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SEDIMENT MOVEMENT FROM LOESSIAL WATERSHEDS

by

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INTERPRETIVE SUMMARY

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Previous studies have shown much variability in the relationship between soil erosion rates and downstream sediment yields in the Missouri River Basin Loess Region. The ratio of sediment yield to soil erosion rate is termed "sediment delivery ratio." The apparent lack of correlation between sediment delivery ratio and watershed size is especially frustrating, because such correlation is basic to the use of the sediment delivery method for predicting watershed sediment yields.

Sediment delivery variations for Treynor, Iowa, research watersheds--by year and by storm--are relatable to season, soil moisture levels, and <u>rainfall-runoff variables</u> for the 1965-1971 data collection period. An improved sediment delivery-drainage area curve for the loessial areas is constructed on the basis of relationships inherent in sediment yield-delivery records--and in the Treynor data.

what are they?

Two separate functions are proposed to improve the understanding of sediment movement. First, sheet-rill erosion equations, when used in watershed estimates, should be refined by the addition of terms to account for the effect of soil moisture and to better express rainfall intensities and durations. The refined equation is then combined with a function that expresses the sediment conveyance-roughness characteristics of a watershed.

SEDIMENT MOVEMENT FROM LOESSIAL WATERSHEDS[1]

by

R. F. Piest, L. A. Kramer, and H. G. Heinemann[2]

Introduction

The loess-mantled region bordering the Missouri River from South Dakota into Missouri is subject to extensive erosion from surface runoff. The favorable climate and the natural fertility of the deep, moderately permeable soil renders the region exploitable for intensive agriculture, even though the terrain is steep enough to cause high erosion rates during intense rainstorms. The erosion processes, if not impeded, deplete soil fertility by removing the humus-enriched topsoil. But even more serious aspects of erosion are (1) dissection of the land surface by rills and gullies and (2) downstream damages by deposition of sediments and sediment-borne agricultural chemicals. Fortunately, the quantities of soil eroded from fields and drainageways of the loessial region each year are not moved en masse to the Mississippi River and thence to the Gulf of Mexico. On the average, such a trip requires a decade or more in an unregulated drainage system. Regardless of regulation, it is necessary to know the amount and location of these sediments for the design and operation of water resource and soil conservation systems.

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[1] Contribution from the North Central Region, Soil, Water, and Air Sciences, Agricultural Research Service, USDA, in cooperation with the Iowa Agriculture and Home Economics Experiment Station.

[2] Hydraulic Engineer, Agricultural Engineer, and Hydraulic Engineer, respectively, North Central Watershed Research Center, USDA ARS, Columbia, Missouri.

The purpose of this study is to review what is known about the sequence of erosion and the movement of soils from loessial watersheds and to extend this knowledge by applying experiences from instrumented watersheds near Treynor, Iowa. We examine inaccuracies resulting from the use of the sediment delivery method to predict sediment yields in the loess region. Then, using previously defined relationships between soil erosion and sediment yield--and insights gained from the intensive measurements on the Treynor watersheds--we (1) identify factors to strengthen the Universal Soil Loss Equation and (2) propose an independent function intended to represent sediment conveyance/retardance properties. The end result, when fully developed, is expected to improve sediment yield prediction procedures.

Procedures for Estimating Erosion Rates and Sediment Movement

Sediment yield estimating procedures for the loessial region have been developed (directly and indirectly) from experiment station erosion plots at Clarinda and Castana, Iowa, and Bethany, Missouri, from streamflow sampling stations operated by the U.S. Geological Survey and the Corps of Engineers, and from reservoir sedimentation surveys by several Federal agencies. These measurements have been widely utilized, some of them beyond the specific purpose for which the information was obtained. Many interpretations and empiricisms have also evolved from these data so that the information can be applied more generally to the multitude of design problems that confront conservationists. Gottschalk and Brune (3)[3] utilized the work of

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[3] Underscored numbers in parentheses refer to Literature Cited, p. 24.

Musgrave and others to develop an expression for predicting sediment accumulation in reservoirs. These sedimentation rate estimates were required for the design of many small detention and desilting reservoirs. Glymph (2) added streamflow sediment records to Gottschalk's reservoir data to relate watershed sediment yields to (1) gross erosion, (2) number of rainfall events equal to or exceeding 1 inch per day during the growing season, and (3) watershed size.

Similar developments have continued, and the conservationist can now select whichever of the following prediction methods best suits his requirements.

1. *The sediment transport (sediment rating curve) method*, in which a relationship between sediment discharge and runoff is obtained by concurrent field measurements: It is necessary to sample the full range of variation in these factors for maximum reliability, but more often some synthesis is required. Once the long-term runoff-sediment relation is established, it is combined with long-term flow frequency data to obtain long-term sediment yields. This method is probably the most costly and time-consuming field mensuration program, but the storm sample data permit insights into erosion processes that are impossible to gain with other methods.
2. *The reservoir sedimentation survey method*, in which accumulated sediment volumes and weights and reservoir trap efficiencies are analyzed for useful general information on sediment yields in a region: Less field work is required in this method, but the data are not as easily adjusted for special or unusual conditions as is the sediment rating curve method based on streamflow samples.

3. The sediment delivery method, in which the sediment yield to some downstream cross section or deposition point is based on (a) an estimate of total upstream erosion rates and (b) an estimate of the percentage or portion of this total that appears downstream: Sediment yields from methods 1 and 2 and computations of total (gross) erosion for a given region form the bases for determining a sediment delivery percentage or ratio. This method is an excellent qualitative tool for pinpointing sedimentation problem areas and for designing conservation structures. But the quantitative accuracy of the method, when applied to the watersheds, is questionable.

4. Methods based on empirical equations derived from measured sediment yields (methods 1 and 2) and watershed hydrologic characteristics: Most of these empirical expressions have severely limited application, even in the region of origin, because the physical laws governing sediment movement are ill-defined.

5. Methods based on equations, nearly all empirical, which express sediment transport in terms of the hydraulic and sediment properties of alluvial channels: These methods are often applied when (a) most of the material eroded from the watershed is sand size or larger and can be found in appreciable quantities in the streambed and (b) there is appreciable channel erosion. Therefore, these methods are not applicable for many small watersheds in the Missouri Valley loess area.

6. The simulated watershed sediment model, which portrays the kinematics of sediment transport through a watershed, from point of origin to deposition, in response to a given rainfall or runoff input: This method is still largely undeveloped.

Beer, et al. (1) measured the sediment characteristics of 24 reservoir watersheds in Iowa and Missouri to test sediment prediction techniques applicable to the loess region. They stated: "Most techniques are empirical and require considerable judgment on the part of the designer." They also concluded that (1) drainage area and sediment delivery ratio are poorly correlated (a good correlation is needed, of course, to apply the sediment delivery method) and (2) the estimates of sheet-rill erosion rates for the watersheds in the region contributed the most variation to the predicted sediment yield. Sediment yields, from reservoir surveys and trap efficiency estimates, were considered some of the most accurately determined variables.

Of the foregoing methods, the sediment delivery method is used most in operational programs for farm conservation and watershed treatment. Equations for estimating sheet-rill erosion, principally the so-called Musgrave and Universal Soil Loss Equations, contain such rational factors as climate, topography, soil, land use, and land treatment and are backed by considerable data from experiment station plots. If the mechanisms causing sediment movement on a watershed surface can be better described, the sediment delivery method has great potential for predicting sediment yields and for use in developing watershed sediment models.

The Sediment Delivery Method

The sediment delivery ratio, D, or percentage, is a measure of the diminution of eroded sediments, by deposition, as they move from the erosion sources to any designated downstream location.

$$D = \frac{Y}{T} \qquad (1)$$

where Y is the sediment yield at the downstream location and

T is the total (gross) erosion (above that location) which includes gully, channel, and sheet-rill erosion.

In the application of the sediment delivery method, Y = DT where delivery ratio is usually obtained from a graphical relation with watershed size. For most design problems, the foregoing equation is considered valid for long-term average annual conditions but is much less applicable for shorter periods. The accuracy of the sediment delivery method could be much improved by insights obtained from an analysis of storm-to-storm variations in sediment delivery. We will show sediment delivery relationships, by storm and by season, in simplified form by considering only the sheet-rill erosion component. This component was obtained at the Treynor watersheds by sampling streamflow from the outflow drainageways just upstream of the gully heads. The effect of the simplification will be discussed later.

Figure 1 is reproduced from Beer, et al. (1) to show the extreme

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Figure 1.--Comparison of computed sediment delivery percentages for 24 reservoir watersheds with curves developed from reservoir data from eastern Nebraska and western Iowa, after Beer, et al.

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variability found in sediment delivery-area relations. Curve A (2) represents about 30 small reservoir watersheds scattered throughout the Missouri River Basin Loess Hills Region; curve B was taken from unpublished data for Mule Creek Basin in southwest Iowa, where the measured sediment deposition exceeded computed erosion rates in several instances. The plotted points represent a study of 24 reservoir watersheds in western Iowa and northwest Missouri surveyed by Beer, et al. (1) and support their statement that sediment delivery percentage is poorly correlated with drainage area. The Musgrave equation, which was used to evaluate sheet-rill erosion rates, was the basis for the sediment delivery calculations. We will try to explain the variability in the sediment delivery-drainage area relation by examining annual and storm sediment data from the loessial watersheds near Treynor, Iowa.

Table 1 is a summary of annual rainfall erosivity parameters (10), 1965-1971, and measured sediment yields from sheet-rill sources from 74- and 83-acre, contour-planted, continuous-corn watersheds 1 and 2 near Treynor, Iowa. Table 2 is a storm summary of rainfall erosivity, runoff, computed sheet-rill erosion, measured sediment yield, and computed sediment delivery ratio for watershed 1.

Sediment Delivery Interpretations--annual basis.--The mean annual rainfall on the watersheds for 1965-1971 (table 1) was nearly 4 inches above the long-term average of 28.6 inches per year recorded at Nearby Omaha, Nebr., but the computed rainfall erosivity was 80 percent higher than the long-term regional value. The annual sediment delivery values ranged from 4 to 72 percent, with a 7-year value of 46 percent. Apparent reasons for year-to-year variations in the sediment delivery percentages are the amount of rainfall.

TABLE 1.--Annual sheet-rill erosion, sediment yield, and percentage delivery, contour-corn watersheds 1 and 2 at Treynor, Iowa, 1965-1971

Year	Rainfall		Kinetic Energy		Rainfall Erosivity Factor (100R)		Sheet-rill Erosion by Universal Equation		Measured Sediment Yield from Sheet-rill Eros. Source		Sediment Delivery	
	W-1	W-2	W-1	W-2	W-1	W-2	W-1	W-2	W-1	W-2	W-1	W-2
	inches		ft-ton/a-inch				tons/acre		tons/acre		percent	
1965	45.3	44.3	30,700	27,700	40,600	36,900	72.0	54.6	44.0	36.4	61	67
1966	20.3	20.5	10,700	11,000	11,900	12,000	24.8	20.9	6.7	8.6	27	41
1967	38.2	37.6	27,100	26,700	60,400	59,800	137.3	113.7	99.1	75.2	72	66
1968	32.3	32.5	19,600	18,600	27,500	27,000	45.1	36.5	3.7	4.1	8	11
1969	31.4	31.5	18,300	18,700	18,200	19,500	32.7	28.5	1.8	1.0	6	4
1970	31.5	30.8	20,200	19,200	36,800	30,400	55.7	37.9	11.8	7.4	21	20
1971	28.9	29.0	16,800	16,500	18,800	16,500	41.8	28.2	20.0	13.3	48	47
7-year mean	32.6	32.3	20,500	19,800	30,600	28,900	58.5	45.8	26.7	20.9	46	46

NOTE: Long-term R Factor for Region is 160 or 100R = 16,000.

TABLE 2.--Sediment delivery and associated information for well-sampled runoff events at watershed 1, 1965-1971

Date	Precipitation[1/]			Runoff				Antecedent Soil Moisture 0-6" depth	Computed Soil Loss[2/]	Measured Sediment Yield	Sediment Delivery
	Amount	Kinetic Energy	Erosivity	Duration Begin	Duration End	Amount	Peak				
	inches	ft-tons / a-inch		hours		inches	cfs	inches	t/a	t/a	percent
1965											
5-17	0.97	947	1,724	2345	0217	0.20	66	1.80	4.55	3.81	84
5-22	.54	479	460	0001	0132	.39	167	2.50	1.22	6.76	554
5-22	.40	310	161	0132	0400	.17	29	2.50	.42	.92	219
5-22	.25	202	83	1446	1700	.14	47	2.50	.22	1.26	573
5-24	.74	664	857	1741	2030	.28	94	2.40	2.26	3.01	133
5-25	.33	300	174	2105	2247	.11	38	2.40	.46	1.19	259
5-26	.10	57	6	0041	0209	.02	3	2.30	.02	.02	100
6-2	.43	344	227	0352	0500	.03	8	2.10	.60	.12	20
6-6	.68	654	693	1721	1852	.37	92	2.05	1.83	2.39	131
6-28	.62	658	829	2248	2327	.10	44	2.00	1.79	1.11	62
6-28	1.22	1,295	3,134	2327	0021	.51	104	2.40	6.76	4.58	68
6-29	.34	325	247	0021	0101	.13	44	2.50	.53	.69	130
7-1	.17	152	49	1855	2045	.06	24	2.30	.10	.24	240
8-29	1.37	1,373	2,800	2337	0140	.15	27	1.45	3.25	.24	7
8-30	.47	435	396	0140	0400	.07	20	1.70	.46	.07	15
9-7	1.27	1,304	2,660	0111	0225	.28	69	2.40	3.08	.32	10
9-7	.54	480	413	0401	0506	.12	27	2.50	.48	.10	21
9-7	.85	801	1,081	0506	0745	.30	46	2.50	1.25	.26	21
9-8	.32	280	157	0600	0800	.12	27	2.50	.18	.16	89

1/ Thiessen weighted.

2/ Computed by the Universal Soil Loss Equation.

TABLE 2.--Continued.

Date	Precipitation1/			Runoff				Antecedent Soil Moisture 0-6" depth	Computed Soil Loss2/	Measured Sediment Yield	Sediment Delivery
	Amount	Kinetic Energy	Erosivity	Duration		Amount	Peak				
				Begin	End						
	inches	ft-tons a-inch		hours		inches	cfs	inches	t/a	t/a	percent
1966											
6-5	0.88	850	1,368	0345	0526	0.08	21	2.08	3.61	1.01	28
6-25	.51	532	660	2308	0040	.05	21	2.50	1.42	.50	35
6-26	.99	996	1,683	0200	0344	.36	147	2.50	3.64	4.69	129
1967											
6-4	3.60	3,415	7,513	2328	0600	1.79	145	2.30	19.84	15.40	78
6-7	1.62	1,765	5,542	1659	1902	1.23	411	2.50	14.63	13.70	94
6-7	.70	584	537	1902	2400	.45	83	2.50	1.42	1.92	135
6-9	.49	466	466	0114	0155	.35	117	2.40	1.23	2.08	169
6-9	.44	377	219	0155	0339	.30	96	2.50	.58	1.60	276
6-9	1.51	1,401	2,914	2044	0200	1.16	212	2.50	7.69	7.38	96
6-11	.93	729	598	2005	0121	.51	113	2.50	1.58	1.73	110
6-14	.86	822	1,085	0523	0809	.50	235	2.40	2.86	3.06	107
6-15	.51	429	279	2026	2200	.19	60	2.23	.60	.81	135
6-20	6.03	6,543	32,584	2104	2400	4.21	438	2.20	70.38	49.70	71
1968											
6-10	.88	868	781	2224	0130	.04	12	1.75	2.06	.38	18
6-13	.90	933	1,838	2139	0025	.21	67	2.11	4.85	2.56	53
7-30	1.48	1,561	4,340	2135	2400	.04	8	1.00	9.38	.08	1
10-16	3.03	2,771	4,849	1842	0030	.40	27	2.00	5.62	.12	2

TABLE 2.--Continued.

Date	Precipitation[1]			Runoff				Antecedent Soil Moisture 0-6" depth	Computed Soil Loss[2]	Measured Sediment Yield	Sediment Delivery
	Amount	Kinetic Energy	Erosivity	Duration Begin	Duration End	Amount	Peak				
	inches	ft-tons a-inch		hours		inches	cfs	inches	t/a	t/a	percent
1969											
4-16	1.05	801	577	0230	0743	0.04	1	2.30	1.04	0.05	5
6-26	.57	557	646	1135	1300	.02	6	2.15	1.40	.08	6
7-17	2.11	1,943	2,448	0558	1032	.17	28	1.65	5.29	.48	9
1970											
5-12	1.65	1,760	5,104	0007	0130	.43	85	1.70	9.19	6.27	68
5-12	.22	200	96	0235	0315	.07	30	2.50	.17	.63	371
7-28	.65	587	599	0239	0355	.02	2	1.80	1.29	.01	1
8-2	2.43	2,839	13,599	2141	2308	.90	391	2.30	15.78	4.28	27
1971											
5-6	.89	787	889	1010	1210	.11	13	1.64	1.60	.56	35
5-6	.25	198	71	1435	1545	.07	12	2.30	.13	.27	208
5-6	.27	225	94	1545	1710	.13	30	2.40	.17	.64	377
5-10	.43	350	200	0137	0347	.19	46	2.20	.36	.98	272
5-10	.19	180	72	1907	2004	.14	49	2.20	.13	.36	277
5-10	.64	639	716	2004	2053	.45	137	2.25	1.29	2.93	227
5-17	.58	609	719	2304	2400	.36	136	1.95	1.90	2.67	140
5-18	.36	320	198	0150	0227	.18	60	2.15	.52	.79	152
5-18	1.34	1,325	2,822	0227	0444	1.03	239	2.25	7.45	7.19	96
5-18	.31	222	75	1025	1147	.17	20	2.35	.20	.27	135
6-10	.18	171	65	0049	0135	.02	6	2.05	.17	.08	47
6-29	1.25	1,213	1,443	2148	2336	.12	26	1.50	3.81	.50	13

and the seasonal distribution of rainfall erosivity; the wet years of 1965 and 1967 had the highest sediment delivery, whereas the driest years, 1966 and 1971, had lowest erosivities but sediment delivery values close to the mean.

Any seeming discrepancies of table 1, such as the wide variation in sediment delivery values for comparable rainfall in 1969, 1970, and 1971, can be partially explained by consideration of the magnitude and seasonal erosivity of the rainfall variable of the Universal Soil Loss Equation. Figure 2 shows that 1969 and 1971 rainfall erosivities were similar and just slightly above the long-term average. However, the largest 1969 storms occurred on July 17 and August 20, whereas the 1971 storms were concentrated on several days in May and June. As a result, the computed sheet-rill erosion rates for 1969 and 1971 differed somewhat, 32.7 and 41.8 tons per acre, respectively; but the measured sediment yields were vastly different, 1.8 and 20.0 tons per acre. Since sheet erosion equations make no provision for the attenuation of sediment in transport through the watershed, we can then rationalize that a watershed "roughness" factor would be relatively low for row crop fields in the May-June, plow-plant season when the surface is bare. Therefore, we should expect a low sediment delivery for 1969 and a relatively high value for 1971.

Figure 2.--Rainfall erosivity variation at watershed 1 during three consecutive years of comparable total rainfall.

The 1970 rainfall amount (table 1) also was comparable to that in 1969 and 1971, but the rainfall erosivity was nearly double. Figure 2 shows a moderately high erosivity [illegible]ng la[illegible]ly May 1970 and a very high erosivity in August resulting from the most intense rainfall of record. The resultant 21-percent sediment delivery is between the values for the other 2 years. This demonstrates the effect of the seasonal occurrence of storms on sediment delivery.

Sediment Delivery Interpretations--storm basis.--Storm variations in gross sheet-rill erosion, sediment yield, and sediment delivery are shown in table 2 for one of the contour-planted, continuous-corn watersheds. Fifty-five of the best-sampled runoff events at watershed 1 in the 1965-1971 period are listed. These represent a varied population, with measured sediment yields ranging up to 50 tons per acre for the event of June 20, 1967.

Computed sheet-rill erosion rates and measured downstream sediment yields (from sheet-rill erosion sources) at Treynor watershed 1 were compared (figure 3). Only 33 percent of the variation in storm sediment yield is explained by computed values of sheet-rill erosion.

Figure 3.--Comparison of erosion rates and sediment yields from sheet-rill erosion source for 52 well-sampled events on contour-corn watershed 1.

To explain the scatter of figure 3, several hydrologic variables were examined for each storm event. The variables included rainfall amounts, rainfall kinetic energy (KE), kinetic energy x high 30-minute rainfall intensity (EI), storm runoff volume, peak runoff rate, season, time, and moisture content in the top 6 inches of the soil profile. Season is the Julian date, and time is the number of days elapsed from January 1, 1965. When all sediment-associated variables were used in a stepwise multiple regression on each of the three dependent variables (sediment yield, erosion, and delivery), the results were:

	Cumulative explained variance, R^2, due to addition of a given independent variable		
Dependent Variable	1st	2nd	3rd
Sediment yield, t/a	Runoff peak (0.81)	Season (0.90)	KE (0.95)
Sheet-rill erosion, t/a	EI (0.96)	Season (0.97)	--
Sediment delivery, %	Soil moisture (0.36)	Season (0.62)	EI (0.83)

Peak runoff rate and season explained much of the variability in sediment yield. Erosion rate was highly correlated with EI, which, of course, is a major variable of the Universal Soil Loss Equation for a given location. Sediment delivery was most predictable on the basis of antecedent soil moisture content, season, and EI.

The appearance of seasonal and antecedent moisture variables that are correlated with sediment delivery can be subject to several interpretations. For the 52 storms considered here, these two variables are relatively independent of each other, r = -0.16. Previous studies (8) showed high sediment delivery percentages for storms occurring during the early crop stage. It was speculated that these were caused by rill development and/or soil moisture differences that were unaccounted for when the Universal Soil Loss Equation, based on plot studies, was applied to watersheds. However, this variation in sediment delivery may also be interpreted to be due to errors in estimating sheet-rill erosion (as Beer, et al. conclude) or to the need for additional variables that can express the sediment conveyance characteristics of a watershed.

Watershed Sediment Conveyance and Roughness Concepts

A watershed sediment conveyance characteristic could be analogous to a hydraulic conveyance function for a channel, such as Manning's formula, in which $V \propto \frac{RS}{n}$. Moreover, watershed sediment conveyance could vary according to

$$D \propto \frac{RS}{n} \qquad (2)$$

where D is sediment delivery of equation 1, an expression of the conveyance properties of a watershed surface and drainage system,

R is an expression of flow geometry,

S is a watershed slope factor, and

n is a watershed roughness factor.

Such a function confirms Maner's findings (4) that sediment delivery percentage in the Red Hills physiographic region in Texas and Oklahoma varies with relief and maximum length of watershed. The latter variables are expressed as a ratio and are comparable to a slope factor. Roehl (9) used data from 15 Southeastern Piedmont watersheds to show that sediment delivery ratios decreased with increasing watershed size and increased with an increase in watershed relief-length ratio. These relationships are all compatible with the concept of a watershed roughness or conveyance factor.

The foregoing watershed sediment conveyance properties are based on differences between watersheds. When considering soil erosion and sediment movement on a single watershed, it is also possible to visualize different conveyance/roughness properties from season to season and from storm to storm. These properties would include differences in rilling, soil moisture levels, and overland flow obstructions.

The apparent sediment delivery from storms occurring in August and September on watershed 1, based on measured sediment yield and sheet-rill erosion calculated by soil loss equations, is nearly always less than 30 percent and is often 10 percent or less (table 2). We originally attributed this apparent low sediment delivery to the inadequacy of the soil loss equation to reflect seasonal erosion rates; that is, a higher erosion rate was computed than actually occurred, and the resulting sediment delivery percentage was too low. However, it is now proposed that the C factor of the Universal Soil Loss Equation, which is 0.63 in the spring and decreases to 0.26 in the fall for these cornfields, is correctly gauging the effect of cover on soil loss rates. But it does not purport to represent a watershed roughness factor, which is needed to obtain the correct sediment delivery ratio and thence the sediment yield.

The sediment conveyance characteristics of a watershed vary from storm to storm in any given season. Figure 4 shows the percentage sediment delivery variation with sediment yield for 31 storms in June from 1965 through 1971 at watershed 1, for which any seasonal effect should be minimal. Some of this variation is due to differences in watershed roughness/conveyance properties such as rill formation, mechanical cultivation, and soil moisture changes. Preexisting rills on the watershed surface can convey eroded soil more efficiently than newly developed rills (5) because the hydraulic geometry is more favorable. We would expect the R factor in equation 2, which would be comparable to the hydraulic radius in the Manning formula, to increase with rill formation as compared with its value for sheet flow.

Figure 4.--Sediment delivery variation with sediment yield for 31 June storms occurring from 1965-1971 at contour-corn watershed 1.

It is impossible at present to state the effect on sediment delivery of soil moisture and mechanical cultivation differences between these June storms or the extent to which these two factors affect (1) the relationship between actual and computed sheet-rill erosion rates on a watershed by the

Universal Soil Loss Equation or (2) watershed conveyance properties even if soil losses are predicted accurately. We also suggest that there is an interaction between antecedent soil moisture content and storm rainfall intensities that cannot be typified by the 30-minute maximum rainfall intensity used for calculating sheet erosion rates. Wet soils are the principal reason that measured sediment yields can sometimes exceed calculated erosion rates. Antecedent soil moisture levels are correlated with sediment delivery, as shown in figure 5. Multiple correlation analyses of sediment delivery for the 31 June storms at watershed 1 show that peak runoff rate, runoff volume, and antecedent soil moisture explain 96 percent of the variation.

Figure 5.--Sediment delivery variation with antecedent soil moisture level, 31 June storms on contour-corn watershed 1, 1965-1971.

Potential for Improving the Sediment Delivery Method

Current agricultural and urban erosion problems can be better solved by a fuller understanding of watershed erosion rates and sediment yields. New insights into watershed sediment movement, on a storm basis, can refine the sediment delivery method and improve its usefulness. These insights can also assist in the development of simulated watershed sediment models. The application of the foregoing analyses to improving the sediment delivery method--to better describe sediment movement from loessial watersheds--would include:

1. The best portrayal of the relationship between sediment yield and drainage area for the loessial region being considered. Piest,

et al. (7) summarized research into the variation of sediment yield with size of drainage basin and found that the sediment yield decreased by about the negative one-eighth power of drainage area. The one-eighth power relation was a somewhat greater decrease in sediment yield with drainage area than Fleming obtained (7) for 250 watersheds on four continents. The slope of the Fleming curve was probably low because it was based on a preponderance of sediment records from large areas and was not completely applicable to small watersheds. It can be reasoned that the sediment yield for miniscule areas approximates total sheet-rill erosion. In an example by Meyer (5), the percentage of total material transported declines rapidly with distance downslope until less than half of the total "point erosion" quantities are delivered to a location 160 feet downslope. Onstad (6) shows that net soil loss on a typical 9-percent, concave slope 75 feet long becomes 0 at about 44 feet (the 100-percent sediment delivery point) and that the sediment delivery percentage to any point farther downslope declines rapidly. With these background data, the best-portrayed sediment yield-drainage area relation for the Treynor area should have a slope approximately as shown in the sediment delivery curve of figure 6.

Figure 6.--Probable drainage area relation with sediment yield and delivery, considering only sheet-rill erosion sources, from Iowa cornfields with an average 9-percent slope.

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2. **The sediment delivery-drainage area relationship dealing only with sheet-rill erosion.** We propose to exclude other sediment

sources and to add them later for individual watersheds whenever applicable. The sediment delivery-drainage area relation differs from the sediment yield-drainage area relation by a constant, $\frac{1}{T}$, since $D = \frac{Y}{T}$ (equation 1). The constant is based on the fact that sheet-rill erosion rates obtained by applying the Universal or other soil-decline equations are not a function of watershed size in an assumed homogeneous region.

3. The assumption that the trend of the sediment delivery-drainage area relation is the same as previously demonstrated for sediment yield-drainage area. Others (7) have shown that sediment delivery decreases with approximately the one-eighth power of drainage area. However, Glymph's curve (figure 1), as derived from Gottschalk and Brune's data for the Missouri River loess hills, was somewhat steeper than the others.

Applying these concepts to Treynor data, the 1965-1971 average annual sediment yield from sheet-rill erosion sources for unterraced, corn-cropped watershed 1 was determined, from streamflow samples and measurements, to be 26.7 tons per acre per year from 74.5 acres (table 1). The sediment delivery, computed by relating sediment yield to the soil loss determined by the Universal Soil Loss Equation, was 46 percent. The sheet-rill erosion rate was 58.5 tons per acre per year. A sediment delivery curve with the ordinate in terms of both sediment delivery percentage and sediment yield is shown in figure 6 for Treynor watershed 1. The constant, k, is evaluated as $\frac{100D}{Y} = 1.72$. The sediment delivery curve was drawn through the point representing watershed 1. Constraints in drawing the curve include the necessity for (1) approaching 100 percent delivery on plot-size areas which form the statistical basis for the soil loss equations and (2) paralleling sediment yield-drainage area relationships.

The shape of the sediment delivery curve for row crop watersheds is apt to vary from that for pasture and small grains because the watershed surface roughness is much greater for the latter. Overland sediment movement on grass and small-grain watersheds must be attenuated more than on row crops; but, from the point where these sediments enter channels and are efficiently transported, sediment delivery should be the same. Therefore, in any given homogeneous region we would expect that, on the average, steep, cultivated watersheds which yielded the most storm runoff would have the highest sediment conveyance. As the effective surface roughness increases for watersheds with more gradual slopes, denser vegetation, or any other circumstances that would retard sediment movement, the sediment delivery ratio versus area relation would decline more rapidly than for steep, row-crop land, to the point where the sediment enters an efficient drainageway. Then the relationship parallels the other curves. These concepts are illustrated in figure 7. In western Iowa, there is a wide variation in the size of watersheds draining into well-defined and efficient channels; the average is between 30 and 50 acres.

Figure 7.--Idealized sediment delivery differences between row crop and pasture watersheds in western Iowa.

The divergence of the sediment delivery curves of figure 7 does not seriously affect the accuracy of sediment predictions based on the sediment delivery method. The preponderance of sediment produced by the sheet-rill erosion process will be from row crop fields, and the use of a row-crop sediment delivery ratio in mixed-cover watersheds will result in only a minor sediment yield overestimate if not corrected. This statement is substantiated by table 3, where measured sediment yields for conservation watersheds 3 and 4 near Treynor are compared with sediment yields from contour-corn watersheds 1 and 2, 1965-1971.

TABLE 3.--Average annual sediment yield, according to erosion source, from Treynor, Iowa watersheds, 1965-1971

Watershed Number	Overland Runoff inches	Sediment Yield		
		Sheet Erosion Source, t/a	Gully Erosion Source, tons	Total t/a
Contour corn, W-1	4.80	26.7	501	33.4
Contour corn, W-2	4.45	20.9	389	25.5
Bromegrass pasture, W-3	1.75	.3	40	.6
Level-terraced corn, W-4	.67	.9	2	.9

Watershed 3 is a 107-acre, bromegrass pasture. Watershed 4 is level terraced and planted to continuous corn. Annual sediment yields from sheet erosion sources at watersheds 1 and 2 averaged more than 20 tons per acre; they were less than 1 ton per acre at watersheds 3 and 4. Gully erosion, which was not considered in the foregoing discussion, averaged 20 percent of the total for the 8-year period.

Summary

A 7-year study of the four loessial watersheds in western Iowa shows much variability of sediment movement. Sediment yields for most years were profoundly influenced by one or two rainstorms, and the 1965-1971 erosivity of rainfall was 180 percent of normal. These findings help to explain some of the variation noted in sediment delivery ratios obtained by short-duration reservoir sedimentation and streamflow sampling studies.

Sediment yields from sheet-rill erosion sources averaged about 80 percent of the total sediment yield; erosion from gullies accounted for the remaining 20 percent. The annual sediment yields from sheet-rill erosion ranged from less than 1 ton per acre on conservation watersheds to 99 tons per acre for a 75-acre, continuous-corn watershed planted on approximate contour.

Sediment yield predictions for ungaged watersheds in the loess soil region can be made on the basis of the sediment experience from Treynor and from other reservoir sedimentation and streamflow sediment measurements, using several of the standard techniques cited. But accurate quantitative predictions would still require a special clairvoyance and considerable judgment. We suggest improvement in the much-used sediment delivery technique as a needed step toward the development of a viable watershed sediment model and for better prediction of sediment movement on loessial watersheds.

For example, although the present Universal Soil Loss Equation is an excellent base for a watershed sediment model, which would be improved by adding an antecedent soil moisture factor, a more complete description of the rainfall erosivity and cropping factors would also be desirable. In conjunction with this modified soil loss equation, a group of terms must be introduced that will express the sediment conveyance/roughness characteristics of the watershed surface. The cropping factor of the Universal equation, for example, may adequately express sheet-rill erosion rates from a small plot, but the efficiency with which these eroded sediments are transported across a watershed surface is unrelated to the erosion process and is presently not accounted for. Similarly, the relief, slope, slope length, surface flow obstructions, watershed size, and drainage densities are all attributes that affect sediment conveyance on a watershed.

A practical, long-range goal for obtaining sediment yield estimates for ungaged watersheds will be the use of watershed sediment models based on sediment delivery concepts. Existing photogrammetric techniques can already produce topographic maps via digital readout from stereoplotters by automated procedures. When such information is combined with climatic and land management variables, it should provide a maximum insight into sediment movement processes and should result in more accurate sediment yield predictions.

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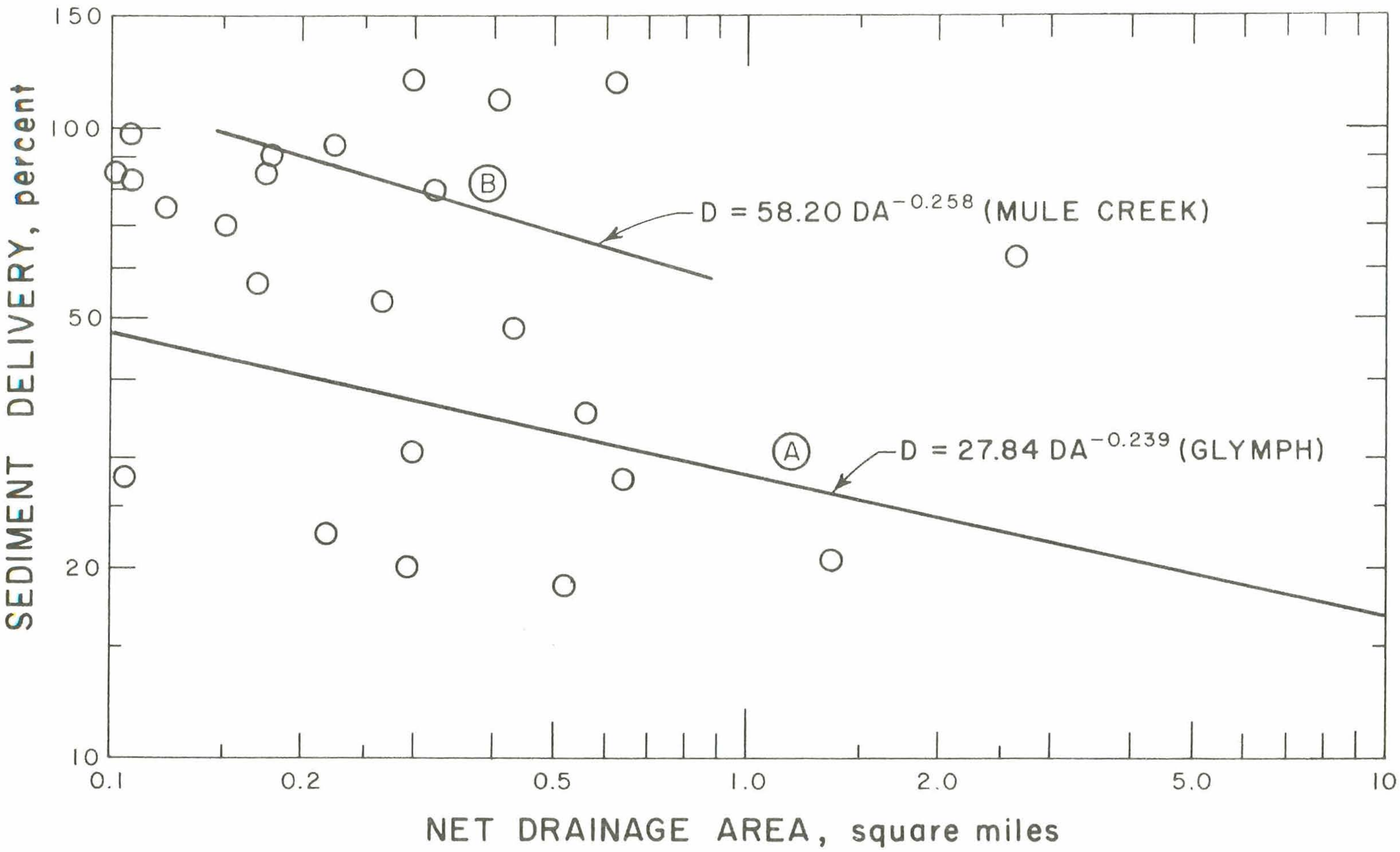
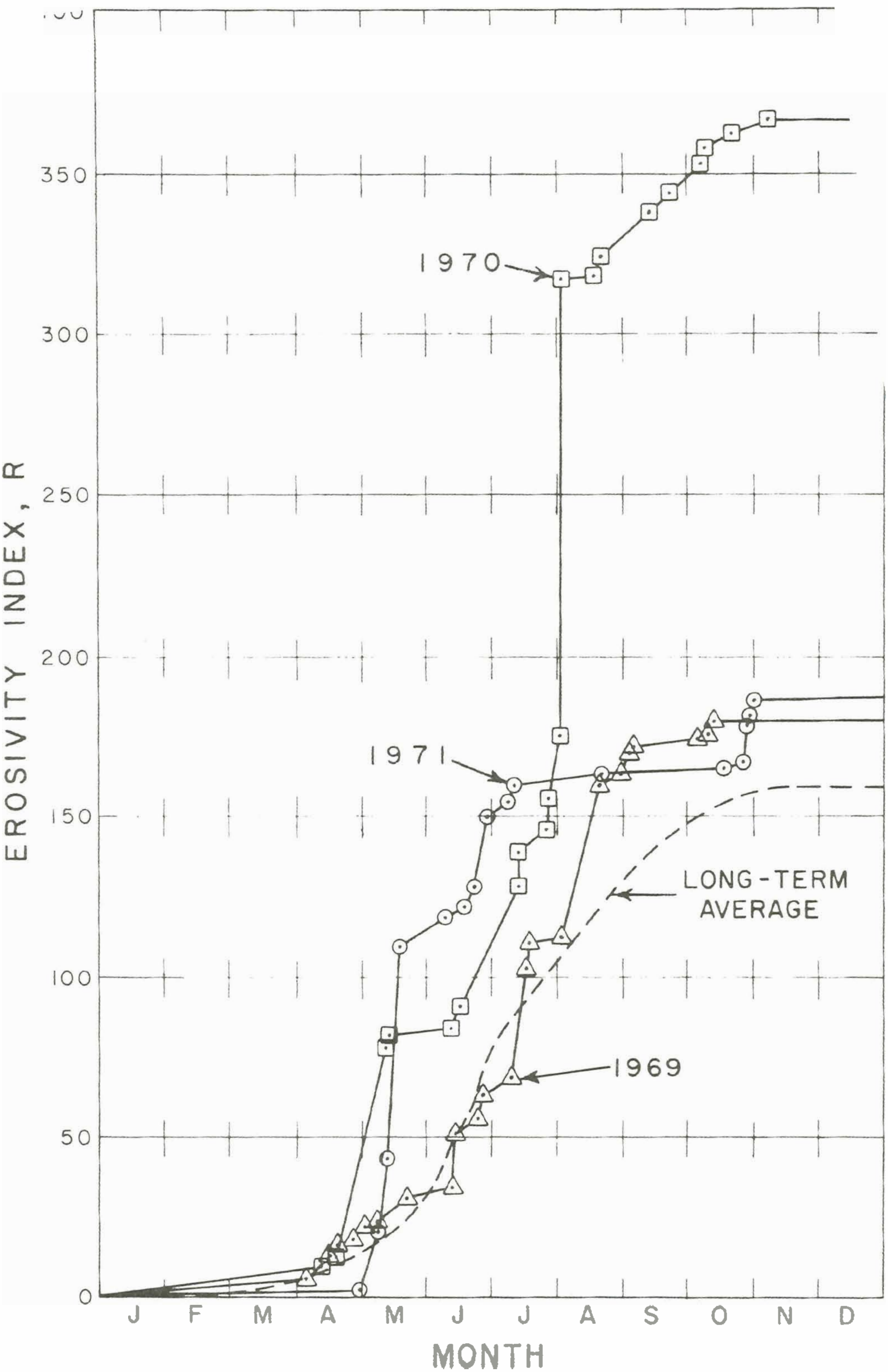


Figure 1.--Comparison of computed sediment delivery percentages for 24 reservoir watersheds with curves developed from reservoir data from eastern Nebraska and western Iowa after Beer, et al. (1).



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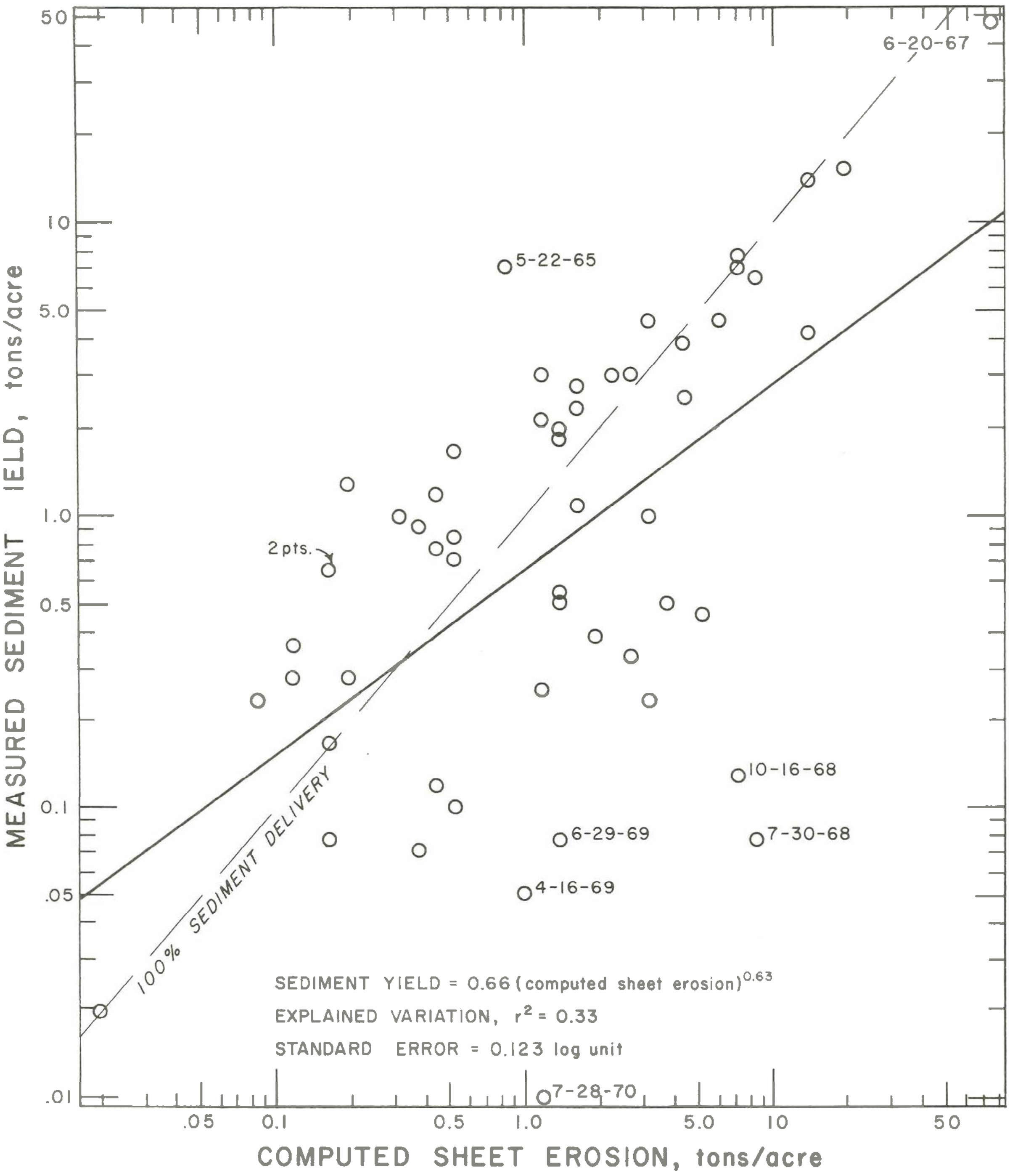


Figure 3.--Comparison of erosion rates and sediment yields from sheet-rill erosion source for 52 well-sampled events on contour-corn watershed 1.

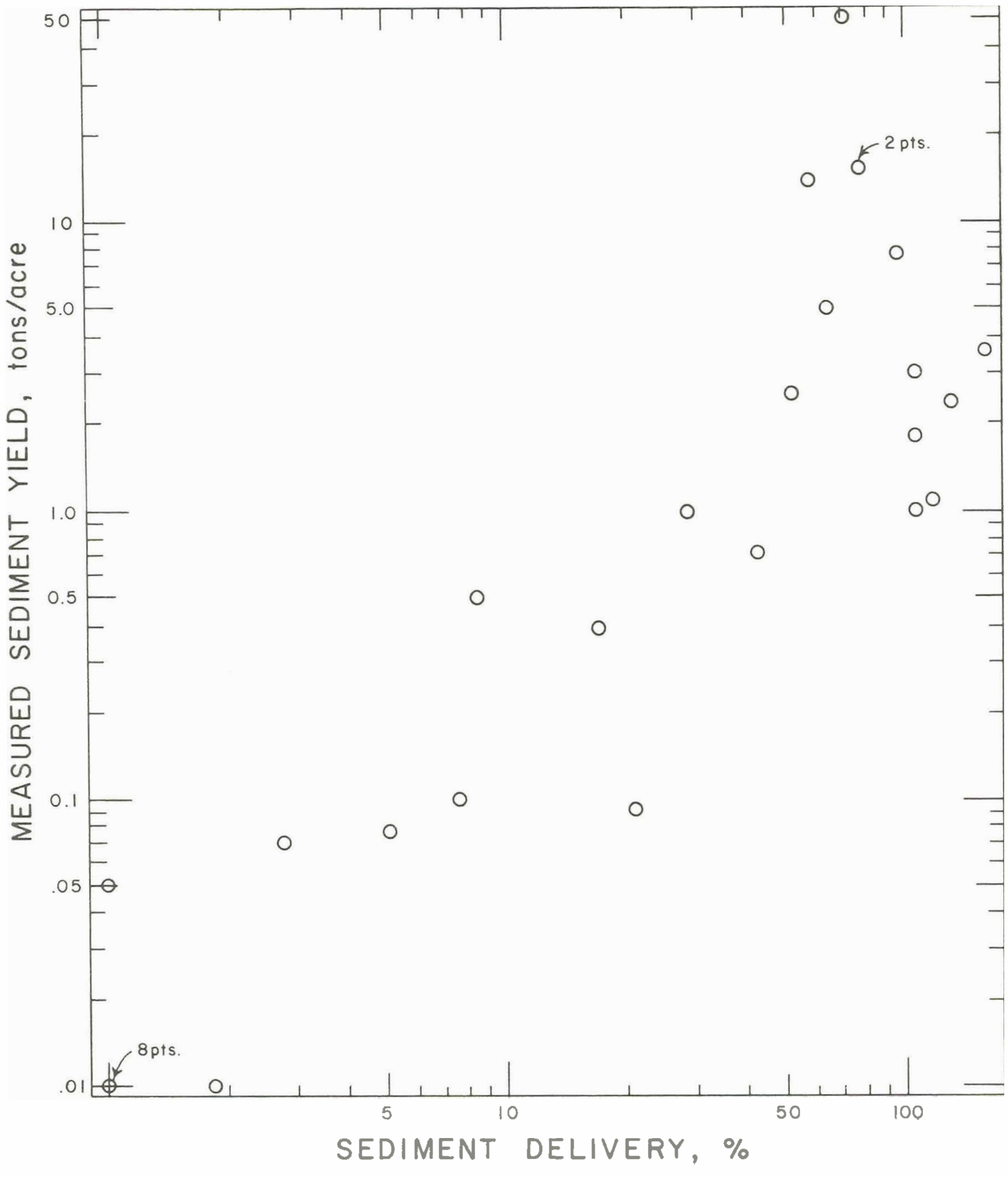


Figure 4.--Sediment delivery variation with sediment yield for 31 June storms occurring from 1965-1971 at contour-corn watershed 1.

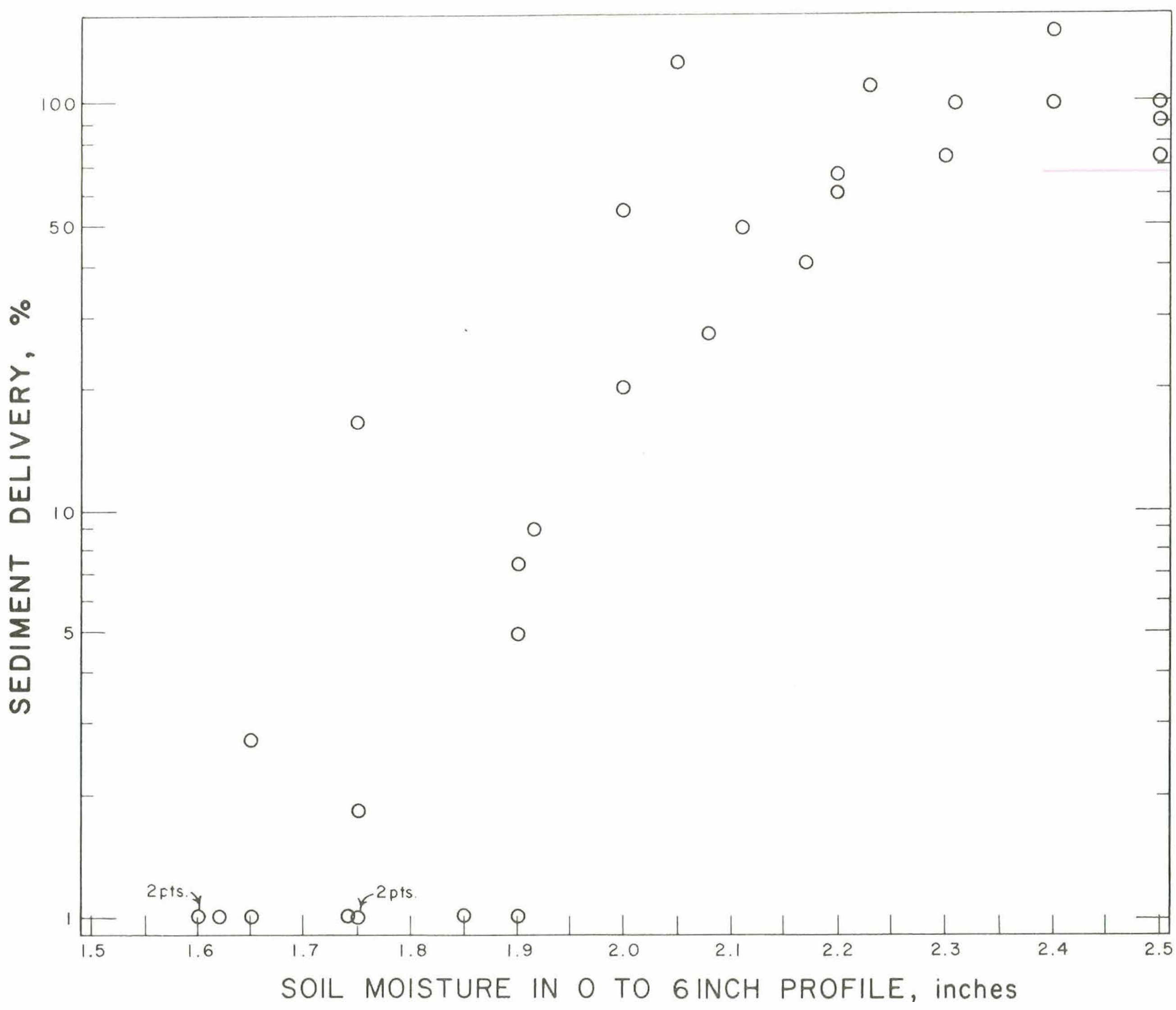
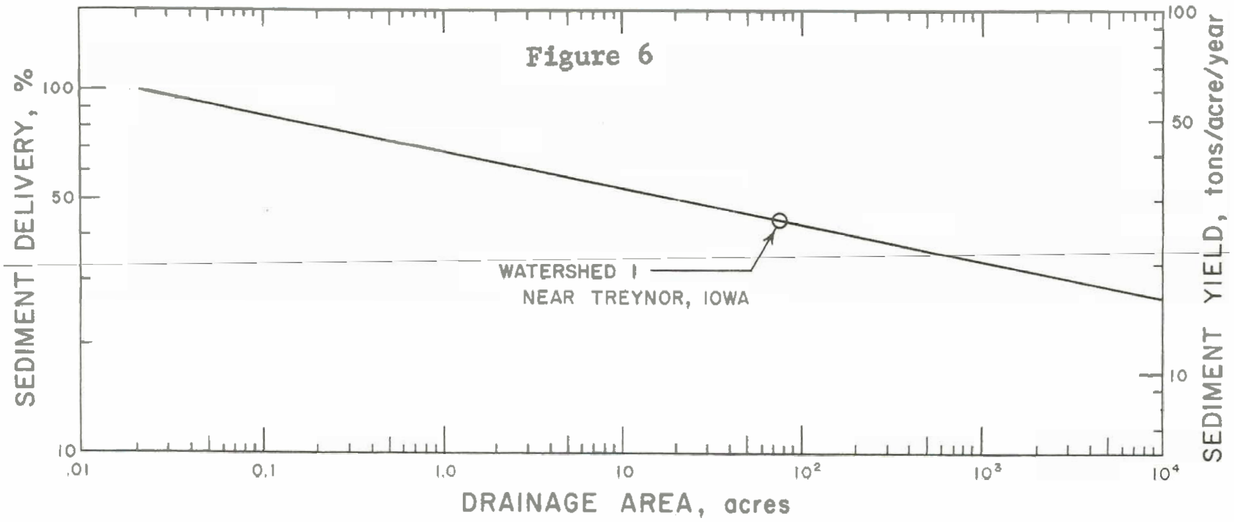


Figure 5.--Sediment delivery variation with antecedent soil moisture level 31 June storms on contour-corn watershed 1, 1965-1971.



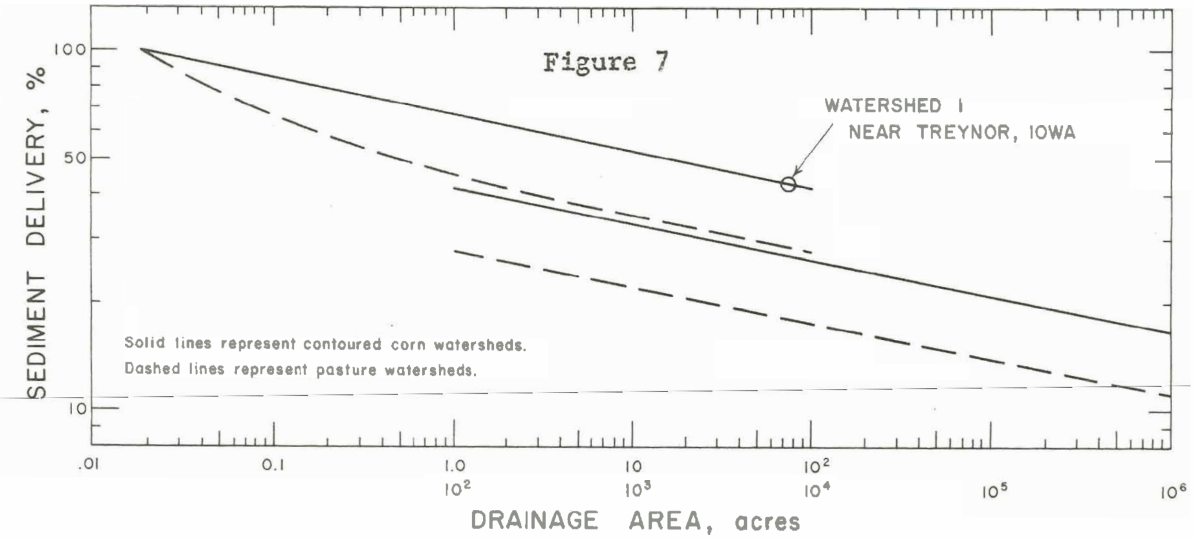


Figure 6.--Probable drainage area relation with sediment yield and delivery, considering only sheet-rill erosion sources, from Iowa cornfields with an average 9-percent slope.

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