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The topographic thresholds of hillslope incisions in southwestern Rwanda

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Abstract

This article presents new quantitative evidence that land use in Rwanda contributes to the development of hillslope incisions.

Two types of hillslope incisions can be distinguished in southern Rwanda. Incisions of the first type drain an area depending on the form and extension on the natural topography and geology. The Runyinya gully (25°) and the Rugabano soil slippage (39°) are two examples. On a logarithmic plot of critical slope inclination at the incision head versus drainage area towards the incision head, both incisions lay sensibly to the right of the Montgomery–Dietrich (M-D) envelope. The latter gives the range of these topographical thresholds for gully and mass-wasting incision in parts of North America. The Runyinya and Rugabano cases obey the linear equation:

$$S_{\mathrm{cr}} = (\pm 0.6)A^{-(\pm 0.6)}$$

where S_{cr} = critical slope gradient (tangent of slope in °) at the gully head or the scar and A = the area (ha) drained towards the incision head.

Hillslope incisions of the second group rely on a run-on area larger than normal because they are localised at the 'outlet' of artificially runoff-collecting systems like roads, soil conservational contour trenches, tracks and other linear landscape elements. Such systems often drain a surface much larger in extension than the natural run-on area to the 'outlet.' These hillslope incisions, taking into account their artificially big drainage area, concentrate more or less along the line:

$$S_{\mathrm{cr}} = (\pm 0.3)A^{-(\pm 0.6)}$$

This line is about in the center of the Montgomery–Dietrich envelope. If, however, only the natural drainage area of these 'outlet' incisions is taken into account, all points fall close to the left

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border or even to the left of the Montgomery–Dietrich envelope. This indicates a much higher probability for incision in those localities receiving supplementary runoff or interflow from outside the natural drainage area. In the case of a soil slippage at Rwaza Hill, detailed stability calculations show that the slope failure should be due to excessive water infiltration into the bottom of a trench. The digging of the trench provoked an increase in the area drained to the slippage head by a factor of 6.

The phenomenon of 'forward' erosion is compatible with the existence of threshold combinations of slope and drained area. For slopes steeper than 7–8°, the phase of regressive erosion does often follow the forward incision event with a delay of several years or more.

Finally, the scanty data set now available for Rwanda suggests that the drainage area critical to hillslope incision on the red-brown ferrallitic soils in Rwanda might be nearly twice as big as those in North America.

Keywords: Forward erosion; Geomorphic thresholds; Gully; Rwanda; Soil slippage; Safety factor

1. Introduction

Hillslopes in southwestern Rwanda are currently affected by mass movements, gully incision and a combination of both. The role of human activities in the development of mass movements and gully incisions is often questioned. Contour ditches about 50 cm

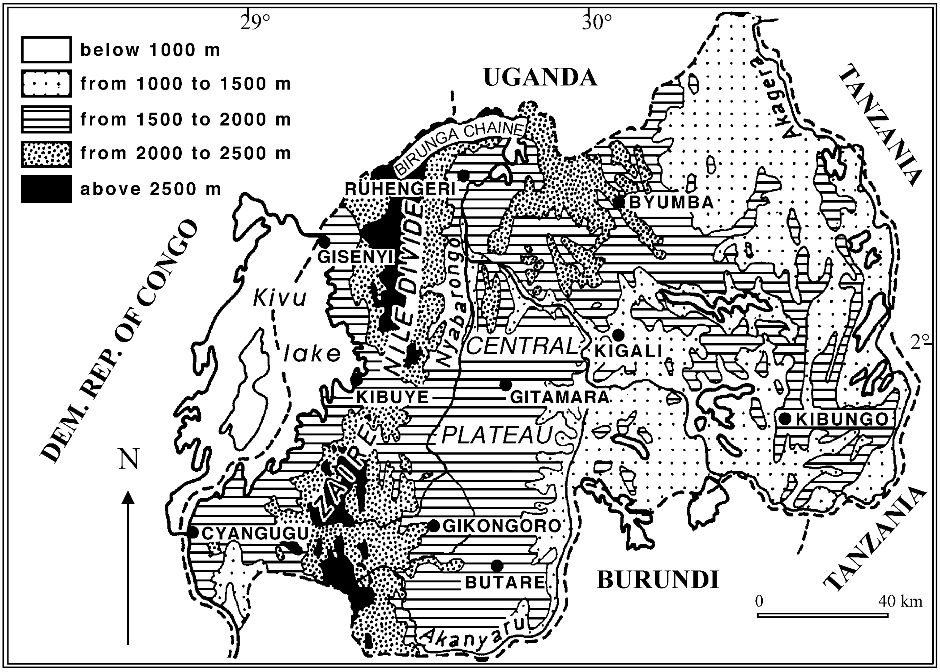


Fig. 1. The topographical map of Rwanda based on Sirven et al. (1974).

wide and 50 cm deep, roads with drainage trenches, footpaths, field borders and other linear structures contribute to the concentration of diffused overland flow (Moeyersons, 1989). Field observations and extensive cartography in the Butare, Gikongoro and Kibuye districts (Fig. 1) between 1977 and 1994 show that more than 50% of the present-day hillslope incisions in southwestern Rwanda are associated with places where runoff is concentrated artificially. This article studies four cases in the vicinity of Butare (Fig. 2). The purpose is to add more substantial evidence to the supposed causal link between the concentration of surface water and hillslope incision. The first case study concerns an artificially induced soil slip on Rwaza Hill. Slope stability calculations are applied, and the drainage area and slope at the incision head are compared with the topographical thresholds as established by Montgomery and Dietrich (1994). The latter criterion is used as a tool for the explanation of the so-called ‘forward’ gully erosion (Moeyersons, 1991) on Sholi Hill and at Tonga and in the case of discontinuous gullies (Heede, 1974) on Mont Gendombi, a series of individual gullies in a thalweg with a concave longitudinal profile. The localities are indicated in Fig. 2.

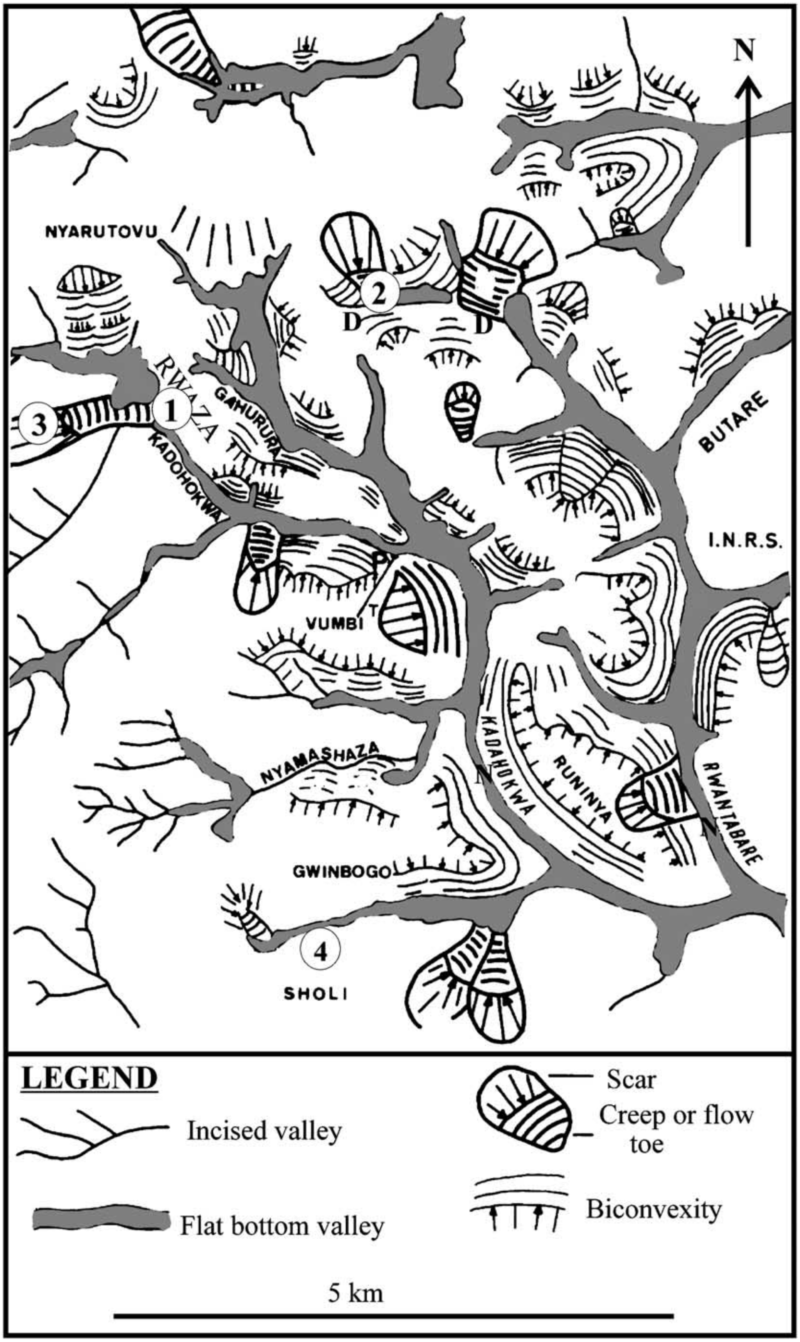
2. Geological, geomorphological and climatic context of Rwanda and the study area

Rwanda occupies the eastern shoulder of the Kivu–Tanganyika rift in Africa. It lies between latitudes 1°04′S and 2°51′S and between longitudes 28°53′E and 30°53′E. The general altitude increases from about 1000 m asl at the edge of the Lake Victoria basin in the east to over 2600 m asl at the crest of the rift shoulder in the west. A dissected fault step more than 1200 m high connects the western side of the rift shoulder with the rift bottom occupied by Lake Kivu at 1400 m asl.

Due to its elevation, Rwanda enjoys a rather mild climate for a country so close to the equator. The mean annual temperature turns slightly around 20°. The two rainy seasons extend from the middle of September to December and from the end of January till May or June, respectively. The annual distribution of the orographic rainfall, issued from the Indian Ocean during the passage of the intertropical convergence belt, reflects the general topography. At Kibuye, it amounts to 1074 mm while at Butare, to 1166 mm (Sirven et al., 1974).

The southern part of the country, including the study area near Butare (Fig. 2), is underlain by Precambrian phyllitic rocks seated in the roof of a granite batholith (République Rwandaise, Ministère des Ressources Naturelles, 1981). The 50- to 100-m-high hilly interfluvial type of rock displays convex cross-sections with a rather flat summit and sides steeping towards the valley. The steepest part of the cross-sections occurs generally only a few meters above the short concavity leading to the flat-bottomed valley and can attain a slope inclination of 40°. The summits converge in the vicinity of Butare to an imaginary ‘Gipfelfluhr’ at an altitude of 1750 m asl. Hills in quartzite enclaves form isolated peaks at a variable height above this level. The slopes on quartzite ridges like the upper part of Mont Gendombi (Fig. 2) can easily attain 45°.

In southern Rwanda, quartzite ridges are not common and most of the landscapes developed on phyllite rocks and shales. This lithology gives rise to a red-brown ferrallitic soil often carrying a ± 50-cm thick humic A-horizon and sometimes buried below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KADAHOKWA
RUNINYA
RWANTABARE
N
GWINBOGO
4
SHOLI
LEGEND
Incised valley
Flat bottom valley
Scar
Creep or flow toe
Biconvexity
5 km

actively colluviating deposits. The red-brown subsoil at Rwaza Hill, often thicker than 1.5 m, has a clay content (particle diameter ≤ 2 μm) between 23% and 33% of its weight. The clay content for the A-horizon varies between 12% and 19%. This difference explains the drop in the hydraulic conductivity at the transition of both horizons from 4.8 to 2.0 cm/s according to ring infiltrometer measurements. There exists a second drop in the hydraulic conductivity at the transition between the brown-red subsoil and the weathered substrate. The latter, in many places, is so strongly enriched with iron oxides that its micro-hydraulic conductivity is, in effect, zero. It has been suggested (Moeyersons, in press) that this weathered rock corresponds with the vesicular laterite covering the African surface in South Africa (Maud, 1965). Subsequent weathering gave rise to the transformation of this ‘laterite’ into a thick humic ferrallitic soil (Maud, 1965; Partridge and Maud, 1987).

Soil slips of the type described and studied below often fail along slide plane bundles or zones at the level or some decimeters below the upper hydraulic conductivity drop in the soil profile. It has also been shown that the ‘secondary’ humic ferrallitic soil has undergone deformations, probably of the creep-type, while slowly sliding or creeping over the unweathered part of the ‘African’ soil. These deep-seated movements are believed to have led, in Late Pleistocene to Middle Holocene times (Moeyersons, in press), to a spatial redistribution of the ferrallitic soil, giving rise to the general convex form of the hills and to lobes and tongue-shaped bodies. As a matter of fact, many of these mass movement bodies seem to be in a precarious state of equilibrium since creep has been measured in a fossil lobe at Rwaza Hill actively eroded at its toe by the Kadahokwa river (Moeyersons, 1989). The morphographic map of the study area (Fig. 2) shows the impact of the deep-seated mass movements on the general morphology.

3. Materials and methods

The simplified Bishop method of slices (Lambe and Whitman, 1979) using electronic tables has been adopted to calculate the safety factor of the soil slip at Rwaza Hill. The program included a study of the soil profiles in the field and the soil mechanical parameters C'_{r} and φ'_{r}, being respectively the residual apparent cohesion and the residual apparent angle of internal friction. In the field, a Thorvane shear device and a portable shear graph have been used, and total unit soil weight (γ_{t}) and the water content (w) at the test localities have been defined in the laboratory in undisturbed samples. Further tests have been executed in the laboratory with a mono-axial shear resistance apparatus (M&O, Montrouge, Paris). This led to the following definitions (Moeyersons, 1989):

$$C'_{\mathrm{r}} = -0.63w + 22.5 \qquad (r = -0.83) \tag{1}$$

$$\varphi'_{\mathrm{r}} = -0.80w + 61.39 \quad \text{if } w \leq 18\% \text{ of the weight of the dry soil} \quad (r = -0.51) \tag{2}$$

Fig. 2. Geomorphological sketch map of the study area with indication of localities. (1) The soil slippage at Rwaza Hill; (2) the gully on the Tonga lobe; (3) the eastern side of Mont Gendombi; and (4) the gullies along the Butare–Nyakibanda road.

$$\varphi'_{\mathrm{r}} = -1.45w + 72.29 \quad \text{if } w > 18\% \text{ of the weight of the dry soil} \quad (r = -0.95) \tag{3}$$

$$\gamma_{\mathrm{t}} = (w + 97.93)/7.06 \qquad (r = 0.76) \tag{4}$$

Further actions concerned the granulometric analysis of soil samples. This was done in the laboratory by a combination of wet sieving of the whole sample, dry sieving of the fraction with a diameter >63 μm and decantation of the fraction finer than 32 μm.

The soil slips and gullies described below are compared with respect to their drainage area and slope at their head with a manually constructed envelope comprising of most values of source area versus slope given for gullies and landslides (Montgomery and Dietrich, 1994, Fig. 11.11) in North America. This envelope (Fig. 3) will be further referred to as the Montgomery–Dietrich (M-D) envelope, and serves as a tool for first comparison. The M-D envelope reference is preferred in the more recent work, e.g. in the Mediterranean belt (Vandekerckhove et al., 2000), because the study area in Rwanda is very hilly, including some slopes of 45°. The M-D envelope includes also such steep slopes.

In the field, a clinometer, allowing readings within an accuracy of about 0.5%, was used to measure the slope inclination along the head of the hillslope incisions. The slope sections involved were all 10 m long and were taken from the incision head in the upslope direction. The definition of the run-on area does not have the same precision everywhere. For the soil slip at Rwaza Hill, it could be defined with the precision of a

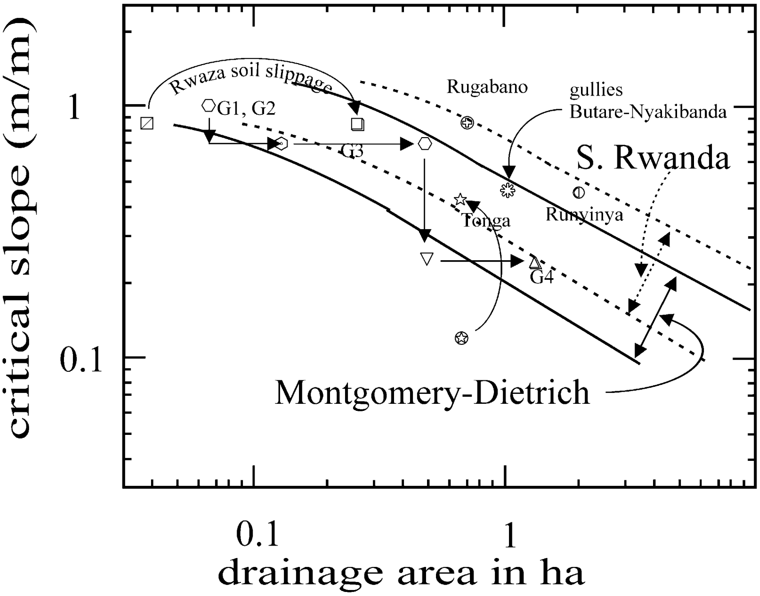

Fig. 3. The envelope of topographical thresholds for gullying and mass movements in North America, except Rock Creek, Oregon and northern Humboldt Range, Nevada (Montgomery and Dietrich, 1994, full lines). Threshold values and tentative envelope for southern Rwanda (dashes).

few square meters. After the rain of the 3rd of June 1979, the traces of runoff towards the head were followed, and the surface subdivided in triangles and squares were measured with measuring tape. The drainage area towards trench 4 was defined by means of measuring tape readings but during dry time. The effect of a rural road passing the topographical hollow has been taken into consideration. The error may be in the order of 200–300 m^2. On Mont Gendombi, an estimation of the natural drainage area towards the four gully heads in question has been done on the basis of detailed pictures taken during the field campaign, our very good knowledge of the situation, and by inspection of the aerial photographs of 1974 (1:50,000). The aerial photographs were not only of limited use because of the scale, but also because of the fact that in 1974, the gullies in question were visibly less developed than in 1984. On the other hand, the area drained by the trenches could easily be deduced from detailed plans made in the field during the 1984 campaign.

The determination of the drainage area in the other cases mentioned is based on detailed pictures, field notes, and plan drawings of the situation and a detailed knowledge of the locations in question, which have been thoroughly visited.

4. The problem of soil slips

4.1. General information of soil slips in Rwanda and problems raised

One frequently occurring mass-wasting process in Rwanda is soil slippage (Chorley et al., 1984). Although sporadically occurring everywhere in the country, the process has been observed to concentrate in the regions of Byumba, Kibuye and to the west of Gikongoro (Fig. 1). It often concerns places where the basal section of the convex slope, often having an inclination approaching 40°, is much longer than around Butare. In the Byumba and western Gikongoro area, these slope sections can attain a length of more than 200 m. The process is only known to occur in places where deep-rooted vegetation like forest is absent. It generally occurs during or within a few hours after heavy runoff events, mostly at the end of the rainy season in May when the water content of the soils is highest. Soil slips occur preferentially on a substrate of phyllitic rocks, where the soil type and clay content respond to the conditions as described above for Rwaza Hill. The affected slope sections are always steeper than 25° and often attain 40°. Scar dimensions vary between a few square meters and one or more hectares. The scar morphology indicates the presence of a simple or composite slide plane, more or less 1 m below the surface, often at the junction between the humic soil horizon and the much more clayey subsoil, or at most, a few decimeters below the top of the latter. Many rills generally incise the scars. The rills start from hollows and pipe-like features in the scar head face at or some decimeters below the transition between the humic horizon and the yellowish or reddish subsoil. They indicate very important interflow in the soil profile at the moment of the slide event and shortly after. The soil slippages typically occur on slopes showing manifest signs of important soil creep: a terracette-like microtopography with soil fissures or crushed zones that are very comparable in pattern to the fissure organization in serial microslumpings (Moeyersons, 1989). Fig. 4 illustrates a scar in the vicinity of Rugabano–Kibuye (Fig. 1).

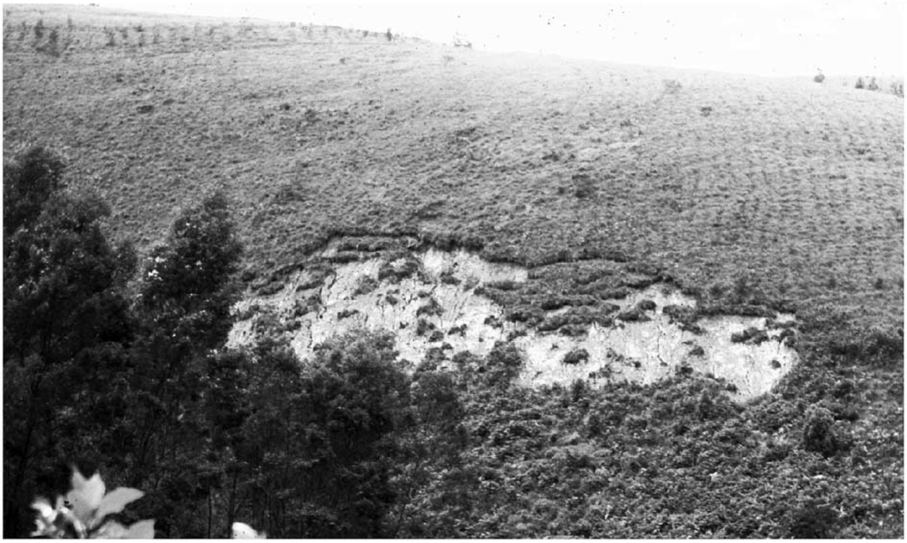

Fig. 4. Soil slippage at Rugabano–Kibuye. The scar affects a convex hill shoulder. With a scar width of more than 45 m, the run-on area amounts to somewhat more than 7000 m^2.

It is typically localised on a convex slope with divergent slope lines. In such topographical position, an incision head of only a few meters wide would have a very small run-on area, but amazingly enough, ‘natural’ soil slips in such a topographical context are always very wide. The one in Fig. 4 occurring on a slope of 39° is 45 m wide, and therefore, is able to drain an area of an estimated 0.7 ha. Compared with the data sets by Montgomery and Dietrich (1994) for North America, the Rugabano soil slip falls to the left of the drained area–slope threshold envelope as defined (Fig. 3).

In opposition to the so-called ‘natural’ soil slippages, there exist a very high number of soil slips considered to be induced by the presence of contour ditches, a soil and water conservation device often used in the country (Moeyersons, 1989). The upper boundary of the scars, often rectilinear, in general follows closely the line of the trenches. The scars are rather small and generally occupy a surface of less than 0.01 ha. The scars often display a more or less rectangular form about twice as long and twice as wide. Fig. 5 illustrates the phenomenon a few kilometers west of Gikongoro (Fig. 1). It has been argued (Moeyersons, 1989) that the presence of the trenches provokes this type of soil slips, but the forwarded evidence is essentially qualitative in nature. One of the obstacles to quantitative data is the fact that the presence of the contour trenches renders, in most cases, a secure estimation of the area drained to the soil slip quite difficultly. A soil slip in more controlled conditions occurred along a newly dug collector trench at Rwaza Hill.

4.2. Soil slippage along collector trench 4 at Rwaza Hill

Several trenches about 50 cm deep and 50 cm wide have been dug at the foot of Rwaza Hill in order to measure soil loss by rainwash (Moeyersons, 1990). The collector trenches

Fig. 5. Concentration of six small “trench” scars in the vicinity of Mudasomwa–Gikongoro. The arrow shows the localization of the inset: position of scar in relation to trench. The person is standing in the trench.

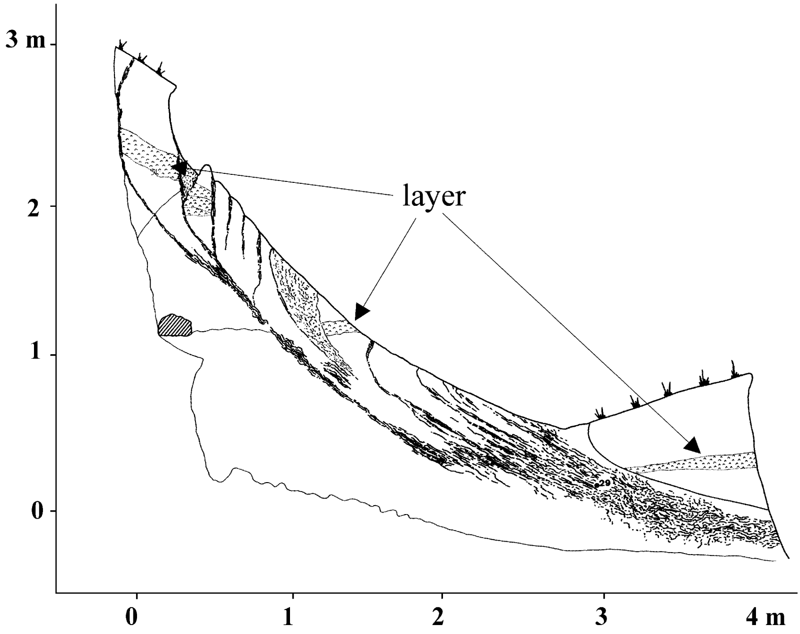

Fig. 6. Section through the soil slippage at Rwaza showing the stratigraphy distortions and the multiple slide planes.

resemble the traditional soil conservational contour ditches in dimensions. Trench 4 was installed in August 1978 at the southwestern side of Rwaza Hill (Fig. 2) just aside of the toe of a creep lobe, where the local slope inclination amounts to 39°. During or shortly after 14.6 mm of precipitation on the 29th of May 1979, part of the trench collapsed. Fig. 6 illustrates the section through the soil slippage. Fig. 7 shows the former position of the collector trench, the water content of the soil in the 3rd of June 1979, the original situation before the slide and the slices used in the simplified Bishop method to calculate stability (Lambe and Whitman, 1979). Basically, the equation

$$F_1 = \frac{\sum \left[c\Delta x_i + (W_i - u_i\Delta x_i)\tan\varphi\right]\left[1/\cos\vartheta_i(1 + \tan\vartheta_i\tan\varphi/F_2)\right]}{\sum W_i\sin\vartheta_i} \qquad (5)$$

is used (Lambe and Whitman, 1979), where $\sum$ = the summation from slice 1 to slice n, in this particular case, $n = 5$ (Fig. 7); $c = C'_\mathrm{r}$ = apparent residual cohesion; Δx_i = the horizontal width of slice i measured in the direction of the slope; $u_i\Delta x_i$ = total upward force by water pressure in slice i; $\varphi = \varphi'_\mathrm{r}$ = friction angle based on effective stresses; ϑ_i = angle between failure surface and horizontal; and W_i = total weight of slice i. All slices are supposed to be 1 m wide measured perpendicularly to the slope lines.

This equation requires a trial and error solution since the factor of safety F appears on both sides of the equation and F_1 has to be equal to F_2. The example of Table 1 illustrates

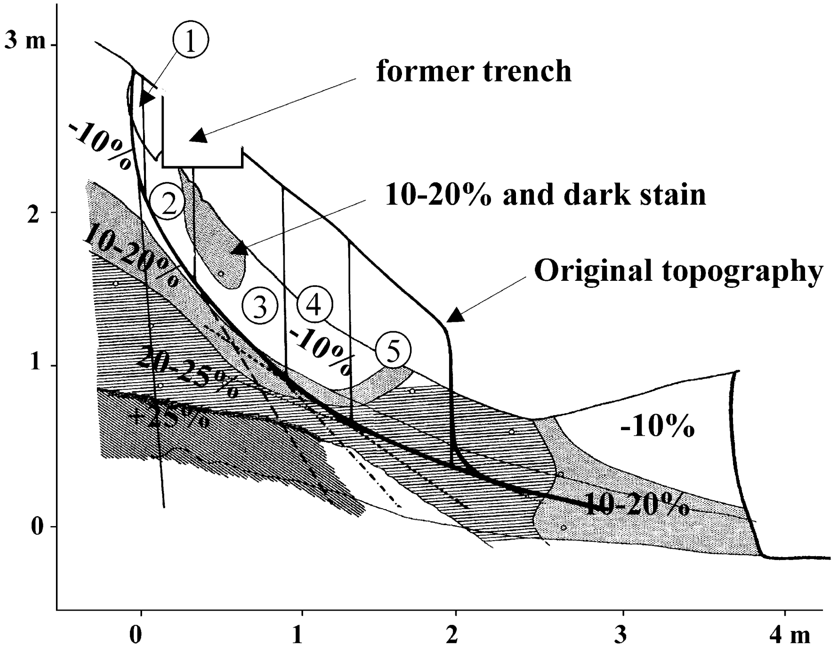

Fig. 7. Soil slippage at Rwaza Hill. Water content in %. Encircled numbers refer to the slices used in the simplified Bishop method.

Table 1

Example of electronic table giving the solution for Eq. (5) for the case where w at the slide planes below slices 1–5 (Fig. 7), respectively, attains the values in column (2), representing the situation at the end of the rainy season in June 1979 (Fig. 7)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Slice	w	Δx_i (m)	h (m)	γ_t (kN/m^3)	W_i (kN)	c (kN/m^2)	cΔx_i (kN)	hw (m)	$u_i\Delta x_i$ (kN)	$W_i - u_i\Delta x_i$ (kN)	φ (°)	(11) tan φ (kN)	(8)+(13) (kN)	M	(14):M	ϑ_i (°)	W_i sin ϑ_i (kN)
1Δ	5	0.04	0.16	14.58	0.05	19.35	0.8	0.0	0.0	0.05	57.39	0.07	0.8	1.00	0.85	72	0.04
2	8	0.37	0.48	15.00	2.66	17.46	6.5	0.0	0.0	2.66	54.99	3.80	10.3	0.96	10.70	61	2.33
3	12	0.68	1.16	15.57	12.28	14.94	10.2	0.0	0.0	12.28	51.79	15.60	25.8	1.04	24.88	47	8.98
4	20	0.50	1.36	16.70	11.36	9.90	5.0	0.0	0.0	11.36	43.29	10.70	15.7	1.01	15.52	38	6.99
5	25	0.77	1.24	16.70	15.95	6.75	5.2	0.0	0.0	15.95	36.04	11.60	16.8	1.01	16.66	29	7.73
Sum of columns 16 and 18 for $F=2.63$															68.60		24.72
If $F_2=2.63$, $F_1=2.63$																	

w = water content in % of dry weight of soil.
Δx_i = the horizontal width of slice i measured in the direction of the slope.
h = average height of slice.
γ_t=(w + 97.93)/7.06 according to Eq. (4).
W_i = total weight of slice $i=\gamma_t h \Delta x_i$.
$c = C'_r$ = apparent cohesion according to Eq. (1).
$u_i\Delta x_i$ = total upward force by water pressure in slice i.
hw = height of water table above slide plane i.
$\varphi = \varphi'_r$ = friction angle based on effective stresses according to Eqs. (2) and (3).
$M = \cos\vartheta_i\,(1 + \tan\vartheta_i \tan\varphi/F_2)$.
ϑ_i = angle between failure surface and horizontal.
All slices are supposed to be 1 m wide, measured perpendicularly to the slope lines.

the degree of stability as calculated for the topographical situation before the occurrence of the slippage and for the conditions of water content as defined during the excavation of the section on the 3rd of June 1979 (Fig. 7). It appears that in this condition of soil humidity, only 5 days after the slippage and 1 day after a supplementary of 3.2 mm of precipitation, $F = 2.63$. It should be mentioned here that this factor of safety is a slight underestimation because the water content adopted for the slide planes has also been used to calculate the weight of the respective slices. Hence, the water content can be seen to decrease toward the surface.

Because the trench has been visited every rainy day, we can confirm that exfiltration never occurred in the scar of the slide, not even the 30th of May. There was also no exfiltration at the base of the slumped block, indicating the absence of seepage at the base of slice 5, but of course, the water content might have been higher on the moment of the slide event than on the 3rd of June 1979 (Fig. 7). Taking into account:

1. that the lines separating the water content classes would have been more or less parallel to the surface in the restored situation of Fig. 7;
2. that seepage parallel to the surface never did attain the level of slide plane 5 (Fig. 7); and
3. that field capacity equals 30%,

the worst possible situation should be that the water content at slide planes 3, 4 and 5 (Fig. 7) should attain 30%, while it should remain lower at the altitude of slide planes 1 and 2 with 10% and 20% water content, respectively. Changing these values in column 2 of the electronic table in Table 1 leads to a convergence of F_1 and F_2 to 1.23, still indicating stability. If seepage at the level of slide plane 5 is not allowed, the situation of the water content in Fig. 7 can lead to instability if water infiltration is simulated from the collector trench. This can be done by introducing higher water contents and seepage pressure in slices 2 and 3. Note that a water content of 33% has to be introduced for the case of seepage. The height of the seeping water table above slide planes 2 and 3 is estimated at 0.1 m. Table 2 summarises the introduced values and mentions the obtained safety factor of 0.93. There is a very strong field evidence that infiltration of water into the bottom of the trench really happened because a wet patch was still visible in the excavated section

Table 2
Values introduced in Table 1 simulating infiltration of water into the soil from the trench bottom
The stability factor F becomes as low as 0.93

Column in Table 1		
1	2	9
Slice	w	hw (m)
1Δ	30	0.0
2	33	0.1
3	33	0.1
4	30	0.0
5	30	0.0

below the former position of the trench (Fig. 7). Moreover, the presence of the trench increased the area drained to the head of the soil slippage. Without the trench, the area drained to the nearly 3-m wide slippage head amounts to about 400 m^2, but with the 18-m long trench, this area becomes about 2.550 m^2. Fig. 3 shows that the soil slippage at Rwaza Hill did fall to the left side of the M-D envelope before the digging of the collector, but to the right inner side of the envelope after digging.

5. Gullying

5.1. Gullying in topographical highs

Qualitative aspects of gully development in Rwanda have been thoroughly documented in a former work (Moeyersons, 1989). Here, the quantitative question of the run-on area–slope thresholds is raised. Gully forms and hillslope incisions of mixed origin often occupy topographical hollows. One example is given in Fig. 8 which shows the hillslope incision of Runyinya. This incision is at about 15 km to the west of Butare (Fig. 1). The area drained to the head is about 2 ha and the slope along the head is 25°. This incision, apparently of mixed origin, falls to the right of the M-D envelope (Fig. 3) just as the case of the Rugabano soil slippage. However, an important number of gullies do not occupy topographical hollows but topographical highs. In such cases, the natural drainage area is much smaller than in topographical hollows due to the divergence of the slope lines. For a narrow (1–2 m) gully head, the run-on area can be as less as a few square meters, but in the observed cases, the small natural run-on area is compensated by a supplementary area drained by runoff collectors like the contour trenches mentioned before. Roads, tracks, field boundaries and all kinds of artificial linear structures crossing the slope lines can play the same role. One example is the gully affecting the convex toe of the fossil creep lobe (Moeyersons, 1989) of Tonga (Figs. 2 and 9). Due to the road and the track, 0.65 ha is drained towards the gully head. The gully incision does not start where the track leaves the road and where the slope of the track is about 10°, but only 40 m away from the road, where the slope of the track amounts to 25°. The situation is depicted in Fig. 3.

5.2. Discontinuous gullying on Mont Gendombi

A series of four individual gullies (Heede, 1974) affects the NW-side of Mont Gendombi just outside the map (Fig. 2). The situation is illustrated (Fig. 10). The two upper gullies (G1 and G2) affect the lower part of the quartzite summital ridge of Mont Gendombi. The two lowermost gullies are developed within a ferrallitic soil similar to the one at Rwaza Hill but here, as thick as 7 m. The outlets of G1 and G2 merge to follow one drainage line in which gully heads 3 and 4 are developed more downslope. The four gullies occupy the left part of a very slightly incised hillslope valley. The right part is occupied by one deep gully which is as long as the four discontinuous gullies put together. This explains why the latter only drains part of the right side of Fig. 10. The longitudinal section of the drainage line is concave, which explains the decrease of the slope along the heads of gullies 1–4 (Table 3). Gullies 1 and 2 are fed by a natural drainage area while

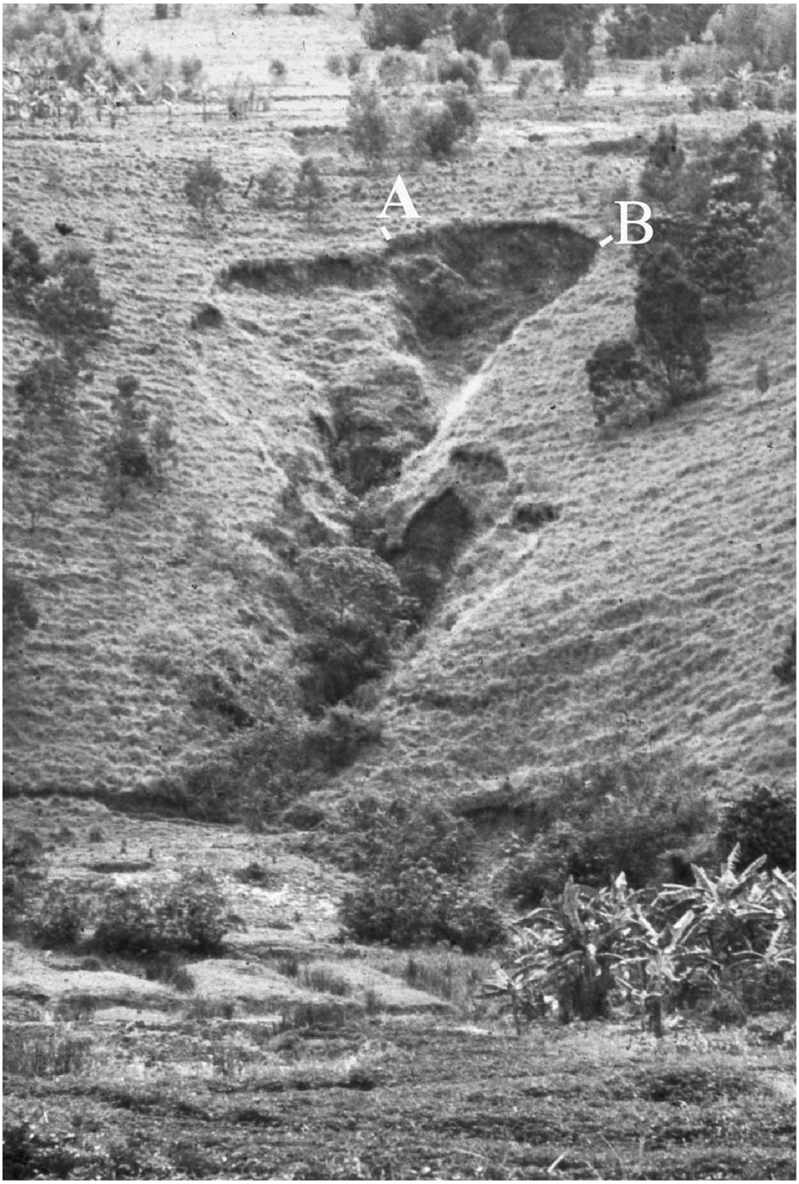

Fig. 8. Gully or bottleneck slide, Runyinya, southern Rwanda. Unfinished slump outlines already the future lateral extension of the head. This hillslope incision is located in a topographical hollow. Area drained towards the head (A–B) is somewhat more than 2 ha and the slope gradient is 25° above the head face.

gullies 3 and 4 drain an area which is considerably larger than their natural drainage area due to the presence of contour trenches. Fig. 10 shows how gully heads 3 and 4 are exactly located at the place where such a ditch releases its waters freely into the drainage line.

Fig. 9. Gully incised in a convex topographical high. The natural surface draining to the gully head is nearly zero, but the gully head is located on a track (between two black arrows), which captures the waters collected by the road (white arrows).

Table 3 summarises the slopes, natural drainage areas and drainage areas due to the presence of the trenches. It appears that the presence of the ditches in the field influences the position of the gullies in relation to the M-D envelope (Fig. 3). Incisions G1 and G2 terminate where the slope inclination 45° at their head decreases to below 40°. The place of gully head 3, if only its natural drainage of 0.15 ha (Table 3) is considered, falls to the left margin of the envelope. The whole drainage line downslope of gully 2 should appear on the M-D envelope (Fig. 3) as a nearly vertical line starting from a point (40°, 0.15 ha) and located for its larger part to the left of the envelope, indicating the low probability for gully incision. However, due to the presence of the trench at gully head 3, the latter drains a supplementary of 0.49 ha and shifts to the right side of the envelope (Fig. 3), where incision is much more probable. In the downslope direction, the incision of gully 3 ends where the slope diminishes to about 20°. If there was, in the downslope direction, only a natural increase of drainage area, the whole drainage line downslope of gully head 3 should again fall to the left of the envelope. However, due to an additional drainage of 0.65 ha supplied by the trench at gully head 4, this locality shifts again to the right of the M-D envelope (Fig. 3).

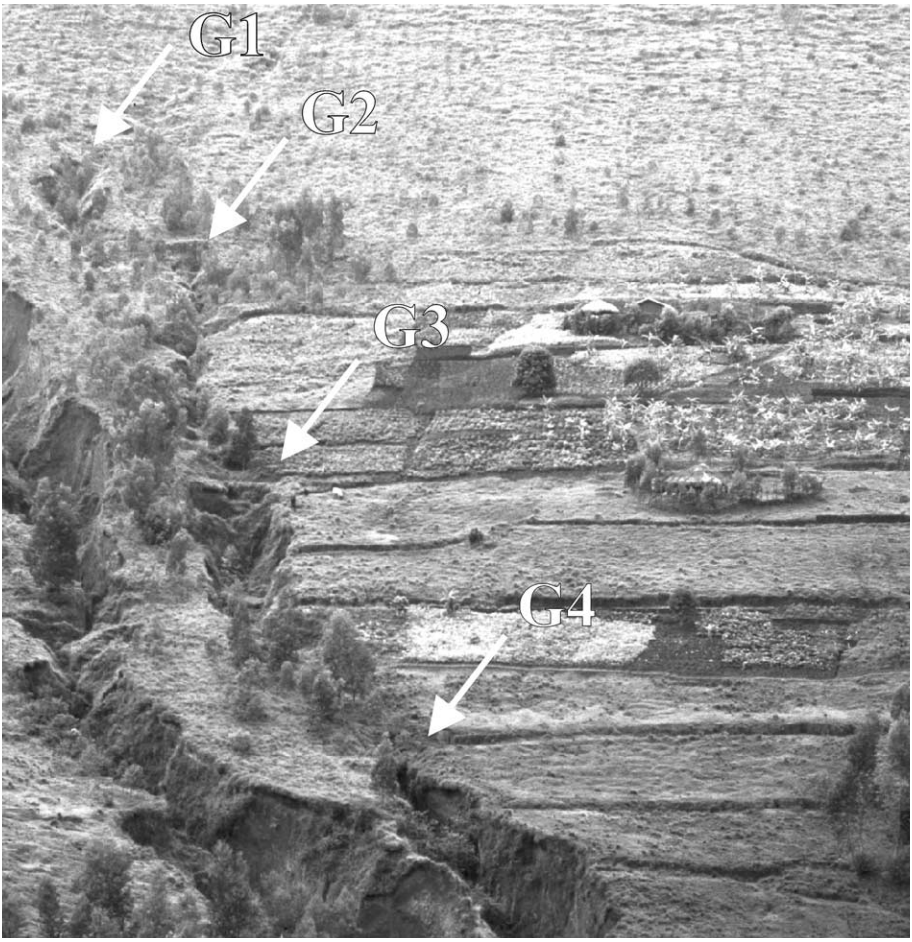

Fig. 10. Mont Gendombi. The upper part of the hill (tree plantations) is on quartzite rocks. The soil conservational trenches conduct supplementary runoff to points G3 and G4. For more information, see Fig. 3 and Table 3.

The Mont Gendombi example shows that the system of conservational contour trenches leads to sudden increases in the drained area at points G3 and G4 of the drainage line. At these two points, the drained area exceeds considerably the natural one. The visual observation that the gully heads coincide with the release points of the trenches and the observation that the drainage area–slope relation jumps from the left to the right in the M-D envelope seem to be satisfactory proof that gullying in this particular case is due to the presence of the trenches.

5.3. Gullying along the Butare–Nyakibanda road

Qualitative information about gullying along this road has been described in an earlier work (Moeyersons, 1989), and it is along one of the gullies that the phenomenon of

Table 3
Slopes above the gully heads and comparison between natural and artificial drainage area of the gullies

Gully	Gully 1	Gully 2	Gully 3	Gully 4
Slope at head	45°	45°	35°	15°
Natural drainage area	0.07 ha	0.07 ha	G1 + G2 + 0.01 = 0.15 ha	0.15 + 0.016 = 0.166 ha
Drainage area due to trenches			G1 + G2 + 0.35 = 0.49 ha	0.49 + 0.85 = 1.34 ha

forward erosion has been monitored (Moeyersons, 1991). Roads in southern Rwanda play a role in concentrating runoff, which, in natural conditions, should be rather diffuse. As a matter of fact, the water is generally not concentrated by the road itself but by the drainage trench between the road and the hillside. At regular distances, the water in the trench is given way below a small bridge in the road to be released on a generally steep slope. In the example where forward erosion has been described (Moeyersons, 1989), the area drained towards the bridge was about 1 ha. The first runoff 'pothole' was located on the point of the convex slope where the slope inclination reaches 21°. This point is situated to the right side of the M-D envelope (Fig. 3), indicating the high probability of incision for these topographical conditions.

6. Discussion of data

6.1. The effect of human soil use on hillslope incision in Rwanda

By comparing the topographical thresholds of the incisions in southwestern Rwanda with the M-D envelope, the case studies in this article add quantitative evidence to the formerly stated qualitative arguments (Moeyersons, 1989) that hillslope incisions in southern Rwanda are often due to the presence of contour trenches (Mont Gendombi), tracks (gully in the toe of the Tonga lobe), roads and their accompanying systems of trenches, gutters, etc. (Butare–Nyakibanda road). These and other linear structures, when crossing the slope, have the capacity to concentrate overland flow supplied by small first order basins or by diffused runoff. On the M-D envelope (Fig. 3), points of incision fall to the left side as long as only the natural drainage area is taken into account. However, if the supplementary artificial supply at the incision head is taken into account, the point of incision jumps to the right side of the envelope. This seems especially true in the case of 'small headed' incisions on topographical heights, convex slope portions with divergent slope lines. Natural soil slips on topographical heights like the one in Rugabano (Fig. 4), however, fall to the right side of the M-D envelope. The reason is their head, generally several meters or tens of meters wide, allowing runoff or interflow to be intercepted from an important surface in spite of their topographical position.

In the case of the soil slip at Rwaza Hill, the stability calculations show that instability is reached under conditions of soil humidity that occur at the end of the rainy season, but during additional water infiltration in the soil from the bottom of the trench. The runoff water supply to the trench was more than six times larger than the direct supply to the slippage head.

6.2. The phenomenon of forward erosion

Forward erosion corresponds with the observed phenomenon on slopes steeper than 7–8° (Moeyersons, 1991) that gullies develop from a certain point on the slope in the downslope direction. It corroborates the theoretical concept that incision needs a combination of geomorphic thresholds. Most authors elaborating this idea (Schumm and Hadley, 1957; Leopold et al., 1964; Patton and Schumm, 1975; Merkel et al., 1988; Montgomery and Dietrich, 1994, just to name a few) think that gully incision demands a minimum runoff discharge in function of the slope. This means that a gully can only start at a minimum distance from the most elevated border of a basin needed to build up the critical runoff discharge. In field studies verifying these theoretical considerations, most authors put the gully head into a plot where the runoff discharge, substituted by the surface drained to the gully head, is plotted against the slope at the gully head. It appears, however, in many studies throughout the world, especially where the slopes are only of the order of 7–8° or less, that gullies actively undergo head retreat (Rutherfurd et al., 1997) after their first incision. Therefore, the correct establishment of geomorphic thresholds for gullies seems only possible if the point can be defined where the gully head took its start. In Rwanda, gully heads on steep slopes seem to remain stable over long periods. In the case of Mont Gendombi, gully heads 3 and 4 did not retreat in the upslope direction between 1974 and 1984. We know that along the Butare–Nyakibanda road, the gully heads, some of which are more than 5 m deep, never underwent so much retreat between 1977 and 1993 as to endanger the road itself. The Runyinya gully was observed to be stable at least from 1979 to 1993. These examples show that eventual subsequent upslope extension is a process not linked to the geomorphic thresholds which determine the localization of the initial forward incision.

6.3. The slope–natural drainage area threshold for the Rwandese environmental conditions

It is known that geomorphic threshold conditions for gullying as well as for landsliding can be expressed by the equation (Vandaele et al., 1996):

$$S_{\mathrm{cr}} = aA^{-b} \tag{6}$$

where S_{cr} = critical slope gradient (tangent of slope in °) at the gully head or the scar, A = the area (ha) drained towards the incision head and a is a coefficient.

Not so long ago, it was thought that the exponent $-b$ was a ‘constant’ approaching -0.40 in the case of gullying (Vandaele et al., 1996) and about -0.60 in the case of mass movements on slopes above 25° (Montgomery and Dietrich, 1994), but a research in the Mediterranean (Vandekerckhove et al., 2000) did not confirm this. Nevertheless, in a first approximation, and taking into account:

1. the restricted precision of the M-D envelope reconstructed here as a tool for first comparison (Fig. 3); and
2. the representation of steep sloping terrain in the M-D envelope reminding Rwandese conditions,

it is thought that this envelope can be adapted to the Rwandese environmental conditions. It can be shifted to the right, parallel to itself, to comprise the Runyinya and Rugabano features and also the conditions of incision at the soil slippage of Rwaza, at Mont Gendombi and along the Butare–Nyakibanda road. The ‘Rwandese’ envelope is shown in dashed lines in Fig. 3. It suggests that the critical drainage area for hillslope incision in the Rwandese ferrallitic soils should be nearly twice as large as in North America. The Rugabano and Runyinya features, being considered as ‘natural’ phenomena in the Rwandese agricultural environment on ferrallitic tropical soil, occupy a line in the slope–drainage area plot, approximately defined as:

$$S_{\mathrm{cr}} = (\pm 0.6)A^{-(\pm 0.6)} \tag{7}$$

It should be noted that all the other incisions proven above to have resulted from direct human interaction like trenches, roads, tracks, etc., are concentrated along a linear belt below this line. In a first approximation, this line can be expressed as:

$$S_{\mathrm{cr}} = (\pm 0.3)A^{-(\pm 0.6)} \tag{8}$$

It is felt that much more data are needed to establish in detail the geomorphic thresholds for hillslope incisions in the Rwandese environment.

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