Erosion + Sed. - Gen.
Gully Erosion

MECHANISMS OF EROSION AND SEDIMENT MOVEMENT FROM GULLIES

by

R. F. Piest, J. M. Bradford, and R. G. Spomer

Presented at

SEDIMENT YIELD WORKSHOP

Oxford, Mississippi

November 28-30, 1972

Interpretive Summary

MECHANISMS OF EROSION AND SEDIMENT MOVEMENT FROM GULLIES

by

R. F. Piest, J. M. Bradford, and R. G. Spomer

The study involves four watersheds, 74 to 150 acres in size, which drain into incised channels. Overall gully erosion rates for the 7-year record were one-fifth of the total. Gully erosion rates were dependent upon the ability of the headcut and channel banks to weather and thereby furnish soil debris for transport. Cleanout of this debris is necessary for continued production of soil debris by bank sloughing and associated processes. The runoff regime at the two nonconservation watersheds is more than adequate to sustain the cleanout process--but there is abundant evidence that the flowing or tractive forces exerted by runoff on the channel boundary are not an effective erosive force.

The ultimate shapes of the study gullies are governed by the depth to glacial till and the expected flow regime.

Variables thought to influence gully stability, such as antecedent soil moisture and well levels and the fluctuation of these levels, were not well correlated with storm gully erosion rates.

MECHANISMS OF EROSION AND SEDIMENT MOVEMENT FROM GULLIES[1]

by

R. F. Piest, J. M. Bradford, and R. G. Spomer[2]

Introduction

Gully erosion occurs in most locations where an erodible soil mantle is exposed to concentrated runoff from rainfall, melting snow, or both. The identifying characteristic of an active gully is an erosional scarp, usually steep sided and several feet high. Gullies can form continuous or intermittent channels. In the Central States they may occur on the perimeter of upland fields and actively advance into the fields. Many of the gullies in northern Mississippi lack drainage areas above the gully rim but are eroded by rainfall, runoff, and associated weathering forces occurring on the gully itself. By contrast, valley head gullies (sometimes called valley trenches) of the Great Plains and the arid, Western United States are often located on ephemeral stream that drain large areas.

Peterson[3] and other early researchers discussed causes for the formation of gullies in valleys of the Central and Western

---

[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, USDA ARS, Columbia, Missouri; Soil Scientist, USDA ARS, Columbia, Missouri; and Agricultural Engineer, USDA ARS, Council Bluffs, Iowa, respectively.

[3] Peterson, H. V. In Trask, P. D. (ed.), Applied Sedimentation, John Wiley and Sons, 1950.

United States. The term "accelerated erosion" was used because land use (misuse) caused by tilling, grazing, roadbuilding, and other activities of man was widely believed to be an important factor affecting gully erosion rates. The cyclic theory of gullying was also widely accepted. Geologists have noted at many locations that some present-day gullies are eroding in drainageways that were previously eroded and filled because of climatic changes or other disturbances to the hydraulic regime in the geologic past. Although both explanations are plausible, perhaps the only benefits from studies showing the historical and geologic progressions of gullies would be estimates of changes in runoff regime and gully hydraulic geometry associated with channel metamorphosis.

Some of the mechanisms affecting the gully erosion in one region may not be similarly operative in another region. Studies at the North Central Watershed Research Center primarily concern valley head gullies draining field-size areas in the Missouri Valley deep loess region. In this report, we discuss the sediment movement from four of these gullies and explore the mechanisms that seem to affect gully erosion rates.

The Study Area

The depth of the erodible loess mantle that overlies glacial till in the Missouri Valley decreases with distance from the river. In the Agricultural Research Service study area near Treynor, Iowa, the loess cap is more than 80 feet thick on ridges and thins to about 15 feet in the valleys. In this rolling countryside, land slopes vary from less than 4 percent along ridges and valleys to about 15 percent on hillsides. Deep gullies in the valleys are generally incised to, or slightly into, the till. Because the loess soil has a moderate percolation rate and the underlying till is relatively impermeable, a saturated zone occurs above the loess-till interface and causes seepage from channel banks. The effect of this seepage on gully stability has been the subject of much conjecture.

The four study watersheds and outlet drainageways are described in table 1.

TABLE 1.--Watersheds and outlet gullies near Treynor, Iowa

Watershed				Outlet drainageway			
				Scarp			Gully Banks
No.	Size, acres	Crop	Treatment	Condition	Distance to measuring weir, feet		
					1965	1972	
1	74.5	Corn	Field contoured	Advancing & raw	260	420	Eroding
2	82.8	Corn	Field contoured	Non-advancing, raw, & chutelike	690	700	Eroding
3	107	Brome grass	Rotation grazed	Stepped	700	700	Mostly Stable
4	150	Corn	Level terraced	Stepped	850	850	Stable

Instrumentation and Measurements

Gully erosion rates are measured by several procedures. Planimetric mapping from low-altitude aerial photos gives sufficient details of linear advance rate and areal change. Volumetric gully erosion rates have been determined by traditional cross sectioning methods and by photogrammetric procedures.[4] In recent years, targeted, low-altitude photos of the eroding channels have been made annually. However, special efforts have been made to define gully sediment movement at all times during storm runoff; this is accomplished by the dual sampling of streamflow at channel cross sections above and below the gully headcut. Nearly all samples were collected--at 1- to 3-minute intervals during rising water stages and less frequently during the recession--with U.S. DH-48 hand sampler by the equal transit rate (ETR) method. Streamflow samples collected near the runoff-measuring weir located below each gully headcut or scarp represent sediment eroded from both the field and the gully, whereas samples collected above the gully headcut should reflect the quantities of sediment contributed by sheet-rill erosion. The difference between these sediment concentrations and erosion rates is a consequence of erosion originating from both (1) the gully headcut and (2) the channel banks between the headcut and the downstream weir. (In some instances, as illustrated in figure 1, sediment from sheet erosion sources above the gully headcut actually exceeded total erosion downstream and resulted in a net deposition of sediment in the gully. This circumstance was a common occurrence on conservation watershed 4, where

----

Figure 1.--Gully filling due to intense storm on unprotected upland field, watershed 4, June 20, 1967.

---

[4] Aguilar, A. M., and Piest, R. F. photogrammetric techniques for precise measurement of eroding landforms. Unpublished; presented to joint National meeting of American Society of Photogrammetry and American Congress of Surveying and Mapping, Portland, Oregon, 1969.

sediment produced from 12 acres below the level terrace system was deposited and held in the channel by vegetative growth.)

Additional measurements utilized in this gully study include rainfall and runoff amounts and intensities, soil moisture content, ground water levels, and various physical and hydraulic attributes of the watersheds and drainage systems.

Data and Interpretations from Field Study

Gully erosion measurements began in 1964 at Treynor watersheds 1 and 2 and a year later at conservation watersheds 3 and 4. Table 2 summarizes sediment yield from both the upland field and the gullied drainageway for all four watersheds, 1965-1971. Overall, about one-fifth of the total sediment yield resulted from gully erosion.

Gully erosion rates from conservation watersheds 3 and 4 were usually of minor importance. (The most significant gully erosion on a conservation area occurred June 20, 1967, on brome grass pasture watershed 3, where an intense 3.9-inch rainfall on the saturated soil surface caused 2.0 inches of runoff and a loss of 120 tons of soil from the gully.) Table 2 also shows that surface runoff and gully erosion rates were much higher for contour-corn watersheds 1 and 2. These two channels are actively eroding--watershed 1 gully mainly by headcut advance and watershed 2 by lateral erosion of gully banks.

Table 2.--Sediment Yield According to Erosion Source from Treynor, Iowa, Watersheds, 1965-1971

Year	Watershed No.	Annual Precip. Inches	Runoff			Sediment Yield		
			Ground Water	Surface	Total	Sheet-rill Tons/Acre	Gully Tons	Total Tons/Acre
			--------Inches--------					
1965	1	45.35	3.56	10.62	14.18	44.1	1,154	59.6
	2	44.34	2.97	10.68	13.65	36.5	656	44.4
	3	44.28	4.62	4.60	9.22	1/ .4	1/ 86	1.2
	4	44.87	10.56	2.51	13.07	1/ .9	1/ 16	1.0
1966	1	20.32	2.54	.65	3.19	6.7	93	7.9
	2	20.53	2.40	.88	3.28	8.6	177	10.7
	3	22.01	2.54	.38	2.92	1/ .1	1/ 10	.2
	4	21.88	5.91	.19	6.10	.6	14	.7
1967	1	38.25	2.27	11.57	13.84	99.0	1,455	118.6
	2	37.61	2.50	10.45	12.95	75.2	1,374	91.8
	3	34.23	3.30	2.65	5.95	.6	120	1.7
	4	34.55	7.28	.73	8.01	2.9	2/ - 23	2.7
1968	1	32.30	1.67	1.15	2.82	3.7	104	5.0
	2	32.50	1.82	1.13	2.95	4.1	43	4.6
	3	31.10	1.59	1.02	2.61	.2	13	.3
	4	32.18	4.23	.12	4.35	.3	2	.3
1969	1	31.42	3.18	2.53	5.71	1.8	118	3.4
	2	31.54	2.97	2.35	5.32	1.1	55	1.7
	3	30.64	3.29	1.73	5.02	.1	19	.3
	4	30.70	6.11	.27	6.38	.1	- 5	.1
1970	1	31.51	2.21	2.14	4.35	11.8	177	14.0
	2	30.82	2.35	1.79	4.14	7.4	171	9.5
	3	28.86	2.19	.37	2.56	< .1	5	.1
	4	28.79	3.99	.13	4.12	.1	< 1	.1
1971	1	28.93	2.06	4.94	7.00	20.0	399	25.4
	2	29.02	2.62	3.84	6.46	13.3	241	16.2
	3	29.70	2.84	1.52	4.36	1/ .4	1/ 30	.6
	4	29.96	5.49	.71	6.20	1/ 1.5	1/ 6	1.6
Averages (1965-1971)	1	32.58	2.50	4.80	7.30	26.7	500	33.4
	2	32.34	2.52	4.45	6.96	20.9	388	25.5
	3	31.54	2.91	1.75	4.66	.3	40	.6
	4	31.85	6.22	.67	6.89	.9	2	.9

1/ Division between sheet-rill and gully erosion estimated.
2/ Negative value indicates channel fill.

Figures 2a and 2b show, respectively, an aerial view of the channel system and a close-up of the gully headcut at watershed 1. The areal growth of this gully from 1965 through 1971 is portrayed in figure 3 by survey period; surface runoff and gully erosion rates for these periods are also tabulated.

Figure 2.--(a.) Aerial view of watershed 1 outlet drainageway, showing sampling footbridges and measuring weir; and (b.) Close-up of gully headcut area, showing upstream drainageway at left, failed soil mass, and seepage.

Figure 3.--Measured gully advances and erosion rates on watershed 1 near Treynor, Iowa.

Gully erosion rates at watershed 2 were nearly as great as those at watershed 1, even though little material was removed from the vicinity of the headcut; the major sediment source was the eroding gully bank in the 700-foot channel reach between the headcut and the runoff-measuring weir. Figure 4a shows gully erosion rates at watershed 2 during the

Figure 4.--(a.) Gully erosion rate from 700-foot length of channel at watershed 2, June 20, 1967; (b.) Gully erosion rate, storm of May 25, 1965, at watershed 1; and (c.) Gully sediment discharges during the first large runoff event of 1971 at watershed 1.

record rainstorm of June 20, 1967. These rates were computed from 20 streamflow samples collected above the gully headcut, 17 streamflow samples collected at the downstream cross section, and known runoff rates provided by continuous water stage records and a calibrated weir stage-discharge relationship. During this storm, 690 tons of soil was eroded from the gully. The gully erosion rate during the most erosive period of the storm was 50 tons per minute.

An examination of gully sediment concentrations and discharges during the course of runoff events showed that at least two general conditions are necessary to cause gullying.[5/] Soil debris must exist and runoff must be sufficient to entrain and transport this debris. In the preceding sections, we have dealt with the total gully erosion process in a general manner; however, in a closer examination of the mechanics of gully erosion, it is necessary to distinguish between the two subprocesses of debris cleanout and renewed debris production. It is sometimes impossible to separate the effects of important variables on these two subprocesses, and this has impeded the study of the mechanics of gullying.

If gully soil debris is produced predominantly by the shearing forces of flowing water, these forces are also sufficient to entrain and transport this fine-grained loessial debris through the channel system. However, evidence at both watersheds 1 and 2 indicates that the shearing or tractive forces on the channel boundary are not the major forces

---

[5/] Piest, R. F., and Spomer, R. G. sheet and gully erosion in the missouri valley loessial region. Trans. of ASAE 11 (6): 850-853, 1968.

causing gully erosion. Aside from the visual evidence of gully head and gully bank deterioration as shown in figure 2b, gully sediment concentrations and discharges of individual storm events often reached a maximum soon after surface runoff began but rapidly decreased before the peak of storm runoff. In some cases, there was a period near the runoff peak when the supply of soil debris in the gully was exhausted and the transport of gully materials was essentially zero (figure 4b). The sediment discharge curve of figure 4b is based on 30 streamflow samples. Figure 4c shows the gully sediment discharge at watershed 1 for one of the runoff events of May 10, 1971, when the gully sediment concentration curve was defined by 32 samples. This was the first large runoff event of the year. Because it was preceded by minor runoff, there were brief periods at the outset of the storm when there was no gully erosion. Temporary gully cleanout occurred on the hydrograph recession before a runoff rate of about 30 cfs. Had tractive force on the channel boundary been the predominant eroding agent during these storms, either by direct shear on the channel boundary or by bank undercutting, a discharge of gully sediments approximately proportional to the square of stream velocity would have occurred and zero transport of gully sediments at significant discharges would not have been experienced.

Sediment transport curves (figure 5) for four successive runoff

---

Figure 5.--Sediment transport relations for successive runoff events of September 7, 1965, watershed 1, near Treynor, Iowa: (a) first event, (b) second event, (c) third event, and (d) fourth event.

---

events at watershed 1 represent the concentration and rate of movement of gully materials with respect to rate of runoff. Sediment concentration graphs were constructed on the basis of numerous streamflow samples, and gully sediment discharges were computed from these graphs. Characteristics of such curves can be summarized from the study of many of these individual sediment transport curves. For example:

1. The overall relationship of gully sediment discharge (and concentration) to runoff during any time interval during a storm indicates the availability of gully debris. Generally, dry conditions prior to an event cause higher placement of the upper limb of the curve (higher gully sediment concentrations) and increase vertical distance between limbs (figure 5a).
2. Cleanout of the gully channel, evidenced by a "break" in the loop in the downward direction, occurs more often when wet conditions exist before a given storm (figure 5c).
3. Renewed erosion, usually caused by sloughing of wetted gully banks, often occurs after the peak of runoff. This is identified on the sediment transport curve by a sharp upward trend. This condition has been noted in other loess areas by the senior author, who has sampled loessial streams at night while suspended from a 40-foot-high overhead cable and has relied on the sound of massive bank segments crashing into the water to indicate that the water stage was beginning to fall.

The effect of prior moisture conditions on gully erosion rates is illustrated by the sediment transport curves for the four successive events of figure 5. Numerical entries on the lower curve of each graph denote 24-hour clock time. Note that debris cleanout was not affected until early in the third runoff event, and bank sloughing occurred just before 4:31 a.m. and again after 4:39 a.m. A comparison of events 1 and 4, which have similar runoff rates, dramatizes the effect of debris cleanout; the gully sediment concentration exceeded 50,000 ppm for the first event but did not exceed 15,000 ppm during the fourth event because debris supply was limited.

Additional insights into processes that affect gullying at Treynor can be obtained by referring to the composite, 7-year streamflow sample record for the two locations at the outlet of watershed 1. The 1,042 streamflow samples of figure 6a were collected just above the retreating gully head; the 1,653 samples of figure 6b were collected downstream from the gully head. All of the runoff that reached the downstream sample point also passed over the gully headcut, except for the small portion generated by rain falling in the gully. Statistics of the relationship, including the least squares regressions, are given on the figures. The same least squares analysis for watershed 2 (not shown)

Figure 6.--(a.) Sediment transport relation representing sheet-rill erosion at watershed 1; and (b.) Sediment transport relation representing sheet-rill and gully erosion at watershed 1.

---

results in the equations $Q_s = 11.6\ Q_w^{1.64}$, $R^2 = 0.89$ (upstream from headcut) and $Q_s = 30.7\ Q_w^{1.53}$, $R^2 = 0.94$ (downstream from headcut). In each case, the sediment discharge, Q_s, is in lbs/min and water discharge, Q_w, is in cfs. The difference between the curves of figures 6a and 6b gives the overall relation between gully erosion and runoff rates for the period of record, because it reflects all sample data. The net relation between gully sediment discharges and runoff rates for watersheds 1 and 2 is given in figures 7a and 7b, respectively.

Figure 7.--(a.) Sediment transport relation for gully of watershed 1, based on 2,700 streamflow samples; and (b.) Sediment transport relation for gully of watershed 2, based on 2,500 streamflow samples.

The trend lines shown were derived from the forced linear fit of data, such as figures 6a and 6b, and a more correct curve-fitting procedure by which all values of the dependent variable were averaged for successive, small increments of the independent variable and a best fit curve drawn through these group averages.[6] In either procedure, the shapes of the resulting curves (figure 7) and the basic conclusions to be drawn from a comparison of the curves are not significantly changed. That is, the gully sediment discharge curve defined by samples for watershed 1 is not as steep as that for watershed 2, and the concentration at watershed 1 increases to a peak value at intermediate runoff rates and decreases thereafter. The watershed 2 gully

---

[6] ASCE Task Committee on Preparation of Sedimentation Manual, Committee on Sedimentation of the Hydraulics Division. sediment measurement techniques: Chapter IV, Sediment Sources and Sediment Yields. Jour. of Hydr. Div. 96 (HY6): 1283-1329, Proc. Paper 7337, 1970.

sediment concentration, by contrast, increases throughout the entire range of runoff. Curve 7a, for the gully of watershed 1, represents and actively eroding headcut and an average 350-foot channel (table 1), and curve 7b, for the gully of watershed 2, represents a slightly eroding headcut and a 700-foot channel; therefore, we can conclude that the sustained gully sediment concentrations of watershed 2 originate from the channel bank. Conversely, headcut erosion at watershed 1 is not enough to sustain a high rate of increase in gully sediment transport as would be expected if tractive forces were mostly responsible for headcut erosion. The stabilization and decrease in gully sediment concentration with increasing runoff at watershed 1 are a consequence of cleanout of headcut materials at moderate runoff rates.

The foregoing conclusion--that gully sediment-runoff relations differ according to whether gully head or gully bank erosion is occurring--is also verified if gully erosion is considered on a storm-event basis. Each of the plotted points of figure 8 represents a

----

Figure 8.--Storm runoff versus runoff-weighted sediment concentration from gully erosion, using all well-sampled runoff events at watershed 1. 1965-1971.

----

single storm that was adequately sampled. (For the 7-year period, 1965-1971, this included 52 events at watershed 1.) That is, dual sediment concentration graphs, derived from streamflow samples collected (1) upstream and (2) downstream from the gully headcut, were well defined. The sediment discharge that originated from the gully was then calculated; this storm gully discharge, divided by the storm runoff and the appropriate conversion constant, is termed a runoff-weighted gully sediment concentration. Figure 8 shows considerable scatter in gully sediment concentration for watershed 1 storm events, and statistical analyses show that sediment concentration is not well correlated with runoff, although the same slight trend of decreasing concentration with increasing runoff is apparent. This is to be expected, since the concentration curve of figure 7a for the watershed 1 gully does not consistently increase with increasing runoff rate.

Sediment concentration is usually considered to be a better erosion indicator than sediment discharge for testing with erosion-causing variables, primarily for two reasons.

1. The product of runoff and sediment concentration is sediment discharge, so there is a statistical bias built into any relationship that may be runoff correlated.
2. Runoff is not a basic variable. Because it is usually well correlated with the erosion parameter, its use tends to mask the effect of more subtle basic environmental variables.

The objective of this study was to obtain a gully erosion relationship for predictive purposes as well as to isolate variables causing erosion, so both gully sediment concentrations and sediment discharges of watersheds 1 and 2 were examined. Figures 9a and 9b show the log linear

---

Figure 9.--(a.) Relationship between runoff and gully sediment discharge, by storm, at watershed 1, 1965-1971; and (b.) Relationship between runoff and gully sediment discharge, by storm, at watershed 2, 1965-1971.

---

relationships between gully sediment discharge and runoff, on a storm basis, for watersheds 1 and 2, respectively. At watersheds 1 and 2, storm runoff volume alone was sufficient to explain 70 and 78 percent, respectively, of the variation in storm gully erosion rate. However, the accuracy of prediction was not especially good. In round numbers, the actual sediment discharge for a storm of known runoff volume will be 50 to 200 percent of the predicted value two out of three times. This information has even less value when applied to another gully.

To improve the prediction equations and to examine the effect of environmental factors on gully erosion, the following variables were tested for 52 well-sampled storms at watershed 1 and for 41 well-sampled storms at watershed 2.

1. Peak storm runoff, inches per hour.
2. Average soil moisture before each storm in the 2- to 6-foot profile, inches. These were determined from approximately weekly readings at six sites on the two watersheds.
3. Change in these soil moisture levels from storm to storm, inches.
4. Ground water well level before each storm for a single well near each gully head, feet. These were based on well level recorders during part of the study and periodic tapedowns for the remainder of the time.
5. Change in well levels from storm to storm, feet.
6. Change in well level from the April 1 well level, feet.
7. Season. Each storm was represented by the Julian date on which it occurred. Snowmelt data were excluded.

8. Time. Each storm was represented by the numerical day of the period beginning with January 1, 1965.
9. Time, hours, since prior precipitation event which exceeded one-half inch.
10. Time, hours, since prior event which exceeded 0.01 inch of runoff.
11. Time, hours, since prior event when runoff peak exceeded 0.5 cfs.

These variables were selected because the weathering of gully walls and headcut is logically related to moisture and seasonal changes occurring between rainstorms.

Stepwise, multiple regression-correlation computer analyses were made using these variables. For some analyses, runoff amount, peak rate, and time were deleted because they proved to be best correlated and probably masked the effectiveness of other intercorrelated variables. A brief summary of the attempt to define variables influencing gully erosion is given here for watershed 1.

Dependent Variable	Variables Tested	Explained Variation, R^2
Gully Sediment, storm tonnage	Storm Runoff Volume	0.70
"	All	.79
"	All except runoff volume and peak	.21
"	All except time	.76
"	All except time, runoff volume, and peak	.21
Gully Sediment, storm concentration, ppm	Runoff Volume	.24
"	All	.43
"	All except runoff volume and peak	.18
"	All except time	.09
"	All except time, runoff volume, and peak	.09

Results of these tests show that the expressions used to represent environmental factors do not greatly improve the relation between runoff and gully erosion. This is puzzling because other techniques show the erosion effectiveness of successive storm events to be drastically different.

For example, consider the successive storm events of May 6, 10, and 18, 1971, at watershed 1, which were very well sampled. Runoff-duration information for these storms is in table 3, and the gully erosion rates are computed using the average runoff-sediment discharge relation of figure 7a. These computed values were compared with measured gully erosion rates for the same storm. The May 6 storm was the first significant runoff event of 1971, and the May 18 storm occurred near the end of a wet period. Table 3 shows that the runoff-weighted sediment concentration of streamflow that is due to gully erosion is greater for the May 10 storm (16,100 ppm) than for the May 18 storm (3,700 ppm). The May 6 gully sediment concentration was highest at 20,200 ppm. This decrease in concentration with time was almost certainly caused by clean-out of existing gully debris and the occurrence of the May 10 and 18 storms before much additional debris could accumulate.

With average antecedent conditions as represented by the curve of figure 7a. the same runoff that occurred May 6 would be expected to produce 30 tons from the gully instead of the measured 58 tons, at a concentration of 10,400 ppm instead of 20,200 ppm. By contrast, the high rainfall and runoff of May 18 would be expected to erode 153 tons from

Table 3.--Gully Erosion for Successive Storms, Comparing Actual Measured Rates with Computed Rates Based on Average Antecedent Conditions at Watershed 1

Runoff Interval cfs	Duration Min.	Mean Runoff Rate cfs	Mean Gully Erosion Rate Lbs/Min	Gully Erosion Lbs.	Runoff Interval cfs	Duration Min.	Mean Runoff Rate cfs	Mean Gully Erosion Rate Lbs/Min	Gully Erosion Lbs.	Runoff Interval cfs	Duration Min.	Mean Runoff Rate cfs	Mean Gully Erosion Rate Lbs/Min	Gully Erosion Lbs.
May 6, 1971					May 10, 1971					May 18, 1971				
0-.1	942	0.05	0.4	377	0-.1	936	0.05	0.4	374	0-.1	568	0.05	0.4	227
.1-.5	225	.3	5.5	1,238	.1-.5	156	.3	5.5	858	.1-.5	379	.3	5.5	2,084
.5-1.0	63	.75	18	1,134	.5-1.0	61	.75	18	1,098	.5-1.0	110	.75	18	1,980
1-2	37	1.5	44	1,628	1-2	68	1.5	44	2,992	1-2	126	1.5	44	5,544
2-3	24	2.5	81	1,944	2-5	47	3.5	123	5,781	2-5	45	3.5	123	5,535
3-4	21	3.5	123	2,583	5-10	26	7.5	305	7,930	5-10	24	7.5	305	7,320
4-5	23	4.5	165	3,795	10-15	12	12.5	550	6,600	10-20	82	15	680	55,760
5-6	19	5.5	210	3,990	15-20	19	17.5	810	15,390	20-40	32	30	1,490	47,680
6-7	20	6.5	255	5,100	20-25	19	22.5	1,080	20,520	40-60	10	50	2,540	25,400
7-9	18	8	330	5,940	25-30	22	27.5	1,350	29,700	60-80	5	70	3,520	17,600
9-11	16	10	430	6,880	30-35	16	32.5	1,620	25,920	80-100	4	90	4,500	18,000
11-13	12	12	530	6,360	35-40	14	37.5	1,890	26,460	100-120	2	110	5,450	10,900
13-15	6	14	630	3,780	40-45	10	42.5	2,150	21,500	120-140	3	130	6,350	19,050
15-18	2	16.5	760	1,520	45-50	5	47.5	2,410	12,050	140-160	2	150	7,150	14,300
18-21	3	19.5	910	2,730	50-60	5	55	2,780	13,900	160-180	2	170	7,950	15,900
21-24	3	22.5	1,080	3,240	60-70	8	65	3,290	26,320	180-200	0	190	8,700	0
24-27	3	25.5	1,240	3,720	70-80	7	75	3,780	26,460	200-220	3	210	9,400	28,200
27-30	2	28.5	1,400	2,800	80-90	2	85	4,250	8,500	220-240	3	230	10,100	30,300
30-33	1	31.5	1,560	1,560	90-100	3	95	4,740	14,220					
					100-110	0	105	5,250	0					
					110-120	1	115	5,650	5,650					
					120-130	1	125	6,100	6,100					
					130-140	2	135	6,550	13,100					
TOTALS				60,319					291,423					305,780
Computed Gully Erosion, Tons				30					146					153
Measured Gully Erosion, Tons				58					186					46
Weighted Gully Sed. Conc., ppm				20,200					16,100					3,700
Runoff, Inches				0.34					1.37					1.47

the gully of watershed 1, instead of the measured 46 tons, if average environmental conditions prevailed. Such differences probably explain much of the scatter in figures 9a and 9b.

To this point, the interplay of basic forces that cause the gully walls to fail eludes us. We have dealt principally with rates of sediment movement from the gully in terms of runoff and similar composite variables that concern the total gully process and have not included physical or mechanical measurements needed for a study of massive soil failures. A recent paper by Bradford, Farrell, and Larson[7/] considers the stability of gully banks by analyzing the forces acting on the soil mass that forms the gully walls. The two-dimensional stability analysis using the Simplified Bishop Method of Slices to calculate critical factors of safety indicates that height of water table, cohesion of soil and rate of water infiltration are controlling factors affecting stability of gully walls.

Any factor that alters the potential resisting forces of the soil (available shearing strength) and the driving forces will influence the failure of the gully walls. The soil-modifying effects of winter freezing and spring thawing--and wetting and drying cycles--influence the soil shearing strength. These weather-caused stresses are difficult to evaluate in a limited field study. The total gully erosion from snowmelt has been negligible on the Treynor watersheds, although much of the damage to

---

[7/] Bradford, J. M. Farrell, D. A., and Larson, W. E. mathematical evaluation of factors affecting gully stability. Approved for publication in Soil Science Society of America Proceedings.

gully banks from freezing and thawing cycles probably contributes to gully growth during the first spring runoff event, as previously shown for watershed 1 on May 6, 1971. Figures 10a and 10b illustrate that snowmelt gully erosion rates are consistently and significantly higher at watershed 1 than at watershed 2, whether the snowmelt occurs on frozen or thawed ground. These erosion differences can hardly be due to differences in tractive force but are probably related to a more erosive plunge pool action on watershed 1. Also, the gully overfall at watershed 1 faces south, and watershed 2 gully head faces west. A south-facing slope is subject to more frequent wetting-drying and freezing-thawing cycles.

Figure 10.--(a.) Gully sediment concentration for event of January 15, 1969, watersheds 1 and 2, frozen topsoil; and (b.) Gully sediment concentration for event of February 25, 1969, watersheds 1 and 2, thawed topsoil.

Concluding Remarks

Neither the geologists' explanation of the cause of gullying nor the limited findings noted herein--that runoff rates at Treynor are the best indicators of gully erosion rates--give much insight into basic erosion mechanisms. But there is some common ground for these findings. The concepts that wetter climatic trends during geologic time (in the midcontinent region) slowed gullying rates and that land abuse in the past dozen decades has accelerated gully erosion are really telling the same story. The balance between runoff and vegetative levels is all important. Langbein and Schumm[8] utilized sediment records to show that erosion levels increase as the climate changes from humid to arid, up to the point where the lessened runoff rates, rather than the deteriorating vegetal cover, would inhibit further increases in erosion. Historic man has, in many respects, created a new climate in which increased runoff rates and decreased vegetal cover combine to accelerate gully erosion.

Surface runoff rates from conservation watersheds 3 and 4 are drastically reduced, compared with watersheds 1 and 2. The channels of these conservation watersheds have responded to treatment by remaining stable, as figure 1 demonstrates. A flow rate of 40 cfs in the gully of watershed 4 did not upset the stable condition, and only a record storm at watershed 3 could cause significant gully erosion there. Apparently, the combination of favorable runoff regimen and suitable channel vegetal cover at these watersheds is sufficient to stabilize the gullies unless some seemingly chance occurrences (or combination of occurrences) take place, such as record runoff, devegetated channel, or critically located rodent burrows.

It would require a significant reduction in surface runoff at watersheds 1 and 2 to bring about stable conditions there, but consider the effect of some conservation practice that would not affect storm runoff volumes but would reduce the runoff rates by one-half and double the flow duration. Based on the sediment transport relationships at these watersheds, a 50-percent runoff-rate reduction would not decrease

---

[8] Langbein, W. B., and Schumm, S. A. yield of sediment in relation to mean annual precipitation. Trans. Amer. Geophys. Union 39 (6): 1076-1084, 1958.

gully head erosion (and would probably increase it somewhat) if the trends of figures 7a and 9a are typical. That this change in runoff would fail to deter gully head erosion is well recognized by farmers who have tried to empty the outflow from small reservoirs gently into a loessial channel and suffered dire consequences. We have ample proof for the statement that gully head erosion can be initiated and sustained by moderate runoff rates once a minimum (but unknown) rate is exceeded.

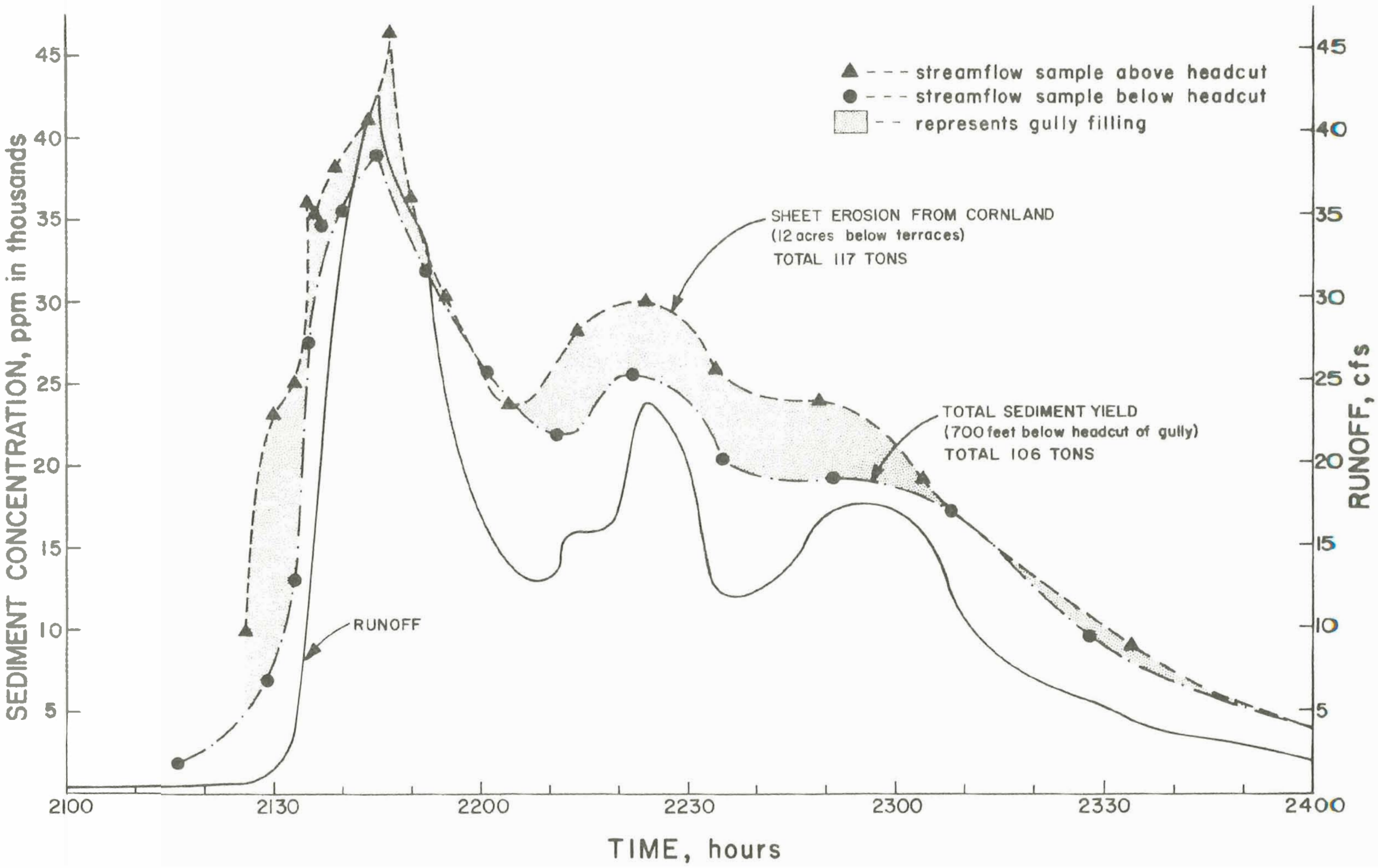
The effect of a 50-percent runoff-rate reduction on channel bank erosion would be great. Based on the experience at watershed 2, as shown by the curves of figures 7b and 9b, we would expect a sizeable reduction in gully erosion rates. The authors' interpretations of the effect of these assumed runoff regimes on gully head and gully bank erosion can be questioned on the grounds that channel debris cleanout has occurred at both locations. Gully bank erosion at Treynor watershed 2 was measured for only a 700-foot channel, however, and active gully enlargement is no doubt occurring over a greater length downstream.

The terminal geometry (final dimensions and slopes) of the gullied channels at Treynor can probably be fixed within close limits for any given channel cross section, because the critical dimension. depth to glacial till, is known. The ultimate width can also be forecast for differing runoff regimes if our present concepts of soil stability mechanisms are valid. Although the depth of bank failure seems related to the location of the seepage plane (see figure 2b), it is likely that the seepage plane does not affect the total masses eroded because the trenching depth is still the governing variable. The effect of gully bank seepage on erosion rates is probably much greater at locations where the trenching depth is not controlled by resistant soil or rock.

Subsurface soil moisture content, well levels, storm antecedent conditions, and seasonal and time trends were tested for correlation with gully erosion rates. Results were not encouraging, possibly because many of the variables may be well correlated with soil slippage mechanisms (which cannot be expressed in this field experiment) but not the sediment removal process. Using a different analytical approach (table 3), the effect of prior moisture conditions for successive rainstorms is clearly illustrated; the May 18, 1971, event with wet prior conditions, for example, caused only one-third of the gully erosion that would occur under average moisture conditions (a measured 46 tons versus a computed 153 tons).

Unstable blocks of soil seem to appear at random along the gully banks in response to unmeasured forces. Our present understanding of the failure sequence is that moisture saturation, mostly by runoff and possibly by a heavy rainfall, causes loss of soil strength and block dislocation by slippage. The importance of this mode of gully bank deterioration and failure has only recently been appreciated by the authors, who have noted the formation of "nickpoints" along channels caused by runoff from tiny drainage areas infiltrating the soil block at the channel edge through heavily sodded grass. Gradual undermining and occasional block overturning accounts for its migration downslope to the point of eventual entrainment. Other mass supply mechanisms may be initiated by streamward displacement of soil blocks caused by lateral pressures released in the gully cutting process--and by shrinkage cracking.

Tractive forces do not play the major role in the erosion of these valley head gullies. That is, the resistance of the channel boundary to erosion exceeds the erosive power of the runoff under most circumstances. The erosive power of runoff plays a minor role in gully growth in the loess study area, except for its relation to transport of eroded bank material--and possibly some plunge pool action.



unprotected Watershed

(a)

(b)

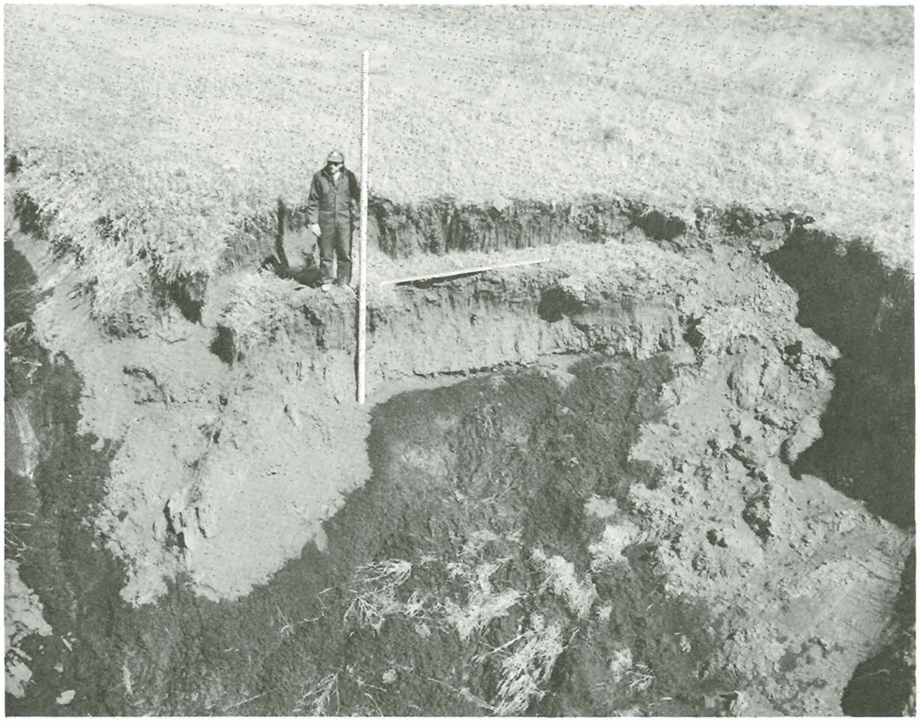
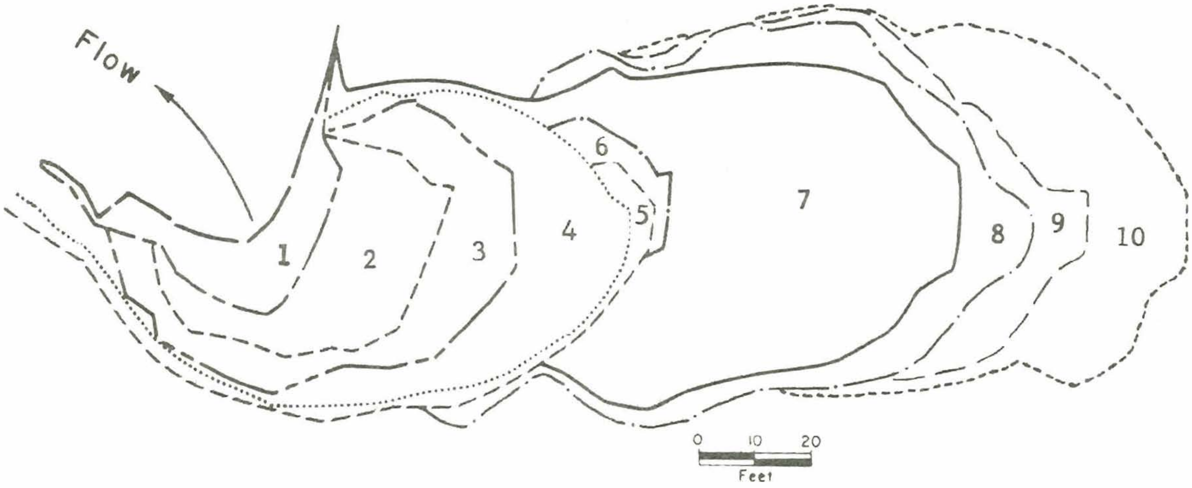


Figure 2.--(a) Aerial view of watershed 1 outlet drainageway, showing sampling footbridges and measuring weir; and (b) Close-up of gully headcut area, showing upstream drainageway at left, failed soil mass, and seepage.



AREA	PERIOD	SURFACE RUNOFF acre-feet	GULLY EROSION tons
1	Nov. 15, 1964-Apr. 14, 1965	25	130
2	Apr. 15, 1965-June 9, 1965	17	510
3	June 10, 1965-Aug. 13, 1965	12	160
4	Aug. 14, 1965-Nov. 15, 1965	14	350
5	Nov. 16, 1965-July 15, 1966	4	90
6	July 16, 1966-May 30, 1967	1	< 10
7	May 31, 1967-June 27, 1967	70	1,440
8	June 28, 1967-Dec. 31, 1969	24	230
9	Jan. 1, 1970-Dec. 15, 1970	13	180
10	Dec. 16, 1970-Dec. 8, 1971	31	400
	TOTALS	211	3,500

Figure 3.--Measured gully advances and erosion rates on watershed 1 near Treynor, Iowa.

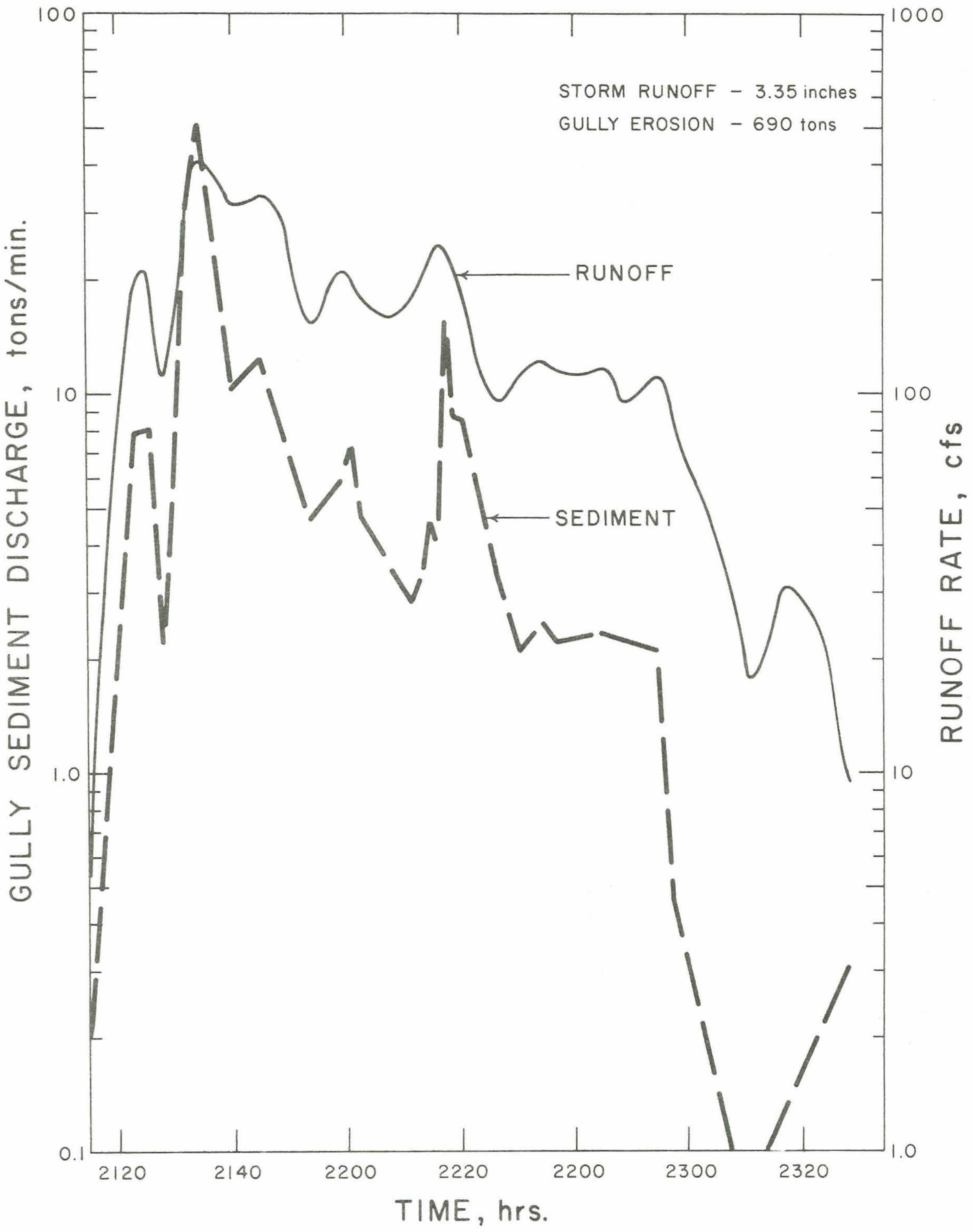


Figure 4.--(a.) Gully erosion rate from 700-foot length of channel at watershed 2, June 20, 1967.

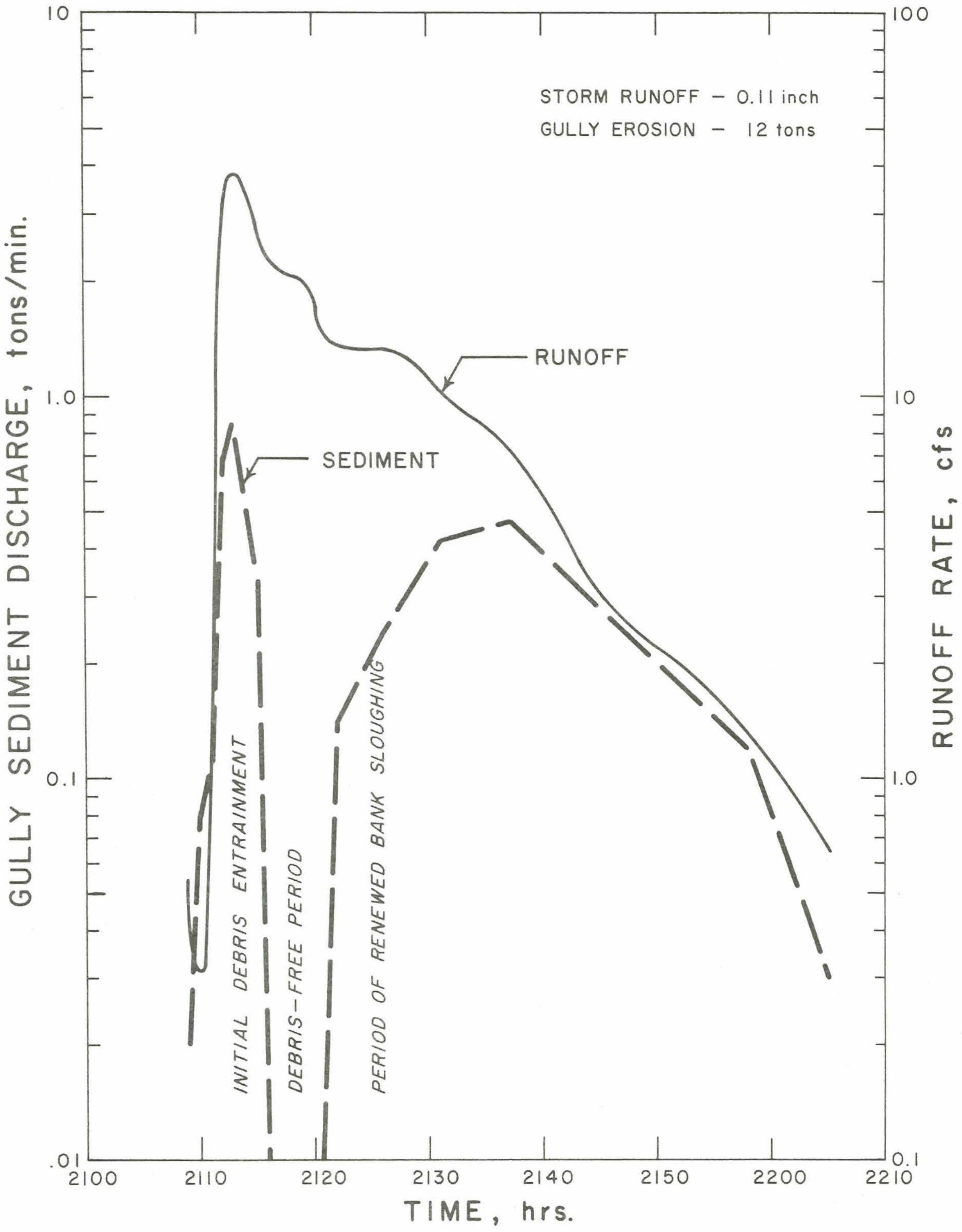


Figure 4.--(b.) Gully erosion rate, storm of May 25, 1965 at watershed 1.

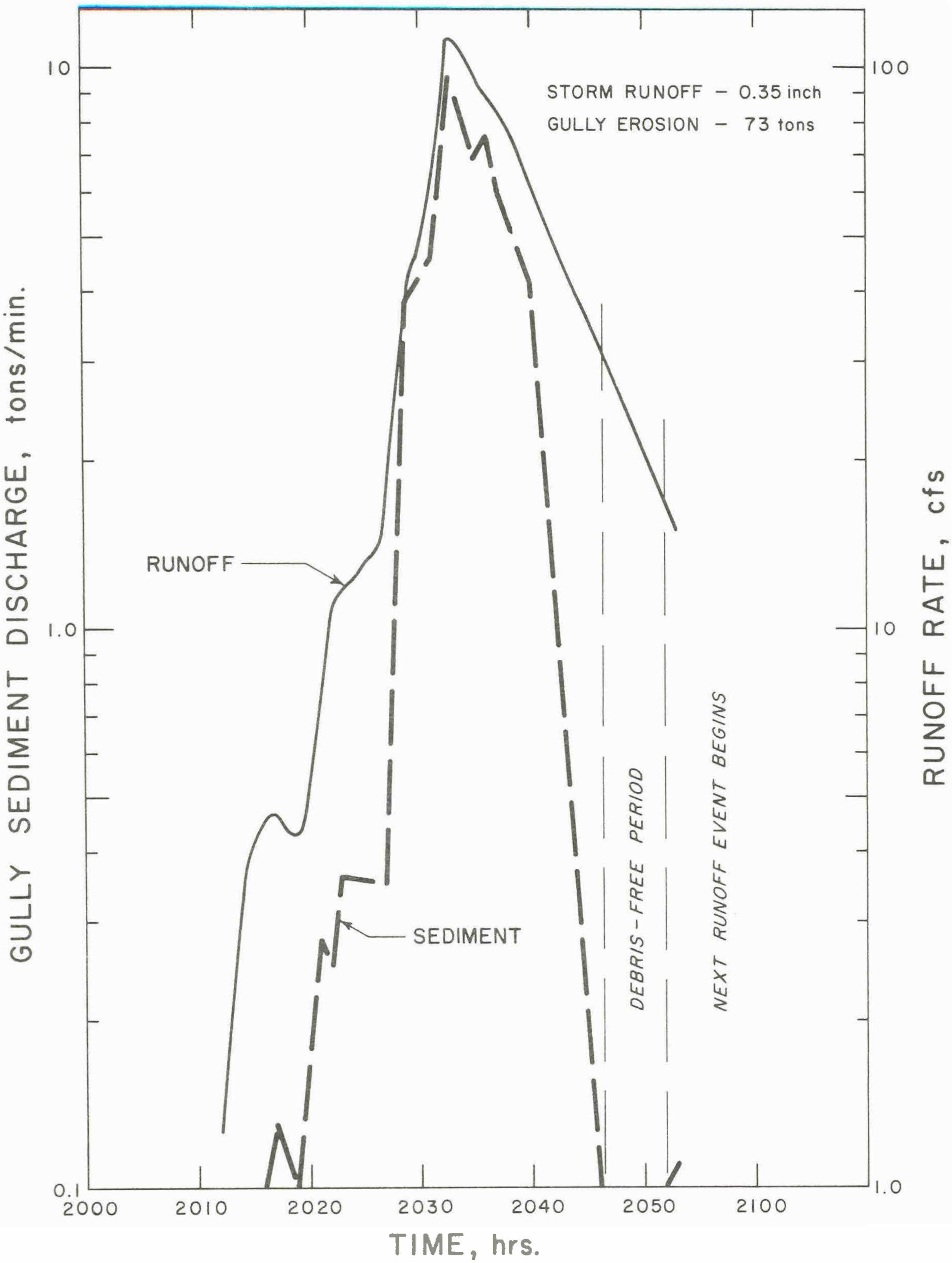


Figure 4.--(c.) Gully sediment discharges during the first large runoff event of 1971 at watershed 1.

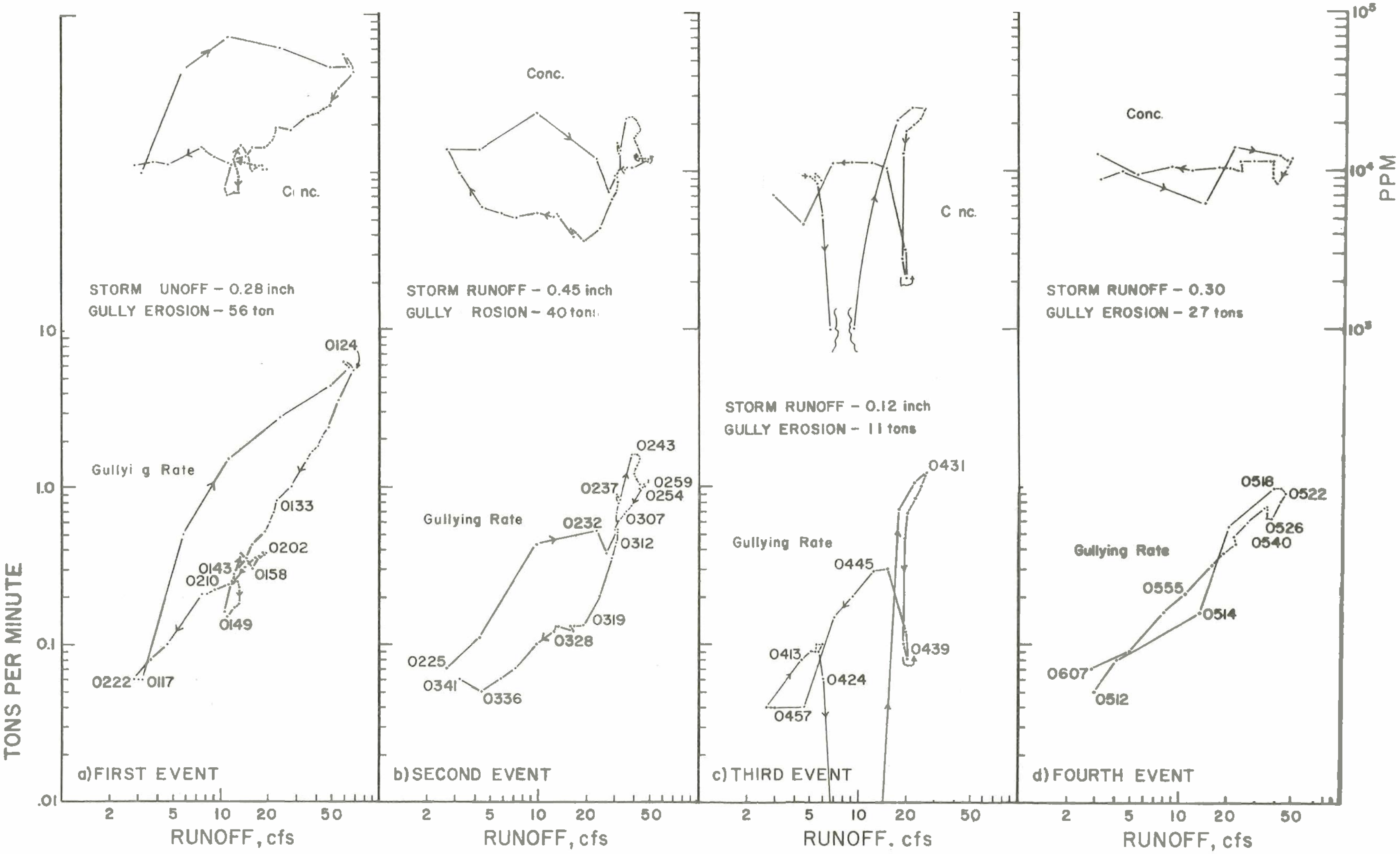


Figure 5.--Sediment transport relations for successive runoff events of September 7, 1965, watershed 1, near Treynor, Iowa.

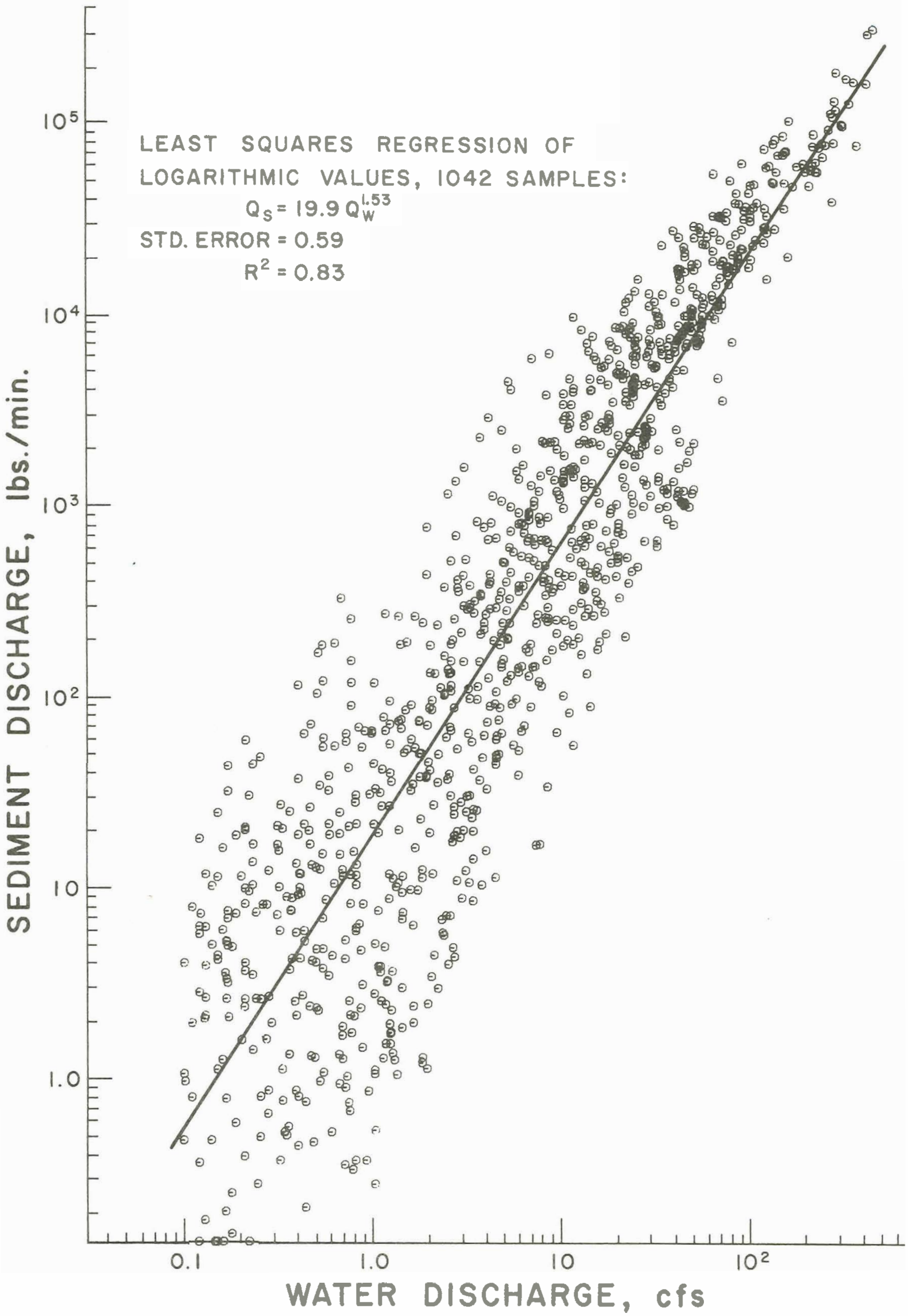


Figure 6.--(a.) Sediment transport relation representing sheet-rill erosion at watershed 1.

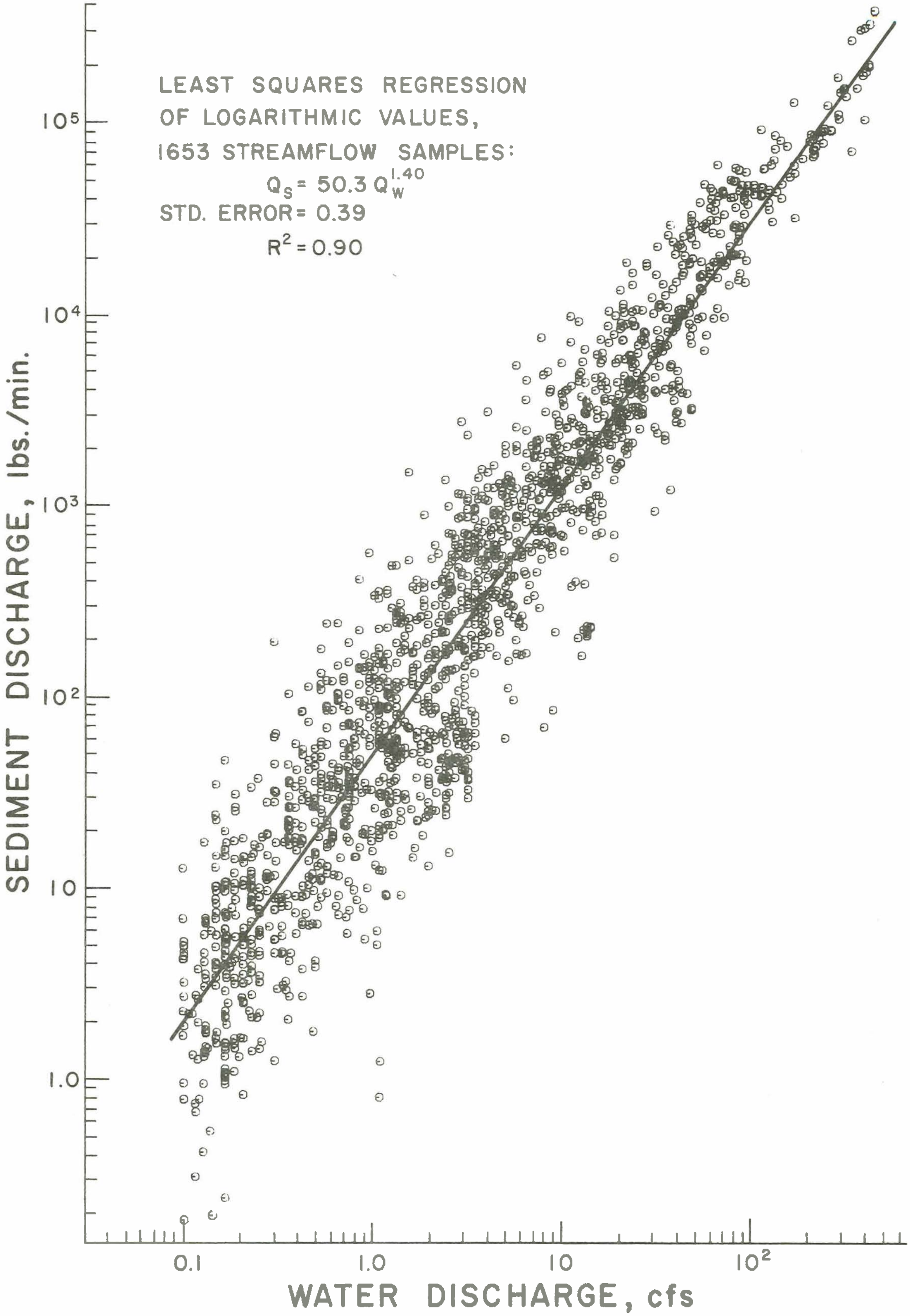


Figure 6.--(b.) Sediment transport relation representing sheet-rill and gully erosion at watershed 1.

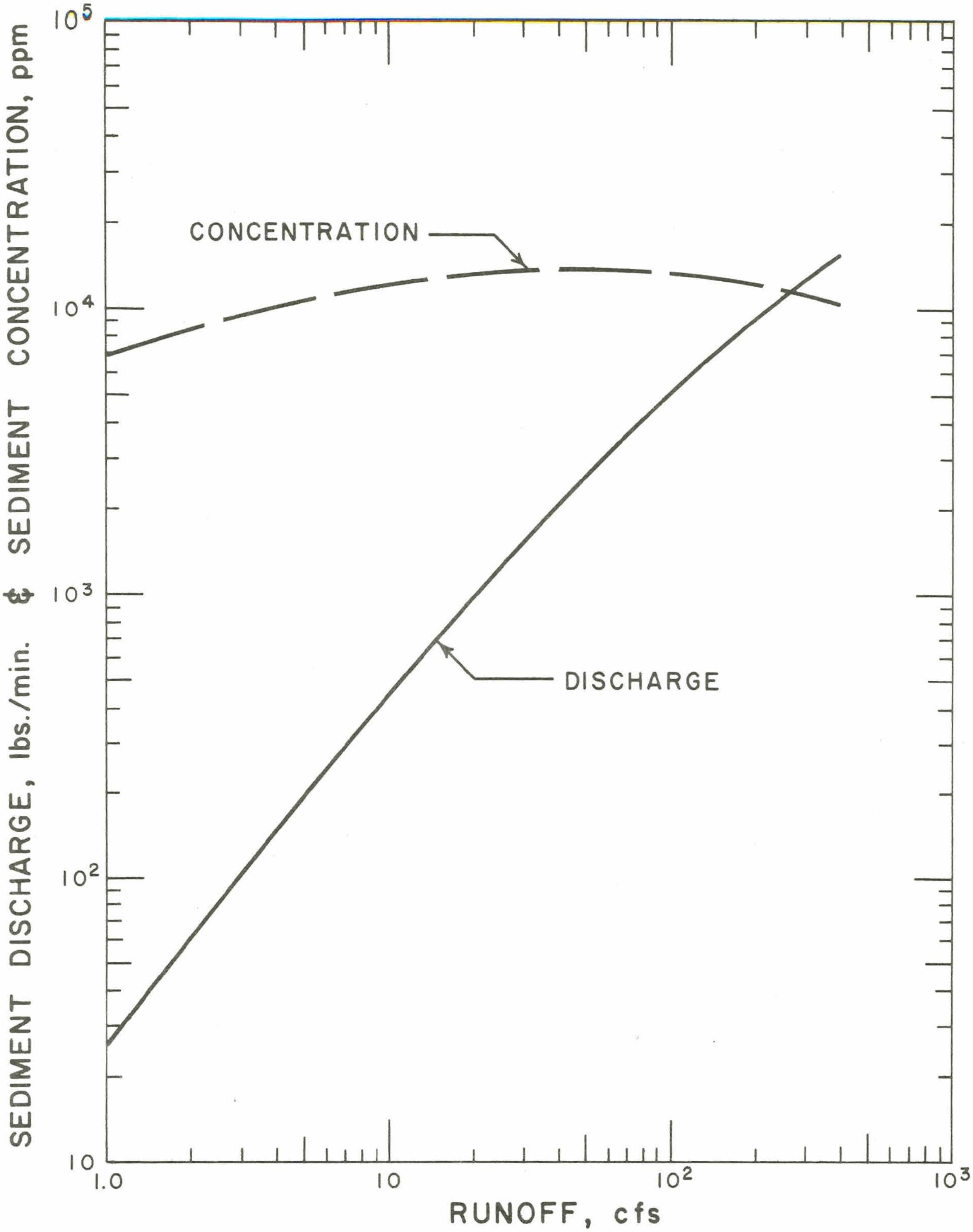


Figure 7.--(a.) Sediment transport relation for gully of watershed 1, based on 2,700 streamflow samples.

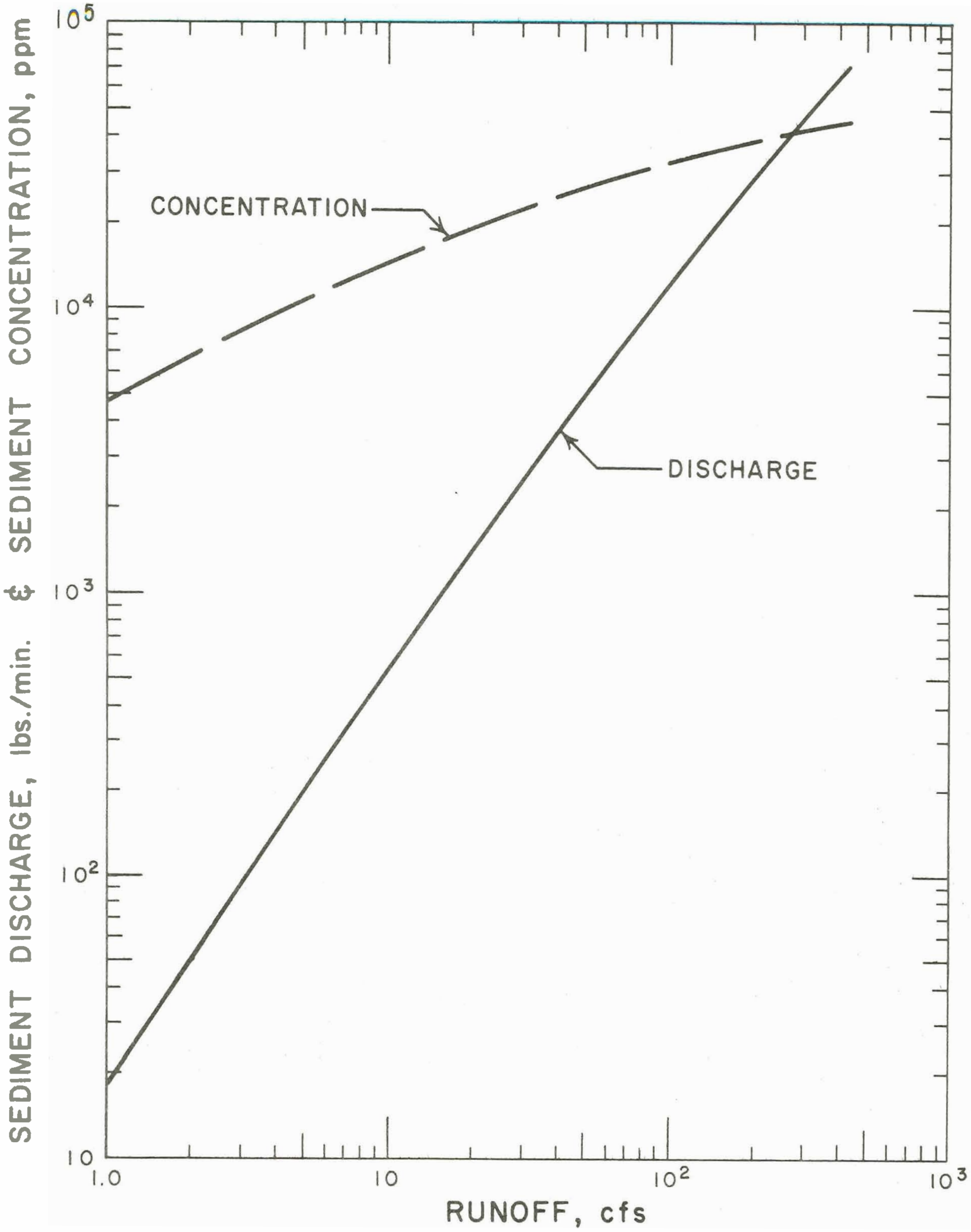


Figure 7.--(b.) Sediment transport relation for gully of watershed 2, based on 2,500 streamflow samples.

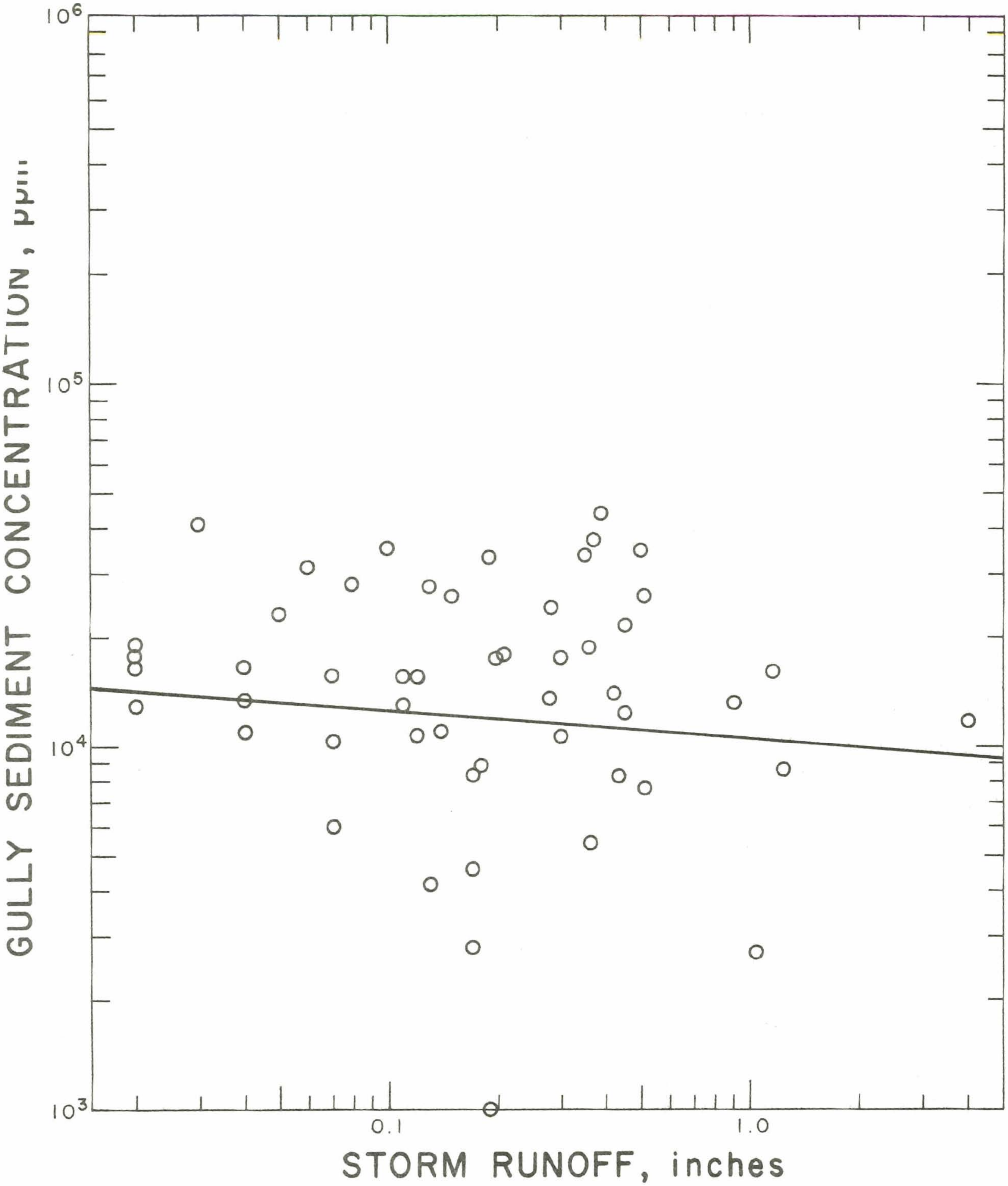


Figure 8.--Storm runoff versus runoff-weighted sediment concentration from gully erosion, using all well-sampled runoff events at watershed 1965-1971.

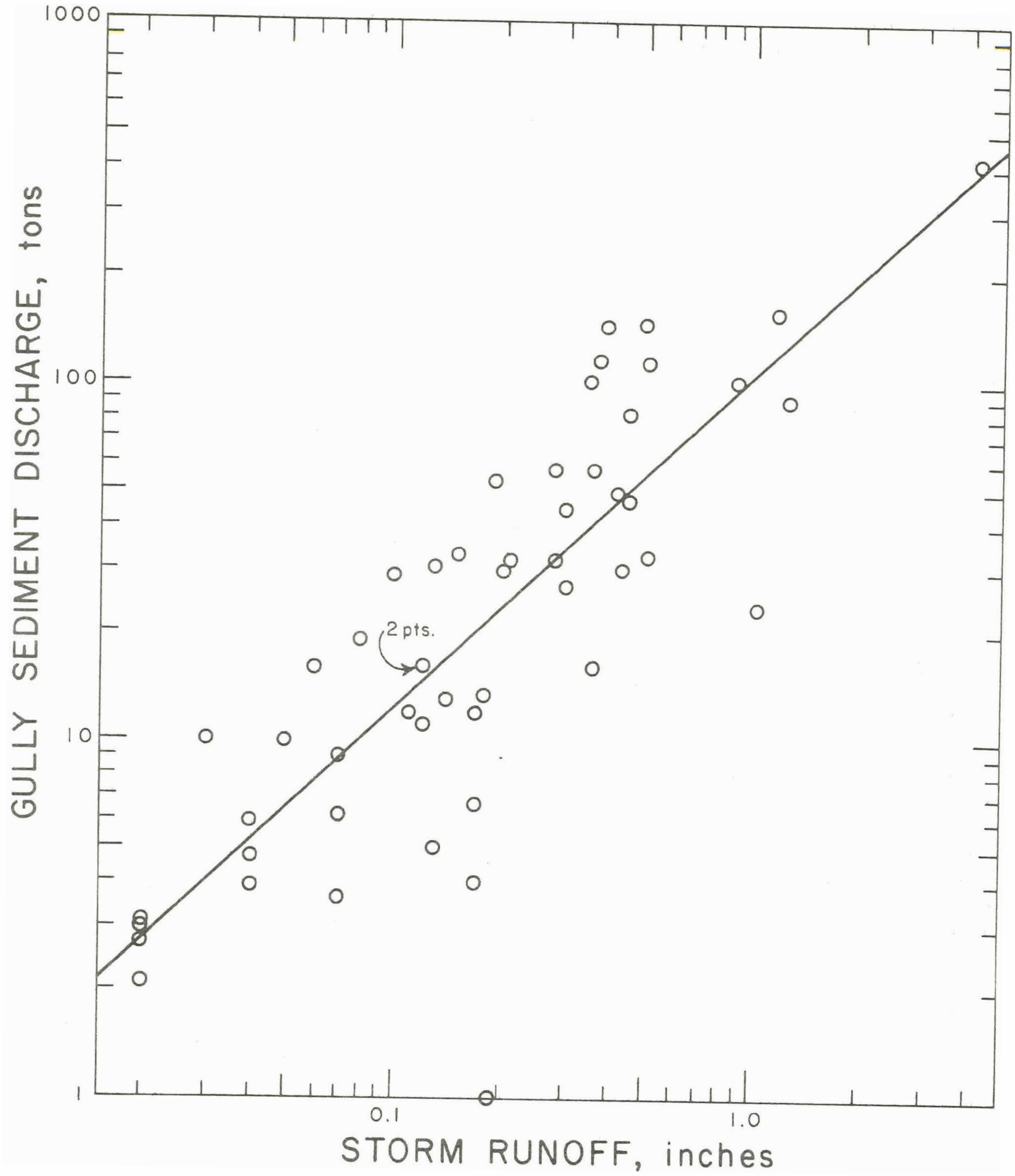


Figure 9.--(a.) Relationship between runoff and gully sediment discharge, by storm, at watershed 1, 1965-1971.

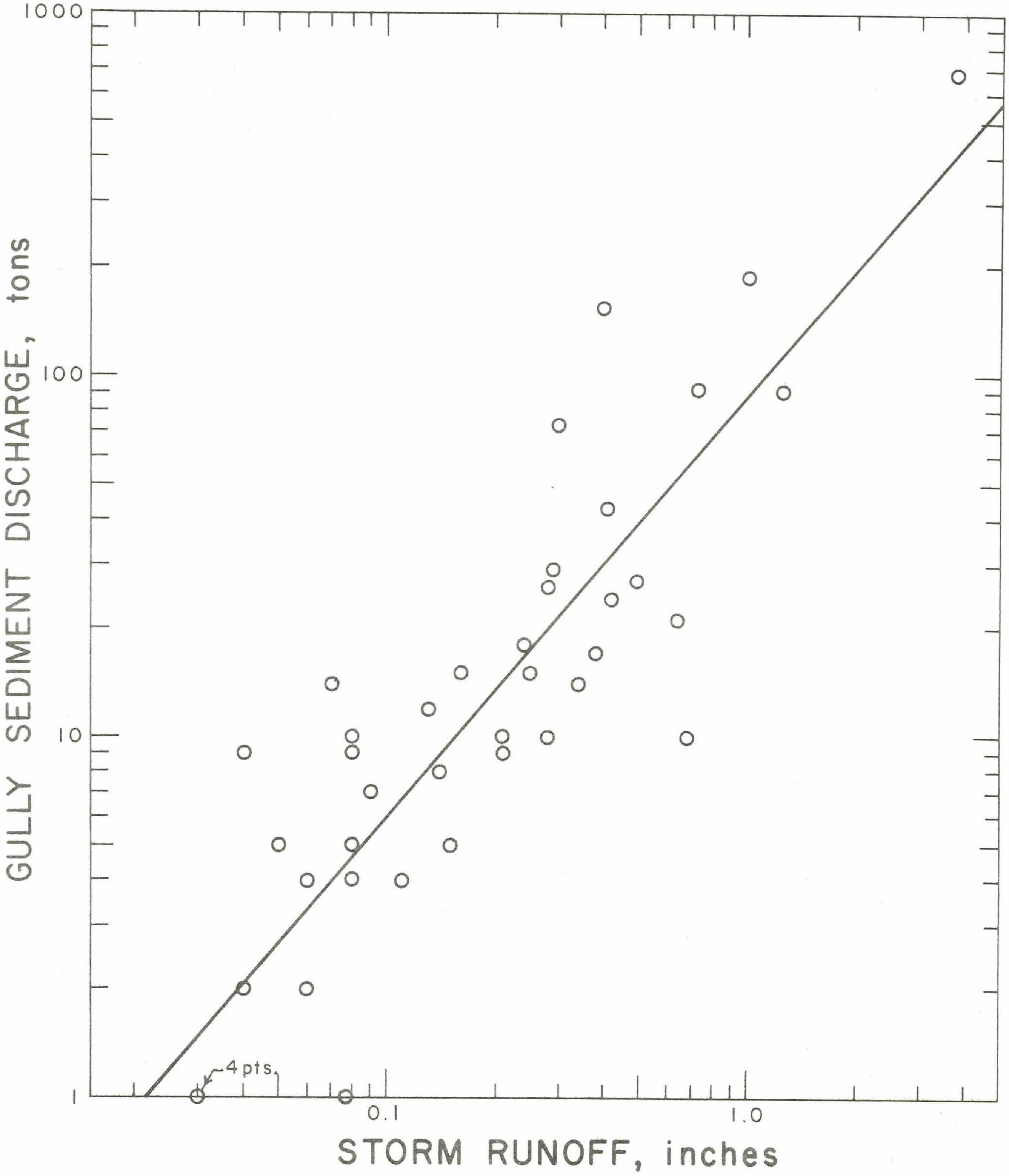


Figure 9.--(b.) Relationship between runoff and gully sediment discharge, by storm, at watershed 2, 1965-1971.

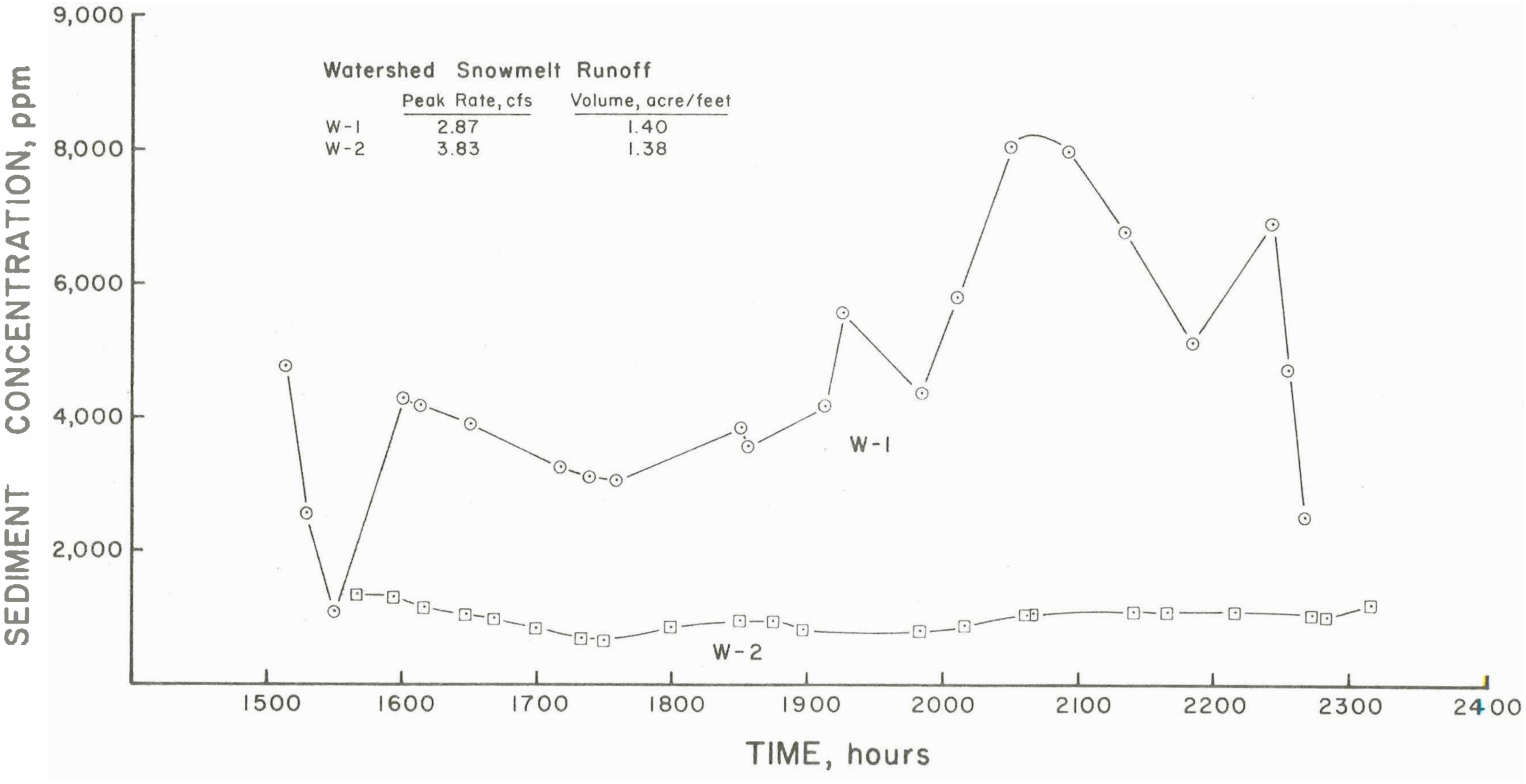


Figure 10.--(a.) Gully sediment concentration for snowmelt of January 15, 1969, Watersheds 1 and 2, frozen topsoil.

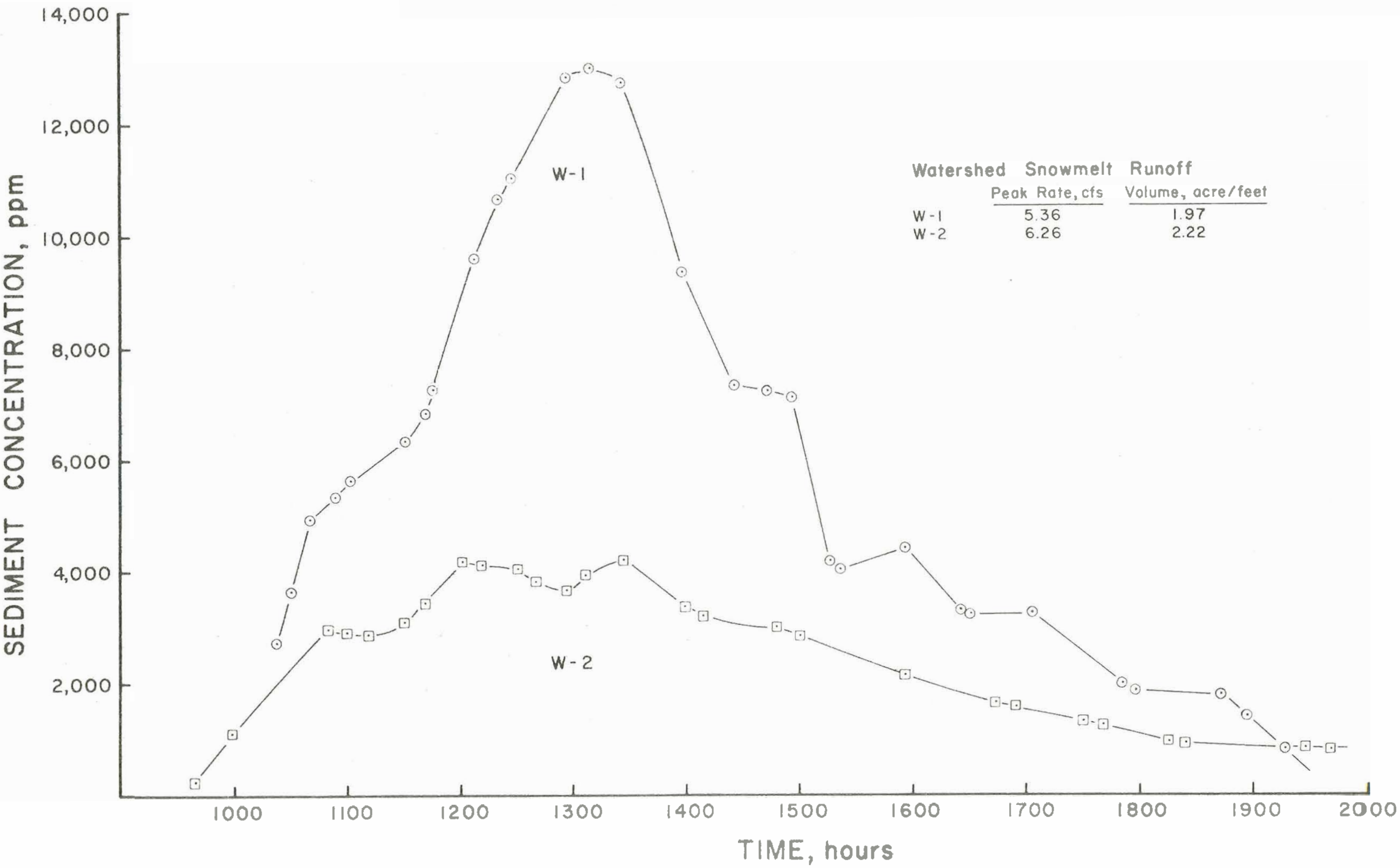


Figure 10.--(b.) Gully sediment concentration for snowmelt of February 25, 1969, watersheds 1 and 2, thawed topsoil.