Gully and streambank erosion

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The areal growth of drainageways is an easily recognized feature of landscape weathering; erosive forces initiate and sustain gully growth and widen stream channels. Drainageway erosion rates are controlled by the hydraulic characteristics of flow and by erosion-resistant properties of soil at the flow boundary. Sediment moving from upstream locations and base level changes caused by dredging or straightening must also be considered. Only in the simplest situation is the erosion rate solely attributable to predictable tractive forces acting upon discrete soil particles, because factors affecting gully and streambank erosion are not necessarily the same as those affecting scour resistance of the streambed. Most gully and streambank erosion is, of course, sustained by runoff, the transporting medium. But it is also related to gravitational and complex interparticle forces--electrochemical and atomic--that vary with both soil-water environment and time (*8*).

Attributes of these forces that have been related to erodibility of gullies and streambanks include Atterburg limits, plasticity index, soil pH, content of $CaCO_3$ and other minerals, dispersion ratio, measures of compressive and shear strength, and many special erodibility functions designed to define the physical, chemical, and environmental properties that determine the resistance to erosion of a streambank or gully head. Yet the properties that control soil erosion resistance have not been conclusively defined.

A special report (*13*) on streambank erosion problems in the U.S. attributed inadequate performance of some streambank erosion control projects to "a lack of understanding of the multiple and interrelated causes and effects of streambank erosion." Our objective is to discuss procedures for estimating erosion rates and to quantify gully and streambank erosion for several locations under study in Iowa and Mississippi. Streambed erosion of channels in noncohesive materials is not discussed.

General Complexities

Not all streams are eroding their banks, but streambank erosion from some 300,000 miles of channels in the U.S. produces an estimated 500 million tons of sediment annually (*1*), which is 1,670 tons per mile of eroding channel. In general, the erosion rate, as measured by bank recession, depends on the nature of the bank materials and the streamflow. Severe gully and streambank erosion problems exist in many parts of the world, although they are most predictable in the highly erodible loess soil regions or where the hydrologic balance of the drainageways and their watersheds is altered. The recession of streambanks can occur by direct or indirect action of flowing water. For example, (a) banks are undercut and collapse by gravity, (b) flow impinges directly on the banks, and (c) banks are saturated and weakened by streamflow or bank seepage. Additional factors contributing to streambank erosion are wave action, ice flows, freeze-thaw and wet-dry cycles, rapid changes in stage, debris, and sediment load.

Fluviomorphic studies at several locations (*5, 6*) show the basic cyclical nature of gully erosion. In western Iowa, Daniels reported that Harrison County had no gullies when the area was settled in about 1850 and that "gullies currently active have been active for about 50 years." The duration of the previous gully cycle in that area was less than 800 years, about 1,100 to 250 years ago. An important question to be answered: Is gully and streambank erosion, even if accelerated by man's intensive land use, still cyclic or has the balance been so disturbed, for example, by the increased levels of overland runoff from cropland, that accelerated weathering of the landscape is an irreversible trend? No general judgments can be made on this subject for all locations, but time-sequence comparisons of channel cross sections for a typical small stream in western Iowa, Steer Creek (*2*), show a recent history of continuous widening with no known natural restraints to prevent further channel growth (Table 1). Another report, of the Nishnabotna River Basin (*14*), shows that the width of the west fork of the river, near its confluence with the east fork, did not change appreciably from 1850 to 1921 but doubled in width by 1950. Similarly, the width of the east fork, as measured at three locations, essentially doubled from 1926 to 1951.

Another question to be answered: Is streambank erosion in northern Mississippi sufficiently controlled by aggradation processes so that the dredged channels will eventually reach a stable width? At present, many of these channels must be dredged to limit flooding. But the channels continue to widen between dredgings because successively larger portions of floods are conveyed through the channel, rather than over the floodplain, with resultant increases in velocity and shear stress that increase streambank erosion.

Estimating Procedures

Gully Erosion

Gully erosional changes have typically been obtained by periodic ground surveys, measurements to reference stakes or concrete-filled

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Table 1. Top widths of Steer Creek channel at selected stations from 1852-1961.

Selected Stations[a]	Channel Top Width (ft)					
	1852[b]	1932[c]	1938	1942	1949	1961
6 + 10	3	7	35	35	45	61
104 + 20	3	7	40	42	60	58
172 + 29	5	7	-	-	-	-
264 + 24	5	-	35	32	50	40
469 + 12	5	-	95	101	110	185

[a] Stationing begins at downstream point in watershed.

[b] Estimated from original land surveys.

[c] Estimated from interview.

holes located in the gully head and bank, and examinations of gully changes from existing maps and aerial photos. Estimations based on such measurements often have been limited in value because causative variables, such as runoff, groundwater, and antecedent conditions, were not also measured. However, studies are producing quantitative information, and some empirical prediction procedures have been advanced. In Mississippi, active gullies with little drainage area other than the raw gully head produced from 2 to 7 inches of sediment annually at the gully outlet; the erosion rate was related to gully relief, areal extent, and the nature of the exposed materials (*7*). For a severely gullied loessial area in Iowa, Beer (*3*) developed the relationship:

$$X_1 = 0.01X_4^{0.0982} X_6^{-0.044} X_8^{0.7954} X_{14}^{-0.2473} e^{-0.0360X_3}$$

where X_1 = gully surface growth (acres), X_3 = deviation of annual precipitation from normal (inches), X_4 = index of surface runoff (inches), X_6 = terraced watershed area (acres), X_8 = gully length (feet) at beginning of period, and X_{14} = length (feet) from gully head to watershed divide.

Thompson's study (*12*) of gully activity at several locations in the U.S. resulted in the relationship:

$$R = 0.15\ A^{0.49}\ S^{0.14}\ P^{0.74}\ E^{1.00}$$

where R = average annual gully head advance (feet), A = drainage area (acres), S = slope of approach channel (percent), P = the total annual rainfall of 0.5 inch or more during a 24-hour period, and E = clay content of eroding soil profile (percent by weight).

The Soil Conservation Service procedure (*10*) for estimating average annual gully advance rate involves the equation:

$$R = 1.5\ A^{0.46}\ P^{0.20}$$

where R and A are defined as above and P is the total annual rainfall of 0.5 inch or more over a 24-hour period that occurred during the time period, converted to an average annual basis (in inches).

The agency recognizes that other factors, inadequately defined, influence the headward advance of gullies; however, it accounts for these factors by using past gullying rates calculated from maps or aerial photos. The equation then becomes:

$$R_2 = R_1 \left(\frac{A_2}{A_1}\right)^{0.46} \left(\frac{P_2}{P_1}\right)^{0.20}$$

in which the subscripts 1 and 2 refer to past and future, respectively.

Streambank Erosion

About 2 percent of the 7 million miles of streambank in the U.S. have serious erosion problems (*13*). Although the quantities of sediment originating from the streambank erosion process usually are small, compared with those from the sheet-rill-gully erosion processes, they can cause significant problems.

No formal procedure for estimating streambank erosion has been developed. Bank recession rates usually are estimated on an average annual basis by comparing cross sections or planimetric details from ground surveys or aerial photos obtained over several years. Areal recession rates are converted to a volume or tonnage basis as needed. Estimating accuracies usually are low because small cross-sectional changes relative to the total cross-section can cause large variations in computed erosion. Also, the labor and expense of cross-sectioning, by either ground or photogrammetric survey, limits the cross-section frequency.

If no channel disturbances are contemplated, future streambank erosion rates are estimated on the basis of past erosion and hydrologic performance. Forecasting future streambank erosion rates for changed channel or flow conditions is often necessary, and using past erosion rates as a basis for estimates can be misleading. Then, criteria for estimating streambank erosion rates are based on channel boundary materials, hydraulic characteristics, contemplated runoff rates, the sediment load, and considerable judgment.

Gully and Streambank Erosion, Western Iowa

The rolling terrain bordering the Missouri River is characterized by a soil developed on a thick loess deposit that blankets the underlying glacial till. Surface runoff and erosion is severe on unprotected rowcrop fields in the region. Drainageways often are incised, ending upslope with an actively eroding gully headcut.

Erosion rates from four gullies in western Iowa were measured during the 10-year period from 1964 to 1973. Gully changes were determined by periodic surveys and by sampling streamflow at two locations on each drainageway--above the headcut and at the downstream measuring weir--to determine the amount of soil removed. Each gully drains a 75- to 150-acre watershed, and its erosion condition is described in table 2, along with the 10-year runoff-erosion summary. The gullies draining watersheds 1 and 2, as portrayed in figures 1 and 2 respectively, were the most erodible. Although the ratio of soil removed from the gully at watershed 3 was large compared with the total sediment yield from the watershed, the quantities were small. Based on these representative watersheds, we concluded that soil movement from gullies in western Iowa constitutes about 20 percent of the total sediment moving in streams of the region.

The pattern of gully erosion at watersheds 1 and 2 was dissimilar in one important respect--the gully draining watershed 1 was actively advancing upstream during the 10-year period while the gully of watershed 2 was eroding principally by lateral enlargement (Figure 2a). The reasons for these erosion differences cannot be explained by examining only two erodible gullies because several causative variables are different, although the gullies are on adjoining fields. Interpretations from hydrologic measurements and frequent streamflow samples, however, give some insights into the factors influencing sediment movement. Table 2 and figures 1 and 2 describe gully erosion at these locations. Other interesting aspects of gully erosion in these drainageways are (*9*):

1. The quantity of gully material removed during a given runoff event is a function of event size and prior storm occurrence.

2. Although the quantities of material removed from these gullies was loosely correlated with surface runoff, about 80 percent of the soil transported from the gully during the 10 years occurred during May and June. The May-June surface runoff during this time was about 55 percent of the annual average. May-June rainfall was 33 percent of the annual average.

3. The measured gully sediment movement during a storm is often uncorrelated with runoff rate or runoff tractive force. [In figure 1c, for example, at 1821 hours, gully soil was being swept past the measuring weir at the rate of 28 tons per minute; 6 minutes later, at the same runoff rate, only 10 tons per minute was being transported. During the May 18, 1971, storm at watershed 2 (Figure 2c) little gully material was transported after 0250 hours, although the runoff rate was nearly 200 cubic feet per second at the beginning of this period.]

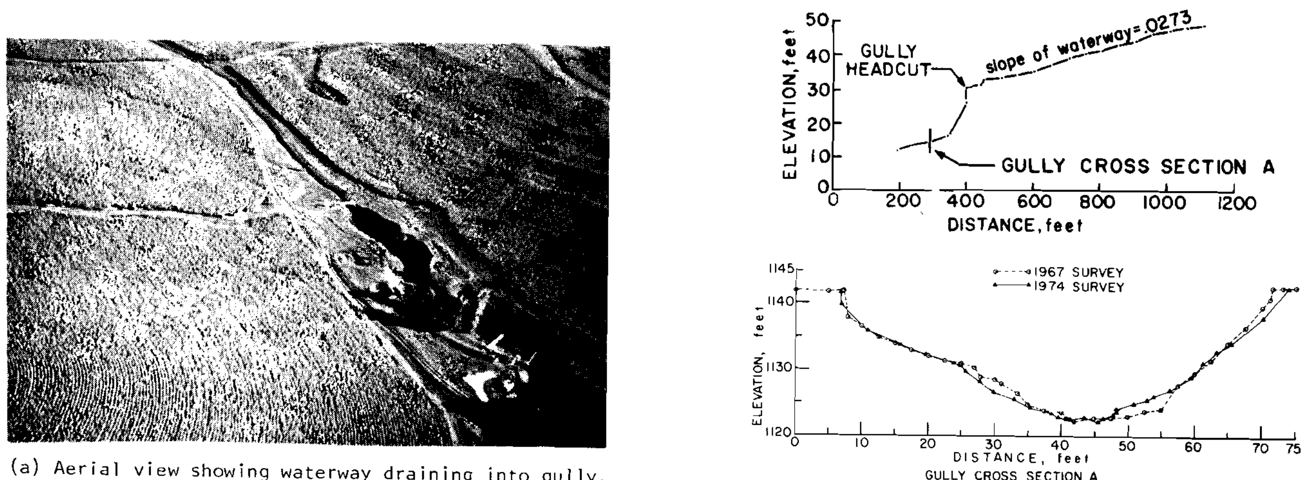
4. The quantities of soil removed from these gullies relative to the storm runoff size is greatest for the first spring storm and is greatly reduced for each subsequent event. This indicates that weathering actions during the fall and winter periods of low runoff may be significant.

Gully Headcut Advance

Gully headcut advance rates were best portrayed by the activity at the gully of watershed 1. During the 1964-1973 period, the gully headcut advanced about 170 feet toward the watershed divide and voided about one-fourth acre of land to a maximum depth of 20 feet. The greatest amount of gully erosion at water-

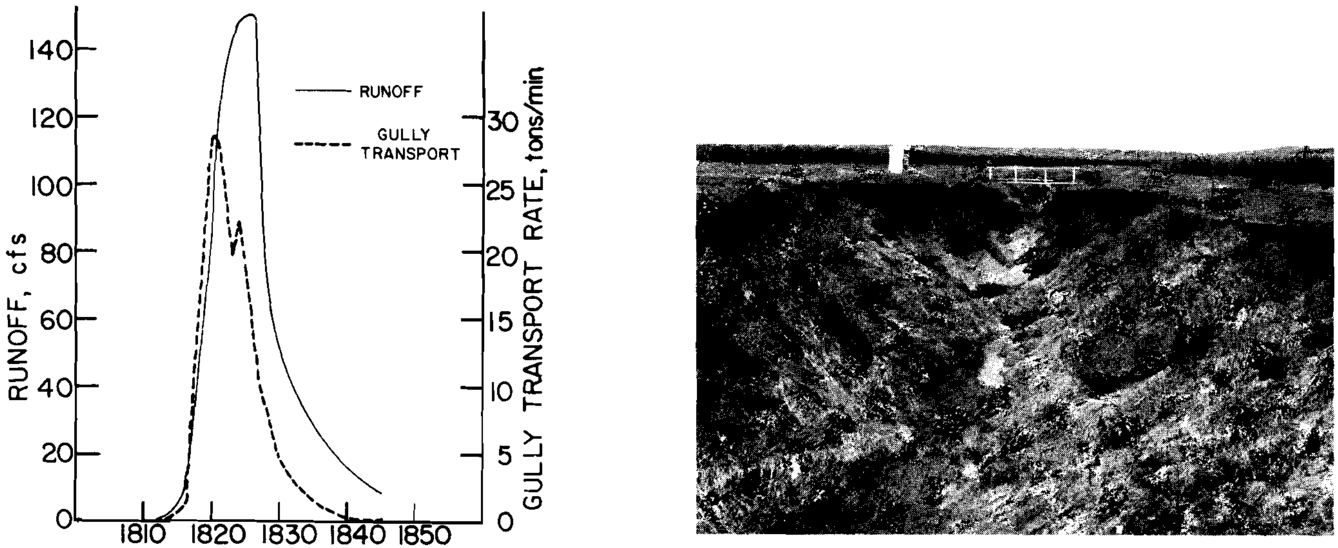
Table 2. Watersheds and outlet gullies near Treynor, Iowa.

Watershed			Gully		Runoff (in), 1964-1973		Gully Erosion, 1964-1973	
No.	Size (a)	Land Use and Treatment	Headcut	Banks	Subsurface	Storm	Total (t)	Percentage of Total Sediment Yield
1	74.5	Corn on approx. contour	Vertical, advancing, and raw	Eroding	30.0	42.3	4,620	21
2	82.8	Corn on approx. contour	Chutelike, nonadvancing & raw	Eroding	32.8	39.6	3,240	18
3	107.0	Rotation-grazed bromegrass, minimum-till corn after 1971	Stepped	Mostly Stable	43.5	14.6	310	33
4	150.0	Level-terraced corn, reduced terrace--Minimum-till after 1971	Stepped	Stable	67.0	13.0	120	6
	Total soil eroded and transported from gullies in 10 years						8,290	20



(a) Aerial view showing waterway draining into gully.

(b) Channel profile and gully cross section.



(c) Soil transported from gully during May 5, 1972 storm.

(d) Close-up of gully head and sampling footbridge.

Figure 1. Gully erosion, watershed 1 near Treynor, Iowa.

shed 1 occurred on June 20, 1967, when 420 tons of soil was removed from the vicinity of the headcut. This quantity was about 10 percent of total soil removed from the 75-acre watershed during the June 20 storm and was less than one-third of the gully erosion during the month, which had a record 20 inches of rainfall.

Most of the soil eroded from the gully head at watershed 1 was derived by successive slumping of soil blocks after they were wetted by rainfall and runoff. These blocks then migrated downslope during successive runoff events by the undercutting and liquefaction of lower-lying soil debris until the channel was essentially cleaned of debris.

Gully Lateral Enlargement

Gully lateral enlargement was best portrayed by the activity in the 700-foot study section of the watershed 2 gully. At the outset of the study, gully enlargement was not considered significant, so complete channel surveys were not made until 1966 (Figure 2a). But a more complete record of gully erosion was obtained from intensive sampling of streamflow beginning in 1965; 1964 was partially estimated. The greatest amount of gully erosion for a single storm event at the 82.8-acre watershed 2 occurred on June 20, 1967, when a 5.82-inch rainstorm caused 3.77 inches of runoff. The gully headcut remained essentially stable, but 690 tons of soil, or 1.0 ton per lineal foot of gully, was removed. For the 10-year period, 2.3 tons was eroded per lineal foot of channel.

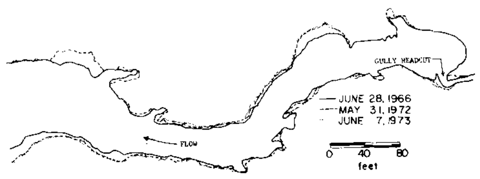
Gully bank enlargement rates were not uniform for the length of channel studied, and the microhydrology at each portion of bank must be carefully examined to rationalize the erosional changes that occur. At the points of greatest streambank recession in figure 2a, for example, small concentrations of runoff from a few thousand square feet of drainage area are absorbed into the soil profile of the grass strip that borders the gully. Inspections show that although there is little runoff over the edge of the gully the added soil moisture to the gully bank reduces the soil shearing resistance and increases the driving force (weight) of the mass. After initial failure of the gully wall, the soil debris gradually migrates downslope and is carried from the channel.

Streambank Erosion

Streambank erosion on large and small drainageways in western Iowa has been discussed by a number of researchers. Taylor (*11*) showed that 48 percent of the sediment transported from the 7,000-acre Steer Creek watershed originated from the channels during the 2-year period 1965-1967; sheet-rill erosion accounted for the remainder. A comparison of cross sections of larger rivers, including the Nishnabotna, shows that these channels are enlarging (*14*). Beer (*2*) closely examined historic records and aerial photos of the Steer Creek channels in Harrison County, Iowa, to show their growth since the original survey in 1852. Beer's measurements through 1961 (Table 1) show a steady increase in channel width. Evidence presented by Beer (*2*) shows that little channel change occurred between time of settlement and 1906, with most erosion occurring since 1932.

Gully and Streambank Erosion, North Central Mississippi

Measurements of gully and channel erosion have been made for several years at locations in the loess hills region of north central Mississippi. This region, lying east of the Mississippi River Delta, was intensively farmed to cotton more than a century ago, before the more fertile lowlands could be drained and used. It was eroded extensively prior to 1900, and at many locations the loess mantle has eroded to the underlying Coastal Plain sands. Gully headcuts of the region have migrated nearly to the drainage divides so that practically no water



PERIOD	AREAL CHANGE square-feet	SURFACE RUNOFF acre-feet	GULLY EROSION tons
June 28, 1966-May 31, 1972	4,360	140	2,000
June 1, 1972-Dec. 31, 1972	1,000	7	5
Jan. 1, 1972-June 7, 1973		13	(Estimated) 5
TOTALS	5,360	160	2,010

Figure 2a.--Measured gully advances and erosion rates.

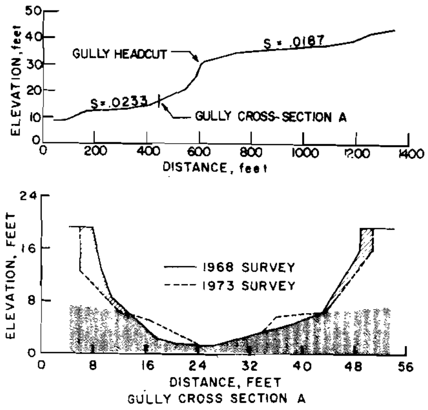


Figure 2b.--Channel profile and gully cross section.

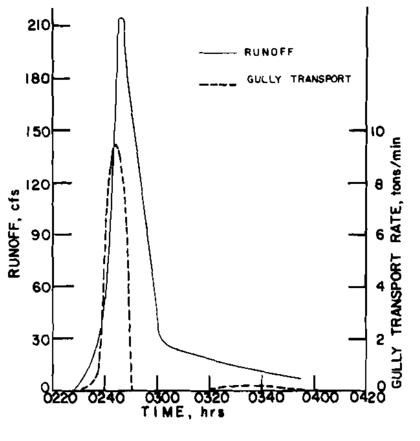
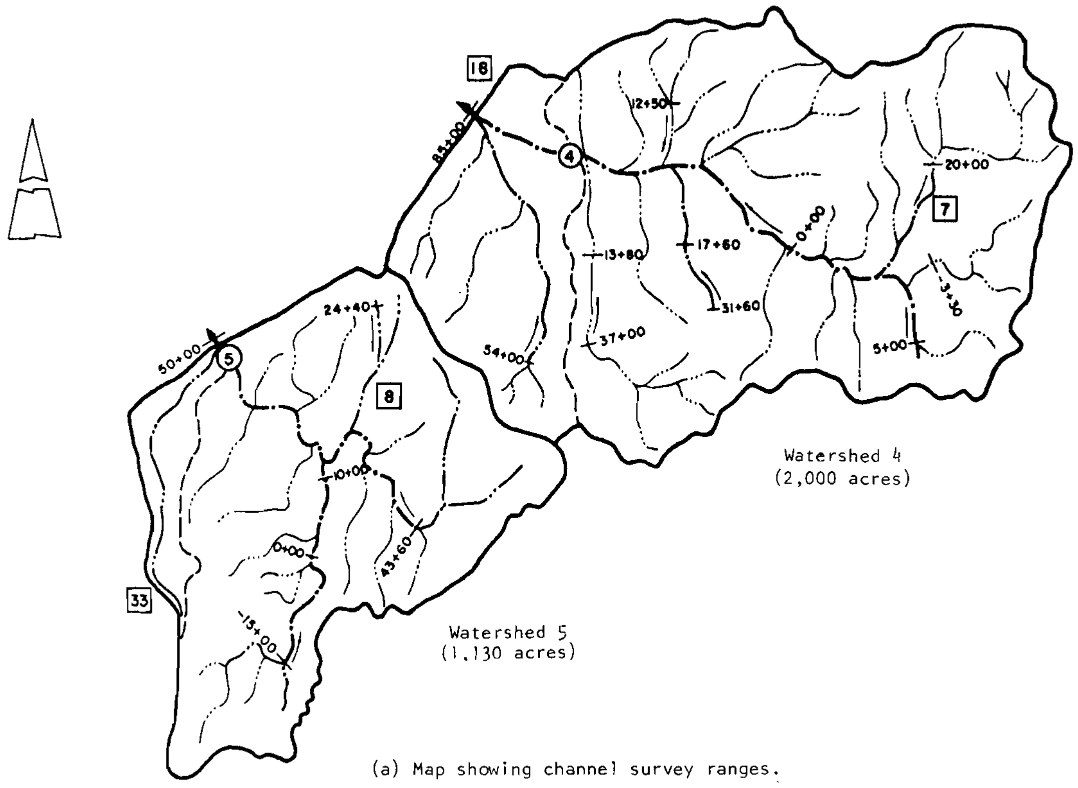


Figure 2c.--Gully erosion for storm of May 18, 1972.

Figure 2d.--Aerial Photo.

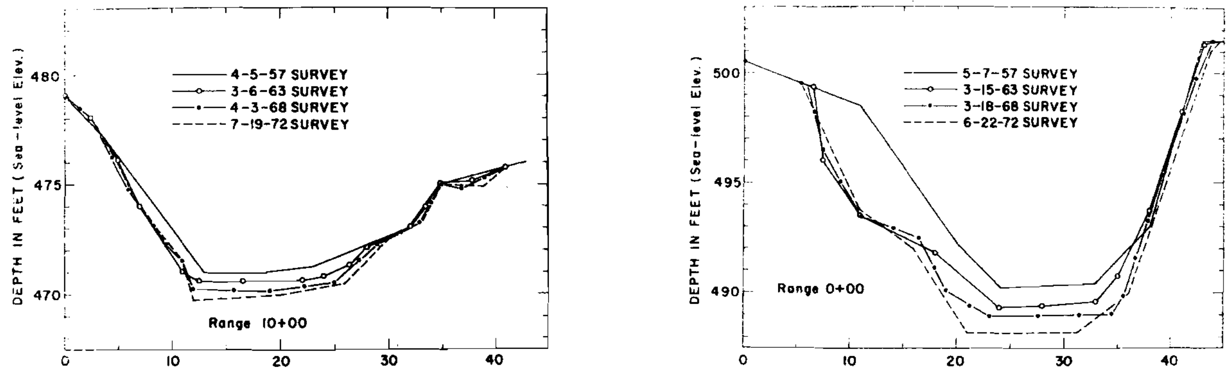
Figure 2. Watershed 2 near Treynor, Iowa.



(a) Map showing channel survey ranges.

(b) Channel at Watershed 5 gaging site.

(c) Typical channel at Watershed 4.



(d) CHANNEL 5 - AVERAGE CROSS SECTION IN FEET

(e) CHANNEL 4 - AVERAGE CROSS SECTION IN FEET

Figure 3. Watersheds 4 and 5, Pigeon Roost Creek Basin, Mississippi.

flows into the gully, and almost all gully erosion is attributable to raindrop impact and slope wash. The upper reaches of drainageways in the region are degrading and the channels are enlarging. The lower channel reaches tend to fill with sand, but the necessity of providing drainage by periodic dredging has increased streambank erosion and the sediment content of streamflow. Measurements of streambank erosion on three channels in the Pigeon Roost Creek Basin, Marshall County, Mississippi, are summarized in table 3.

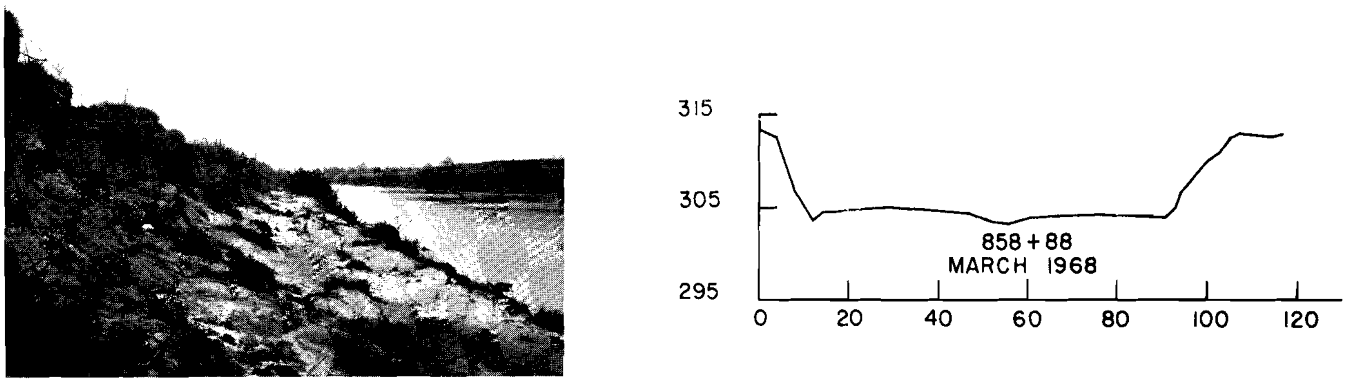
Streambank erosion rates from 6.1 miles of natural channel, 1957-1972, were determined at Pigeon Roost Creek subwatersheds 4 (3.5 miles) and 5 (2.6 miles). These erosion rates were compared with those from 3.9 miles of dredged and straightened channel of watershed 34, which is typical of larger streams of the region. Quantitative estimates of streambank erosion rates for channels 4 and 5 were obtained from channel cross sections spaced about 500 feet apart and surveyed at approximate 5-year intervals (Figure 3). Streambank erosion rates for channel 34 were determined from similar surveys in 1970 and 1972. Quantities were based on the average change in area, as reflected by resurveys, assuming a unit weight of 90 pounds per cubic foot for the eroded soil. An example of the increased channel area due to dredging and widening near gaging station 34 is shown in figure 4.

The periods of streambank erosion measurement were not concurrent, so several methods for comparing erosion rates in the channel reaches were considered. Watersheds 4 and 5, which are adjoining, experienced 260 tons and 130 tons erosion per channel mile per year, respectively. In terms of contribution to the turbidity of streamflow, the runoff-weighted concentration of the sediment eroded from the study reaches were 990 ppm and 260 ppm, respectively, for channels 4 and 5. For each watershed, the streambank sediment contributed to streamflow was 19 percent and 5 percent, respectively, of the measured sediment discharge.

Differences in streambank erosion rates between channels 4 and 5 may be attributed

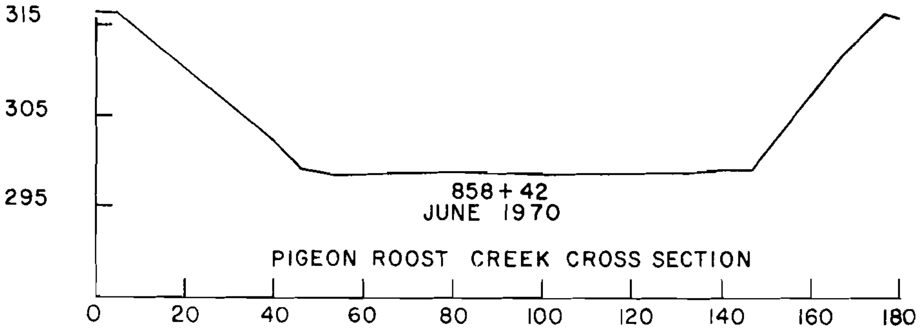
Table 3. Streambank erosion measurements for three channel reaches, Pigeon Roost Creek Basin.

Explanation	Watershed 4	Watershed 5	Watershed 34
Watershed size, acres contributing	1,580	1,000	74,900
Period of study	10-1-57-- 9-30-72 (15 yrs)	10-1-57-- 9-30-72 (15 yrs)	10-1-70-- 9-30-72 (2 yrs)
Total storm runoff through study reach, inches (from nearby gaging station)	78.3	168.7	13.8
Total measured sediment discharge, ton/acre (at gaging station)	45.2	98.0	9.6
Length of channel surveyed, miles	3.50	2.57	3.90
Length of eroded bank in surveyed channel, miles	4.63	2.91	6.00
Length of stable bank in surveyed channel, miles	2.37	2.23	1.80
Av. channel gradient ft./ft.	.0046	.0047	.0015
Total streambank erosion:			
a. surveyed reach, tons	13,900	5,000	44,500
b. tons per bank mile eroded	3,000	1,720	7,430
c. tons per bank mile per year	200	114	3,720
d. tons per channel mile per year	260	130	5,700
Portion of measured watershed sediment yield, percentage	19	5	6
Erosion, tons/inch runoff/channel mile	50.9	11.5	825
Erosion, tons/inch runoff/bank mile	38.4	10.2	536
Average concentration of streamflow due to sediment eroded from study reach, ppm	992	262	378



(a) Typical channel reach.

(b) Cross section before dredging.



(c) Cross section after dredging, channel widening was by streambank erosion.

Figure 4. Streambank erosion on dredged reach of channel 34.

partially to land use differences in the watersheds. Watershed 4 has less cultivated and more forested land, 15 percent and 45 percent of total watershed acreage, respectively. About 25 percent of watershed 5 is cultivated and 25 percent is forested. Most of the remainder on both watersheds is pasture or idle land, with some 2 percent in gullies. The improved cover condition of watershed 4 helped reduce the amount of eroded material reaching the channel system and thereby increased the competence of the stream to scour its channel. Conversely, the greater soil losses from watershed 5 fields probably decreased proportionately the capacity of the flowing water to transport streambed and streambank material. The runoff response reflects these land use differences. The storm runoff per unit area from watershed 5 is double that from watershed 4, as noted in table 3 and explained by Bowie and his colleagues (*4*).

These average annual streambank erosion rates on natural channels 4 and 5 are not impressive when compared with the estimated national average of 1,670 tons per mile of eroding "problem channel" (*1*), although the concentrations and sediment tonnages involved can adversely affect water quality and cause problems downstream. However, the streambank erosion rate from the 3.9-mile dredged reach of channel 34 is more than triple the national average, or 5,700 tons per channel mile per year. In the dredging operation, the natural vegetation along channel banks is removed, and the banks are unprotected for a time. The flow regime through the newly dredged channel also was altered, and the increased capacity to carry floodflows rather than spread them over the floodplain resulted in increased velocities. Measurements at the nearby gaging station show an increase in mean velocity at bankful stage from 8 feet per second before dredging to more than 13 feet per second afterward. Other factors affecting streambank erosion include the relatively long duration of floodflows from the drainage area above channel 34 and characteristics of the sediment transported in the stream.

The water content of streambanks in channel 34 usually remains relatively high between storm runoff events. The occasional long duration of high stages increases the streambank moisture content to saturation, and with the resulting reduction in shear strength, the increased weight of the saturated streambank causes large sections of the bank to slide into the stream. Streambank erosion rates are related (*13*) to the total quantity of sediment in transport and the ratio of bed load to suspended load. Also, a reduction in sediment inflow can increase the energy of streamflow available to erode the channel boundary. If a wide channel is necessary for the efficient transport of a large bed load, any change that reduces the suspended load reaching a channel system could induce movement of bed material, thereby creating conditions that could cause the channel to widen. A conservation land use, therefore, would be one of the factors contributing to this condition.

Summary

Reliable procedures for estimating gully and streambank erosion rates for any given set of existing or anticipated hydrologic circumstances are unavailable because the basic factors affecting erosion are not well defined. The severity of gully and streambank erosion problems were shown to vary among several regions.

Gully erosion of the smaller drainageways in western Iowa, estimated on the basis of measurements from representative watersheds, was about one-fifth of the total sediment yield. Streambank erosion downstream was a smaller portion of the total, but a significant quantity in terms of pollution potential. Moreover, many streams in the region will most likely continue to enlarge because no restraints to further growth are foreseen.

Gully erosion has long been a problem in north central Mississippi. Most gully heads have advanced to near the drainage divide, and the 2- to 7-inch erosion rate, based on the areal extent of the eroding headcut, depends on rainfall splash and the runoff generated. The magnitude of streambank erosion on small, naturally degrading drainageways in the region is relatively low. Because deposition occurs in most of the larger drainageways and they must be dredged periodically, a high rate of streambank erosion results. Principal reasons for the increased streambank erosion rates are increased channel conveyance and attendant increases in runoff velocities and tractive forces, reduced vegetative cover on dredged streambanks, and a change in the sediment content of runoff due to land use changes.

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