GEOINFORMATION IN GULLY EROSION STUDIES IN TAITA HILLS, SE-KENYA, PRELIMINARY RESULTS

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ABSTRACT

Gully erosion is a serious form of water erosion damaging agricultural areas and constructed sites such as bridges and roads, and causing siltation of rivers and reservoirs. Gully erosion has been studied in Taita Hills applying airborne digital camera orthomosaics and GIS for small-scale studies, and field measurements for large-scale studies. The objectives are 1) detection of distribution and intensity of gully erosion within Taita Hills and its changes during the last 50 years, 2) determination of the main factors affecting gully erosion and 3) development of methodologies for gully erosion hazard assessments both at large and small scales.

1. INTRODUCTION

Gully erosion causes severe damage to agriculture and constructed sites (such as bridges, roads and settlements). As well as the on-site damage, off-site effects of gully erosion include siltation of rivers and reservoirs. Nevertheless, erosion studies in the past have mainly concentrated on sheet and rill erosion, since both forms of erosion can be studied through standard erosion plots (Poesen *et al*., 2003). Recent developments both in GIS-techniques (e.g. Martínez-Casanovas, 2003) and photogrammetric techniques (e.g. Daba *et al*., 2003) have introduced new methodologies for gully erosion studies.

Gullies are "relatively permanent steep-sided water courses which experience ephemeral flows during rainstorm" (Morgan, 1995). The size of the gullies varies from shallow 0.3-1 meters deep gullies to over 20 meters deep ravines (Bergsma, 1996). Gullies normally have a distinctive propagating head, which is the morphological expression between stable and unstable regimes (Rebeiro-Hargrave, 2000) and where overland flow from the catchment above enters or falls into the gully. The most important processes of gully propagation are concentration and the incision of overland flow, gully wall collapse (slumping) and piping (e.g. Morgan, 1995).

Gully erosion was studied in three different locations on the foothills of Taita Hills (Figure 1): Mwatate, Chawia and Msau/Mbale. The first location represented active gully erosion within abandoned sisal plantations, and within a township (squatters) in the lower foothills. The second location is indicative of gully systems related to deforestation and overgrazing on the foothills. The last location consisted of gullies within cultivated and grassland areas.

2. OBJECTIVES AND METHODS

The general objectives of the study include how landscape degradation and gully erosion change can be detected through multi-temporal sets of aerial photographs (1955, 1993 and 2004) and how gullies are distributed over Taita Hills area. Secondly, the aim of the field study was to collect sufficient data for the determination of the main factors affecting gully erosion in the area. The data collected will later be subjected to multivariate statistical analysis for the determination of the importance of different factors (e.g. Vanwalleghem *et al*., 2003). This will be accomplished by multivariate statistical techniques with both field data and GIS-data, collected from the aerial photographs, existing maps and Digital Elevation Models (DEMs).

Finally, all the information collected will be applied in the development of methodologies for gully erosion hazard assessments. Both multivariate statistical techniques (e.g. Guzzetti *et al*., 1999; Luoto *et al*., 2001; Martinez-Casasnovas *et al*., 2003) and the "critical slope" concept (e.g. Kirkby *et al*., 2003; Morgan & Mngomezulu, 2003; Moyersons, 2003) will be applied in the assessments (for equations see Pellikka *et al*., 2004).

The gullies in the study areas were identified from the digital aerial images from 2003 (February-March) and 2004 (January-February), which were processed into projected and seamless orthomosaics (EnsoMOSAIC® version 5.02, Erdas Imagine® version 8.6, ArcView® version 3.2). Gully densities (length in meters/ha) and single gully lengths were calculated with different GIS-tools (e.g. Arc/INFO®), e.g. overlays and map algebra.

The field study was conducted during the dry season in January-February 2004. Single gullies were selected (n=30) for the field investigation on the site according to accessibility and differentiation from the other sites (erosion factors). The sampling scheme of the site followed the pattern, presented in Figure 2.

Random samples were collected in the present basin (catchment), along three transects from the gully head to the catchment area, at the gully head, and along gully sides (n=236). The sampling within the plots included GPS-positioning, simple physical measurements (including slope gradient, aspect and gully depth), field spectral measurements (Field Spec Pro®), field shear vane tests, vegetation and rock fragment cover measurements, and removing surface soil samples. Simple classification of water erosion forms (e.g. sheet, rill, deposition) was applied within each plot (Table 1) (applied from Morgan 1995; Bergsma 1996).

Collected soil samples were analysed using visible-near infrared spectroscopy technology in the soil laboratory of the World Agroforestry Centre, ICRAF, Nairobi (Shepherd & Walsh, 2004; Shepherd et al., 2003). Some of the samples are subjected to normal physical soil tests (e.g. physical and chemical proper ties) and calculation of spectral soil erosion (SEI) and soil fertility (SFI) indexes (Shepherd, 2004, personal comm.).

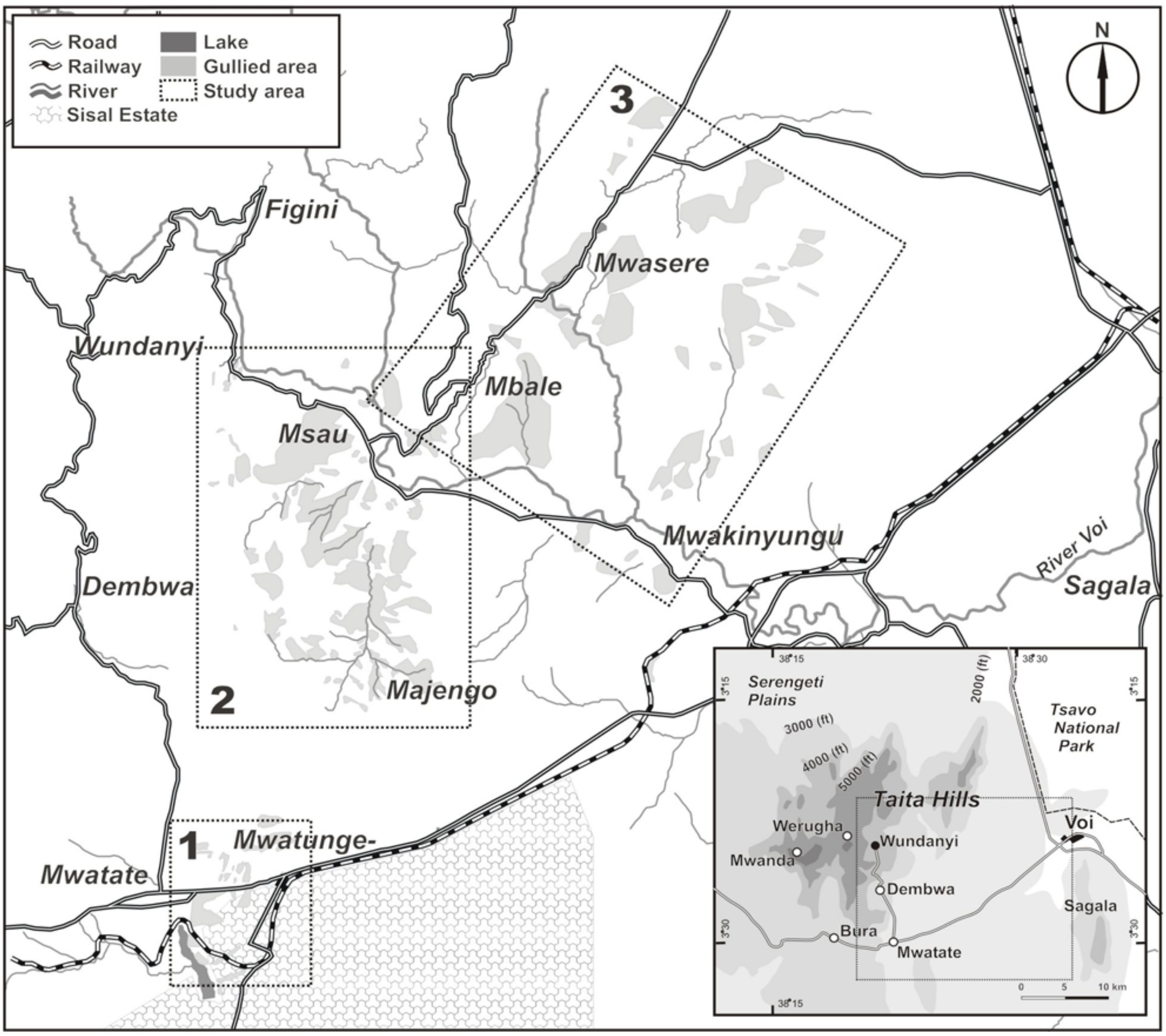

Figure 1. Study areas of gully erosion within Taita Hills, southeastern Kenya.

3. GULLY DATABASE

A gully database of the area will be constructed at two different scales (1:50 000 and 1:10 000) for the basis of change detection, gully erosion factor analysis and gully erosion hazard assessments. Gully erosion can be detected from aerial photographs through detailed stereographic interpretation techniques. Recommended scales for the interpretation of gullies from aerial photographs vary from 1:10 000 or larger (gully growth detection surveys) up to 1:40 000 (reconnaissance type surveys) (Bergsma, 1996). The ground resolution and scales of aerial photography used for the interpretation in Taita Hills (Figure 3) are as follows: ~0.46 m/1:30 000 (year 1955), ~0.14-0.21 m/1:10 000 (1993), ~0.64 m/1:10 000 (2003) and 0.30 m/1:10 000 (2004) (Pellikka *et al*., 2004).

Dependent variables (Appendix 1) for the purpose of multivariate analysis of the characteristics of controlling factors of gully erosion include gully length (m) and density (m/ha). The volume (m^3) and area (m^2) of the gullies will be used as variables only in large-scale studies with selected gullies and their catchments (approx. 30). Also applicability of gully length and density change (between the years 1955-2004), as dependent variables will be investigated.

Numerous independent variables include different erosion factors (e.g. topography, lithology, soils and land use) close to the gully head, sides, body, gully system and catchment. High resolution DEMs of the area will be generated using the TOPOGRID function (Hutchinson, 1989) in Arc/INFO® workstation and the tools available in EnsoMOSAIC® (Holm *et al*., 1999). All the variables are connected to dependent variables (gully length etc.) by IDs.

4. PRELIMINARY RESULTS

The digital aerial images and field observations depict serious landscape degradation and gully system propagation in the research areas. Both wide spread soil erosion and gully erosion were a consequence of past and present human activity and were clearly impacting on current socio-economic activities.

Table 1. Erosion classification used in the field.

Code	Process	Degree	Features in the field
S1	Sheet erosion	Low to moderate	Soil level slightly higher upslope side of plants and boulders; tree root exposure, soil mounds or splash pedestals < 5 cm, slight crusting
S2	Sheet erosion	Severe	Tree root exposure, soil mounds, or splash pedestals 5-10 cm, severe crusting
R1	Rill erosion	Low to moderate	Rill depth 1-10 cm
R2	Rill erosion	Severe	Rill depth 10-30 cm
D	Deposition	Deposition	Deposition features
X	No erosion	None	None

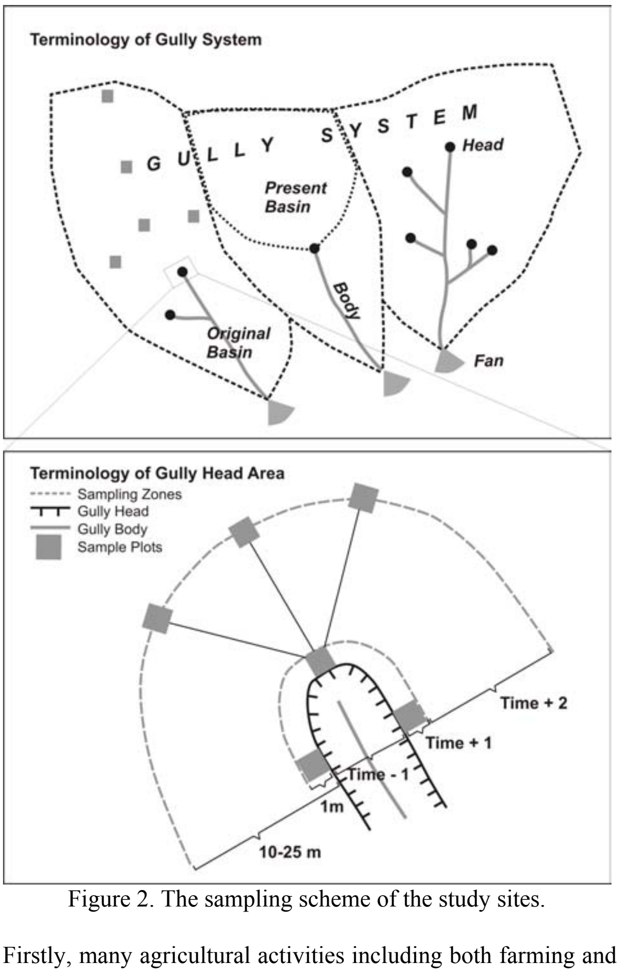

Figure 2. The sampling scheme of the study sites.

Firstly, many agricultural activities including both farming and grazing are suffering from gully erosion, which decreases the quantity and quality of the agricultural land available. Secondly, the expanding gully systems are incising commercial sisal plantations. Finally, gullying is a serious threat to the constructed sites and affects both settlements, such as squatters in neighbouring town Voi (Hurskainen, 2004), Mwatate and (Figure 3) and roads (Figure 4), the condition of which, especially during the rainy season, is noted to be very poor (Hermunen *et al*. 2004). Minor effects in the area include siltation of the rivers, which in many cases has led to the shortage of surface water in several areas (e.g. Hermunen *et al*., 2004).

Common to the distribution of gully systems in all locations was aggressive deforestation, mainly for charcoal firewood, uncontrolled overgrazing and herd induced surface compaction, and inappropriate land management techniques, such as over weeding, vegetation burning and lack of managed ditches beside roads and terraced fields.

The end product of unmanaged vegetation clearance at each location is exposure of bare surfaces and active gulling. During rainstorms, the bare surfaces in catchments and around gullies are susceptible to rain splash erosion and following compaction, overland flow and the removal of the organic top soils. The main processes for gully head propagation in the areas studied is the concentration of overland flow from the catchment area above the gully head and wall collapse within the gully itself.

In Mwatate, previously deforested topsoils have been eroded from the local hill slopes, transported by gullies, and deposited in a sisal plantation reservoir, the storage capacity (90 000 m^3) of which has decreased remarkably during the last 50 years. Diminishing water supply is impacting on current sisal plantation productivity. The expanding gully systems are incising commercial sisal plantation, which has led to land abandonment. Following abandonment and death or removal of the sisal plants, these areas are settled by squatters and become more susceptible to gully head expansion.

In Msau, deforestation and the bare surface exposure is clearly evident in the digital aerial images. With increased regional slope, large gully systems have developed and have rendered the land unusable for agriculture and construction purposes. In areas more suitable for agriculture, uncontrolled deforestation, poor vegetation cover and overgrazing has led to removal of topsoil, leading to intense red patches and silting of local water supplies.

4.1. Soil strength

The field plot results show high average soil shear strength around the gully heads and gully walls. The shear strength values correspond with soil bare earth exposure and crusting of the soil surface. The impact of high catchments soil strength is positive, since subsurface root movement disturbs the soil surface, enhance rainfall infiltration, restrain seed growth, and diminishes the effects of water erosion.

Crusting of the soil surface is caused by high and unimpeded evaporation rates. The evaporation rate for the Taita foothills is 1500 mm per year compared to precipitation of 400 mm per year (Pohl & Niedermayr 1979). The impact of surface crusting is severe: A hardened, almost baked surface inhibits rainfall infiltration and seed growth, and maximises the velocity of overland flow.

Conversely, average shear strength taken from catchment areas with reasonable vegetation cover is high, as shown in Figure 5. These measurements are associated with tree and sisal roots, which increase soil strength within the soil column.

Figure 3. Gullies are extending to the squatters along the roadside in Mwatate. Aerial photograph orthomosaics (Photo from the year 2004, ground resolution app. 0.3 m) form the basis of the gully database of Taita Hills.

4.2. Soil erosion features

Sheet erosion and rill erosion forms infer topsoil has been detached and transported away from exposed intact areas. Field observations counted more sheet and rill erosion forms in the abandoned sisal area than the deforested and grassland areas. However, observations for severe sheet or crusted wash surfaces, and deep rill erosion forms were markedly high for the deforested, overgrazed area and low in the grassland areas. Observations of deposition of locally eroded topsoil were also highest in the deforested overgrazed area. A subjective analysis of the simple field classification (see table 1) would imply severe sheet and rill erosion, and high deposition forms are good predictor variables for chronic soil erosion.

A comparison between the field classification of erosion forms and spectral analysis of soil samples taken from the field plots (n=236) show deforested and overgrazed area with high soil erosion index values, as illustrated in Figure 6.

Nevertheless, the high count of small sheet erosion and rill erosion forms taken from the abandoned sisal field in Mwatate are not reflected by the laboratory derived Soil Erosion Index (SEI). One explanation is that rills observed on the abandoned sisal fields are temporal and reworked and slowly smoothed out after storm periods. Whilst rills observed in the deforested Msau are more akin to permanent shallow channels and feed into gully head and sidewalls.

4.3. Soil fertility

Overland flow erodes and transports topsoils from hillslopes to the gullies. The gullies efficiently flush the eroded material out of the local system. This process has serious impacts for soil quality and inherent soil fertility.

Figure 4. Rapidly extended gully has cut the road in Msau. (Photo: T. Sirviö)

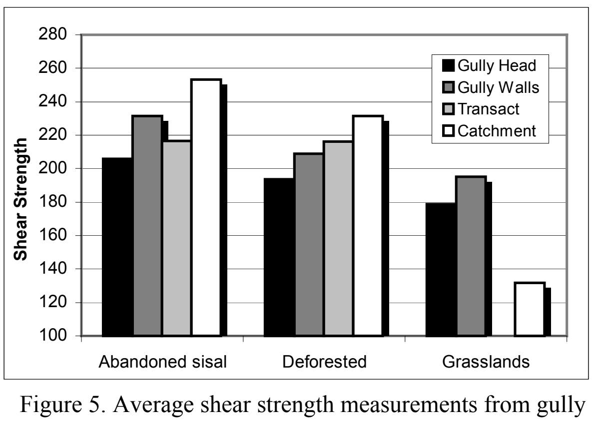

Figure 5. Average shear strength measurements from gully heads and catchments (n=236 plots).

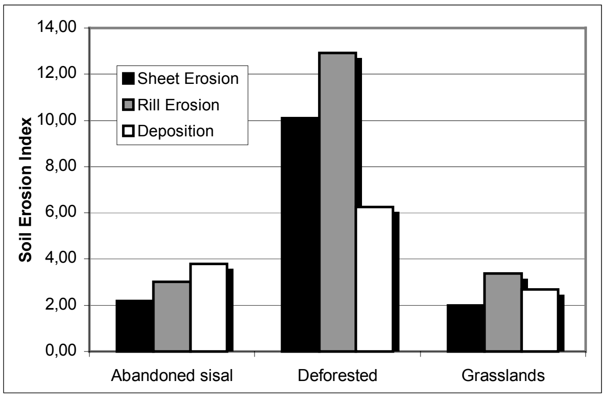

Figure 6. Average Soil Erosion Indexes (SEI) compared to field observations of erosion forms.

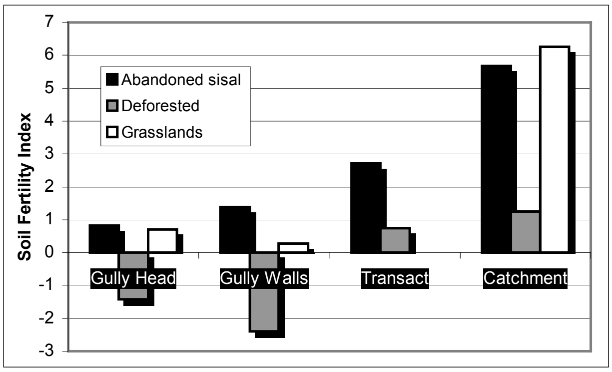

Figure 7. Average spectral index of soil fertility (SFI) from gully heads and catchments. There is a clear reduction of soil fertility in the gullied areas when compared to the catchment areas.

The distribution of spectral soil fertility index (SFI) shows carbon content of the surface soil decreasing from the catchment area towards to the gully head, as depicted in Figure 7. There are marked differences between the studied locations.

Mwatate, representing sisal abandonment, has low soil fertility in the gullied area, moderate values along the transects, and high values in the catchment area. Msau, representing deforestation and overgrazing, has negative soil fertility around the gullied area and small values in the catchment areas, which have been overgrazed. Chawia, representing overgrazed grasslands, also has low soil fertility values around the gully head.

5. SUMMARY

Gully erosion imposes serious effects on the inhabitants of Taita Hills. Active gullying is occurring in all the studied locations. Large-scale land degradation and propagating gully systems are clearly visible from the digital area images. Most of the causes of landscape degradation are human induced. The main causal factors are uncontrolled deforestation, overgrazing and surface compaction, and poor land management. The impacts are severe, the loss of top soil leading to silting of reservoirs and rivers, a chronic reduction of soil fertility near the gully system, and the actual loss of productive land.

The field measurements indicate that bare exposed surfaces near and around the gullies are extensively crusted. Since crusted soils inhibit rainfall infiltration and seed growth, the exposure of bare surfaces should be avoided in Taita Hills. Counted water erosion forms such as sheet, rill and deposition forms observed in the bare surfaces can be used as input predictor variables for general erosion hazard assessment. The laboratory spectral analyses indicate that soil fertility is drastically reduced in the gullied areas, therefore limiting the ability of a gullied system and local ecosystem to recover.

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Appendix 1. Collected gully and gully change variables.

GULLY & GULLY CHANGE VARIABLES (Dependent)					
Variable (1955- 2004)	***Zone***	***Code***	***Units***	***Data Source***	***Scale***
Gully Length	Body	L & Δ*L*	m	AP 1955, 1993, 2003 & 2004, GIS	Both
Gully Density	Grid	D & Δ*D*	m/ha	AP 1955, 1993, 2003 & 2004, GIS	Both
Gully Area	Body	A & Δ*A*	m^2	AP 1955, 1993, 2003 & 2004, GIS	Large
Gully Volume	Body	V & Δ*V*	m^3	AP 1955, 1993, 2003 & 2004, GIS	Large

GULLY CATCHMENT VARIABLES (Independent)				
Catchment variable	***Codes***	***Units***	***Data Source***	***Scale***
Catchment Area (present & original)	CatP & CatO	m^2	AP 1955, 1993, 2003 & 2004, DEM	Both
Present & original catchment -ratio	CatP/CatO	Index	AP 1955, 1993, 2003 & 2004, DEM	Both
X-coordinate, Y-coordinate	CatX, CatY	m	AP 2003 & 2004, DEM, GIS	Large
Altitude (maximum, minimum, average)	CatZmax, CatZmin, CatZ	m^3	AP 2003 & 2004, DEM	Large
Average slope gradient & aspect	CatSG, CatSA	°	DEM, GIS	Both
Average slope form (convexity)	CatSF	Index	DEM, GIS	Both
Proportion of vegetation cover	CVC	%	GIS	Both
Proportion of land use X	CatLUX	%	AP 1955, 1993, 2003 & 2004, SPOT, GIS	Both
Proportion of lithology X	CatLitX	%	AP 2003 & 2004, geol. maps	Small
Proportion of soil type X	CatSoilX	%	AP 2003 & 2004, geol. maps, SPOT, DRS	Large
GULLY HEAD VARIABLES (Independent)				
Gully head variable	***Code***	***Unit***	***Data Source***	***Scale***
X-coordinate, Y-coordinate	HeX, HeY, HeZ	m	Field meas., AP 1955, 1993, 2003 & 2004, DEM, GIS	Both
Slope Gradient and Aspect	HeSG, HeSA	°	Field meas., DEM	Both
Height of the Gully Head cut	HeH	m	Field meas., DEM	Large
Soil Clay, Sand & Silt Content	HeSClC, HeSSaC, HeSSiC	%	Field meas. & laboratory, DRS, GIS	Large
Soil Fertility Index	HeSFI	Index	Field meas. & laboratory, DRS, GIS	Large
Soil Erosion Index	HeSEI	Index	Field meas. & laboratory, DRS, GIS	Large
Soil Shear Strength	HeSS	kPa	Field meas.	Large
Proportion of Rock Fragment Cover	HeRFC	%	Field meas.	Large
Proportion of Ground Vegetation Cover	HeVC	%	Field meas.	Large
Distance to Human Structures	HeDH	m	AP 2003 & 2004, GIS	Both
GULLY BODY VARIABLES) (Independent)				
Gully Body Variable	***Code***	***Unit***	***Data Source***	***Scale***
Average Gully Width & Depth	BoW, BoD	m	AP 2003 & 2004, GIS	Large
Gully Width/Depth Ratio	BoW/D	Index	AP 2003 & 2004, GIS	Large
Gully Width/Length Ratio	BoW/L	Index	AP 2003 & 2004, GIS	Large
Stream order (number)	BoO	Index	AP 2003 & 2004, GIS	Both
Distance to the nearest gully	BoDist	m	AP 2003 & 2004, GIS	Both
Aver. Slope Gradient of Gully Bed	BoSGBed	°	AP 2003 & 2004, GIS	Large
Aver. Slope Gradient along Gully Surface	BoSGSur	°	AP 2003 & 2004, GIS	Large
GULLY SYSTEM VARIABLES (Independent)				
Gully System Variable	***Code***	***Unit***	***Data Source***	***Scale***
Number of gullies within a system	SyGN	Number	AP 2003 & 2004, GIS	Both
Length of gullies within a system	SyGL	m	AP 2003 & 2004, GIS	Both

(AP=Aerial orthophotographs, GIS=Geographic Information System Database including derivatives from different GIS operations, DEM = Digital Elevation Model & DRS = Diffuse Reflectance Spectroscopy, SPOT = SPOT-images)