Geogr. Fis. Dinam. Quat.
21 (1998), 255-266, 11 figg., 11 tabb.

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AN APPLICATION OF DE PLOEY'S Es MODEL FOR A QUICK APPRAISAL OF THE GULLY EROSION ACTIVITY IN A SMALL WATERSHED IN THE ERITREAN HIGHLANDS (HALHALE, DEBARWA) (****)

ABSTRACT: RODOLFI G., VIGIAK O. & ONGARO L., *An application of De Ploey's Es model for a quick appraisal of the gully erosion activity in a small watershed in the Eritrean Highlands (Halhale, Debarwa).* (IT ISSN 0391-9838, 1998).

The future development of the new State of Eritrea shall be based, above all, on the expansion of agricultural activity by means of the conservation and better utilization of two fundamental resources: soil and water. Therefore the control of soil erosion, the main degradational process causing the progressive desertification of large areas, is one of a long list of problems to be solved in a short time. Soil erosion features, such as gullies, which are widespread in the Eritrean Highlands, may give us an important insight for the evaluation of both the intensity and the dynamics of these active landforms, and thus allow us to select the most appropriate criteria for impeding their aggressiveness. On the other hand, given the lack of basic research and information, the methodology to be employed must be simple, quick and easy to apply, as well as low-cost. *De Ploey's Es Model*, applied to a small watershed in the Upper Mareb Valley in the Eritrean Highlands near Asmara, has not only verified severe soil erosion activity and the urgent need for control measures, but it has also tested a valid monitoring tool, capable of working even in areas for which there is pratically no information available.

KEY WORDS: Es model, Gully erosion, Eritrean Highlands.

RIASSUNTO: RODOLFI G., VIGIAK O. & ONGARO L., *Un'applicazione del metodo Es di De Ploey per la valutazione rapida dell'erosione di tipo gully in un piccolo bacino dell'Acrocoro Eritreo (Halhale, Debarwa).* (IT ISSN 0391-9838, 1998).

Lo sviluppo futuro del nuovo Stato di Eritrea dovrà essere soprattutto basato sull'incremento dell'attività agricola, per mezzo della conservazione e della migliore utilizzazione delle due principali risorse naturali: il suolo e l'acqua. Per questo, nella lunga lista dei problemi da risolvere in tempi brevi figura il controllo dell'erosione del suolo, il principale processo di degradazione che sta causando la progressiva desertificazione di vaste aree. Alcune forme di erosione, come i *gullies*, largamente diffusi sull'Acrocoro Eritreo, possono costituire elementi molto idonei per valutare sia l'intensità che la dinamica di tale processo, in modo da stabilire i criteri più appropriati per mitigarlo. D'altra parte, a causa della mancanza di informazioni di base, le metodologie da impiegare devono essere semplici, veloci e facili da applicare, oltre che di basso costo. Il *modello Es di De Ploey*, applicato in un piccolo bacino rappresentativo dell'Alta Valle del Fiume Mareb sull'Acrocoro Eritreo nei pressi di Asmara, non solo ha accertato la presenza di una severa erosione in atto e l'urgente necessità di misure di controllo, ma ha anche verificato un valido metodo di monitoraggio, idoneo ad essere impiegato in situazioni di quasi totale mancanza di informazioni di base.

TERMINI CHIAVE: Modello Es, Erosione tipo gully, Acrocoro Eritreo.

1. INTRODUCTION

After its 30 year struggle for liberation, the new born State of Eritrea now has to deal with heavy depauperation of the natural resources on which its economy is based. Strong signs of the devastation are still very evident in the landscape: systematic deforestation, due to increased anthropic pressure, a result of the lack of alternative sources of energy, caused the break in the already frail natural equilibrium. Other factors, both of an environmental and a socio-economic nature, helped make the situation worse: a climatic change towards an increase in aridity (extension of the dry season), land expropriation, a land tenure unsuited

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(****) *Research financed by Murst 60% fund «Geomorphological constraints to agricultural land use in semiarid countries» (Resp. G. Rodolfi).*

Authors are very grateful to many persons whose help has been of fundamental importance in carrying out and concluding this reaerch. Among them, we particularly mention Prof. Camillo Zanchi for having provided the raingauge used in the field, Dr. Cesare Giordani and his technicians of the Istituto Agronomico per l'Oltremare for their assistance during the analyses of soil samples, Mr. Iyassu Ghebretatios, head of the Soil Research Section of the Eritrean Ministry of Agriculture for the assistance given in the field as well as in the laboratory.

FIG. 1 - A typical landscape of the Eritrean Highlands during the dry season: the contour bounds on bare slopes are unable to impeding the increasing soil degradation by strong erosional processes (*photo Rodolfi*).

to the social situation, added to the lack of safety during war times.

In the forested, as well as in the agricultural areas, which are almost the only productive ones, the devastation signs are due to accelerated soil erosion processes, still active, linked to the lack of the even most elementary control techniques: there are marked signs of uncontrolled runoff, sheet and channel erosion (fig. 1). This situation has already led to an initial consideration (FAO, 1994a): water erosion is one of the most critical problems that Eritrea must deal with in the near future.

Rational land use plannning, aimed at the best, feasible utilization of the natural resources of the Country, is essential for a quick and long-lasting economic recovery. The basic instruments needed to achieve this goal are practically non-existent at the moment; the topographic cover is far from being complete and up-to-date; there are no basic thematic maps, even at small scale, to work on. In the current situation there is no reliable evaluation of the capability of the natural resources, or of environmental constraints; they are practically unknown.

This research originated as an attempt to answer the conclusive remarks of the FAO Mission's final report (FAO, 1994a); it suggested a speedy experimentation and a consequent adoption of techniques which, within a short time, could give the basic information for evaluating soil erosion or for setting the criteria for a rapid soil conservation plan. In particular, attention was paid to estimate gully erosion, i.e. the soil erosion due to concentrated water runoff; the latter seems to be the process which is most responsible for accelerated soil degradation in every Country characterized by an arid and semiarid climate, with a strong seasonal contrast.

In Eritrea this active process, which leaves evident signs on the slopes, moving large amounts of soil, has only recently been observed. Their rapid evolution makes the control of the gullies really difficult, especially considering the poor level of the locally availaible means. Therefore, it would be necessary not only to operate for the stabilization of the existing gullies, but it is even more important to prevent their formation and evolution in the areas at risk, such the ones where the most erodible soils outcrop.

2. MATERIALS AND METHODS

The reasearch was been carried out in a small watershed located about 40 Km South-East of Asmara (fig. 2) which, after a preliminary recognition by means of satellite images (Landsat TM) and field checks, was considered as representative of the basaltic landscape of the Eritrean Highlands. As a first step we went on with the detailed geomorphological and soil survey, in order to subdivide the watershed into homogeneous land units. We then chose two representative gullies, on which we measured the data required by *De Ploey's Es Model*, troughout the entire rainy season (summer 1995).

2.1 THE EXPERIMENTAL SITE

The site is located in the neighbourhood of the Halhale Experimental Station of the Eritrean Ministry of Agricul-

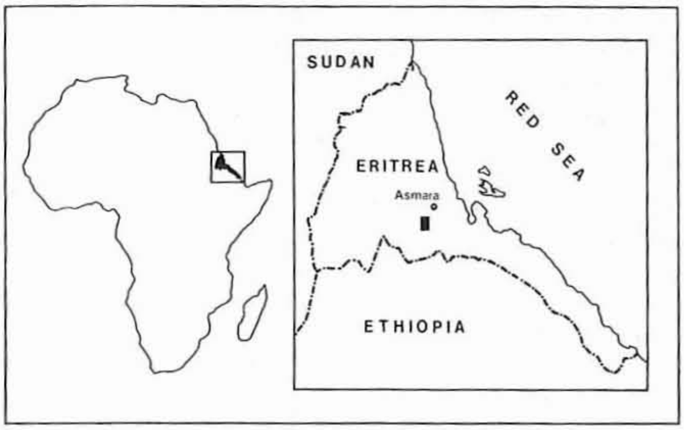

FIG. 2 - Location of the Halhale study area.

ture, near Debarwa, 37 km South of Asmara, on the Asmara-Mendeferà road (15° 04'N, 58° 49'E, WGS coordinates). It corresponds to a small watershed belonging to the Upper Mareb River catchment, and it extends for about 260 ha with altitudes ranging between 1910 and 2020 m a.s.l. It is reproduced in full in the sheet 7055 II of the 1:50000 map drawn up by the Defense Mapping Agency Topographic Centre (USA), as well as in the aerophotos nos.1299 and 1300 (approximate scale 1: 50.000) of the flight on 5th November 1964 (VCH 1370 PMW AF 58.3).

2.1.1 *Climate*

Many Italian Authors (Tancredi, 1906; Dainelli & Marinelli, 1909; Eredia, 1932; Fantoli, 1936, 1939, 1946, 1966) and, more recently, FAO (1984) analyzed the climate of Eastern Africa, and the Eritrean one in particular. We refer here to the data recorded at Debarwa (simple raingauge - 1880 m a.s.l.) and Asmara (full meteorological station, 2372 m a.s.l.), shown in the tables 1, 2, 3 and 4.

From the diagram of fig. 3, relative to the situation in Asmara, we can see that there are two main rainy periods: a shorter one («small rains» in spring, with about 130 mm equally distributed among April-May-June) and a longer one («great rains» in summer, with about 400 mm, during July, August and the beginning of September). During fall and winter there is a long period with very scarse rainfall

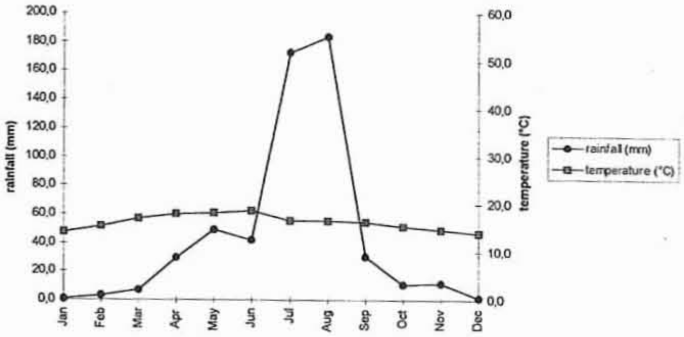

FIG. 3 - Rainfall-temperature diagram for the Asmara thermo-pluviometric station (2372 m a.s.l.). Recording period: 1903-1992.

TABLE 1 - Mean monthly and annual rainfall (mm). Source: Fantoli, 1966

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
ASMARA (1903-1953) 2372 m a.s.l.	0.7	3.3	7.1	29.6	48.7	41.2	173.1	183.6	30.7	10.7	11.5	1.5	541.7
DEBARWA (1927-1946) 1880 m a.s.l.	0.0	0.9	15.1	70.9	54.7	61.0	184.8	229.6	39.1	17.5	12.5	4.1	690.2

TABLE 2 - Number of rainy days. Source: Fantoli, 1966

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
ASMARA (1903-1953) 2372 m a.s.l.	1.0	1.2	1.8	5.6	6.2	5.2	17.8	17.0	5.7	2.4	2.7	1.5	68.1
DEBARWA (1927-1946) 1880 m a.s.l.	0.0	0.3	1.4	6.8	5.7	7.0	15.6	16.2	2.5	2.2	2.1	0.2	60.0

TABLE 3 - Maximum precipitation (mm of rain in 24 h) in Asmara. Source: Fantoli, 1966

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
ASMARA (1932-1940) 2372 m a.s.l.	3.5	16.6	20.0	56.7	92.5	60.4	101.5	107.5	63.6	22.5	35.5	11.5	107.5

TABLE 4 - Temperature (°C) in Asmara (2372 m a.s.l.) - in the period 1906-1982. Source: Fantoli (1966), FAO (1984)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
T max	22.6	24.0	25.2	25.2	25.1	26.0	21.7	21.6	23.2	21.9	21.6	21.7	23.3
T min	6.0	6.8	8.7	10.8	11.1	11.4	11.4	11.4	9.5	8.8	7.6	6.5	9.2
Daily excursion	16.6	17.2	16.5	14.4	14.0	14.6	10.3	10.2	13.7	13.1	14.0	15.2	14.2
T x	14.3	15.4	17.0	18.0	18.1	18.7	16.6	16.5	16.4	15.4	14.6	14.1	16.2

(no more than 50 mm). Therefore, the climate of the Eritrean Highlands could be defined, according to the Köppen classification, as altitudinal coolwinter tropical subhumid.

From the comparison of the tables 1 and 2 we can note how the elevation a.s.l. plays an important role in the rainfall distribution: in comparison with Asmara, Debarwa records more rainfall in total, but distributed among a lesser number of rainy days. It probably means that the rain intensity in Debarwa may reach higher values than the maximum recorded in Asmara in August (107.5 mm/24hs). These values are characteristic of rainfalls with strong erosive power (fig. 4).

2.1.2 *Geological outlines*

The physiography as well as the geology of Eritrea was studied by many Italian Authors in the past (Dainelli & Marinelli, 1912; Marinelli, 1913; Stefanini 1933, Merla & Minucci, 1938; Dainelli, 1943) and, more recently, by Abul-Haggah (1961) and Merla & *alii* (1979) again. In general terms, the phases which gave the morphology of the Eritrean Highlands its present general features are the following:
I - formation of the Precambrian basement, trough the Pan-African tectonic events;
II - long-lasting period of tectonic stability (about 400 My) during which the Precambrian basement was eroded and peneplained, with formation of irregular, variably thick lateritic crust;
III - first major transgression of the sea (Early Mesozoic) on the Horn of Africa, from SE to NW, with the deposition of Adigrat sandstones and Antalo limestones; it did not reach the Debarwa area, in which the lateritic crust continued its evolution so much that it began to be eroded in several stretches;
IV - general and extended uplift *en bloc* (Upper Eocene - Oligocene) of the basement which reached more the actual elevation, being slightly tilted (0.6%) towards SW and accompanied by some more or less intense N-S trading deformations, linked to the primitive formation of the Red Sea («*pre-rift*» phase);
V - strong volcanic activity, as fissural flows, which formed a thick (up to 600 m) sequence of alternating basalts and pyroclastic deposits (the Authors does not completely agree if it this activity followed the main uplift or coincided with it);
VI - late tectonic event with a great crustal dislocation (Upper Oligocene - Lower Miocene?): definitive opening of the Red Sea rift and last volcanic outpouring, with the injection, as in the surroundings of Debarwa, of a doleritic dyke sworm, which crossed the basement, the lateritic crust and the basalts as well;
VII - beginning of a new erosion cycle: the hydrographic network became progressively deeper, until it was cut into the volcanic sequence entirely, carving the crystalline basement.

The entire Halhale watershed is included in the region defined as «basaltic plateau» by Abul-Haggah (1961); it includes Southern Hamasien, Seraye and the Northern boundaries of the Mareb River catchment (fig. 5). The geological formation which dominates the landscape is the above mentioned Cainozoic volcanic sequence, well known as «trappean series» (Blanford, 1869, 1870) or «serie stratoide» (Merla & Minucci, 1938). It consists mainly of thick doleritic-olivinic basalts, interlayered with felsic pyroclastic sediments.

A characteristic landscape has been modelled in this material: flat-topped mountains, locally named *«amba»*,

FIG. 4 - An approaching rainstorm is showing its potential erosive power. A wide gully channel in the foreground is carved in a shallow red soil (photo Vigiak).

with stair-like slopes, due both to the tabular layering and the differential erosion affecting the two main alternating lithotypes. The doleritic dykes, N-S trading, injected during the last volcanic activity, stand out clearly from the other volcanites, as they are more weathering-resistant, and in some places they form real «walls», as one can observe near Debarwa. The lateritic crust, well preserved in this area, does not outcrop in the Halhale watershed.

During the last morphogenetic phase (still active) slope processes, in particular the surface water runoff, have become the main morphogenetic agent: soils developed on basalt have been, and still are, subject to severe erosion. Probably, this phase underwent the influence of tectonic events as well as the alternating dry-wet climatic conditions during Quaternary. Machado & *alii* (1995) from a study of the sediments in some reservoirs of the Tigray near Axum (in a same pedo-climatic situation of that of Debarwa area) have clearly stressed the cyclic alternance of wet periods, with formation of vertic soils, and dryer ones (three, at least, from 600 A.D.) with intense soil erosion. Once again in the Ethiopian Highlands, Berakhi & Brancaccio (1993) ascribe to a period of prolonged aridity the formation of the widespread pediments, due to sheetwash.

In fact, the eroded material was deposited at the foothills, forming thick colluvial mantles, or in the main alluvial plains during floods. Vertic soils, once called «grumosols» (Oakes & Thorp in Principi, 1957) developed on the clay-rich colluvial deposits. The alluvial deposits are sandy loam textured, weakly structured and very prone to erosion (Colombo & *alii*, 1995).

2.1.3 *Soil-landform units*

Referring to NULM (Nine Units Landsurface Model, Conacher & Darlymple, 1977) the Halhale watershed morphology can be subdivided into the following units (fig. 6):
A - convex summits of hilly reliefs (association of convex interfluves, seepage slopes and creep slopes),

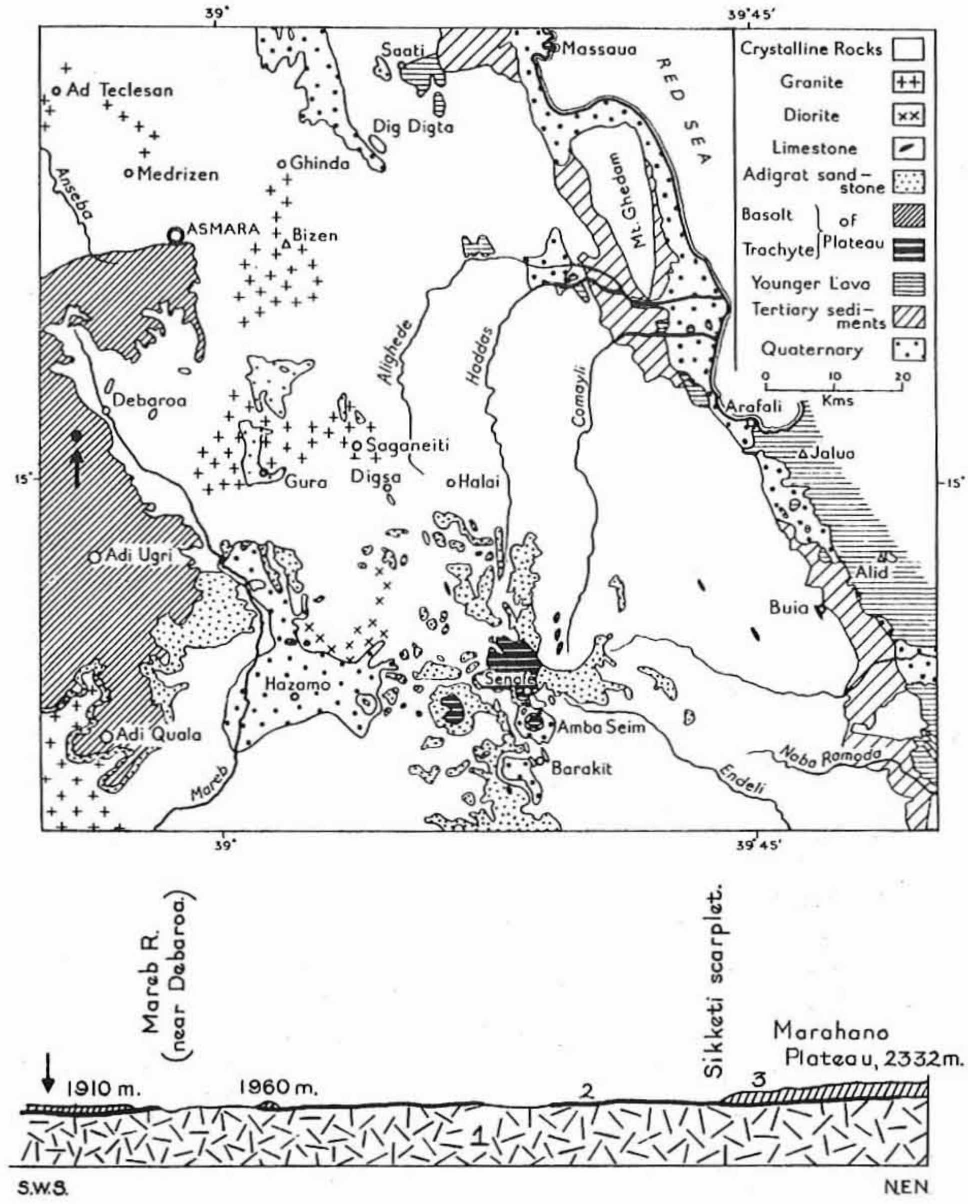

FIG. 5 - a) Geological sketch map of the Central Eritrea; b) Schematic cross profile of the Debarwa area. Arrows indicate the location of the Halhale test catchment (from Abul-Haggah, 1961, slightly modified).

B - transportational midslopes,
C - colluvial footslopes,
D - alluvial toeslopes.

Unit A is the most extensive in the watershed (51.1% of total area, tab. 5). Its profile, convex in the upper part, becomes straight and steeper as we come down; the passage to the lower units is marked by a concave reach. Maximum slope angles are 15-18%, but in some places they can reach 35%; slope lengths vary between 20 and 100 m. According to the FAO-Unesco Classification, soils can be classified as *Eutric Leptosols* (lithic phase) or *Eutric Cambisols* (on the gentlest slopes). Vegetation cover is an open shrub, dominated by *Acacia etbaica*. This unit is considered as «marginal land» by the local communities (villages) and utilized as common grassland and for wood collection. Unfortunately, the lack of a correct management leads to land abuse, especially in the village neighbourhoods. Overgrazing is normal practice, therefore vegetation cover never exceeds 60%, even during the rainy season: water erosion has no obstacles at all.

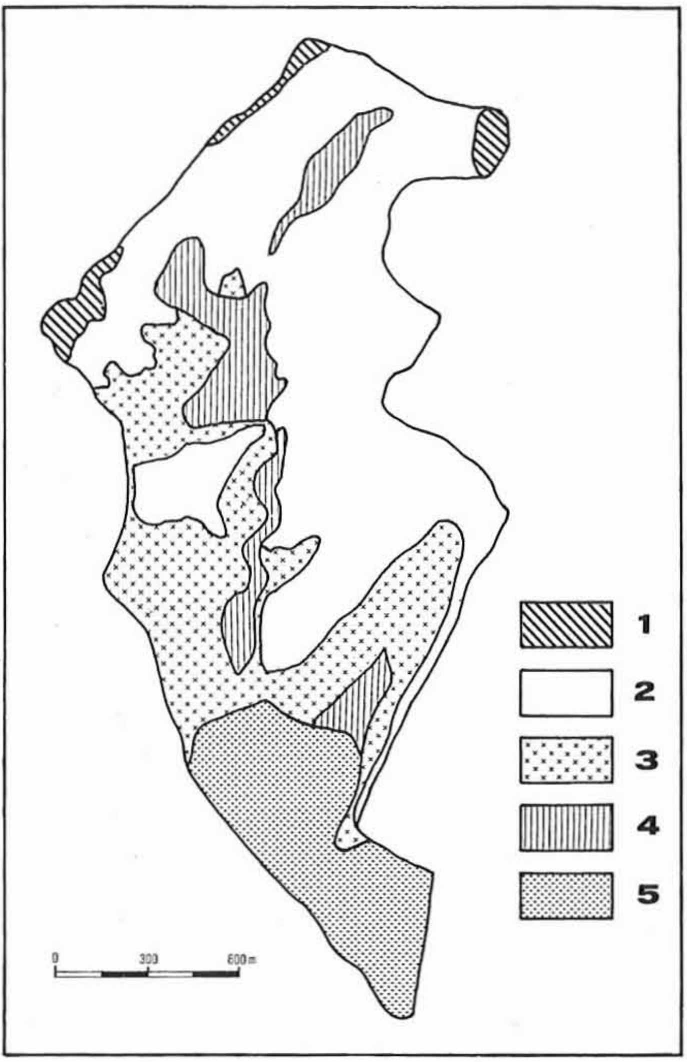

FIG. 6 - Sketch map of the Halhale test catchment, showing the distribution of the NULM's units: 1) rock outcrops; 2) convex summit of hilly reliefs (*unit A*); 3) transportational midslope (*unit B*); 4) colluvial footslope (*unit C*); 5) alluvial toeslope (*unit D*).

The unit B, here in form of pediment, links hillslopes to footslopes and constitute 24.1% of the watershed. Its profile is linear or slightly concave, with a 7-8% mean slope angle. Soils are mostly *Eutric Cambisols*. Vegetation and land utilization types are similar to those of the previous unit, even if pasture prevails as a result of easier accessibility. Utilization pressure is heavier and this causes clear erosional features: many rills and sporadic but deeper channels (gullies) can be observed near clear effects of sheet erosion.

The unit C forms the lower concave reaches of the slopes. They occupy about 10% of the watershed surface. Slope angles range from 3% to 5%. Soils (*Eutric Vertisols*) can present drainage problems and a high shrink coefficient; however, they are deep and fertile. The main land utilization type is the cultivation of cereals and other annual rainfed crops. In some places, cultivation is hindered because of the development of deep gullies; in those areas pasture becomes the only possible utilization, thus making the situation worse.

The unit D occupies the lowest part of the watershed for the 15% of its surface. Recurrent flood events from the main river gave soils (*Eutric Cambisols,* with some characteristics close to to the ones of *Fluvic Cambisols*) a sandy loamy texture. As in the previous unit, they are cultivated with cereals and, to a lesser extent, with vegetables. In spite of their almost flat slopes, these areas can become prone to sheet erosion hazards, particularly where the cereal cultivation is extensive and mechanized: the use of a disk plough can lead to the crushing of the soil structure and the formation of surface crusts during successive rains, so that the erosion hazard is increased. Along the riverbanks basal undercutting can be very active, especially where banks exceed 3 m in height.

2.2 DE PLOEY'S ES MODEL

Gully erosion is not univocally correlated with site conditions and there are many ways in which gullies can develop (Morgan, 1990). Due to the lack of basic information,

TABLE 5 - Area occupied by each NULM unit in the HalHale test catchment and relative dominant soil types

Land unit		Soil types	Area occupied	
			ha	%
A	Convex interfluves	Rock outcrops, *Mollic-Eutric Leptosols*	7.1	2.7
	Seepage and creep slopes	*Mollic-Eutric Leptosols, Eutric Cambisols*	125.5	48.4
B	Transportational midslope	*Eutric Cambisols*	62.5	24.1
C	Colluvial footslope	*Eutric Vertisols*	25.6	9.9
D	Alluvial toeslope	*Fluvic-Eutric Cambisols*	38.8	15.0

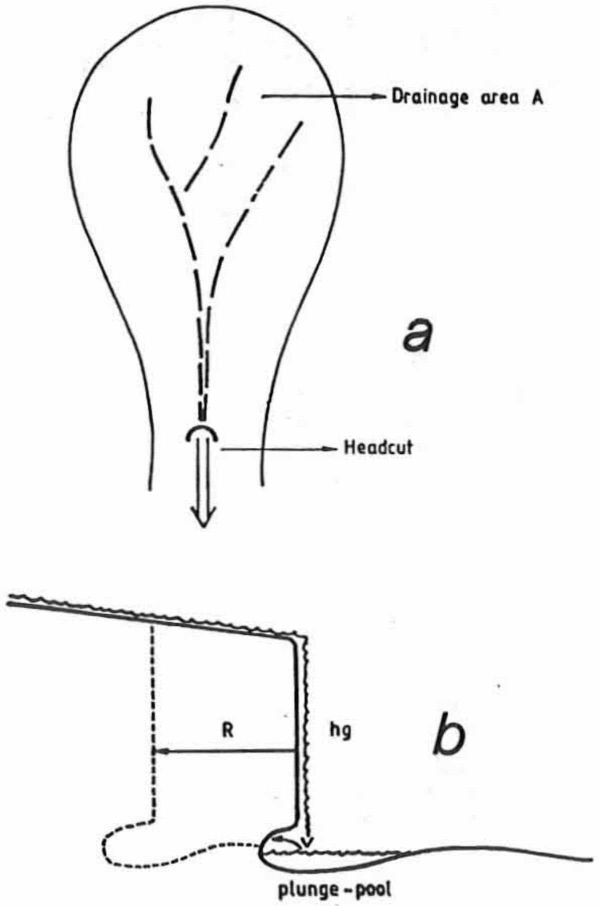

FIG. 7 - Main features of a gully: a) planimetry; b) profile. (h_g = height of the gully head; R = retreat) (from De Ploey, 1989, simplified).

we tried a direct evaluation of gully erosion susceptivity by applying *De Ploey's Es Model* (De Ploey & *alii*, 1995), an empirical but holistic approach to soil erosion study.

The model is based on a proportional relationship, expressed by the *Es* (Erosion susceptivity) coefficient, between the eroded soil volume and the energy, both potential and kinetic, consumed for the «geomorphic work» (fig. 7). The *Es* coefficient which, in other words, measures the total «resistance» of the environment to erosion, is a typical «black box» coefficient. It does not allow us to distinguish between the different processes determining it, but it is flexible and valid for every process combination, over a short or long period. The model can be applied to every kind of hydrographic unit, whatever its extension may be, and it can be referred to every time span. One of its main properties, which was the determining factor for its adoption in our situation, is the reduced number, and the easy «measurability», of the required inputs. Therefore it has proved to be particularly useful in environments lacking in basic information land characteristics and qualities, as is often the case in Developing Countries.

With regard to gully erosion, the *Es* coefficient is calculated by the following formula:

$$E_s = V_g/(A.P.g.h_g) \qquad (1)$$

where:

V_g = eroded soil volume in a certain time lap (m^3)
A = surface of the gully drainage area (m^2)
P = total rainfall on the surface A in the same time lap (m)
g = gravity acceleration (m/s^2)
h_g = height of the gully head (m)

The *Es* coefficient is expressed in s^2/m^2, the dimensional of which may not be immediately clear: multiplying both numerator and denominator by soil and water density respectively, means switching from volumes to masses, the ratio is expressed in kg/kJ. This represents a direct relationship between the removed material and the process motive-power (De Ploey, Moeyerson & Goossen, 1995) (tab. 6).

2.3 AN APPLICATION OF THE *DE PLOEY'S ES MODEL*

The data required to apply the model to two selected gully catchments were evaluated directly on the field in the following ways.

Rainfalls (factor P) were measured by a SIAP rain-gauge (0,2 mm precision) from July 17 to September 6, 1995, that is to say almost the entire rainy season. We missed only the first rainy week, during which only one important event occurred; considering that it was the first real storm after the dry season, we can assume it did not trigger remarkable erosive processes. The rain-gauge records are shown in tab 7.

Of all the gullies affecting the slopes, the two most representative were chosen: one (G1) in a colluvial footslope

TABLE 6 - Correlation between type and density of vegetation and *Es* values (from De Ploey, Moeyerson & Goossen, 1995)

$1x10^{-5}\ s^2/m^2 < Es < 5x10^{-5}\ s^2/m^2$	$3x10^{-6}\ s^2/m^2 < Es < 1x10^{-5}\ s^2/m^2$	$1x10^{-6}\ s^2/m^2 < Es < 3x10^{-6}\ s^2/m^2$
• Badlands in different climate belts • Cultivated land with a predominance of cropland • Steppic areas or areas with a natural open savanna woodland • Intensively degraded grasslands and savanna areas often due to overgrazing	• Partly degraded steppic woodlands or savanna with duricrusts including laterite cappings • Areas underlain by soils with a high water absorption capacity (very sandy soils, chernozem) • Areas with mixed farming: arable lands, prairies and forested slopes	• Areas with occasional gullying and predominantly thalweg gullying • Forested catchments with dispersed cultivation • Perennial grasslands and savanna woodland with appreciable runoff coefficients during storm events

TABLE 7 - HalHale (Debarwa): rainfall events during the 1995 rainy season

date	amount *(mm)*	intensity *(mm/h)*	duration *(min)*
July 18th	2.9	2.9	40
July 20th	19.1	24.5	465
	0.6	1.2	15
July 23rd	0.2		
July 24th	18.9	17.0	125
July 25th	17.5	18.7	140
July 26th	1.5		75
July 27th	5.6	5.0	170
July 28th	6.0	11.2	35
July 29th	18.5	9.1	230
July 30th	3.1	6.2	10
July 31st	5.0	5.8	30
Aug 1st	4.6	9.1	25
Aug 3rd	0.8		15
Aug 4th	2.1	2.9	20
Aug 5th	5.0	8.7	35
Aug 6th	6.2	12.5	30
Aug 7th	25.8	27.4	160
Aug 8th	0.4		10
Aug 9th	2.3	4.2	40
Aug 10th	2.9	5.0	160
Aug 13th	0.6		20
Aug 16th	9.4	16.2	100
Aug 17th	2.1	2.9	100
Aug 19th	6.0	10.0	45
Aug 20th	9.4	2.9	270
	1.2		10
Aug 22nd	0.4		10
Aug 24th	0.2		
Aug 25th	3.5	7.1	30
Aug 26th	7.7	7.1	80
Aug 27th	2.1	4.2	20
Aug 28th	0.2		
	0.6		190
Aug 29th	9.8	19.1	75
Aug 31st	8.9	6.7	155
Sept 1st	8.1	16.2	30
Sept 2nd	11.2	19.5	45
Sept 3rd	5.4	9.6	155
Sept 4th	19.7	30.3	75
Sept 5th	5.6	10.4	40

(unit C), and the other (G2) in a transportational midslope (unit B).

The total eroded volumes (Vg) were measured following a methodology suggested by Hudson (1993, fig. 8). At both sides of each gully channel two rows of wood stakes (50 cm height) were placed at a distance of 8 m from each other; the stakes of each couple were connected by a nylon rope, in order to define the transversal sections on which the measurements would be carried out. Other ropes, with a reference mark every meter, were fixed on the opposite gully banks at the ground level, to keep them as steady and as horizontal as possible; they served as a reference for measuring the depth of the gully channel in a transversal section with an interval of 1 meter. In correspondance with particular reaches of the gully channel (-close to the banks or in correspondance with sharp breaks in the tranversal profile) this interval was reduced to decimeters, in order to represent the section and its time-dependent variations as precisely as possible. The measurements were carried out by means of a metallic metric wheel (precision half a centimeter). A topographic sketch of the stake net was drawn and the distance between stakes recorded.

During the rainy season 5 field checks were carried out, normally on the day after heavy rainfalls[1]. In this way we were able to measure the enlargement of the control sections during the season:

$$D = S_1 - S_0$$

where:

D = enlargement of the section in the time lap t_1-t_0
S_1 = section at the time t_1
S_0 = section at the time t_0.

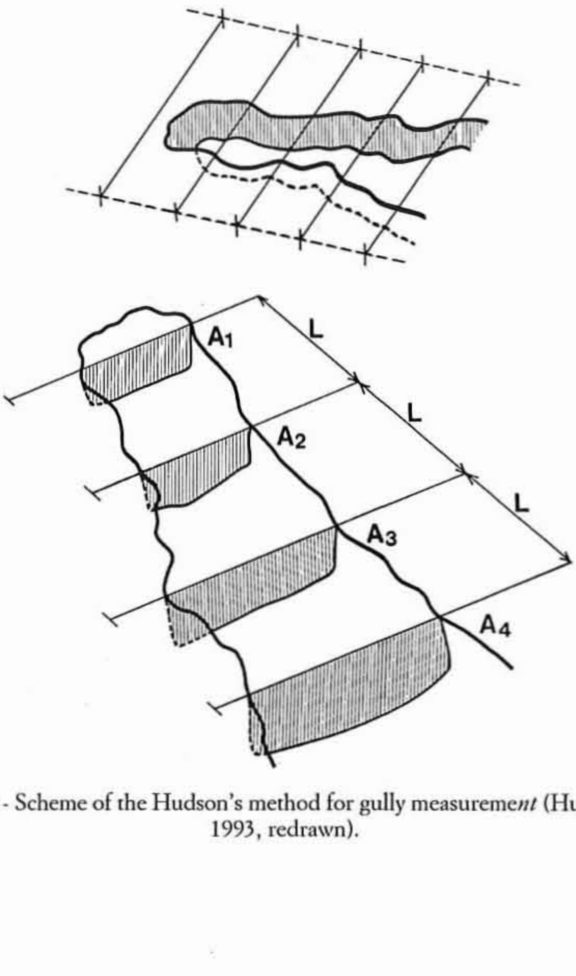

FIG. 8 - Scheme of the Hudson's method for gully measureme*nt* (Hudson, 1993, redrawn).

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[1] Many mishaps occurred: sometimes the ropes were cut by rodents or, in order to correct the deformation due to their elasticity loss, especially for the longer sections, we had to tighten them up again. In some cases the stakes were found slightly shifted, so some data were judged unreliable and then rejected. The reconstitution of tranversal profiles was not simple, but thanks to some tricks adopted in the field survey, e.g. to always tighten the ropes from the same side, it was possible to avoid some systematic errors.

The eroded volume was calculated, as suggested by Hudson (1993), as the sum of the product of the distance between two consecutive sections and the halfsum of their respective D:

$$V_{ti\text{-}t0} = \Sigma_{i=1} L_{i\text{-}(i\text{-}1)} D_i + D_{i\text{-}1} \tag{2}$$

where:

$V_{ti\text{-}t0}$ = volume loss in the time gap t_1-t_0
L = distance between the i section and the i-1 section
D_i = enlargement of the i section in the time gap t_1-t_0
$D_{i\text{-}1}$ = enlargement of the i-1 section in the same time gap.

The gully headcut height (h_g) was measured directly on the field; the gully watershed surface (A) was appraised by photogrammetry, on a stereoscopic couple. To make the gully erosion dynamic clear, some measurements of the resistance of the soil to shear stress and penetration on the gully-banks were carried out, using a Torvane scissometer (vane-test) and a pocket penetrometer respectively. The measurements were repeated every 10 cm on soil saturated by a sprinkler, recording the mean of 3 values. The shear stress resistance of a saturated soil is one of the parameters positively correlated to soil erodibility in gully forms (Poesen & Govers, 1990). This datum allows us to calculate the critical runoff velocity, beyond which erosion starts, using the Rauws & Govers (1988) equation:

$$V_{cr} = 0.86 + 0.56{*}C' \tag{3}$$

where:

V_{cr} = critical runoff velocity (cm/s),
C' = shear stress resistance (kPa)

By comparing the shear stress resistance of the upper soil horizon to the slope angle (Rauws & Govers, 1988) it is possible to predict not only when and where gully erosion will take place, but also the kind which will develop. Moreover, according to Poesen & Govers (1990), the WDR (width-depth ratio) is an interesting parameter for characterizing the gully and controlling its evolution. If, going deeper into the soil, the shear stress resistance increases, the WDR will become higher (WDR > 1); on the contrary, if it decreases, the gully channel will tend to deepen (WDR < 1). However, Rauws & Govers (1988) warn not to use the equation for clay-rich soils and for shear stress resistance values exceeding 9 kPa.

2.3.1 Gully G1

The watershed of the first surveyed gully extends for about 15 ha, from the hillcrest to the colluvial footslope, where the main channel has developed, through the transportational midslope. The degradation of both soil and land is clear: once the area was cultivated, but now its only possible utilization is pasture (fig. 9). The proximity to the Halhale settlement and to a rural road stresses its exploitation: the vegetal cover at the end of the rainy season occupied less than 35% of the total area, in spite of the high soil fertility (*Eutric Vertisols*, tab. 8).

The periodic surveys were carried out in 11 test sections placed in a 100 m stretch of the gully channel (about 1 every 10 m). The average width and height of the gully channel were 9 m and 0.60 m respectively, their maximum 16 m and 1,10 m. The U-shaped trasversal section had a

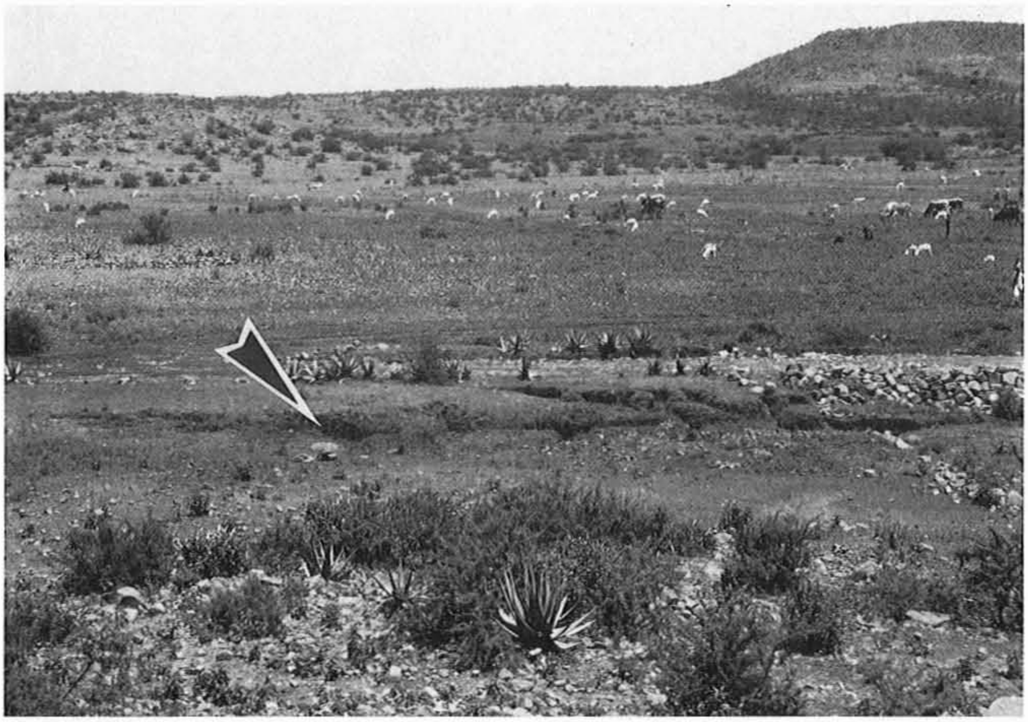

FIG. 9 - General view of the upper part of the gully G1 drainage area. Note the cattle density, causing overgrazing (photo Vigiak).

TABLE 8 - Main analytical data of *Eutric Vertisol* in the gully G1

Depth *(cm)*		0 - 20	20 - 40	40 - 80
Texture *(%)*	Coarse sand (1 - 2 mm)	3	4	3
	Fine sand (0.005 - 1 mm)	15	13	15
	Coarse silt (0.002 - 0.005 mm)	9	8	6
	Fine silt (0.002 - 0.005)	19	21	18
	Clay (< 0.002)	54	54	57
C *(%)*		1.03	0.8	1.18
N *(%)*		0.07	0.06	0.06
C/N		14.71	13.33	19.67
P *(ppm)*		<1	<1	<1
$CaCO_3$ *(%)*		tr	3.0	tr
pH *(H_2O)*		8.3	8.4	8.5
CEC		45.0	48.4	53.0

mean WDR of about 15. The total volume of soil removed from the test area, i.e. the void represented by the gully channel, was about 460 m^3. Only in the summer of 1995 we did record a soil loss of more than 40 m^3. However, by direct field survey, we were able to verify that the retreat of the gully head occurs in two phases: at the beginning there is quite a slow removal of the upper soil layer (first 10 cm), then the soil below is eroded within a short time, till the channel deepens up to 50 cm (fig. 10). In other words, just upstream of the main gully head some small hollows, few cm deep, which are the lines along which the gully will develop, can be observed. The runoff destructive action is favoured by the cracks caused by the volumetric reduction of the soil during the shrink; on the gully banks, exposed to the air, cracks and fissures, even remarkable,develop. Some tests carried out on the soil have showed volumetric reduction up to 37% from the plastic limit to shrinkage limit. The cohesion among aggregates is weakened, up to the point of its detachment; consequently, the gully develops by collapse of the walls even during the dry periods.

2.3.2 *Gully G2*

The watershed of the second equipped gully occupies an area of about 16 ha (157.018 m^2); it extends almost entirely in unit B (transportational midslope). Like the first one, its channel also runs close to a rural road. Perhaps this is not a coincidence: both sites are used as normal sheperd ways. Overgrazing is once again the main cause of land degradation: in the middle of August the vegetation cover was 35%, as opposed to the 60% of other areas in the same pedo-geomorphological situation. The first 70 m of the channel from the gully head were equipped with 11 cross-profiles, about 8 m apart from each other. These U-shaped cross-profiles had an average depth of 40 cm, with a maximum of 70 cm, i.e. more or less the soil depth (*Eutric Cambisols*, tab. 9). The channel width reaches 20 m in some parts, with an average WDR of 22.5 and a maximum of 30.

The gully G2 develops in a completely different way from G1. Here, given both clay content (37%) and recorded values, the shear stress values are acceptable according to Rauws & Govers (1988) assumptions. It is worth pointing out that, at a depth of about 40 cm, a sharp decrease in soil resistance occurs, thus indicating the presence of a more erodible horizon. Not far from the channel, water infiltrates into the upper soil horizon, then flows through the weaker B horizon and comes out the channel walls as seep-

FIG. 10 - Upper part of the gully G1 drainage area. Close-up view of the gully's main headcut, the position of which is marked in fig. 9 by the arrow (photo Vigiak).

TABLE 9 - Main analytical data of *Eutric Cambisol* in the gully G2

Depth *(cm)*		0 - 12	12 - 60
Texture *(%)*	Coarse sand (1 - 2 mm)	2	2
	Fine sand (0.005 - 1 mm)	20	24
	Coarse silt (0.002 - 0.005 mm)	16	8
	Fine silt (0.002 - 0.005)	34	29
	Clay (< 0.002)	28	37
C *(%)*		0.92	0.90
N *(%)*		0.08	0.07
C/N		11.50	12.86
P *(ppm)*		2	<1
$CaCO_3$ *(%)*		—	—
pH *(H_2O)*		7.8	8.0
CEC		37.1	45.5

TABLE 10 - Rainfall, eroded soil volumes, and Es values for the gully G1. ($A = 145854$ m^2; $hg = 0.7$ m; $g = 9.8$ ms^{-2})

Period	Rainfall (mm)	Eroded volume (m^3)	Es (s^2/m^2)
July 13' – 25th	58.2	22.42	0.0003850
July 26th – Aug. 1st	44.3	9.19	0.0002073
August 2nd – 10th	45.5	7.11	0.0001562
Aug. 11th – Sept. 5th	112.2	3.33	0.0000297
TOTAL	260.2	42.05	0.0001604

TABLE 11 - Rainfall, eroded soil volumes, and Es values in the gully G2 ($A = 157018$ m^2; $hg = 0.4$ m; $g = 9.8$ ms^{-2})

Period	Rainfall (mm)	Eroded volume (m^3)	Es (s^2/m^2)
July 13' – 25th	58.2	5.08	0.0001382
July 26th – Aug. 1st	44.3	1.67	0.0000634
August 2nd – 10th	45.5	2.88	0.0001101
Aug. 11th – Sept. 5th	112.2	3.98	0.0000591
TOTAL	260.2	13.61	0.0000913

FIG. 11 - Small hollows and pipes at the head of gully G2; the nylon rope crossing the gully channel is clearly visible (photo Vigiak).

age. In this way many little pipes develop (fig. 11); as they grow progressively wider, they trigger the collapse of the upper layer. A similar process has already been observed (FAO, 1994 b) on heterogeneous soils.

3. RESULTS AND DISCUSSION

The equation (1) was solved for every site, for every time lap between two subsequent surveys, as well as for the entire rainy season. In the gully G1, given the values of $A = 145{,}854$ m^2, $g = 9.8$ m/s^2, $hg = 0.7$ m, for every time lap the amount of rain (P), eroded volumes (V) and the resulting Es values (tab. 10) were calculated. The Es value for the entire rainy season is 16×10^{-5} s^2/m^2. However, during the rainy season a marked and progressive decrease in erosion susceptivity can occur. Likewise, for the gully G2, given the values of $A = 157{,}018$ m^2, $g = 9.8$ m/s^2, $hg = 0.4$ m, the seasonal Es value is $9 \times 10^{-5} s^2/m^2$ (tab. 11). The gully erosion susceptivity of both sites is certainly worrying: the Es values fall into the highest hazard class (De Ploey, Moeyerson & Goossen, 1995). In particular, the highest values of erosion susceptivity are reached at the beginning of the rainy season, while they tend to decrease with the passing of time. This is probably due to the increase in the protective effect of vegetation cover, as it grows.

Of course, the reliability of the results obtained is affected by many approximations linked to the speed of the methodology, as well as to the short period of the field surveys. Nevertheless, a similar experience could easily be repeated in the same areas in order to reduce the margin of error. In particular, the main source of error lies in the method employed to measure the eroded soil volumes. The field experience has allowed us to learn and select some simple tricks for increasing its reliability, such as the use of metallic stakes with a ring to fix the rope to, or the replacement of the nylon rope with less deformable cables, not to be left in the field but set up at every check, maybe using some rapid-link systems, i.e. snaplinks. The costs would increase, but so would the level of accuracy.

4. CONCLUSIONS AND SUGGESTIONS

The gully erosion, recently affecting the foothills and colluvial plains of this part of Eritrean Seraye, appears to be severe and it certainly cannot be neglected. The local population has no knowledge of effective control techniques; therefore, in order to hinder this type of erosion, it is necessary to organize an information campaign quickly in order to diffuse correct reclamation criteria, before the increasing degradation makes it impossible to recover these areas, unless at very high costs. It is also important that the research and monitoring activity, which has just begun, goes ahead. The aim of this work was to show how the careful observation of two representative gullies allowed us to obtain objective, even if approximate, information regarding the magnitude of a particular type of erosive process, within a very short lap of time, using De Ploey's Es Model. We have also underlined the need for timely intervention. This is, in our opinion, the real meaningful result, especially if we consider the almost total lack of basic information.

If this experience were to remain isolated, it would have no value; however we hope it will be continued and improved by those who have to work in similar environmental conditions.

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