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The dynamics of gully head recession in a savanna environment

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Abstract Field measurements have been carried out to investigate the processes and rates of gully head recession in a tropical wet-and-dry location in Nigeria, over three wet seasons. A combination of gully wall erosion processes and gully floor basal sapping is found to enhance headscarp recession and gully widening through a cycle of undercutting, collapse and removal of collapsed material. The average recession rate was 2.32 m year^{-1}, and the fastest recession was 4.7 m year^{-1}. These rates amount to 8.6 m^3 year^{-1} and 20.4 m^3 year^{-1}, respectively, yielding an average loss of some 41 m^3 ha^{-1}. The major on-site factors accounting for these results include the amount of runoff arriving at each gully head, the texture and structure of the aeolian material into which gully heads are cut, and the absence of land management of the gullied zone. To stabilize the gullies, the recession cycle must be broken.

INTRODUCTION

Soil erosion, particularly in the Tropics, has been a vexed issue. Studies of soil erosion have highlighted the processes and factors that influence its occurrence, and its environmental effects, not the least of which is the loss of farmland (Olofin, 1978). Sheet wash and gullying comprise the two major types of erosion in humid and sub-humid areas.

In Nigeria, studies of soil erosion have been undertaken in both the humid area (Jeje, 1972, 1985; Ofomata, 1965, 1981) and the savanna zone (Ologe, 1972, 1973; Olofin, 1978, 1984). Rainfall erosivity is generally high in the Tropics. Courtney & Trudgill (1984) believe that up to 60% of rainfall is erosive, and Olofin (1980) contends that erodibility is high in soils composed mainly of silt and fine sand, while a high content of silt and clay results in large losses through mass movement. These hydrological and soil factors, together with slope angle, crop management and land conservation practices are the most important in a savanna zone such as that of the study area.

This paper presents the results of investigations into site factors and processes of gully head recession for a sub-humid savanna area of Nigeria. The data base spans three consecutive wet seasons, 1974 to 1976, with observations updated in 1986.

CLIMATE AND SITE CONDITIONS IN THE STUDY AREA

Figure 1 illustrates the location of the study area in the River Chalwa basin, Kano State, Nigeria. The area is characterized by a sub-humid savanna climate. The wet season lasts for about four months from June to September, sometimes beginning in the latter half of May. The mean annual rainfall is 860 mm, of which more than 35% may occur in August alone. The two wettest months, July and August, account for more than 60% of the rainfall.

The most relevant rainfall characteristic for soil erosion is rainfall intensity, which averages 30–40 mm hr^{-1} (Kowal & Kassam, 1978). Intensities of up to 80 mm hr^{-1} occur during rainstorms at the onset (May/June) and

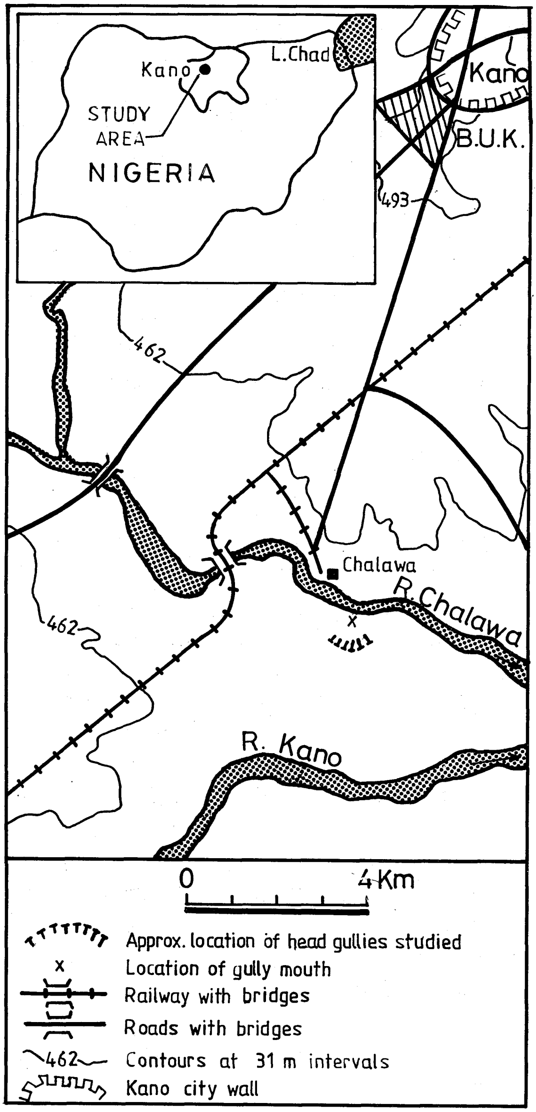


Fig. 1 Location of study site.

end (September) of the wet season (Leow & Olge, 1981), with storms lasting from 20–30 min. Storms occurring during the onset of the wet season, usually accompanied by winds in the range 50–70 km hr^{-1}, cause the most damage because the soil cover at that time is usually scanty, and cultivated fields have been ploughed.

The annual mean temperature is 27°C with an annual range of about 10°C. The warmest period occurs shortly before the rains in April and May when monthly mean temperatures of 30°C or more, and daily ranges less than 6°C are common. The coolest months are December and January when the tropical continental air mass, propelled by northeast Trade winds, prevails over the area. During this period the monthly mean temperature is about 22°C, with daily minima often dropping below 15°C, but maxima of over 30°C are quite common.

The site is underlain by crystalline rocks of Precambrian age which constitute the Basement Complex. Outcrops of these rocks, mainly igneous and metamorphic, occur everywhere on the landscape, including the bed of the Chalawa Channel. The channel itself is alluvial, 2 m deep and incised into an older broader channel about 240 m wide.

A terrace and upland plain, at the edge of which the gully heads are located, are overlain by aeolian material. The drift is about 1 m deep on the terrace where it covers past alluvial infills, except in the gully floors where it is completely absent. On the upland plains it is up to 2.5 m thick and overlies an ancient pediplain developed on the regolith of the Basement Complex rocks, the upper part of which has been covered by drift material (Fig. 2). Thus, the upland plains and terraces are depositional landforms whose mean slope angle ranges from 0–1.5°, separated by almost vertical scarps.

In the Nigerian Savanna aeolian material is believed to have "a modal

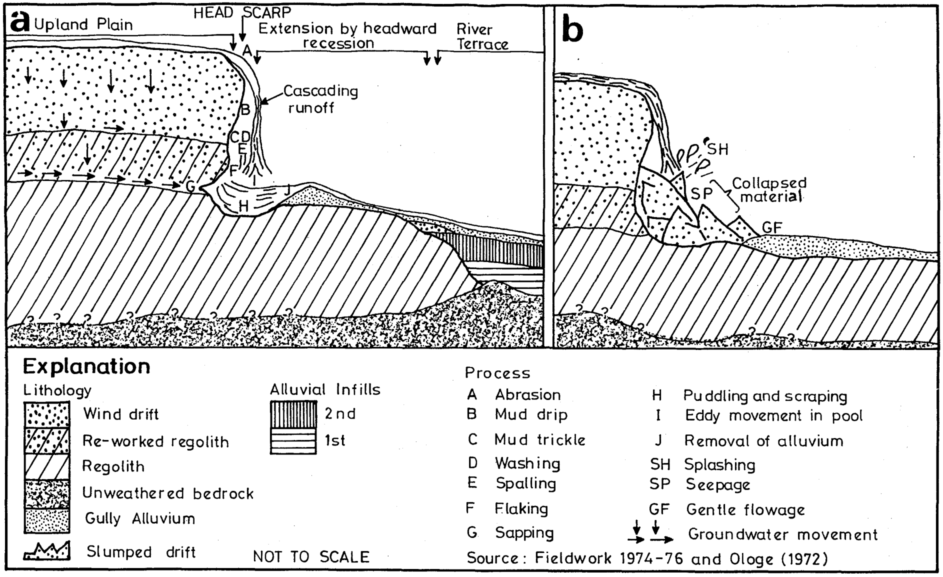


Fig. 2 Idealized stratigraphy of the site, and fluvial processes on (a) active and (b) stabilizing headscarps.

grain size in the fine sand to coarse silt range with a considerable percentage of clay size minerals" (Smith, 1982, p.39). The silt and clay fraction is estimated to be up to 50% by weight, clay alone accounting for 20–30% (Smith, 1982), although Ologe (1972) has pointed out that the material is coarser in the northern than in the southern parts of the area, and that both its thickness and extent decrease southwards. The study area is located in the northern part of the drift zone. The texture of the material at the site is illustrated in Table 1, which shows that the dominant grain size is silt to fine sand. The material easily crumbles once it is saturated but develops a crust under high intensity local rains. The grain size range also implies a high index of particle detachability under such intensities, particularly since the fines in this zone are believed to be removed from the top 10 cm of the soil profile (McTainsh, 1986).

For moderate rainfall intensities, sufficient water passes through the material, removing fine particles further down the profile and encouraging spring flow at the textural discontinuity existing between the aeolian material or reworked regolith layer and the regolith proper (Fig. 2). The discontinuity at the aeolian sediment/regolith interface occurs because the regolith is more compacted and has a higher clay fraction percentage.

Since 1979 dams have been constructed on the major tributaries of the Chalawa River upstream of the study site. These dams, and sand quarrying on the bed of the Chalawa, have initiated an incision into the channel of the river to a depth of 1.5 m and have resulted in a lowering of the stage by at least same margin. In response, gully floor and gully heads at the edge of the upland plain have been reactivated.

Land use at the site is characterized by rain fed cultivation of grains on the upland and terrace plains every year. Dry season market gardening cultivation is practised at some points at the edge of the low terrace, using a *shaduf* irrigation system.

The gullies under study are characteristic of those occurring on the

***Table 1** Particle size distribution of gully head aeolian material (% by weight)*

Sample	*Grain size (mm) Classification*	*0.500 to 0.750 Medium sand*	*0.200 to 0.500 Fine Sand*	*0.045 to 0.200 V. fine sand*	*0.02 to 0.045 Fine to coarse silt*	*0.002 to 0.02 V. fine silt*	*Finer than 0.002 Clay*	*Silt Clay %*
G1		*3.9*	*8.3*	*44.1*	*12.3*	*25.1*	*6.3*	*43.7*
G2		*4.1*	*5.3*	*45.7*	*9.7*	*28.9*	*6.2*	*44.8*
G3		*4.3*	*5.5*	*46.4*	*10.2*	*25.9*	*7.8*	*43.0*
G4		*3.6*	*5.6*	*46.0*	*9.7*	*28.1*	*7.0*	*44.8*
G5		*3.7*	*6.5*	*45.5*	*8.7*	*29.0*	*6.6*	*44.3*
G6		*4.6*	*8.1*	*46.0*	*6.7*	*28.0*	*6.6*	*41.3*
Mean		*4.0*	*6.6*	*45.6*	*9.6*	*27.5*	*6.7*	*43.8*
Standard deviation		*0.4*	*1.2*	*0.7*	*1.7*	*1.5*	*0.5*	*1.0*
Coefficient of variation (CV)		*9*	*18*	*2*	*17*	*5*	*8*	*3*

NOTE: The low CV values show that the aeolian material is approximately the same over the area.

valley sides of incised stream channels in the savanna areas of Nigeria. Such gullies are usually initiated on the vertical bends of the channels and work their way upslope by a process of headscarp recession (Ologe, 1972, 1973). As the channels themselves have been affected by polycyclic processes of incision and infilling under alternating pluvial and arid phases in the past (Smith, 1982), the current active gully heads are located at the boundary of the extended river terrace and the upland plains and are characterized by a steep and dissected upland edge.

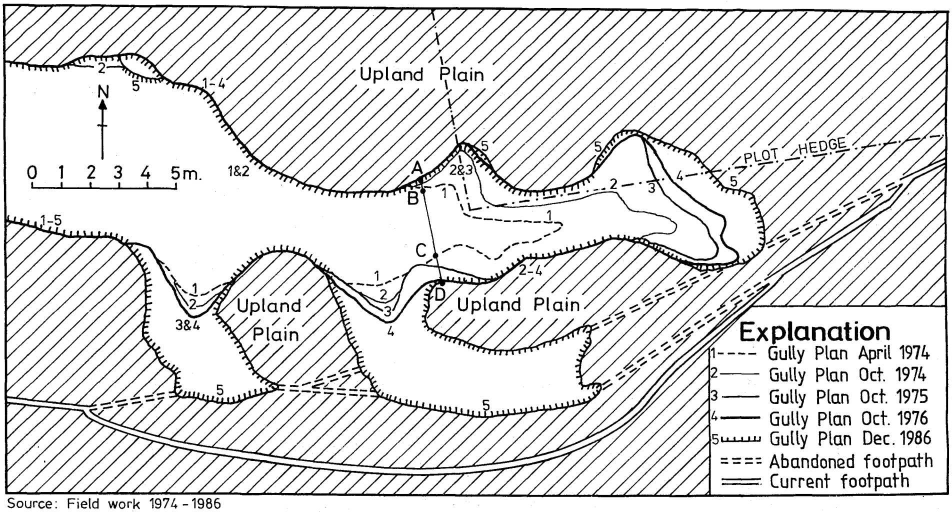
The gully heads in this study are located 500 m from the incised channel of the Chalawa River, (Fig. 1), and are contained in a strip 500 m long and about 25 m wide at the edge of the upland plain.

METHODS OF STUDY

The unit studied was randomly selected from other units along the Chalawa River channel. Six active gully heads were considered. Field methods include the annual measurement of gully head dimensions in relation to fixed points, and the survey of gully plans at the end of each wet season (following the initial pre-wet season measurement in April 1974).

At each gully head, the following geometric variables were determined. Total top width (TTW) is the average (whole) top width of the gully in the receded section, such as line "AD" in Fig. 3, taking into account the pre-existing width.

Receded top width (RTW) is the average top width of each gully in the receded section such as lines "AB" and "CD" in Fig. 3, ignoring the pre-existing (BC) width. Base width (BSW) is the average bed width of each gully in the receded section, while the total depth (TDP) is the average depth in



Source: Field work 1974 - 1986

Fig. 3 Changing plan of head of Gully 1 between April 1979 and December 1986.

the receded section. The length of recession (RTL) is taken as the top length because headscarps are almost vertical, except for slight undercutting at the base. The changes in the plans and dimensions of the gully heads have been used to estimate the amount of sediment volume eroded (VER) and the surface area affected.

Field observations were also undertaken during the wet seasons to assess qualitatively processes and factors of headscarp recession. To this end, the land use, vegetation cover, effects of footpaths on runoff and actual erosion processes were observed.

All measurements and observations were made from April 1974 to October 1976. The escalation of sand quarrying and the construction of dams from 1976–1977 forced the cessation of observations since these activities introduced external factors. However, observations and measurements were updated in December 1986 when the most active gully head (Gully 1, Fig. 3) was surveyed and mapped. Samples of the sediment were also taken for all gully heads from a depth of 50–100 cm for particle size analysis.

HEADSCARP RECESSION PROCESSES AND GULLY HEAD CHARACTERISTICS

Field observations have revealed that the density, alignment and length of footpaths that lead into a gully head control the catchment area that drains into each gully head. Thus, different volumes of runoff are received by gully heads, even though both the upland plains slope angles and the rainfall intensity and amount are uniform over the sites. Although the runoff variable has not been quantified, it was observed that Gully 1 received the greatest amount of runoff during the period of study.

When runoff arrives at a receding gully head, the processes of soil erosion illustrated in Fig. 2(a) are set in motion. The runoff uses its load to abrade the upper edge of the headscarp before plunging to the gully floor where it creates an eddy pool. The eddy motion encourages flaking and basal sapping, aided by merging groundwater at the drift-regolith interface. On the gully wall, mud drip, mud trickle, washing and spalling occur, while puddling and scraping take place beneath the pool. The force of the plunging torrent pushes eroded material clear of the base of the gully wall, presenting a fresh base to be acted upon, until the overhanging material collapses or slides. The collapsed material slows the process down (Fig. 2(b)) until removed. If it is not removed, the gully head stabilizes.

These processes resulted in headscarp recession, measured during the period of the study. Table 2 illustrates the characteristics of the six gully heads at the end of the main study period (1974–1976) with additional information on recession of these gully heads obtained during the 1986 wet season. The total top width (TTW), which averages 4.85 m, and the mean total depth (TDP) of 2.18 m are the two least dispersed of the geometric characteristics; each has a value of 12% as its coefficient of variation. The mean volume eroded (VER, 25.66 m^3) was the most variable at 75%, while the mean receded top width (RTW) and base width (BSW) were also widely

Table 2 Mean values of some geometric variables for selected gully heads

Gully	*Base width (m)*	*Total top width (m)*	*Total depth (m)*	*Receded top width (m)*	*Receded top length (m)*	*Volume eroded* (m^3) *	*1986 Field check receded top length (one wet season) (m)*
1	*0.48*	*4.00*	*2.25*	*3.36*	*14.20*	*61.34*	*1.00*
2	*1.15*	*5.27*	*2.00*	*0.72*	*3.20*	*5.98*	*1.00*
3	*0.53*	*4.25*	*2.50*	*3.17*	*7.70*	*35.61*	*1.50*
4	*0.50*	*4.60*	*2.52*	*2.40*	*8.25*	*30.15*	*2.10*
5	*1.00*	*5.25*	*2.00*	*1.30*	*5.35*	*12.31*	*0.00*
6	*2.20*	*5.75*	*1.80*	*0.92*	*3.05*	*18.56*	*0.50*
Mean	*0.98*	*4.85*	*2.18*	*1.98*	*6.96*	*25.66*	*1.02*
Standard deviation	*0.61*	*0.62*	*0.27*	*1.22*	*3.80*	*19.37*	*0.67*
Coefficient of variation	*62*	*12*	*12*	*62*	*55*	*75*	*66*

* *Total volume eroded from all the gullies in three wet seasons = 154* m^3. *The surface area actually affected = 190* m^2.

variable (55, 62 & 52%, respectively).

Table 2 shows that the mean rate of recession during the study period was 2.3 m year^{-1}, which is considered rapid. The rate at which Gully 1 receded (4.7 m year^{-1}) is high. These rates are equivalent to the removal of an average of 8.6 m^3 year^{-1} of sediment from each gully and 20.4 m^3 year^{-1} from Gully 1 alone. Some 154 m^3 of earth was removed during the three wet seasons. The strip affected is about 1.25 ha. Thus, in the active gully zone 41 m^3 ha^{-1} year^{-1} of sediment is removed by the gullying process alone.

Field surveys in 1986 showed that the rate of recession for that wet season was relatively slower than that of the study period in all the gully heads, except for Gully 4 which receded about 2 m (Table 2). However, the difference between the 1976 and 1986 Gully 1 plan (Fig. 3) shows that there must have been a period of episodic recession during the intervening decade in the region.

A statistical analysis relating some gully head characteristics to the rate of recession, indexed by the volume of material eroded (VER), provides the inter-relationships contained in Table 3.

Two variables stand out in their pattern of relationships. One is that TTW is negatively related to TDP, RTW, RTL and VER; but positively with BSW; all significant at, at least, 5% level. The second is the TDP which (in addition to its relationship with TTW) is negatively and significantly related to BSW, but positively (though insignificantly) related to RTW, RTL and VER. These r-values range between +0.58 and +0.67, indicating that with a larger sample size, these relationships could be valid. Other relationships can be read off Table 3.

DISCUSSION

In general, it is argued that valley side gullying in a savanna environment is

Table 3 Pair-wise correlation matrix of gully head variables

	BSW	TTW	TDP	RTW	RTL	VER
Base width (BSW)	1					
Total top width (TTW)	+0.84*	1				
Total depth (TDP)	-0.90*	-0.83*	1			
Receded top width (RTW)	-0.67	-0.83*	+0.67	1		
Receded top length (RTL)	-0.73@	-0.89*	+0.58	+0.75@	1	
Volume eroded (VER)	-0.70	-0.92**	+0.62	+0.81*	+0.98***	1

Degrees of freedom (n - 2) = 4.
*** Significant at 0.1% level,
** Significant at 1.0% level.
* Significant at 5.0% level.
@ Possible valid relationship (significant at 10%).

initiated by the incision of the main river channel (Ologe 1972, 1973), and that the depth of gully incision is set by the local base level (Smith, 1982) provided by the height of flow in the main channel (Olofin, 1984). The recent channel incision, resulting in the reactivation of gully floors, underlines the importance of the control exerted by the main channels on gully side erosion. Thus, the gullies were probably initiated during the first incision of the Chalawa channel; headscarps working their way upslope to their current location.

However, the present study has shown that other environmental factors and human interference controlled the growth of the gullies once they had been initiated. Prominent among them are the lithology of the surface material; the pattern and intensity of rainfall, the amount of runoff reaching the gully heads, land use, and land management. While each factor may be isolated for discussion, it should be noted that they can be additive in terms of effect.

The texture of the sediment referred to above is dominated by silt to fine sand particles, which develop crusts under high rainfall intensity, but which still permit sufficient water to infiltrate during rainfalls of moderate to low intensities to initiate spring flow at the drift-regolith interface. This flow results in basal sapping of headscarps similar to that observed by Piest *et al.* (1975) for vertical loess banks and head cuts in Iowa.

Since the texture and depth of the drift are relatively uniform at all the gully heads, a uniform effect should be expected, more so since rainfall inputs and slope conditions are also uniform. Uniformity in these factors appears to control the similarities in total gully depth and width at the "mature stage", but not the characteristics of the active headscarp (such as the rate of incision) which are very variable. This author contends that site factors influence such variation.

One such factor is the amount of runoff that reaches the headscarps. As mentioned earlier, this variable was not quantified. However, a qualitative evaluation suggests that Gully 1 (Fig. 3) receives at least double the amount of runoff reaching the other gully heads because it has the largest drainage area, thus explaining its very rapid rate of recession.

Coupled with the amount of runoff are land use and management practices. Land use in the study site lays the land bare at the onset of rains, when the greatest erosion occurs. In many cases, cultivation is carried right to the edge of gully heads, and footpaths which represent the divides within the flat upland terrain, run up to the edge of the gully heads. The effect of the land use/management factors differ from one gully head to the other. Variation in the rate of recession, volume eroded and other gully head characteristics relate directly to their combination. In other words, gully heads that receded the most (Gully 1, for example) are those where the combination of land use and management factors present the greatest risk of soil erosion.

It also appears that the characteristics of pre-existing gullies near the receding headscarp provide a set of dynamic or intrinsic factors that influence the rate of recession and the volume of material removed. These factors can explain, in part, the relationships described earlier (Table 3). The wider gully heads recede mainly laterally, with limited headward cuts, while the shallower ones recede without basal undercutting (which would have accelerated the process) because their floors are still within the sediment layer. However, the wider gully heads are also the relatively shallower ones. It follows then that in addition to the factors already described, differential rates of recession and related characteristics are also explained by a dynamic factor associated with the differences in the geometric characteristics of the older sections of the gully heads, in so far as they affect the cycle of undercutting, collapse and removal of gully head material.

CONCLUSION

Although the incision of the main channel initiates valley side gullying in the area, the rate of growth of incipient gullies is dependent on other environmental and anthropogenic factors. Much of the eroded material is lost at the onset of the wet season each year, mainly through mass wasting arising from a sequence of undermining, collapse of undermined materials and the subsequent removal of collapsed material. It is estimated that some 41 m^3 ha^{-1} $year^{-1}$ is lost in this way.

This soil erosion rate constitutes a great loss of agricultural land and should be brought under control. It appears that in order to inhibit or completely stop the process of gully head recession in the study area (and in similar environments), the sequence must be broken. The most appropriate point to intervene is the removal stage. Once the removal of the collapsed material is prevented (through sediment traps and other methods), undermining, flaking and washing will be checked and subsequent collapse can be prevented. In addition, runoff reaching the gullies should be reduced in velocity and in quantity through the creation of grass barrier strips and other obstacles around the gullies, and by preventing footpaths from running into gully heads. The resultant increase in infiltration will not increase basal sapping if removal of collapsed material has been prevented. If this is not done, increased infiltration will do more harm than good in this type of situation. Also, the gully walls and headscarps should be treated to produce gentler slopes, especially in urban settings, in the manner described by Olofin (1987). Man must also develop better land management practices in the area.

It should be noted that results presented in this work and the techniques suggested relate only to aeolian-covered plains of the sub-humid savanna zone of Nigeria, and areas with similar hydrological and site characteristics. Even in such areas more extensive and quantified research is required before firm conclusions can be made about the dynamics of gully head recession.

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