GULLY MORPHOMETRIC CONTROLS IN A LATERITE TERRAIN, GUYANA

Contrôle morphométrique des ravins sur terrain latéritique. Guyane anciennement britannique.

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RESUME

Une analyse statistique de la morphométrie des ravins formés dans les terrains latéritiques des savanes de Rupununi (Guyane) fait apparaître une interdépendance entre différents paramètres. Cette dernière est l'indice de l'équilibre qui existe entre les éléments de la morphologie du système fluviatile, dès les phases de jeunesse et de maturité de leur développement.

Une analyse en composantes principales permet d'identifier cinq caractéristiques de la morphologie des ravins qui sont indépendantes entre elles : dimension du profil en travers, longueur, pente des versants, pente du profil en long et longueur du cours.

Une analyse en régression montre que si la pente des collines exerce une influence sur l'apparition et la densité des ravins (r = 0,8), elle n'exerce aucune influence significative sur l'évolution ultérieure qui est contrôlée par la nature du substratum et par la lame ruisselée. La première explique de 57 à 70 % et la seconde de 10 à 32 % des variations dans la morphologie des ravins. Ensemble, ces deux facteurs interviennent pour 78 à 89 % dans les variations de la largeur, de la longueur et de la pente des ravins.

Il est suggéré que la croissance des ravins peut être prévue grâce à une bonne connaissance de la nature du matériel érodé et de la surface des bassins.

ABSTRACT

The relevance of analysis of gully morphometric controls is briefly outlined. Statistical analyses of gully morphometric properties and controls in the laterite terrain of the northern Rupununi Savannas, Guyana, reveal strong interdependence of gully parameters, which indicates that equilibrium conditions between the form elements of fluvial systems are established even at the youthful and mature stages of their development. Elimination of redundancy among the battery of morphometric variables was achieved through principal axis factor analysis which identified five orthogonal dimensions of gully morphology (cross-sectional area, gully length, side slope gradient, bed slope gradient, and bed width).

The regression analyses reveal that although hillslope gradient exercises a strong controll on the initiation and frequency of gullies (r = 0.8), it has no significant influence on the subsequent development of gully form which is controlled principally by the nature of the material into which the gully is incised, and by the volume of overland flow. The former explains between 57 % and 70 % of the variance in gully morphology while the latter accounts for between 10 % and 32 %. The two parameters together explain between 78 % and 89 % of the variations in gully size, length, and

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slope gradient. These findings suggest, therefore that the rates of gully growth can be predicted from knowledge of gully material and catchment area.

INTRODUCTION

In spite of the fact that gullies have become very common phenomenon in many parts of the world, and gully erosion has serious consequences for agriculture, water quality, the life span of reservoirs stream channel processes and floodplain development, very few attempts (HEEDE, 1970; ODEMERHO & SADA, 1984) have been made to analyse quantitatively the morphology of gullies and their controlling factors as has been done for drainage basins and stream channels. Most research on gullies and gully erosion have been directed towards :

a) the identification of the causes of gullying;
b) the mechanisms and rates of gully growth;
c) the assesment of the contribution of gully erosion to total sediment yield;
d) the prediction of gully growth on the basis of field phenomena, and
e) the formulation of gully reclamation schemes.

These studies, however, are not based on any detailed analysis of gully morphological controls. Such analysis is desirable because although gullies are fluvially-eroded channels, they differ considerably from rills, stream channels and stream networks (IMESON & KWAAD, 1980; WILLIAMS & MORGAN, 1976). Since gullies are mostly recent features of the landscape, their morphology reflects more closely the mechanics and dynamics of current fluvial processes as constrained by vegetative cover, topography, and the texture, cementation and uniformity of the earth materials into which they are incised. Thus HEEDE (1970) saw the understanding of gully morphology as "a first step in evaluating gully processes... and a connecting link between past, present, and future gully events". The preceding considerations also suggest that efforts at predicting future gully growth (SEGINER, 1966; UNITED STATES SOIL CONSERVATION SERVICE, 1966; IMESON & KWAAD, 1980), are likely to be anchored to a stronger foundation if based on detailed knowledge of gully morphological controls. Although the effects of these factors on gully plan, geometry, and shape have been discussed theoretically by LEUDER (1959), very little attention has been paid to the quantitative evaluation of these gully controls. The investigation reported in this paper aims at bridging this information gap by reporting the findings of a mathematical evaluation of the factors controlling gully morphometric properties in a laterite terrain.

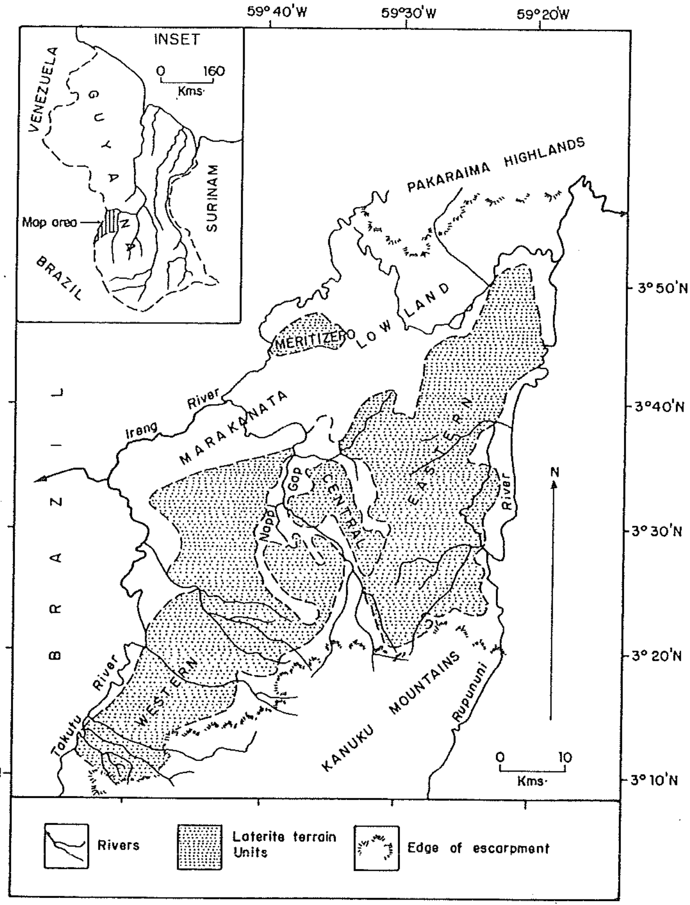
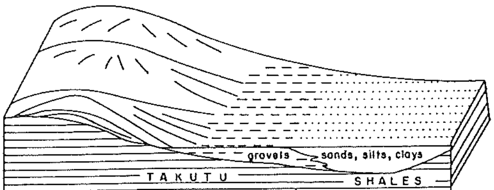


Fig. 1 : Location of the Northern Rupununi Savanna, Guyana

STUDY AREA

The study area is the 1.942 km^2 laterite terrain of the Northern Rupununi Savanna, Guyana (fig. 1). A lowland terrain, occurring generally at altitudes between 100 m and 150 m above sea level, the Northern Rupununi Savanna is bounded in the north and south by the maturely-dissected Pakaraima Mountains and the lofty Kanuku Mountains respectively (fig. 1). It is an area of undulating laterite gravel ridges



Landform Units	Hill and Slope Zone	Terrace Zone	Baixa
Surficial materials	Laterite blocks and gravels	Sheetwash materials -fine gravels and coarse sands	Fine sands, silts, and clays
Active Processes	Gullying, rilling and sheetwash erosion	Sheetwash deposition	Sheetwash and lacustrine deposition
Drainage	Pinnate	Fan type – rapid internal	Impeded

Fig. 2 : Typical landscape units of the laterite terrain

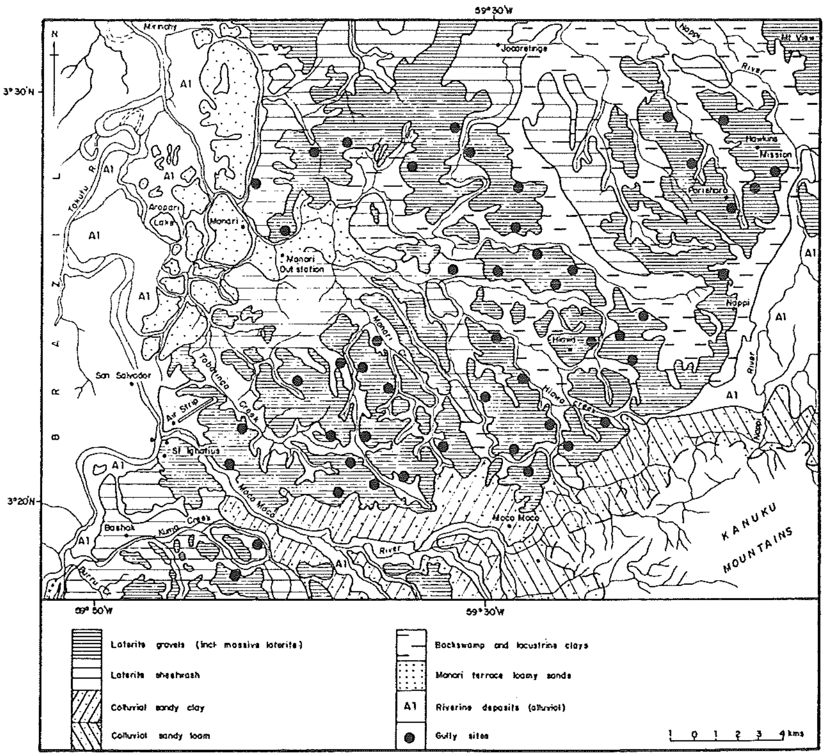


Fig. 3 : Superficial materials of the laterite terrain, and location of gully sites

maturely dissected by wide, flat-bottomed valleys (baixas), and everywhere riddled with gullies (fig. 2). Laterite caps are completely absent in the terrain, having desintegrated into massive and blocky laterites (longest axis over 5 cm), coarse gravels, and fine pisolitic gravels which mantle the hillsslopes; the terraces and baixas are vast accumulations of sheetwash, backswamp, and lacustrine deposits (fig. 2,3). Laterite gravels with longest axis between 1 cm and 5 cm are the most widespread (fig. 4).

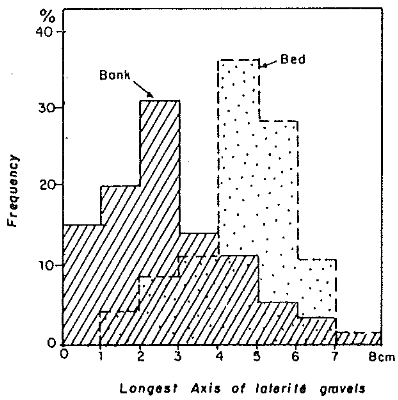


Fig. 4 : Frequency distribution of laterite gravel sizes

The Rupununi savanna vegetation is a tongue-like extension of the Rio Brance savannas of Brazil into the interior of Guyana. The savanna vegetation is the open woodland type and comprises of *Curatella americana, Brysonima crassifolia,* and *Trachypogor plumosis* which is the dominant grass. The baixas are extensive sedge flats with tall grasses and trees or terrawads. The distribution of savanna species in this laterite terrain is clearly related to relief and soil moisture conditions and the boundaries between the various savanna vegetation types as well as between savanna and forest vegetation are clear-cut (LOXTON, *et al.*, 1958).

Temperature is high all year round with a mean monthly range of about 3° C and a slight variation around a monthly mean of 28° C. The rainfall regime (fig. 5) is characterised by a short rainy season of four to five months' duration (May - August), and a prolonged dry season lasting approximately eight months (September - April). Between 60 % and 80 % of the mean annual rainfall of 1,5 m falls during the four months of the wet season. In general, the rain falls as heavy showers lasting an average of 45 minutes.

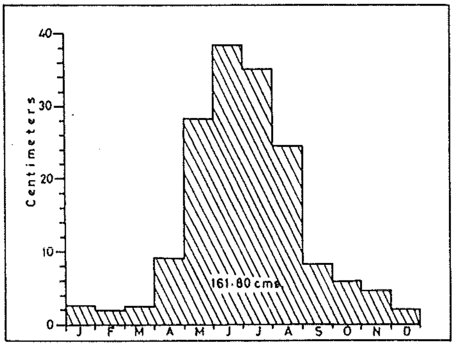


Fig. 5 : Rainfall regime, St. Ignatius

Infiltration rates are fairly low because of poor structural conditions at the soil surface, and so, in most storms there is appreciable runoff from the slopes into the waterlogged baixas and swamps which become rapidly inundated (LOXTON *et al.*, 1958). Flash high rainfall intensity, low infiltration rates, high runoff and the bunchy habit of the grass growth promote very active sheet erosion which is the dominant denudational process in the region (KESEL, 1977).

STUDY METHOD

Forty-nine simple first-order valley-side gullies were selected randomly for detailed study (fig. 3). The morphology of the gullies was quantified by the measurement of fourteen parameters (Table I). These were then related to hillslope gradient, catchment area, and gully bank and bed materials by simple correlation and multiple regression analyses, the results of which are presented in Tables II and III. In landscapes predominanted by hortonian overland flow, slope gradient exercises a strong control on runoff velocity and the intensity of fluvial dissection (HORTON, 1945; ABRAHAMS, 1980; DUNNE, 1980). Since the dominant runoff is hortonian overland flow, runoff volume should be strongly correlated with the catchment areas of the gullies. Thus PATTON & SCHUMM (1975), in a study of thresholds of gully incision in alluvial valleys in northwestern Colorado employed catchment area as a surrogate for discharge as has been widely done in hydrological studies when data on discharge are unavailable.

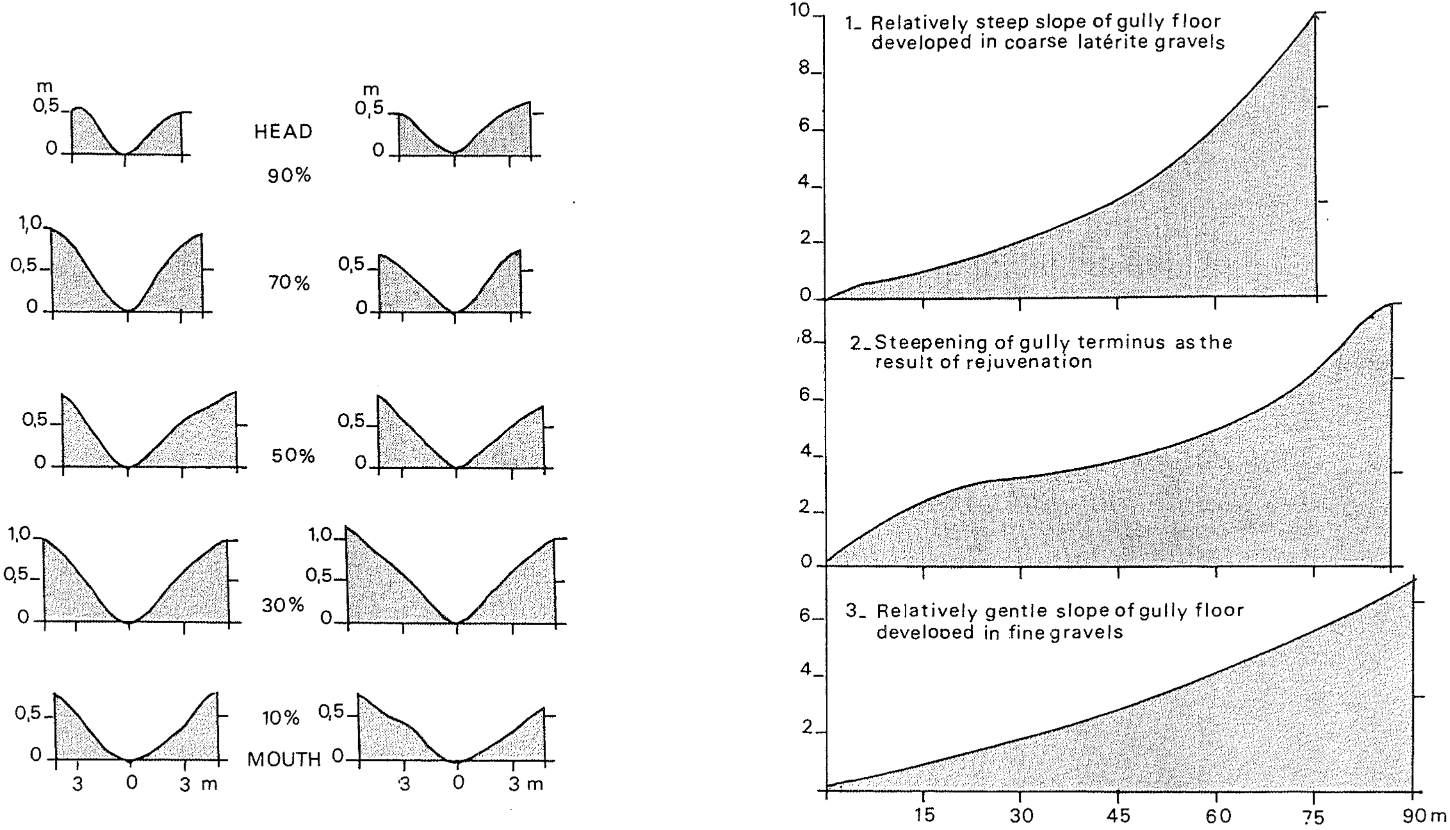


Fig. 6 : (A) typical cross-section and (B) longitudinal profiles of gullies in the laterite terrain

Since the hillslopes and gully walls and floors are generally mantled by laterite gravels, the size of these materials should exercise some control on runoff velocity and erosional processes. The average gradient of the valley-side into which each gully was incised was measured with Abney level.

Samples of the top 15 cm of the laterite soil were collected at regular intervals of 1 m along the walls and bed of the surveyed cross sections in each gully. After wet-sieving to remove the sand, silt and clay fractions, the remaining laterite gravels were weighed and expressed as percentage of the weight of the original air-dried sample, and the value was used to characterize gully material. The longest axes of some randomly selective gravels in each sample were measured. A correlation of average gravel size and percentage weight of gravels reveals very strong relationship between the two parameters ($r = 0.931$). The analyses, therefore, involve fourteen dependent morphometric parameters and three controlling variables (Table I).

The univariate distribution of each parameter was tested for normality using Snedecor's tests for, symmetry and kurtosis (SNEDECOR, 1956). None of the variables was found to be normally distributed, but logarithmic transformation produced distributions that are not sgnificantly different from the normal at the 0.01 level.

GENERAL CHARACTERISTICS OF THE GULLIES

The descriptive statistics of the parameters are presented in Table I. Most of the gullies have extended headward as far as the convex segments near the summits of the laterite ridges and hills. Gullies are almost completely absent on the low hills (relative relief less than 5 m) with extremely gentle slopes (averaging 3°) and fine laterite materials. The gullies are all valley-side gullies cut into hillslopes whose gradients vary between 5° and 30°. The gully systems are, therefore, simple in plan and have fairly direct courses, the average sinuosity index being 1.28.

The gullies are relatively short, gully length varying between 15 m and 100 m. Although the courses are direct, narrow winding channels are incised into the beds of some gullies. Where these channels impinge on the base of gully wall, they effect local steepening of the footslope. The gullies are floored with coarse laterite gravels and reconsolidated gravels, and they tend to have evenly sloping long profiles except for the relatively steeper gully heads and some rejuvenated gully mouths (fig. 6). Weak concavity of gully long profiles has also been reported by other investigators (BRICE,

Parameters	Symbol	Mean values	Coefficient of variation (%)
A : Gully Morphometry			
Length (km)	L	47.1	73.4
Relative relief (m)	H	6.8	82.6
Mean bed width (m)	Wb	8.3	24.7
Mean shoulder width (m)	Ws	12.6	67.3
Mean maximum depth (m)	dmax	1.8	77.9
Mean depth (m)	dm	2.1	81.7
Mean maximum side slope	θgmax	22°	91.4
Mean side slope	Ogm	18°	90.7
Mean bed slope	θb	9°	22.8
Width/depth ratio	W/d	9.2	56.6
Shoulder width/bed width ratio	Ws/Wb	8.8	38.7
Mean side slope/bed slope ratio	θgm/θb	1.8	28.7
Mean cross-sectional area (m^2)	A	4.8	63.4
Mean hydraulic radius	R	0.17	61.5
B : Controlling variables			
Hillslope gradient	θh	16°	66.4
Gully material (mm)	Gm	2.4	82.6
Catchment area (m^2)	CA	879	77.8

Tab. I : Descriptive statistics of the gully attributes analysed.

1964; STOCKTON, 1965; HEEDE, 1970). Although the bed slope varies between 5° and 20°, the coefficient of variation is small (22.7 %). Gully heads are pointed and inclined at moderately steep gradients which exceed 10° in only few gullies developed in massive and blocky laterites where gully head slopes of up to 36° were recorded. Head scraps, therefore are of rate occurrence in this laterite terrain. Gully head rims are moderately pointed, the average semi-circularity ratio being 1.28. Bed width is limited and varies between 3.5 cm and 14 cm. The shoulder width/bed width ratio is high (3.35 - 17.86) with a mean of 8.79. Gully cross sections are thus generally V-shaped (fig. 6).

Gully wall sides are smooth with extremely straight and steep slopes which merge abruptly with the valley bottom (fig. 6). The change in slope at the top of gully side is, however, gentle, the straight segment being replaced by a small convexity. The gradient of the straight segment varies between 9° and 37° but it is fairly uniform in each gully. Gully sides are about twice as steep as the thalwegs, the ratio of side slope to thalweg slope ranging from 0.7 to 3.7 with a mean of 1.81 and a standard deviation of 0.63. Maximum gully depth varies between 1.06 m and 3.2 with a mean value of 1.81 m. Shoulder width varies from 5 m to 20 m. The shoulder width/depth ratios are, therefore, high (4.3 to 19). The interfluve between adjacent gully systems are smoothly rounded to sharply crested where gullies are closely spaced, but flat where gullies are far apart.

RESULTS AND DISCUSSION

The results of the Pearson's product moment correlation analysis, presented in Table II, indicates that most of the gully morphometric properties are strongly interrelated. Of the 91 correlation coefficients, only 25 (27 %) are not significant at the 0.05 level and 55 (60 %) are significant at the 0.01 level. This finding is important as it indicates that equilibrium conditions between the form elements of fluvial systems are established even at the youthful and early mature stages of their development. It also suggests that there is considerable redundancy in the morphometric parameters of gullies as widley reported for drainage basins. This means that it should be possible to reduce the array of parameters to a small subset that adequately simulate gully morphology.

The product-moment correlation matrix of the transformed data was therefore, subjected to the principal axis method of factoring (HARMAN, 1960). The first five

	L	H	Wb	Ws	dmax	dm	θgmax	θgm	θb	w/d	Ws/Wb	θgm/θb	A	R	θh	Gm
L																
H	76															
Wb	31															
Ws	50	64	36													
dmax	40	73		84												
dm		58		74	95											
θgmax	35	68		49	84	83										
θgm	63			58	91	93										
θb		49			54	58	58	62								
W/d		29	40		-50	-65	-71	-73	-39							
Ws/Wb		29	-67	37	51	47	49	53	-39	-40						
θgm/θb	29					30	32	33	-46	-49	56					
A		41		64	73	73	55	55	37	-39	56					
R		59		87	93	92	64	80	53	-37	46		76			
θh	29					30	32	33	-46	-40						
Gm	76	63	35	-61	78	71	80	75	82	-69	-43		76	72	52	
CA	86	54		49	69	61	48	52	44				83	75	67	33

* tabulated value = r x 100; correlations which exceed ± 28 and ± 38 are significant at the 0.05 and 0.01 levels respectively. See Table I for interpretation of notations.

Tab. II : Significant correlation coefficients : gully parameters and controlling factors.

VARIABLES	FACTORS				
	I	II	III	IV	V
Lenght	12	18	32	90	17
Relative relief	38	42	-22	<u>75</u>	11
Mean bed width	22	-23	05	19	<u>91</u>
Mean shoulder width	<u>87</u>	07	05	42	11
Mean maximum depth	<u>79</u>	52	-06	29	-03
Mean depth	<u>78</u>	62	-04	03	01
Mean maximum side slope	40	<u>88</u>	-06	26	-14
Mean side slope	58	<u>70</u>	-06	13	-12
Mean bed slope	32	48	89	-01	-11
Width/depth ratio	18	-80	-13	32	22
Shoulder width/bed width	43	21	-06	13	-<u>83</u>
Mean side slope/mean bed slope	14	36	<u>79</u>	05	01
Mean cross-sectional area	<u>91</u>	19	03	01	-24
Mean hydraulic radius	<u>84</u>	31	-09	14	01
Eigenvalue	4.57	3.50	2.03	1.90	1.72
Percentage of eigenvalue	31.12	28.83	13.82	12.94	11.71
Cumulative % of eigenvalue	31.12	54.95	68.77	81.71	93.42

The loadings have been multiplied by 100

Tab. III : Related factor-weight matrix of the principal axis : Morphometric properties of gullies

Idependent variables	r	Cumulative R^2 (%)	Increase
(a) **Gully cross-section area**			
Gully material	.76	57	57***
Catchment area	.70	89	32***
Hillslope gradient	.19	92	3*
(b) **Gully wallslope**			
Gully material	.80	64	64***
Catchment area	.48	80	16**
Hillslope gradient	.32	88	8**
(c) **Gully bed slope**			
Gully material	.82	68	68***
Hillslope gradient	-.46	85	17**
Catchment area	.44	95	10**
(d) **Gully length**			
Gully material	.76	58	58***
Catchment area	.68	87	29**
Hillslope gradient	.29	89	2*
(e) **Gully bed width**			
Gully material	.35	12	12**
Catchment area	.18	13	1*
Hillslope gradient	.00	13	0*

*** Significant at 0.01 % level, ** Significant at 0.05 % level, * Not significant.

Tab. IV : Summary of stepwise multiple regression results of factors controlling gully morphology.

principal axis (these having eigenvalues greater than 1.0) were rotated using the varimax method of factor rotation in order to produce an orthogonal transformation of the factors. The rotated factor-weight matrix, which shows the percentage contribution of each variable to each of the factors, is presented in Table III. These five factors together account for 93.42 % of the variance in the data.

The first factor is heavily loaded on five of the 14 variables; shoulder width, maximum and mean depth, cross-sectionnal area, and hydraulic radius. This factor accounts for 31 % of the variance in the data matrix and is identified as the gully size variate. The second factor contributes an additional 24 % to the variance and it has maximum and mean side slope, and the width/depth ratio loading heavily on it. It is clearly the gully side slope variate. Factor III explains 14 % additional variance and is heavily loaded on gully bed slope and the side slope/bed slope variables; it is identified as the gully bed slope variate. Factors IV and V which contribute 13 % and 12 % respectively to the variance in the data matrix are identified as the gully length slope and bed width variates respectively. The defining variables of the five orthogonal dimensions of gully morphology in this laterite terrain, therefore are cross-sectional area, maximum side slope, bed slope, length, and bed width.

Two important conclusions can be drawn from this analysis. Firstly, gully cross-sectional variables are more strongly interdependent than the parameters describing gully longitudinal profile. Secondly, the orthogonality of the cross-sectional and longitudional variables suggests that the processes that effect changes in gully length and relief probably have little effect on the form of gully cross-sections. Length and relief of a gully are determined by the rate of gully head retreat, which itself is controlled by the nature of the processes and materials in the gully head region. Gully head processes include abrasion, dripping, trickling, washing, spalling, sloughing and pudding (OLOGE, 1972). Gully cross-sections, on the other hand, are shaped by sheetwash and creep on the side slopes and the nature of flow of water on gully floors.

Stepwise multiple regression analysis were then carried out with each of the five morphometric factor defining variables as the dependent parameter. The results, summarised in Table IV, suggest that hillslope gradient exercises some significant control on only gully wall and bed slope gradients, accounting respectively for 8 % and 10 % of the spatial variations in the two morphometric parameters. The nature of gully bank and bed materials and the volume of overland flow appear to be the dominant factors controlling gully form in this laterite terrain (see also Tab. II).

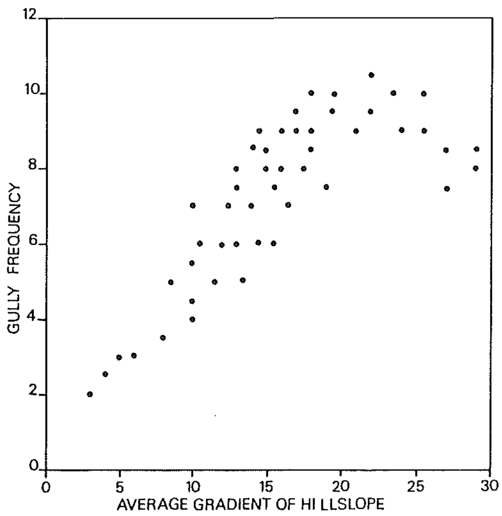


Fig. 7 : Scattergram of the relationship between gully frequency and hillslope gradient in the laterite terrain

Hillslope gradient has been widely reported in the geomorphic literature as exercising strong controls on texture of dissection in landscape predominated by hortonian overland flow (ABRAHAMS, 1980). This is also the case in the study area where slope gradient alone explains about 63 % of the variance in gully frequency (fig. 7). As for gully morphology, however, hillslope gradients' strongest correlation is with bed slope, and the observed relationship is even inverse ($r = -0.458$). The weak correlations of all the gully morphometric properties with hilslope gradient suggest that, although the latter plays a dominant role in the initiation of gullies through its control on the velocity of overland flow and the source area size required for channel initiation and sustenance, it has little effect on the subsequent evolution of gullies and the morphology and shapes of established gullies which appear be controlled primarily by gully materials and the volume of overland flow delivered to the gullies. This can be attributed to the fact that once a rill breaks through the armour of laterite rubbles derived from the breakdown of the duricrust, and is incised into the impermeable lower motlled clay and pallid zones of the laterite soil profile the erodibility and stability of these subsoil materials control the mechanics and dynamics of gully widening and deepening, and therefore gully form. it is significant, therefore, that 11 of the 14 morphometric properties analysed have very strong correlations with gully material (Tab. II), the lower correlations of the remaining three being attribuable to the observed conservative nature of these parameters in the study area (Tab. I). Gully bank and bed materials, therefore, exercise a predominant control on all the orthogonal dimensions of gully morphology, accounting respectively for 57 %, 65 %, 70 %, and 58 % of the spatial variations in gully cross sectional area, wall slope, bed slope, and length; and between 63 % and 92 % of the total variance explained by the three factors. Gully materials, however, exercise stronger controls on the slope dimensions because the gradient of slopes in granular non-cohesive materials is determined principally by the angle of repose of the materials. Size of granular, materials also infiltration runoff volume and velocity, and therefore, the rate of gully wall denudation.

The equally strong relationships of gully cross sectional area and gully length with gully materials suggest that larger gully cross-sections and longer gullies are associated with coarser laterite materials. Gullies with coarse laterite materials tend to have smaller width/depth ratio, and this is attributable to a more rapid rate of vertical erosion by concentrated flow on gully bed (mean of 1.75 cm per year) compared with shoulder widening (0.18 cm per year) effected primarily by sheet wash and creep processes. The greater efficiency of vertical erosion may be attributed to the steep gradients of the gully beds, while the extremely low rate of gully widening point up the uneffectiveness of sheetwash on the gully walls, and this is attributable to the high calibre and resistance to shallow overland flow of the coarse laterite gravels and blocks which mantle the gully walls. The dominant denudational process on these gully walls are rainsplash erosion and creep, and this probably accounts for the broad convexity of gully walls mantled with coarse materials. Thus the larger cross-sectional areas associated with coarse laterites are due to the greater depths of the gullies. Gullies incised into finer laterite gravels, on the other hand, have higher width/depth ratios due to the observed greater rate of gully wall erosion. The gentle gradients of their floors favour accumulation of sheetwash materials and the reconsolidation of pisolithic laterite gravels. Field measurements over the two year study period revealed a mean annual aggradation rate of 1.32 cm. The gully cross sections, therefore, are broad v-shaped with relatively small areas. The strong negative correlation between width/depth ratio and gully material ($r = -0.692$) suggests that the v-shape of gullies tends to become less pronounced as the size laterite materials increases. In fact, where massive laterite outcrops on gully walls and close to gully floor, cross profiles are characteristically U shaped or asymetrical. The greater efficiency of sheetwash erosion in semi-arid and savannah landscapes account for the gentle slopes and higher width/depth ratio of gullies cut into fine laterite gravels.

Gully material explains about 58 % of the variance in gully length. Gully length is controlled by the rate of gully head retreat which in turn is influenced by the nature of processes and materials in the gully head region. Gully head is a zone of convergence of both surface and subsurface flow, the nature and intensity of wich are determined by the hydraulic properties of the earth materials and source area size. Gully heads retreat primarily through mass wasting processes, and this explains why gully head in general are characterised by scarps or steep gradients. Fine laterite materials possess greater cohesion and resistance to mass wasting processes than coarse gravels on account of the higher silt and clay content in the soil matrix. Thus higher rates of slumping and collapse occur where gully heads are mantled with coarse laterite rubbles. Gullies incised into coarser materials are likely, therefore, to retreat at a faster rate.

Gully catchment area has been used in this study as surrogate for the volume of runoff involved in gully processes. This is predicated on the assumption that in landscapes predominated by hortonian overland flow larger catchment areas should contribute greater volume of runoff for gully wall, bed and head denudational processes.

Gully morphometric properties are strongly correlated with the volume of overland flow generated within each gully catchment area (Table II) and this factor accounts for between 15 % and 32 % of the variance in gully size, and 10 % in gully bed slope.

Taken together, the three indepent variables explain only 13 % of the variance in gully bed width. This is attributable to the conservative nature of bed width in this terrain. The three factors, however, account for over 88 % of the spatial variations in the other four orthogonal dimensions of gully morphology. The analysis, however, suggest that the morphology of gullies in this laterite terrain is strongly related to the nature of materials on gully wall and bed, and secondarily to runoff volume.

CONCLUSION

In spite of its relevance to an understanding of gully processes and the prediction of future gully growth, the analysis of gully morphological controls has received very little attention. An attempt has been made in this paper to bridge this information gap through statistical analyses of factors controlling gully morphology in a laterite terrain. The findings reveal that the gradients of the hillslopes into which the gullies are incised exercise strong control on gully frequency but have no significant effect on gully form, which is controlled principally by gully bank and bed materials and the volume of runoff. The two factors together explain between 78 % and 89 % of the spatial variations in the four principal orthogonal underlying dimensions of gully morphology.

Two important conclusions cam be drawn from these findings. Although hillslope gradient and the mechanical properties of hillslope materials are important constraints on stream channel initiation and texture of dissection in landscapes predominated by hortonian overland flow, the subsequent development of the incised channels and their morphology are controlled principally by subsurface soil properties and the volume of flow. Consequently, rates of gully growth can be predicted from knowledge of the properties of subsurface soil and gully catchment area.

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