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# SOIL EROSION AND SEDIMENT TRANSPORT FROM GULLIES[a]

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## INTRODUCTION

In controlling or minimizing erosion rates from gullies, one must consider the causes of gullying as well as the overall effect of gullying on the environment—both on site where the land surface is voided and downstream where the gully sediments and sediment-absorbed chemicals are deposited. Gully erosion rates have been quantified for specific locations by several researchers (2,13,16) using aerial photo time-lapse comparisons, erosion stakes, sedimentation surveys, or historic or geologic evidence. The severity of gully erosion, relative to sheet-rill and other erosion types, has also been put into perspective for several locations (5,11). But the processes that cause gullying have not been quantitatively related to gully erosion rates. We will analyze the importance of such gully processes and forces as: (1) Tractive forces acting on the gully boundary; (2) mass wasting of gully banks and scarps; and (3) gully "cleanout" of wasted soil debris. We will also examine the influence of ground water and channel seepage on erosion rates of valley-bottom gullies for several gullied watersheds in western Iowa.

## GULLY EROSION PERSPECTIVE

The rate of soil erosion and transport from gullies is complexly related to hydrologic vagaries and to the local environment. Dvorak (in an unpublished study) described the initiation of some Nebraska valley-bottom gullies: ". . . following a local weakening in the flood plain by any of the following—shrinkage crack, cattle trampling, concentration of runoff, reduced natural channel vegeta-

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(over)

hundred feet downstream from each gully headcut. The difference in sediment content of these samples is a consequence of erosion originating from the gully headcut or the channel banks between the headcut and weir, or both; samples collected above the headcut closely approximate the sediment yield from sheet-rill erosion sources on each field.

Gully erosion for the 9-yr period for minimum-conservation, (contour-planted) corn watersheds 1 and 2 was 4,540 tons ($4.1 \times 10^6$ kg) and 3,170 tons ($2.9 \times 10^6$ kg) (Table 1). This contrasts with 310 tons ($2.8 \times 10^5$ kg) and 70 tons ($6.3 \times 10^4$ kg), respectively, for conservation watersheds 3 and 4. Gully erosion contributed about 20% of total sediment yield on watersheds where both sheet-rill and gully erosion were severe. Relative gully erosion rates on conservation watersheds varied widely, but the quantities eroded were insignificant, except during very large rainstorms.

Total runoff for all corn-cropped watersheds averaged about 7 in. (180 mm)/yr, but the surface runoff component was much greater for nonconservation areas. The lower total runoff from the bromegrass watershed is probably attributable to greater evapotranspiration during the longer growing season (14).

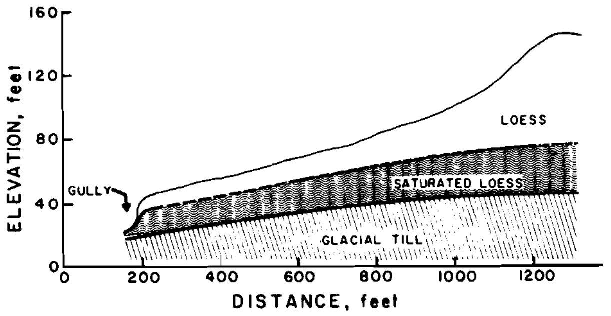


**FIG. 1.—Representative Geologic Section of Watersheds near Treynor, Iowa (1 ft = 0.305 m)**

The summary information confirms that the high runoff rates from subsurface sources at watershed 4 [55 in. (1,400 mm) from 1964-1972, more than double that from either watershed 1 or 2] did not increase gully erosion rates. The effect of seepage on gully stability has been the subject of much conjecture, especially because recommended soil conservation measures increase subsurface waters and influent channel seepage. Increased subsurface water can lower the shearing resistance of erodible channel banks by increasing the internal stresses within the soil mass (reduced cohesion and increased seepage pressures) and by increasing the shearing forces along any potential failure plane (gravity loading).

The intensive streamflow-sampling program to separate sediment yield, at all times, according to sheet-rill or gully erosion source, was not begun until 1965. The approx 125 surface runoff events occurring since 1965 show that most gullying occurs early in the runoff season (May-June). Table 2 compares May-June, 1965-1972, gully sediment transported with the 8-yr total.

Only one-third of the average annual rainfall caused four-fifths of the gully tion, or change in base grade—an initial furrow could develop in just one runoff event." In particular, disproportionate gullying can result from unusually heavy rainstorms. Dvorak and Heinemann (4) reported that more than 98% of the sediment eroded from a gully reach in Dry Creek, Frontier County, Nebraska, occurred during the first year of the April, 1951-April, 1956 measurement period. For the Treynor, Iowa watersheds cited herein, the heavy rainfall of June, 1967 (1 month) caused one-third of the total 9-year gully erosion.

Most observers recognize that man has aggravated gullying in two significant respects: (1) He has created, purposely and by chance, local disturbances in drainageways and flood plains that have triggered gully erosion activity; and (2) his influence on both the urban and rural environment has resulted in increased runoff rates that can more effectively sustain the gully erosion cycle and initiate new gullies.

Many types of gullies exist and many specific causes of gullying have been advanced. Woodburn (19) found that the rainfall and resulting slope-wash on small upland areas in Mississippi were sufficient to cause severe gully erosion, and the sandy subsoil seemed ". . . to melt like sugar and flow away like grainy syrup." Field measurements indicated a 2-inch. (51-mm)/yr sediment yield from these eroding gullies; this is about 300 tons/acre (67 kg/m$^2$). Palmer (9) stated that freezing and thawing in New England increased the rate of gully development, with massive slumping after the spring thaw. Only small amounts of runoff were necessary to maintain gully activity in sandy river terraces of the Connecticut River Valley. He also indicated that piping, induced by seepage, caused gully erosion. Heede (7) cited piping in his study of Colorado gullies. Tuckfield (17) verified the effect of frost action as a cause of gully widening in England. Ireland, et al. (8) observed that gentle prolonged winter and spring rains in the southern Piedmont caused caving and crumbling of gully walls, with commensurate channel widening. (This could have resulted in part from prior freeze-thaw weathering.) Gully clearing and deepening was then accomplished by intense rainstorms in summer and early fall. The effect of seepage in these eroding Piedmont gullies was considered minor. Most of these causes are present to some degree in the eroding gullies of western Iowa.

### Studies in Western Iowa

An erodible loess soil mantle overlies glacial till in the rolling countryside of western Iowa. Deep gullies in the small upland valleys of the region are usually incised to the more resistant till surface, and a saturated zone that occurs above this relatively impermeable loess-till boundary causes seepage from gully banks (Fig. 1).

Four watersheds near Treynor, Iowa, are described in Table 1. The conditions of the gullied drainageways also are given, along with the runoff-erosion summary for the 1964-1972 period of measurement. Runoff rates were determined by a calibrated weir and water-level recorder located in the outlet gully of each watershed downstream from the headcut. Gully erosion was measured by periodically surveying to obtain planimetric details of gully widening and headcutting and by occasionally cross sectioning to obtain volumetric information. To define gully sediment transport rates at all times during storm runoff, streamflow was sampled immediately upstream from the headcut and at the weir several

**TABLE 1.—Watersheds and Outlet Gullies near Treynor, Iowa**

| Watershed | | | | OUTLET DRAINAGE WAY | | | | Runoff 1964–1972 | | Gully Erosion (1964–1972)[a] | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Scarp (Headcut) | | | | | | | |
| | | | | | Distance to measuring weir, in feet | | | | | | |
| Number (1) | Size, in acres (2) | Crop (3) | Conservation treatment (4) | Condition (5) | 1964 (6) | 1972 (7) | Gully Banks (8) | Subsurface,[b] in inches (9) | Surface, in inches (10) | Total, in tons (11) | Portion of total sediment yield, as a percentage (12) |
| 1 | 74.5 | Corn | Minimum[c] | Vertical, advancing, and raw | 260 | 420 | Eroding | 22.1 | 39.7 | 4,540 | 22 |
| 2 | 82.8 | Corn | Minimum[c] | Chutelike, nonadvancing & raw | 690 | 700 | Eroding | 22.8 | 36.7 | 3,170 | 16 |
| 3 | 107.0 | Brome grass | Rotation grazed | Stepped | 700 | 700 | Mostly Stable | 29.0 | 13.5 | 310 | 47 |
| 4 | 150.0 | Corn | Level terraced | Stepped | 850 | 850 | Stable | 55.0 | 9.7 | 70 | 3 |
| | | | | | | | | | | 8,090[d] | 19[d] |

[a] Gully erosion was partly estimated for 1964.
[b] Obtained by measuring fair weather or base flows.
[c] Fields are farmed on approximate contour.
[d] Total gully sediment rate for 9 yr, all watersheads.
Note: 1 acre = 4,045 m²; 1 ft = 0.305 m; 1 in. = 25.4 mm; 1 ton = 907 kg.

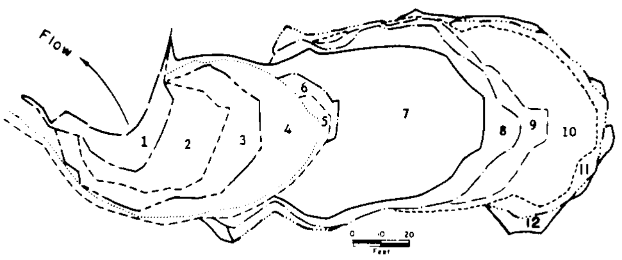
**TABLE 2.—Average Annual Early-Season (May–June) Transport of Gully Sediments, 1965–1972**[a]

| Water-shed number (1) | Rainfall | | Rainfall Erosivity | | Surface Runoff | | Sediment from Gully | |
|---|---|---|---|---|---|---|---|---|
| | In inches (2) | Percentage of total (3) | (4)[b] | Percentage of total (5) | In inches (6) | Percentage of total (7) | In tons (8) | Percentage of total (9) |
| 1 | 10.7 | 33 | 14,600 | 50 | 2.7 | 57 | 365 | 76 |
| 2 | 10.5 | 32 | 13,900 | 52 | 2.4 | 54 | 294 | 83 |

[a] Gully erosion rates for 1964 were not defined by streamflow samples and are not included in this tabulation.

[b] Rainfall erosivity unit is the product of rainfall kinetic energy times high 30-min storm intensity, as described by Wischmeier and Smith (18).

Note: 1 in. = 25.4 mm; 1 ton = 907 kg.



| AREA | PERIOD | AREAL CHANGE square feet1/ | SURFACE RUNOFF acre-feet2/ | GULLY EROSION tons3/ |
|---|---|---|---|---|
| 1 | Nov. 15, 1964-Apr. 14, 1965 | 470 | 25 | 130 |
| 2 | Apr. 15, 1965-June 9, 1965 | 840 | 17 | 510 |
| 3 | June 10, 1965-Aug. 13, 1965 | 930 | 12 | 160 |
| 4 | Aug. 14, 1965-Nov. 15, 1965 | 1250 | 14 | 350 |
| 5 | Nov. 16, 1965-July 15, 1966 | 390 | 4 | 90 |
| 6 | July 16, 1966-May 30, 1967 | 130 | 1 | < 10 |
| 7 | May 31, 1967-June 27, 1967 | 2960 | 70 | 1440 |
| 8 | June 28, 1967-Dec. 31, 1969 | 970 | 24 | 230 |
| 9 | Jan. 1, 1970-Dec. 15, 1970 | 580 | 13 | 180 |
| 10 | Dec. 16, 1970-Dec. 8, 1971 | 1410 | 31 | 400 |
| 11 | Dec. 9, 1971-May 15, 1972 | 610 | 6 | 340 |
| 12 | May 16, 1972-May 22, 1973 | 560 | 17 | 70 |
| | TOTALS | 11,100 | 234 | 3,910 |

1/ 1 square foot equals 0.093 square meters.
2/ 1 acre-foot equals 1,233 cubic meters.
3/ 1 ton equals 0.907 metric tons.

FIG. 2.—Measured Gully Changes and Erosion Rates, Watershed 1, near Treynor, Iowa

**TABLE 3.—Gully Erosion for Successive Storms, Comparing Actual Measured Rates on Average Antecedent Conditions at Watershed 1**

| May 6, 1971 | | | | | May 10, | | |
|---|---|---|---|---|---|---|---|
| Runoff interval, in cubic feet per second (1) | Duration, in minutes (2) | Mean runoff rate, in cubic feet per second (3) | Mean gully erosion rate, in pounds per minute (4) | Gully erosion, in pounds (5) | Runoff interval, in cubic feet per second (6) | Duration, in minutes (7) | Mean runoff rate, in cubic feet per seconds (8) |
| 0-0.1 | 942 | 0.05 | 0.4 | 377 | 0-0.1 | 936 | 0.05 |
| 0.1-0.5 | 225 | 0.3 | 5.5 | 1,230 | 0.1-0.5 | 156 | 0.3 |
| 0.5-1.0 | 63 | 0.75 | 18 | 1,134 | 0.5-1.0 | 61 | 0.75 |
| 1-2 | 37 | 1.5 | 44 | 1,628 | 1-2 | 68 | 1.5 |
| 2-3 | 24 | 2.5 | 81 | 1,944 | 2-5 | 47 | 3.5 |
| 3-4 | 21 | 3.5 | 123 | 2,583 | 5-10 | 26 | 7.5 |
| 4-5 | 23 | 4.5 | 165 | 3,795 | 10-15 | 12 | 12.5 |
| 5-6 | 19 | 5.5 | 210 | 3,990 | 15-20 | 19 | 17.5 |
| 6-7 | 20 | 6.5 | 255 | 5,100 | 20-25 | 19 | 22.5 |
| 7-9 | 18 | 8 | 330 | 5,940 | 25-30 | 22 | 27.5 |
| 9-11 | 16 | 10 | 430 | 6,880 | 30-35 | 16 | 32.5 |
| 11-13 | 12 | 12 | 530 | 6,360 | 35-40 | 14 | 37.5 |
| 13-15 | 6 | 14 | 630 | 3,780 | 40-45 | 10 | 42.5 |
| 15-18 | 2 | 16.5 | 760 | 1,520 | 45-50 | 5 | 47.5 |
| 18-21 | 3 | 19.5 | 910 | 2,730 | 50-60 | 5 | 55 |
| 21-24 | 3 | 22.5 | 1,080 | 3,240 | 60-70 | 8 | 65 |
| 24-27 | 3 | 25.5 | 1,240 | 3,720 | 70-80 | 7 | 75 |
| 27-30 | 2 | 28.5 | 1,400 | 2,800 | 80-90 | 2 | 85 |
| 30-33 | 1 | 31.5 | 1,560 | 1,560 | 90-100 | 3 | 95 |
| | | | | | 100-110 | 0 | 105 |
| | | | | | 110-120 | 1 | 115 |
| | | | | | 120-130 | 1 | 125 |
| | | | | | 130-140 | 2 | 135 |
| Totals | | | | 60,319[a] | | | |

[a]Computed gully transport = 30 tons; measured gully transport = 58 tons; weighted
[b]Computed gully transport = 146 tons; measured gully transport = 186 tons; weighted
[c]Computed gully transport = 153 tons; measured gully transport = 46 tons; weighted
Note: 1 cfs = 0.028 $m^3/s$; 1 lb/min = 0.453 kg/min; 1 lb = 0.453 kg; 1 ton = 907

sediment movement. This circumstance can be partly attributed to greater rainfall and runoff intensities of thunderstorms received while the land surface was denuded or sparsely vegetated, because the May-June rainfall erosivity index (18) was 50% of average annual value and surface runoff was about 55% of average annual runoff. But the most probable reason for large May-June gully transport rates is that accumulation of gully soil debris is greatest before the spring runoff season. Concentrations of gully materials decrease with successive spring rainstorms, although some debris is produced throughout the year.

**with Rates Computed by Flow Duration-Sediment Rating Curve Methods (3) Based**

| 1971 | | May 18, 1971 | | | | |
|---|---|---|---|---|---|---|
| Mean gully erosion rate, in pounds per minute (9) | Gully erosion, in pounds (10) | Run-off inter-val, in cubic feet per second (11) | Dura-tion, in minutes (12) | Mean run-off rate, in cubic feet per second (13) | Mean gully erosion rate, in pounds per minute (14) | Gully erosion in pounds (15) |
| 0.4 | 374 | 0-0.1 | 568 | 0.05 | 0.4 | 227 |
| 5.5 | 858 | 0.1-0.5 | 379 | 0.3 | 5.5 | 2.084 |
| 18 | 1,098 | 0.5-1.0 | 110 | 0.75 | 18 | 1,980 |
| 44 | 2,992 | 1-2 | 126 | 1.5 | 44 | 5,544 |
| 123 | 5,781 | 2-5 | 45 | 3.5 | 123 | 5,535 |
| 305 | 7,930 | 5-10 | 24 | 7.5 | 305 | 7,320 |
| 550 | 6,600 | 10-20 | 82 | 15 | 680 | 55,760 |
| 810 | 15,390 | 20-40 | 32 | 30 | 1,490 | 47,680 |
| 1,080 | 20,520 | 40-60 | 10 | 50 | 2,540 | 25,400 |
| 1,350 | 29,700 | 60-80 | 5 | 70 | 3,520 | 17,600 |
| 1,620 | 25,920 | 80-100 | 4 | 90 | 4,500 | 18,000 |
| 1,890 | 26,460 | 100-120 | 2 | 110 | 5,450 | 10,900 |
| 2,150 | 21,500 | 120-140 | 3 | 130 | 6,350 | 19.050 |
| 2,410 | 12,050 | 140-160 | 2 | 150 | 7,150 | 14,300 |
| 2,780 | 13,900 | 160-180 | 2 | 170 | 7,950 | 15,900 |
| 3,290 | 26,320 | 180-200 | 0 | 190 | 8,700 | 0 |
| 3,780 | 26,460 | 200-220 | 3 | 210 | 9,400 | 28,200 |
| 4,250 | 8,500 | 220-240 | 3 | 230 | 10,100 | 30,300 |
| 4,740 | 14,220 | | | | | |
| 5,250 | 0 | | | | | |
| 5,650 | 5,650 | | | | | |
| 6,100 | 6,100 | | | | | |
| 6,550 | 13,100 | | | | | |
| | 291,423[b] | | | | | 305,780[c] |

gully sediment concentration = 20,200 ppm; runoff = 0.34 in.
gully sediment concentration = 16,000 ppm; runoff = 1.37 in.
gully sediment concentration = 3,700 ppm; runoff = 1.47 in.
kg; 1 in. = 25.4 mm.

Consider, for example, three successive well-sampled rainstorms in May, 1971 at watershed 1 (Table 3). The measured gully transport is given for each storm. These measured rates are compared with computed gully transport rates based upon runoff-duration records for these storms and the average 8-yr sediment runoff relation as defined by 2,700 streamflow samples. The use of these data in the "Sediment Rating Curve" procedure (3) results in a close approximation of the sediment transport rate from the gully under average conditions.

Two important conclusions can be gleaned from Table 3. First, the relative sediment discharge, if we use the gully sediment concentration (runoff-weighted) for each storm as an index, decreases from 20,200 ppm-3,700 ppm from May 6-May 18 because debris supplies were mostly depleted. Secondly, if measured sediment discharge is compared with that which would be expected under average conditions, the measured gully transport for May 6 is nearly double the computed, or 58 tons ($5.3 \times 10^4$ kg) versus 30 tons ($2.7 \times 10^4$ kg); the May 18 actual transport was only 46 tons ($4.2 \times 10^4$ kg) as compared with the computed 153 tons ($1.4 \times 10^5$ kg). Values for May 10 are intermediate.

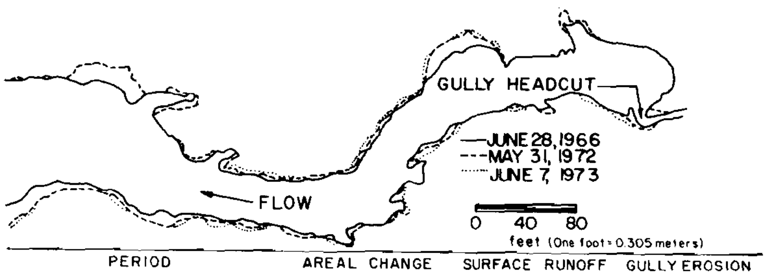
## GULLY PROCESSES EXAMINED

The movement of soil from the gully at any given time is a function of the sediment transport capacity of runoff and the rate of soil detachment. Soil detachment processes can include freeze-thaw and wetting-drying action on gully banks, mass wasting of gully banks due to added moisture quantities and seepage pressures, and shearing forces acting on the channel boundary. The hydraulic capacity for transport of gully sediment is very large for watersheds 1 and 2. But the rate at which eroded gully materials become available is somewhat less than the entrainment capacity of the runoff, and the gully transport rate is reduced to zero during some runoff periods.

The transport rates of sediment originating from the drainage outlet gullies of minimum-conservation watersheds 1 and 2 were much greater than for conservation watersheds 3 and 4 (Table 1). Fig. 2 and 3 summarize the areal change in these gullies for the several survey periods. Watershed 1 gully has been changed mainly by headcut advance, whereas the gully growth of watershed 2 has been principally by lateral enlargement. The erosion differences in these two gullies cannot be accounted for completely because too many variables are operative, even though the gullies are on adjoining fields. The hydrologic measurements and streamflow samples, however, make it possible to evaluate several forces that might be expected to influence sediment movement from gullies.

**Tractive Forces Acting on Channel Boundary.**—The roles of runoff tractive forces and stream power in the gully erosion process can be appraised by examining the flow through a typical gully cross section. Fig. 4(*a*) shows the drainageway profile in the vicinity of the gully headcut on watershed 2. Fig. 4(*b*) shows a typical gully cross section as it changed in the 5-yr period, 1968-1973. The stream power per unit length of gully can be approximated satisfactorily by using Manning's formula to compute realistic stream velocities in terms of the hydraulic radius. Velocities in the gully were also estimated from stage-discharge records and current meter measurements at the downstream weir section. For the cross section in Fig. 4, with $S = 0.0233$ and a maximum $n = 0.075$, Manning's formula becomes: $V = 3.02\ R^{2/3}$, in which $V$ = mean stream velocity, $LT^{-1}$; $R$ = hydraulic radius, L.

The tractive force, $\tau = \gamma RS$, and stream power $\omega = \tau w V = \tau P V$; in which $\tau = FL^{-2}$; $\gamma$ = specific weight of fluid, $FL^{-3}$; $S$ = slope of energy gradient; $w = P$ = flow width and wetted perimeter and are approximately equal, L. The unit stream power during four runoff events is compared with measured gully erosion rates in Table 4. The table shows that the storm-to-storm rate of movement of gully materials is not consistent for any given runoff rate or boundary shear value and even varies widely between similar rates on rising and falling stages of the same hydrograph. Variable gully transport rates at comparable runoff are related to the amount of gully bank debris in the channel.



| PERIOD | AREAL CHANGE square feet (square meters) | SURFACE RUNOFF acre - feet (cubic meters) | GULLY EROSION tons (metric tons) |
|---|---|---|---|
| JUNE 28, 1966 - MAY 31, 1972 | 4,360<br>(405) | 140<br>(173,000) | 2,000<br>(1,810) |
| MAY 31, 1972 - DEC 31, 1972 | 1,000<br>(93) | 7<br>(8,630) | 5<br>(5) |
| DEC 31, 1972 - JUNE 7, 1973 | | 13<br>(16,000) | 5<br>(5) |
| TOTALS | 5,360<br>(498) | 160<br>(197,630) | 2,010<br>(1,820) |

FIG. 3.—Measured Gully Changes and Erosion Rates, Watershed 2, near Treynor, Iowa

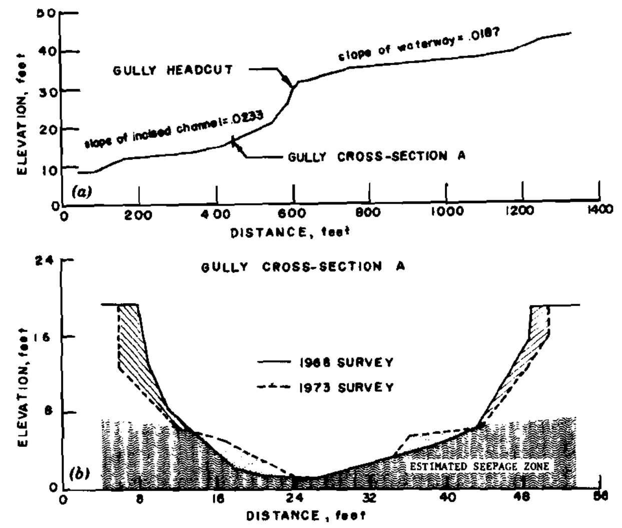


FIG. 4.—Watershed 2: (*a*) Drainageway Profile; (*b*) Typical Gully Cross Section (1 ft = 0.305 m)

Loose soil debris is the prime sediment source in these gullies, and much less runoff is necessary to remove this debris than the runoff forces exerted during

**TABLE 4.—Estimated Tractive Forces During Four Events as Related**

| Runoff rate, in cubic feet per second (1) | Flow Geometry | | Tractive force, in pounds per square foot (4) | Unit stream power, in pounds per second (5) | | | |
|---|---|---|---|---|---|---|---|
| | Area, in square feet (2) | Hydraulic radius, in feet (3) | | | May 22, 1965 | | |
| | | | | | Rising stage (6) | Peak stage (7) | Falling stage (8) |
| 10 | 4 | 0.6 | 0.9 | 15 | 1 | — | 1 |
| 50 | 14 | 1.0 | 1.5 | 70 | 8 | — | 14 |
| 130 | 29 | 1.5 | 2.2 | 180 | — | 0 | — |
| 250 | 48 | 2.1 | 3.1 | 370 | — | — | — |
| 430 | 70 | 2.5 | 3.6 | 610 | — | — | — |

[a] Rounded values used.

Note: 1 cfs = 0.028 $m^3/s$; 1 sq ft = 0.093 $m^2$; 1 ft = 0.305 m; 1 psf = 47.9 $N/m^2$;

most storms. We measured velocities greater than 10 fps (3 m/s) in the partly incised drainageway about 30 ft (9 m) above the headcut of watershed 2 [see Fig. 3 and 4(*a*)], but noted only minor erosion of the waterway.

Figs. 5 and 6 further show that loose soil debris, not soil scoured from the gully boundary by runoff forces, is the prime source of gully sediment in western Iowa. Discharge of sediment from the gully of watershed 2, during storm runoff on May 18, 1971 (Fig. 5), was defined by 29 streamflow samples. Nearly all of the eroded gully material [90 tons ($8.2 \times 10^4$ kg)] was transported during the early minutes of the storm. Essentially no gully erosion occurred after 2:50 a.m., even though runoff rates still exceeded 100 cfs (2.80 $m^3/s$), and boundary shear forces were high. Fig. 6 shows gully sediment transport rates for May 5, 1972, at watershed 1, based on 18 streamflow samples. On this first large storm of the year, an unusually large quantity of weathered soil debris [217 tons ($2.0 \times 10^5$ kg)] was transported from the gully. Although total cleanout of gully soil debris during the early part of the storm was not evident, the rates of sediment produced during the hydrograph recession were minimal, because the sediment supply was drastically reduced. The great reduction in the transport rate of eroded soil from the gully during these storms also verifies that the tractive forces of runoff along the channel boundary do not play a major role in the erosion of some gullies. These circumstances were presented in more detail by Piest, et al. (10) and were observed by Schumm (12), who stated: "In poorly cohesive alluvium, or that with a small percentage of silt-clay, the channel widens rapidly by bank caving after initial dissection—and disintegrates upon impact or later under the eroding action of flood waters."

**Slope Stability and Mass Wasting.**—If a two-part cycle of soil debris production and subsequent debris transport is the requisite for continued gully growth, and if the soil is not eroded primarily by boundary shear forces, then mass (gravity) wasting of gully banks must occur. The specific causes of mass wasting are unknown, but must be related to soil water changes. A special field-modeling experiment in western Iowa was devised to impose soil water stresses on a

**to Transport of Sediment from Gully of Watershed 2ᵃ**

| Measured Gully Sediment Rate, in tons per minute | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| June 20, 1967 | | | May 18, 1971 | | | May 5, 1972 | | |
| Rising stage (9) | Peak stage (10) | Falling stage (11) | Rising stage (12) | Peak stage (13) | Falling stage (14) | Rising stage (15) | Peak stage (16) | Falling stage (17) |
| — | — | — | 0.4 | — | 0.4 | 0.2 | — | 0.1 |
| 0.7 | — | 0.2 | 5 | — | 0 | 3 | — | 1 |
| 4 | — | 6 | 8 | — | 0 | — | 5 | — |
| 25 | — | 7 | — | 9 | — | — | — | — |
| — | 50 | — | — | — | — | — | — | — |

1 lb/sec = 0.453 kg/s; 1 ton/min = 907 kg/min.

length of gully bank to determine the sequence of failure. Changes in soil-water content and pore-water pressure were also to be noted, and time-lapse stereophotos of the targeted gully bank were taken to furnish sequential maps to quantify failure masses and shapes.

Fig. 7 shows the study site where two in-line trenches were dug 15 ft (4.6 m) shoreward and parallel to a 75-ft (23-m) length of gully bank that was straight and vertical. The original plan to add water to the trenches and raise the saturation level along the gully bank was unsuccessful because macropores in the loess made it impossible to raise the seepage plane more than about 1 ft (0.3 m). Also, some of the soil below the seepage plane remained unsaturated.

However, a pattern of bank failure emerged. Failure of the vertical bank always began by chipping and flaking of soil from near the toe, until considerable undercutting was evident. Many of the flakes and chips were of appreciable size [Fig. 7(*b*)], and seemed to have been dislodged by seepage waters directed to them through macropores. Some evidence exists that these macropores were formed by collapse of loess in the saturated zone of the lower soil profile (6). After sufficient undercutting, the massive top portion of the bank would cave in.

An analysis of forces affecting gully bank stability must involve a number of simplifying assumptions as to size and shape of failure mass and failure surface, mode of failure (as by shear) and applicable theory (such as the Mohr-Coulomb equation), and amount and change in soil cohesive strength in response to soil water changes. Then, along with a knowledge of measurable properties of loess—particle sizes and shape, cohesive strength, coefficient of internal friction, soil density, and perhaps collapsibility—it is possible to test a simplified two-dimensional model with ranges of values of important variables that affect gully bank stability.

If a gully bank subject to pore-water stresses fails by gravity, it must be due to changes in the strength of the failure mass or the driving forces acting on it, or both. When the ratio of these resisting-to-driving forces is lowered

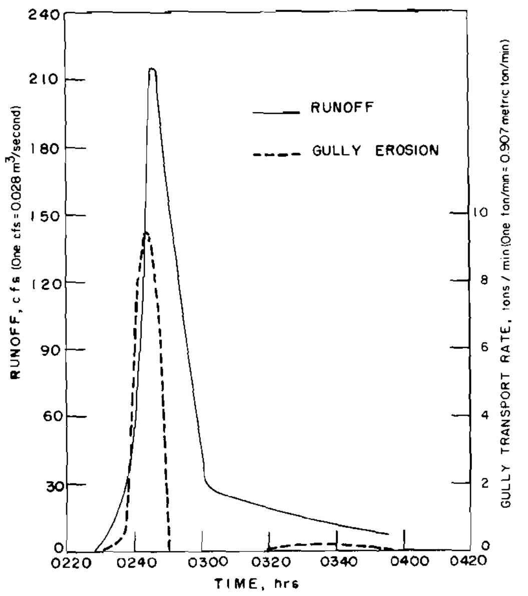


FIG. 5.—Gully Sediment Transport for Storms of May 18, 1971, Based on 29 Streamflow Samples at Watershed 2

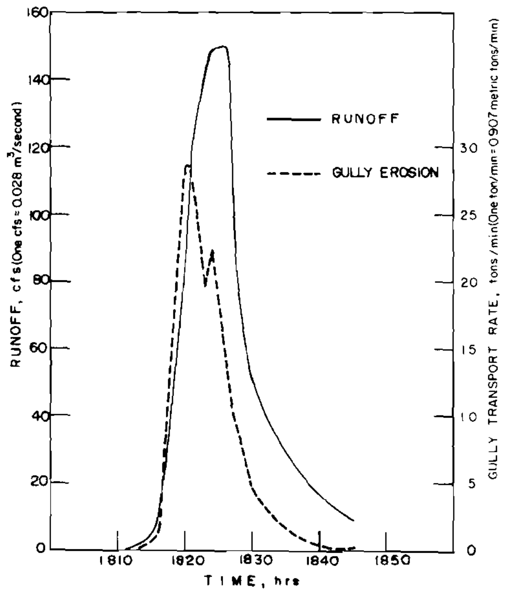


FIG. 6.—Gully Sediment Transport for Storm of May 5, 1972, Based on 18 Streamflow Samples at Watershed 1

to less than unity, the bank will fail. The Simplified Bishop Method of Slices, programmed for computer operation in LEASE 1 (1), was used to compute factors of safety for various loading and boundary conditions. Variables that were considered included soil bulk density and water content, angle of internal friction, bank height, rate of water infiltration, height of vertical bank, and position of water table. Soil cohesive strength was assumed to be zero for a saturated soil system at zero hydrostatic pressure, and cohesion above the saturated zone was attributed solely to negative pore pressures. Results of this analysis showed that height of water table, soil cohesive strength, and rate of water infiltration are controlling factors affecting stability of gully banks in the loess soils of western Iowa. Taylor and Johnson (15) formulated models for two ground-water flow systems to test the response of a bank stability model to changing pore-water pressures and soil strength properties.

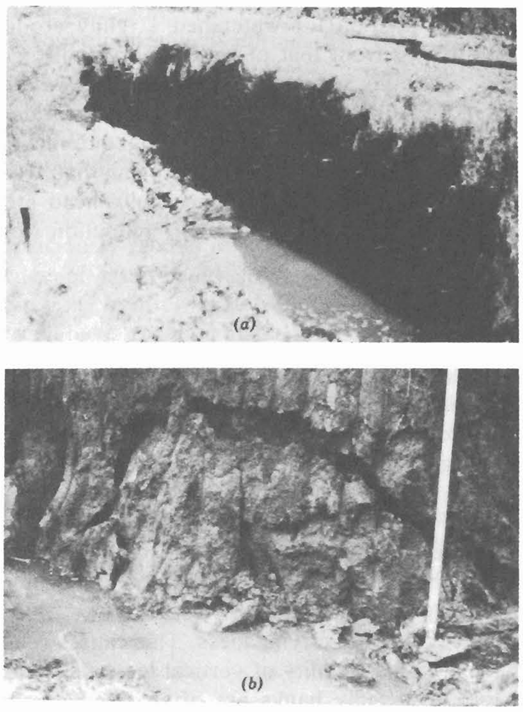


**FIG. 7.—Field Modeling Experiment Site Showing: (*a*) Vertical Gully Bank; (*b*) Close-Up of Failure Chip**

**Concepts of Channel Cleanout.**—The rates and quantities of runoff needed to clean out a channel, and thereby maintain conditions favorable to gully weathering and mass wasting, are sufficient for minimum-conservation watersheds 1 and 2 but not for conservation watersheds 3 and 4. After a gully bank fails, the degree of slope is reduced to a stable value. Without adequate runoff to remove the debris—produced by shear, liquefaction, undercutting and downslope migration, or by other means—the slope may become vegetated and resist all subsequent erosional forces. Further gullying will take place only when a random disturbing element, such as a rodent hole or extremely large runoff rate, occurs.

The channels of watersheds 3 and 4 have responded to conservation treatment by remaining stable. A flow rate of 40 cfs (1.1 $m^3/s$) in the gully of watershed 4, e.g., did not upset the stable channel condition; at grassed watershed 3, only a record rainstorm that produced a peak runoff of 217 cfs (6.08 $m^3/s$) caused appreciable gully erosion.

On minimum-conservation watersheds 1 and 2, surface runoff would have to be decreased significantly before debris cleanout would be markedly reduced. Piest, et al. (10) considered the effect of reducing storm runoff rates (not volumes) on watersheds 1 and 2 by some conservation treatment. They found that the gully sediment transport relation for watershed 1 (gully eroding primarily by advancing headcut) differed from that of watershed 2 (gully eroding primarily by channel widening). The gully sediment concentration at watershed 1 increased to a maximum at moderate runoff rate and then leveled off or decreased slightly; the concentration at watershed 2 increased throughout the range of runoff. Therefore, at watershed 1, a conservation treatment that would lower flood peaks but not flood volumes would not reduce gully head erosion and might even increase it; at watershed 2, the same runoff reduction would be expected to reduce gully erosion.

## Summary and Conclusions

Environmental conditions favor the initiation and growth of valley-bottom gullies in the loess soils region of the Missouri River Basin, as is evidenced by their prevalence. Processes of mass wasting of gully banks and scarps were mainly responsible for gully growth. The loose soil debris represented the prime sediment source in the gullies. If the Treynor watersheds are representative, approximately one-fifth of the total sediment polluting the streams of western Iowa originates from gullies. Causes of gullying vary according to boundary restraints (base level, channel slope, and resistant soils) that are typical of a given region. Most valley-bottom gullies in western Iowa are incised to glacial till, through a saturated zone of overlying loess. This causes seepage into gullied channels, which decreases the stability of vertical loess banks and headcuts.

The dimensions of failed gully banks are often fixed or predetermined by the seepage level. Many of these slumped masses are truncated at the seepage line. Progressive downbank movement of the mass continues over a period of time until storm runoff is sufficient to remove the loosened soil. The presence of a seepage zone is usually associated with a boundary restraint, such as the erosion-resistant glacial till layer in western Iowa. This limits the depth of gully incisement. In similar loess soil regions with no seepage, as in west-central Nebraska, depth for gully cutting has no limit, and serious gully erosion has resulted. It is not known whether these forces that cause massive gully growth in ephemeral channels are more or less benign than the seepage forces in Iowa gullies.

Increased water infiltration into the soil profile, as was accomplished on level-terraced watershed 4, is an excellent conservation measure that does not alone cause gullying because of increased seepage pressures or ground-water levels. When one of the mutually dependent gully enlargement processes—channel debris cleanout by runoff—is drastically reduced, as in conservation watersheds 3 and 4, mass wasting and gully head advancement is essentially halted.

The tractive forces and stream power of runoff for the gullies of minimum-conservation watersheds 1 and 2 were more than adequate to remove accumulated gully debris, but were not the principal mechanisms for detaching or otherwise eroding soil from the gully boundary. Mass wasting of gully banks and headcuts was due to moisture-related forces that diminished soil cohesive strength and increased shearing forces. Water disposal obviously is the prime factor to be managed in any gully-control efforts at these locations.

The Treynor studies tend to verify that a large part of the gully soil debris accumulates during winter and early spring and is flushed from the channel with the first spring rainstorms. The relative quantities moved are greatly reduced for each subsequent runoff event during the year. As much as four-fifths of the 1965-1972 soil movement from gullies occurréd during May and June, with one-third of the rainfall and five-ninths of the surface runoff. Results of slope-stability analyses indicate that height of water table, soil cohesive strength, and rate of water infiltration are the main factors controlling stability of gully banks.

The erosion and transport rate of soil from any particular gully bank or headcut seems to be capriciously related to hydrologic and site variables. Nevertheless, overall knowledge of interrelated erosion-causing mechanisms is needed and can be helpful in gully control. With additional quantification of gully-affecting variables, we will have the potential to assess the likelihood of success of any given or projected conservation system or to determine detrimental or beneficial effects of land use and channel changes.

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374

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**11069 EROSION AND SEDIMENT TRANSPORT FROM GULLIES**

KEY WORDS: **Erosion; Gullies; Hydraulics;** Mass wasting; **Sedimentation; Sediment transport;** Soil mechanics; Tractive forces

ABSTRACT: Field observations of four gullied watersheds, 74 acres to 150 acres (30 ha-61 ha) in size, showed that gully erosion was one-fifth of the total sediment yield during a 9-yr period. Erosion rates were dependent upon mass wasting of loessial gully banks and headcuts. For the nonconservation watersheds, tractive forces exerted by runoff on the channel boundary did not detach appreciable amounts of undisturbed soil but were more than adequate to entrain the soil debris yielded by mass-wasting processes. Gully erosion was minimal on conservation watersheds: the runoff was generally below the levels required for gully debris removal, and the degree of slope was reduced to a stable value. Soil mechanics principles, applied to strength/stability aspects of gully banks in western Iowa, indicate that the height of the water table, soil cohesive strength, and rate of water infiltration are controlling factors. Initial field and laboratory model experiments have provided insight into variables that affect the mass-wasting process.

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