Figure 1).

The study portion of the basin lies almost wholly on metamorphosed sedimentary rock of the Missoula Super Group (approximately 92 percent). The extreme upper reaches of the basin, where the creek is intermittent and of low gradient, are on granodiorite (Morrison and Maierle 1978; Figure 2). Soils formed in hard sediments are predominantly loamy skeletal, mixed, Typic Cryochrepts. Soils formed in granodiorite are predominantly, coarse loamy, mixed, Typic Cryochrepts (USDA, Soil Conservation Service, Personal Communication 1982).

Monitoring of runoff and suspended sediment began at the beginning of the 1979 water year and continued through the 1984 water year (October 1, 1978 — September 30, 1984).

Residual water yield increase, traceable to timber management activities prior to 1978, was considered to be inconsequential based on aerial photo analysis and calculations using the runoff model. The residual water yield increase was calculated to be about one percent. Old roads and skid trails have stabilized to the extent that little sediment is coming from them.

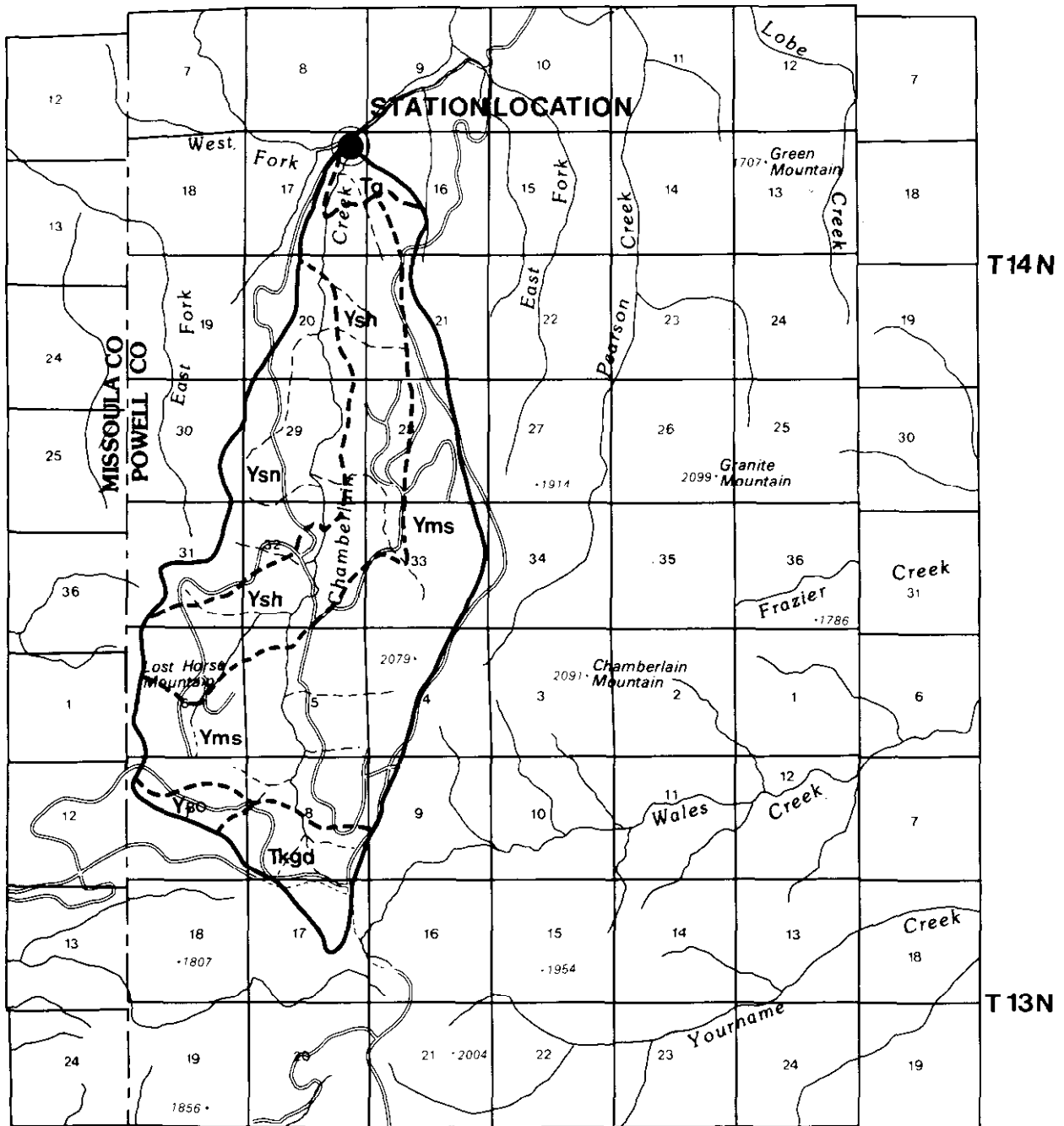
Figure 1 LOCATION MAP



● Weather Station

▨ Chamberlin Creek Drainage

FIGURE 2 GEOLOGY



R13W

- | | | | | | |
|--|----------------------------|-------------|--------------------------|------------|---------------------|
| | BOUNDARY | Tg | Tertiary Gravels | Ysh | Sheppard Fm. |
| | ROAD | Tkgd | Granodiorite | | |
| | TRAIL | Ybo | Bonner Quartzite | | |
| | STREAM | Yms | Mount Shields Fm. | | |
| | INTERMITTENT STREAM | Ysn | Snowslip Fm. | | |

1 0 1 2
MILES



Timber removals and road construction occurring from 1978 to 1982 resulted in about eight percent of the basin being in "Equivalent Clearcut Acres" (ECA). The runoff model used in this analysis (USDA, Forest Service 1973) indicates that basin ECA has to exceed 15 percent before an increase in annual discharge will be realized. Debano (1977) reports that in the southwest, selection cutting of up to 45 percent removal has little effect on water yield, while clearcutting (either large or small openings) increased water yield almost in proportion to the area cleared. Megahan (date not available) reported no increase in water yield in Appalachian highlands with 12 percent of the forest stand removed. Foggin and Forcier (1974), in their study of first order basins in western Montana with at least 75 percent basal area removed (nine years old), report that crude estimates of surface discharge generally indicate a greater discharge flowing from clearcut basins than from similar forested basins.

METHODOLOGY

Annual runoff and suspended sediment yield measurements were made to validate existing predictive models. The models tested are "Vegetation Manipulation Guidelines" (USDA, Forest Service 1973) and "Guide for Predicting Sediment Yields from Forested Watersheds" (USDA, Forest Service 1981). These are currently in use by the Forest Service in Region One.

The Vegetation Manipulation Guideline model is based upon "Hydrology of Mountain Watersheds" (USDA, Soil Conservation Service 1971), a study involving numerous basins in western Montana over a number of years. This model shows a "consistent relationship" between annual runoff and annual precipitation in undisturbed basins ($r = 0.96$, that portion of the model used for comparison has an r of 0.84). The Forest Service model in conjunction with the SCS model, provides a means of estimating the increase in runoff traceable to reduced evapotranspiration resulting from timber management activities. The model also accommodates recovery of evapotranspiration and the effect of removing less than 100 percent of the vegetation in a given area. This latter aspect is the "Equivalent Clearcut Acre" which is that portion of vegetation removal, per unit area, which responds hydrologically the same as one acre of clearcut. The model was used to determine if management activities had:

- (1) Caused an increase in annual runoff.
- (2) Resulted in a change in the slope of the precipitation runoff regressions.

The sediment model "Guide for Predicting Sediment Yields from Forested Watersheds" (USDA, Forest Service 1981) provides quantified estimates of sediment yield prior to management activities (natural sediment yield). It also provides a means of comparing sediment yields, over time, for a variety of management scenarios. This model is based upon Forest Service research on granitic watersheds with gradients near 60 percent. Geologic erosion factors are calculated for a variety of basin bedrock types using acid igneous (granitic) basin erosion rates as the reference point. The model was used to compare measured versus predicted sediment production.

Discharge was measured with a Price AA current meter 9-12 times/year with most measurements occurring during spring runoff (mid-May to mid-July). Suspended sediment sampling occurred when discharge was measured. These data were used to construct hydrographs and suspended sediment curves which were the basis for calculating annual runoff and suspended sediment production.

Precipitation data were obtained from the National Oceanic and Atmospheric Administration (Ovando, Montana SSE) and the University of Montana Lubrecht Experimental Forest weather station which are ten miles east and west of the drainage (Figure 1).

RESULTS

RUNOFF

Annual runoff versus precipitation, compared on the basis of model slope does not appear to have changed as a result of recent timber management activities. Slope analysis, using a two sample "t" test indicated there is no difference at the 99.9 percent confidence level (Tables 1 and 2). Correlation coefficients for the runoff versus precipitation curves (Table 1, Figure 3) are similar, these factors indicate that the model and Chamberlain Creek basin respond similarly to precipitation input. Measured annual runoff was 5.5 percent greater than runoff calculated from the model (i.e., runoff based on isohyetal map precipitation). This is not significant at the 99.9 percent level (Table 2).

TABLE 1
SUMMARY OF STATISTICAL DATA COMPARING RUNOFF
CURVES AND PFANKUCH MODEL

	Slope	r ¹	Confidence Limit
1. Runoff Model (precipitation vs. runoff)	0.0475	0.839	99.9
2. Chamberlain Creek			
a. Ovando SSE NOAA (precipitation vs. runoff)	0.0493	0.892	95.0
b. Lubrecht Forest (precipitation vs. runoff)	0.0449	0.883	95.0

¹ Correlation Coefficient

TABLE 2
CHAMBERLAIN CREEK RUNOFF AND SUSPENDED SEDIMENT PRODUCTION

	Water Year					
	1979	1980	1981	1982	1983	1984
Annual runoff-acre feet ¹	3170	3617	3589	5439	4174	4814
Maximum instantaneous discharge — ft ³ /sec	26.4	70.6	22.3	66.3	38.3	38.8
Annual suspended sediment production — tons	10.9	36.6	12.0	29.5	21.2	28.1
Spring runoff period sediment production — percent of total	92.7	96.2	88.3	95.3	76.9	88.6
Suspended sediment production tons/sq mi/yr	1.1	3.6	1.2	3.0	2.1	2.8
Calculated total sediment (bed load suspended) tons/sq mi/year ²	1.4	4.5	1.5	3.8	2.6	3.5
Annual precipitation — inches						
Ovando SSE NOAA center of Sec. 12, T13N, R12W	9.8	17.6	13.2	16.3	15.5	14.2
Lubrecht Exp. Forest SE¼SE¼, Sec. 12, T13N, R15W	14.1	20.0	16.4	22.7	19.5	18.6

¹ Annual runoff as estimated from the model is 3,917 ac ft/year. Average annual runoff as measured for six years is 4,133 ac ft/year. Measured runoff is about 5.5 percent greater than calculated runoff.

² Hammer, R. G. Personal Communication. 1981. Suspended sediment represents about 80 percent of total load (bed load plus suspended sediment) in hard sedimentary rock basins.

SEDIMENT

Calculated total sediment load (bed load plus suspended sediment) ranged from 1.4 to 4.5 tons/sq mi/year (Table 2). Total load was calculated by assuming that suspended sediment represents 80 percent of the total load in hard sedimentary rock basins (R. G. Hammer, Personal Communication 1981). These data compare favorably with the sediment model which provides a figure of 5.2 tons/sq mi/year from hard sedimentary rock basins in a "natural" (undisturbed) state.

Annual suspended sediment production, within the limits of these data, is linearly related to flow as shown in Figure 4. The correlation coefficient for these data is 0.97, significant at the 99 percent confidence level.

Spring runoff periods provide 77 to 96 percent of the annual suspended sediment production. Correlation coefficient data is similar to that for annual sediment production.

Figure 3
Annual Precipitation vs. Runoff

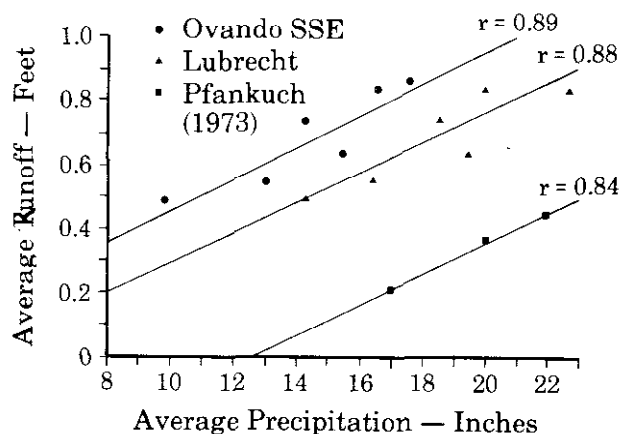


Figure 4
Run-off Flow vs. Suspended Sediment Production

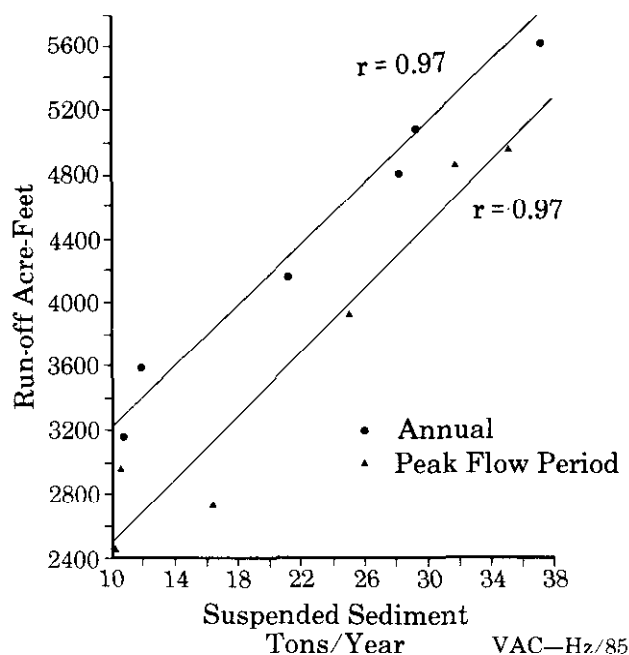
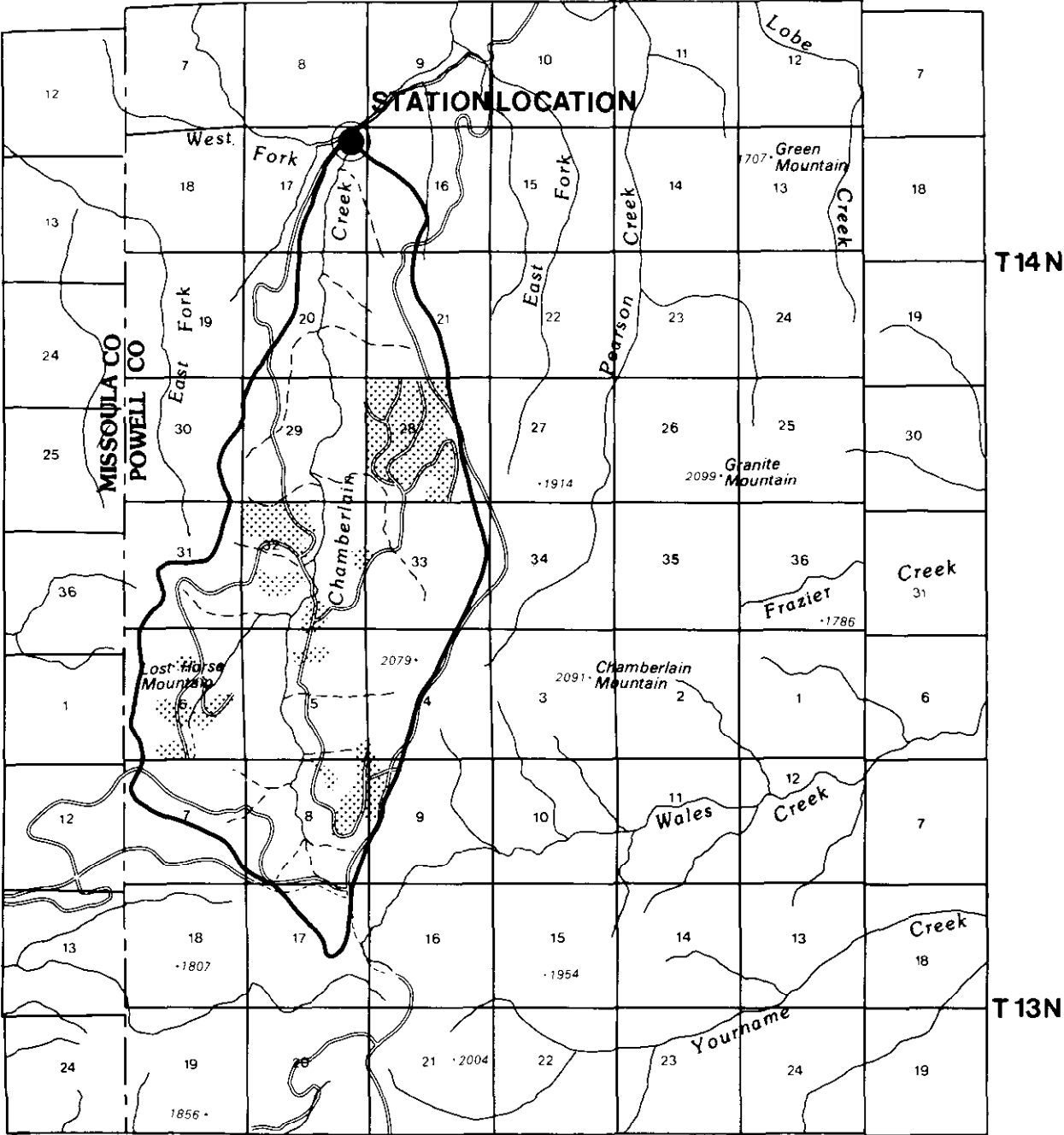


FIGURE 5 Cutting Units



- BOUNDARY
- ROAD
- TRAIL
- STREAM
- INTERMITTENT STREAM
- Cutting Units



CONCLUSIONS

The following conclusions were derived from data generated by this analysis.

1. Increase in runoff, traceable to vegetation removal, has not reached the detection limit (the model establishes that removal of up to 15 percent of crown cover has no effect upon water yield).
2. The runoff-precipitation relationship as defined by the model is valid on this type of basin (rate of runoff and annual runoff data support this conclusion).
3. The sediment model's estimate of 5.2 tons/sq/mi/year for total sediment production is basically valid for this type of basin. Note that although there have been recent timber management activities, the location of the cutting units and roads generally away from stream channels resulted in little or no sediment moving into stream channels (Figure 5).
4. Sediment production approaches the natural erosion rate. Annual sediment production and channel condition support this conclusion.

FUTURE WORK

Model validation will continue. In 1984 continuous discharge measurement, spring runoff period continuous suspended sediment sampling, and a precipitation gage were installed in the basin to provide additional data.

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RIVER SEDIMENT BUDGET

By Edward F. Sing, M. ASCE, Hydraulic Engineer,
US Army Engineer District, Sacramento, California.

ABSTRACT

In the analysis of river basins, river engineers have developed complex analytical techniques for evaluating the sediment transport characteristics of rivers and their watersheds but have overlooked a simple yet useful tool - the sediment budget. This budget, much like its financial counterpart, identifies inputs and outputs to the river system and the relative importance of each to the system. A case study will be presented of a sediment budget developed for the Sacramento River in Northern California. Evaluation of the budget, together with results from more complex analytical models of the River, provided a comprehensive view of the response of the river system to proposed additional bank protection measures in the upper Sacramento River.

INTRODUCTION

In a financial budget, the assets and liabilities of a financial unit are identified, quantified and balanced. Similarly, the purposes of a sediment budget are to identify and quantify sources of sediment (as well as water) and its movement through a river system. In the budget, the total annual sediment input to the system from tributaries, upstream sources, ungauged watersheds, bank erosion and bed degradation is balanced against sediment delivered to the downstream areas, overbank areas (including flow diversions) and bed aggradation. Utilization of the budget allows the assessment of the relative importance of various sources, identifies river reaches where the river's sediment transport capacity exceeds or is inadequate to transport the imposed load and identifies deficiencies in the water and sediment data bases. Evaluation of the budget data base also can provide a comprehensive view of the response of a river system to changes in the input values.

River engineers have developed ever more complex and sophisticated analytical techniques for evaluating the sediment transport characteristics of rivers and their watersheds. However, the simple but effective sediment budget can be used to complement the results from the more complex techniques. To illustrate the utility and simplicity of the sediment budget, following is a case study of its use on the Sacramento River in Northern California to provide a comprehensive view of the response of the river system to proposed additional bank protection measures in the upper Sacramento River.

AREA OF INVESTIGATION

The study area covers the Sacramento River from Keswick Dam downstream for 240 miles to Sacramento with a drainage area of about 23,500 square miles. (See Figure 1.) (Corps, 1981) The Sacramento River is an alluvial stream originating near the slopes of Mount Shasta and flowing generally southward through the Sacramento Valley to Suisun Bay at Collinsville. Its principal tributaries arise in the Cascade Coast Range Mountains on the west and in the Sierra Nevada Mountains on the East. The average annual natural runoff transported by the Sacramento River is approximately 17 million acre-feet. Peak flows are normally experienced during the winter months of December, January, and February. Secondary peak flows of smaller magnitude often occur during the months of May and June as a result of snowmelt runoff from the surrounding mountains. Little or no rainfall occurs in the Sacramento River Basin during the summer and early fall months. Thus, these months have a history of low

river flows. However, the natural flows of the Sacramento River have been greatly modified primarily by regulation of runoff. Shasta Dam, located about 9 miles north of Redding above Keswick Dam on the mainstem of the Sacramento River, helps to control floodflows and increase summer flows.

The Sacramento River regularly floods low-lying basins on both sides of the river between Red Bluff and Ord Ferry (near Butte City) as a result of winter and spring storms. Butte Basin, beginning near the vicinity of Chico and extending south to Sutter Buttes, is the most northerly of the natural flood relief basins flanking the Sacramento River. (See Figure 1.) (USGS 1978). Below Ord Ferry (River Mile 184) the river is contained by levees on both banks, with floodflows prevented from overtopping the levees by an extensive system of weirs and bypass channels. Moulton Weir (River Mile 158) and Colusa Weir (River Mile 146), the northernmost elements of the system, divert floodflows into Butte Basin, resulting in a decrease in the mean annual discharge in the River of 1.2 million acre-feet between Butte City and Colusa. Further south, Tisdale Weir (River Mile 118) diverts floodflows into Sutter Bypass, resulting in a decrease in the mean annual discharge in the River of 342,000 acre-feet from Colusa to Knights Landing.

Floodflows within the Sutter Bypass combine with flows from the Feather River approximately 10 miles upstream of its confluence with the Sacramento River. The Feather River joins the Sacramento River near Verona and increases the mean annual discharge by about 8 million acre-feet. Floodflows in the Sacramento River in the area of its confluence with the Feather River are allowed to flow over the Fremont Weir (River Mile 82) and into the Yolo Bypass, to relieve flood pressures through the city of Sacramento. At Sacramento, the American River joins the River and increases the mean annual discharge by about 2.5 million acre-feet. Below Sacramento, the Sacramento River enters the Sacramento-San Joaquin Delta, the southernmost element of the system.

SEDIMENT TRANSPORT STUDIES

Sediment transport and related studies were conducted as part of the Sacramento River and Tributaries Bank Protection and Erosion Control Investigation to determine the potential effects relative to sediment transport that might be induced by a proposed comprehensive channel stabilization plan along the upper reaches of the Sacramento River. Among other objectives, these studies evaluated what reductions would be produced by implementation of the plan in the rates of sediment delivery to the mainstream of the River: (1) by Reaches; (2) to the flood control bypasses; and (3) at Sacramento. Various analytical techniques were used to evaluate the sediment transport characteristics of the River system under both preproject (existing) and project (with proposed bank protection) conditions and address all the questions posed of the overall investigation. A major component study of the Investigation involved the use of sediment budgets to evaluate preproject and project conditions, supplemented by information from mathematical sediment transport models of the river system. Another component study involved development of the bank erosion and bar deposition volumes in the unleveed and partially unprotected reach between Red Bluff (River Mile 243) and Colusa (River Mile 143). The breakdown of these volumes into fines (wash load) and coarse (bed material load) fractions is based on data obtained from bank and bar material samples and is shown in Table I below:

TABLE I
BANK EROSION AND BAR DEPOSITION VOLUMES
RED BLUFF TO COLUSA 2/

River Reach	Type	Sediment Volumes 1/		
		Fines (<0.062 mm)	Coarse (>0.062mm)	Total
240+ to 199	Erosion	275	1,995	2,270
	Deposition	32	1,618	1,650
199 to 168	Erosion	1,048	2,402	3,450
	Deposition	251	2,259	2,510
168 to 143	Erosion	937	863	1,800
	Deposition	130	1,170	1,300
Total	Erosion	2,260	5,260	7,520
	Deposition	423	5,047	5,460

Notes:

1. In 1,000's tons per year; 2. River Miles 243 to 143

SEDIMENT BUDGET (Existing Condition)

The first step of the budget study was a compilation of a list of tributary areas and inflow/diversion point to the Sacramento River from Keswick Dam (River Mile 302) to Sacramento (River Mile 60). From this list, 21 tributary, inflow/diversion points and mainstem stations were chosen to be included in the budget. These represented major diversions and/or sediment contributors for which some water and sediment data were available or could be developed. The principal source of sediment data was the data acquisition program conducted by the United States Geological Survey (USGS-Sacramento Subdistrict) for the Sacramento District Corps of Engineers between Water Year (WY) 77 and WY80. Data at all program stations included water and suspended load discharge data with some measured bedload discharge. Because not all stations were operated for the full program period, the USGS was requested by the Corps of Engineers to compile available sediment data consisting of monthly and yearly sediment and water contributions to the river for the nineteen year period 1961-1979, which includes two wet-dry hydrologic cycles, and to synthesize any missing data within this period based on analysis of the available data. All stations used in the USGS study had water discharge data while most had at least some suspended load data. A few either had no sediment data or only fragmentary records.

The sediment budget shown in Figure 2 was derived using the USGS results and other information on bank eroded material (Corps, 1983), bar deposition, bypass deposition, etc. developed in other elements of the District's investigation. The stations analysed by the USGS include only mainstem river stations and major tributaries. Contributions to the system from other sediment sources (such as from ungauged watershed areas, bank erosion, bed degradation, etc.) and diversions from the system (such as bed, bar and overbank deposition, irrigation canals and pumps, natural overflows, streambed mining, etc.) were estimated from a variety of information sources (Vanoni, 1977). This sediment budget represents current (preproject) conditions and is divided into

six river reaches as defined by main channel USGS river stations. The budget is annotated with some of the assumptions utilized in its development. Within each reach the sum of the inflowing load at the upstream main channel station with sediment inputs (tributary inflow, bank eroded material, etc.) and outputs (dredging, diversions, channel deposition, etc.) was computed and then subtracted from the outflowing load at the downstream main channel station. The resulting value is listed as an "imbalance" in the table. Positive values of imbalance indicate that the computed sediment outflow (at the downstream main channel station of the reach) is greater than the computed sum of upstream inputs within the reach (negative numbers indicate the converse).

Although the imbalances shown in Figure 2 are well within the general level of accuracy of sediment transport evaluations, they can also be attributed to many factors such as errors in suspended sediment measurements and insufficient data on sediment discharges, channel degradation and aggradation, and commercial sand and gravel extractions. The imbalances could also be due to changes in the physical system over time, such as water imports/exports, flow regulation, levees, natural overflows, etc. Also, sediment discharge relationships are highly variable and can be a function of water discharge, season and antecedent conditions. However, no effort was made to remove the imbalances as available data did not justify changes.

Estimates of transported fines and coarse material were based on size fraction distributions developed primarily for the sediment transport simulations (HEC-6 computer models). The sediment transport simulations were another component study of the overall investigation. The two general sediment size classes were chosen to roughly correspond to their primary mode of transport: the fines as suspended load (a function of availability), and the coarse fractions as bedload (a function of channel hydraulics).

SEDIMENT BUDGET (Project Conditions)

The project condition sediment budget was developed to aid in evaluating the effects of stabilizing the banks of the upper Sacramento River. The project bank protection was assumed to be 100 percent effective and the corresponding bar growth eliminated. These assumptions represent a limiting condition. Further, the "imbalance" values developed in the preproject sediment budget were assumed valid (i.e., the same as the preproject) for the project condition budget. Trap efficiencies of the Butte Basin, Sutter Bypass, and Yolo Bypass were also assumed to remain constant. Results of the Project Condition Sediment Budget are also presented in Figure 2. This budget represents the limiting (ultimate) case of bank protection.

The existing condition or preproject budget reveals some interesting basin transport characteristics. Table II is a summary of system sources and sinks derived from the budget:

TABLE II
SACRAMENTO RIVER BASIN
SUMMARY OF INFLOWS/OUTFLOWS ^{1/}
(Existing and Project Conditions)

	Preproject (Existing)		Project
<u>Sediment Sources (Basin Inflows)</u>			
Sacramento River at Keswick	240		240
Bank Erosion	7,520		0
Gaged Tributary Areas	3,860		3,860
Ungaged Tributary Areas	470		470
Other (Sutter Bypass Return)	610		376
<u>Sediment Sinks (Basin Outflows)</u>			
Bar Deposition	5,460		0
Diversions	2,597		1,424
Sacramento River at Sacramento	3,250		2,129
(Imbalance)	(1,393)		(1,393)
	<u>12,700</u>	<u>12,700</u>	<u>4,946</u>

^{1/} In 1,000 Tons per year

These figures show the bank eroded material, at 7.5 million tons per year, is by far the primary source of material available for transport. While the total of the system inflows is 12.7 million tons per year, the total load (as can be seen in Figure 2) passing any of the mainstem river stations doesn't exceed 4.3 million tons per year. The total load at any mainstem station is relatively uniform, on the order of 3 million tons per year. This would tend to imply massive deposition in the main river. Historical records show this has not been the case; although much of this eroded material is deposited into bar deposits, a large quantity is diverted over the weirs into the bypasses.

Examining the differences between the preproject and project budgets provides insight into the disposition of the eroded sediment in the system. The difference represents the reduction in sediment deposition and of delivery of sediment to various locations along the River and to the Bay-Delta system, which could be expected under project conditions. These reductions are presented in Table III. The figures indicate that bank eroded material is the source of about one million tons of the material transported past Sacramento. This is approximately one-third of the material annually transported past Sacramento. Therefore, if a project were to halt bank erosion entirely, a reduction of one-third of the transport past Sacramento could be expected.

Using a technique of routing the net amount of bank material (i.e., Eroded less Deposited Volume) through the river system, the distribution of reduced deposition in the river's overflow areas can be determined (as shown in Table IV). It shows that about one half of the material (all sizes) deposited in the Colusa Weir Bypass and Settling Basin is bank eroded material as is about one third of the deposition in the Sutter Bypass.

TABLE III
COMPARISON OF SEDIMENT LOAD
AT VARIOUS RIVER STATIONS
VS. BANK ERODED MATERIAL
(IN 1000 TONS/YEAR)

	Portion of River Sediment Discharge Which is Bank Eroded Material			Sediment Discharge of River		
	Fines	Coarse	Total	Fines	Coarse	Total
	(<0.062mm)	(>0.062mm)		(<0.062mm)	(>0.062mm)	
<u>Sacramento River At:</u>						
Hamilton City	243	377	620	2881	1039	3920
Butte City	1030	516	1546	3469	851	4320
Colusa	1599	(-7)	1592	2442	588	3030
Knights's Landing	1355	(-7) 1/	1348	2017	573	2590
Sacramento	1123	2	1125	2216	1124	3250

1/ Negative value denotes deposition of bank eroded sediments.

TABLE IV
DEPOSITION OF BANK ERODED SEDIMENTS
VS. TOTAL DEPOSITION-EXISTING CONDITIONS
(IN 1000 TONS/YEAR)

	Deposition of Bank Eroded Sediments 1/			Total Deposition Existing Conditions		
	Fines	Coarse	Total	Fines	Coarse	Total
	(<0.062mm)	(>0.062mm)		(<0.062mm)	(>0.062mm)	
<u>BUTTE BASIN</u>						
Natural Overflow to Long Bridge	0	4	4	-	-	- 2/
Colusa Weir Basin	56	97	153	190	146	336
<u>SUTTER BYPASS</u>						
Long Bridge to Tisdale Weir	16	37	53	74	61	135
Tisdale Weir Basin	20	0	20	30	50	80
Tisdale Weir to Hwy 113	192	68	260	546	137	683
<u>YOLO BYPASS</u>						
Fremont Weir to Sacramento Delta	196	0	196	351	77	428
<u>OTHER</u>						
Agricultural Diversions	79	0	79	130	0	130
TOTAL	559	211	770	-	-	-

1/ Assuming the bank protection project is 100% effective, the Project Reduction in Deposition is equivalent to the Deposition of Bank Eroded Sediments.

2/ Information not available.

CONCLUSIONS

Sediment budgets can be used as a simple but useful tool to identify and quantify sediment inflows and outflows to a river system and aid in evaluating the disposition of sediments within the system itself. In essence, it is a "book-keeping" system. The sensitivity of various elements of the budget to changes in other elements can be readily evaluated.

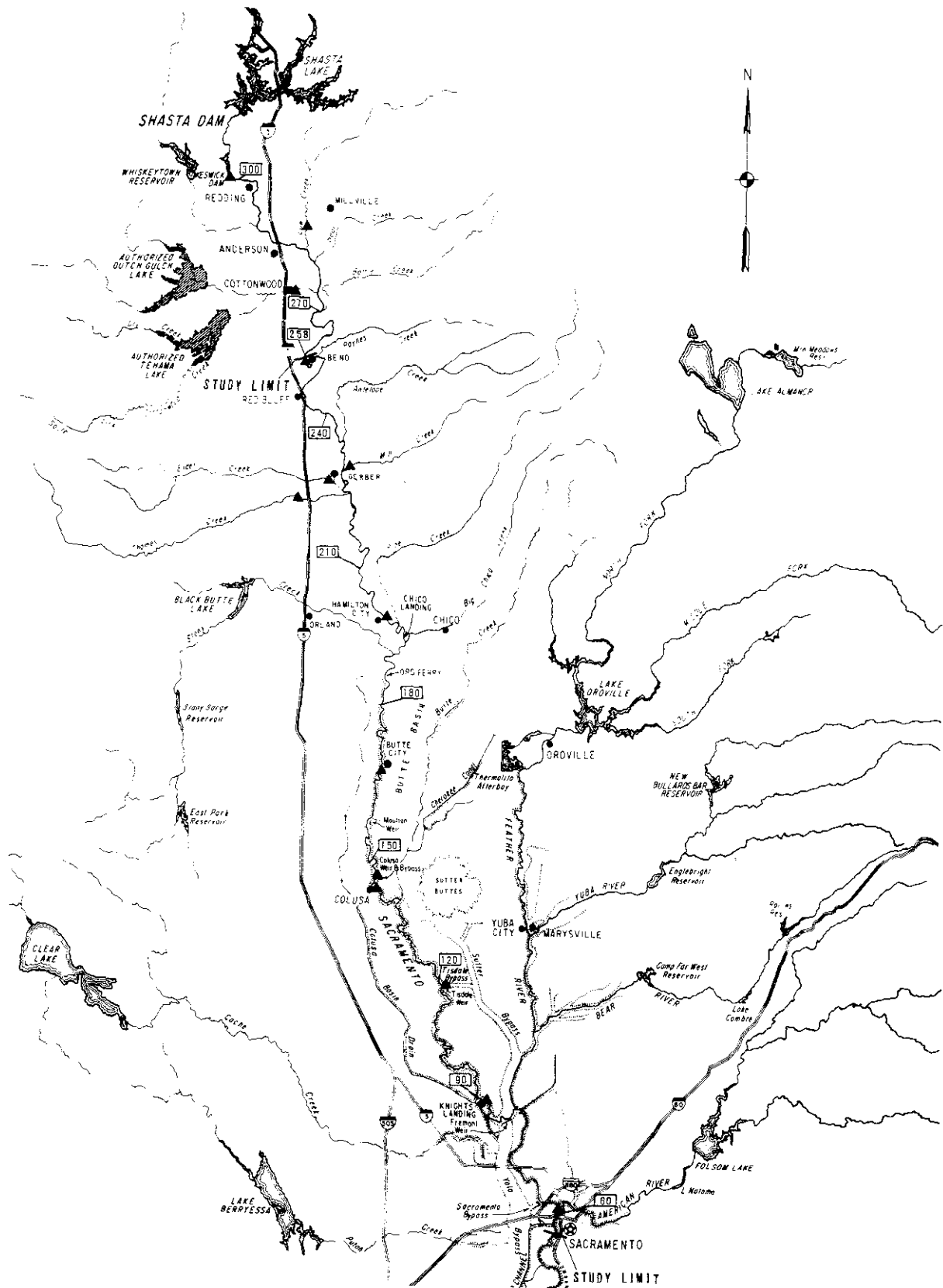
A case study has been presented of the impacts of a proposed comprehensive bank protection program on the upper portion of the Sacramento River in Northern California. Evaluation of the budgets for this study revealed that bank eroded material contributes about 60%, or 7.5 million tons per year, of the total sediment inflow of 12.7 million tons per year into the river system (Corps, 1983). Much of this eroded material is carried down through the river system and deposits into the flood control bypasses and downstream navigation channels. This material must be removed if the effectiveness of the flood control system and the navigation channels are to be maintained. Assuming that the proposed bank protection project is 100% effective in reducing the bank erosion rate, it is estimated the amount of material passing Sacramento will be reduced one million tons per year resulting in a significant reduction in the amount of dredging required in the downstream ship channels and flood control bypasses.

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Sacramento River Basin
Study Area Map

SACRAMENTO RIVER
(KESWICK TO SACRAMENTO)
SEDIMENT BUDGET

RIVER MILE	MAIN STEM TRIBUTARY	DRAINAGE AREA (Sq. Mi.)	$Q_w \times 10^6$ SFD	EXISTING (PREPROJECT)				PROJECT CONDITIONS			
				$Q_s \times 10^3$ TONS/YEAR			REFERENCE	$Q_s \times 10^3$ TONS/YEAR			REFERENCE
				CLAY AND SILT	SAND AND GRAVEL	TOTAL		CLAY AND SILT	SAND AND GRAVEL	TOTAL	
302	Koswick	6,468	3.718	223	17	240		223	17	240	
280	Cow Creek	425E	0.249	163	57	220		163	57	220	
273	Cottonwood Creek	927W	0.308	551	359	910		551	359	910	
271	Battle Creek	357E	0.182	28	12	40		28	12	40	
--	UNGAGED AREA	217E	723								
--	200 T/sq. mi./year	245V		169	51	220	1a, 2	169	51	220	1a, 2
--	500 T/sq. mi./year	261W									
--	Imbalance	--	0.239	546	-166	380		546	-166	380	16
260	Bend Bridge	8,900	4.696	1,680	330	2,010		1,680	330	2,010	
230	Elder Creek	136W	0.033	98	32	130		98	32	130	
230	Mill Creek	133E	0.111	46	24	70		46	24	70	
225	Thomas Creek	284W	0.135	513	317	830		513	317	830	
219	Deer Creek	210E	0.115	138	92	230		138	92	230	
240/199	Bank Erosion	--	--	275	1,995	2,270	3	0	0	0	17
240/199	Bar Deposition	--	--	-32	-1,618	-1,650	4	0	0	0	17
--	UNGAGED AREA	349E	1,172								
--	100 T/sq. mi./year	611V		130	30	160	1b, 15	130	30	160	1b, 15
--	300 T/sq. mi./year	212W									
--	Imbalance	--	-0.169	33	-163	-130		33	-163	-130	16
199	Hamilton City	10,835	4.921	2,881	1,039	3,920		2,638	662	3,300	
--	Natural Overflow	--	-0.110	-120	-10	-130	5, 6	-110	-6	-116	5, 6
199/168	Bank Erosion	--	--	1,048	2,402	3,450	3	0	0	0	17
199/168	Bar Deposition	--	--	-251	-2,259	-2,510	4	0	0	0	17
--	UNGAGED AREA	220E	1,240								
--	50 T/sq. mi./year	288V		51	9	60	1c, 6	51	9	60	1c, 6
--	50 T/sq. mi./year	732W									
--	Imbalance	--	0.289	-140	-330	-470		-140	-330	-470	16
168	Butte City	12,075	5.100	3,469	851	4,320		2,439	335	2,774	

SACRAMENTO RIVER
(KESWICK TO SACRAMENTO)
SEDIMENT BUDGET
(Continued)

RIVER MILE	MAIN STEM TRIBUTARY	DRAINAGE AREA (Sq. Mi.)	$Q_w \times 10^6$ SFD	EXISTING (PREPROJECT)				PROJECT CONDITIONS			
				$Q_s \times 10^3$ TONS/YEAR			REFERENCE	$Q_s \times 10^3$ TONS/YEAR			REFERENCE
				CLAY AND SILT	SAND AND GRAVEL	TOTAL		CLAY AND SILT	SAND AND GRAVEL	TOTAL	
168	Butte City	12,075	5.100	3,469	851	4,320		2,439	335	2,774	
158	Moulton Weir	--	-0.063	-142	-8	-150		-100	-3	-103	18
146	Colusa Weir	--	-0.485	-659	-348	-1,007	7	-463	-137	-600	7, 19
168/143	Bank Erosion	--	--	937	863	1,800	3	0	0	0	17
168/143	Bar Deposition	--	--	-130	-1,170	-1,300	4	0	0	0	17
	UNGAGED AREA	15V	--	0	0	0	1c	0	0	0	1c
--	Imbalance	--	-0.088	-1,003	400	-633		-1,033	400	-633	16
143	Colusa	12,090	4.464	2,442	588	3,030		843	595	1,438	
118	Tisdale Weir	--	-0.310	-372	-78	-450		-128	-78	-206	20
--	Imbalance	--	0.128	-53	63	10		-53	63	10	16
90	Knights Landing	14,535	4.282	2,017	573	2,590		662	580	1,242	
82	Sutter Bypass	--	1.188	592	18	610	16	384	9	393	21
82	Yolo Bypass	--	-1.134	-552	-28	-580	8	-221	-28	-249	8, 22
80	Feather River	5,291	2.873	553	837	1,390		553	837	1,390	
63.4	Sacramento Weir	--	-0.058	-98	-52	-150	9, 10, 11	-68	-52	-120	9, 10, 11, 23
60.1	American River	1,936	1.298	39	1	40	9, 10, 12	39	1	40	9, 10, 12
--	Diversion	--	-0.208	-130	0	-130	13	-51	0	-51	13
	UNGAGED AREA	315E	--	28	2	30	1b	28	2	30	1b, 16
--	Imbalance	--	0.364	-323	-227	-550	14	-323	-227	-550	14, 16
60	Sacramento	23,502	8.605	2,126	1,124	3,250		1,003	1,122	2,125	

INTERPRETIVE COMMENTS:

- I. Negative sign indicates:
 - a. Inflow greater than outflow load.
 - b. Material going into storage (deposition).
 - c. Material leaving system (sink).
- II. Positive sign indicates:
 - a. Inflow less than outflow load.
 - b. Material coming out of storage (scour).
 - c. Material entering system (source).
- III. Size fraction distributions taken from HEC-6 runs (generally sediment weighted averages), unless noted otherwise.
- IV. Imbalance due to general bed aggradation or degradation, uncertainties of contributions from ungaged tributary areas, possible errors in gaged tributary contributions and other unknowns.

SEDIMENT CONCENTRATION AND CHANNEL MORPHOLOGY

Richard J. Janda and David F. Meyer
U.S. Geological Survey
Cascades Volcano Observatory
5400 Mac Arthur Blvd.
Vancouver, WA 98661

ABSTRACT

Debris flows and hyperconcentrated streamflows in the North Fork and mainstem of the Toutle River leave a channel narrower, straighter, and with finer bed material grain size due to the yield strength, the low turbulence, and the high shear stress of the flows. Alternatively, sediment-laden high flows of comparable discharge commonly widen stream channels and deposit mid-channel bars. Changes caused by high flows are due to high rates of bedload transport, readily erodible banks, and local aggradation. High flows with low sediment concentrations and denser flows with high sediment concentrations leave a similar sandy bed.

INTRODUCTION

The 18 May 1980 eruption of Mount St. Helens initiated a series of volcanic debris flows (lahars), hyperconcentrated flows (lahar-runout flows), and flows with high suspended-sediment concentrations that profoundly changed the morphology of the Toutle River. These flows delivered extremely large quantities of sediment to the Cowlitz and Columbia Rivers (Janda and others, 1981; Meyer and Janda, in press). Peak discharges and associated suspended-sediment concentration for the major 1980-1984 channel-sculpting flows on the North Fork and mainstem of the Toutle River are presented in Table 1. Measurements of water and suspended-sediment discharge and sediment particle-size distributions for the Mount St. Helens-affected streams are reported in Dinehart and others (1981) and Dinehart (1985). Changes in channel morphology are documented by repeated photography and surveys of monumented cross-sections (Janda and others, 1981; Lisle and others, 1983; Meyer and others, 1985). The purpose of this paper is to show that the impact of debris flows and hyperconcentrated streamflows on channel morphology is strikingly different than the impact of more dilute sediment-laden flows of comparable discharge.

EFFECTS OF DEBRIS FLOW AND HYPERCONCENTRATED FLOW

Four lahars have had significant impact on the Toutle River channel morphology since 18 May 1980 (Janda and others, 1981; Waitt and others, 1983). The first lahar formed on the morning of 18 May 1980 from deflation of a pyroclastic surge in the headwaters of the South Fork Toutle River. The largest and most destructive lahar formed during the late morning and afternoon of 18 May 1980 from slumping, flowing, and spring discharge from water-saturated parts of the 1980 Mount St. Helens rockslide-avalanche deposit in the North Fork Toutle River valley. Smaller lahars formed on 19 March 1982 and 14 May 1984 from eruption-induced snowmelt in the crater of Mount St. Helens.

The 18 May 1980 North Fork Toutle lahar flowed as a fully developed debris flow for 100 km to the Columbia River. The other lahars transformed from

Table 1.--Instantaneous peak discharge (Q), and peak suspended-sediment concentration (C), for noteworthy flood and laharc events after-18 May 1980, for unregulated streams near Mount St. Helens Washington.
[Peak discharges are in cubic meters per second. Peak suspended-sediment concentrations are in milligrams per liter.
The gaging station codes are the same as those used in Figure 1.]

Station Code and Drainage Area in km ²									
KIDW					TOTW				
736					1285				
THIW					1326				
Date of Peak					Date of Peak				
Q	C	Q	C	Q	Q	C	Q	C	C
MY 1980									
18 MAY 1980	2890	1,800,000			24 JAN 1982	649	89,300	1040	54,400
19 MAY 1980	57	1,320,000			25 JAN 1982	368	58,000		
27 AUG 1980	50	568,000			13 FEB 1982	416	67,800		
MY 1981					MY 1983				
7 NOV 1980	244	180,000			29 OCT 1982	725	168,000	436	46,400
21 NOV 1980	210	101,000			3 DEC 1982	1080	100,800		
1 DEC 1980					16 DEC 1982	340	200,000	634	99,800
2 DEC 1980	286	140,000			5 JAN 1983	300	131,000	663	39,400
3 DEC 1980					10 MAR 1983			264	21,400
MY 1982					MY 1984				
22 DEC 1980	1	60,000			3 NOV 1983	309	352,000	295	
25 DEC 1980					13 NOV 1983			309	
25 DEC 1980					17 NOV 1983	229	65,400	377	49,900
26 DEC 1980					20 NOV 1983			314	35,500
26 DEC 1980					24 NOV 1983	204		276	33,300
26 DEC 1980					3 JAN 1984	261	83,027	388	69,200
16 FEB 1981					24 JAN 1984	385	61,244	442	49,800
17 FEB 1981					25 JAN 1984	416	50,300	498	44,800
19 FEB 1981					MY 1985				
19 FEB 1981					7 JUN 1985				274
22 DEC 1980					Station Code				
KIDW					TOTW				
736					THIW				
Date of Peak					Date of Peak				
Q	C	Q	C	Q	Q	C	Q	C	C
MY 1980									
18 MAY 1980	2890	1,800,000			24 JAN 1982	649	89,300	1040	54,400
19 MAY 1980	57	1,320,000			25 JAN 1982	368	58,000		
27 AUG 1980	50	568,000			13 FEB 1982	416	67,800		
MY 1981					MY 1983				
7 NOV 1980	244	180,000			29 OCT 1982	725	168,000	436	46,400
21 NOV 1980	210	101,000			3 DEC 1982	1080	100,800		
1 DEC 1980					16 DEC 1982	340	200,000	634	99,800
2 DEC 1980	286	140,000			5 JAN 1983	300	131,000	663	39,400
3 DEC 1980					10 MAR 1983			264	21,400
MY 1982					MY 1984				
22 DEC 1980	1	60,000			3 NOV 1983	309	352,000	295	
25 DEC 1980					13 NOV 1983			309	
25 DEC 1980					17 NOV 1983	229	65,400	377	49,900
26 DEC 1980					20 NOV 1983			314	35,500
26 DEC 1980					24 NOV 1983	204		276	33,300
16 FEB 1981					3 JAN 1984	261	83,027	388	69,200
17 FEB 1981					24 JAN 1984	385	61,244	442	49,800
19 FEB 1981					25 JAN 1984	416	50,300	498	44,800
22 DEC 1980					MY 1985				
25 DEC 1980					7 JUN 1985				274

[1 Discharge peak partly from pond breakouts on the avalanche deposit.
[2 Peak discharge resulted from a laharc originating in the crater.
[3 Peak discharge less than base.

debris flow to hyperconcentrated flow because of dilution with over-ridden streamflow. The 18 May 1980 South Fork Toutle lahar transformed from debris flow to hyperconcentrated streamflow beginning about 50 km from the volcano (near the confluence of the North and South Forks of the Toutle River, fig. 1). The same type of transformation occurred in the 19 March 1982 North Fork Toutle lahar beginning about 27 km from the volcano (near DRS-N1, fig. 1), and in the 14 May 1984 North Fork Toutle lahar beginning about 17 km from the volcano (near Coldwater Lake, fig. 1).

Lahars and lahar-runout flows have straighter streamlines, higher bulk density, and less turbulence than more dilute flows of comparable size. High concentration flows cause considerable scour on the steep outer flanks of the volcano and the rockslide-avalanche deposit. Along the lower North Fork and mainstem Toutle River, deposition is more prevalent than erosion during these events. Massive lateral berms of sediment accrete to the sides of the channel, particularly on the outsides of stream bends. The berms reduce channel width and sinuosity (Table 2; figs. 2 and 3). Widespread deposition also occurs in areas of overbank flow (figs. 2 and 3). The lahars shove woody debris and riparian vegetation to the flow margins, destroy the pool-and-riffle bed configuration, and bury pre-existing cobble and boulder streambeds with sandy sediment (fig. 4). The net effect is for channel width-depth ratios usually to decrease in both scoured and aggrading reaches, with the formation of narrow, hydraulically smoother channels. Consequently, post-lahar stream velocity, flood wave celerity, and flood peak discharge are higher than during comparable pre-lahar conditions (fig. 5; Orwig and Matheson, 1981). The pattern of channel modifications caused by passage of a lahar is displayed best in reaches of the North Fork Toutle River upstream from the Green River

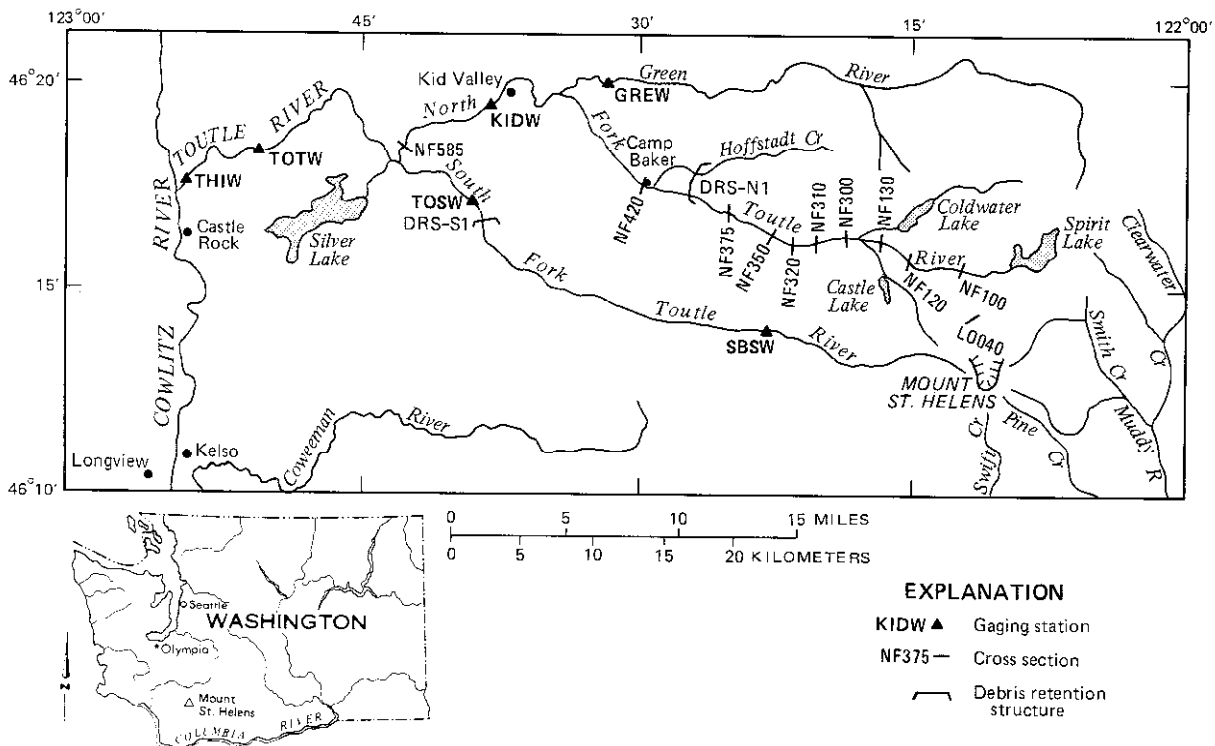


FIGURE 1. — Location of Mount St. Helens area, the Toutle River basin, and localities discussed in text and tables 1 and 2.

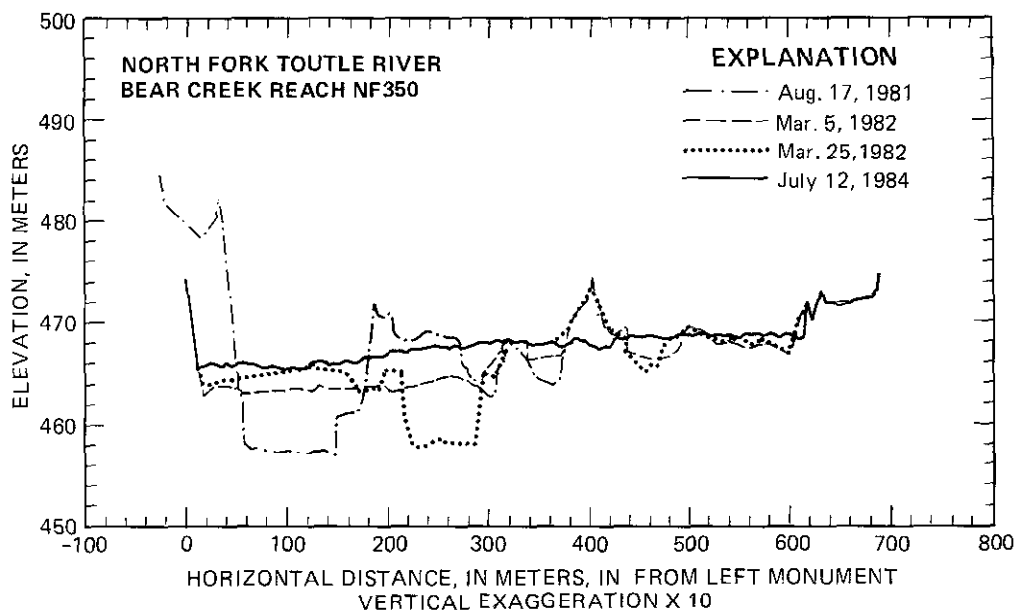


FIGURE 2. — Channel cross-section profile of the North Fork Toutle River.
See figure 1 for location.

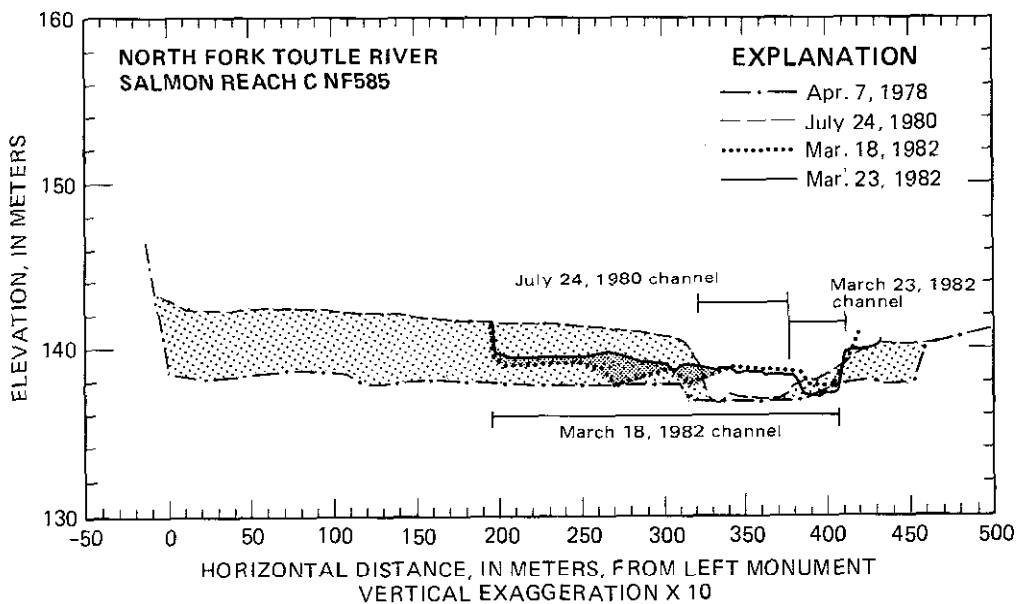


FIGURE 3. — Channel cross-section profile of the North Fork Toutle River.
See figure 1 for location. Light shading represents May 18, 1980 North Fork Toutle lahar deposits. Darker shading represents March 19, 1982 hyperconcentrated flow deposits.

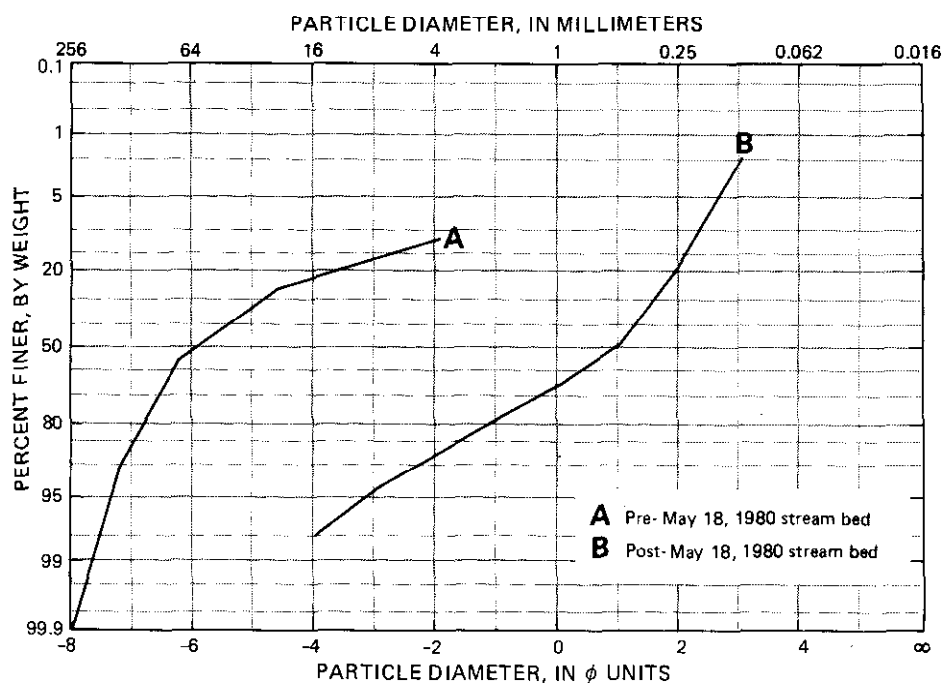


FIGURE 4. — Grain size distribution of the North Fork Toutle River stream bed near cross section NF585 before and after the May 18, 1980 lahars.

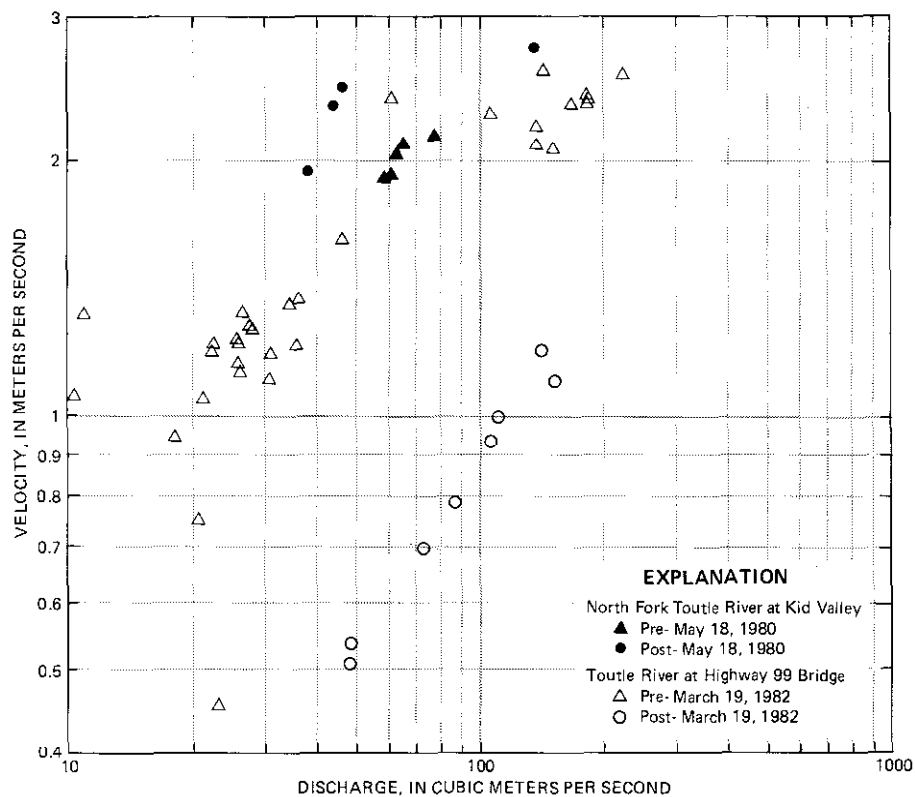


FIGURE 5. — Relation between stream discharge and average velocity at the Toutle River at Highway 99 (THIW, fig. 1) before and after the May 18, 1980 lahars and at the North Fork Toutle River at Kid Valley (KIDW, fig. 1) before and after the March 19, 1982 lahar.

Table 2.--Examples of Changes in Channel Width (ΔW) and Thalweg Altitude (ΔT) Caused by Different Types of Flows on Channels on the 1980 Mount St. Helens Rockslide-avalanche Deposit.
[Locations are shown in figure 1. Peak discharge and associated suspended-sediment concentrations for these flows are presented in Table 1.]

Identification number	Sediment-laden flows of February 1982 $\Delta W/\Delta T$ m	19 March 1982 lahar $\Delta W/\Delta T$ m	14 May 1984 lahar $\Delta W/\Delta T$ m
L0040		-73.3/-2.8	-20.4/-3.0
NF100			-19.2/-3.6
NF120			-28.1/-1.4
NF130	0.5/-2.8	-31.6/-6.4	-77.7/-1.9
NF300			37.9/1.2
NF310	93.5/-1.4	-91.4/0.7	0.0/0.9
NF320	81.9/-1.3	-22.0/-7.8	
NF375	0/1.4	-91.4/0.7	
NF420	33.0/2.2	-138/-2.3	
NF585	0/0	-80.5/-0.7	

(fig. 1). The pattern along the lower North Fork and main stem Toutle River is complicated by rapid expansions and contractions in channel width caused by bedrock constrictions and tributary junctions.

The majority of channel incision probably occurs during the recession of debris flows in downstream reaches. Following the 19 March 1982 lahar, recessional streamflow was incising the channel along much of the rockslide-avalanche deposit more than 12 hours after the peak flow. Reductions in channel width resulting from lahar flow do not persist. The lateral berms are comprised of sediment that is quickly eroded by subsequent streamflow. Channel aggradation is usually concomitant with post-lahar channel widening and occurs over several days to a few weeks. However, channel initiation by lahars is common on the north flank of the volcano and on the rockslide-avalanche deposit. This has had a more persistent impact on the landscape than changes in channel width and has played a major role in the erosional development of those areas.

EFFECTS OF SEDIMENT-LADEN STREAMFLOW

Suspended-sediment concentrations during rain-induced high flows in the Toutle River have to date been less than the threshold for hyperconcentrated flow. Concentrations approaching 400,000 mg/L have occurred during major flows. Daily mean suspended-sediment concentration at the North Fork Toutle River at the Kid Valley data site (KIDW) exceeded 100,000 mg/L only 1.4 percent of the time during WY 1982, 0.3 percent of the time during WY 1983, and not at all during WY 1984.

High discharge ($>200 \text{ m}^3/\text{s}$ at TOTW, fig. 1) and sustained high flow (100 to $500 \text{ m}^3/\text{s}$ at TOTW, fig. 1) cause widespread bank erosion and deposition of

mid-channel bars along the lower North Fork and mainstem Toutle River. Vigorous stream bank erosion is observed along all alluvial reaches. The annual increase in channel width during WY 1982 and WY 1983 was commonly more than 25 percent in both degrading and aggrading reaches (Meyer and Janda, in press). Aggradation is more common than degradation and appears to be persistent along the North Fork Toutle River between Elk Rock and the mouth of the Green River and between KIDW and the confluence with the South Fork Toutle River (fig. 1). The streambed in the reach between Elk Rock and Green River has locally aggraded more than 10 m (fig. 3). Aggradation downstream from KIDW is generally less than 2 m. Erosion is more prevalent volumetrically than deposition due to a greater amount of material being eroded from the stream banks than is deposited on the bed, especially during high flows (Meyer and Janda, in press). The net effect of sediment-laden streamflow is to form wide shallow channels. Cobble and boulder surface layers form during low flow periods but are scoured away or buried by sand during higher flows. The impact of sediment-laden streamflow on velocity-discharge relationships at KIDW and the Toutle River at Tower Road (TOTW) data site is not systematic. Perhaps the hydraulic effects of decreased surface bed-material size are compensated by the effects of increased width-to-depth ratios.

DISCUSSION

Sediment-laden streamflow along the Toutle River that causes widespread stream bank erosion, localized aggradation, and downstream increases in suspended-sediment discharge is a response to increased runoff and erosion in areas devastated by the 1980 eruption of Mount St. Helens. These same phenomena are a common response to extensive vegetation and land surface disturbance in the headwaters of steep rivers lined with erodible sediments. Rapidly eroding rivers with sandy gravel beds, high water discharge, and low to moderately high suspended-sediment concentrations (average, less than 2000 mg/L; rarely greater than 10,000 mg/L) provide the most graphic examples. Geographic areas with rivers of this type include northern California (U.S. Dept. of Agriculture, 1970; Janda and others, 1975; Kelsey, 1980; Lisle, 1981), Oregon Cascade Mountains (Anderson, 1954; Beschta, 1984), and New Zealand (Mosely, 1978; Pearce and O'Loughlin, 1978; Adams, 1981; Beschta, 1984).

The association of localized channel incision with flood plain deposition and lateral accretion of berms, like that observed along the Toutle River during and following lahars and lahar-runout flows, are observed elsewhere in response to debris flow and hyperconcentrated streamflow. The impact of debris flows on the morphology of small steep streams that are comparable to streams on the steep outer flanks of Mount St. Helens is well known. Channelized debris flow commonly causes intense scour in steep channels (Pierson, 1980; Campbell, 1975). Channel width is often reduced by deposition of lateral berms and marginal levees (Desloges and Gardner, 1984; Johnson, 1984).

The impact of hyperconcentrated flows on the morphology of the Yellow River in China and its tributaries is well documented (Qi, 1982; Zhang and others, 1982; Qi and Zhao, 1985). The suspended sediment transported by the Yellow River is predominately silt. The passage of hyperconcentrated floods with suspended-sediment concentrations of 400,000 to 1,000,000 mg/L causes formation of narrow deep channels. Net bed scour associated with a single

flood can be as much as 10 m. When suspended-sediment concentration declines to less than 400,000 mg/L following a high flow, aggradation, braiding, and stream bank erosion quickly restore a wide shallow channel to the Yellow River.

The channel shapes of the sand-dominated Toutle River and the silt-dominated Yellow River display remarkably similar responses to floods with widely different suspended-sediment concentration. This similarity suggests that channel shapes are determined by the hydraulic characteristics of the flow as well as by the physical characteristics of the stream bed and banks.

The tendency for debris flows and hyperconcentrated flows to reduce sinuosity and width and to increase the depth of channels formed by high flows with lower suspended-sediment concentration reflects 1) the significant yield strength of the deposits, 2) the apparent cohesion of the deposits due to extremely poor sorting and relatively high percentages of clay compared to streamflow deposits, and 3) the relative magnitude of these events. Debris flows commonly occur in channels that are formed by streamflow of lesser magnitude. This was true of both the 18 May 1980 flows throughout the Toutle River system and of the 19 March 1982 flow through the North Fork Toutle. The thread of maximum discharge commonly occurs along the axis of the valley, regardless of pre-existing sinuosity, during both large streamflows and debris flows. However, during debris flows, the channel is filled with a fluid having significant yield strength. As the flow comes to rest, the entire flood plain is filled with this material. Recessional flows cut new channels on the surface of this deposit. This newly incised channel cuts a path along the axis of steepest slope, which corresponds to the former maximum velocity axis. Relative to streamflow deposits, the debris-flow deposits are extremely poorly sorted, angular, and contain more fine-grained material, and can thus maintain high banks. Further downcutting occurs until equilibrium is reached, and the channel begins to meander. This return to normal streamflow processes and channel characteristics may occur over several weeks, as was the case after March 19, or over several years, as was the case after May 18.

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LANDFORM MODIFICATIONS AT A NUCLEAR-WASTE BURIAL SITE

By J. R. Gray, U.S. Geological Survey, WRD, Urbana, Illinois

ABSTRACT

Relations among runoff, sediment transport, landform modifications, and precipitation were evaluated at a 20-acre, low-level radioactive-waste burial site near Sheffield, Ill. Precipitation, runoff, and sediment discharge were measured in three basins comprising two-thirds of the site area and in a 3.5-acre basin in undisturbed terrain 0.3 mile south of the site. The effects of slope, land use, and physical characteristics of surficial material on runoff and sediment transport were evaluated at four plots averaging 114 square feet in size--two on-site and two in the undisturbed basin. Preliminary results indicate the mean annual precipitation of 36 inches from July 1982 through June 1984 produced a mean of 8 inches of runoff annually from the site, compared to less than a mean of 2 inches of runoff annually from the undisturbed basin. Mean annual storm-sediment yields from the site of 2 tons per acre were more than 200 times greater than yields from the undisturbed basin. A total of 302 collapse cavities were documented at the site from October 1978 through September 1985. Two-thirds of the collapses occurred in the months of February, March, and April. Sixty-two percent of the collapses occurred in swales or near trench boundaries. Approximately three times more soil is moved downward by collapse than by surface transport.

INTRODUCTION

The long-term integrity of sites used for shallow land burial of low-level radioactive wastes will depend on complex interactions between the physical, chemical, and biological processes that modify the waste-containment system. Failure to contain wastes at existing burial sites in the United States most commonly involves processes that affect the trench cover. In a humid environment, the burial site is particularly susceptible to processes involving water movement. The erosive action of water can damage the trench cover and produce opportunities for infiltration, and may eventually result in exposure of trench contents. Water entering the trench can dissolve radionuclides, which may then migrate in ground water and contaminate deeper ground water or emerge as surface seeps. In addition, subsidence of waste and fill material may be accelerated by increases in soil moisture. The resulting collapses within the trenches facilitate entry of more water. (Department of Energy, 1984, p. 3-4.)

The Sheffield low-level radioactive-waste burial site is one of six commercially-operated sites in the United States, and one of four in humid climates. Two years after the last trench was closed in 1978, Heim and Machalinski (1980, p. 7) observed that the reworked loess deposits that form the surficial material throughout the site area was highly susceptible to erosion. Subsequent reports by Kahle and Rowlands (1981) presented an evaluation of trench cover collapses documented since 1978. Above-background concentrations of tritium--a radioactive isotope of hydrogen--were first detected in ground water in the southeastern part of the site in 1975; in 1982, tritium was detected in ground water in a plume migrating from the site toward a lake 800 feet east of the site boundary.

This paper describes methods and results of U.S. Geological Survey studies of runoff, sediment transport, and landform modifications at a low-level radioactive-waste burial site in Illinois. The purpose of the study is to provide information on surface processes for use in the development of criteria for selecting future waste sites. Specific study objectives are fourfold:

1. Determine runoff and sediment yields from the site and from a nearby undisturbed drainage basin.
2. Determine relations among rainfall, runoff, and sediment transport.
3. Document types and rates of landform modifications.
4. Provide a data base and analytical means for evaluating changes in hydrologic processes at the site over time.

STUDY AREA

The Sheffield burial site is located on 20 acres of rolling terrain 3 miles southwest of Sheffield in northwestern Illinois. An undisturbed 3.5-acre basin located 0.3 mile south of the site was used as a control site for comparative studies. The site drains to intermittent streams that flow into Lawson Creek--a 5th-order tributary of the Mississippi River. The climate of the area is continental, with warm summers and cold winters.

Waste-burial operations began in August 1967. A cut-and-fill process was used to construct 21 trenches ranging from 35 to 580 feet long, 8 to 70 feet wide, and 8 to 26 feet deep. The last two trenches that were filled were built with walls of silty clay that extended above the existing land surface. Waste containers, including concrete vessels, large steel boxes, steel barrels, wood boxes, and cardboard boxes, were randomly deposited in the trenches and then covered with material excavated from the trench. (Russell Moore, US Ecology Corp., Sheffield, Illinois, oral commun., 1983.) The movement of excavating machinery over backfilled trenches formed a compacted layer over which fill material was mounded. Trench covers and adjacent areas were seeded to establish a vegetation cover. By April 1978, when burial operations ceased after the depletion of suitable burial space, 3 million cubic feet of waste with a total activity of over 60,000 curies had been buried. Ninety percent of wastes buried were generated by nuclear-fuel cycle facilities.

By summer 1982, the site was approximately 67-percent vegetated with a variety of species dominated by orchard grass (Bromus inermis) and red clover (Trifolium pratense). Maintenance at the site includes mowing to a height of approximately 4 inches and repairing damages to the surface caused primarily by erosion and collapse. Eroded areas are normally regraded and seeded. Collapse cavities are typically backfilled with soil, compacted by driving heavy machinery over the backfill, and seeded. The undisturbed area is 99 percent vegetated with timothy grass (Phleum pratense)--the dominate species. Average height of vegetation in the summer months is 1.7 feet. This area was used for row-crop agriculture in the early 1960's and was last used in the late 1970's as pasture (Roy Moore, Sheffield, Illinois, oral commun., 1981).

METHODS OF STUDY

Studies of runoff, sediment transport, and landform modifications began in June 1982. Continuous-record gaging stations measured rainfall, runoff, and sediment discharge from three basins comprising two-thirds of the site area and from the 3.5-acre undisturbed area (fig. 1). Similar measurements were made on runoff from four plots averaging 114 ft² in size, two within a gaged basin on-site and two on the undisturbed area (table 1). These plots were sited to evaluate the effects of slope, land use, and the physical characteristics of surficial material on runoff and sediment transport. Four recording raingages, including an on-site meteorological station, measured depth and intensity of precipitation. Surveys of vegetation were made annually to define areal and temporal variations in cover density. Photographic surveys were made periodically to record surface conditions at the site and to document areas of erosion and collapse.

Runoff and sediment transport

Continuous-record gages

Artificial controls were used to stabilize and constrict the channel downstream from each gage, thereby simplifying the procedure of obtaining accurate records of discharge (Rantz, 1983, p. 12). Stations 1 and 3 were equipped with Parshall flumes (Kilpatrick and Schneider, 1983). A V-notch weir and the entrance to a culvert were controls at stations 2 and 4, respectively. Battery-operated microcomputers (data loggers) processed and recorded rainfall and stage data, and activated pumping samplers during periods of runoff. Rainfall accumulations in excess of 0.01 inch were recorded at 1-minute intervals. Stage was recorded once-daily during periods of zero and very low flow, and as often as every minute during medium and high flow. Water discharge was computed from stage data and the stage-discharge relation developed for each gage (Kennedy, 1983). Data loggers actuated pumping samplers as frequently as 1-minute intervals based on time, stage, and rate of stage change. Sampler intakes were anchored in sections of maximum turbulence to obtain samples representative of the total sediment load. Manual samples were collected throughout the water column during several runoff periods. Water-sediment samples were analyzed for sediment concentration and grain-size distribution. Concentration analyses were used with water discharge to derive total sediment discharge (Guy and Norman, 1970; Porterfield, 1972).

Computation of water and sediment discharges was facilitated by a computer program capable of accepting stage and sediment data on uneven time increments. A period of runoff was computed by converting stage to discharge and summing discharges weighted for the appropriate time interval. Two methods were used to derive sediment discharge. The first method was used when sufficient samples were available to define the temporal distribution of sediment concentration during a runoff period. The program approximated a manually-drawn curve through the concentration values with a quasi-Hermite spline interpolation procedure (IMSL, 1982). Concentrations were interpolated from the curve at each discharge node. Instantaneous sediment discharges were computed from water discharges and sediment concentrations, weighted for time, and summed to obtain sediment transported for the runoff period.

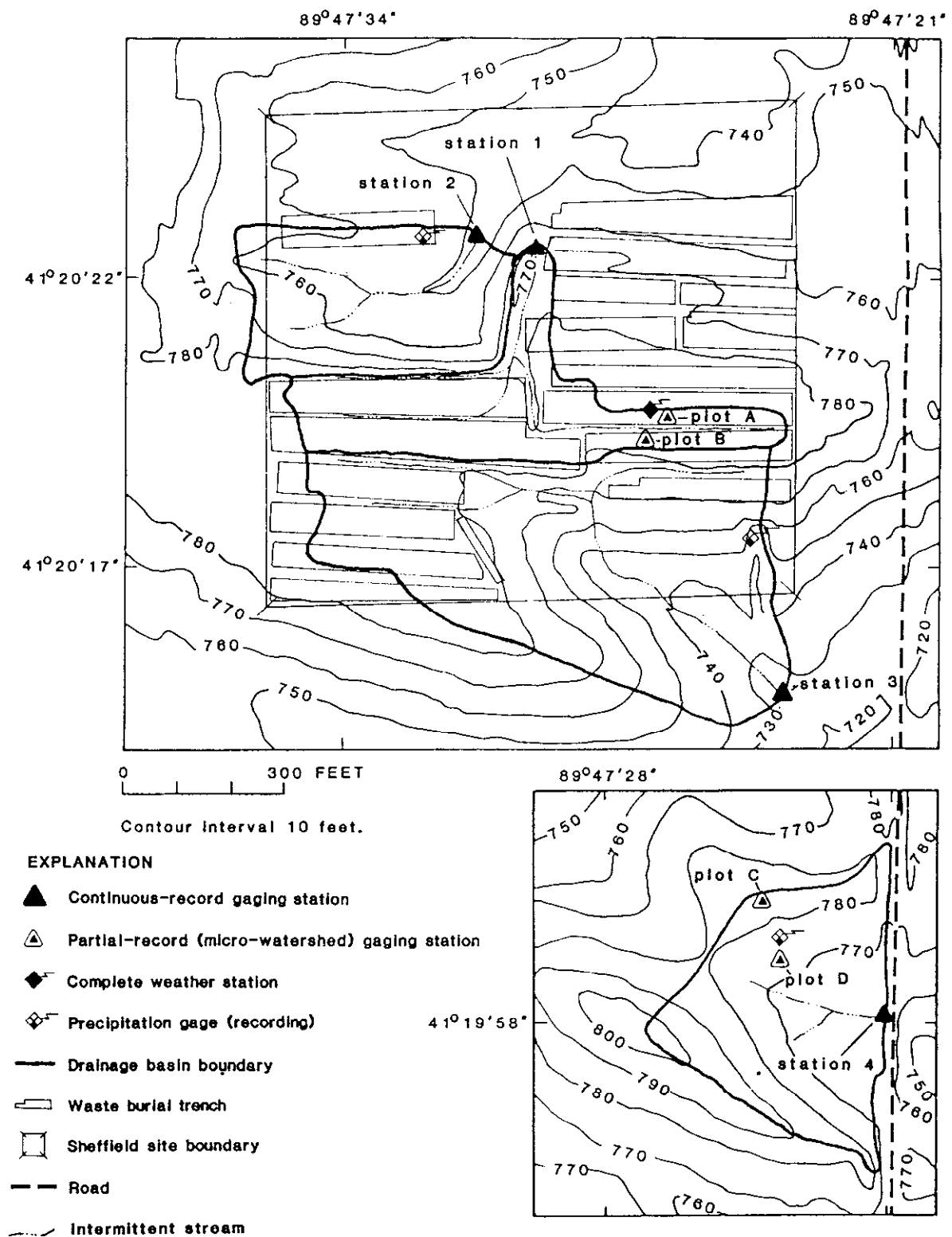


Fig. 1. Topography and surface drainage divides at Sheffield site and nearby undisturbed area.

The second method for sediment discharge computation was based on the water-discharge hydrograph and a least-squares linear-regression relation between the common logarithms of instantaneous discharge and sediment concentration. All samples collected at a gage were used to develop the regression relation. Concentration was derived from each discharge and the regression relation, then used to compute instantaneous sediment discharge. Sediment discharge for the period was obtained as described above. In order to reduce the standard error of the regression equation, a qualitative variable was included in the equation to separate the November to April period (dormant season) from the May to October period (growing season) (W. O. Thomas, U.S. Geological Survey, written commun., 1982). Although sediment discharges were computed for all runoff periods by the regression-relation method, results were used only when a lack of samples precluded the use of the first computational method.

Runoff and sediment transport data from continuous-record gages were used to estimate water and sediment yields from the total site area. Concurrent measurements of precipitation, evapotranspiration, and runoff were used to derive estimates of infiltration. Measurements made at the undisturbed basin were used for comparing and evaluating site yields.

Plot gages

Two methods were used for runoff and sediment transport measurements at plots. Plot C was equipped to collect total surface runoff in two 30-gallon containers for later measurement and sample collection. The dekaport-divisor system (Gray and deVries, 1984) was used at the other three plots. A 5-gallon primary collecting vessel at these plots temporarily stored surface runoff. Flow exceeding 4 gallons in the primary collector was pumped from the primary vessel until 1 gallon remained. Pumpage was routed through a cone-splitting chamber, which divided flow into 10 equal parts; one part was retained and was used with that stored in the primary collecting vessel to compute runoff and to sample for total sediment concentration.

Water and sediment yields from the plots were computed by methods described by Gray and deVries (1984). The results were used to estimate water and sediment yields from trench covers and to compare these yields with runoff and sediment yields from similar-size areas of different land uses and slopes.

Discharge and sediment-transport data from the eight gages were used to calibrate a rainfall-runoff-sediment-transport simulation model for the site and undisturbed area. The calibrated model may be used to characterize the hydrologic impacts of changes in site management practices prior to their implementation, or to simulate hydrologic processes for proposed waste sites. The model may also serve as one means of evaluating the long-term yields from the site.

Collapse

Records on site surficial conditions have been maintained by the site contractor since October 1978. The site was inspected at least monthly and more often during and following rainfall or snowmelt periods. Information provided usually included estimated cavity dimensions and approximate location relative to trenches. An estimate of borrow material volume used to fill the cavity was occasionally noted.

Most cavity volumes were computed from cavity dimensions and a formula for a right cylinder. Ten cavity volumes were based on the estimated amount of borrow material used to fill the void. Weights of collapsed material were computed from cavity volumes and a mean bulk density determined for site-surficial material of 97.4 pounds per cubic foot.

FACTORS AFFECTING LANDFORM MODIFICATION

Precipitation and runoff

Precipitation measured from July 1982 through June 1984 averaged 36 inches annually; this amount equaled the long-term (36-year) annual mean for the area based on records from nearby National Weather Service stations. Mean annual runoff from the site was 8 inches compared to less than 2 inches from the undisturbed basin. Mean annual evapotranspiration totaled 26 inches at the site.

Runoff at the continuous-record gages typically was confined to a period during and immediately following rainfall or snowmelt. The relation of runoff to precipitation varied seasonally and areally. The ratio of runoff to precipitation during the dormant season averaged 0.27 at the site and 0.06 at the undisturbed basin. During the growing season, this ratio averaged 0.19 at the site and 0.02 at the undisturbed basin. A minimum of approximately 0.6 inch of rainfall typically was required to induce runoff at the site. More than 1.4 inches of rainfall was usually required to induce a measurable amount of runoff at the undisturbed basin.

Runoff at each plot also varied seasonally (see table 1); flow often exceeded 1 percent of precipitation in the dormant season but rarely in the growing season. Runoff from plot D was consistently greater than from plot C. However, trench cover runoff from plot A was typically less than that from plot B. The thicker fill of loess over the compacted layer at plot A provided greater potential for moisture absorption than the thinner layer beneath plot B. These results suggest that the physical characteristics of trench covers exert a stronger influence on the ratio of runoff to precipitation than slope.

Sediment transport

Surface runoff on-site occurs initially as unconfined sheetwash which gradually concentrates in small, poorly defined rills. Rills converge to form gullies which tend to be as wide as they are deep (fig. 2). Gullies in excess of 1 foot depth have been measured (Heim and Machalinski, 1980, p. 4-8). Sediment yield measured on-site averaged 2 tons per acre annually during the period July 1982 through June 1984. Assuming uniform erosion from the site during this period, this yield would lower the land surface approximately 0.01 inch. Approximately 97 percent of sediments transported were silt- and clay-size. Sediment discharges at continuous record gages on-site were related to basin slope (table 1). Annual sediment yields were greatest at station 1, totaling 6 tons per acre; and lowest at station 2, totaling 0.1 ton per acre. Land use also was a factor in sediment transport; yields at station 4 totaled approximately 0.005 ton per acre annually. The absence of a compacted layer near the surface, along with a mean 22 percent greater cover density than the site combined to increase infiltration and retard runoff and sediment transport at the undisturbed area. Data collected at station 1 indicated that



Collapse following snowmelt, March 1979



Gully erosion, summer 1983

Figure 2.--Collapse and erosion at the Sheffield site.

Table 1. Gaging-station characteristics and sediment yields at the Sheffield study area

Station name	Gage* type	Location	Drainage area (acres)	Slope (percent)	Mean annual sediment yield (tons/acre-year)
Station 1	CR	on-site	3.25	6.4	6
Station 2	CR	on-site	2.82	2.0	1
Station 3	CR	on-site	7.42	5.8	0.1
Station 4	CR	off-site	3.52	7.3	0.005
Plot A	P	on-site	0.0026	14.3	+
Plot B	P	on-site	0.0028	3.1	+
Plot C	P	off-site	0.0026	3.0	+
Plot D	P	off-site	0.0026	16.2	+

* CR - Continuous record, P - Plot; + Annual sediment yields not reported.

erosion from bare areas provides a great deal of sediment available for transport. Until April 1984, the drainage area for this basin included a 1-acre area southwest of the present drainage divide that consisted primarily of part of a chemical waste-burial facility devoid of vegetation. A berm was erected to divert all runoff from this 1-acre area away from the radioactive-waste burial site. Peak sediment concentrations of 23,000 mg/L measured before berm construction decreased an order of magnitude after diversion. Vegetation had stabilized sediments deposited within the gaged area soon after the berm was installed.

Collapse

Collapse of trench covers has been a fundamental problem affecting the stability of low-level radioactive-waste disposal sites. Collapses can be caused by a combination of:

1. Failure and internal erosion of either the trench walls or trench covers into void spaces between waste packages.
2. Compression and consolidation of the earth cover and trench cap material under its own load.
3. Compression and compaction of the waste in the trenches.

The volume of voids between randomly-deposited waste packages could be on the order of 50 percent of the space occupied (White, 1982, p. 262-263).

A total of 302 collapse cavities were documented on-site from October 1978 through September 1985 (Kahle and Rowlands, 1981; US Ecology Corp., written commun., 1983, 1984, 1985). Although most cavities were less than 10 feet in diameter, two exceeded 18 feet (fig. 2). The depth of one cavity was estimated to be 20 feet. Cavity volumes were log-normally distributed around a median size of 9 cubic feet. Sixty-two percent of the collapses occurred in swales or near trench boundaries, and the remainder were over trench interiors. Collapse cavities were more prevalent following periods of rainfall or snowmelt when the soil was at or near saturation. Two-thirds of the recorded collapses occurred in the 3-month periods of February, March, and April. Collapses have occurred at a rate of 43 per year over the 7-year period ending in September 1985. However, the rate has increased substantially since the summer of 1982. Prior to October 1982, mean rate of recorded collapses was 26 per year. From October 1983 through September 1985 an annual mean of 67 collapses have occurred.

A total of 850 tons of sediment moved downward by collapse in the 7-year period of record. This corresponds to 6 tons of sediment per acre of site area annually. Approximately three times more sediment was moved downward by collapse than by surface transport annually.

DISCUSSION

Trench covers are engineered barriers designed to prevent or retard surface water infiltration and are an integral part of the surface-water control plan at low-level radioactive-waste disposal sites. They control percolation by increasing surface runoff, soil-moisture storage, and evapotranspiration. If hydrologic processes at the undisturbed basin near the Sheffield site are representative of processes at the preburial site, trench covers have inhibited infiltration and increased surface runoff more than fourfold.

Sediment yields measured on-site are more than 200 times greater than undisturbed basin yields; however, estimates based on information from the U.S. Soil Conservation Service (Alan Madison, oral commun., 1985) and Khanbilvardi and Rogowski (1984, p. 866) indicate that erosion from a 20-acre, 8-percent-slope basin in row-crop agriculture near Sheffield to be approximately 4 tons

per acre annually. Annual sediment yields from a 20-acre row-crop agricultural basin near Rockford in northern Illinois was 1 ton per acre in 1979-81 (Allen and Gray, 1981, p. 46). On-site sediment yields at Sheffield are comparable to those estimated for row-crop agricultural fields in the region. Plot data indicate that little runoff or sediment transport occurs from atop trench covers. Rills, gullies, and bare areas are likely sources for most sediment transported from the site.

Low-level radioactive-waste burial sites can have short-term and long-term effects on the surface-water system. In the short term, the burial site can more actively affect the surface-related hydrologic factors such as runoff, infiltration, and erosion. In the long term, hydrologic conditions at the site will tend to be similar to those existing prior to site operation (Chang, 1982, p. 264). Trench caps tend to become more permeable with the passage of time because of cracking caused by waste subsidence and the cyclic process of root growth followed by decay of the roots, creating water channels. Gas generation from the decomposition of waste can develop channels for infiltration of surface water. Other factors such as frost heave and disruption of soils by burrowing animals tend to increase the permeability of the site cover. It is possible, then, that site precipitation, runoff, and sediment transport relations over the long term can approach those at the undisturbed area. The long-term hydrologic effects of a transition would include reductions in surface runoff and sediment transport, with corresponding increases in infiltration--enhancing the potential for increased percolation of water through wastes.

SUMMARY

Relations among runoff, sediment transport, landform modifications, and precipitation were evaluated at a low-level radioactive-waste burial site near Sheffield, Ill., and at a nearby undisturbed basin. The mean ratio of runoff to precipitation at the site was over four times greater than at the undisturbed basin. Sediment yields at site gages were over 200 times greater than yields at the undisturbed area. Approximately three times more sediment was moved by collapse than by surface transport annually. The annual rate of collapse has increased 2.6 times since September 1982. It is likely that site precipitation, runoff, and sediment transport relations will become similar to the responses exhibited at the undisturbed area over the long term.

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SEDIMENT YIELD OF THREE DRAINAGE BASINS IN GUAM

By Patricia Shade, U.S. Geological Survey, Honolulu, Hawaii

ABSTRACT

Nearly all surface runoff on Guam occurs in the southern part of the island where steep volcanic uplands are dissected by numerous streams. The mean annual rainfall in the area is about 100 inches and typhoons as well as droughts are common. Sediment yields for three drainage basins in southern Guam were estimated using flow-duration and sediment-rating curves, and the PSIAC (Pacific Southwest Inter-Agency Committee) formula. The PSIAC

estimates of total sediment yield are 1,200 tons/yr/mi² for the Talofoyo, 1,385 tons/yr/mi² for the Ylig, and 1,210 tons/yr/mi² for the Ugum basins. These estimates compare favorably with estimates of sediment yields from several similar basins on the island of Oahu, Hawaii. It appears that the PSIAC method can be useful in estimating sediment yields in some tropical areas.

INTRODUCTION

The Talofoyo, Ylig, and Ugum River basins are located in southern Guam, where surface water is the major source of domestic water supply. The purpose of this study is to determine the mean annual sediment yields from these three river basins for use in future water supply development. The flow-duration sediment-rating-curve method is used to estimate mean annual suspended-sediment yield for each of the basins. The PSIAC formula is used to estimate mean annual total sediment yields.

Guam is the largest of the Mariana Islands, located about 1,370 miles south-east of Tokyo and about 1,500 miles east of the Philippine Islands. The island is 30 miles long and varies from 4 to 11.5 miles wide (fig. 1). The climate is warm and humid, and the mean annual temperature is about 81° F. There is a dry season from January through May, and a wet season from July through November; June and December are transitional months. The mean annual rainfall ranges from about 80 inches in the west-central coastal areas to about 100 inches in the highest mountain areas in southern Guam. About 15 to 20 percent of the total rainfall occurs during the dry season, about 70 percent during the wet season, and the remainder during the transitional months. Typhoons are fairly common in the wet season. Drought is also common and may be expected to occur from February through April in 3 out of 4 years.

There are three broad physiographic areas: the northern limestone plateau; the central mountains; and the southern volcanic mountains. The Ugum River joins the Talofoyo River about 0.5 mile above Talofoyo Bay. The basins are underlain generally by deeply weathered consolidated noncalcareous sedimentary rocks, with low permeabilities, derived from volcanic rocks, except along the lower reaches of the streams where the valley flats are underlain by alluvium. In its steep upper basin, the Ylig River and its tributaries flow across deeply weathered volcanic rock and the valley flat is underlain by alluvium (Ward and others, 1965). The soils are predominantly clays.

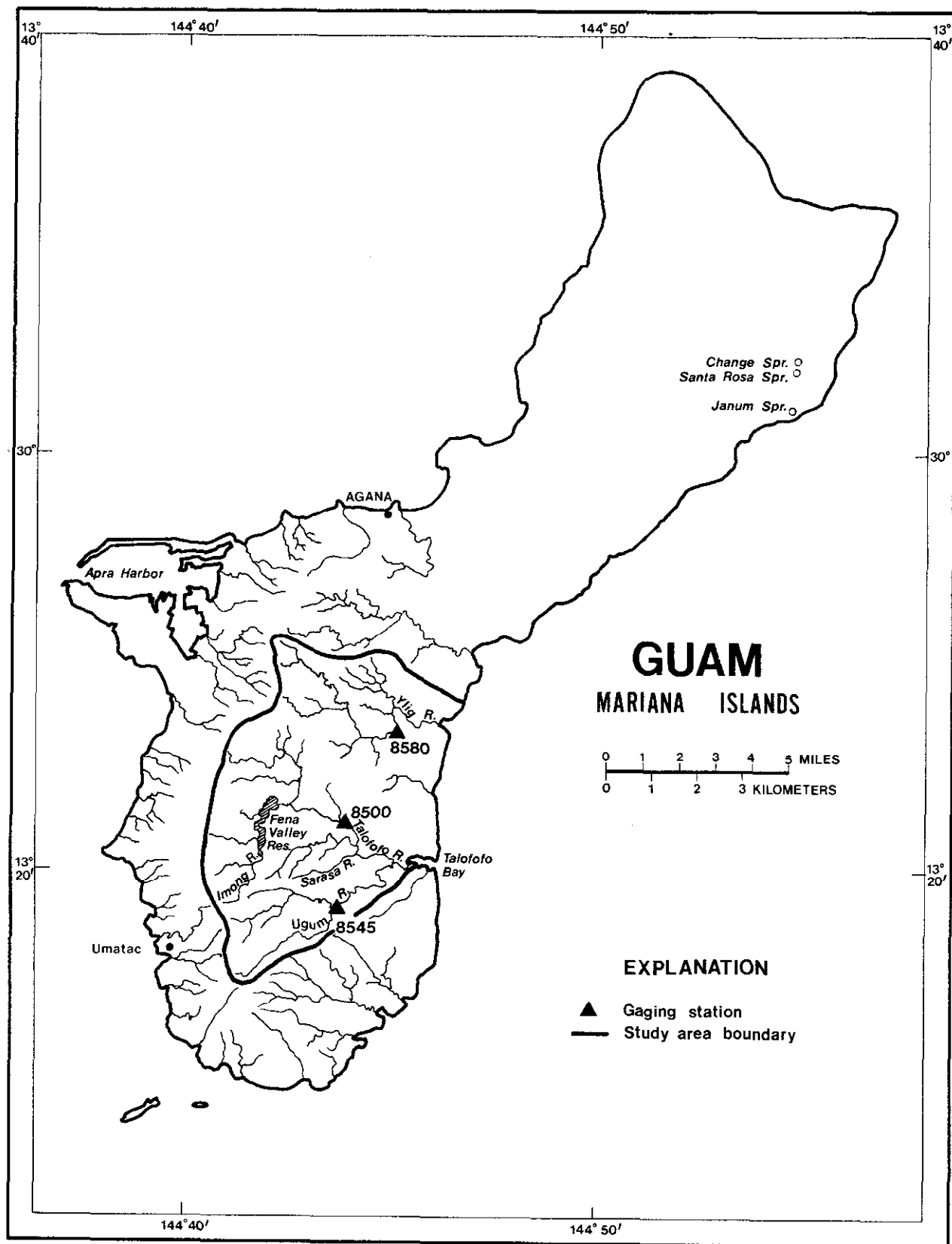


Figure 1. Gaging station locations in study area of the Island of Guam.

Nearly all the surface runoff occurs in the southern part of the island. Because of the generally low permeability of the rocks there, about half the average rainfall runs off during the rainy season. At the end of the wet season, streamflow decreases rapidly to the low flow maintained by slow ground-water discharge (Ward and others, 1965).

The upland part of the study area is steep and dissected by numerous streams. Surface gradients range generally from 15 to 100 percent and decrease toward the east, where the streams have more gentle gradients. Farming, grazing, and small settlements predominate in the eastern part of the study area and in the valley flats. A naval installation surrounds Fena Reservoir, and the remainder of the basin uplands is undeveloped. Vegetative cover on the uplands is largely swordgrass and scattered trees, with broad-leafed forests in the ravines and valleys (Tracey and others, 1959).

CALCULATION OF SEDIMENT YIELD

Use of Flow-Duration and Sediment-Rating Curves

Estimates of the mean annual suspended-sediment discharge from the Talofoto (16.2 mi²), Ylig (6.48 mi²), and Ugum (5.76 mi²) drainage basins were made using flow-duration and sediment-rating-curves (Miller, 1951). Nine years of streamflow record for the Talofoto River, 28 years of record for the Ylig River, and 4 years of record for the Ugum River were available to prepare the flow-duration curves. These curves show the percentage of time within the total period of record that a specified daily discharge was equaled or exceeded. Because the upper end of the curve represents the flows that transport most of the sediment, the Talofoto and Ylig curves have been modified as by Jones and others (1971) to account for high flows of short duration--less than one day. Peak flows generally persist for about two hours on these rivers. The mean annual flood, therefore, with a recurrence interval of two years, approximates the 0.01 percent frequency on the duration curve: $\frac{2}{2 \times 365 \times 24} = 0.011$ percent. The mean annual flood was plotted and a dashed line was drawn from that point tangent to the flow-duration curve. The Ugum River streamflow records are too short to have any confidence in this modification.

Sediment rating curves were prepared for each of the rivers (fig. 2). On these graphs are plotted the mean daily or instantaneous suspended-sediment discharge, when only intermittent samples are available, against the mean daily or instantaneous water discharge. For the Talofoto basin a power-curve regression line through the points was determined by the least-squares method. For the Ylig and Ugum basins the clumping of data at one end of the graphs caused a bias fit of the power-curve regression lines. Therefore, the data were fit by eye for the Ylig basin and using class-average data points for the Ugum basin.

The estimated mean annual suspended-sediment yield for the Talofoto basin is about 460 tons/yr/mi²; for the Ylig basin, 1,160 tons/yr/mi²; and for the

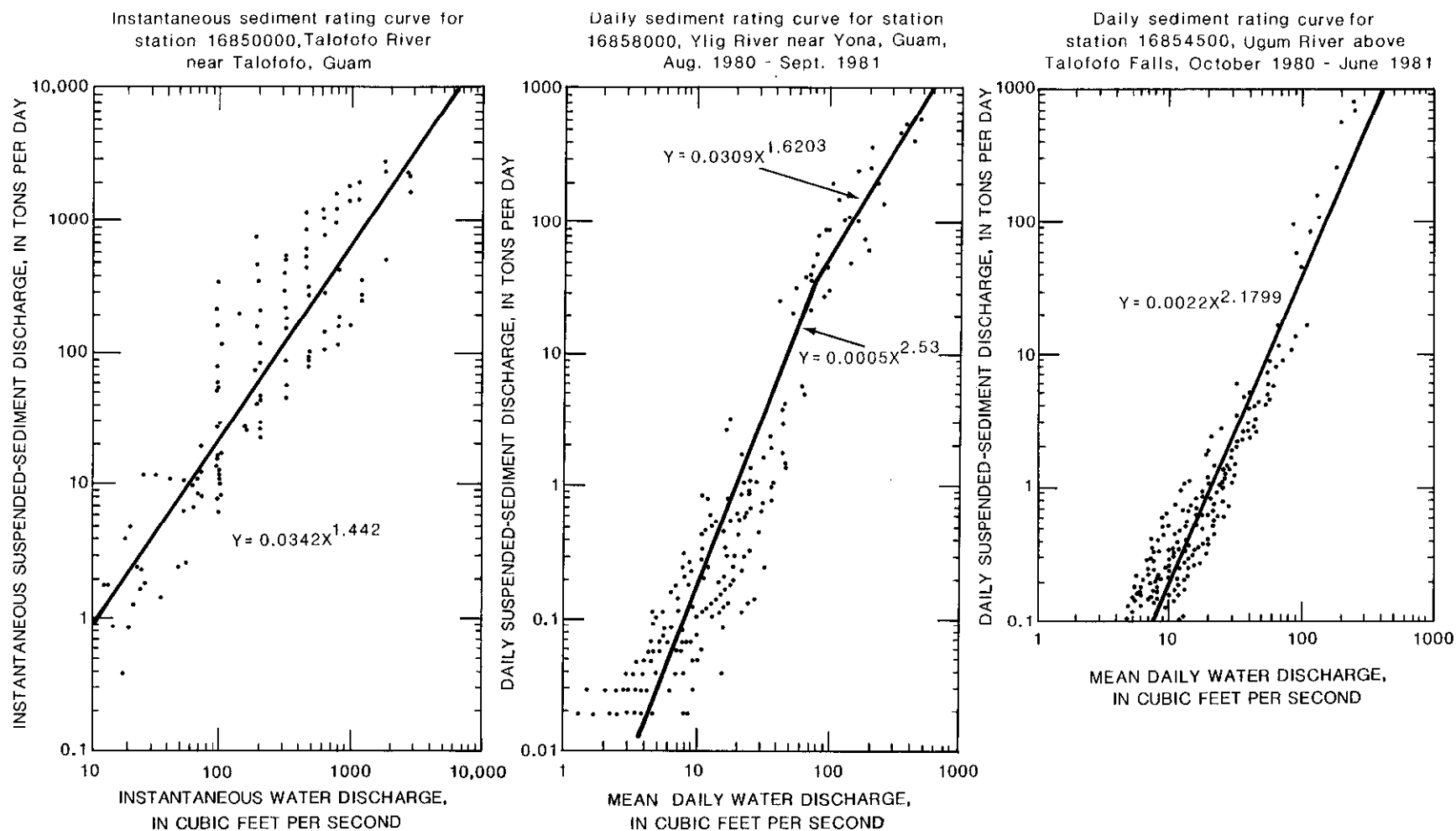


Figure 2. Sediment rating curves for the Talofofo, Ylig, and Ugum Rivers.

Ugum basin, 1,455 tons/yr/mi². The Talofoto basin yield should be considered a minimum estimate due to the lack of daily data. The Ugum basin estimate is considered of only fair reliability as there are few high-flow data points available to define accurately the slope of the line in figure 2. Because of the limited sediment data for the Talofoto, Ylig, and Ugum River basins and the short period of streamflow records, the computed suspended-sediment yields are, at best, estimates. These estimates establish a range of suspended-sediment yields in conjunction with the results from the Pacific Southwest Inter-Agency Committee (PSIAC) method.

Pacific Southwest Inter-Agency Committee (PSIAC) Method

The Pacific Southwest Inter-Agency Committee (1968) developed the PSIAC method to estimate sediment yields, for the Pacific Southwest. This method has been used successfully in Hawaii (B. L. Jones, oral communication, 1982), and Guam's soils, geology, runoff, and rainfall characteristics are similar to Hawaii's. Also, the effect of annual droughts in Guam, and the moderate available moisture capacity of the clay soils in the study area (Park, 1978) parallel some of the conditions in the Pacific Southwest. Thus, the PSIAC method should apply to Guam. Although the PSIAC method was originally recommended for areas of 10 square miles or greater, Shown (1970) indicates good results for basins between .02 and 7.5 square miles. His PSIAC estimates correlated closely with sediment yields measured by reservoir sedimentation data but were usually lower than the measured yields.

The PSIAC formula takes into account surface geology, soils, climate, runoff, land use, topography, ground cover, upland erosion, channel erosion, and sediment transport in determining sediment yields. For each of these factors a sediment yield characteristic value is assigned that represents the relative significance in the yield rating, which is the sum of these values. The yield rating is converted to a sediment yield for the basin (table 1). To test the applicability of the PSIAC formula in southern Guam, it was applied to the Fena Reservoir basin, where reservoir sedimentation data is available.

Table 1. PSIAC values for factors affecting sediment yield

	Fena
Surface geology -----	4
Soils -----	7
Ground cover -----	-9.6
Climate -----	10
Runoff -----	10
Topography -----	20
Land use -----	5
Upland erosion -----	15
Channel erosion and sediment transport ---	25
<u>Total</u>	<u>86.4</u>

Note: The basin is within the 75-100 rating which translates to a mean annual sediment yield of 2.0 acre-ft/mi².

The Fena Reservoir watershed is a 5.81 mi^2 sub-basin located in the western part of the Talofofo drainage area (fig. 3). The area is undeveloped and generally hilly to very steep. The clay soils support broad-leaved evergreen forests with a dense undergrowth of grasses and scrub. Areas of open savanna also occur throughout the watershed, where fires occur during droughts. Sediment accumulation in Fena Reservoir from 1949 to 1979 averaged about $2,500 \text{ tons/yr/mi}^2$ (Curtis, 1984), assuming an average deposited weight of 46 lb/ft^3 . This sediment accumulation was determined by sonic soundings, and is believed to be the most reliable sediment data available for southern Guam. From data provided by Curtis (written communication, 1982) it was determined that the reservoir sediment was composed of about 85 percent clay and silt size particles and 15 percent sand and gravel size material. Typically sand and gravel sizes are transported in tributary streams as bedload, and silt and clay sizes as suspended load. Therefore, if it is assumed that 85 percent of the Fena Reservoir sediment was suspended load and 15 percent bedload, then from the 30-year sediment accumulation of $19,000,000 \text{ ft}^3$ the following is computed: 735 tons/yr/mi^2 bedload assuming a deposited weight of 90 lbs/ft^3 ; and $1,760 \text{ tons/yr/mi}^2$ suspended load assuming a deposited weight of 38 lb/ft^3 . This estimate of suspended-sediment yield for the Fena

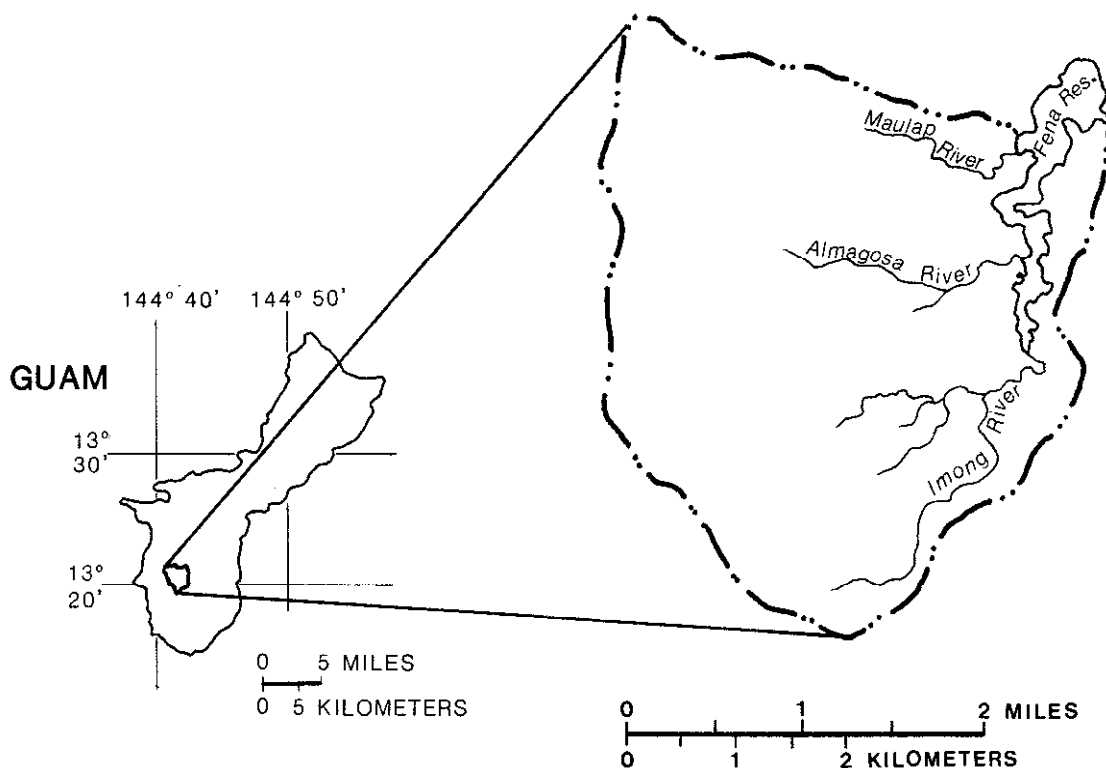


Figure 3. Location of Fena Reservoir drainage area, (from Curtis, W. F., written communication, 1982).

Reservoir drainage basin is higher than the range (460 to 1,455) calculated for the Talofoyo, Ylig, and Ugum basins by the use of flow-duration and sediment-rating-curves; however, it is probably more accurate because of the better quality of available data. Similar to Shown's (1970) results using the PSIAC formula, this PSIAC estimate of mean annual sediment yield, 2.0 acre-ft/mi², is 20 percent lower than Curtis' (1984) estimate of accumulated sediment in the reservoir (2.5 acre-ft/yr/mi²).

The PSIAC values for the Talofoyo, Ylig, and Ugum basins are listed in table 2. Using the same distribution of 85 percent suspended material at 38 lb/ft³ and 15 percent bed material at 90 lbs/ft³ assumed in the Fena Reservoir watershed, and the conversion of acre-ft to ft³, the computation gives a mean annual total sediment yield of 1,200 tons/yr/mi² for the Talofoyo, 1,385 tons/yr/mi² for the Ylig, and 1,210 tons/yr/mi² for the Ugum basins. The bedloads are 355, 410, and 355 tons/yr/mi² for the Talofoyo, Ylig, and Ugum

Table 2. PSIAC values for factors affecting sediment yield

	Talofoyo	Ugum	Ylig
Surface geology -----	1.9	2	1.6
Soils -----	8.4	8.5	9
Ground cover -----	-8.4	-8.5	-5.8
Climate -----	10	10	10
Runoff -----	10	10	10
Topography -----	15	15	15
Land use -----	5	5	5
Upland erosion -----	15	15	15
Channel erosion and sediment transport -	20	20	20
Totals	<u>76.9</u>	<u>77</u>	<u>79.8</u>

Note: A PSIAC rating of 75-100 translates to a mean annual sediment yield of 1.0 - 3.0 acre-ft/mi².

basins respectively, and the mean annual suspended-sediment yields for the Talofoyo, Ylig, and Ugum basins are 845, 975, and 855 tons/yr/mi² respectively. The estimates of mean annual suspended-sediment yield from the flow-duration sediment-rating-curve method of 460 tons/yr/mi² for the Talofoyo, 1,160 tons/yr/mi² for the Ylig, and 1,455 tons/yr/mi² for the Ugum basins, together with the PSIAC estimates, establish a reasonable range of suspended-sediment yields for the basins.

COMPARISON OF RESULTS WITH HAWAIIAN DATA

The sediment yields estimated for the basins in southern Guam have been added to table 3 from Jones and others (1971). The range of suspended-sediment, bedload, and total yields calculated for the basins in southern Guam compare well with the yields from several Oahu basins.

Table 3. Computed annual sediment yields for streams

Station		Drainage area (mi ²)	Mean annual sediment yield (Tons per square mile)		
Number	Location		Suspended load	Bedload	Total
2128	Hawaii	4.3	650	--	--
2130	Hawaii	45.7	700	500	1,200
2160	Hawaii	26.4	880	--	--
2230	Hawaii	6.07	630	470	1,100
2293	Hawaii	5.18	970	620	1,590
2605	Hawaii	5.34	710	75	785
2705	Hawaii	3.21	910	--	--
2739	Hawaii	4.38	960	530	1,490
2835	Hawaii	3.73	1,300	900	2,200
2840	Hawaii	.93	--	650	--
2845	Hawaii	2.26	1,400	500	1,900
Talofoyo	Guam	16.2	460-845	355	1,200
Ylig	Guam	6.48	975-1,160	410	1,385
Ugum	Guam	5.76	855-1,455	355	1,210

CONCLUSIONS

Reasonable values of mean annual suspended-sediment, bedload, and total sediment yields for the Talofoyo, Ylig, and Ugum River basins have been calculated using flow-duration and sediment-rating curves and by the PSIAC methods. These values are similar to estimates made for several basins on the island of Oahu, Hawaii. Similarly, the PSIAC estimate for sediment yield from the Fena watershed was verified by reservoir survey data. The reasonable estimates of sediment yields from the basins in southern Guam indicate the usefulness of the PSIAC method for some small tropical watersheds.

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HYDROPOWER IMPACTS ON EROSION AND SEDIMENTATION

By Walter M. Linder, Chief, Hydrologic Engineering Branch, U.S. Army Corps of Engineers, Kansas City District, Kansas City, Missouri and Tsong C. Wei, Hydraulic Engineer, U.S. Army Corps of Engineers, Missouri River Division, Omaha, Nebraska

ABSTRACT

The Harry S. Truman Dam and Reservoir, located in the headwaters of the Lake of the Ozarks, includes hydropower and flood control as project functions. During design and construction numerous concerns were expressed that peaking power operations would cause extensive downstream bank erosion and resuspension of the existing sediment deposits in the Lake of the Ozarks. In response to these concerns, a study was undertaken to identify the probable extent of erosion of the cohesive soils found in the bed and banks of the upper Lake of the Ozarks. The study required collection of a large amount of field data, analysis of the erodibility of the cohesive soils and stability of exposed banks, and mathematical modeling of sediment transport under various hydropower and flood control operations. The results of the study indicated erosion of banks and redistribution of the existing sediment deposits would not be a significant problem. Three years of intensive observations of actual project operation indicate the study conclusions were essentially correct.

INTRODUCTION

Hydropower can provide a rapid response to changing loads in a power system. However, it also has the potential for creating adverse impacts as a result of rapidly changing downstream flows. Harry S. Truman Dam (HST), located in west-central Missouri on the Osage River, see Figure 1, includes facilities for pump storage and power generation, flood control, and recreation. The Osage River immediately downstream of HST forms the headwaters of the 90-mile long Lake of the Ozarks (LOZ), an extremely popular midwestern recreation area. The Lake of the Ozarks, formed by Bagnell Dam which was completed in 1931, is owned and operated by Union Electric Co., a private corporation. The flow regime of the upper LOZ is a direct consequence of releases from HST. Discharge to LOZ from power generation can be as high as 65,000 cubic feet per second (cfs). As much as 27,500 cfs can be discharged in the reverse direction during pumping operations.

After construction of the project was nearly complete, numerous parties expressed concerns that there would be unacceptable adverse impacts on the downstream environment due to large daily stage fluctuations, high flow velocities, flooding of overbank areas, severe bank erosion, resuspension and redistribution of the existing sediment deposits, and increased turbidity. In response to these concerns, the Corps of Engineers conducted extensive hydrodynamic and sediment transport studies covering approximately the upper 30 miles of LOZ.

PHYSICAL SETTING

The Osage River originates in east-central Kansas and flows in an easterly direction for approximately 500 miles to the Missouri River near Jefferson City, Missouri. The drainage area is 15,300 square miles, of which 11,500

miles lie above HST. Five upstream reservoirs control 1,590 square miles of the drainage basin above HST.

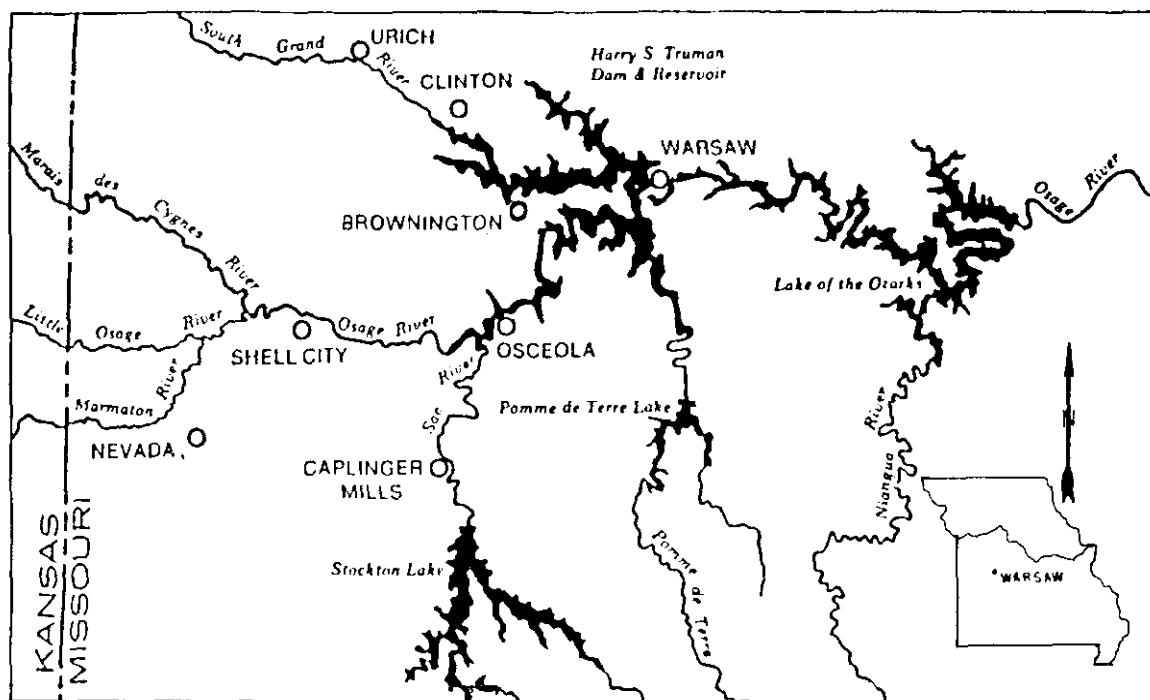


Figure 1 - Area Map

Suspended sediment was routinely measured on the Osage River at Osceola, MO (see Figure 1) during the periods 1943-51 and 1972-76; and on the South Grand River at Brownington, MO from 1943-51 to obtain data for estimating sediment inflow to HST. At Brownington, the suspended sediment concentration ranged from 1 milligram per liter (mg/l) to 13,850 mg/l, with a mean of 680 mg/l. The concentration at Osceola was lower and ranged from 3 mg/l to 5,270 mg/l, with a mean of 520 mg/l. Both stations were moved to Clinton and Schell City, MO at the upper end of the reservoir in 1980 to serve as sediment inflow measuring stations. The sediment transported by the Osage River is composed of clay, silt, and traces of fine sand, with an average clay-silt-sand ratio of 69/27/5. The material is very cohesive in nature due to its high clay content.

Sediment deposition in LOZ has been periodically surveyed since impoundment began in 1931. The sediment ranges established by Union Electric Co. have been resurveyed in 1940, 1948, 1961, 1974, 1979, and 1985. Longitudinal profiles along the thalweg are shown in Figure 2. A classic delta-like deposit begins near Warsaw and crests near LOZ mile 70, about 23 miles below HST. The depth of deposit at that point was about 30 feet in 1974. A short distance upstream of Bagnell Dam, the depth was about 2 feet. Based on measurements of sediment deposits accumulated in LOZ, the annual sediment load passing Warsaw prior to closure of HST was estimated to be 2,100 acre-feet per year wet volume. The material found in the delta deposits becomes progressively finer in the downstream direction. In the first 10 miles below HST the median grain size is approximately 20 microns, which reduces to about 6 microns and smaller farther downstream. The material is a cohesive silty clay with a cation exchange capacity (CEC) ranging from 15 to 32 millequivalents/100 grams

(meq/100g). The CEC, which is a measure of the type and amount of clay, is directly proportional to the cohesive property of the sediment. It ranges from 0 for pure sand to about 150 meq/100g for Bentonite, the most active clay.

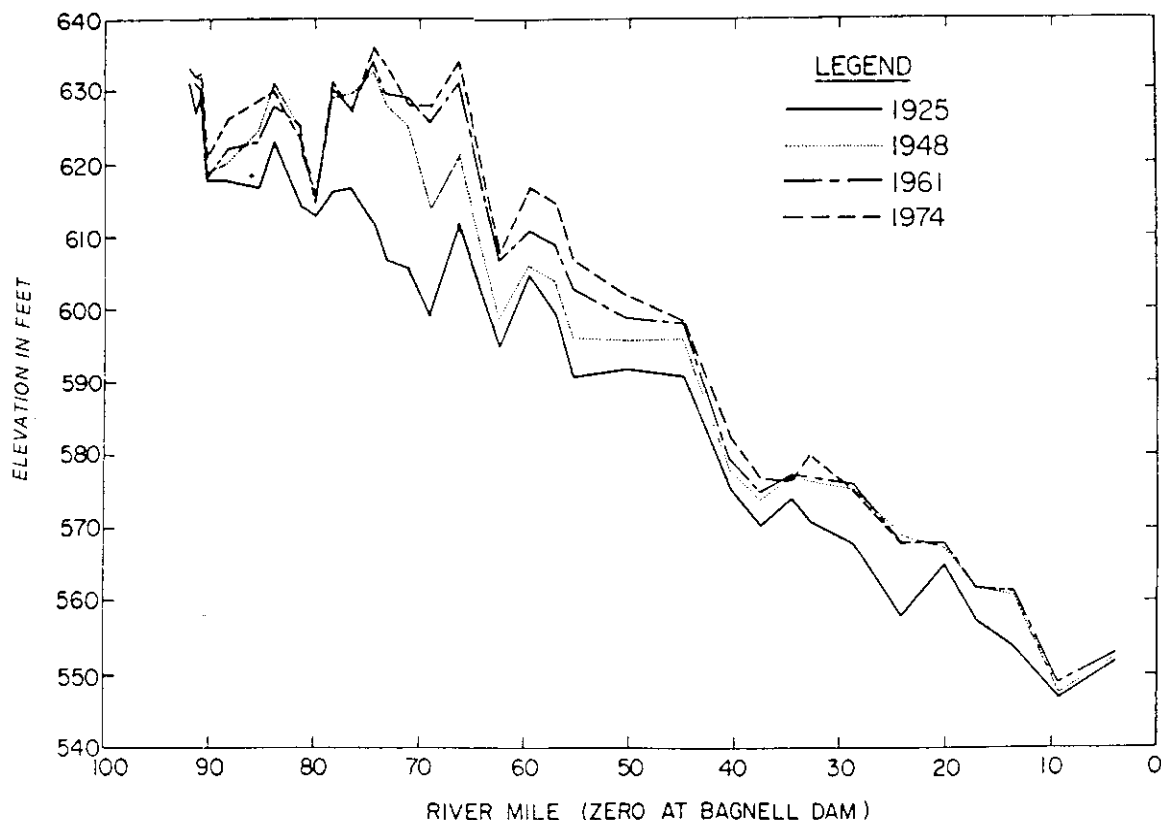


Figure 2 - Longitudinal Profile of Lake of the Ozarks Along the Thalweg
The banks in the upper LOZ are composed of the same material, but in a much more consolidated state. Flood flows have formed low natural levees of silt and fine sand on the overbank at some locations in the upper portion of the lake. Extensive shoaling has formed across the mouths of coves and tributaries, leaving only one or more narrow entrances. At very low levels of LOZ, the entrance to some coves is completely blocked by these shoals.

HYDRAULIC AND SEDIMENT TRANSPORT STUDIES

In order to evaluate the impacts of the HST power operation on the downstream environment, the following approach was used: (a) reconnaissance of the study area by experienced technical personnel, (b) collection of field data including a resurvey of established sedimentation ranges and collection of samples of water and bed and bank materials, (c) analysis of the above samples to define sedimentation parameters for mathematical modeling, and (d) mathematical simulation of hydrodynamics and sediment transport in LOZ under various power and flood control operations. Detailed results of these studies may be found in various reports (Ariathurai, 1970; Ariathurai, 1980; and Corps of Engineers, 1980).

More than 130 borings were made of the bed and banks of the upper 30 miles of LOZ. These included 54 auger borings of bank materials and 78 borings made to obtain 5-inch diameter undisturbed samples. About half of the undisturbed

samples were obtained from the bottom of LOZ using barge-mounted equipment. Of the 78 borings for undisturbed samples, 54 were used to obtain undisturbed samples for erodibility testing. The remaining undisturbed samples were used for permeability and strength tests for analysis of bank stability. The erodibility tests included determination of (a) resistance to erosion of the various stratum of bed and bank material, (b) rate of erosion when it is eroded, (c) potential to aggregate in suspension, (d) settling velocity, (e) density and resistance to erosion when it is redeposited, and (f) turbidity generation potential.

The erodibility of the sediment was determined by testing undisturbed samples in a rotating cylinder apparatus. Most of the samples were found to be highly resistant to erosion. In most cases, surface erosion was not evident; rather, cracks would form in the samples with increasing shear and finally chunks of material were removed by the shearing flow. Many samples were too soft to form test specimens for use in the rotating cylinder apparatus.

Stability studies of the banks were conducted to identify potentially unstable slopes and to estimate the volume of soil that might be involved in slides (Corps of Engineers, 1980). Since rapid drawdown conditions would be most severe close to HST, stability studies were concentrated in the upper reaches of LOZ. Factors of safety greater than about 1.1 were found for all sites investigated except for one isolated location on the left bank about $3\frac{1}{2}$ miles below HST.

UNSTEADY FLOW SIMULATION

The hydrodynamics of the LOZ as the result of HST power generation and pump-back operations were simulated using a program developed by Missouri River Division and Kansas City District of the Corps of Engineers (Linder and Wei, 1984). The unsteady flow model is a one-dimensional, implicit finite difference model that solves the Saint-Venant equations for the flow depth at the cross section and the flow velocity at the midpoint between two consecutive cross sections. The HST releases were used as the upstream boundary condition and the Bagnell Dam releases as the downstream boundary condition. A low steady flow discharge of 500 cfs was used as the initial condition. During the calibration and verification process, tributary inflow, channel conveyance, channel and overbank roughness, and off-lake storage of cove and tributary arms were adjusted to reconstitute observed data.

In order for SEDIMENT IIH, which assumes a rectangular cross section for one-dimensional analysis, to utilize the hydraulic parameters generated by the unsteady flow program it was necessary to convert the actual cross sections to equivalent rectangular sections using:

$$A = W(T-B) \quad (1)$$

where A = Cross section area

W = Average or representative width

T = Water surface elevation

B = Average or representative bed elevation

Using the maximum and minimum stages and flow areas from the flow simulation, the equivalent widths and bed elevations for each cross section were determined using equation (1). The equivalent width and bed elevation at each cross section along with discharge, flow velocity, and water surface elevation data were then used in SEDIMENT IIH to compute the sediment transport in LOZ.

MATHEMATICAL MODELING OF SEDIMENT TRANSPORT

SEDIMENT IIH is a two-dimensional, depth averaged, dynamic finite element, cohesive sediment transport model (Ariathurai and Krone, 1976; Ariathurai, 1980). It incorporates empirical formulas to describe the processes of scour, settling, and deposition for cohesive sediments. Although the model is capable of handling two-dimensional sediment transport, it was used one-dimensionally for studies of sediment transport in the main body of the lake.

Unlike non-cohesive sediments which depend on their own weight to resist transport, detachment of cohesive bed material must first break the interparticle force that binds the material together. The entraining force, the hydraulic shear stress at the bed, must be strong enough to break the interparticle bonds in order to cause erosion. Laboratory observations reveal there are two distinct erosion processes as the shear stress increases. At low shear stress the bed materials are entrained particle by particle from the bed surface. This process is called "surface erosion", and the associated shear stress is defined as the critical shear stress. At higher stress levels exceeding the bulk shear strength of the bed, it changes to "mass erosion" where large pieces of the bed material are instantly suspended in the flow. When the shear stress on the bed becomes less than or equal to the critical shear stress, deposition may occur. The shear stress associated with an incipient net rate of deposition is called the critical shear stress for deposition. As deposition continues, the overburden pressure causes the material to consolidate and consequently increase its density and resistance to erosion. The thickness of deposition layers in the model is based on Krone's (1962) criteria which requires about 25 mm of sediment to provide the necessary density variation.

SEDIMENT IIH uses the logarithmic velocity distribution to estimate the shear stress on the bed for fully developed turbulent flow. It also uses the approach suggested by Krone (1962) to estimate a rate of deposition from suspension which is based on the probability of particles sticking to the bed.

The sediment properties described below were established from the laboratory analysis of field samples. From standing cylinder laboratory test results, the settling velocity was determined to be:

<u>Concentration (g/l)</u>	<u>Settling Velocity (mm/sec)</u>
0.0 - 0.3	0.01
0.3 - 10.0	$0.05 \times C^{4/3}$
10.0	1.00

where C is the concentration in grams per liter.

From measurements of the cation exchange capacity and comparison to the results of viscometer measurements, bulk densities, and CEC by Krone (1962) on other sediments, the following bulk density, γ_b , and critical shear stress, τ_c , for each layer of deposition was obtained:

<u>Layer</u>	<u>γ_b (Kg/m³)</u>	<u>τ_c (dynes/cm²)</u>
1	1100	0.7
2	1119	1.5
3	1159	5.4
4	1280	12.0

where layer 1 is at the surface and each layer is assumed to have a thickness of 25 mm and will consolidate to the next higher value of density and critical shear stress. The bottom layer, number 4, can reach an unlimited thickness if deposition continues. A value of 0.7 dynes/cm^2 was selected as the critical shear stress for deposition. For the one-dimensional condition used in the study, an effective turbulent diffusion coefficient, D_x , of $100 \text{ m}^2/\text{sec}$ was used based on previous experience with similar problems for which field calibration data was available. A value of 20 mg/l sediment concentration was assumed as the initial condition for all elements in the model. An average value of 86 mg/l was used as the upstream boundary condition based on measured concentrations of HST spillway flows during construction. Downstream at Bagnell Dam it was assumed there would be no change in the sediment concentration from initial conditions.

Flow conditions selected for sediment transport simulations included flood control releases of 34,000, 40,000, and 54,000 cfs and a generation/pumpback cycle of 65,000/27,500 cfs at LOZ elevations between 652 and 660. Flow duration for all cases was 1 week. The results of the simulations showed only the softer surface layers would be eroded. The maximum suspended sediment concentrations occurred near the crest of the existing delta and all of the material was deposited farther downstream. Pumpback did not resuspend the material and move it back upstream. The extent of scour and deposition for 1 week of power operation is shown in Figure 3.

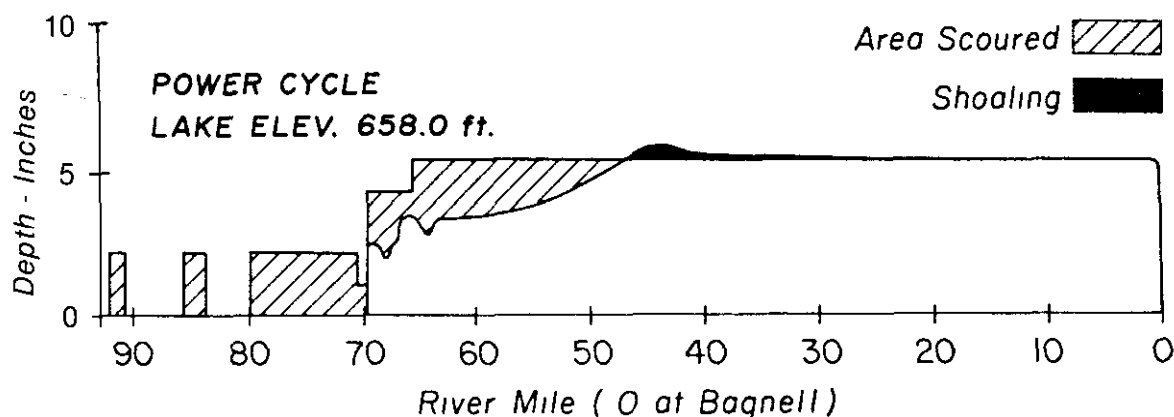


Figure 3 - Erosion-Deposition For One Week Power Cycle

Two-dimensional simulations of shoaling rates in four different coves were also conducted. These showed shoaling rates in the coves would be greater for power operations than for natural conditions when using LOZ suspended sediment concentrations that existed prior to closure of HST. Since HST intercepts nearly all sediment transported by the Osage River, the net result is a significant reduction in the rate of deposition across the cove inlets and in the coves.

FIELD OBSERVATIONS

In response to continued concerns, the Corps of Engineers in December 1981 agreed to proceed slowly with power operations at HST. Except for flood control purposes, releases were initially limited to two power units. Downstream conditions were observed for a period of time until it was determined adverse impacts were not occurring. Power releases were increased to three units early in 1982 and to four units in June of 1983. Since that time no more than four units have been used for power peaking operations.

An extensive monitoring program was initiated early in 1982 for the purpose of documenting the nature and magnitude of any changes that might be occurring. The results of field observations are presented in three monitoring reports (Corps of Engineers, 1982, 1983, and 1984).

Based on the results of the previous studies, the geographic extent of the monitoring extends from HST downstream for a distance of approximately 33 miles. Observations include continuous recording of water levels; measurement of flow velocities in LOZ and cove inlets; bank line surveys to document erosion rates; suspended sediment sampling to estimate sediment transport and to provide comparison with mathematical model predictions; and resurvey of ranges to determine the extent of any bottom scour or redistribution of existing delta deposits.

Five stage recorders were installed in March 1982 to supplement the existing recorders in the outlet channel (0.4 mile downstream) and at Highway 7 at Warsaw (1.7 miles downstream). These locations were 3.8 miles downstream, 12.3 miles downstream, 1 mile up Turkey Creek Cove which is located 12.6 miles downstream, 22.2 miles downstream, and 33.6 miles downstream. As to be expected, the greatest stage fluctuation occurs in the area nearest the dam. The amount of stage fluctuation also varies with the initial level of LOZ, with greater fluctuations occurring at the lower lake levels. In general, as shown on Figure 4, stage fluctuations have agreed very well with mathematical model predictions.

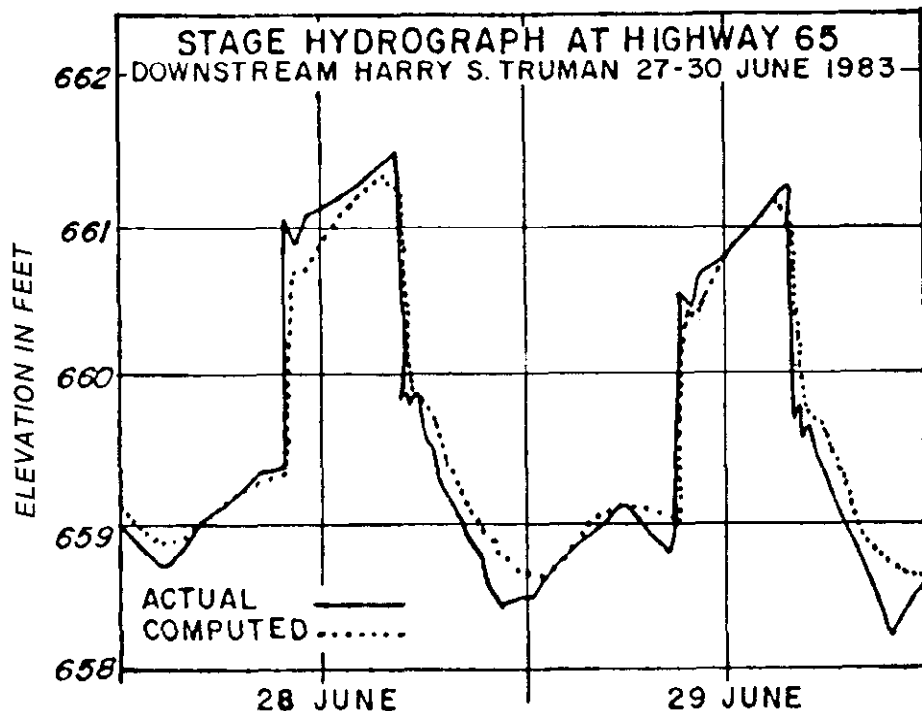


Figure 4 - Comparison of Computed and Recorded Stages in the Lake of the Ozarks 4 Miles Below Harry S. Truman Dam

Flow velocity measurements were obtained both in the main body of LOZ and in various cove inlets. Velocity measurements in LOZ were concentrated at the locations of the stage recorders. During power peaking operations, the measurements consisted of a series of vertical velocity profiles at approximately

15-minute intervals at a single location in the cross section. During flood control releases, vertical velocity profiles were obtained at selected points in each cross section in order to determine the lateral distribution of flow. The highest velocities are located within the first few miles downstream of HST and decrease in the downstream direction.

Velocity measurements in cove inlets consisted of a series of vertical profiles at one or more points across the inlet during the rising and falling stages of the power operation hydrograph. Maximum flow velocities in cove inlets nearest the dam were relatively high, approximately 9 ft/sec. The inlet of one cove was widened to approximately double the cross-sectional area. This reduced inlet velocities approximately 40 percent.

Depth integrated suspended sediment samples were obtained at the location of velocity measurements during power and flood control operations. Velocities and suspended sediment concentrations at various locations in LOZ for a flood control release of 50,300 cfs are shown on Figure 5. The suspended sediment concentration shows an increase in the downstream direction which peaks near the location of the greatest depth of delta deposit and then declines farther downstream. This trend has also been observed during power peaking operations and indicates some erosion of the bed and banks is occurring in the upper reaches of LOZ and the eroded material is being deposited on and downstream of the existing delta. This trend was also shown by the mathematical simulation of sediment transport.

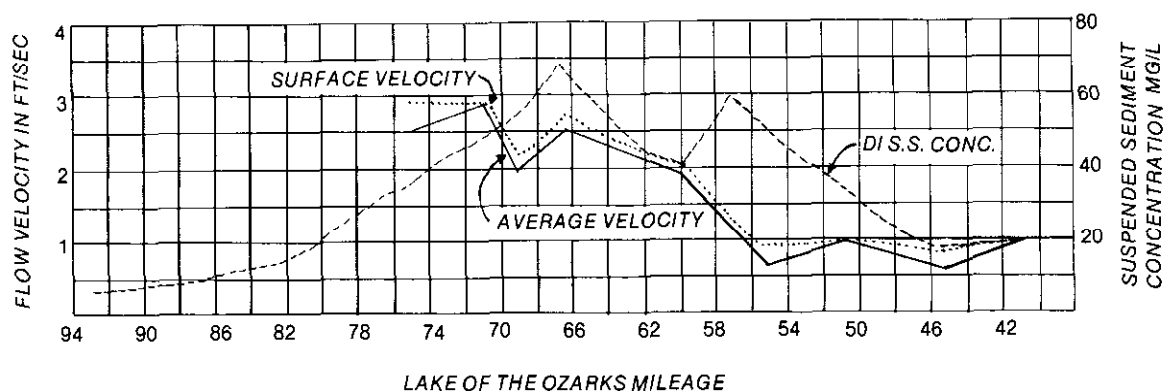


Figure 5 - Suspended Sediment and Velocity Profiles in the Lake of the Ozarks, 50,300 cfs HST Release

Although initial studies indicated the bank lines downstream of Truman Dam were generally resistant to erosion, some areas appeared to be more susceptible to erosion due to the presence of sand or gravel in the bank or they were subject to direct attack by the flow. Twelve sites were initially selected for periodic surveys. Except for two sites, all were within the first 5 miles downstream of the dam. Surveys generally extended 30 to 40 feet riverward of the bank line, but were extended to the channel thalweg once in 1983 and again in 1984. Figure 6 illustrates survey results at the bank erosion monitoring site directly opposite the outlet channel and Figure 7 shows a time history of erosion at this site. Bank erosion to date has been between 1 and 2 feet per year and it appears bank lines are beaching or receding to a slope between 1V on 5H to 1V on 6H. The surveys extended to the center of the channel indicate that little or no general widening or deepening has occurred.

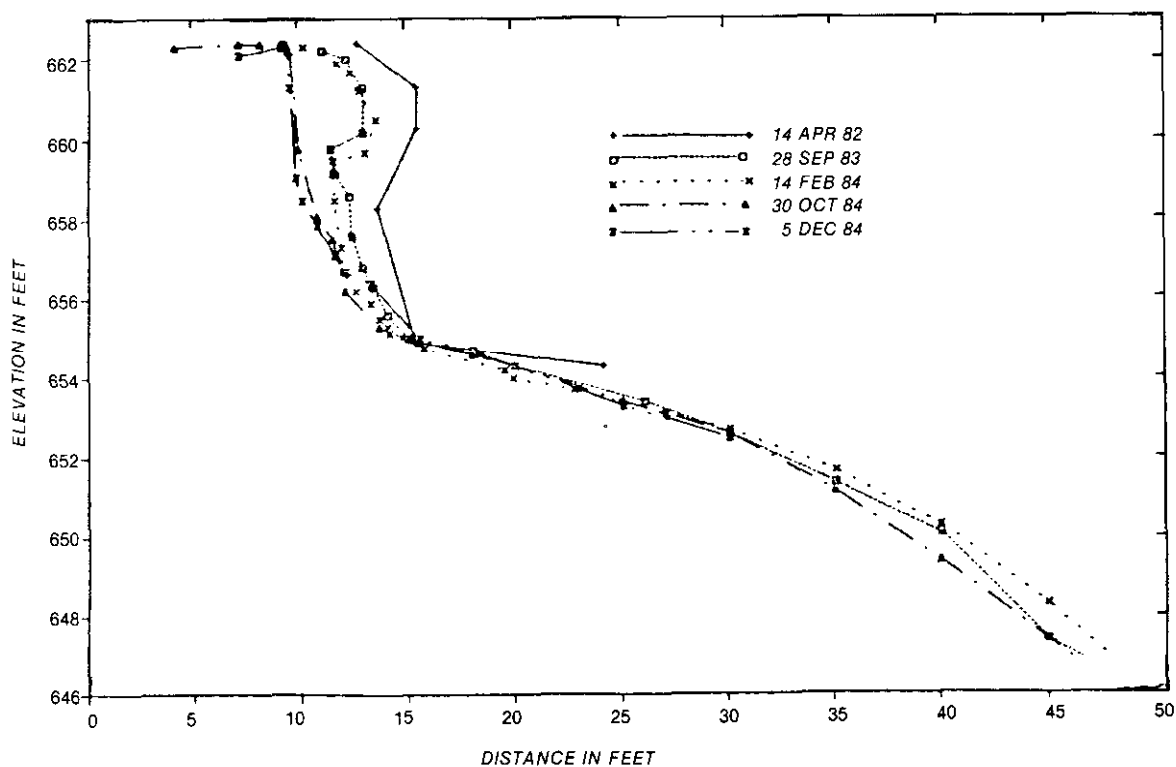


Figure 6 - Bankline Profiles Opposite the Harry S. Truman Outlet Channel

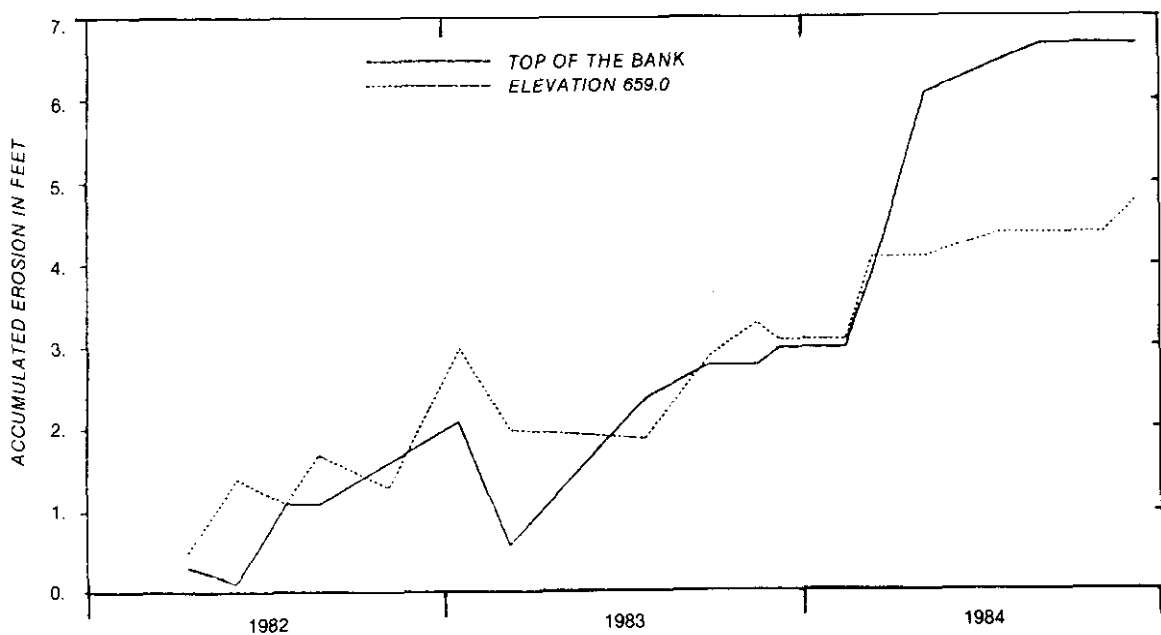


Figure 7 - Time History of Erosion of Bankline Opposite the Harry S. Truman Dam Outlet Channel

SUMMARY AND CONCLUSIONS

A direct comparison between model simulations and observed impacts is difficult as the power operation at HST has been different from that assumed in the initial studies. Hydrodynamic and sediment transport simulations assumed worst case conditions, that is daily generation at 65,000 cfs followed by pumpback at 27,500 cfs. For various reasons, actual project operations have been significantly different. Pumpback has been deferred indefinitely because of unacceptable fish kills during pumpback testing and, in response to concerns about downstream impacts, the number of units used for power peaking operation has been restricted.

Bank stability studies showed little potential for instability resulting from power operation, and there is little, if any, evidence of bank failures. There has been generalized bank erosion in the first few miles downstream of HST. However, the rate of erosion has been slow, 1 to 2 ft/yr, and the bank line appears to be beaching at slopes from 1V on 5H to 1V on 6H. A number of factors contribute to bank erosion other than direct removal of soil particles by the flow. Wetting and drying, and freezing and thawing, loosen the soil particles at the surface and make them more easily removed by the flow. Wave action by boat wakes also appears to be a major cause of bank erosion.

Mathematical simulation of the hydrodynamics and sediment transport downstream of hydropower plants can be an effective tool for predicting probable impacts. However, it requires a substantial effort in collecting adequate data for model input, calibration, and verification. The monitoring program shows there is generally good agreement between predicted and observed stage fluctuations and flow velocities downstream of HST. Collection of adequate sediment transport data for direct comparison with model predictions is difficult, but trends observed to date support model predictions.

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EROSION AND SEDIMENT YIELD FROM FLATLANDS

By C. E. Murphree, Agricultural Engineer, C. K. Mutchler, Hydraulic Engineer,
USDA Sedimentation Laboratory, Oxford, Mississippi

ABSTRACT

Sediment yield and erosion research has been conducted on the flatlands of the Mississippi Delta since 1972. This report reviews that research and summarizes sediment yield studies under natural rainfall and other research, using the rainfall simulator, to adapt the Universal Soil Loss Equation (USLE) for use on low slopes. Rainfall, runoff, sediment yield, and sediment particle size data from three flatland watersheds with drainage areas of 15.6, 18.7, and 259 ha have been summarized. Sediment yield prediction equations are derived for the two smaller watersheds. Size distributions of sediments from the two smaller watersheds (15.6 and 18.7 ha) are compared with the outflow sediments from the larger 259 ha watershed. Soil loss data collected from plots under simulated rainfall, on low slopes (0.1 to 3.0 percent), from different slope lengths and using seedbed preparation tillage practices unique to this region, indicated that changes in R, L, S, and C factors would enhance USLE predictions on low slopes such as those encountered on Lower Mississippi Valley Alluvium cropland.

INTRODUCTION

Flatlands is defined as land with very low slopes such as those on the Mississippi Delta. The Mississippi Delta is part of the Lower Mississippi Valley Alluvium which encompasses about 8.1 million ha of alluvium - derived soils. Other flatlands are part of the flood plains found along the many streams that drain upland areas. A large portion of the Nation's best cropland is found on land with such low slopes. Thus, in terms of crop production, it is very important to consider the conservation of flatland soils.

Research in 1972 to 1974 on a watershed in the Mississippi Delta documented the high erosion potential of these flatlands (Murphree et al. 1976). The average annual sediment yield was 29 t/ha from a 16-ha watershed. Rainfall during the 2-year period of this experiment was 33% greater than the average annual.

This paper reports later research on this same area and reviews research on other watersheds in the flatland areas of Mississippi. Also, research on adapting the Universal Soil Loss Equation (USLE) for use on low slopes is described.

SEDIMENT YIELD

Rainfall, runoff, and sediment yield were measured from two adjacent flatland watersheds that drain into a small pond and from the outlet of the pond from 1972-1984. In addition, rainfall, runoff and sediment yield were measured from a large natural Delta watershed at its outlet from 1975-1984. A description of these areas follow:

McWilliams Watersheds

Two watersheds selected for this research are located on the G. L. McWilliams Farm near Clarksdale, MS. One has silty clay soil and the other has silt loam soil. These watersheds drain into a pond as shown in Fig. 1.

The soil on the north watershed is Sharkey silty clay (Vertic Haplaquepts). The soil on the other watershed is Commerce silt loam (Aeric fluvaquents) (15 percent), Bruin silt loam (Fluvaquentic eutrochrepts) (57 percent), Tunica silty clay (Vertic haplaquepts) (11 percent) and Sharkey silty clay (17 percent) along the watershed border. We will refer to these watersheds as the Sharkey and Commerce watersheds.

The drainage area of the Commerce watershed is 19 ha, that of the Sharkey watershed is 16 ha. The watersheds had been formed to a mean slope of 0.2 percent. Cotton rows spaced 1 m apart were oriented up-and-down the slope, with a mean slope length of 169 m for the Commerce watershed and 186 m for the Sharkey watershed. Runoff generally followed each individual row middle until it entered the main east-west V-ditches (Fig. 1).

Data from the McWilliams Watersheds are given in Table 1 for the 5 year period (Nov 1975 - Oct 1978). Practically all the precipitation was in the form of rainfall. The 5-year average rainfall measured at the watersheds was within 2 percent of the long term average (Murphree and Mutchler, 1981).

Using data collected during 237 storm runoff events, we developed simple linear relationships of sediment yield (SY), runoff (RO), and rainfall (P) using data grouped by seasons. Relationships for $SY = f(RO)$ and $RO = f(P)$ were derived using individual storm data or groups of storms if individual storm data could not be identified. These two sets of equations were combined algebraically to show $SY = f(P)$ for monthly values, Table 2. Predicted sediment yield using the equations in Table 2 was 99% of measured sediment ($r^2 = 0.96$) for the Sharkey watershed and 97% of the measured sediment from the Commerce watershed ($r^2 = 0.96$).

Many flatlands watersheds have some flow restriction that slows the runoff and allows sediment to deposit before leaving the watershed. In this case, the pond (Fig. 1) below the two McWilliams watersheds is a remnant of an old drainage pattern that was altered by filling in from the south end of the present pond to the large drainage ditch. We replaced a small outlet pipe with a 38 cm concrete underground pipe with a drop box structure and V-notch weir to facilitate pond outflow measurement and sediment sampling. Measured runoff and sediment yield from the pond are given in Table 1.

During the months of relatively high runoff (November-June) trap efficiency of the pond was about 63 percent while during the months of low runoff, (July - October) 81% of the sediment from the watersheds was trapped in the pond.

Fisher Watershed

The Fisher Watershed, located at Glen Allen, MS, is 259 ha in size. All the slopes in the watershed are natural and cropping is mixed cotton, soybeans, and wheat. In contrast to the small McWilliams watersheds, the Fisher watershed is much larger, has several restrictions throughout the interior of

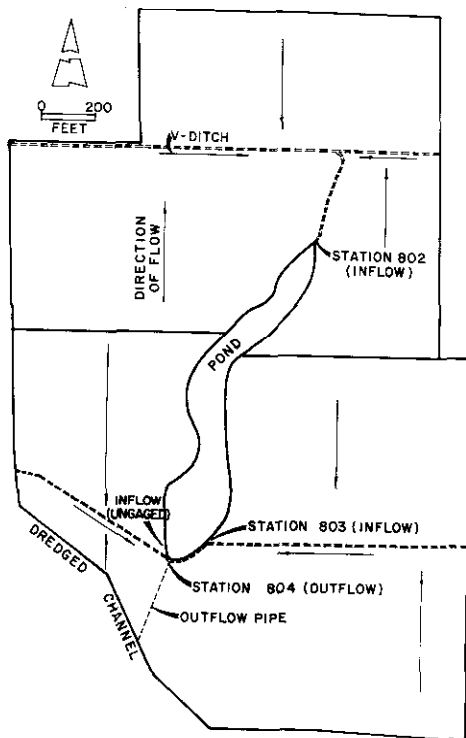


Fig. 1. McWilliams Watershed

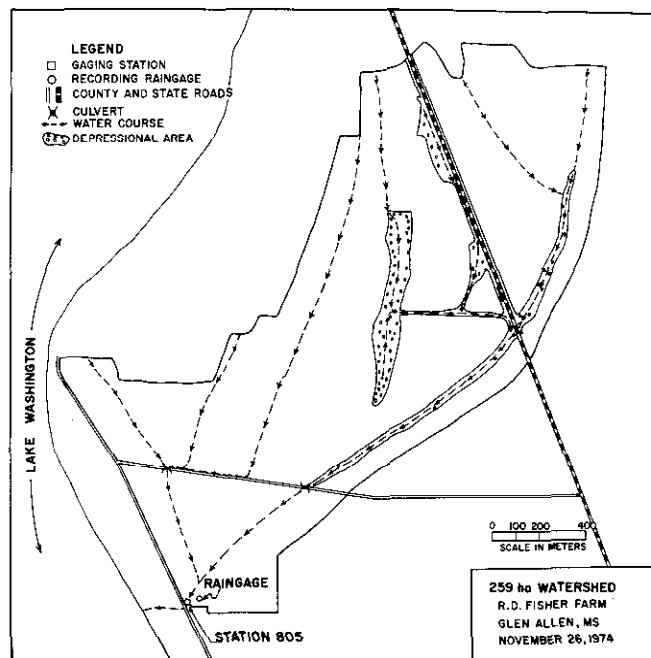


Fig. 2. Fisher Watershed Map

the watershed and includes various natural depositional areas. All of these characteristics are commonly found throughout the Delta. The predominant crop in the 259-ha watershed is cotton (193 ha), followed in area by soybeans (35 ha), and wheat (6 ha). The remaining 25 ha consists of 20 ha of wooded depressional areas with depths less than 0.8 m, about 1.7 ha of other small wooded areas and approximately 3.3 ha of hard surface road and grassed right-of-way.

The watershed topography is typical of ungraded farmland in the Delta. It contains a series of natural ridges and depressions with gently sloping areas between. Figure 2 shows the general drainage pattern within the watershed. Row directions for cotton and soybeans were generally up and down slope; however, some rows in the lower part of the watershed were across the slope when cross slopes were adequate for good surface drainage. Slopes on the cultivated fields within the watershed ranged from 0.2 percent to 1.4 percent. Slopes greater than 0.6 percent generally had a slope length less than 66 m.

The soils in the watershed are Tutwiler and Dubbs silt loams (Typic Hapludalfs), Dundee silt loam (Aeric Ochraqualfs) and a very small area of Tensas silty clay loam (Vertic Ochraqualfs). The Tutwiler and Dundee soils are the predominant soils in the watershed comprising over ninety percent of the drainage area. These soils are found on the natural levees that commonly occur throughout the Delta and are among the most productive soils in the region.

Table 1. 5-year average monthly rainfall, runoff, and sediment yield from McWilliams watershed - 802, 803, and pond - November 1973 - October, 1978.

Month	Rainfall (mm)	Watersheds w/o pond ¹			Watersheds with pond ²		
		Runoff (mm)	Sediment Yield (t/ha)	Conc. ³ mg/L	Runoff mm	Sediment Yield t/ha	Conc. ³ mg/L
Nov	162	82	0.814	995	75	0.271	361
Dec	93	39	0.666	1700	39	0.213	550
Jan	136	79	1.42	1790	78	0.726	937
Feb	85	45	1.83	4040	45	0.798	1790
Mar	102	38	1.93	5050	38	0.776	2020
Apr	103	32	1.54	4860	30	0.648	2180
May	122	62	3.34	5350	62	1.08	1750
Jun	153	79	3.56	4530	71	1.06	1490
Jul	78	9	0.417	4730	8	0.072	894
Aug	93	26	0.345	1310	3	0.078	309
Sep	92	7	0.078	1070	5	0.011	195
Oct	52	3	0.009	307	11	trace	448
5-yr Ave Ann	1270	503	16.0	3170	478	5.74	1200

¹ Combined Sharkey and Commerce watersheds; drainage area is 34.3 ha.

² Pond area is 1.6 ha, total area 35.9 ha.

³ Discharge weighted concentration.

Table 2. Linear relationships of monthly sediment yield (SY)¹ and rainfall (P)² for similar tillage and soil moisture periods of the year.

Period	Watershed	Equation	Number of Storms	Equation Number
November-January	Sharkey	$SY = -0.40 + 0.096 P$	61	(1)
February-June	Sharkey	$SY = 0.92 + 0.272 P$	89	(2)
July	Sharkey	$SY = -0.77 + 0.142 P$	24	(3)
August-October	Sharkey	$SY = 0.27 + 0.050 P$	63	(4)
November-January	Commerce	$SY = -0.45 + 0.105 P$	61	(5)
February-June	Commerce	$SY = 1.41 + 0.370 P$	89	(6)
July	Commerce	$SY = 1.32 + 0.217 P$	24	(7)
August-October	Commerce	$SY = 0.32 + 0.061 P$	63	(8)

¹ Units for sediment yield (SY) are metric tons per hectare.

² Units for precipitation (P) are centimeters.

Average annual rainfall (Table 3) for the 6-year record (1975-1980) was 57 mm greater than the 27-year average reported by the Delta Branch Experiment Station, Stoneville, MS, located about 40 km north of the watershed (Table 3). This departure is well within one standard deviation of the long term average. Annual departures were fairly well distributed on both sides of the mean.

Annual runoff for the 6 years averaged 394 mm. This amount contrasts with the 503 mm per year measured during a prior 5-year study (1973-1978) from the smaller, McWilliams watershed (Murphree and Mutchler, 1981) located 130 km north of Glen Allen. The average annual rainfall on the Fisher watershed was 11 percent greater than rainfall on the McWilliams watershed, but the runoff from the McWilliams watershed was 28 percent greater. Although these averages reflect results from two different periods of time; there was a 3 year overlap between the two periods, and the magnitude of differences are so high that different runoff characteristics for the two watersheds are evident. The smaller runoff from the larger watershed is attributed to several factors: (1) an intense deep tillage practice on the larger watershed where subsoiling is done each fall after harvest, 2) more infiltration due to longer travel time and hydrologic soil groups of the larger Fisher Watershed which indicate a lower runoff curve number, 3) ponded water trapped on the larger ungraded watershed and higher drainage efficiency of the smaller graded watershed. The most significant factor for the difference in runoff when comparing the monthly runoff values is the deep tillage practice in the fall. During the months of November, December, and January, immediately after subsoiling, runoff from the Fisher Watershed (259 ha) averaged 83 mm while runoff from the McWilliams watershed (34.3 ha) was 191 mm, a difference of 108 mm for the 3 month period.

Table 3. Average monthly measured precipitation, runoff, and sediment yield from the 259 ha Fisher Watershed, 1975-1980.

Month	Measured Precipitation ¹ mm	Measured Runoff mm	Measured Sediment Yield t/ha	Sediment Concentration ² mg/L
January	118	39	0.269	688.
February	110	45	0.399	893.
March	177	69	1.027	1490.
April	135	60	1.431	2400.
May	169	56	1.029	1850.
June	111	24	0.287	1180.
July	153	45	0.509	1140.
August	50	2	0.009	368.
September	80	5	0.018	341.
October	77	5	0.011	240.
November	130	21	0.076	359.
December	94	23	0.173	760.
Average Ann.	1404	394	5.238	

¹ Precipitation record (6-year average) from Fisher Watershed 1975-1980.

² Discharge weighted values.

The average annual sediment yield of 5.3 t/ha was high considering that 10% of the watershed is normally ponded in addition to temporary storage in other depressional areas common to natural slopes. In contrast, the 15.6-ha McWilliams watershed in Coahoma County, Mississippi (Murphree and Mutchler, 1981), which had no ponded areas and was graded to a 0.2 percent slope, yielded about 15.7 t/ha y.

Average monthly sediment yields and discharge weighted concentrations were greatly affected by tillage and cover variations throughout the year. The months August through November can be described as a non-tillage period with crop canopy and cover, and weed cover combined approaching 100 percent. Sediment concentrations and sediment yield were lowest during this period. The period December through February had almost no canopy cover, but a large amount of residue and winter weeds provided almost 100% cover to the undisturbed soil surface. However, subsoiling during the period destroyed about 25 percent of the ground cover throughout the watershed. March, April and May were months of final seed bed preparation, planting, plant emergence, and early crop growth. They were also a period of intensive tillage with almost no ground cover and crop canopy. The highest erosion occurred during this period causing high sediment yields and high sediment concentrations (Table 3). June and July were months of crop canopy establishment with canopy increasing to about 100 percent by the end of July and tillage for weed control ending by the middle of July.

A comparison of average monthly sediment yield between the Fisher and McWilliams watersheds shows that sediment yield is highly dependent on runoff volume. Also, sediment concentrations are dependent on soil texture and cover. Intensive tillage for seedbed preparation, planting and cultivation (Feb.-Jul.) on the McWilliams watersheds lasted 6 months and on the Fisher watershed 5 months (Mar.-Jul.). However, sediment yield from both watersheds during the tillage period was about 80% of the average annual sediment yield.

While the sediment yield distribution through the year for both watersheds is similar, the amount of sediment from the 259-ha watershed was significantly different from the McWilliams watershed above its pond. The sediment yield from the smaller McWilliams watershed (34.3 ha) excluding the pond, was 3 times greater than the sediment yield from the Fisher Watershed (259 ha). This can be attributed to several factors: 1) increased transport efficiency of the smaller graded watershed and the naturally occurring depositional areas and flow restrictions within the larger ungraded Fisher Watershed, 2) larger depth of runoff from the smaller watersheds, 3) greater proportion of clay and fine silts on the soil surface that can be transported in the slow flows encountered in the flatland area. However, sediment yield from the Fisher watershed was about the same as from the McWilliams watershed measured at the pond outlet.

SEDIMENT PARTICLE SIZES

Particle size analyses of the watershed soils and sediment outflow for the McWilliams and Fisher Watersheds are summarized in Table 4.

Particle size analysis of sediment outflow samples from storms representing a wide range of runoff rates and soil conditions throughout the year showed that

no sand particles (>0.063 mm) left the Fisher or the McWilliams watersheds at the outlet gaging stations. About 85% of the sediment outflow from both the Fisher watershed and 1.6 ha pond at McWilliams was clay (<0.002 mm), and at least 95% of the outflow from all the study area watersheds was finer than 0.016 mm in size. These results were also found by Dendy (1981) for two much smaller flatland watersheds of 2.6 and 7.2 ha each and graded to 0.2 percent slope in Sunflower County, MS.

These data show that for the low slopes and low transport capacities encountered in the Delta, suspended clay and fine silt can be transported significant distances. Clay enrichment ratios (McDowell et al., 1984) were 1.8 and 5.3 for the McWilliams and Fisher watersheds, respectively. This is particularly significant because most of the farm chemicals transported by sediments in runoff are carried by the clay fraction of sediment (McDowell et al., 1981; McDowell et al., 1982).

EROSION

When the USLE was developed some years ago, most conservationists thought that erosion was not significant on slopes less than about 3 percent. Therefore, the USLE was developed from data using steeper slopes. The excessive erosion measured from the McWilliams watershed discussed earlier showed that erosion control on low slopes was needed. Thus, one of our objectives in flatland research was to adapt the USLE for use on flatlands.

Table 4. Comparison of dispersed sediment and surface soils from the Fisher and McWilliams Watersheds.

	Clay $<.002\text{mm}$	Silt (mm)					Sand $>0.063\text{mm}$
		0.002 0.004	0.004 0.008	0.008 0.016	0.016 0.031	0.031 0.062	
Fisher Watershed:							
Surface soil - %	16	2	5	8	22	35	12
Outflow sediments - %	85	4	4	4	2.3	0.7	--
Annual Sediment Yield by Size Fraction - t/ha	4.45	0.21	0.21	0.21	0.12	0.04	--
McWilliams Watershed:							
Surface soil - %	39	8	11	13	14	10	5
Outflow Sediments - %	67	11	10	6.0	4.4	1.4	0.2
Annual Sediment Yield by Size Fraction - t/ha	10.7	1.8	1.6	1.0	0.7	0.2	0.03
1.6 ha Pond Outflow - %	85	9	4.2	1.4	0.4		

The familiar USLE is $A=RKLSCP$, where A is the estimated soil loss and R, K, L, S, C, and P, respectively, represent rainfall erosion index, soil erodibility, slope length, slope steepness, cropping and management, and erosion control practices.

The higher levels of soil moisture found on flatlands usually increase soil erodibility. Barnett et al., (1978) found K-factors for Commerce silt loam and Sharkey clay soils to be much higher than previously estimated. Soil strength is lower when moisture is high, soil detachment is greater, and rainfall excess is greater on flatlands. Using erosion plot data from Holly Springs, MS, Mutchler and Carter (1983) found that soil erodibility varied throughout the year with the highest erodibility in the cool, wet season and the lowest during the dry, hot time of the year. They proposed an erodibility coefficient, K_C , as

$$K_C = 1 + 0.69 \cos[(t-2.147) 2\pi/12]$$

where t is expressed in months (Jan 15 is 1.5) and the argument of the cosine is in radians. Of course, for average annual erodibility values, this variability can be neglected.

Slope length and steepness relationships given in AH-537 (Wischmeier and Smith, 1978) for the USLE were derived generally from data taken from slopes above 3 percent. Soil loss is assumed proportional to slope length (λ) to an exponent m, $SL = \lambda^m$, where m is related to slope steepness (θ). Mutchler and Greer (1980) collected data from slope lengths of 23, 46, 91, and 183 meters on a 0.2 percent slope. These data were used with values of m from AH 537 for steeper slopes to formulate

$$m = 1.2 (\sin \theta)^{1/3}$$

where θ is the slope angle in degrees (Mutchler and Murphree 1981). Thus, very small values of m would be used for flatland slopes and values for higher slopes as given in AH537 would be relatively unchanged for steeper slopes up to 12 percent.

Research by Murphree and Mutchler (1981) showed that the slope function for the USLE given in AH537 over-predicted soil loss from low slopes. They proposed a correction factor of

$$S_C = (\beta/2) + 0.5$$

where

$$\beta = 1 - 0.67 \exp (-160. \sin \theta)$$

to be used as a multiplier to the present slope factor of the USLE.

The cropping and management factor, C, of the USLE should be the same on flatlands as on steeper slopes. However, tillage on flatlands is often more intensive and ridging used in the spring to provide a warmer seedbed, especially for cotton, requires higher C-values. Murphree and Mutchler (1980) measured C-values for cotton ranging from 0.10 to over 1.00 for cropstages with an annual average of 0.58. The large cropstage values were due to the

tillage and ridging in the cool season of the year. These values were computed from data without consideration of the soil erodibility variation mentioned earlier.

The practice factors, P, used in the USLE generally do not apply (approach a value of 1.0) on flatlands. However, the protective effect of surface water layers becomes more important on low slopes in high rainfall areas of the Southeast. Mutchler and McGregor (1983) found that maximum erosion rates on 0.1 percent slopes occurred under an average runoff depth of about 2 mm. Little change in erosion rates occurred for depths greater than about 20 mm. Mutchler and Murphree (1981) proposed to account for the surface water depth effect in the R-factor with a coefficient ranging from 100% (for slopes of 1%) to 90% (for slopes of 0.1%) and an R-factor of 300 (customary US units); and from 90% (for slopes of 1%) to 70% (for slopes of 0.1%) and an R-factor of 600; and by linear interpolation for intermediate slopes and R-values.

SUMMARY

Sediment yield and erosion studies on flatlands were conducted in Mississippi since 1972. Early results established the seriousness of erosion on low slopes - the average annual sediment yield was 29 t/ha from a 16-ha watershed. This loss was measured from 2 years of excessive rainfall. However, 5-years of data from near normal rainfall allowed a more reliable measurement of 16 t/ha from two adjacent watersheds with an area of 34 ha graded to a slope of 0.2%. This sediment yield indicated an excessive erosion rate. When the effect of a natural 1.6-ha pond below the watersheds was included, the annual sediment yield was reduced to 6 t/ha; however, the excessive rate of erosion on the cropland was unchanged.

Sediment yield from a larger, 259-ha, watershed was 5.2 t/ha·y for a 6-yr average. This watershed has natural slopes, numerous depressions, and mixed crops. Measured sediment yield from this large, natural Delta watershed was not much less than from the smaller watersheds that included a pond. However, deep tillage on the larger watershed was credited with contributing to less runoff which reduced sediment yield. Also, grading on the smaller watershed increased runoff response, especially for smaller storms, which contributed to a larger sediment yield. Probably the most important result of the sediment yield studies, however, was the measurement of surprisingly large amounts of sediment leaving flatland watersheds.

Sediment transport capacities for the low slopes of the Delta are low; however, suspended clay and fine silt were easily transported. About 95% of the sediment outflow from all the research watersheds was finer than 0.016 mm. Clay enrichment ratios were 1.8 and 5.3 for the McWilliams (35.9 ha) and Fisher (259 ha) watersheds, respectively.

The factors of the USLE were modified for estimation of erosion on flatlands. Proposed changes reduced the effect of the R factor because of deeper surface water depths on low slopes under high intensity rainfall. A variable K factor was suggested to more closely describe higher erodibility in the cool, moist part of the year. The slope length exponent was decreased to reflect the lower observed soil losses on very low slopes than were predicted by the current USLE. Likewise, the steepness factor was modified to better estimate low slope erosion. Higher soil loss ratios are needed for certain stages of

crop growth to reflect the more frequent tillage and bedding used in flatland cropping practices. For very low slopes, the P factor properly approaches 1.0 and modifications are not necessary.

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SAGEBRUSH RANGELAND EROSION AND SEDIMENT YIELD

By Clifton W. Johnson, Hydraulic Engineer and Nancy D. Gordon, Hydrologist,
USDA, Agricultural Research Service, Northwest Watershed
Research Center, Boise, Idaho

ABSTRACT

Runoff, erosion, and sediment transport in the Reynolds Creek Experimental Watershed have been studied for about 20 years. Results show that sediment yields are mainly from rainfall events below about 1400 m elevation and from snowmelt-associated events above that elevation. Sediment yields ranged from near zero amounts in drought years to over 3 times the mean value in flood years. In 4 of 18 years at the Reynolds Outlet sampling station, the single largest storm event contributed over 50 percent of the yearly sediment yield. Bedload transport samples during a peak flow event showed that the maximum transport rate, 400 kg/min/m, near the stream center was about 6 times the mean in the cross-section. Rainfall simulation-soil loss studies were conducted to determine Universal Soil Loss Equation (USLE) soil erodibility, K, and cover-management, C, values on sagebrush rangeland sites.

INTRODUCTION

Erosion and sediment yield on the approximately 50 million ha of sagebrush rangeland in the United States are a great concern to land managers and users. There is a need to quantify current erosion and sedimentation rates and to predict future rates resulting from management actions (Chugg and Lovely, 1982). Overgrazing, mining, and other abusive land uses have removed protective vegetation cover, reduced productivity, and increased stream and reservoir sedimentation (Branson et al., 1981).

Because of the need for quantitative information on water resources, floods, erosion, and sediment yields from extensive sagebrush rangelands of the Columbia Plateau and Great Basin provinces, the Reynolds Creek Experimental Watershed was established in 1960 as a representative area for rangeland hydrology studies (Robins et al., 1965). The 234 km² watershed was instrumented to collect data on precipitation, weather, soil water, runoff, erosion, and sediment yield. Watershed instrumentation began in 1960 and most runoff and sediment measuring stations were operable by 1966. The objectives of this paper are to describe the watershed and instrumentation, and to summarize results of erosion and sediment yield studies.

WATERSHED DESCRIPTION AND INSTRUMENTATION

Reynolds Creek is a north-flowing perennial stream in southwest Idaho and the experimental watershed outlet is located about 16 km upstream from its confluence with the Snake River. Physical characteristics of the Reynolds Creek Watershed above the Outlet Station and three subwatersheds with long-term records are listed in Table 1. Locations of the study watersheds and streamflow-sediment sampling stations are shown in Fig. 1. Average

Table 1. Physical characteristics, Reynolds Creek watershed and subwatersheds.

Category	Watershed			
	Reynolds Outlet	Macks Creek	Reynolds Tollgate	Reynolds Mountain
Drainage area, km ²	233.72	31.75	54.44	0.40
Elevation range, m	1098-2227	1138-1891	1403-2227	2019-2144
Average precipitation, mm/yr	475	500	724	1056
Average runoff, mm/yr	80	75	251	526
Average suspended sediment yield, t/ha/yr	0.53	0.59	0.75	0.21
Sediment record period, yrs	1967-84	1968-82	1967-84	1969-84
Soil erodibility, K ¹	0.027	0.026	0.026	0.027
Slope steepness, S ¹	20	22	22	15
Cover management factor, C ¹	0.011	0.010	0.008	0.006

¹ Based on the Universal Soil Loss Equation, $A = KLSCP$; where A is soil loss, K is soil erodibility, L is slope length, S is slope steepness, C is cover-management, and P is an erosion control practice. Metric units are as described by Foster et al. (1981).

yearly precipitation and runoff ranges from about 250 mm and 2 mm, respectively, at 1100 m elevation to about 1140 mm and 500 mm, respectively, at 2200 m elevation.

Generally, precipitation is about 75 percent snow at the highest elevations and runoff from these areas is mainly from snowmelt. In contrast, at the lowest elevations, the amount of runoff from summer thunderstorms is about equal to that from winter snowmelt and rain on frozen soil. Suspended sediment yield, roughly 90 percent of total sediment yield, ranged widely from year to year.

Sediment sampling facilities are operated concurrently with precalibrated weirs and flumes (Johnson et al., 1966; Johnson and Gordon, 1984). U.S. PS-67 and U.S. PS-69 automatic pumping samplers at large watershed stations, Chickasha, Isco*, and Manning* samplers at small watershed stations, and U.S. DH-48 hand samplers (Allen, 1981) for calibration, have been used to determine suspended sediment transport rates and suspended sediment yields. Maps of Reynolds Creek topography, geology, soils, and vegetation were completed a few years after watershed investigations began

* Specific product names are included for reader information and in no way constitute endorsement or warranty by the U.S. Department of Agriculture, Agricultural Research Service.

REYNOLDS CREEK WATERSHED STREAMFLOW AND SEDIMENT SAMPLING STATIONS

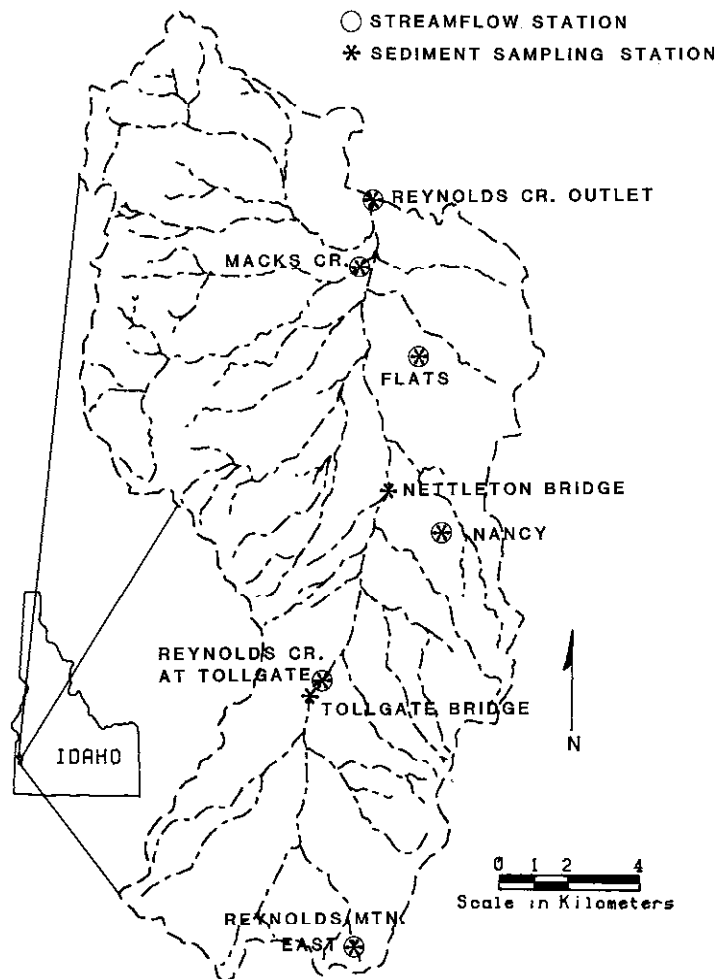


Fig. 1. Reynolds Creek Experimental Watershed--location of streamflow and sediment sampling stations.

(Stephenson, 1977). The land slope ranges from about 3 percent on the valley floor to over 50 percent on the mountainous uplands. Geology and soils are very complex with volcanic and sedimentary rocks overlying the granitic base and soils weathered from granite, basalt, and rhyolite. Sagebrush dominates the vegetation, and cover ranges from about 25 percent bare ground on the 250 mm precipitation areas to almost complete ground cover on forest areas with over 1000 mm annual precipitation.

Cattle grazing is the major land use with low precipitation-elevation areas grazed in the spring and highest areas grazed in late summer and fall. There are about 800 ha of irrigated hay and grain cropland in the valley. The watershed also receives considerable recreational use for deer and bird hunting, off-road vehicle use, snowmobiling, and fishing.

SEDIMENT YIELDS

Sediment yields determined from runoff records, suspended sediment samples, and limited bedload samples at long-term stations on Reynolds Creek and subwatersheds are summarized in Table 2. The lowest yields occurred during the severe 1977 drought at most stations, and the highest yields occurred in peak runoff years 1969, 1972, and 1982. Sediment yield at the Tollgate station (54.4 ha) was greater than from the Reynolds Creek Outlet station (233.7 ha) in 1976 due to sediment deposition and irrigation diversions between stations. Analysis of the reduction in stream sediment loads by irrigation diversions showed that 17 percent of suspended sediment was removed from Reynolds Creek by the irrigation system (Johnson and Smith, 1979). Sediment yields include measurements of bedload material in a coarse sediment catchment at Reynolds Mountain and estimates of bedload transport

Table 2. Sediment yield in metric tons at Reynolds Creek Watershed stations.

Water Year	Reynolds Mountain East		Macks Creek	Reynolds Creek at Tollgate		Reynolds Creek at Outlet
	suspended	bedload ¹		suspended	bedload ²	
1967	---	8.4	---	8272	---	12217
1968	---	1.6	346	1425	---	3932
1969	10.1	5.1	5734	9430	---	35686
1970	19.8	8.1	3220	5254	---	13943
1971	2.9	6.7	5278	7094	---	26410
1972	10.5	2.0	4912	6437	---	33929
1973	6.2	2.2	1041	972	62	2301
1974	9.6	2.3	1101	2023	433	5227
1975	7.7	5.0	1768	5349	1740	8945
1976	7.6	3.5	204	1996	217	2639
1977	0.5	0.4	7	46	0.1	2954
1978	6.3	4.7	503	2069	469	7490
1979	5.3	3.0	1482	1506	135	10591
1980	8.3	3.2	79	1456	158	3844
1981	5.6	3.6	130	1035	177	1693
1982	7.9	2.8	2433	5746	8978	29500
1983	13.8	6.2	---	6640	4239	19775
1984	16.9	4.9	510	6792	8048	14250
Mean t/yr	8.7	4.1	1882	4086	---	12481
Mean t/ha/yr	0.21	0.10	0.59	0.75	---	0.53

¹ Collected in catchment and measured yearly.

² Calculated from bedload-runoff equation based on 1975-76 studies.

using bedload samplers at Reynolds Tollgate. However, bedload sampling facilities were inadequate at Macks Creek and Reynolds Outlet for sampling bedload during major floods when boulder transport was common.

The contribution of the greatest individual runoff-sediment event each year is shown in Fig. 2, where peak event sediment yields in 1969, 1971, and 1979 associated with rain-on-snow and frozen soil were greater than sediment yield the remainder of the year. The contribution of single events is not as great from areas dominated by snowmelt runoff. Sediment yields in 1968 and 1977 were mostly from a few intense thunderstorms; however, such events on a long term basis contribute only about 3 percent of total suspended sediment yield. The sediment yields in 1982, 1983, and 1984 were lower than expected for the highest runoff amounts of record.

A double mass analysis of cumulative runoff versus sediment yield at the Reynolds Creek Outlet shows a trend toward greater sediment yield per unit of runoff in 1967-72, 1979, and 1982 than in other years, Fig. 3. Again, this greater yield was caused by large rain-on-snow and frozen soil events.

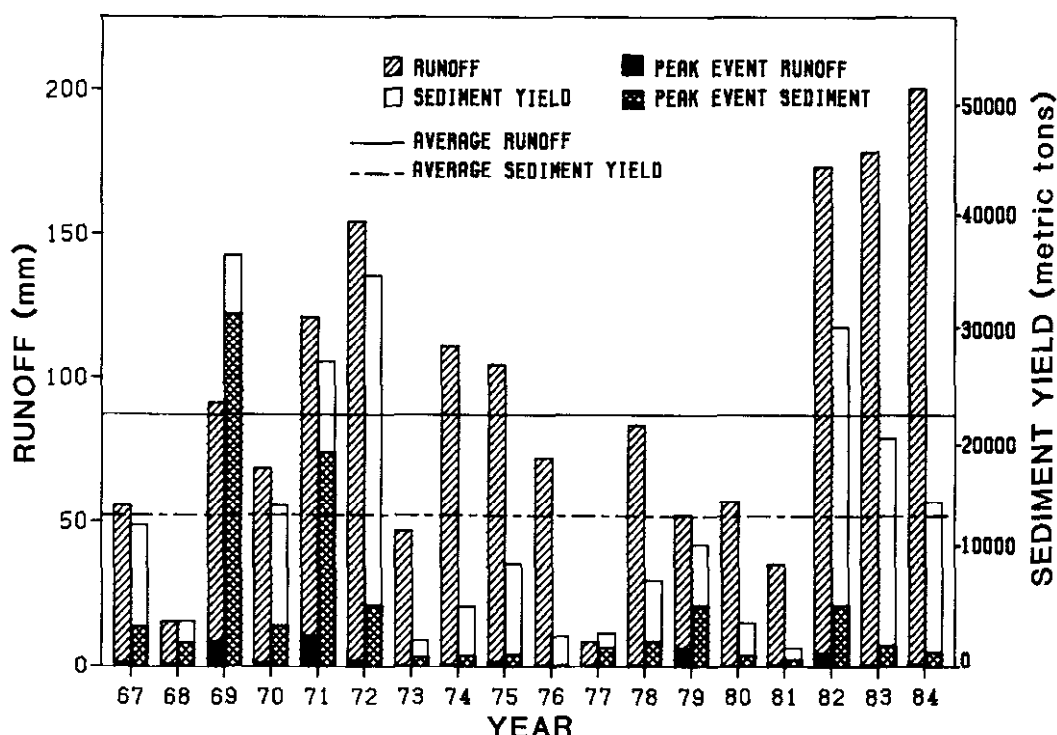


Fig. 2. Water year runoff and suspended sediment yield, Reynolds Creek Outlet station.

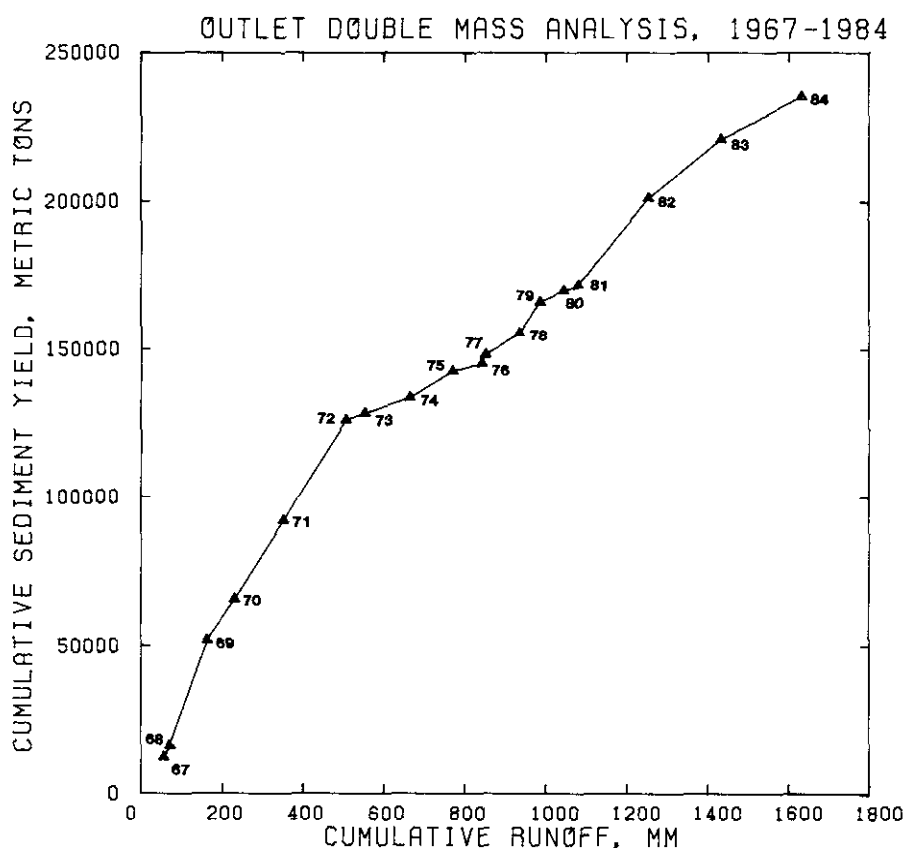


Fig. 3. Double mass curve, Reynolds Creek Outlet, 1967-84.

Runoff, sediment yield, and number of events each year from small watersheds at the Flats (yearly precipitation of 241 mm, 1180 m elevation, and drainage area 0.91 ha) and Nancy (yearly precipitation 279 mm, 1400 m elevation, and drainage area 1.26 ha) sites are summarized in Table 3. Yearly precipitation is 38 mm greater and the elevation is 220 m higher at the Nancy watershed than at the Flats watershed. The Nancy watershed is only 7 km from the Flats, yet the Nancy watershed has three times the number of snowmelt runoff events, 75 percent more snowmelt runoff, and about the same snowmelt sediment yield. About the same number of rainfall-runoff events occur at both sites, but runoff is nearly six times greater and sediment yield over three times greater at the Flats from rainfall events. Efforts to obtain similar information at elevations higher than the Nancy site have not been successful because of blowing snow, ice on the ground, and instrument failures.

BEDLOAD SAMPLING AND TRANSPORT

Reynolds Creek Watershed stream channels are generally formed in alluvial gravel and boulders with occasional bedrock exposures. Channel slopes range from about 2 percent in the valleys to over 20 percent in the steep uplands. The major streams transport large quantities of sand, gravel, and boulders during flood events and this material is not measured by conventional suspended sediment sampling. Helley-Smith bedload samplers (Helley and

Table 3. Summary of water year runoff and sediment yield from source watersheds at Flats and Nancy, 1972-84

Water Year	Event Type	Watershed					
		Flats			Nancy		
		Runoff, mm	S. Yield, t/ha	No. Events	Runoff, mm	S. Yield, t/ha	No. Events
1972	snowmelt	10.42	0.077	2	13.65	0.072	8
	rain	0.04	0.002	1	0	0	0
1973	snowmelt	0.12	0	1	0.09	0	2
	rain	0.16	0.001	2	0.08	0	1
1974	snowmelt	0	0	0	0.76	0.004	2
	rain	0	0	0	0.06	0	1
1975	snowmelt	0.05	0.001	2	0.66	0.002	4
	rain	0	0	0	0.11	0.002	2
1976	snowmelt	0.29	0.003	1	1.00	0.002	6
	rain	0	0	0	0	0	0
1977	snowmelt	0	0	0	0	0	0
	rain	--- ¹	0.135 ¹	1	0.47	0.082	2
1978	snowmelt	0	0	0	0	0	0
	rain	0.49	0.049	1	0.06	0.001	3
1979	snowmelt	0.11	0.015	2	--- ²	---	2
	rain	0.11	0.005	1	0	0	0
1980	snowmelt	0.04	0	2	0.23	0.001	3
	rain	0.21	0.003	4	0.10	0.001	2
1981	snowmelt	0.11	0.001	1	0.10	0.001	4
	rain	0	0	0	0	0	0
1982	snowmelt	1.81	0.005	4	3.30	0.003	7
	rain	4.72	0.040	2	0.259	0.018	3
1983	snowmelt	0	0	0	0.25	0.001	2
	rain	0.66	0.079	3	0.16	0.006	3
1984	snowmelt	0.95	0.003	3	1.10	0.002	14
	rain	0.28	0.100	3	0.04	0.004	2
MEAN				<u>TOTAL NO.</u>			<u>TOTAL NO.</u>
	snowmelt	0.99	0.008	18	1.76	0.007	54
	rain	0.56	0.032	18	0.10	0.009	19

¹ Recorder malfunction - partial record.

² Severe freezing - no record.

Smith, 1971) with 76 mm and 152 mm square openings were used at selected runoff-measuring stations to determine bedload transport rates during selected runoff events.

Original Helley-Smith sampler bags with 0.2 mm mesh plugged easily with organic debris and larger bags were developed and tested to assure sampling accuracy (Johnson et al., 1977). Bedload samples were collected by wading in small streams and shallow water depths and by supporting the samplers on bridges in large streams. Large boulders and cobbles being transported by peak flows occasionally obstructed the sampler openings and made sampling difficult.

Emmett (1980) and bedload sampling on Reynolds Creek Watershed indicated that a large portion of bedload transport occurred in a narrow part of the total channel width. Temporal variations in bedload transport rate in these gravel-bed streams were also large. The following procedure was used in sampling bedload transport at Reynolds Creek stations:

1. Sampling locations were established on straight channel reaches with stable banks or at bridges where concrete sills were constructed to provide a smooth surface for sampler placement.
2. Cross-sections were permanently marked where individual samples were to be taken.
3. During a bedload transport event, suspended and bedload samples were taken at premarked intervals across the stream to establish the zone of maximum bedload transport.
4. Samples were then taken frequently at points of maximum transport and occasionally at points of lower transport during the event.
5. Clearly tagged samples in sturdy canvas bags were dried, stored, and analyzed to determine weights by particle size for each sample.

Two bedload sampling stations at bridge sites on Reynolds Creek provided the most reliable data on transport rates during minor flood events (Johnson and Smith, 1978). Bedload transport rates in the zone of maximum transport and averages for the cross section are shown in Table 4. Maximum transport was about six times the cross-section average at peak flows and about twice as great at low transport rates. Also, the particle size was much greater in the zone of maximum transport.

Extrapolated values of bedload transport for Reynolds Creek at Tollgate using regression equations from sample data are questionable because data have not been collected during greatest floods. (See 1982 and 1984 values for Tollgate in Table 2.) Much additional work remains to be done in sampling and analyzing bedload transport for steep gravel-bed streams such as Reynolds Creek.

RAINFALL SIMULATION-EROSION STUDIES

A rotating boom rainfall simulator (Swanson, 1965) was used on 30 plots 3.05 m wide by 10.7 m long at 3 sites on the Reynolds Creek Watershed to test use of the Universal Soil Loss Equation (USLE) on sagebrush rangelands (Johnson et al., 1984). Soil erodibility factor (K) values determined by rainfall simulation on tilled plots were slightly less than values determined using the soil erodibility nomograph (Wischmeier and Smith, 1978). The difference

Table 4. Sediment Transport: Tollgate and Nettleton Bridges,
Reynolds Creek

Date	Location	Q, M ³ /sec	Max. transport (kg/min/m)	Total transport (kg/min/m)
2/28/75	Tollgate Bridge	1.78	1.32	0.57
5/10/75	" "	4.08	79.40	22.91
5/10/75	" "	4.86	77.99	36.31
5/13/75	" "	4.33	142.14	31.13
5/13/75	" "	4.70	197.48	36.70
5/14/75	" "	5.97	65.95	51.58
5/01/76	" "	2.08	6.21	2.08
5/03/76	" "	2.43	1.92	0.92
5/10/75	Nettleton Bridge	4.76	82.73	24.01
5/13/75	" "	3.96	81.70	18.59
5/14/75	" "	5.95	401.07	61.81
5/14/75	" "	6.09	156.63	37.39
4/08/76	" "	2.97	6.41	3.39
4/10/76	" "	2.78	4.13	2.32
5/01/76	" "	2.63	5.99	2.53
5/03/76	" "	2.49	2.00	1.11

was probably due to a lack of a true fallow condition on the plots and rock fragments in the soil surface. Soil loss rates on 6 grazed plots ranged from 0.05 to 0.68 t/ha and on 6 plots ungrazed for 10 years ranged from 0.01 to 0.12 t/ha. USLE cover-management factor (C) values using rainfall simulation were generally less than estimated by the subfactor method of Dissmeyer and Foster (1981) on ungrazed plots and 2 grazed plots with excessive cover. C factor values on 4 other grazed plots were greater than estimated. Soil losses per unit of rainfall were usually greater from wet and very wet runs than from dry runs, using a rainfall simulation application rate of approximately 60 mm/hr. Further study of rangeland erosion rates is needed to determine USLE subfactors for root, canopy, ground cover, and surface roughness effects.

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SEDIMENT YIELD FROM A GULLY

By Norman H. Welch, Soil Scientist, USDA, ARS, Water Quality and Watershed Research Laboratory, Durant, Oklahoma

ABSTRACT

Rainfall, runoff, and sediment yield were measured from a .599-ha. gullied watershed with a gullied area of 22%. Rainfall, total watershed runoff, runoff from the ungullied area of the watershed, and runoff volume times peak runoff rate for 72 storms were fitted by linear and logarithmic least square analyses to the sediment yield from the gullied area of the watershed. The equations developed were used to predict sediment yields from the gullied area for comparison with measured yields for 64 storms. Runoff volume times peak runoff rate explained a larger percent of the variation in sediment yield from gullied area than the other variables. Negative yields were predicted by four of the linear equations at low values of the independent variables. There was a trend with all of the equations for the error to increase as the independent variable increased. Prediction errors were as high as 80 to 90% for some of the larger storm events. The unexplained variation is due to changes in the susceptibility and availability of material for erosion and transport and to changes in watershed hydrologic conditions.

INTRODUCTION

Sediment is the greatest single pollutant of surface water. It lowers the quality of water for municipal, industrial, and recreational uses and often damages areas where it is deposited and depletes the soil resource from which it erodes. In assessing the magnitude of sediment yield from a watershed area, it is important to consider the area from which the sediment originates and its relationship to the channel system and other sediment source areas within the watershed. It is often necessary to make separate estimates of the contribution of each sediment source area. Gully erosion, when present in a watershed, is often a major sediment contributor and it is usually fed directly into the channel system.

A number of factors are known to influence gully erosion. Among those studied have been various topographic and geometric gully features, rainfall, runoff, soils, cover, and bank stability. The effect of a single factor is not well understood and when studied with the interactive or confounding effect of other factors, definition of single- or multiple-factor effects becomes almost impossible. This is primarily because the influence of a single factor cannot be isolated when studying natural gullied areas. As a result of its complexity, the process of gullying has not been well defined by quantitative relationships.

Past studies have indicated drainage area, drainage area plus precipitation, or runoff, to be important factors related to gully erosion. Thompson (1964) found the rate of advance of gully heads to be related to watershed area, rainfall, and clay content of the overfall area. Beer and Johnson (1963) found an index of surface runoff, terraced area of the watershed, gully length, and the distance from the end of the gully to the watershed divide to be the best predictors of change in gully surface areas. Watershed area was the most significant factor in estimating average advancement rate in work by Seginer

(1966). Watershed area, precipitation, terraced area, distance from head cut to watershed divide, and other factors are often either direct or indirect indicators of runoff. Since runoff is the transporting and, oftentimes, the eroding agent, it should be strongly related to gully erosion.

Piest (1975) studied the influence of a number of factors on gully erosion rates. On two watersheds, runoff explained 70 and 78 percent of the variation in gully erosion rate, but prediction accuracy was not especially good. Two-thirds of the time, actual gully sediment discharge would be one-half to two times the predicted value. He concluded that for the watersheds studied, runoff does not give a good insight into basic erosion mechanisms and would be of less value when applied to another gully. Heede (1975) also concluded that gully development is not controlled by water flow alone.

The conditions at the time of an event affects the erosion or sediment yield from that event. Soil moisture, vegetative cover, time from last event, whether the event is the first following a freeze-thaw season, and other factors alter the influence of a specific event. These factors are extremely important in a short time span, but are probably less significant when averaged over a long time span. This report presents results from a detailed study of rainfall, runoff, and sediment yield from a small watershed where gully erosion is predominant.

PROCEDURE

Rainfall, runoff, and sediment yield were collected from a 0.599-hectare watershed with a gullied area of 0.130 hectare, or 22 percent of the watershed. The watershed is located in the reddish prairie soil resource area in central Oklahoma. Soils on the watershed are Renfrow and Kingfisher silt loams, a Udertic Paleustoll and Udic Argiustoll, respectively. Annual precipitation during the 4 years of the study was 63.83, 112.14, 72.24, and 78.28 centimeters, respectively. The watershed was formerly cultivated, but has been used for rangeland for 30 to 40 years and is in poor range condition. The gully has eroded down to soft sandstone in some parts of the watershed. The major source of sediment was widening, and a slight deepening of the channel in some sections.

Runoff from the watershed was measured with an H-flume instrumented with a continuous water stage recorder. Sediment samples were collected during storm events with a Chickasha sediment sampler (Allen, et al., 1976). Using this information, total watershed sediment yield was computed for each storm. The sediment yield from the gullied area was determined by subtracting the yield from the ungullied area from the total watershed yield. The yield from the ungullied area was determined from measured yield data from a similar adjacent watershed. During the period of record, the estimates showed that an average of only 4 percent of the total watershed yield originated from the ungullied area.

In order to evaluate the effect of runoff from the total watershed and from the ungullied area, runoff was assumed to originate from three delineated areas of the watershed. The three delineated areas of the watershed were the ungullied area (0.470 hectare), the gullied area with sandstone exposed (0.013 hectare), and the remainder of the gullied area (0.116 hectare). Two estimates of runoff from the gullied areas were made. In both estimates it was

arbitrarily assumed that 100 percent of the precipitation falling on the exposed sandstone appeared as runoff. Runoff from the remainder of the gullied area was arbitrarily assumed to be 90 percent and 70 percent of the precipitation falling on that portion of the watershed for the first and second estimates, respectively. Runoff from the ungullied area of the watershed was the total volume of runoff minus the runoff volume attributed to the two gullied areas. Using this method, total watershed runoff volume must exceed total precipitation multiplied by the percent runoff for the two gullied areas before any runoff is attributed to the ungullied area of the watershed. Also, total watershed runoff volume must exceed total precipitation multiplied by percent runoff from the area of exposed sandstone before any runoff is attributed to the remainder of the gullied area.

Runoff from the ungullied area of the watershed, total watershed runoff, precipitation, and runoff volume times peak runoff rate for each storm event were related to sediment yield from the gullied area by least squares analysis. For storm events where runoff from the ungullied area was estimated as zero, a value of .000001 was used in the logarithmic equations instead of zero. These data were also analyzed by multiple regression, stepwise regression, and factor analysis techniques, but are not discussed because they provided little additional information and predictions were no better than the single factor least square predictions. Equations for predicting sediment yields were developed using data collected on 72 storms which occurred in 1972 and 1973. Linear and logarithmic equations were developed for each of the variables. These equations were used to predict sediment yields from the gullied area for storms that occurred in 1974 and 1975. The predictions were then compared to measured values for these years.

RESULTS AND DISCUSSION

The highest correlation and the lowest standard error of estimate is associated with runoff volume times peak runoff rate for both the linear and the logarithmic equations (table 1). Four of the linear equations predict negative yields from the gullied area at low values of the independent variable, similar to those discussed by Beer (1963) and limit the usefulness of the equations.

The correlation between measured and predicted yields is shown in table 2. The explained variation ranges from 66 to 92 percent. Runoff volume times peak runoff rate explains a larger amount of the variation than any of the other variables. The least amount of variation is explained by precipitation. The prediction error for individual storm events for these variables and for total watershed runoff is shown in figures 1 through 3.

There is a general trend for the linear equation to underpredict at both the lower and higher precipitation values and to overpredict at intermediate values (figure 1). This trend is reversed at the intermediate and high precipitation values with the logarithmic equation. Both equations diverge from the measured yield at high precipitation values but in opposite directions. The sediment yield for the largest precipitation event during the validation period (9.91 cm) was underpredicted by the linear equation and overpredicted by the logarithmic equation. However, the largest error in predicted yield was for a precipitation event of 3.61 cm on April 29, 1975 where both equations underpredicted (figure 1).

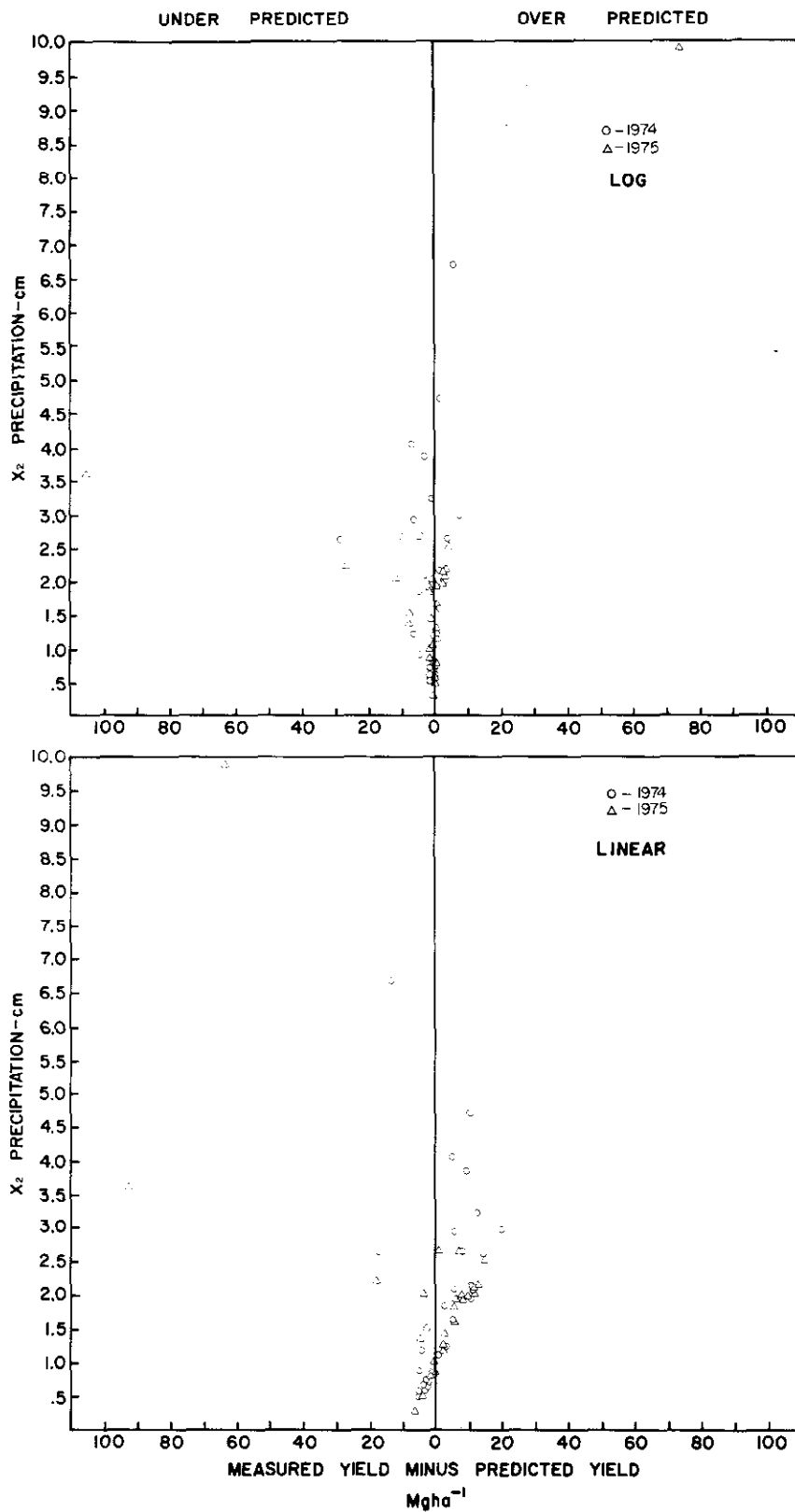


Figure 1. Errors in Sediment Yield Prediction using Precipitation to Predict Sediment Yield.

Table 1. Regression equations to predict megagrams per hectare of storm sediment yield from gullied area

Regression Equation	Correlation Coefficient	Standard error of estimate
<u>Linear</u>		
$X_1 = 9.983 X_2 - 9.120$	0.73	15.279
$X_1 = 16.842 X_3 - 3.622$	0.86	11.441
$X_1 = 23.899 X_4 - 1.394$	0.88	10.527
$X_1 = 22.017 X_5 - 1.755$	0.88	10.747
$X_1 = 1.550 X_6 + 3.494$	0.95	6.993
<u>Logarithmic</u>		
$\ln X_1 = 2.7418 \ln X_2 + 6.0402$	0.76	2.099
$\ln X_1 = 1.6352 \ln X_3 + 9.0001$	0.95	1.087
$\ln X_1 = 0.6628 \ln X_4 + 9.4648$	0.83	1.827
$\ln X_1 = 0.7104 \ln X_5 + 9.3676$	0.86	1.708
$\ln X_1 = 0.7879 \ln X_6 + 1.6038$	0.96	0.877

X_1 = Storm sediment yield from gullied area - Mgha^{-1}

X_2 = Storm precipitation - centimeters

X_3 = Storm runoff from total watershed - centimeters

X_4 = Storm runoff from ungullied area of watershed, assuming 100 and 90% runoff from the two gullied areas, respectively - centimeters

X_5 = Storm runoff from ungullied area of watershed, assuming 100 and 70% runoff from the two gullied areas, respectively - centimeters

X_6 = Runoff volume times peak runoff rate - $\text{m}^3 \times \text{m}^3/\text{s}$

The prediction errors using total watershed runoff for the linear and logarithmic equations are shown in figure 2. The linear equation for runoff produced a similar error pattern as the linear equation for precipitation, with underprediction at both low and high values. The prediction for the logarithmic equation was close to the measured yield for the largest runoff event, but the linear equation underpredicted by a large amount. The largest prediction error was for a runoff event of 2.74 cm on April 29, 1975 where both equations underpredicted. This is the same event where the prediction error was the largest for the precipitation equations.

The prediction errors using runoff volume times peak runoff rate for the linear and logarithmic equations are shown in figure 3. There was a trend for both equations to underpredict the storms in 1974 and 1975. The largest prediction error for both equations was also for the storm on April 29, 1975.

It is apparent that factors other than those studied contribute to the variability in gully sediment yield. The time of occurrence, sequence of events, and condition of the watershed at the time of an event would have an effect on

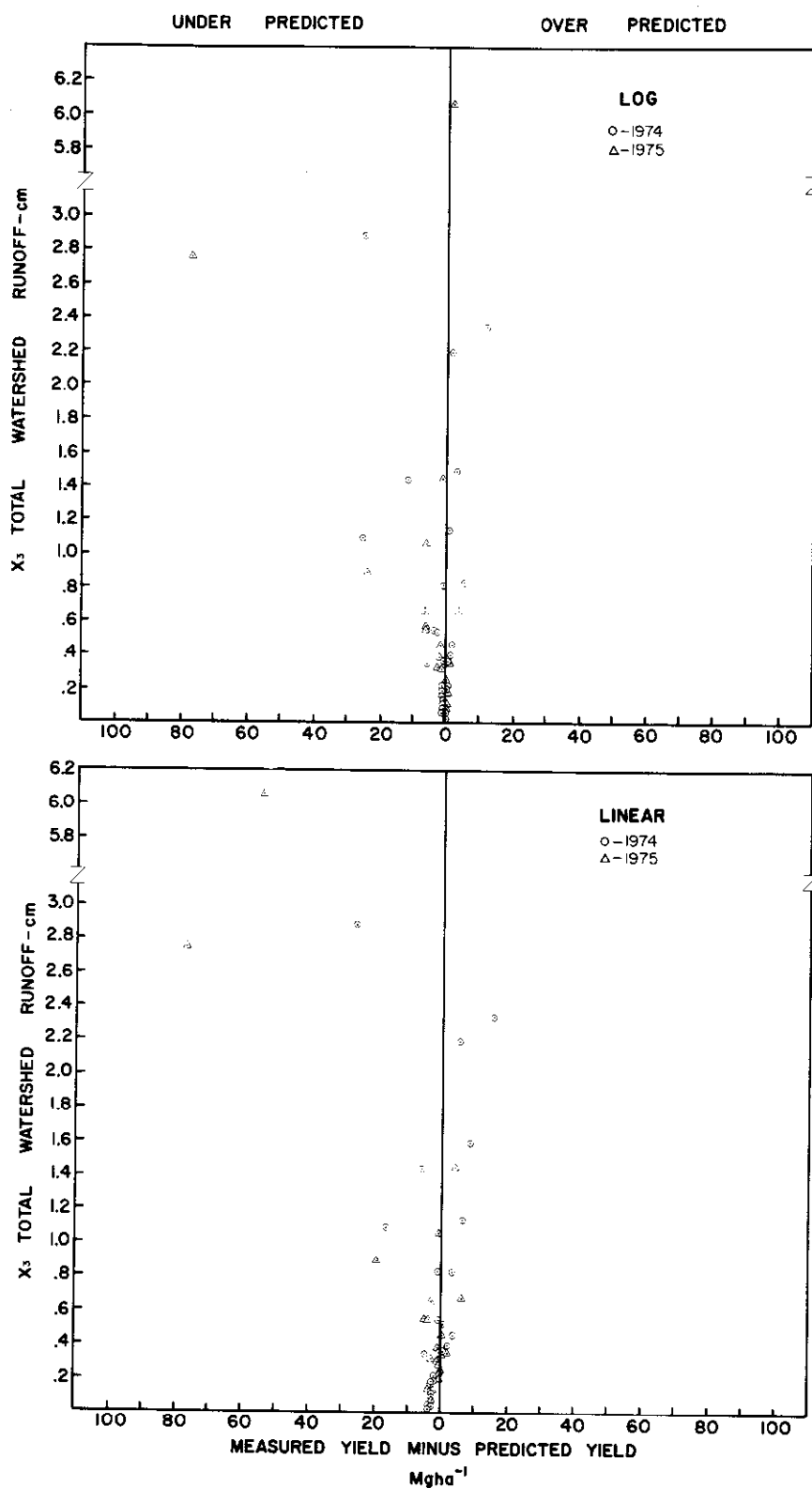


Figure 2. Errors in Sediment Yield Prediction using Total Watershed Runoff to Predict Sediment Yield

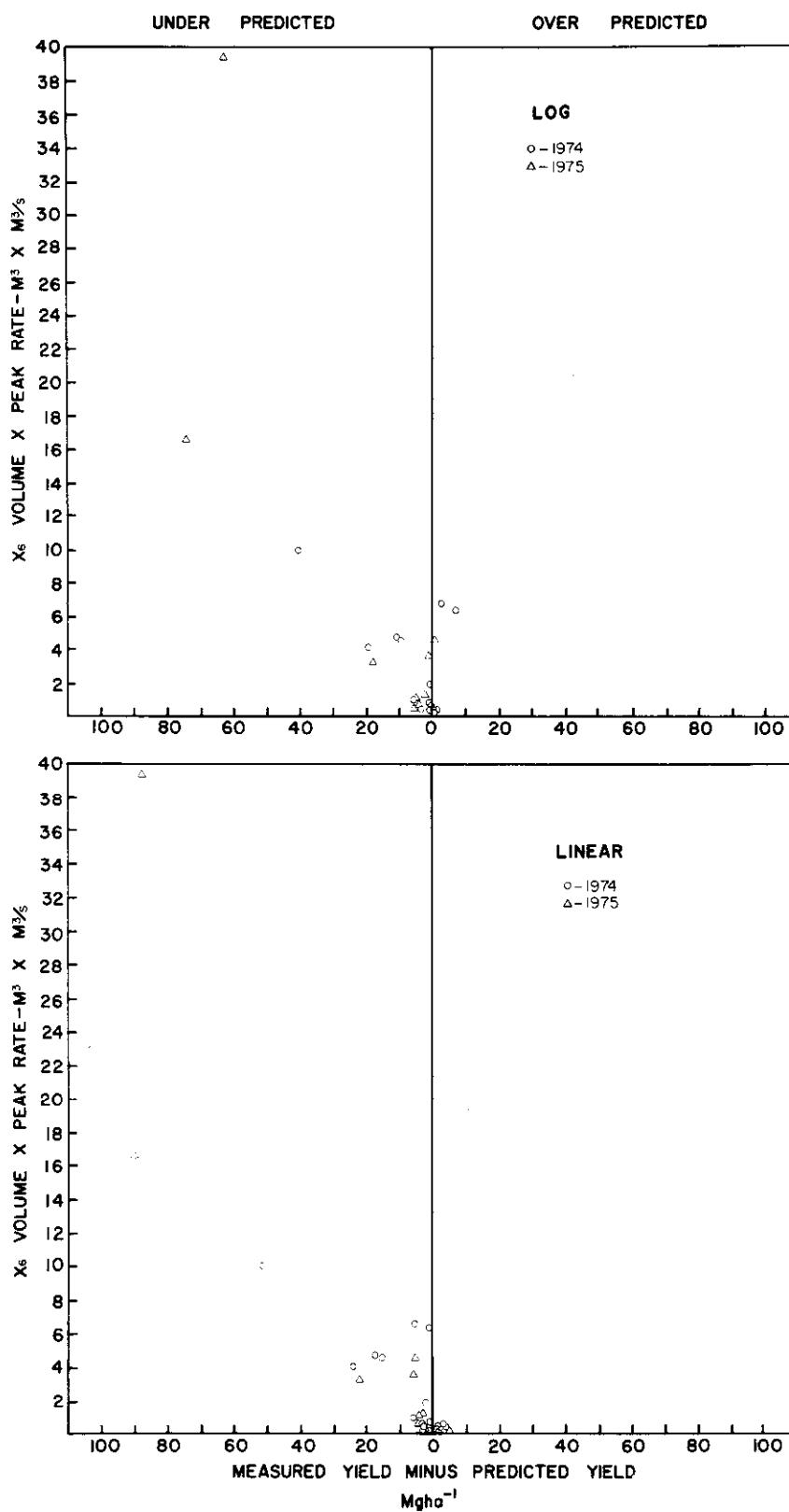


Figure 3. Errors in Sediment Yield Prediction using Peak Runoff Rate to Predict Sediment Yield

the sediment yields from a particular event. Table 3 shows the varied response in measured sediment yield from several precipitation events and runoff events of similar size. Observation of field conditions offer a partial explanation for the varied response.

Table 2. Relationship between measured and predicted storm sediment yield from gullied area in 1974 and 1975

	X ₂	X ₃	X ₄	X ₅	X ₆
	Correlation Coefficient	Correlation Coefficient	Correlation Coefficient	Correlation Coefficient	Correlation Coefficient
	<u>Linear</u>				
X ₁	0.81	0.92	0.93	0.92	0.95
	<u>Logarithmic</u>				
X ₁	0.82	0.91	0.87	0.88	0.96

X₁ = Storm sediment yield from gullied area - Mgha⁻¹

X₂ = Storm precipitation - centimeters

X₃ = Storm runoff from total watershed - centimeters

X₄ = Storm runoff from ungullied area of watershed, assuming 100 and 90% runoff from the two gullied areas, respectively - centimeters

X₅ = Storm runoff from ungullied area of watershed, assuming 100 and 70% runoff from the two gullied areas, respectively - centimeters

X₆ = Runoff volume times peak runoff rate - m³ X m³/s

The winter months are characterized by precipitation of low intensities with very little runoff. The amount of rangeland vegetative cover declines over winter and reaches a low point during late winter or early spring. Alternate wetting and drying and freezing and thawing increases the susceptibility of the gully banks to erosion. Therefore, the gully banks are the most susceptible to erosion when the more intense spring rains occur. The sediment yield for a particular event then depends upon conditions at the time of the event and the amount and intensity of the event. One large event may remove all the material from the banks which is highly susceptible to erosion and transport it out of the gully system. Several small events may remove only a portion of the material each event but not provide adequate runoff to transport all of the material out of the gully system. The material is then available for transport by later events. Once the material loosened by the overwintering period has been removed, the availability of easily eroded material decreases and the susceptibility of the banks to erosion decreases to some degree. Simultaneously with this process is an increase in vegetative growth as the season progresses which also alters the effect of a specific event.

The process described provides an explanation of why a single factor fails to explain a larger part of the variability in storm sediment yields. However, to quantify and define a functional relationship for the factors discussed would be difficult, if not impossible, under field conditions. Massive slump or bank failure was not a major factor in the watershed under study, but is a

dominant factor in gully erosion in other areas of the country. However, the subprocesses of debris production and debris cleanout as discussed by Piest (1975) appear to be operating in both Iowa and Oklahoma. The discontinuity of these subprocesses increases the complexity of the relationship between sediment yield and a single variable such as precipitation or runoff.

Table 3. Variability of measured storm data from several similar size precipitation and runoff events during 1974 and 1975

Storm Date	Precipitation (cm)	Total Watershed Runoff (cm)	Volume x Peak Rate Runoff ($\text{m}^3 \times \text{m}^3/\text{s}$)	Measured Gully Sediment Yield (Mg ha^{-1})
<u>Similar Size Precipitation Events</u>				
03-10-74	2.62	1.09	4.00	34.50
09-15-74	2.62	0.36	0.23	2.40
10-27-74	2.64	1.12	1.91	9.02
06-10-75	2.64	1.45	4.64	16.08
05-25-74	2.13	0.15	0.08	1.50
08-27-74	2.06	0.08	0.01	0.30
09-02-74	2.06	0.53	0.50	5.94
01-02-75	2.13	0.66	0.14	1.03
06-23-75	2.03	1.04	3.60	14.70
10-25-74	0.84	0.10	0.01	0.40
11-03-74	0.89	0.53	0.45	4.81
05-14-75	0.81	0.25	0.03	0.69
05-28-75	0.86	0.33	0.06	1.45
<u>Similar Size Runoff Events</u>				
04-29-74	6.68	2.87	9.90	70.70
04-29-75	3.61	2.74	16.60	119.40
08-10-74	4.70	2.18	4.73	27.50
10-30-74	3.87	2.34	6.75	19.70
05-01-74	2.92	1.60	6.29	14.20
08-09-74	4.04	1.42	4.56	26.20
02-20-74	1.83	0.81	0.45	6.52
04-11-74	3.23	0.81	0.99	10.90
04-07-75	2.21	0.89	3.27	30.60
<u>Similar Size Volume X Peak Rate Events</u>				
08-10-74	4.70	2.19	4.73	27.48
06-10-75	2.64	1.45	4.64	16.08
04-11-74	3.23	0.81	1.00	10.91
05-13-75	2.64	0.65	1.14	10.08
09-02-74	2.06	0.53	0.50	5.94
07-07-75	2.01	0.38	0.51	3.23

SUMMARY AND CONCLUSIONS

Gully sediment yields were related to storm rainfall and runoff for a small watershed where gully erosion was predominant. Linear and logarithmic equations were fitted by least square analysis to measured data from 72 storms in 1972 and 1973. These equations were used to predict sediment yield from the gullied area of the watershed for comparison with 64 storms measured in 1974 and 1975.

The largest amount of variation in sediment yield was explained by runoff volume times peak runoff rate. Precipitation explained the least amount of variation. Negative yields were predicted by four of the linear equations at low values of the independent variable. There was a trend with all equations for the error to increase as the independent variable increased. Prediction errors were as high as 80 to 90 percent for some of the larger events.

Neither precipitation nor runoff is the sole factor in gully erosion. However, runoff is the transporting agent and the eroding agent to varying degrees. The unexplained variation is due to changes in the susceptibility and availability of material for erosion and transport, and to changes in watershed hydrologic conditions. These variables, or the variables which the interactive and confounding effects of these variables make their study under field conditions extremely difficult.

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EPHEMERAL GULLIES AS SOURCES OF SEDIMENT

By C. R. Thorne, Assoc. Prof., Engineering Research Center, and Lyle W. Zevenbergen, Graduate Research Associate, Colorado State University, Fort Collins, CO, 80523, and E. H. Grissinger, Soil Scientist, and J. B. Murphey, Geologist, USDA-ARS Sedimentation Laboratory, Oxford, MS, 38655

ABSTRACT

Ephemeral gullies form in swales where concentrated surface runoff occurs due to flow convergence. Current methods of estimation do not properly account for erosion caused by ephemeral gullying. Cooperative research between the Engineering Research Center, Colorado State University, and the USDA-ARS Sedimentation Laboratory has identified the topographic controls of ephemeral gully size and location. These controls form the basis for a simple, preliminary technique to predict ephemeral gully erosion. The study has revealed that ephemeral gullies experience repeated cycles of cut and fill between tillage events so that actual soil loss due to concentrated flow may be several times the volume indicated by periodic measurements of channel x-sectional area. Also, ephemeral gullies may increase rill and interrill erosion and accelerate the removal of the detached soil from the field. In addition, their infilling during tillage operations is in effect, a form of mechanical erosion. Consequently, ephemeral gullies are extremely damaging in ways that go far beyond the erosion due to the cutting of the gully channel. Evaluation of the true role of ephemeral gullies in field erosion systems requires a process-based hydrology and sedimentation model.

INTRODUCTION

Recently, action agencies concerned with the prediction and control of erosion in arable fields have recognized the possibility that the current methods do not estimate total erosion due to runoff. Specifically, it has been proposed that in addition to rill and interrill erosion by raindrop impact and surface runoff, concentrated flow may lead to significant erosion through gullying, with the channels generated being eradicated by normal tillage so that they do not fall under the classification of regular gullies. There is evidence that these features, here called ephemeral gullies because they are only present in the field for certain periods of the year, are responsible for serious erosion over and above that currently being predicted (P. Forsythe, personal communication, 1983). A study of ephemeral gullies is being undertaken by researchers at the Engineering Research Center, Colorado State University, and the USDA-ARS Sedimentation Laboratory, under a specific cooperative agreement. The purposes of this study of ephemeral gullies are to identify the parameters controlling their formation, to measure their contribution to total erosion, and to develop effective conservation practices to control them. Several other studies are also underway at other research institutions, universities, and experimental facilities, with somewhat similar aims, but employing entirely different approaches.

In this paper we present some of the findings of our study to date. First, ephemeral gullies are defined. Second, the mechanics of ephemeral gully initiation are described, and specific criteria which may be used to predict their likely location and size are presented. The approach presented provides a preliminary and simplified means of estimating the importance of ephemeral

gullies as sediment sources. Finally, the controls and driving forces behind ephemeral gully development between tillage events are discussed and various scenarios for gully progression are outlined. These illustrate that the actual erosion attributable to the presence of ephemeral gullies in a field may be very different from the simple volume voided in the gully channel and that further study of hydrologic and sedimentary systems in fields is essential to fully define the role of ephemeral gullies.

DEFINITION OF EPHEMERAL GULLIES

In concept, ephemeral gullies are easily defined as the "missing link" between rills and permanent waterways. Mildner (1983) defined ephemeral gullies as being "usually larger than rills, occurring and recurring in depressional areas, forming a dendritic pattern unless another pattern is imposed by row alignment, and being partially or totally erased and filled in by normal tillage operations without the need for special equipment." In practice, this definition contains some overlap with previously defined features such as rills and gullies. Also, it is neither a morphogenetic nor a morphological definition - that is, it neither defines ephemeral gullies wholly by the way they form nor by their size and shape when they have formed. Finally, it depends on farming practices and equipment as well as natural processes, and so will vary from one farm to another as well as between regions. Consequently, while Mildner's definition recognizes that ephemeral gullies are significantly different from rills and regular gullies, and thus represents a vital starting point for their study, it is purely a working definition, subject to change and development as our understanding of the processes responsible for ephemeral gully formation improves. The first objective of our study was then to identify the controls of ephemeral gully location and establish the ephemeral gully's role in the field's hydrologic and sedimentary system.

EPHEMERAL GULLY FORMATION

An ephemeral gully forms where there is sufficient magnitude and duration of concentrated surface runoff to initiate and sustain erosion and flow channelization. Surface runoff may be produced over an entire field by precipitation events of great intensity and duration. Runoff becomes concentrated in low points, or swales, where flow lines converge from neighboring high points, or spurs (Fig. 1). In plowed fields the furrows usually are somewhat parallel to the contours, so that furrow flow likewise converges into swales down secondary slopes. So, with or without a furrow pattern, runoff concentrates in the swales. An exception occurs when furrows run parallel to the main slope. Here swale concentration is inhibited, but furrow erosion is greatly intensified, often to unacceptable levels. Under these circumstances, erosion due to furrow incision probably exceeds that which would occur due to ephemeral gullying, so that this procedure is not an attractive way to prevent ephemeral gully formation.

Rainfall of insufficient intensity or duration to produce general surface runoff over the field may still generate runoff in swales (Dunne and Black, 1970). This is the case because levels of soil saturation are higher in swales, as water which has infiltrated higher up the field returns to the surface. Consequently, the frequency of surface runoff is greater in swales than on spurs, so that flow is concentrated there in time as well as in space.

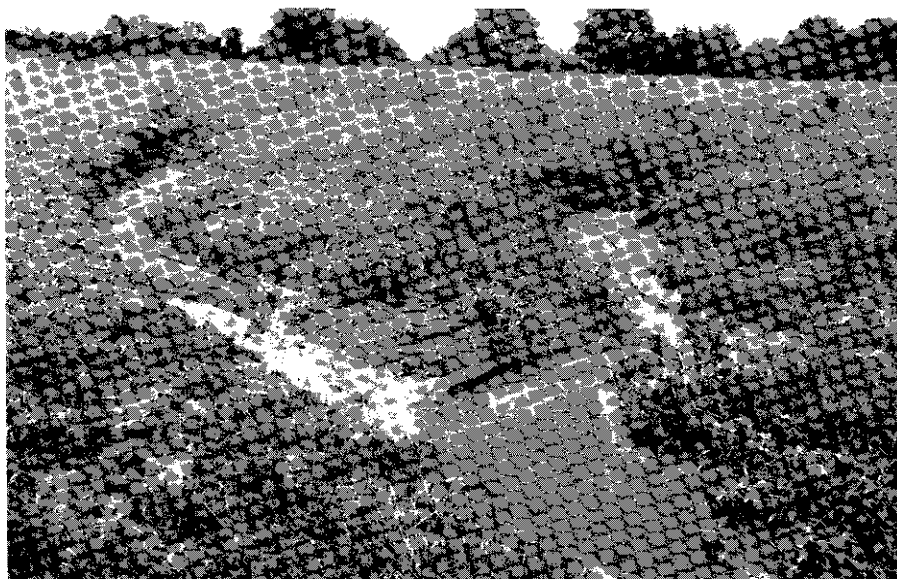


Figure 1. Ephemeral gully produced by converging flow due to swale and spur topography (Panola County, Mississippi).

As concentrated surface runoff is found mostly in swales, it is to be expected that ephemeral gullies that form due to concentrated flow erosion should be found there also. However, not every swale contains a gully and so there is clearly a critical or threshold level of flow concentration required to initiate an ephemeral gully in a particular swale. The initiation of erosion by flowing water is an extremely complicated problem that is not fully explained at present. In general terms it is known that as flow intensity increases the probability of detachment and entrainment of surface particles or aggregates of particles also increases. Many measures of flow intensity have been used to try to predict the amount of material eroded, the two most commonly applied being velocity and boundary shear stress. To date, no single measure has proved entirely satisfactory.

The most general and, in some ways, most successful parameter of flow intensity is streampower (Yang, 1977). This is defined by:

$$\omega = \rho g Q S \quad (1)$$

where ω = streampower, ρ = mass density, g = gravitational acceleration, Q = volumetric discharge, and S = energy slope. This is often expressed in terms of streampower per unit bed area (Bagnold, 1966) or per unit weight of water (Yang, 1972). From equation (1) it is clear that for water, which has almost constant density, the streampower depends on the product of discharge with slope.

Once erosion has been initiated under concentrated surface runoff, positive feedback between flow and erosion results in the channelization of the previously wide and shallow flow. This occurs because the depression created by the erosion immediately captures more of the flow (Q), leading to the concentration of streampower and further erosion, which captures more of the

flow and so on. This feedback ceases either when the flow subsides at the end of the runoff event, or when the channel has enlarged to the point where the boundary stabilizes. This latter condition develops because as the channel enlarges further, the near boundary velocity gradient is reduced and the boundary shear stress (which depends on the velocity gradient) decreases to the point where entrainment ceases. The shape of the resulting channel depends on the properties of the soil and particularly on the stratigraphy. If the soil erodibility is constant with depth, a channel of parabolic cross-section results (Lane and Foster, 1980) (Fig. 1). If the erodibility decreases owing to a plow-pan, fragipan, or some other less erodible layer, then a wide, shallow, rectangular channel develops (Fig. 2). The final width is limited by the ability of the flow to erode the bank toe (Lane and Foster, 1980).

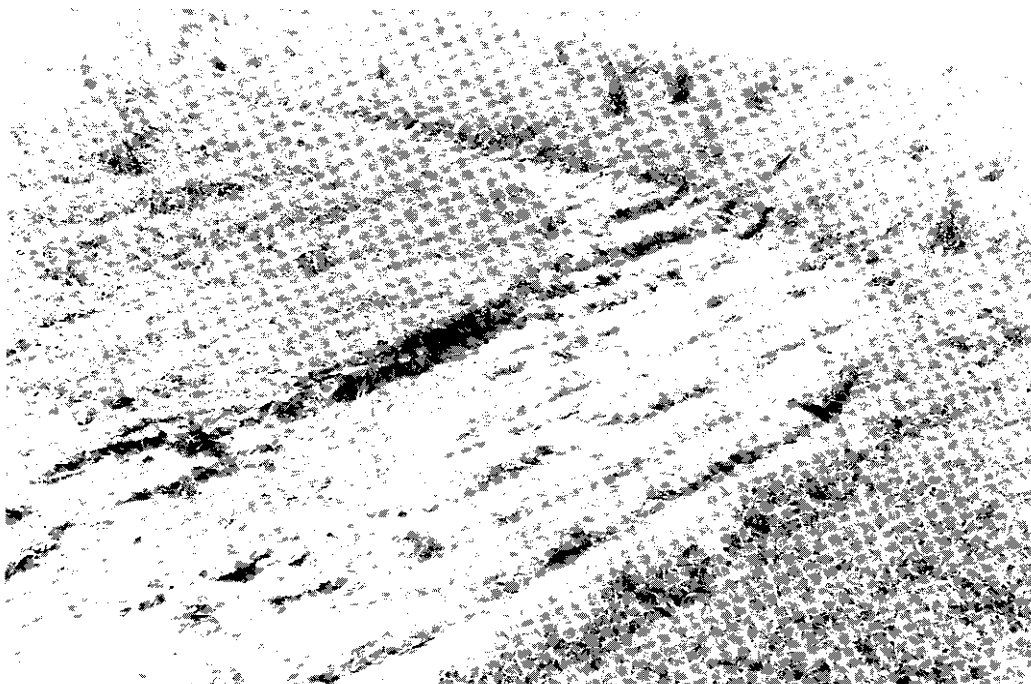


Figure 2. Ephemeral gully widening due to a non-erodible layer (Panola County, Mississippi).

In summary, the location and size of the ephemeral gully is controlled by the generation of concentrated surface runoff of sufficient magnitude and duration to initiate and sustain erosion for a particular soil. The concentration of surface runoff is controlled by flow convergence in swales. The final size and shape of the channel depend on the quantity of runoff, the soil properties, and the stratigraphy. These factors form the basis for a method to predict, objectively, the location and size of ephemeral gullies in arable fields.

PREDICTION OF EPHEMERAL GULLY EROSION

The method uses an analysis of field topography to identify areas prone to ephemeral gully formation. Evans (1980) developed a topographic analysis based on the differentiation of elevation between points in a uniform grid of

spot elevations covering an area. Zevenbergen and Thorne (In Press) have modified and further refined Evans' general approach and have developed a version specifically applicable to the prediction of concentrated runoff.

In this method, a grid of evenly spaced points is established covering the whole area in question. The elevation of each point is recorded and stored in a suitable computer, for this study either a microcomputer or a mainframe. The slope, aspect, planform curvature, and upstream drainage area for each point inside the grid matrix are then calculated by programs in Basic or Fortran for the micro or mainframe machines, as appropriate. The Fortran program is freely available in the literature (Zevenbergen and Thorne, In Press) or from the authors. The microcomputer program identifies likely locations for ephemeral gullies using a compound topographic index (CTI) for each grid point, defined by:

$$CTI = A \cdot S \cdot PLANC \quad (2)$$

where, CTI = Compound Topographic Index, A = upstream drainage area, S = local slope, and PLANC = planform curvatures. Planform curvature (PLANC) is a measure of the landscape convergence, negative for spurs and positive for swales. It represents the degree of convergence of surface runoff leading to flow concentration. Upstream drainage area (A) is used here as a surrogate for runoff discharge as the two are usually strongly positively correlated. The local slope (S) and upstream area (A) produce an indication of streampower of surface runoff as previously discussed. The compound topographic index (CTI) then represents the major parameters controlling the pattern and intensity of concentrated surface runoff in the field. However, the likelihood of ephemeral gully formation due to this concentrated flow still depends upon the susceptibility of the soil to erosion. Erosion susceptibility is difficult to define because it depends on many factors including geographical region, soil type, organic matter, tillage, crop type and stage, and conservation practice. No theoretical method exists to predict the susceptibility of a particular field to ephemeral gully formation. Instead, a pragmatic approach has been adopted. This is based on a threshold concept that there is, for a particular region/soil/management/crop/conservation-practice combination, a critical CTI value for ephemeral gully formation (CTI_c), representing the particular intensity of concentrated flow necessary to initiate erosion and channelization under those circumstances. Swales or portions of swales with CTI values below critical would not be expected to have an ephemeral gully in an average year, while those with values higher than critical would be expected to have a gully. The critical CTI is estimated on the basis of experience with the field in question. The procedure is, in consultation with the farmer, to identify a grid point located close to the gully head in each swale, in an average year. Such points should have CTI values that approximate the critical value obtained for all the swales. This method is quite robust. The gully head does not have to be precisely located to within a foot and a satisfactory estimate of the critical value is fairly certain provided that several points are being averaged. This method has been applied to a large number of sites in Mississippi, to build up a data base of critical values for common soils and crops in that region. For example, for row-cropped soybeans on a Memphis soil the critical CTI has been found to be 13. An application to our experimental field site is shown in Fig. 3. The actual and predicted locations of ephemeral gullies are seen to agree almost exactly.

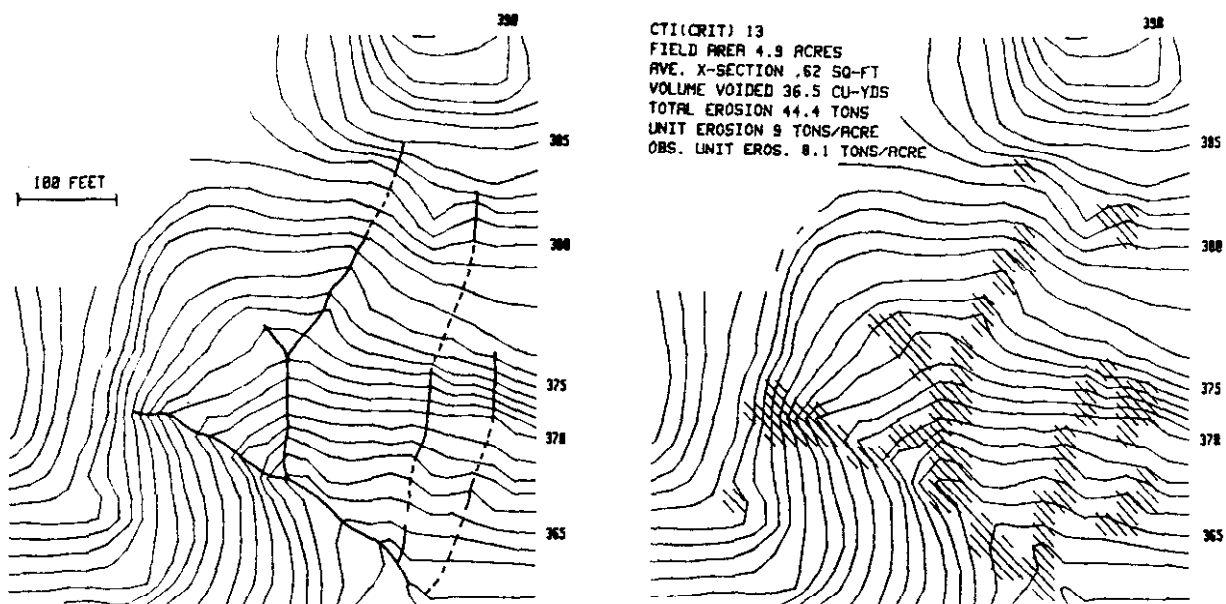


Figure 3. (a) Experimental site in Goodwin Creek Watershed showing contours and ephemeral gullies, fall 1984.
 (b) Computer prediction of ephemeral gully locations and volume voided based on topographic analysis.

Having correctly predicted the location of ephemeral gullies in a field, the next step in calculating the erosion is to predict their size. The approach currently used is empirical, although a theoretical approach is being developed.

In the empirical approach, values of CTI less than the critical value are excluded and only those greater than the critical value for gully initiation are used to estimate gully cross-sectional area. The justification is that reaches with larger upstream areas, slopes and/or stronger convergence would be expected to have bigger gullies than areas with smaller values. On the basis of data from observations of field topography and gully dimensions in Mississippi kindly supplied by Dr. Lawson Smith of the Waterways Experiment Station, the following relation was established:

$$X\text{-AREA} = \frac{(CTI)^{1/4}}{5} \quad (3)$$

where X-AREA = cross-sectional area of the ephemeral gully after one year of development, and CTI = the compound topographic index for the gully reach in question, with $CTI > CTI_c$.

This is a crude approximation based on limited data. However, it allows a "quick and dirty" estimation of the magnitude of ephemeral gully erosion. It cannot be expected that such a relation can be transferable between regions, although such relations could be developed for different regions and soils.

Application of this method to the experimental field site in Mississippi produced the results listed in Fig. 3b. The erosion predicted approximates the observed value. Note that the method not only correctly identifies the gully-head locations but successfully predicts that some gullies are discontinuous - because of the flattening of gradient and divergence of flow that occurs at some points along their paths.

A simplified version of the ephemeral gully analysis for use with hand held calculators is also available. It is intended for the evaluation of ephemeral gullies as sediment sources in situations where the detailed topographic data necessary for the full method are unavailable (Thorne et al., 1985).

DISCUSSION

The analysis presented here provides a simple means to estimate the erosion involved in the formation of ephemeral gully channels in croplands. This was the original request of the interested agencies. However, closer inspection of the role played by ephemeral gullies in the movement of water and sediment in the field reveals that the erosion indirectly attributable to them may be very different from that involved in the voiding of the channel.

The section on ephemeral gully formation concluded with equilibrium being established between the flow and the channel dimensions. In reality this equilibrium, if attained, is very short lived. The gully is modified almost continuously by subsequent runoff events and by subaerial processes, such as desiccation and slaking, between runoff events. The actual development of a particular gully system is unpredictable because it depends on meteorological conditions which are indeterminate. Still, types and trends of gully development can be discussed to illustrate the point that ephemeral gullies can be extremely damaging to the field and can generate soil loss magnitudes much greater than those indicated by periodic measurements of voiding of the channel. The two major trends are degradation and aggradation.

Degradation results from a condition where the sediment output from a reach is greater than the input from upstream, the bed and banks being scoured to make up the difference. In ephemeral gullies, degradation often takes place through headcutting - that is the generation of a headcut or overfall where the bed breaks through a resistant layer such as a plow-pan or fragipan. Degradation enlarges the gully channel through bed lowering and widening due to bank failures that result from oversteepening of the gully sides. Degradation works through the gully system and ultimately through furrows and rills that drain into the gully. It is not unusual to see a small headcut in every furrow crossing a swale, and for these headcuts to progress all the way up the furrow to the drainage divide. In doing so, headcuts deepen the furrows and steepen their side slopes. In turn, this accelerates interrill erosion processes because raindrop impact causes more soil loss on steeper furrow sides. Clearly, the effects of ephemeral gully degradation in enhancing erosion extend throughout the field. A field example is shown in Fig. 4.

Aggradation occurs when the sediment output from a reach is less than the input from upstream, the bed elevation increasing as the excess sediment is stored. Aggradation often occurs after a major degradational phase, beginning at the downstream end of an ephemeral gully system and progressing upstream.



Figure 4. Degradation in an ephemeral gully leading to furrow scouring and widening (Panola County, Mississippi, spring 1985).

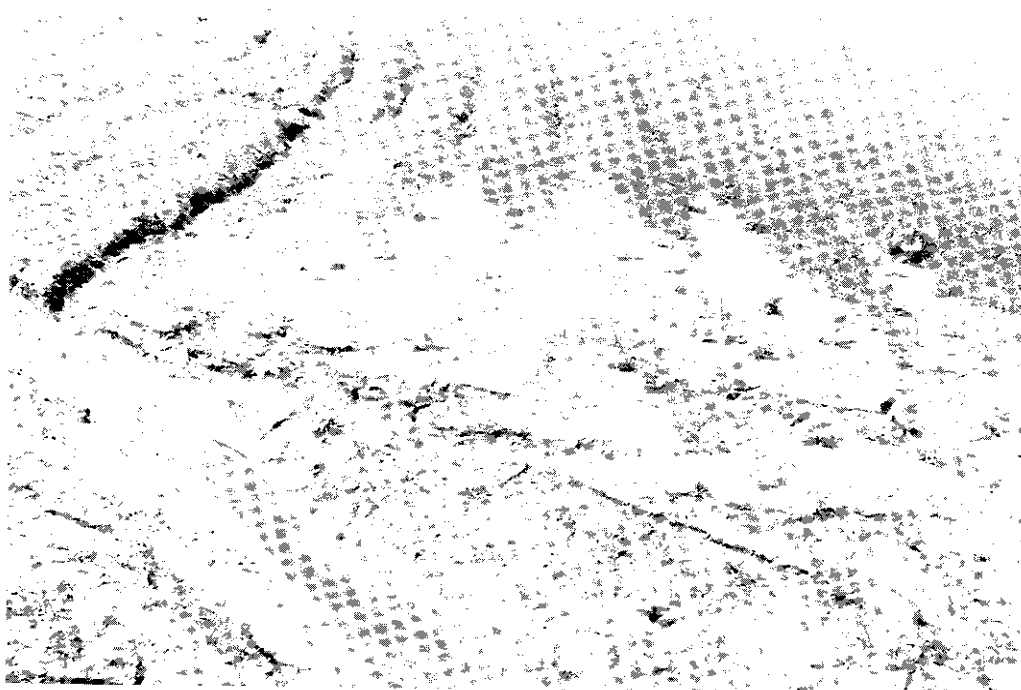


Figure 5. Aggradation in an ephemeral gully leading to furrow sedimentation and burial of vegetation (same gully as Fig. 4).

During aggradation, the channel may become braided and furrows and rills which are tributaries to the gully may become filled with sediment. A field example is shown in Fig. 5. Under these circumstances, furrow and interrill erosion are inhibited, but plants or seedlings adjacent to the ephemeral gully may be buried.

In actuality, aggradation and degradation occur simultaneously in different reaches of the ephemeral gully network. The photographs shown in Figs. 4 to 6 were taken on the same day on the same gully, but at locations progressively further downstream. Examination of the most downstream reach reveals a secondary zone of degradation (Fig. 6) working its way upstream and cleaning out the sediment stored in both the main channel and the furrows.



Figure 6. Secondary degradation in an ephemeral gully leading to removal of soil temporarily stored in an aggraded reach (same gully as Figs. 4 and 5).

There are then cycles of cut and fill in the system, the frequency of which depend on sequences of flow events in the field. This means that the sediment volumes may be cut and filled several times over between tillage events, so that the actual soil loss by concentrated flow may be several times that observed in measuring the volume voided from the gully network, even including the enlarged furrows. Also, the ephemeral gully is able to transport coarser material, including soil aggregates, more efficiently than rills and furrows, so that eroded soil that would be redeposited in a field without ephemeral gullies may be lost from the field via a series of transport and storage periods. To this total must be added the mechanical erosion that occurs when the field is tilled to fill in the channels. The soil tilled into the gully is more susceptible to erosion than undisturbed material. Consequently, concentrated flow preferentially re-excavates this material reforming the channel and restarting the cycle of degradation. Finally, ephemeral gullies

increase the drainage density in a field so that more surface runoff is produced, again promoting rill and concentrated flow erosion.

To evaluate ephemeral gully erosion and indeed total erosion from the field correctly for these circumstances requires a full process-based, dynamic non-lumped hydrology and sedimentation model. Such models are under development in the form of CREAMS II: the latest version of the ARS field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems (Knisel, 1980). However, this model is not presently suitable for use at field office level by non-specialist personnel. While this situation will change, at present there is still a need for simplified but easily applied methods of ephemeral gully erosion prediction like that presented here. It is important to recognize that such simplified methods do not tell the whole story and should in due course be replaced by process-based models that more fully account for the complexities of the system, when these models have developed from the research to the application stage.

ACKNOWLEDGEMENTS

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SEDIMENT IN MUGU LAGOON
VENTURA COUNTY, CALIFORNIA

By Lyle J. Steffen, Geologist, Watershed Planning Staff, Soil Conservation Service, United States Department of Agriculture, Davis, California.

ABSTRACT

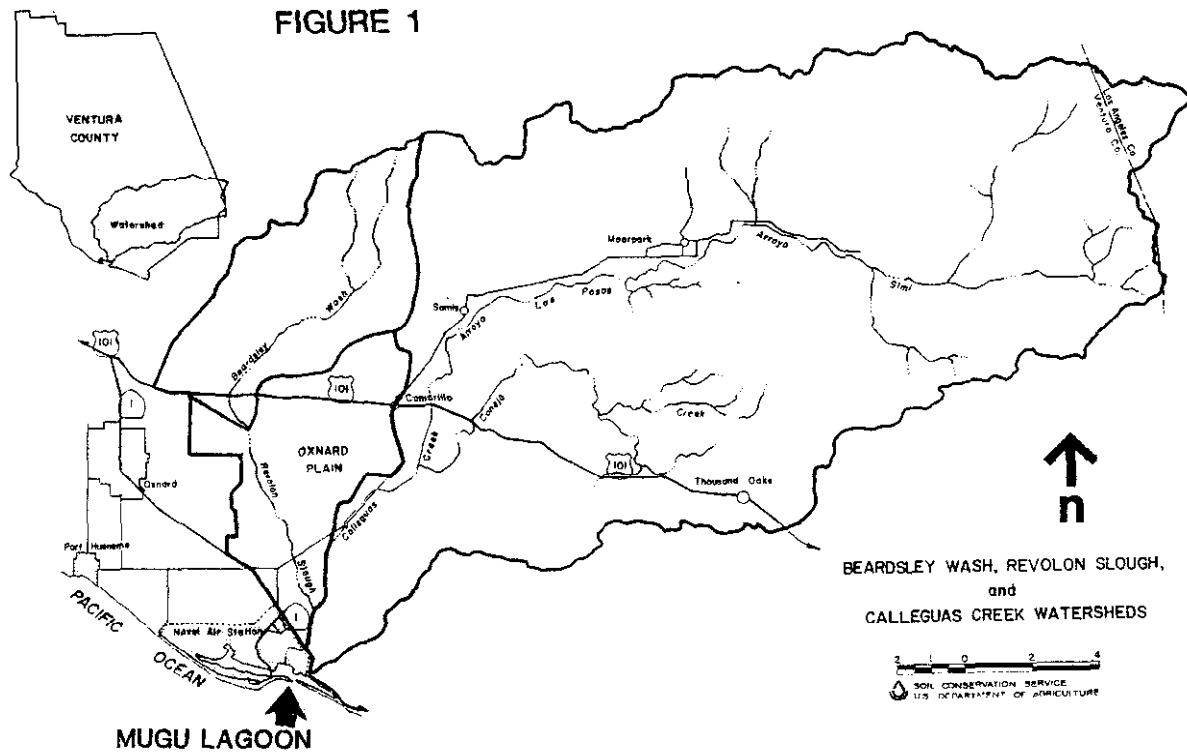
Mugu Lagoon is one of the last remaining natural salt marsh systems in southern California. In the last 80 years, sedimentation in the lagoon has increased from a geologic rate of 0.17 foot per century to an accelerated rate of 1.5 to 3.3 feet per century. If the present rate remains the same, by the year 2030, sedimentation will increase upland habitat from 125 acres to 570 acres while decreasing salt marsh habitat from 1,130 acres to 685 acres.

SETTING

Mugu Lagoon is located in Ventura County, 25 miles southeast of Ventura, California (Figure 1). It is on land owned by the United States Navy at the Pacific Missile Test Center at Point Mugu. The lagoon covers 1,130 acres, 5.0 feet above mean sea level. It is one of the last remaining natural salt marsh systems in southern California and is the outlet for Revolon Slough, Beardsley Wash and Calleguas Creek watersheds (Figure 1). Land use in these watersheds includes citrus and avocado orchards (20,700 acres) on moderately to steeply sloping land. Vegetables are grown on the Oxnard Plain (11,600 acres) and on the flatter slopes in Beardsley Wash and Calleguas Creek watersheds (16,400 acres). Rangeland (131,900 acres) or urban land (27,200 acres) occurs on steep slopes. The drainage area above Mugu Lagoon is 207,800 acres.

Climate in the area is the Mediterranean type with long, dry, warm summers and cool, wet winters. Coastal fogs are common and average annual rainfall is 12 inches on the coast and 20 inches in the mountains. The average frost-free season is 332 days.

A sediment study of Mugu Lagoon was conducted in 1981 to generate information for planning an outlet channel from the Revolon Slough Watershed into the environmentally sensitive lagoon. Results from this study were used to define future conditions in the lagoon with and without an outlet for the Revolon project. This paper describes changes in sedimentation rates and patterns in the lagoon from 1980 to 2030. The sediment study showed that the outlet, a higher and longer bridge on Highway 1, caused no change in future sedimentation rates or patterns in Mugu Lagoon.



HISTORIC SEDIMENTATION RATES

Mugu Lagoon formed about 3,000 years ago in a depression caused by subsidence (California Division of Mines and Geology, 1973). The location of the depression relative to the Ventura area shoreline allowed the lagoon to form.

The shoreline is a result of the prevailing wind, ocean currents and the resistance of rocks exposed to wave attack (Putnam, 1942). These coastal processes appear to be in equilibrium at Mugu Lagoon because the shoreline has changed little in historic time (Handin, 1951). Beach formation along this shoreline is controlled by the movement of sand along the coast by ocean currents (U.S. Corp of Engineers, 1953). The location of aggrading beaches and analysis of mineral composition of beach sands indicate that the direction of this littoral drift is southeast.

Berquist's study of Bolinas Lagoon in Marin County (1979) indicated that the transition of coastal lagoon to coastal plain is geologically very rapid. It is natural for lagoons to fill with sediment. The tidal inundation area of Mugu Lagoon has decreased from an original area of 2,000 acres to about 700 acres (at 3 feet above mean sea level). This indicates that about 5 feet of sediment has been deposited in the lagoon. If the average thickness of sediment deposited over the 1,300 acres during the past 3,000 years was about 5 feet, the rate of sedimentation was 0.17 foot per century.

RECENT SEDIMENTATION RATES

Warne (1971) concluded that sediment deposition in Mugu Lagoon over the past century was 1.5 to 3.3 feet. This represents a ten-fold increase over the geologic rate of accumulation.

The accelerated rate of sedimentation in Mugu Lagoon is due to erosion and increased runoff from urbanization and agricultural development on steep slopes. Sheet and rill erosion rates of 15 to 25 tons per acre per year are not uncommon in avocado and citrus orchards. Farm roads in the orchards can erode up to 100 tons per acre per year. Both the orchards and urbanized areas concentrate runoff. Streambank erosion rates of 1000 to 2000 tons per bank mile are not uncommon along Calleguas Creek, Beardsley Wash and their major tributaries along the northern boundary of the watershed.

Figure 2 shows how the lagoon has changed in area from 1876 to 1978. Macdonald's report (1976) on the lagoon illustrates changes from 1857 to 1962 in more detail. Land filling on the U.S. Navy property to the west has encroached on the lagoon. Sedimentation has filled in some of the tidal creeks in the upland portions of the lagoon and much change has occurred beneath the water surface. Sediment has decreased lagoon depth and changed the bottom substrata from sand to mud (Onuf, 1981; Dow, 1981, Warne, 1971).

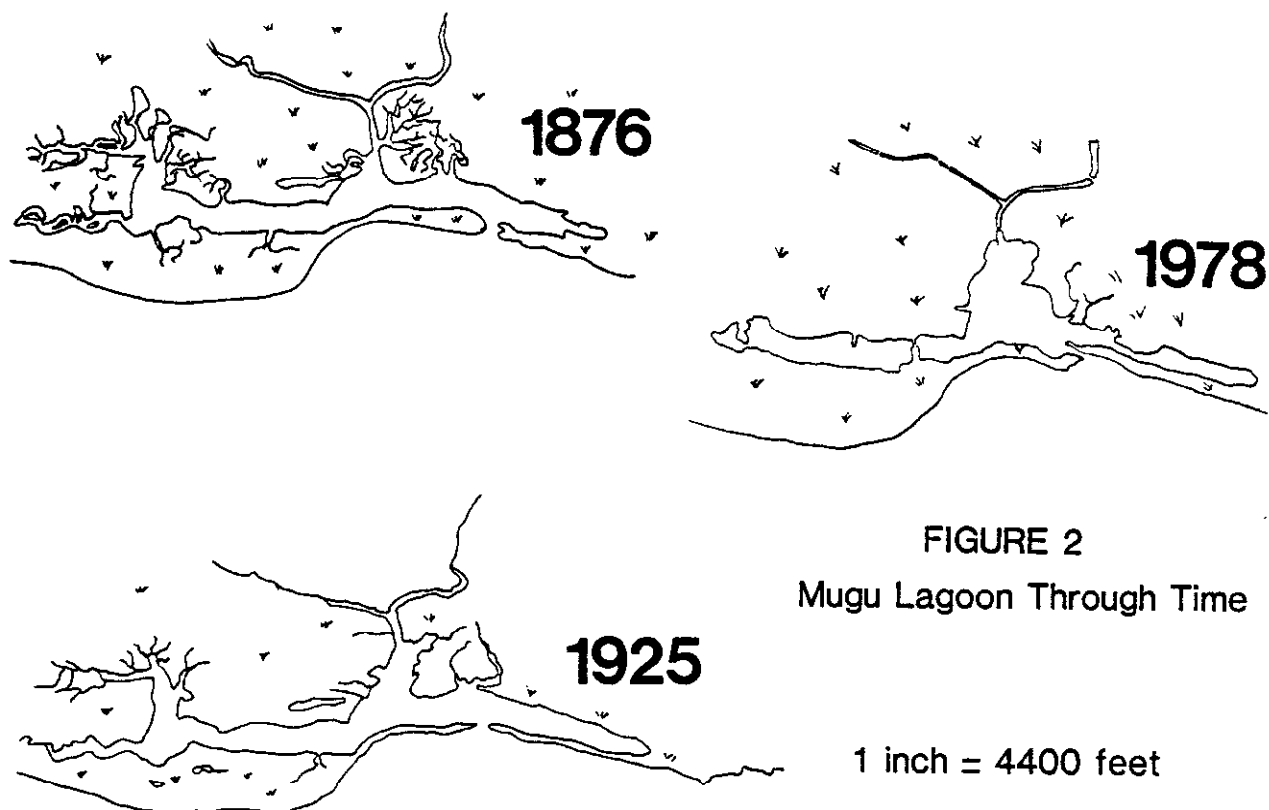
Deep dredging occurred in the lagoon when fill was required for construction of Navy facilities in 1952 and 1961. The increased capacity in the lagoon was about 2,150 acre-feet. Based on hydrographic surveys in 1964 and 1972, sedimentation, primarily from the flood of 1969, has exceeded this capacity. A flood in 1978 caused significant deposition and about 380,000 tons (440 acre-feet) of sediment were deposited in the lagoon in a 1980 storm.

The 1978 and 1980 storms were more severe than the 1969 storm, yet together they did not cause as much sedimentation as in 1969. This may have occurred because the 1969 storm filled the dredged areas, thereby reducing the storage capacity. With a smaller "pool" volume, less sediment was trapped in the lagoon during 1978 and 1980.

Using field studies and measured sediment yield rates for a 50-year storm by Scott and Williams (1978), SCS determined future storm sediment yields to Mugu Lagoon from its tributary watersheds. Based on the dredging history, it was assumed that 50 percent of the sediment delivered to the lagoon actually deposited in the lagoon:

<u>Frequency of Storm (years)</u>	<u>Sediment Deposited in Mugu Lagoon acre-feet</u>	<u>Sediment From Revolon-Beardsley acre-feet</u>	<u>Sediment From Calleguas Creek acre-feet</u>
100	336	43	293
50	278	36	242
10	124	20	104
2	37	7	30

Table source: USDA, Soil Conservation Service 1981.



In order to predict sedimentation rates in Mugu Lagoon, the storm sediment yields had to be converted to an average annual figure. The average annual sediment deposited in the lagoon can be estimated by plotting the sediment deposited versus the storm frequency and measuring the area beneath the resulting curve. This average annual figure is 54 acre-feet combined from Calleguas Creek and Revolon Slough. In comparison, the volume of sediment estimated to be deposited in the lagoon after a 50-year storm is 278 acre-feet.

There is a discrepancy in the amounts of sediment deposited in the lagoon based on dredging data and the 54 acre-feet per year estimated by the SCS. Dredging data indicated 150 acre-feet of sediment deposited in the lagoon annually over the past 29 years. The difference in rates is apparently due to the much lower trap efficiency of the lagoon as it fills with sediment and the tidal prism decreases in volume. The sediment yield from the three closely spaced, major storms of 1969, 1978 and 1980 included in the dredging data also contributed to higher than normal rates of deposition.

CHANGES IN MUGU LAGOON

Changes in Mugu Lagoon over the next 50 years (1980-2030) were estimated using the average sedimentation rate of 54 acre-feet per year. In actuality, the spacing and magnitude of storms that occur over the next 50 years will dictate how fast the lagoon fills with sediment. Since it is not possible to predict the storm patterns, the average annual sedimentation rate was used. By predicting to 50 years, the low and high runoff years should balance.

The number of years it will take for the lagoon to fill with sediment can be estimated using the average annual sedimentation rate and knowing the capacity of the lagoon. Ventura County developed 1-foot contour maps of the lagoon. Cross sections were made from Highway 1 to the ocean across the central arm of the lagoon to estimate its capacity at different elevations. Capacity of the east and west arms was also estimated.

Grain sizes of sediment from the eroding areas were compared to grain sizes of sediment in the Revolon and Calleguas channels above Highway 1. This comparison indicated that the sediment reaching Mugu Lagoon is primarily silt and clay (less than 0.075 millimeter or 0.003 inch in diameter). This sediment size is carried in suspension and requires quiet water for deposition (velocities of flow less than 1 to 2 feet per second). Due to a lack of predictive equations, a qualitative approach is required when describing sedimentation rates of suspended sediment. A qualitative approach is summarized here and discussed in more detail in "Sedimentation Patterns in the Lagoon." Three assumptions were made in order to predict the volume of sediment deposited in the lagoon from 1980 to 2030. One assumption was that the annual rate of sediment yield to the lagoon remains constant and another is that no sediment is dredged from the lagoon. The third assumption is that after 20 years of sediment deposition, the trap efficiency of the lagoon drops from 50 to 25 percent due to the decreased storage capacity:

$$\begin{array}{rcl} 54 \text{ acre-feet/year} \times 20 \text{ years} & = & 1,080 \text{ acre-feet} \\ + 27 \text{ acre-feet/year} \times 30 \text{ years} & = & \underline{810 \text{ acre-feet}} \\ & & 1,890 \text{ acre-feet} \end{array}$$

About 1,890 acre-feet of lagoon capacity is assumed to be lost due to sedimentation from 1980 to 2030. (Contour lines were redrawn on the present map to represent this loss).

The vegetation of Mugu Lagoon is primarily controlled by elevation and the accompanying tidal influence. As the lagoon fills with sediment, intertidal areas will be reduced and associated vegetation will change. Figure 3 is a projection of the vegetation pattern predicted for Mugu Lagoon in the year 2030. Elevations, as related to distribution of vegetation types, were predicted based upon present sedimentation rates. As the figure and following table indicate, the amount of Salicornia-dominated marsh vegetation will be reduced from 720 acres to 420 acres. As areas of the lagoon fill with sediment they eventually will be above tidal influence and upland vegetation will replace the Salicornia-dominated marsh. The area of upland vegetation will increase from 125 acres to 570 acres.

	1980-Existing Conditions (acres)	2030-Future Conditions (acres)
Upland habitat (elevation exceeds 5 feet)	125	570
Salicornia marsh (elevation 2-5 feet)	720	420
Intertidal mud flats (at -2 feet tide)	305	170
Subtidal areas (at -2 feet tide)	90	75
Exposed sandbars (at +2 feet tide)	15	20

Table Source: USDA, Soil Conservation Service 1981.

SEDIMENTATION PATTERNS IN THE LAGOON

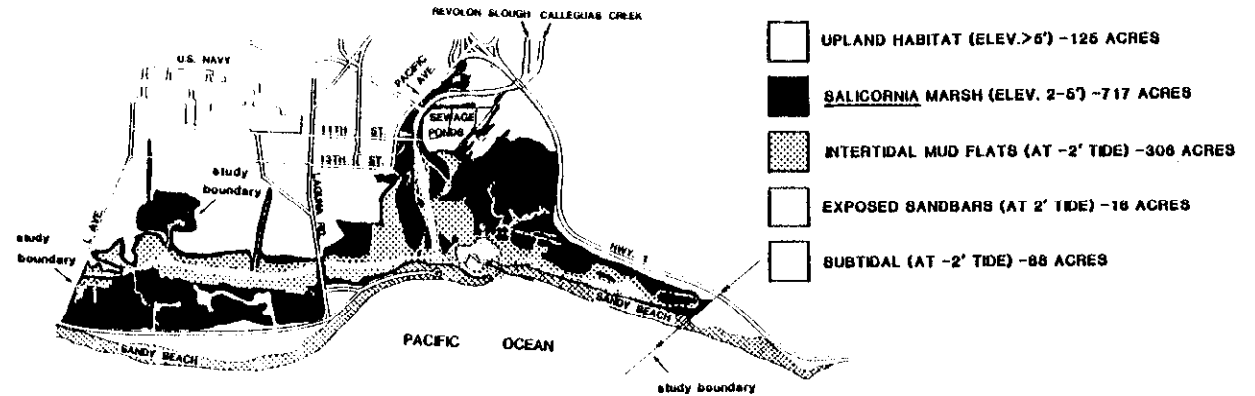
Because the sediment entering Mugu Lagoon from its tributary watersheds is fine grained and carried in suspension, a qualitative approach to describing sediment deposition was used. Vegetation patterns shown in Figure 3 correspond to sedimentation patterns.

Two studies document the sediment transport processes in the San Francisco Bay and delta system (Smith, 1963; Arthur, 1976). Some analogies between this major system and Mugu Lagoon can be made. The two studies conclude that the sedimentation pattern is in continuous flux. The daily pattern is changed by seasonal fluctuation and the seasonal pattern is changed by the flood-drought cycle. Geologic influences such as differential settlement, tectonic uplift, subsidence and the rise of the Pacific Ocean 0.04 to 0.08 inches per year--further complicate the sedimentation pattern. These processes are all active in Mugu Lagoon so areas of sediment deposition and scour may change with time.

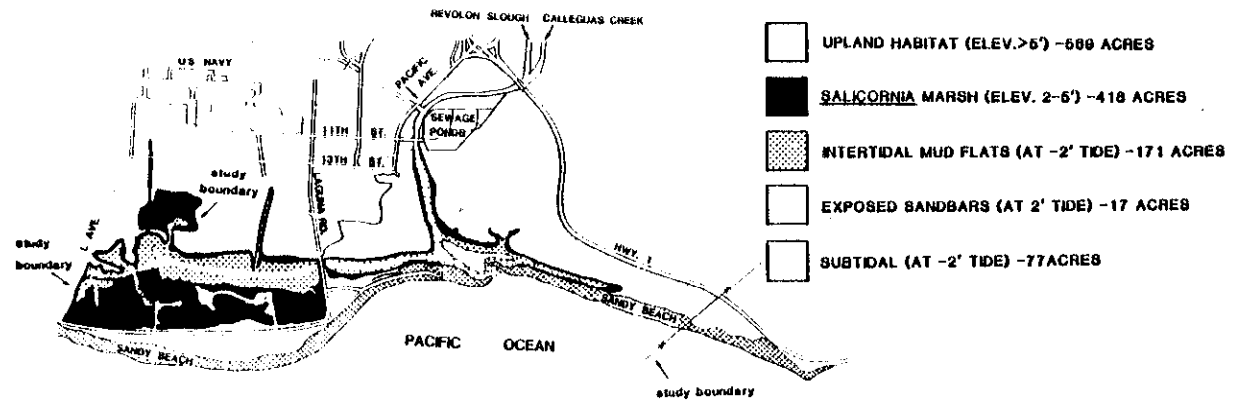
Fluvial systems supply sediment to both San Francisco Bay and Mugu Lagoon. Very little of the sediment reaching the bay is moved to the ocean by the fluvial runoff. Rarely does sediment-laden fresh water flow over the saline bay water and discharge directly into the ocean. The opposite is true for the much smaller Mugu Lagoon. Floodflows move through the lagoon rapidly and transport great volumes of silt and clay to the ocean.

VEGETATION PATTERNS IN MUGU LAGOON

1980 PRESENT CONDITION



2030 FUTURE WITHOUT AN OUTLET



• ELEVATIONS ARE IN FEET FROM MEAN SEA LEVEL

• THE MAP AND ACREAGE DO NOT INCLUDE ISOLATED POCKETS OF MARSH OR APPROXIMATELY 303 ACRES (MACDONALD 1978) OF SALT MARSH VEGETATION WEST OF L AVENUE

FIGURE 3. Comparison of Vegetation Patterns in Mugu Lagoon, Ventura County, CA, over a 50-year period.

In the storm of February 1980, the barrier beach was eroded in three places at different times by storm runoff (Dow, 1981). For 10 hours near the peak of the flood, about 500 acre-feet of fresh water per hour flowed through the lagoon.

The volume of the bay's tidal prism, 1.575 million acre-feet, makes the tides the primary mode of fluvial sediment transport through the bay system. The competency and sediment transport capacity of the ebb tides are 30 to 40 percent greater than the flood tides. This process is not significant in Mugu Lagoon. The volume of the tidal prism is only 1,100 acre-feet below the Highway 1 bridge.

Major sediment inflow into Mugu Lagoon occurs during floods when the fresh water volume of flow greatly exceeds the volume of the tidal prism. As the floods recede, the tides may wash some suspended sediment out of the lagoon. Once the sediment is deposited, it must be resuspended for the tides to move it. Resuspension could result through tidal action, wind-caused waves, dredging, water craft turbulence or marine organism action. The small size, lack of access for water craft and orientation of the lagoon to prevailing winds, all indicated the tidal prism is not the primary mode of sediment transport in the lagoon.

When specific conductivity of water is greater than 1,100 micromhos per centimeter, clay particles carried in suspension will flocculate (seawater is about 57,000 micromhos per centimeter). As flocculation increases, more clay will settle on the bay or lagoon floor. The large volume of water in the bay and delta system makes flocculation an important part of the sedimentation process.

Flocculation occurs in the lagoon during low flows and near the beginning and end of major floods. Since the sediment load and fresh water flow in a flood are greatest at the peak of the flood, flocculation is rare when most of the sediment load of the storm is delivered to the lagoon. So flow velocities probably affect sedimentation in Mugu Lagoon more than flocculation.

The bay and delta studies conclude that the effects of tides and wind drive the estuarine sedimentation processes. In Mugu Lagoon simpler patterns of deposition, such as those in rivers, may be at work. Since the sediment deposited in Mugu Lagoon comes from major infrequent floods, rather than daily flows, deposition patterns from flooding must be considered.

In a river system, as the water rises and goes over the banks, velocity of flow drops rapidly outside the river banks. With this velocity drop, the sediment settles on the banks of the river and natural levees develop. The process helps preserve the channel by building up its banks and floodplain. The lagoon channel, from the Highway 1 bridge to the central arm of the lagoon, has been maintained in its present location for over one hundred years (Figure 2). Scour keeps the channel open during flood flows. Upland areas adjacent to the channel indicate that significant deposition does occur just outside the channel.

During flooding, the central arm of the lagoon bears the brunt of sedimentation. Eddies during the storm runoff and tidal action will also distribute some sediment into the east and west arms. The location and restricted opening at the entrance to the west arm at Laguna Road mean little sediment will actually reach the west arm. Tidal action has also scoured some of the mud and organic detritus from the west arm. Its bottom has actually become more firm over the past few years because the Navy increased the size of culverts at the Laguna Road opening in 1978 (personal communication, Dow, 1982; and Wolf, 1982).

FUTURE SEDIMENTATION PATTERNS

It is predicted that the west arm will not change significantly over the next 50 years. As more cohesive bottom layers develop in the west arm, tidal scouring will diminish.

The east arm gradually will fill with sediment as silt and clay wash into it during and after flood flows and settle in quiet water areas. As the tidal prism is reduced by sedimentation, the inner bars of beach sand will advance into the east arm. Restricted tidal flushing will further increase sediment deposition.

As the "delta" of sediment raises the upland areas and advances toward the barrier beach, ocean wave action will begin eroding the toe of the "delta." This means an open water area may be preserved between the barrier beach and the encroaching upland areas and ensure continued tidal flushing in the western arm. As the central and east arms fill with sediment, tidal flows may increase in velocity and elevation from the decreased volume of the tidal prism. It is very difficult to estimate the magnitude of this effect because of the dynamic nature of tidal action.

The inner bars of beach sand may encroach on this open water area between the upland and the barrier beach. The bars enlarge as breakers suspend the sand and the incoming tides carry it into the lagoon mouth. Velocities, and thus transport capacity, of the outgoing tides are greater than the incoming tide, so the bars are slowly growing. With sedimentation decreasing the tidal prism, the bars may grow more rapidly, eventually closing off the east and west arms to tidal flushing. Again, it is difficult to estimate the magnitude of this effect due to the dynamics of the physical system.

Based on these predicted sedimentation patterns, a channel for Calleguas Creek and Revolon Slough flows will wind its way to the ocean across the new coastal plain. The channel will remain open as a result of periodic scouring during flooding. The Mugu Lagoon tidal prism will be reduced to an estuarine system with tidal flushing up Calleguas Creek, Revolon Slough and the west arm. Within the next 100 years most of Mugu Lagoon, with the exception of the west arm, could be replaced by a coastal plain and a small estuary.

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