Gully Development in the Deep Loess Hills Region of Central Missouri[1]

G. ROLOFF, J. M. BRADFORD, AND C. L. SCRIVNER[2]

ABSTRACT

A small gully in a headslope position in loess over glacial till was instrumented to monitor the downslope flow of water within the soil profile (throughflow) and sampled to investigate soil properties related to the processes of gully development. The importance of local stratigraphy to subsurface water movement and the relations of both to localized failure events were examined. Throughflow convergence toward the gully head was the predominant factor in lessening soil strength and in precipitating gully failure events. The exact failure mechanisms were not clear. Failure occurred along cracks created by either freezing-thawing or wetting-drying cycles.

Overland flow was responsible for the removal of failure debris but not for bank erosion.

Additional Index Words: **soil strength, geomorphology, erosion, slope stability, ground water.**

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BECAUSE SEVERAL GEOMORPHIC and man-induced factors are involved in gullying processes, fully understanding such processes and their interactions is a difficult task. Daniels and Jordan (1966) suggested that gully formation is part of the normal landscape evolution in the thick loessial region of Iowa, with man's activities either triggering or hastening the geomorphic processes actuated in gullying cycles (Piest et al., 1975).

Stratigraphy influences gullying processes in most landscapes. In the Treynor, Iowa, area of Land Resources Area M-107, Iowa and Missouri deep loess hills (Soil Survey Staff, 1965), the growth rate of valley-bottom gullies and the geometry of the walls are controlled by the relative soil strengths, permeabilities, thicknesses, and structural features of the different units of the Deforest formation alluvium, a recent loess-derived alluvium (Bradford et al., 1978, and Bradford and Piest, 1980). Valley-side gullies normally are developed entirely within Wisconsin age loess. Loess or loess-derived soils became very low in strength when saturated, which increases the susceptibility of the gully banks to mass wasting. Overland flow is responsible only for the transport of the fallen debris (Bradford et al., 1978). The absence of overland flow will interrupt the sequence of mass wasting and debris transport and stabilize the gully system.

Gullying is also a frequent erosion phenomenon in the deep loess hills region of central Missouri, degrading valuable farmland and increasing sediment load in local streams. Valley-bottom gullies cut through local alluvium; in the lower landscape positions gully development processes are essentially the same as reported for Iowa's alluvial drainageways. Valley-side and valley-head gullies normally cut into natural loess and eventually into the underlying glacial till. The surface area affected can be considerable, especially when gully bottoms reach the till that decreases downcutting rates and increases widening rates. The widespread gullying in upper landscape positions, with shallow gully bottoms and small drainage areas above gully heads, is probably a regional peculiarity.

This study was an attempt to assess the influence of the local stratigraphy and regolith characteristics upon gully development. Special attention was given to the interactions between stratigraphy and throughflow movement and to soil properties related to gully wall stability.

MATERIALS AND METHODS

An undisturbed valley-head gully about 2 m deep and 3 m wide was selected in an area 570 m north and 100 m west of the southeast corner of sec. 22, T. 50 N., R. 17 W., Franklin Quadrangle, about 3 km east of Highway 87 at a point approximately 12 km south of Glasgow, Missouri, in Howard County. The drainage area above the study gully head was less than 70 m^2.

Two main stratigraphic units are recognized in the area: a thick loessial layer atop a till-derived clayey paleosol. The glacial till was deposited during Kansan time (Frye et al., 1968), and the paleosol could have evolved during Yarmouth-Sangamon times or later depending upon the erosional history (Ruhe, 1969). The loessial layer is of Wisconsin age (Heim, 1961), but its more precise nature and time of deposition are unclear. It is possible that the loessial layer is mostly Peoria loess, the predominant loess in central Missouri.

In the east-west cross section perpendicular to the gully longitudinal axis (Fig. 1), the buried paleosol surface was almost parallel to the modern surface (Fig. 2) as determined by holes drilled for instrument placement and other additional borings. The buried surface appeared depressed at about the gully head. Along the gully axis (north-south cross section in Fig. 1), the buried surface was flat at the summit, dipping suddenly just upslope from the gully head.

The soil at the summit, where the loess thickness was about 4.7 m, was a fine silty, mixed, mesic Typic Hapludalf[3] and was classified as the Winfield series (Soil Survey Staff, 1978). The loess thicknesses decreased to about 2.8 m at the gully head, and at that position the soil was classified as fine, mixed, mesic Aeric Ochraqualf, according to the profile description on Table 1. The low chroma colors throughout the B horizons suggested a wetter regime than expected on a summit position.

The gully was instrumented with three water wells and nine groups of piezometers and tensiometers in three rows of three batteries each, all upslope from the gully head (Fig. 1). Piezometers and tensiometers were used to monitor positive and negative pressure heads, respectively. Such an arrangement was a modification of the set up used by Bradford and Piest (1977) to investigate gully wall stability. In the present study, each battery consisted of three piezometers and three tensiometers placed sequentially in 0.5-m increments from near the till-derived paleosol upward to the present surface; the piezometers were in the three lowermost depths. Corresponding instruments in all batteries were placed at identical elevations (Fig. 3).

The tensiometers and piezometers were read weekly from 1 Sept. 1977 until 1 Dec. 1977 and again in March 1978. Rainfall data was recorded with a rain gage. Additional surface water was applied to a 20-m wide by 10-m long area upslope from the gully head from 15 Oct. to 9 Nov. 1977. About 10 mm of water were trickled across the surface 20 by 10 m area daily.

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[2] Former Graduate Student, Univ. of Missouri, presently Visiting Professor, Universidade Federal do Paraná, Caixa Postal 672,80000 Curitiba-PR, Brazil; Soil Scientist, USDA-SEA-AR, Dep. of Agronomy, Purdue Univ., West Lafayette, IN 47907; and Professor of Agronomy, Univ. of Missouri, Columbia, MO 65211.

[3] R. Renkoski, 1978, Univ. of Missouri, personal communication.

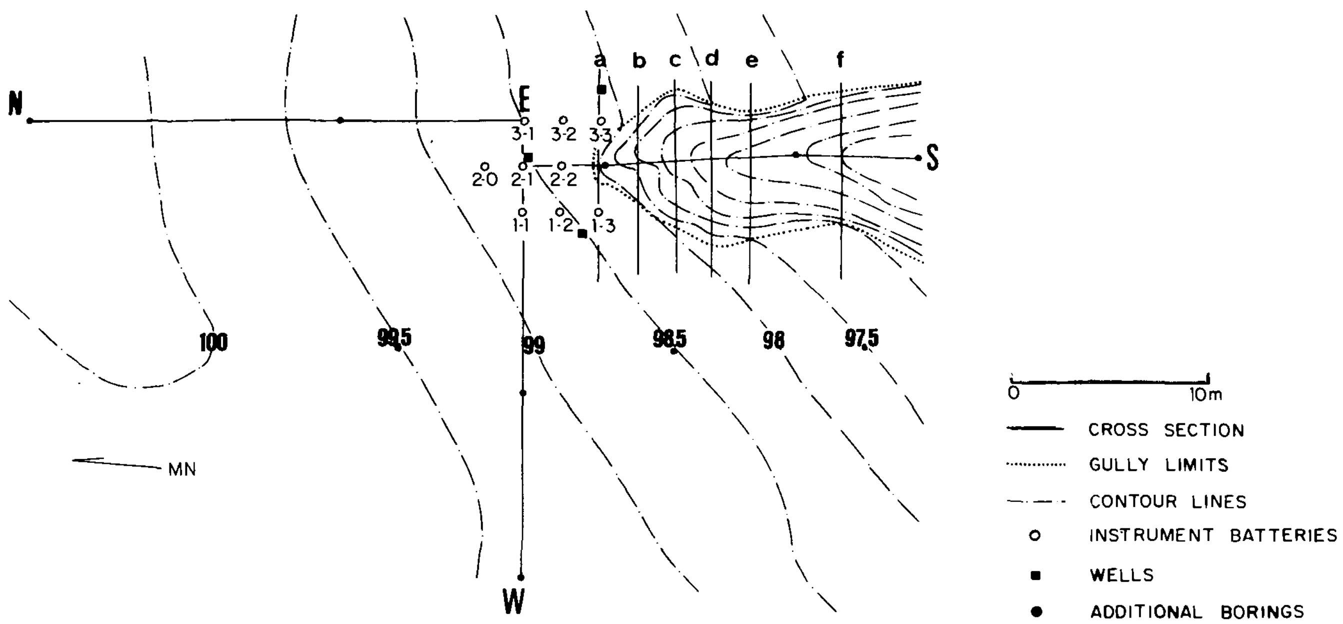

Fig. 1—Localization of instruments, cross sections, and additional borings and morphology of gully at the study site. Contour lines in 0.5-m intervals above arbitrary datum (MN = magnetic north).

In late spring of 1978 a pit was dug at the gully head for profile description, and samples were taken for physical, chemical, mineralogical, and mechanical analyses; methodologies and references are given in Table 2.

Direct shear tests were used to assess strength characteristics of soil layers and to provide parameters for slope stability analyses. Large blocks of soil from the B3, C2, and IIBb horizons were carved from the pit. Cores were then hand trimmed from the undisturbed samples to fit the shear box. The shear box used in this study was a standard Wykeham Farrance[4] Shear Box Apparatus (model WF 2500). All tests were run on 6.36-cm diam and 2.00-cm thick cylindrical specimens. The samples were immersed in deaired water for 2 to 4 days, consolidated under a known load for 2 to 5 days, and sheared at a strain rate of 0.0005 cm/min for the B3 and C2 horizons and 0.00005 cm/min for the IIBb horizon. Detailed procedures are described in Bradford (1980).

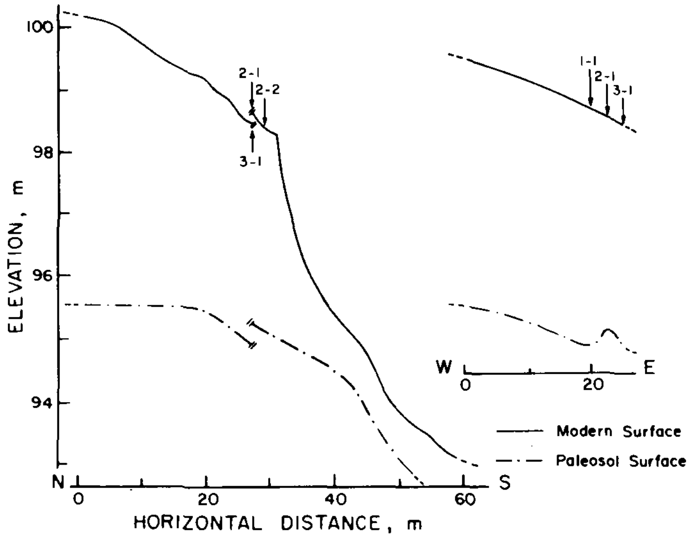

Fig. 2—North-south and east-west cross sections of a gully headwall, showing the relation of the modern to the buried paleosol surfaces. Instrument battery numbers are shown above the modern surface.

RESULTS AND DISCUSSION

Water Movement

The buried paleosol had a clay content about twice as great as the overlying loessial layer, and most of the clay fraction was montmorillonitic (Table 3). Visual observations at the site area indicated that (i) the paleosol restricted the downward movement of water

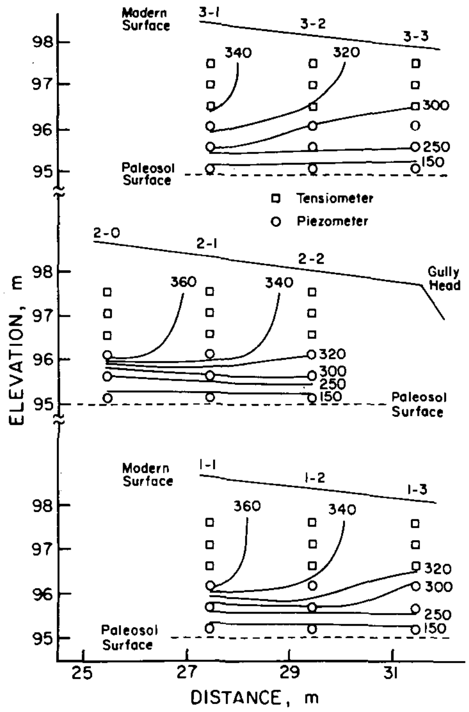

Fig. 3—Lines of equal pressure head (centimeters of water) for 8 Nov. 1977, at locations above the gully headwall. Open and full dots represent piezometers and tensiometers, respectively. Modern and paleosol surfaces are shown by thin and dotted lines, respectively. Instrument battery numbers are shown above the modern surface.

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[4] Trade names and company names are included for the benefit of the reader and do not imply endorsement or preferential treatment of the product by the USDA.

Table 1—Soil profile description from the gully headwall.

Horizon	Depth, cm	Description
Ap	0-10	Dark yellowish brown (10YR 4/4) silt loam; weak fine granular structure; many root and worm channels; clear smooth boundary.
B11	10-27	Dark brown (7.5YR 4/3) silty clay loam; moderate fine subangular blocky structure; few prominent black (10YR 2/1) mottles; many root and worm channels; clear smooth boundary.
B12	27-49	Dark brown (7.5YR 4/4) and brown (10YR 5/3) silty clay loam; moderate medium subangular blocky structure; few root and worm channels; common fine prominent black (10YR 2/1) mottles; clear smooth boundary.
B2t	49-80	Dark yellowish brown (10YR 4/6) and light brownish gray (2.5YR 6/2) silty clay loam; moderate medium subangular blocky structure; common fine prominent black (10YR 2/1) mottles; few root and worm channels; thin continuous clay films on faces of peds; gradual smooth boundary.
B3	80-139	Dark yellowish brown (10YR 4/6) and light brownish gray (2.5YR 6/2) silty clay loam; weak coarse blocky structure; common fine prominent black (10YR 2/1) mottles; clay films lining old root channels and some vertical faces; diffuse boundary.
C1	139-150	Light brownish gray (2.5Y 6/2) silt loam; many medium distinct dark yellowish brown mottles; massive; diffuse boundary.
C2	150-190	Brown (10YR 5/3) silt loam; massive; many small pores lined with clay films; gradual smooth boundary.
C3	190-283	Brown (10YR 5/3) silt loam; few medium prominent black (10YR 2/1) mottles; massive; some pores lined with clay films.
IIAb	283-320	Yellowish brown (10YR 5/4) silty clay loam; weak medium subangular blocky structure; few medium prominent black (10YR 2/1) mottles; few pores lined with clay films; clear smooth boundary.
IIBb	>320	Dark yellowish brown (10YR 4/4) clay; weak medium to coarse blocky structure; few fine prominent black (10YR 2/1) mottles; few round pebbles (1-2 cm in diameter); ped surfaces shiny due to abundant clay or slickenslides.

Table 2—Analyses performed, methodologies, and references.

1. Particle size—hydrometer method (Day, 1965, p. 562).
2. Bulk density—core method (Blake, 1965, p. 375).
3. Salt pH, extractable phosphorus, exchangeable cations, organic matter —routine procedures (Brown et al., 1977).
4. Mineralogy of the clay fraction—X-ray diffraction (Whittig, 1965, p. 689).
5. Direct shear test—consolidated-drained (Bowles, 1978, p. 175); 2-day saturation period; rate of shear 0.0005 cm/min for B3 and C2, 0.00005 cm/min for IIBb; using specimens trimmed from undisturbed soil blocks.

due to its low vertical hydraulic conductivity, (ii) the paleosol perched a water table during most of the year, and (iii) the paleosol was normally unsaturated. In many of the gullies in the area, seepage zones occurred on the faces of the walls above the paleosol surface. Scott[5] and Gilbert[6] documented the saturation of soils above the paleosol in similar settings due to the restricted downward movement of water. Even after a month of very little rainfall, water well readings indicated the presence of a water table about 1 m above the surface of the IIBb horizon. The water table rose significantly upon the application of surface water, eventually reaching the surface at the well (Fig. 2) located about 4 m upslope from the gully head (after 147 mm of rain in 9 days from 31 Oct. to 8 Nov.).

Piezometric head data recorded on 8 November were used to plot equipotential lines by graphic interpolation, assuming that each row of instruments materialized a vertical plane running from the gully head and parallel to the gully axis (Fig. 3). Pressure head was greatest in the upslope piezometers about 1 m above the IIBb surface in all three planes. Above this point, pressure head values were coincidental with depth from surface, i.e., there was free water.

Examining the equipotential lines in Fig. 3, we see that water flow was downward toward the paleosol and the lower gully headwall at the paleosol interface. Throughflow was slightly directed from plane 1 toward plane 2 and from plane 2 toward plane 3. This was probably due to the direction of surface water flow from the higher elevation of plane 1 and the lower elevation of plane 3.

Since the flow conditions were in the transient state, the high water potential gradients above the paleosol implied a low hydraulic conductivity and unsaturation in the paleosol.

Gully Wall Stability

Loess and its derived soils are subject to loss of strength upon water addition because the clay bonds weaken (Sheeler, 1968). Bradford et al. (1978) suggested that a decrease in soil strength due to infiltration or a rise in the water table is a major factor in gully wall failure in the deep loess hills region of western Iowa. The behavior of the equipotential lines in our study indicated that water concentration at or

Table 3—Physical, mineralogical, and chemical properties of soil samples from the gully headwall profile.†

Horizon	Depth	Clay	Bulk density	Mineralogy§	pH	Organic matter	P	Ca^{2+}	Mg^{2+}	K^+
	cm	%	g/cm^3			%	ppm	meq/100 g		
Ap	0-10	28	1.35	M > K > MI	5.4	2.1	17	6.2	2.8	0.4
B11	10-27	36	--‡	M > K > MI	5.0	1.1	13	8.5	4.4	0.3
B12	27-49	36	--	M > K > MI	4.8	0.6	37	8.1	4.6	0.3
B2t	49-80	38	--	M > K > MI	4.8	0.5	65	8.9	5.1	0.3
B3	80-139	29	1.38	M > K = MI	5.2	0.5	127	8.3	4.8	0.3
C1	139-150	26	--	M ≫ K > MI	5.3	0.7	85	7.6	4.4	0.2
C2	150-190	28	1.44	M ≫ K = MI	5.6	0.6	126	7.2	3.9	0.2
C3	190-283	24	1.45	M ≫ K = MI > V	5.6	0.7	69	6.1	3.1	0.1
IIAb	283-320	31	--	M > K	5.7	1.6	3	9.3	4.1	0.2
IIBb	>320	64	1.46	M > K	5.4	0.7	1	18.4	7.8	0.9

† Values listed are averages of at least three replications, except for mineralogy.

‡ Not sampled.

§ M = montmorillonite, K = kaolinite, MI = mica, V = vermiculite, ≫ = more than twice as much. Relative amounts were estimated from peak heights, comparing K and MI in a 1:1 basis, and M and K in a 4:1 basis.

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[5] Scott, J. W. 1963. A characterization of selected soils with respect to drainage class. M.S. Thesis. Univ. of Missouri, Columbia.

[6] Gilbert, F. L. 1966. Soil moisture characterization of a northwest Missouri landscape. M.S. Thesis. Univ. of Missouri, Columbia.

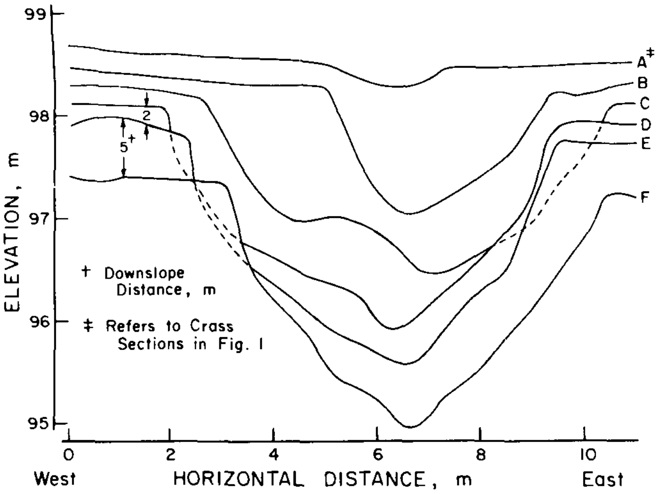

Fig. 4—Gully cross sections transversal to the axis downslope from the gully head.

near the gully headwall should decrease the stability, eventually producing slope failure. Cross section A on Fig. 4 was located at the gully headcut. Failure debris were responsible for sidewall slopes that were less steep on the left side of cross sections C, D, and E than on the right and for the ridges present on the bottom of cross sections C and D. We could see that such debris had recently fallen and had not been removed by overland flow. Visual observation also showed that the failures occurred at a wetter zone within the profile caused by throughflow concentration from upslope.

Results of the consolidated, drained direct shear tests on the undisturbed samples (Fig. 5) indicated that the internal friction angles (ϕ) of the B3 and IIBb horizons were equal, whereas that of C2 was greater. The lower ϕ indicates reduced particle interlocking and particle-to-particle sliding friction during shear. Physical, chemical, and mineralogical properties of the soil influence ϕ, but macrostructural aspects of the soil also have a major influence (Spangler and Handy, 1973; Bradford, 1980). The low cohesion value for the IIBb horizon can partly be explained by the high content of clay that was mostly montmorillonite. The distance between particles increases and cohesion is reduced when montmorillonite swells upon saturation. The soil samples in direct shear were first saturated and then consolidated and sheared. However, the IIBb horizon, under a consolidating pressure of 1450 g/cm^2, swelled upon the addition of water. The relatively greater amount of montmorillonite present in the clay fraction of the C2 horizon compared with the B3 horizon reduced cohesion in a similar way. Other factors might affect both friction angles and cohesion, but analysis of such factors was beyond the scope of this study.

Stability of the gully walls was analyzed, assuming (i) slab failure (Lohnes and Handy, 1968) through the slope toe and (ii) deep rotational slip failure (Bailey and Christian, 1969). The maximum height of a vertical cut before slab failure was calculated by the Culmann method (Carson, 1971), assuming the depth of the tension crack (Z) is zero. Isotropy was also assumed since the method does not handle anisotropic soil conditions. Results indicated that a vertical bank of B3 horizon soil would have to be 6.3 m high before failing and the C2 horizon 4.5 m high in the absence of vertical cracks. Under the assumption that the depth of the tension crack is

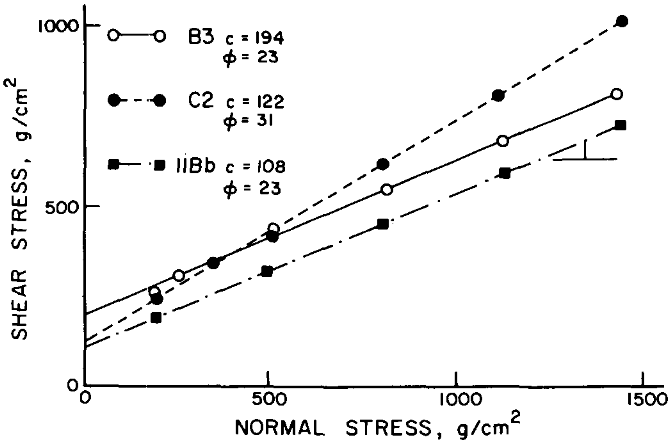

Fig. 5—Results of the direct shear tests for three horizons of the gully headwall. *c* represents cohesion (y-intercept), and ϕ is the angle of internal friction (slope of line).

$$Z = (2c/\gamma) \tan [45^\circ + (\phi/2)]$$

where c is the soil cohesion, ϕ is the soil friction angle, and γ is the unit weight of the soil mass. The critical heights for vertical banks in B3 and C2 horizons assuming slab failure through the toe are 3.1 m and 2.2 m.

To test whether instability can be predicted by a circular arc type failure, the simplified Bishop method of slices was applied to different slopes using a computer program (Bailey and Christian, 1969). The headwall slope (42°) was found to be stable even under additional stress produced by the pressure head.

The assumptions of slab failure without tensile cracks and of deep-seated, circular arc failure overestimated maximum wall heights. The gully under study and others within the same setting had walls shorter (3 m high at most) than the shortest predicted stable walls; however, they were nevertheless unstable. The actual slope heights are comparable to those predicted for vertical slopes with the crack depth equal to the tensile stress depth. Since the slopes were not vertical and the failure zone was not a trapezoidal slab, the above mechanism also seems inappropriate for describing failure.

Failures occurred in small slabs ranging from roughly 0.3 to 1.5 m in length, 0.2 to 1.0 m in width, and 0.1 to 0.5 m thick. Failure events usually followed rainy periods, and the bottom of the failure slab coincided with the seepage zone. During winter and early spring, freezing and thawing seemed to control failure; during the summer and fall, the shrinking and swelling due to cycles of soil drying and wetting promoted cracking. Failure planes followed natural cleavage planes within the soil mass, as similarly reported by Bradford and Piest (1977). Thus under these conditions, gully failure was highly unpredictable.

The measured cross sections of the study gully and a quick survey of gullies within the same drainage basin revealed that gully walls higher than about 1 m had slope angles ranging from 40° to 50° and were made up primarily of weathered failure debris. Most walls shorter than 1 m were of natural soil and were nearly vertical. The soils in this setting are noncalcareous.[7] Daniels (1966) reported that gully walls in leached soils of southwestern Iowa do not stand vertically; in unleached loess calcium carbonate cements the structure and adds strength to the soil (Turnbull, 1968). Soil collapsibility as a cause for gully wall instability according to Handy's (1973) criteria, however, was not important in the landscape of our study; the B11, B12, B2t and IIBb horizons were safe from collapse (clay content > 32%), whereas the other horizons had a low chance of collapsing upon saturation. Also, the bulk densities were higher than those subject to collapse.

Gully wall stability seemed to be indirectly related to overland flow. The runoff and debris transport processes described for the thick loessial area near Treynor, Iowa (Piest et al., 1975) appeared to be operative in this central Missouri site. No streamflow samples from gullied watersheds have been collected; however, visual observations indicated that the shearing or tractive forces of runoff on the gully boundaries were not the major forces causing gully erosion. There was no evidence of large amounts of soil scoured from the gully boundary. Gully erosion depended on debris supply, and the cleanout of this debris depended on sufficient runoff to entrain and transport this debris. The drainage areas above the valley-head gullies were small; however, the debris volumes to be transported were also small compared with the Treynor, Iowa loessial area.

CONCLUSIONS

1) In this upper landscape position, throughflow was controlled by the buried paleosol surface. The convergence of throughflow to the gully lower headwall was (i) visually verified by the occurrence of seepage water above the IIAb surface on the upslope wall of the sampling pit and (ii) experimentally verified by the construction of flow nets from piezometer measurements.

2) Throughflow convergence causes wetter soil conditions to occur for longer periods of time within landscape depressions immediately above the gully headcut. Soil strength is reduced as montmorillonitic clay bonds weaken by wetting and swelling and since low amounts of calcium carbonate are present to act as a cement. This strength reduction leads to failure events whose exact mechanics are not clear. However, failure planes follow cleavage planes within the soil mass caused by freezing-thawing and wetting-drying cycles. These cycles reduce stability by providing a greater number of cleavage planes. The soil profile is anisotropic in mechanical behavior, thus making quantification of failure processes very difficult.

3) Failure debris is deposited against the gully wall due to gravity forces. The reduction in wall slope and the additional resisting forces added to the system by the fallen debris increases gully stability. Piping processes were absent; the outflow rate of water seeping out of the gully headcut was insufficient to transport fallen debris or to overcome the strength of the natural material.

Gully development rates at such upper landscape positions are thus very slow and probably depend on infrequent but intense rainfall events. Such rainfall would carry the failure debris downstream and allow new failures, thus renewing the cycle of mass wasting and debris transport.

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[7] No reaction to 0.1*N* nitric acid.