CATENA SUPPLEMENT 8 p.55–70 Braunschweig 1987

RILL DEVELOPMENT IN A WET SAVANNAH ENVIRONMENT

O. **Planchon**, E. **Fritsch** & C. **Valentin**, Abidjan

SUMMARY

A 136 ha-watershed, representative of the wet savannah environment, was selected in northern Ivory Coast to analyse rill development in relation to environmental circumstances. Several detailed maps were produced by an interdisciplinary team indicating the distribution of soils, vegetation cover, sealed surface areas, land use together with geomorphology and rill patterns. In addition, 81 linear incisions, including pre-rills, rills, gullies and deep gullies, were surveyed thus enabling a quantitative analysis, based upon the length and the volume of incision. Rill depth is mainly controlled by slope inclination and the density of incisions by slope length and permeability. Three distinctive rill systems could be distinguished within the catchment:

- On upper slopes pre-rills, rills and gullies depend upon surface flow which in turn is governed by soil surface features.
- Midslope, gullies and deep gullies are mainly induced by the steeper slope. Pedological analysis shows that lowering of land surface has been partly originated by pedological processes of lateral leaching which, besides, have induced some forms of piping erosion.
- The downstream system consists of rills developed on clay deposits and joins the brook, but is not connected to the other two systems. except for heavy rainstorms, this downslope system starts operating in the late rainy season once the foothill watertable becomes sufficiently shallow to permit hydraulic continuity of the overall rill pattern.

RESUME

Un bassin versant de 136 ha, représentatif de la savane humide du nord de la Côte d'Ivoire, a fait l'objet d'une étude sur les facteurs d'érosion linéraire. A la suite d'un travail interdisciplinaire, plusiers cartes détaillées ont été dressées concernant les sols, la végétation, les organisations pelliculaires superficielles, l'utilisation des terres ainsi que le relief et le réseau de drainage. De plus, les profils de 81 incisions linéaires ont été relevés, ce qui a permis une étude quantitative fondée sur la longueur et le volume d'incision; plusieurs formes d'érosion linéaire ont été distinguées: proto-griffes, griffes, ravinaux et ravines. La profondeur des incisions dépend surtout de la pente alors que leur densité est davan-

---

ISSN 0722-0723
ISBN 3-923381-07-7

D-3302 Cremlingen-Destedt, W. Germany
3-923381-07-7/87/5011851/US$ 2.00 + 0.25

tage reliée à la longueur de pente et à la perméabilité. Trois systèmes d'érosion linéaire ont pu être différenciés:

- Celui de haut de versant, constitué de proto-griffes, de griffes et de ravinaux, dépend du ruissellement superficiel et des conditions de surface.
- A la mi-versant, la formation de ravinaux et de ravines est induite par une pente plus marquée. L'analyse pédologique montre que l'abaissement topographique est à imputer, pour une bonne part, à des processus pédologiques de soutirage qui se manifestent notamment par des formes d'érosion en tunnel.
- En bas de versant, des griffes entaillent des dépôts colluvio-alluviaux argileux. Ce troisième système rejoint le marigot mais n'est pas relié morphologiquement aux deux systèmes précédents. Exception faite des forts orages, ces griffes ne deviennent fonctionnelles qu'en fin de saison des pluies, lorsque la remontée de la nappe de bas de versant assure la continuité hydrologique de l'ensemble du système de drainage.

1 INTRODUCTION

Rill erosion may be an extremely severe form of erosion in regions exposed to heavy rainfall such as the wet tropics. Among the variables controlling rill development, the overriding importance of slope-induced hydraulic conditions has been recognized in many studies (MOSLEY 1974, KALMAN 1976, SAVAT & DE PLOEY 1982, GOVERS 1985). The important influence of soil and bed rock characteristics have also been emphasized (SAVIGEAR 1960, ROLOF et al. 1981). Because of the complexity of the interacting factors involved, full understanding of rill development still remains a difficult task. It is necessary first to clearly define the terms which will be used. As widely accepted, a distinction will be made between interrill erosion resulting mainly from detachment by raindrop impact, and rill erosion resulting from detachment by concentrated flow. Furthermore four types of incision were distinguished:

1. Pre-rills: due to the irregular microtopography, surface runoff does not flow parallel to the slope but meanders and anastomoses. Where discharge increases, flow tends to concentrate in straighter channels among the tufts of grass. When linear flow was not associated with conspicuous traces of incision but only affected the few top millimeters of soil surface, the feature was termed "pre-rill". It was considered important to identify this minor form of linear erosion since it was assumed that it represented the initial stage in rill development.
2. Rills: shallow and narrow channels that only affect topsoil layers (depth <0.15 m).
3. Gullies: water courses cut into subsoil. These are formed with sloping sides and V-shaped bottoms (0.15 m $<$ depth $<$ 1 m).
4. Deep gullies: differ from ordinary gullies not only by their depth (1 m) but also by their U-shaped or inverted T-shaped bottoms. Several headcuts usually occur along their profile. Moreover, the low slope

inclination of the gully floor does not reflect the landform of the gully catchment.

This paper describes relationships between the evolution of linear incisions and the controlling factors.

2 GENERAL DESCRIPTION OF THE BOORO-BOROTOU WATERSHED

When selecting the catchment, it was prerequisite that its environmental characters was representative of the north west of Ivory Coast, in an area where soils had recently been mapped (1/200,000 scale). The Booro-Borotou, 136 ha-watershed meets this requirement well. It is located about 25 km north of Touba. Mean annual rainfall recorded over a period of 33 years, is 1359 mm (standard deviation: 220 mm), of which 69% falls during the rainy season (BROU 1986).

Except during dry years, base flow continues throughout the dry season. The part of the total flow which is due to the drainage of the water table largely exceeds runoff flow which only represents 15.3% in 1984, and 17.3% in 1985 of the total (CHEVALLIER, pers. comm.), which is common in this climatic zone (DUBREUIL 1985).

The bedrock consists of undulated injection gneiss. A fracture network characterized by joints and bedding-planes is perpendicular to the stream. Main geomorphic features are presented in fig.1. Due to a capping iron pan, the four remnants of plateaus are scrapped with concave slopes up to 22°. The upper slope segment is generally rectilinear with a gentle slope (1°). A slope break occurs at midslope where indurated layers, together with an iron pan, outcrop locally. Downslope segments are convex-concave with inclination of 3°. In foothill areas, concave depressions, perpendicular to the stream, have developed mainly on the right bank, which join the stream with very low slope angle. The valley floor is generally concave with slope gradient of 3°.

A detailed pedological study was carried out. The three-dimensional structure of the soil mantle was investigated, describing and sampling nine toposequences. Complementary observations were required to unravel the great complexity of the lateral variations between the toposequences. Three main pedological domains were differentiated (tab.1):

1. in upper hillslopes, a ferrallitic domain comprises four remnants of cuirassed plateaus and their surroundings.

2. a ferruginous domain which covers the most part of the watershed. From a classifying viewpoint, these soils may be considered as ferrallitic soils grading into ferruginous soils, as they will be termed hereafter. They are affected by two main processes:

    - impoverishment in iron and clay that originates from the topsoil. Downstream this is emphasized in association with pronounced degradation of the physical properties.

    - accumulation of iron in the deeper layers which result in the development of indurated layers which outcrop locally midslope.

3. Downslope, the hydromorphic domain is related to the permanent

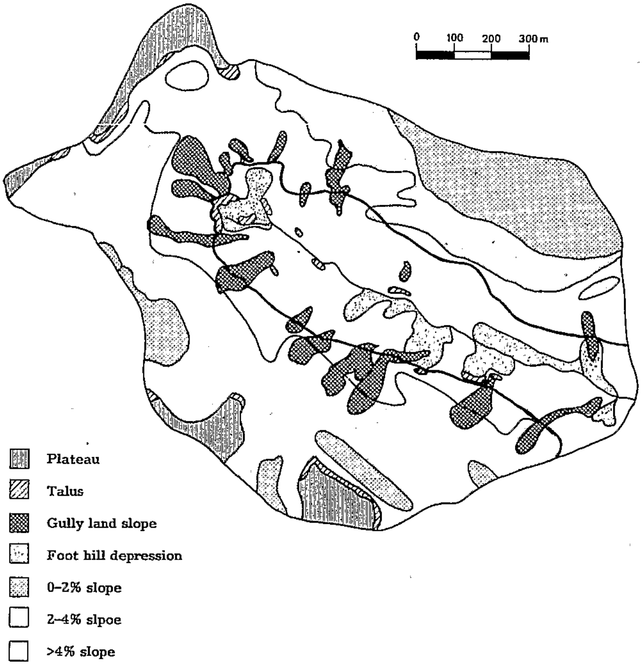

Figure 1: *Map of the main landform features.*

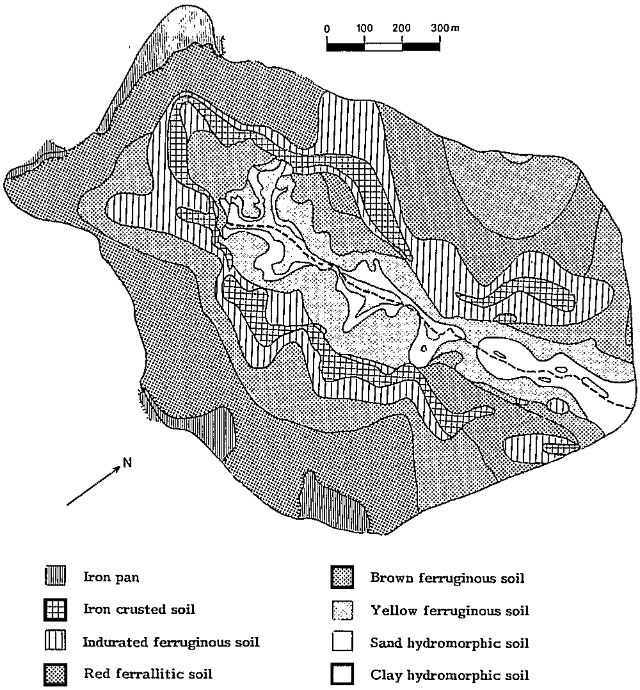

Figure 2: *Soil map.*

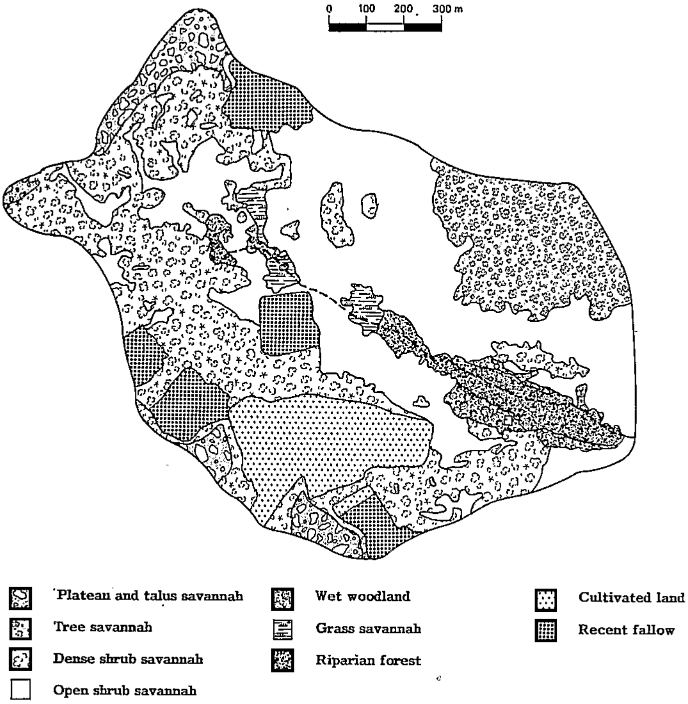

Figure 3: *Vegetation, land use map.*

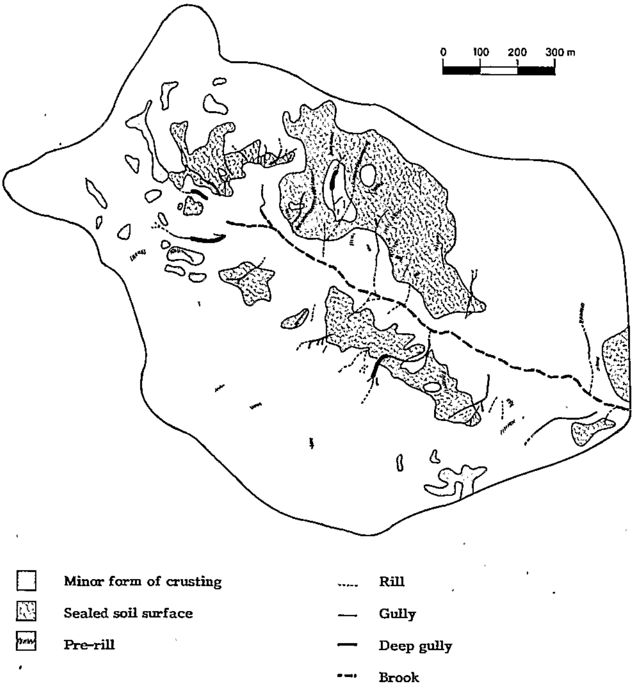

Figure 4: *Surface features and rill pattern map.*

Soil	Texture of the topsoil	Clay content of the topsoil %	Texture of the subsoil	Maximum distance to the water divide (m)	Mean percent slope
Ferrallitic					
Iron pan	Sandy Clay Loam	25	Iron pan	200	2
Red Ferrallitic	Sandy Clay Loam	38	Clay	400	6
Ferruginous					
Brown ferruginous	Sandy Loam	14	Sandy Clay Loam	550	7
Indurated ferruginous	Sandy Loam	17	Indurated	490	6
Iron crusted	Sandy Clay Loam	25	Iron crust	460	8
Yellow ferruginous	Sand	06	Loamy Sand	600	7
Hydromorphic					
Sand hydromorphic	Sandy Loam	11	Sand	580	6
Clay hydromorphic	Silty Clay Loam	26	Clay	580	5

Table 1: *Main characteristics of the soil types.*

Land unit	Range of cover over year (%)	Maximum distance to the water divide (m)	Mean percent slope
Plateau and talus savannah	15–90	200	12
Tree savannah	40–90	360	1
Dense shrub savannah	30–90	450	6
Open shrub savannah	10–90	550	6
Savannah with sealed soil surface	05–80	410	7
Wet woodland	50–100	540	7
Grass savannah	50–100	600	6
Riparian forest	90–100	570	9
Cultivated land	<5–90	400	1
Recent fallow	05–80	550	5

Table 2: *Main characteristics of the land units.*

water table which drains towards the stream exporting first iron, then clay. As a result a thick gray sand layer develops and may locally extend upward to the midslope iron pan. In such a location, this layer cannot result from colluvial processes. Downstream from the depression and in the valley bottom, fine black colluvial-alluvial deposits overlie this sand layer.

The distribution of soils within the catchment (fig.2) results from material transfers. Accumulation of iron which caps midslope areas occurs precisely where regolithic layers are shallowest. Lateral leaching of iron and clay originates from soil surface upslope and from deep layers downslope. Such processes should be responsible for overall lowering of the land surface, downstream of the midslope iron pan. Evidence is based on the occurrence of **in situ** relict regolith within the leached sandy layers and on structural relationships between these layers and the watertable. Such volume decrease due to internal lateral leaching has been documented in Burkina Faso by BOULET et al. (1977).

A specific study of the surface features was undertaken including vegetation, land use and soil surface differentiations such as micro-topography and surface seal. Six main vegetation map units were identified (fig.3).

Owing to the vegetation cover and faunal activity, soil surface sealing is mainly a seasonal phenomenon in most of the watershed. However,the most severely affected areas were mapped (fig.4). Primary forms of surface degradation occurs upslope within finger-shaped glades which penetrate into the dense shrub savannah and the surface of which is slightly sealed. These glades are continuous with more severely crusted surfaces which occur within the open shrub savannah. These areas correspond to a further stage of surface degradation and are characterized by grass tussocks with a soil level above the surrounding surface (the difference in elevation varies from 3 to 15 cm). The bare patches (0.2 to 1.0 cm diameter) are severely crusted and infiltrability is limited to 10 mm/hr under simulated rainfall (phot.1). The ultimate stage of surface change occurs downstream, where surface roughness gradually increases so that microtopography forms step-like features.

Only a small part of the catchment is cultivated, but because of annual anthropogenic bush fires, vegetation recovers slowly after cultivation. Features associated with short fallow (less than 7 years) are easily recognizable in the fields (fig.3). Finally, 10 land units have been differentiated (tab.2).

3 THE LINEAR EROSION PATTERNS

3.1 THE CHANNEL NETWORK

Linear erosion is a frequent phenomenon within the watershed (fig.4). The channel network is not digitate but axial; usually, individual incisions have no tributary, or if any, very short one. The rill network is discontinuous. Upslope and midslope rills are generally not morphologically connected to the downslope rills which occur on the clay hydromorphic soil and which join the stream.

Most frequently the incision depth, hence the rill type, varies along the slope: moving from upslope towards the valley bottom, a pre-rill which originated within a sealed soil surface may turn into rill, gully or deep gully before vanishing in the sand hydromorphic soil and reappearing in the form of a rill in the clay hydromorphic soil. This complexity will be illustrated through an example (fig.5).

The selected incision drains a 11.1 ha catchment. The distance from the pre-rill head to the water divide is 320 m. The variations along the slope of the longitudinal and perpencidular cross sections are presented in fig.6. Several portions can be distinguished: upslope, a 30 m long pre-rill developed in a 2 years old cassava field. When cutting into the ridges of a cotton field, it changes into a 20 cm-deep and 2 m-broad rill. Downstream, between 90 and 160 m from the pre-rill head, the uncultivated soil gradually becomes more indurated and is dissected by a 50 cm-gully. At 160 m, a first headcut occurs between this gully and a 1.30 m-deep gully. It corresponds to the limit between the midslope iron pan and the less resistant brown ferruginous soil. A second headcut is located 20 m

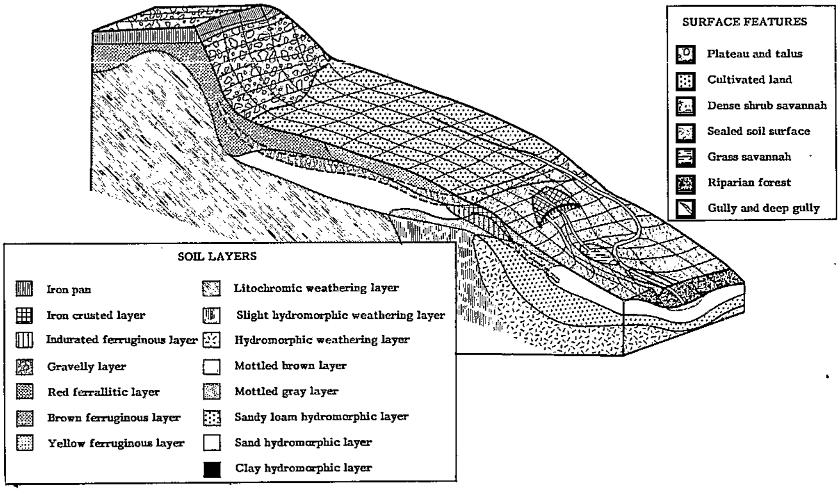

Figure 5: *Block diagram illustrating the rill example.*

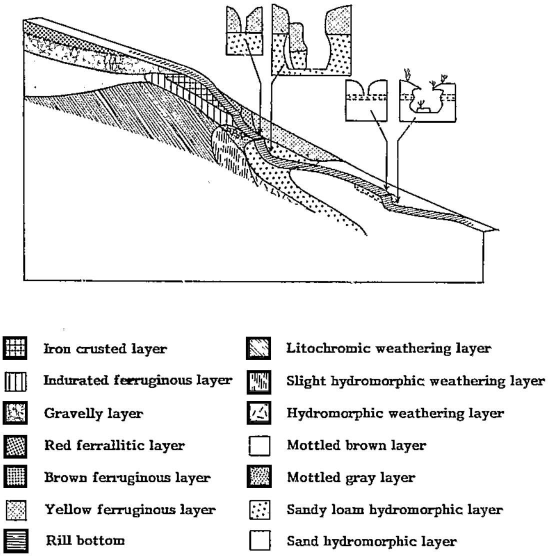

Figure 6: *Longitudinal section of the rill example, with four cross sections.*

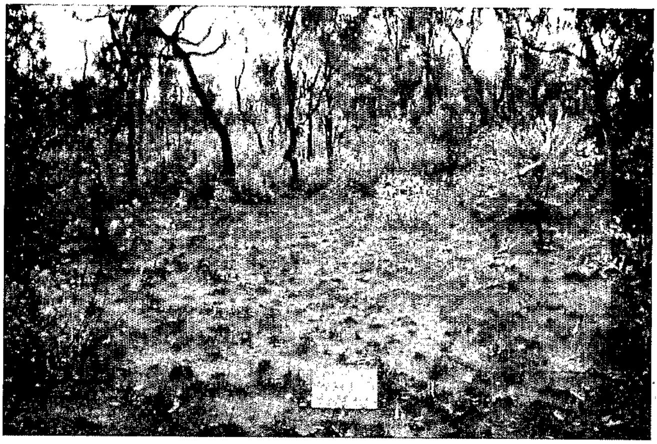

Photo 1: *Sealed soil surface associated to typical microtopography.*

Photo 2: *The deepening and the broadening of the example rill when reaching the depression.*

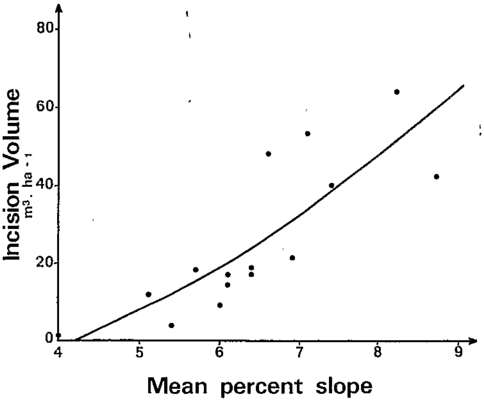

Figure 7: *The impact of the mean percent slope on the incision volume.*

downstream; the incision deepens to 3 m where the lateral leaching of iron and clay make the soil materials even less resistant. The gully banks remain vertical wherever they cut into the sandy gray layer but they are undermined where incision also affects the hydromorphic materials. Such mass wasting may be ascribed to the sapping of the watertable. As shown in fig.5, the gully direction clearly deviates towards the centre of a depression precisely where it enters the zone affected by the water-table, namely where soils are subject to the ultimate lateral leaching. The inclination of the gully bottom, 1.8°, is lower than the steepness of the ground surface, the gully depth gradually decreases from 3 to 0.8 m, between 180 and 260 m. When joining to the depression, the gully deepens to 1.4 m and broadens from 0.8 to 2 m (phot.2). Its sides are severely caved in. Gradually, the gully depth decreases so that at 300 m incision is no longer perceptible (phot.3). At 310 m, entering in the grass savannah where the water-table ocasionally reaches the surface, an anastomosed rill system is observed which is channelled and deepens to 0.60 cm at 340 m where the riparian forest occurs before joining the stream at 370 m.

4 QUANTITATIVE STUDY

4.1 METHODS

Quantitative variables include those describing environmental conditions (tab.1 and 2) and those describing gully characteristics (tab.3).

In each soil and land unit, the mean slope inclination was assessed from the 1/2,500 topographic map using the grid point sampling technique described further. The variations of soil cover (tab.2)

Photo 3: *Sand deposits in the low section of the example rill before turning into deeper rill.*

along the year was estimated using detailed vertical photographs taken at 5 m above ground level and pint points method in the field. In each unit, the maximal distance from the water divide was measured on the 1/2,500 maps. Moreover, in order to use the model of BOON & SAVAT (1981), mean grain size was determined for each unit.

In the field, 81 linear erosion features were topographically surveyed. In each,depth, groundlevel and bottom widths were measured enabling the computation of the cross section, considered as trapezoid. Since these measurements were performed every 10 m along the incisions, their volume and length could be rather accurately evaluated. In ad-

		Pre-rill	Rill	Gully	Deep gully
Depth (m)	Mean	0	0.1	0.6	1.5
	Standard deviation	0	0.1	0.8	0.6
Cross section (m^2)	Mean	0	0.1	0.8	3.1
	Standard deviation	0	0.2	1.0	2.2
Length (m)	Total	1250	2780	1190	500
Volume (m^3)	Total	0	274	915	1470
Slope percent parallel to the incision	Mean	5	6	8	12
	First quartile	3	4	5	5
	Standard deviation	3	3	6	11
Distance to the water divide (m)	Mean	304	358	396	385
	First quartile	220	270	280	300
	Standard deviation	111	116	147	105

Table 3: *Main characteristics of the incisions.*

	Iron crusted soil	Yellow ferruginous soil	Clay Hydromorphic soil	Brown ferruginous soil	Sand Hydromorphic soil	Indurated ferruginous soil	Red ferrallitic soil	Mean
Mean cross section (m^2)								
Rill	0.11	0.07	0.07	0.14	0.05	0.14	0.13	0.10
Gully	0.77	1.06	0.44	1.09	0.68	0.61	0.75	0.77
Deep gully	4.62	3.80	-	2.27	1.40	3.60	3.80	2.94
Volume (m^3/Ha)								
Rill	5	3	12	2	2	4	1	2
Gully	24	18	-	7	4	7	3	7
Deep gully	35	19	-	11	13	7	10	11
Total	64	40	12	20	18	18	14	20
Length (m/Ha)								
Pre-rill	27	14	9	11	-	11	7	9
Rill	40	39	163	15	29	28	8	20
Gully	31	17	-	6	6	11	4	9
Deep gully	8	5	-	5	9	2	3	4
Total	106	75	172	37	44	52	22	42
Slope percent parallel to incision								
Pre-rill	6	6	5	6	-	5	5	5
Rill	5	7	5	6	6	6	6	6
Gully	9	9	3	7	3	6	8	8
Deep gully	28	11	-	10	7	10	6	11

Table 4: *The influence of soil type on the rill characteristics.*

dition, slope inclination parallel to the rill was measured every 10 m. To compare the influence of the different environmental factors, length and volume were expressed per hectare. These variables were combined with the type of erosion feature: prerill, rill, gully or deep gully (tab.3).

The relationships between linear erosion forms and environmental parameters were determined using the field data together with data collected by simultaneous sampling of the topographic, soil and surface features maps. Data from the maps were collected at 2,200 sample points (16 points/ha) using the grid point sampling technique. The frequency of each relationship was calculated as a percentage of the whole sample (tab. 4 and 5).

	Scaled soil surface	Wet wood-land	Riparian forest	Dense shrub savannah	Open shrub savannah	Grass savannah	Recent fallow	Cultivated land	Mean
Mean cross section (m^2)									
Rill	0.13	0.10	0.04	0.14	0.10	0.07	0.10	0.08	0.10
Gully	0.85	0.82	0.60	0.73	1.20	0.67	0.77	-	0.77
Deep gully	3.70	1.56	3.55	3.63	1.18	-	-	-	2.94
Volume (m^3/Ha)									
Rill	5	3	1	2	2	9	0	1	2
Gully	34	18	14	7	10	3	4	0	7
Deep gully	14	27	27	10	5	0	0	0	11
Total	53	48	42	19	17	9	4	1	20
Length (m/Ha)									
Pre-rill	31	6	0	5	11	0	4	6	9
Rill	40	37	35	14	25	121	4	14	20
Gully	17	22	24	9	8	4	5	0	9
Deep gully	9	17	8	3	4	0	0	0	4
Total	97	81	67	31	48	125	13	20	42
Slope percent parallel to incision									
Pre-rill	6	5	-	5	6	-	3	4	5
Rill	7	6	6	5	7	6	6	4	6
Gully	7	7	8	9	7	5	8	-	8
Deep gully	13	8	25	10	5	-	-	-	11

Table 5: *The influence of land unit on the rill characteristics.*

5 RESULTS AND DISCUSSION

5.1 SLOPE-INDUCED HYDRAULIC CONTROL

For units affected by rill erosion, a procedure of step-wise multiple regression was adopted whereby the least significant contributory variables (based on t-value) are progressively dropped.

The most significant individual variable on rill volume is slope steepness: $n=15$, $r=0.82$. The other variables are randomly correlated with rill volume and were eliminated. Mean slope steepness of each unit appears as a major controlling factor since 67% of the incision volume variations can be accounted for regardless of soil type and land unit. The regression curve (fig.5) indicates that no rill develops on units where mean slope inclination is below a threshold value of 2° (i.e. 4%) which agrees closely with the observations of SAVAT & DE PLOEY (1982).

As shown in tab.3, the slope steepness parallel to incisions influences the depth of incision. Below 4° (7%), incisions remain shallow (pre-rills and rills), between 4° and 6° (7% and 10%), gullies occur whereas deep gullies develop on slopes steeper than 6°.

The variables tested were not well correlated individually with rill density, expressed as length of incision per hectare. However, a two-variable equation containing maximal length to the water divide and clay content of the top soil gives a significative correlation coefficient of 0.66 ($n=15$).

These results may be discussed in terms of hydraulic parameters. As shown by several authors (SAVAT 1979, PLANCHON 1985), rills can only start when all particle size fractions can be equally removed by a critical flow verlocity which depends on slope inclination and unit discharge. Our results suggest that incision depth is mainly controlled by slope gradient whereas rill density is influenced by unit discharge, assuming that unit discharge depends upon slope length and clay content, as assessed by BOON & SAVAT (1981).

The nomographs of BOON & SAVAT (1981) permit prediction of the initiation of rill incision. They require data

Photo 4: *Sediment deposits from sheet runoff erosion at the bottom of a cultivated field.*

on slope length, slope steepness, median grain size and clay content of the top soil. In our case, results match the predictions for 10 units out of 18. Discrepancies may be ascribed to two main sources of error:

1. incorrect estimation of permeability: rill should not develop either in the sealed surface unit in the fringe forest since both estimated permeabilities exceed 250 mm/hr, but both units are among the most affected by linear erosion. This is probably enhanced by runoff factors which are more favourable than can be predicted by textural conditions. In the case of the sealed surface unit, infiltrability assessed under rainfall simulation is only 10 mm/hr, whereas drainage conditions in the fringe forest are seriously impaired by the permanent water-table. Conversely, despite predictions, no rilling is observed on the iron pan, plateau and talus savannah units. Infiltrability on the talus savannah unit under simulated rainfall is 15 mm/hr (CHEVALLIER & SAKLY 1985) exceeding the predicted permeability (6 mm/h) because clay is mainly found in the form of water-stable aggregates.

2. heterogeneity of units along the hillslope. According to their intrinsic characteristics, the brown and yellow ferruginous soils together with the open shrub savannah and the riparian forest should not be exposed to linear erosion hazards. The fact that they are actually eroded may be therefore attribute to external factors: they receive surface flow from runoff contributing areas located upstream.

5.2 SOIL COVER

No clear influence of soil cover on linear erosion has been established. Incomplete soil cover, as for the sealed surface, enhances sealing and hence discharge, favouring incipient linear erosion. Yet, once rill flow has initiated from upstream, the canopy is largely unsuccessful in eliminating it. Even the most complete soil cover comprising high trees (30 m high) and dense understorey are ineffective since the riparian forest and the wet woodland are among the most severely affected units (tab.5).

5.3 LAND USE

The question arises whether cultivation accelerates rill erosion. On the one hand, cultivated and fallow lands are not severely affected by linear erosion (tab.5). This result may be attributed to the land use system which is rather conservative. The red ferrallitic soils which are mainly selected by the farmers for clearance, present low linear erosion hazard. Owing to their intrinsic properties, they fall on the "no risk class" of the BOON & SAVAT (1981) nomographs. Moreover, the duration of cultivation is limited to 5 to 7 years, interrupting irreversible processes of soil surface degradation. On the other hand, fields are affected by runoff and sheet erosion as indicated by sand deposits (phot.4). Besides, it has been shown that tillage, like ridging, may accelerate linear erosion. Even though land degradation remains limited within the cropped lands, cultivation can be a contributory factor on other soils as suggested by the important gully located downstream from the cotton fields.

6 RILL DEVELOPMENT SYSTEMS

Quantitative data together with structural observations enabled us to identify three rill systems within the watershed.

6.1 UPSLOPE SYSTEM

Under natural conditions a complex runoff system develops upslope due to gradual degradation of land surface conditions along the hillslope. Change in infiltration conditions starts in the elongated glades within the dense shrub savannah (fig.4). Although the soil surface is only slightly sealed, observations on runoff plots have demonstrated that overland flow originates from them and is three times larger than in the surrounding dense shrub savannah. The next stage of land surface degradation consists of the sealed surfaces areas occurring within the open shrub savannah. As already mentioned, infiltrability within this unit is low (10 mm/hr) as assessed under simulated rainfall. In this case, rill generation is enhanced by rainsplash impact which seals the soil surface between the grass tussocks. This process is further encouraged as microtopography increases downhill. This overall system is controlled by overland flow due to impaired surface physical conditions.

As demonstrated by CHAUVEL et al. (1977) in an analogous pedologic environment in southern Senegal, pedoclimatic conditions drier than those required for ferrallitic pedogenesis, may foster the disjunction of fine and coarse soil components and trigger lateral leaching of finer particles and the transformation of ferrallitic soils into ferruginous soils. Such changes usually originate from the topsoil. This gradual deterioration of soil surface along the hillslope might be partly related to these geochemical processes.

6.2 MIDSLOPE SYSTEM

Due to the slope-break, circumstances are favourable in the midslope for the deepening of incisions. In addition, as illustrated by the example, gullies may turn into deep gullies once the incision reaches the laterally leached soils. In reducing intrasoil strength, and in precipitating gully failure events, throughflow governs the development of the deep gullies which are confined to this midslope system, whereas overland flow removes the debris from bank collapse. This system is therefore mainly controlled by a combination of processes which include increased slope angle, hence velocity, surface flow and throughflow.

As already mentioned, the slope break might have been induced by the overall lowering of land surface downstream of the midslope iron pan. This may partly result from internal lateral leaching within the layers affected by the lateral drainage of the water-table. The question still arises about the differentiation of linear erosion. Observations of deep layers located 1.5 m below a gully bottom have shown eluviation of iron along a tunnel-like feature. This suggests the existence of linear throughflow deep under the gully. Such underground flow might be responsible for piping which in turn should guide the rill pattern.

6.3 FOOTHILL SYSTEM

The foothill rills which join the stream have their own operating system, mainly controlled by the seasonal variations of the water-table level, as revealed by visual observations with piezometers. The two systems mentioned above start operating in the early rainy season and participate in loading the downslope groundwater body. At this time, except during heavy rainstorms, upstream rill flow usually infiltrates into the unsaturated sand hydromorphic soils and consequently rarely communicates with the valley bottom rills. As sand hydromorphic soils become waterlogged, due to the upward shift of the water-table, the midslope water-courses system can connect with the foot-hill system which then becomes fully operative. The hydrological connection of the three systems to the stream is therefore a time dependent-phenomenon. Long after the end of the rainy season, rill base flow may continue to drain the footslope water-table.

7 CONCLUSIONS

This study of the rill pattern within a savannah watershed leads to several conclusions:

1. The volume of linear erosion expressed per hectare is mainly governed by slope inclination. More precisely, the depth of incision is intimately related to hillslope steepness. The rill density, expressed in m/ha, is also related to slope length and topsoil clay content. However, the predicitve model of BOON & SAVAT (1981), based on simple hydraulic parameters, was validated for only 10 map units out of 18. Although slope steepness and discharge (through low permeability and slope length) actually combine to generate shear stress, they are not the only active factors. The occurrence of throughflow and the foothill water-table make the development of rill pattern more complex. When studying rill erosion in the wet tropics, one should keep in mind that surface and subsurface erosion are often combined.

2. Three rill systems can be identified: upslope incisions which include prerills, rills and gullies are governed by overland flow whereas the midslope system is also influenced by throughflow and piping. The initiation of deep gullies appears as a more complex process than mere deepening. The foothill rill system is

mainly controlled by the water-table level.

3. Several recurrence intervals should be taken into account in interpreting the various erosion factors. Rills may develop very quickly in a cultivated field, while the development of deep gullies may be influenced by long term pedological processes such as lateral leaching or the gradual upward encroachment of a water-table along the hillslope.

ACKNOWLEDGEMENT

The authors wish to express their sincere thanks to Prof. R. Bryan for the cheerful and constructive comments he made on the text.

8 REFERENCES

[BOON & SAVAT 1981] BOON, W. & SAVAT, J.: A nomograph for the prediction of rill erosion. In: Soil Conservation, Problems and Prospects. Ed. by R.P.C. Morgan, J. Wiley, Chichester, 303–319.

[BOULET et al. 1977] BOULET, R., BOCQUIER, G. & MILLOT, G.: Géochimie de la surface et formes du relief. I. Déséquilibre pédobioclimatique dans les couvertures pédologiques de l'Afrique tropicale de l'ouest et son rôle dans l'aplanissement des reliefs. Sciences Géologiques, **30**, 235–243.

[BROU 1985] BROU, K.: Analyse et traitement des observations des postes pluviométriques de Touba et de Bouna. Techn. Report, ORSTOM, Adiopodoume, 27 p.

[CHAUVEL et al. 1977] CHAUVEL, A., BOCQUIER, G. & PEDRO, G.: Géochimie de la surface et formes du relief: III. Les mécanismes de la disjonction des constituants des couvertures ferrallitiques et l'origine de la zonalité des couvertures sableuses dans les régions intertropicales de l'Afrique de l'ouest. Sciences Géologiques, **30**, 255–263.

[CHEVALLIER & SAKLY 1985] CHEVALLIER, P. & SAKLY, F.: Etude du rapport pluie-débit sous pluie simulée sur un petit bassin versant de savane humide (Booro-Borotou, Côte d'Ivoire). Techn. Report, Orstom, Adiopodoumé, 29 p.

[DUBREUIL 1985] DUBREUIL, P.L.: Review of field observations of runoff generation in the tropics. Journal of Hydrology, **80**, 237–264.

[GOVERS 1985] GOVERS, G.: Selectivity and transport capacity of thin flows in relation to rill erosion. CATENA, **12**, 35–49.

[KALMAN 1976] KALMAN, R.: Etude expérimentale de l'érosion par griffes. Revue de Géographie Physique et de Géologie Dynamique, **18**, 395–406.

[MOSLEY 1974] MOSLEY, M.P.: Experimental study of rill erosion. Transactions of the ASAE, **17**, 909–913.

[PLANCHON 1985] PLANCHON, O.: Utilisation d'un simulateur de ruissellement pour l'étude expérimentale de l'érosion. Tech. Report, Orstom, Adiopodoumé, 16 p.

[ROLOFF et al. 1981] ROLOFF, G., BRADFORD, J.M. & SCRIVENER, C.L.: Gully development in the deep loess hills region of central Missouri. Soil Science Society of America Journal, **45**, 119–123.

[SAVAT & DE PLOEY 1982] SAVAT, J. & DE PLOEY, J.: Sheetwash and rill development by surface flow. In. Badland Geomorphology and Piping. Ed. by R. Bryan and A. Yair. Geo. Abstracts, Norwich, 113–126.

[SAVIGEAR 1960] SAVIGEAR, R.A.G.: Slopes and hills in West Africa. Zeitschrift für Geomorphologie, Supplementband **1**, Contributions internationales à la Morphologie des Versants. Ed. by P. Birot and P. Macar, 156–171.

Address of authors:
O. Planchon, E. Fritsch and **C. Valentin**
ORSTOM, B.P. V-51
Abidjan, Côte d'Ivoire