CATENA vol. 18, p. 309–324 Cremlingen 1991

RAVINE FORMATION ON STEEP SLOPES: FORWARD VERSUS REGRESSIVE EROSION. SOME CASE STUDIES FROM RWANDA

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Summary

Observations on steep slopes in Rwanda reveal that human interventions on surficial drainage can introduce gullying on places where runoff normally leads to diffuse or ephemeral rill erosion. In such cases, an initial runoff incision or slide scar, respectively due to an artificial concentration of runoff or underflow, grows in downslope direction, mainly by runoff incision. This type of progressive or forward gully development contrasts with the more classical regressive development, here only observed in places where the flow gradient is less than 7°–8°.

1 Introduction

Rwanda is located in Central Africa between 1°04′ and 2°51′ South and 28°53′ and 30°53′ East, and occupies the highly dissected highlands to the East of Lake Kivu. Here, steep sided convex hills alternate with flat sometimes wide, valleys. This hillform is mainly due to diffuse processes as creep and diffuse wash (MOEYERSONS 1989). Agricultural activities, once restricted to slopes of less than 10° but now extending over nearly the whole territory, have led to the development of two varieties of gullies and ravines; ones that develop by headward and forward erosion, respectively. The first variety is located in flat bottomed and marshy valleys where choked river beds are widening and deepening and active gully head retreat can be observed in many remote source areas. The second variety developes on the steep hill sides where ravines often end up at the break of slope between the hill and the valley and are most times not connected by a clear channel with the changing drainage system in the valley bottom. These hill side ravines are comparable to the second gully type, described by DE OLIVEIRA (1989) at Bananal, Sao Paolo, Brazil. They are not so numerous, but when they eventually appear, they often form very impressive features (photo 1).

Gullies are generally considered to develop by headward erosion. The walls of the ravine, left behind in the migratory trajectory of the head often evolve by mass movements (BLONG 1982, DE PLOEY 1974, DONKER & DAMEN 1984). The upslope migration of the head can follow from the erosive action by concentrated runoff (MELTON 1965, HURAULT 1971). IRELAND, SHARP & EAGLE (1939) showed the active role in gully head retreat by that part of the

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0341–8162/91/5011851/US$ 2.00 + 0.25

Photo 1: *Ravine system on Mont Gendombi.*

water current, adhering to the head wall, and the only indirect effect of the free falling water jet in scouring out a plunge pool: the latter need to be deepened out close to the base of the gully head to destabilise the wall. In other cases ravine head migration was attributed to the collapse of tunnels and pipes (DONKER & DAMEN 1984), formed by hypodermic water flow below the root netwerk of grasses or bushes (HAIG 1981) or in deeper soil horizons (GIBBS 1945, JONES 1971 and 1981, STOCKING 1977, GERSTER 1976). Head scar retreat can also be due to mass movements (SCHOUTEN & RANG 1984), resulting from basal sapping at the bottom of the head where a temporary water table exists (HIGGINS 1982, FEENEMAN 1932, DUNNE 1980). VAN DEN BRINK & JUNGERIUS (1983) state that ravines often develop in places where a porous stratum covers a less permeable deeper horizon: the drop in hydraulic conductivity favours the development of a temporary or perennial water table, what leads to the processes of mass wasting, described above.

Most previous studies refer to gullying in rather flat areas while the ravines studied in Rwanda develop on hill slopes ranging from 10° to 35°. Field observations here indicate the same variety of ravine forming processes but an original way of gully development, by "forward" instead of "backward" erosion. "Forward" erosion is characterized by a primary water scour incision or mass wasting scar, originating somewhere in mid-slope position and extending in time in downslope direction without appreciable headward retreat. In such cases the head is the oldest, and most times the deepest and largest point of the ravine. Forward ravine development generally occurs where human activites lead to changes in the natural drainage pattern of the hill slopes. This article focuses on the way in which this second type of ravines develops.

2 Pedological and slope hydrological context of hill side ravines in Rwanda

2.1 Relation between runoff and underflow

Hill slope ravines in Rwanda are generally underlain by phyllitic rocks carrying a kaolinite soil, sometimes several meters thick. A typical soil profile consist of a A1-humic horizon, 0 to 50 cm thick, eventually separated from the underlying red-brown sub-soil by a diffuse stone-line, generally containing angular quartz or quartzite gravels with a diameter between 1 and 10 cm. The thickness of the sub-soil is of the order of 2 to 3 m or more. This horizon is separated from the weathered bedrock by an argillaceous layer, containing abundant angular quartz elements with a diameter of about 0.5–2 cm and quartzitic and phyllitic angular rock fragments of much bigger dimensions (5–20 cm).

Many field observations have illustrated the particular way in which this soil profile is drained during and shortly after heavy rain showers: besides runoff at the surface, important underflow is evidenced in some places by the presence of tunnels, macropores and cavitities, concentrated at the transition between the humic A1-horizon and the subsoil, and in the transitional clayey-gravelly layer separating the soil from the weathered bedrock. This model of subsurficial drainage is thought to be due to a combination of textural and structural soil characteristics.

In the first place, there is the clay content: at the surface it attains values of the order of 10%, while deeper in the soil values above 20% and even 30% are very common. A first increase, although gradual, occurs around the transition between the humic A1-horizon and the more clayey sub-soil. A second increase in clay content occurs in the basal claye gravelly layer, which covers the bedrock. The upper hydraulic discontinuity has been confirmed by oedometer tests, showing that Darcy's k is of the order of $10^{-3} - 10^{-4}$ cm/s in the humic horizon, while values of 10^{-5} cm/s and less are obtained deeper in the soil profile. But this difference is only partly due to the higher mentioned gradual textural differentiation. Tests on samples with comparable textural composition but with different humic contents (up to 4% of the total weight) showed a positive correlation between humic content and hydraulic conductivity (MOEYERSONS 1989).

Another reason to accept two drops in the hydraulic conductivity is the presence of two stone layers: a diffuse one at the A1-subsoil transition, and a compact one just above the bedrock. J. MOEYERSONS (1989) showed experimentally that a stone-line in tilted position acts as a coveyor belt for lateral water mi-

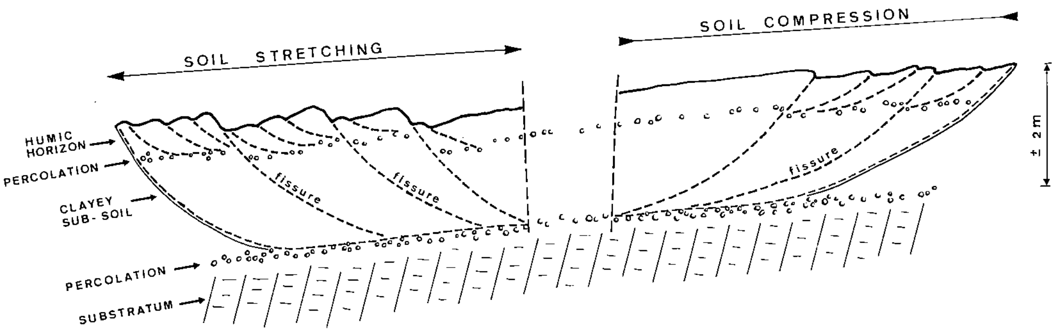

Fig. 1: *Fissures (dashed line) and slight displacements along fissures in stressed and compressed soil sections (J. MOEYERSONS 1989).*
A typical "terracette" morphology results from the displacements. Fissures deviate runoff water to lower soil horizons, especially in sections of stretched soil.

gration in the soil. Therefore, important lateral water migration can be expected in the soil at both levels where stoney fragments occur.

It thus appears that the existing soil texture favours to a certain degree underflow at the two levels mentioned. However, the textural differentiation within the soil profile cannot fully explain the important underflow discharges, especially at the lower level. As mentioned, the sub-soil above this level has a hydraulic conductivity of only 10^{-5} cm/s (± 0.1 m/day) or less. But the type of soil, described here, is often heavily fissured, mainly as a result of creep, especially on slopes steeper than 20°–25° (J. MOEYERSONS 1989). In places where creep stretches the soil in downslope direction, these fissures plunge from the surface to the level of the upper and lower stoneline (fig. 1) and bypass the soil. Important here is the conclusion that the risk for mass wasting becomes higher when the runoff coefficient increases, because bypass water quantities will then become more important.

These fissures play an important role in the variable nature of hill side gully formation. Their degree of development and accessibility for water determines whether places where runoff concentrates or develops will see vertical incision or mass movements and piping, or a combination of both, as processes of gully initiation. The variable interaction of these processes during further development often obliterates convincing evidence to decide whether the ravine consists of a slide scar, remoulded afterwards by running water or of a vertically incised gully, affected later on by mass movements.

2.2 Spatial organisation of runoff and underflow

Runoff on a slope is classicially treated as a continuous body of water, regularly increasing in discharge with slope length. The same is true for lateral seepage and underflow. But the situation on the Rwandese hills is often quite different: lateral redistribution of runoff by roads and drainage trenches leads to marked discontinuities with a drop in runoff discharge downslope of the trench or road and an important increase in concentrated runoff where the water is again released on the unprotected slope.

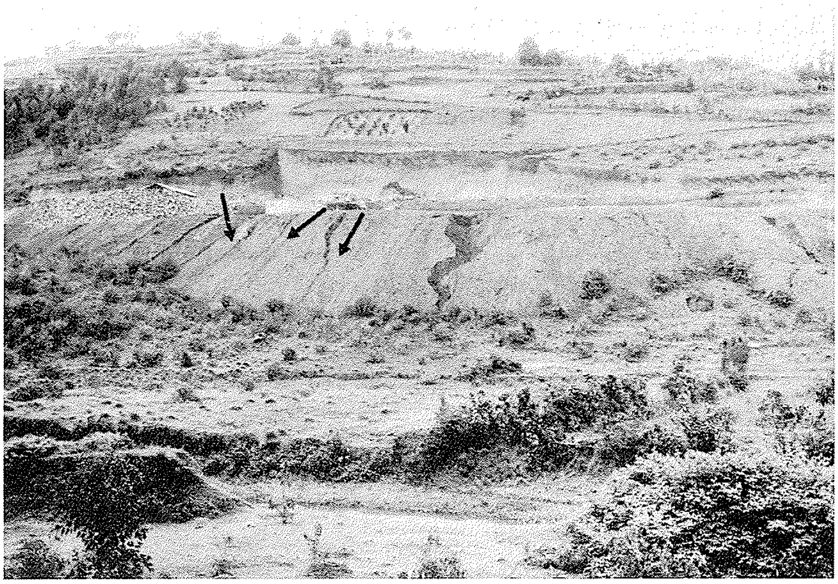

Photo 2: *Forward gully development on dumped soil. Gullies indicated by arrows did not yet reach the valley floor.* ↑

Photo 3: *Rills in the right foreground are fed by runoff waters, spilling over the road from where the photograph was taken. The arrow indicates a rill which ends in the middle of the field.*

The spatial reorganisation of runoff will also influence the distribution of underflow, especially in the cases discussed above, where soil fissures can bypass the soil. Sudden underflow discharge increases may occur below trenches and on places where runoff discharge suddenly increases.

In the following sections the phenomenon of forward gully development will be illustrated by a few examples where the relative importance of water erosion versus mass wasting could be more or less assessed.

3 Forward gully development mainly by runoff incision

Forward gully development, mainly by runoff incision, has only been observed on slopes steeper than 7°–8°. The initial gully head incision is located on places where either the flow gradient and/or the runoff discharge suddenly increase. Cases of forward gully development have been observed under various conditions.

A first example is shown on photo 2. A steep slope of artificial fill receives runoff water from the platform. Gullies can be seen to develop from the top of the slope in downslope direction. Forward rill and gully development has also been observed in cultivated fields. The soil, loosened by hoeing, has an increased storage and infiltration capacity and a reduced resistance to water erosion. Runoff from upslope, entering these fields, provokes here slaking and liquefaction (MOEYERSONS 1989) and rills develop from the upper rim of the field in downslope direction (photo 3). Forward rill and gully development can also start from the drip line of house roofs or from the base of plants such as cassava and sorgho, producing stem flow.

But one of the main causes for forward gully development is the use of trenches. Runoff waters from considerable surfaces are laterally deviated and then released from a given point on a steep and not protected soil surface. Two of the most forthcoming cases are documented. Fig. 2 illustrates the case of a road trench, fig. 3 shows how subhorizontal trenches in steep sloping farmland concentrate runoff waters at their exits on a mean drainage line. In both cases ravines develop in downslope direction from the point where the water is released. It is evident that the retreat of the gully head in upslope direction is blocked, as no or only insufficient quantities of runoff and/or seepage water arrives in the ravine head from there.

We had opportunity to follow the forward development of a new ravine after a gutter was installed below the road Nyabikenke-Butare. This case corresponds to the situation of fig. 2. Peak discharges of more than 50 liters a second have been observed during a rainstorm. The convex slope below the point of release was about 40 m long and increased from 21° to 33° in downslope direction. The vegetation consisted of sparsely planted *Eucalyptus* sp. trees and a discontinuous grassy cover of individual tufts of *Eragrostis* sp. In the first days, the water from the gutter spreaded open in a triangular cone (fig. 4A). Here, diffuse erosion took place and small hydraulic steps originated. But in the mean time a series of potholes developed in the direct downslope line of the gutter outlet. During the first showers they overflowed during the heaviest part of the rainstorm. But gradually the first created potholes became deeper and wider, and formed a single perched channel, big enough to

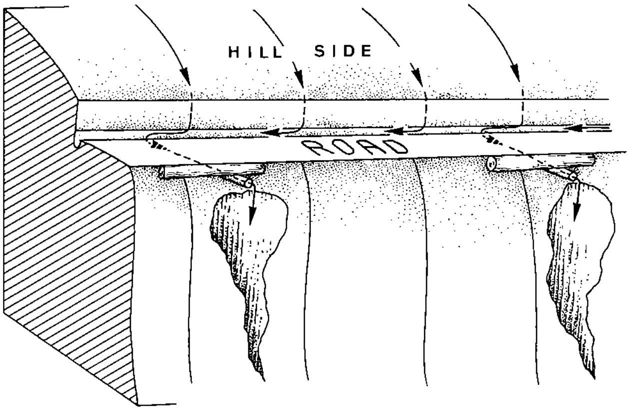

Fig. 2: *Ravines at the end of gutters.*

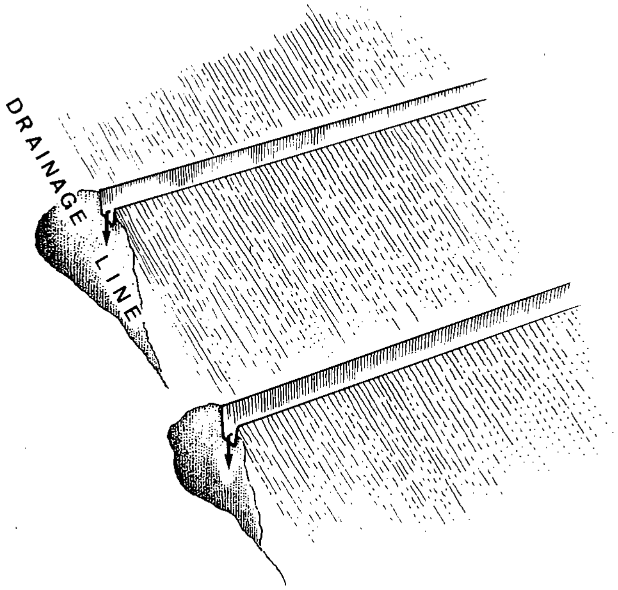

Fig. 3: *Ravines where drainage trenches end in a main drainage line.*

contain the whole water jet. In the same time other potholes, formed downslope (fig. 4B), became in their turn, deeper and coalesced with the first channel. It took about 5 years for the ravine to develop from the gutter outlet to the basal concavity of the slope, over a distance of about 40 m (photo 4). Many observations along the roads in Rwanda have shown that not all ravines succeed to develop in downslope direction till they reach the valley. Some old ravines are still perched and it seems that the length over which they develop in downslope direction is in some way dependent from the peak discharges.

In cases as illustrated on fig. 3, a series of discontinuous ravines (HEEDE 1974)

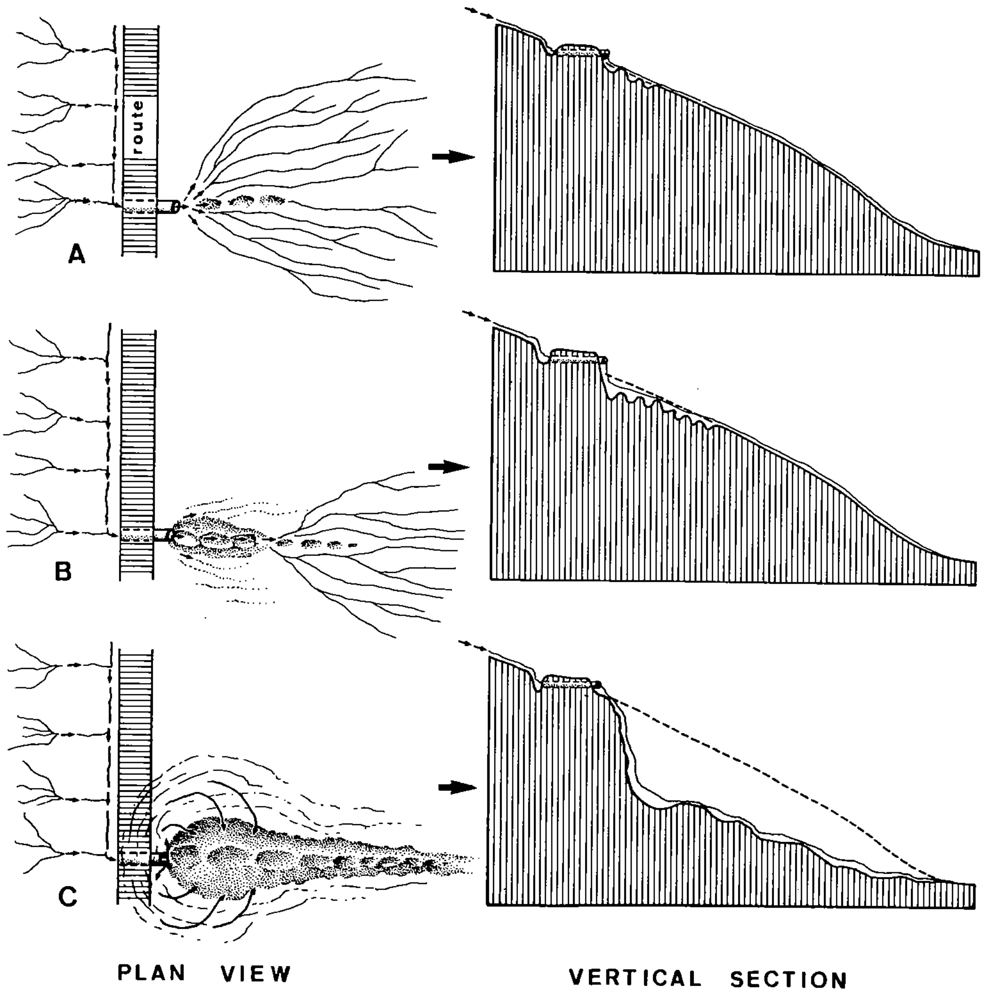

Fig. 4: *Observed way of development of the gully on photo 4.*

or "initial ravines" (LEOPOLD, WOLMAN & MILLER 1964) originates in the mean drainage line from the points where trenches or ditches assure a lateral water supply. A series of seven ravines has been observed at Nyarutovu, near to Butura. Fig. 5 shows schematically the long section of the three lowermost ravines. It appears that all ravines, without exception start at the point where a subhorizontal draining trench (A in fig. 5) gives on the main drainage line.

Another series of ravines has been observed on Mount Gendombi, Runyinga (photo 1). The case here is intersting as it illustrates the influence of the soil type on the ravine formation. The upper part of the slope carries a gravelly lithosol, developed over quartzitic rocks. Slope inclination here is close to 45°, and the gullies are not well pronounced, displaying smoothened walls. Gully inci-

Photo 4: *Five year old ravine below the road on Sholi hill. Its development is illustrated on fig. 4.*

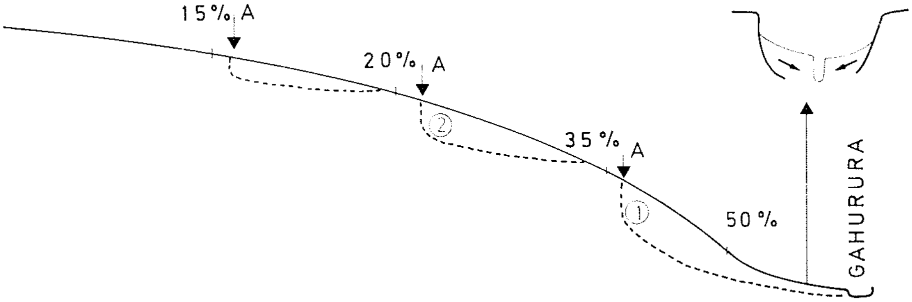

Fig. 5: *Series of ravines in a main drainageway on Nyarutovu hill. The ravine heads are located where trenches end up (system of fig. 4).*

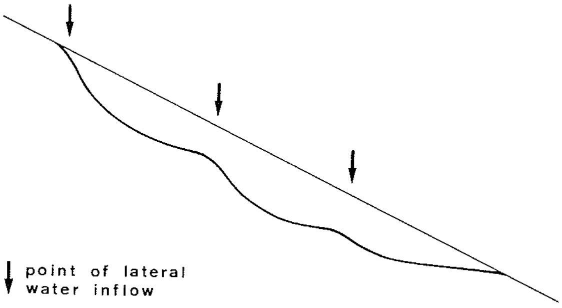

Fig. 6: *Mont Gendombic: knickpoints in the longitudinal profile of perched ravines at the place of lateral water inflow.*

sion becomes deeper and sharply edged from the point where the substrate becomes phyllitic and where the soil is of the kaolinitic type as described above. The slope gradient decreases here to 35° and less. The drainage line to the right is composed of a series of three single but smaller, perched, ravines. It is visible on the photograph how the head of the two lowermost ravines is located on the place where the subhorizontal drainage lines release their waters. Inspection in the field has also shown that the longitudinal profile of every individual ravine is stepped, knick points being situated where other ditches deliver their waters laterally to the ravine (fig. 6).

The drainage line to the left is composed out of one single continuous ravine that, according to local inhabitants, is more than one hundred years old. This ravine is irregular both in width and depth, and its longitudinal profile is stepped and characterised by the presence of plunge pools. Some of them, situated on places where subhorizontal drainage trenches join the ravine, are active. Others are inactive and partly colonised by arbustic vegetation. Old people told that the left drainage line, just as the right one, started as a succession of individual gullies. It is suggested that the evolution to one continuous ravine is partly due to shifting of the points of lateral water supply whereby superposition of different generations of forward developing ravines occurs.

It has been observed that a ravine, developed by forward erosion, can undergo a further evolution: from the points of lateral water supply a secondary ravine can develop by regressive erosion along the trajectory of forced runoff flow in a trench or on a road, inclined most times less than 7°.

One such a case has been monitored during several years. The ravine in question, on Runyinya hill near to Butare, actually consists of two sections (fig. 7). Section A is situated on a convex slope steepening below the incised road from 22° to 40°. Section B makes an angle of nearly 90° with section A and follows the trajectory of the road with a slope of 5°–6°. In 1977 only section A existed. It resulted from forward erosion caused by runoff water spilling over the road. At that time the ravine head was about 3 m deep and was characterized by a plunge pool. From September 1977, section B started to develop from the existing ravine head by regressive erosion. Fig. 8 shows the rapid evolution between 1977 and 1984: regressive erosion and considerable deepening took place and the knick point in the long profile between sections A and B completely vanished. In 1986 the ravine reached a depth of more than 7 meters, and the southern wall of the B section showed the first signs of regressive slumping, threathening the slope above the road.

4 Ravines resulting from mass movements in normal conditions of slope drainage

Ravines resulting from mass movements generally occur on slopes of 25° or more, displaying a typical terracette morphology. The terracettes result from slow displacements of soil banks along curved fissures, introduced by creep (MOEYERSONS 1989) as shown in fig. 1. During these relative movements, the fissures are often transformed into a 5 to 10 cm wide belt of pulvurized and aggregated earth, displaying a high porosity. Runoff, as explained higher, enters here the soil

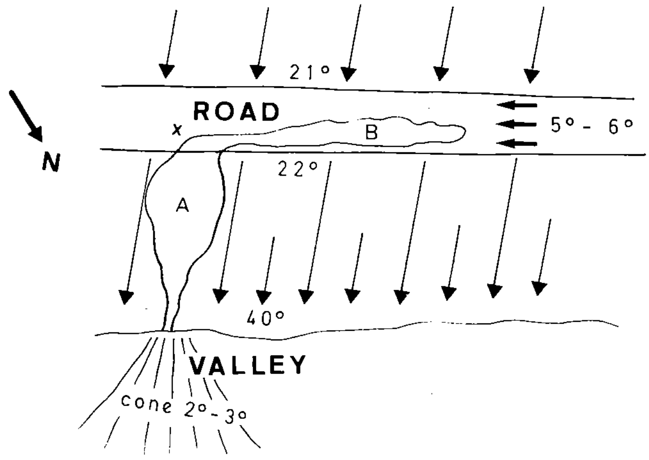

Fig. 7: *Plan view of the ravine in Runyinya hill.*

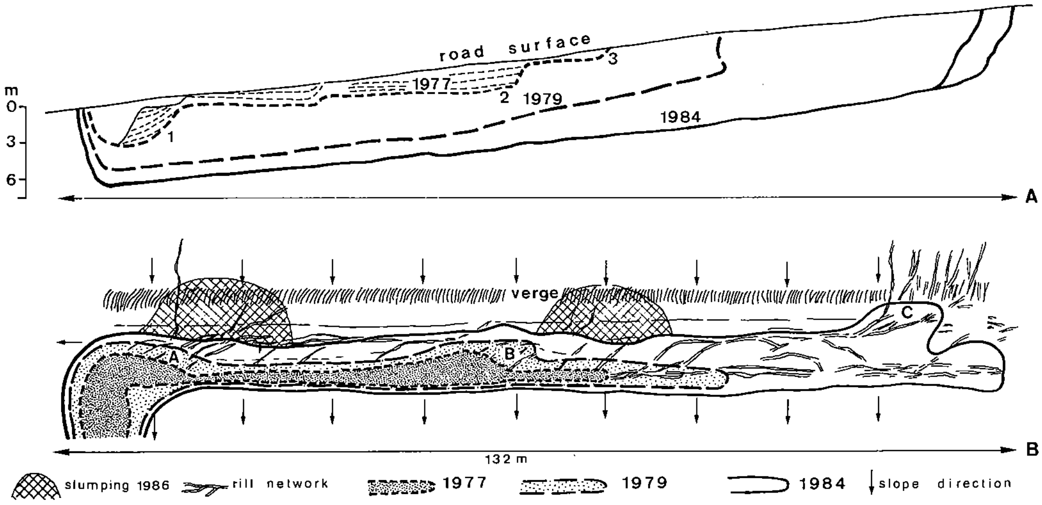

Fig. 8: *Accelerated evolution of section B of the ravine on Runyinya hill.*

and arrives quickly at its base. During or shortly after heavy rains it happens that the base of the soil becomes wetted and even saturated, while the overlying soil, except along the fissures, remains rather dry. Stability calculations (MOEYERSONS 1989) show that this conditions can destabilise slopes steeper than about 25°. On undercut slopes, e.g. by a road, restricted ravine formation by retrogressive slumping has been observed (photo 5).

On not undercut and rectilinear slopes, slump scars can also develop on localities in mid-slope position where creep leads to alternative stretching and com-

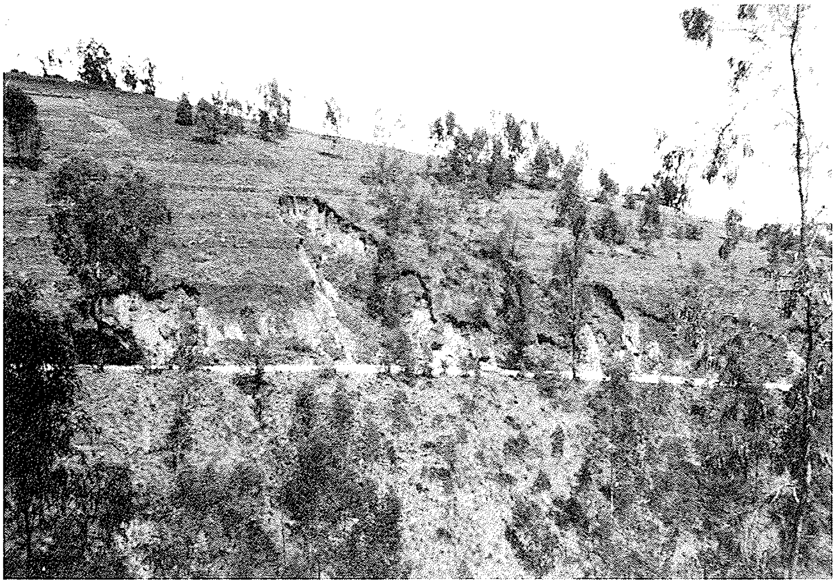

Photo 5: *Ravines by regressive slumping starting from the road cut. Central Rwanda.*

pression of the soil. In such cases fissure patterns will develop (fig. 1) which give rise to slump scars, perched on the slope. Generally the first movement occurs at the scar head and leads to supplementary compression of the soil mass downslope, already compressed by creep. The first movement in the developing scar head is followed by bulging of the compressed zone and an increase of the pore water pressure. The whole soil mass eventually bursts open, becomes highly liquidified and flows as a mud stream over the slope in downward direction, leaving behind a mud track, starting from the perched scar. It is clear that in such cases, the initial scar does not result from repeated retrogressive slumping in the head scar, although this type of evolution cannot be ruled out once the perched scar exists. Nevertheless, the sudden emplacement of the perched scar can concentrate diffuse runoff and in the meantime the runoff coefficient on the bare scar surface becomes higher. For this reason there will be a sudden increase of concentrated runoff at the downslope end of the scar and forward gully development can start to deepen the track of the debris flow.

There exist also many not perched ravines, initiated by slumping and situated on convex slopes. The scar is typically located in the place where the slope gradient falls below the equilibrium slope of 25° (fig. 9). An example of this type of slide scar ravine is situated on Rwaza Hill in Southern Rwanda and has been revisited several times between 1977 and 1987. During this 10 year period, the ravine head was essentially stable, and it is likely that important upslope migration of the head will never occur, neither by slumping nor by vertical incision by runoff: the slope above the ravine head becomes lower than the 25° limit, and

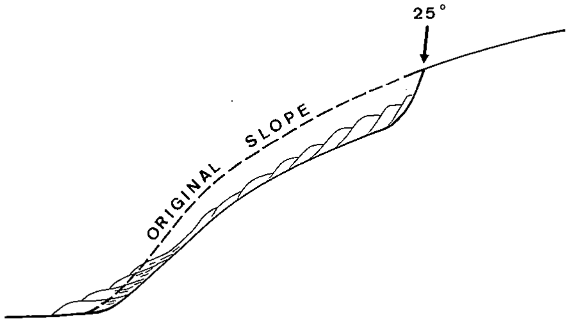

Fig. 9: *Typical geomorphological position of slide scar ravines on holl sides in Southern Rwanda.*

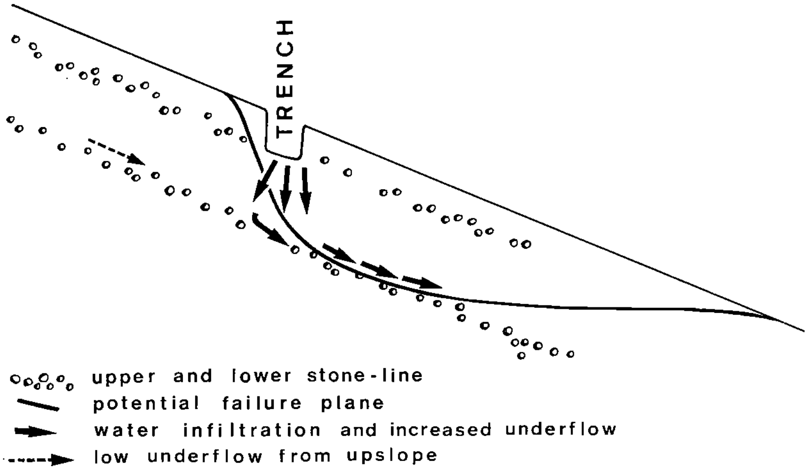

Fig. 10: *Sudden increase of underflow below trench and frequently observed position of scar head to trench.*

the ravine is not situated into a slope hollow so that concentration of runoff seems unlikely.

On the other hand, the series of slumped blocks in the slide track, although fixed by Eucalyptus trees, underwent considerable erosion during the ten years of observation. This erosion was essentially provoked by runoff water, produced on the bare scar head, and some runoff coming from higher on the slope.

It appears thus that after its first development, the ravine in question evolves by forward erosion provoded by a local increase of runoff discharge on the stable scar head. It can, off course, not be ruled out that the higher runoff discharge would contribute to a higher water content and an eventual remobilisation of the slumped blocks, actually resting in the slide track.

5 Sliding under artificial conditions of slope drainage

The case described above reflects a more or less natural situation where slope drainage was not changed by human action. But during the last years the proliferation of the system of trenches (fig. 3) has led to an increase of small slidings, starting from the trenches as a result of massive infiltration there. But retrogressive slumping has never been observed in such cases. The high stability of the scars seems to be due to the low underflow discharge from upslope (fig. 10).

The resulting slidings are comparable to the perched slides, described above, although the scar form not necessary coincides with a preexisting fissure, introduced by creep. Once the scar exists, it receives generally high runoff discharge, laterally nourished by the trench so that forward gully development by runoff incision can start as in the case of figures 2 and 3.

6 Discussion

The case studies, mentioned, show that a perched ravine incision can develop on steep slopes in mid-slope position. In the case of runoff, this incision starts where there is a sudden increase in flow gradient and/or in discharge and/or in soil erodibility. This primary incision can also result from sliding, due to a sudden increase in underflow. The impossibility of upslope migration of the ravine head is thought to be due to insufficient runoff (in the case of runoff incision) or underflow (in the case of a perched scar), coming from upslope. However, in the case of lateral supply of runoff water, the supply axis (e.g. a trench, inclined less than 7°–8°), can be affected by regressive erosion, leading to a lateral ramification in the head of the perched ravine.

The development of the primary ravine incision in downslope direction and its perched nature might be explained by a drop in erosive power of the runoff current downslope of the incision head. Two factors might contribute to this. First, there must be a sudden load increase at the incision point, resulting in a reduced transporting capacity downslope. Secondly, runoff discharge might gradually drop in downslope direction in cases where runoff from a low permeability surface (e.g. a road) enters a more permeable area.

One of the consequences of forward ravine development is that estimation of ravine erosion should be based on other parameters than head retreat rate. Widening, deepening and increase of ravine length in downslope direction are here the parameters to be used.

It also appears that forward gully development most times results from human interventions on slope drainage. Concentration of runoff without providing a reinforced flow channel till the hill foot seems to be the main raison.

It is not clear why the regressive ravine development by pure runoff incision could only be observed where the flow gradient, approaching to the ravine head, is less than 7°–8°. In first instance it was thought that examples of regressive ravine formation by runoff on steeper slopes had been overlooked or missed. But it is amazing that also in the literature no examples are cited where it is explicitly mentioned that headward retreat by pure runoff incision leads to ravine formation in steeper slopes. It can therefore not be excluded that, for an unkonwn reason, ravine gully heads might not be able to migrate in upslope direction on slopes steeper than 7°–8°, when runoff is the only driving force.

This could be one of the reasons why the steep sided and rounded hills neither by their form nor by their stratigraphical record show any evidence to have been much ravinated in recent geological times: their steep sides might be a natural protection against regressive runoff incision, starting from the valleys. Only human intervention in the slope drainage has lately introduced a process apparently not common in natural conditions on steep slopes: forward ravine formation.

On the other hand, the lack of evidence for ravination in the recent geological past indicatss that also deep sliding ravines, as the one at Rwaza hill, are a rather new phenomenon. Their introduction might be related to an increase of the runoff coefficient on fissured ground, as explained higher. This increase might result from the destruction of the natural tree savanna vegetation for agricultural purposes.

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