GIS and Remote Sensing for Mapping Soils and Erosion Hazard in the Kaya Region, Burkina Faso

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Abstract

Interpretations of TM satellite data and of aerial photographs are important tools for soil mapping. They enable planning of the field survey by directing the observations to the most informative sites. GIS enables control on validity of interpretation units for selected terrain characteristics as well as a check on accuracy of boundaries of mapping units by studying the relationship of spectral information with specific terrain data.

It also provides for a powerful instrument to compose useful combinations of thematic data and evaluate their informative value.

In this study, schemes were made on information acquisition, reconnaissance soil mapping and erosion hazard mapping in a second phase, using remote sensing, GIS and dBase.

During the fieldwork at scale 1:30,000 of the second phase, emphasis was laid upon filling up gaps in observation on soils. A land use map was constructed and observations were done to build up a terrain database according to the SOTER system. GIS was used to arrive at mapping units with uniform soil, slope percentage, slope length, land cover and land use to serve regional erosion study. The so-called SWEAP programme was used to calculate soil loss per land unit according to USLE and SLEMSA. Finally, the data on soil loss were translated in erosion hazard classes.

Résumé

Les interprétations des données du satellite TM et des photos aériennes sont d'importants outils pour la cartographie du sol. Ils permettent de planifier la surveillance du terrain en orientant les observations vers les sites les plus instructifs.

Le SIG permet un contrôle sur la valeur des unités d'interprétation des caractéristiques sélectionnées du terrain ainsi que la surveillance de la précision des limites des unités cartographiques en étudiant la relation entre l'information spectrale et les données spécifiques du terrain.

Il fournit aussi un instrument puissant qui est en mesure de faire des combinaisons utiles de données thématiques et d'en évaluer la valeur informative. Dans cette étude, des plans ont été établis sur les acquisitions de l'information, sur la cartographie du sol à l'échelle de reconnaissance et la cartographie des risques d'érosion dans une seconde phase en utilisant la télédétection, le SIG et dBase. Durant les recherches sur le terrain à l'échelle 1/30 000 de la seconde phase, l'accent a été mis sur l'élimination des lacunes dans l'observation du sol. Une carte d'utilisation des terres a été produite et des observations servant à constituer une base de données du terrain ont été faites suivant le système SOTER. Le SIG a été utilisé pour arriver aux unités cartographiques avec une uniformité en sol, pourcentage et longueur de la pente, couverture du sol et l'utilisation du terrain afin de servir aux études régionales sur l'érosion.

Le programme nommé SWEAP a été employé pour calculer la perte de terre par unité de terrain selon USLE and SLEMSA. Finalement, les données sur les pertes de terres ont été traduites dans la catégorie: risque d'érosion.

1. Introduction

The Kaya area (approx. 190 km²) is located north-east of the capital Ouagadougou in Burkina Faso (Fig. 1) between the coordinates 13°13'30"-13°6'0" N and 1°2'36"-1°6'48" W.

Geologically, the area consists of Precambrian schist, metavolcanites, migmatite and granite. In the Pleistocene, when relief of the schist landscape was more pronounced, plinthite was formed in soils of the piedmonts, which irreversibly hardened into ironstone. After intensive erosion of the schist hills and the piedmont zone, remnants of ironcaps generally form the highest components of the landscape.

The present ironcaps with footslopes are for reasons of high stoniness, low water holding capacity and high run off generally not used for annual cropping but for extensive grazing. Therefore, shrub vegetation and more or less permanent spots with stable herbs are present, leading to accumulation of aeolic material, which upon erosion by run off is transported downslope covering clay loams in broad valley land, containing valley bottoms (*bas fonds*) and adjacent pediments.

The analysis of drainage pattern identifies areas with high gully erosion in the valley bottoms. Normally, clay loams are exposed at these sites.

Gullied land and nearly abandoned badlands were found locally in the valley land of the study area. However, marks of sheet and rill erosion are found to be dominant features.

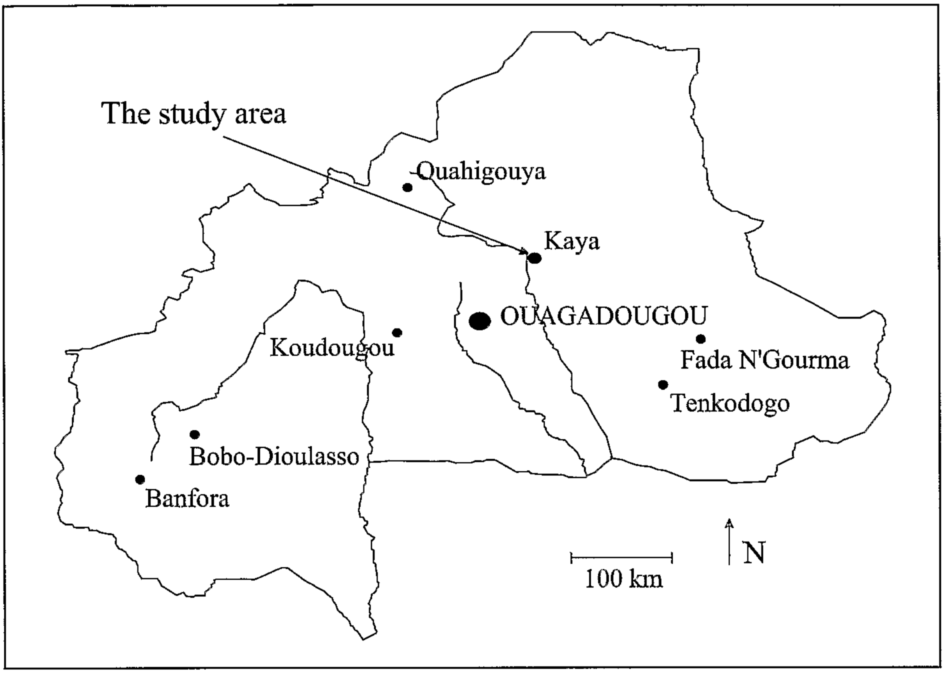


Figure 1. Location of the study area.

The variations in texture and soil depth are generally great in the valley land and the study area as a whole, which indicates different susceptibility to erosion of the soil units. In order to get insight in the erosion hazard of the soil units in the study area, soils as well as land use and land cover were identified.

The present research focuses on the application of remote sensing and GIS, using ILWIS (Integrated Land and Watershed management Information System: VALENZUELA, 1988) and erosion models to estimate erosion hazard in the study area with its specific terrain conditions. For this purpose, soil and terrain properties were described according to the SOTER system (World SOils and TERrain digital database: VAN ENGELEN and PULLES, 1991). The SWEAP (SOTER Water Erosion Assessment Program: VAN DEN BERG, 1992) programme was used to calculate soil loss according USLE (Universal Soil Loss Equation, WISCHMEIER and SMITH: 1978) and SLEMSA (Soil Loss Equation Model for Southern Africa: STOCKING *et al.*, 1988). The outcome of the erosion model calculations was used to estimate erosion hazard of the different mapping units.

2. Theoretical considerations on GIS

The present research is an example of information fusion. Several inputs belonging to different levels are combined. Each level has specific properties and requires its own quality measures and fusion technique (BARTL and PINZ, 1992). For instance, the level of aerial photo-interpretation may be combined with that of a classified satellite image. There are requirements for matching these levels and for fusion of information. For example, some mapping units may be identified by both levels. Others are not since level properties are different. Still information of both levels can be valuable for the research.

To enable coverage of two images, the image data of one image have to be made conform to the other (registration). Satellite imagery has a pixel by pixel registration, which by lack of sufficient topographic data may be the tool to be used for registration of other imagery. However if topographic data at suitable scale are available, the satellite image is georeferenced, that is map coordinates are assigned to the image data.

Information on aerial photographs has to be linked with that of topographic maps and/or satellite imagery by rectification: identical points are identified on both images and the software takes care of making both images conform in projection. For areas with high relief, appropriate techniques for correcting aerial displacement should be used.

The next steps are the location of observation points and mapping units as well as the study of thematic attributes.

In reconnaissance mapping, we identify complex terrain objects as aided by interpretation of remote sensing data and terrain observation. Observation points are registered of which the attributes are described in a separate database. The soil unit is an elementary object in an aggregation hierarchy as described by MOLENAAR and JANSSEN (1992), while the physiographic unit is a complex object.

The codes of mapping units on their turn may have a hierarchical structure: landscape - land unit - soil unit.

Since it concerns mapping at reconnaissance scale, the elementary object has a certain complexity, being often heterogeneous in soil conditions. At larger scales, the elementary object will generally be more homogeneous.

Other properties of the terrain, such as land cover, land use and vegetation, will be related to soil conditions in a variable way if human influence is high. Remote sensing is describing mainly surface characteristics of the earth surface (land cover etc.). Complete fusion with soil characteristics cannot be expected at high human impact.

Nevertheless, the information is of interest for environmental mapping. The link between remote sensing data, primarily in raster structure and GIS with object data in vector format can be done by identification of the raster elements (pixels): classification with the final aim of object identification (MOLENAAR and JANSSEN, 1992).

Classified remote sensing image data of one acquisition may be combined with remote sensing data of another acquisition or with image data of another information level by crossing. The latter (e.g. by matrix) is a means to enable information fusion, that is combine information of different levels (e.g. soil and land use).

3. GIS applied in this research

The method applied in this research is illustrated in the flow chart of figure 2 (scheme modified from the example given by MOLENAAR and JANSSEN, 1992). The flow of information sources and acquisition, including control on accuracy and second fieldwork are indicated in this scheme. The TM image was georeferenced by GPS data.

The main GIS activities were in the fields of referencing aerial photographs with TM imagery and crossing of map data. Data modelling and classification were final activities.

4. Reconnaissance soil mapping

The study area was mapped at a scale of 1:30,000 aided by TM satellite data (acquisition: January 8, 1991), enlargements of aerial photographs with original scale 1:50,000 (acquisition: January, 1982) and aerial photographs of scale 1:30,000 (acquisition: October 1981).

The method used for soil mapping is illustrated in table 1. Five stages are recognized. The innovative methods are presented in bold characters. For physiognomy used as a basis for description of soil surface and other terrain properties, the reader is referred to POUGET and MULDERS (1988).

Table 1. Reconnaissance soil mapping.

	Stage	Method	Results
I	Pre-fieldwork	SII (Satellite Image Interpretation)	First appraisal of land cover
		API (Air Phot-Interpretation)	Physiographic units and drainage pattern.
II	First fieldwork	Landscape guided soil and terrain observation	Land description, soil data, location of observations on APs
		Physiognomy, field reflectance, dBase	Reflectance data, terrain database.
III	Digital data processing	SAD* classification, georeferencing and rectification, APs-TOP**-SAD	Prel. land cover map, observations map, roads map, drainage systems map, physiographic map, preliminary soil map.
		Crossing of prel. soil map with SI	Control on boundaries of mapping units.
		Queries to terrain database + API	Sites to investigate in final fieldwork.
IV	Final foeldwork	Soil and terrain observation at sites/outcome III, dBase	Completion of terrain database
V	Final digital data processing and interpretation	Queries to terrain database, API, SII and classification	Final legends, final maps on land cover, land use and soil.

* SAD : SAtellite Data; **TOP : TOPographic data.

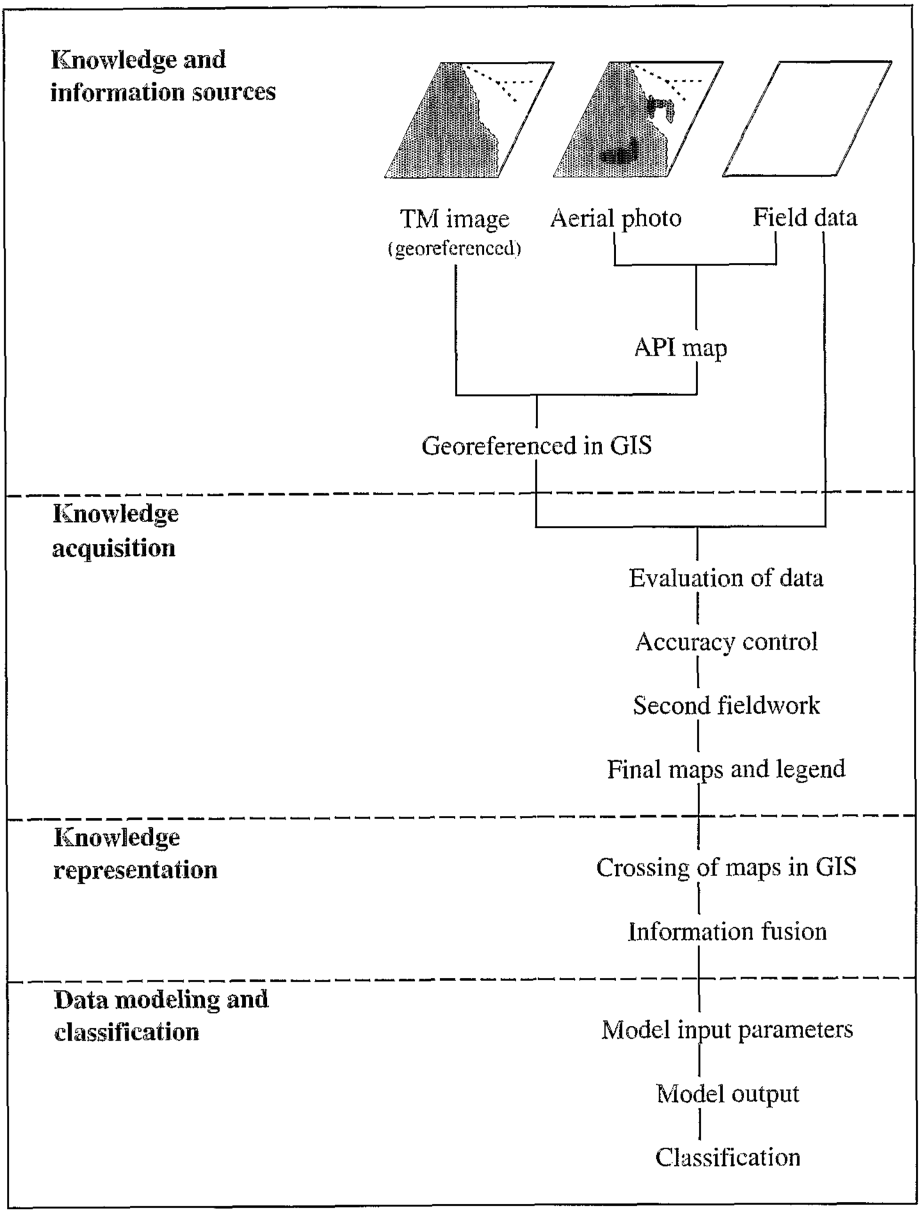


Figure 2. Flow chart of information acquisition, fusion and data classification.

The physiognomic description is used with field reflectance data to get understanding of the multispectral reflectance of land cover. Modelling has to be used to arrive from detailed measurement at land components to land cover data, which can be correlated with low resolution remote sensing data (MULDERS *et al.*, 1992).

For satellite image interpretation and crossing of preliminary soil map with the satellite image, the reader is referred to MULDERS and CASTERAD (1996).

The repeated interaction of interpretation maps with the terrain database to control boundaries and improve accuracy cannot be emphasized too much. Besides digitizing map and image data, it is the most outstanding aspect of the proposed method. Also dBase actions to produce the final legend belong to this category.

5. Erosion hazard mapping

The method applied for erosion hazard mapping in this research is based on characterizing soil units by SOTER properties and subsequent application of SWEAP software to calculate soil loss according to the USLE and SLEMSA erosion models.

The SOTER methodology, normally applied at exploratory scale, is used in this research to characterize soil units at reconnaissance 1:30,000 scale.

The method is schematically represented in Table 2. In this table, c- and f-values are mentioned.

The c-value is the cover and management factor in USLE. The factor is 0 for complete protection of soil and 1 for a clean-tilled fallow. Since it concerns multiple land use types with permanent or shifting cultivation and grazing, a physiognomic appraisal of % of trees, grass + herbs and crops per land use type produced the best results, using c-factors according to KASSAM (1991; results on c-factor estimations are given in MULDERS, 1995).

The f-value stands for the SLEMSA intrinsic soil erodibility in dependence of soil texture class and type of soil development (VAN DEN BERG, 1992).

Interpretation of TM satellite imagery (NDVI or Normalized Difference Vegetation Index) was used for estimation of density of land cover. The resulting land cover map was crossed with the land use map to produce land use units with classified vegetation cover: LUCO in Table 2.

To arrive at soil units with specified land use and vegetation cover, the soil map was crossed with the LUCO map: LUCOSO in Table 2. Queries to the terrain database and statistical calculations in dBase were the tools to define the average characteristics per unit. However, the estimation of slope length needed a specific approach as detailed below.

The characteristic slope length, needed for SOTER formulation (phase IV, Table 2), was difficult to estimate by lack of field data on slope direction. However, GIS may help, also in this case. The ILWIS system enables processing a distance map, representing isodistance lines as determined by the distance to nearest drainage ways (Fig. 3).

The distance map was crossed with the LUCOSO map. Each unit of the LUCOSO map could be characterized by pixel frequency and distance measures (Fig. 4: example).

In figure 4, unit A312 representing (very) gently sloping glacis (valley land), is partly adjacent to the drainage way (0-150 m). However, different populations are found around 175 m and 320 m distance from the drainage way.

The graphs appeared to represent complex units. It was necessary to simulate different forms of the LUCOSO map and estimate formulae to determine average slope length per unit. Some of the simulated forms are given in figure 5.

Table 2. Reconnaissance erosion hazard mapping acc. SOTER and SWEAP.

	Stage	Method	Results
I	Pre-fieldwork	Interpretation land cover, land use and soil maps	First appraisal of eroded areas
		API and SII	Selection of observation sites.
II	Fieldwork	Observation of SOTER characteristics, dBase	Field characteristics SOTER database.
		API, SII and terrain observation	Details on erosion and accumulation. Land cover.
III	Laboratory analyses	Analyses of topsoil samples.	Texture, EC and OM.
IV	Digital data processing	Crossing land use and land cover maps.	LUCO combination.
		Crossing LUCO with soil map.	LUCOSO combination.
		Queries to terrain database.	Legend terrain, soil and land cover LUCOSO units.
		Produce distance map.	Distance of drainage ways.
		Crossing of LUCOSO with distance map.	Slope length (SLEN).
V	Application of SWEAP	SOTER data file.	Completion of SOTER database incl. III and SLEN.
		TAB files.	Climatic data, land use and vegetation (c- and f- values).
		Run the models.	Soil loss and factors USLE and SLEMSA.
		Classification soil loss.	Erosion hazard rating.

Neglecting the d = 0 value, the graph in figure 4 is thought to be built on GD from d = 0-100, RO from d = 100-280 and GD from d = 280-500. Based on the simulated forms of figure 5, approximations of formulae to calculate the slope length, or the length of unit as measured from the drainage way, were made, using y-x d-values, average frequencies and weighted average d-values of segments in case of complex curves, such as that from figure 4. Attention should be paid to hills with opposite slope directions and different distances to drainage ways from one direction and others, which lead to errors in estimation of slope length.

The resulting slope length data per LUCOSO unit were registered to complete the SOTER file. The TAB files with data on climate, land use and vegetation were compiled to run SWEAP, the programme compiled to calculate soil loss according to USLE and SLEMSA.

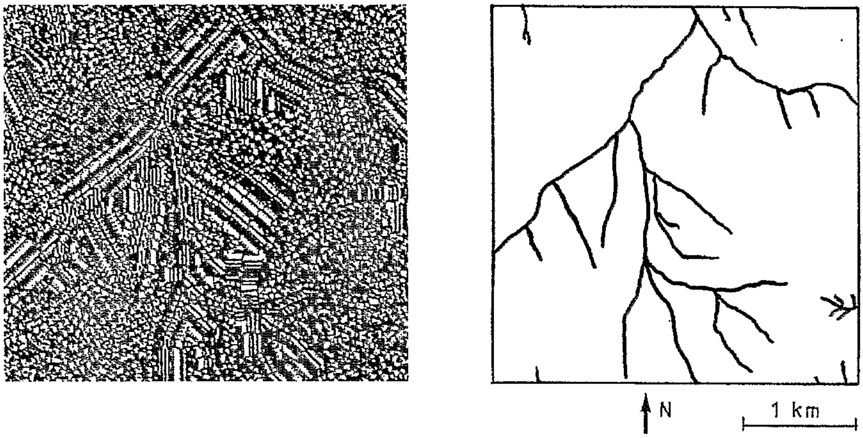


Figure 3. ILWIS/iso-distance (left) and drainage pattern (right) of central part of the Kaya Region.

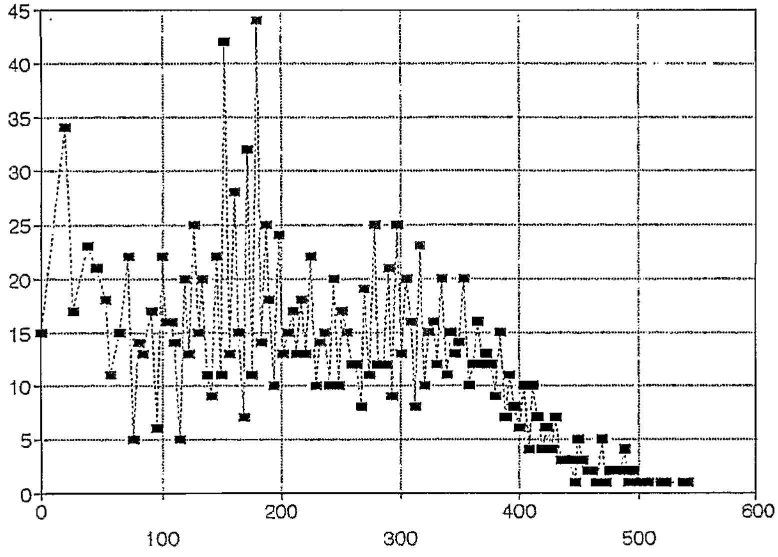
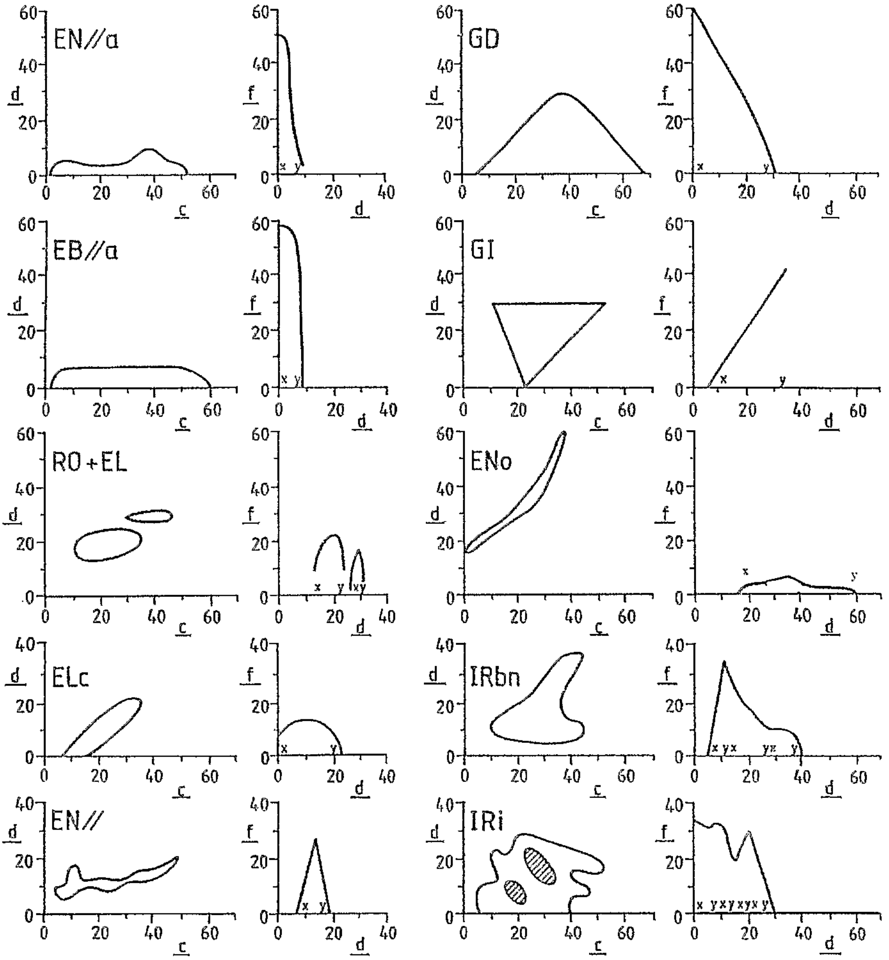


Figure 4. Graph of frequency (y-axis) and distance of drainage ways (x-axis) of unit A312 with AV, produced by QPRO.



EB = elongated broad
EL = Ellips
EN = elongated narrow way
GD = gradual decrease
GI = gradual increase
IR = irregular
RO = rounded
//a = parallel and adjacent to drainage way

c = distance in 20 m units along (//) drainage
d = distance in 20 m units from drainage way
f = 20 m x 20 m pixel frequency
o = oblique to drainage way
i = containing inclusions
c = cut off by drainage way
bn = starting broad from drainage way but
continuing narrow

Figure 5. Simulated forms for distance appraisal of mapping units.

6. Results

The area was subdivided into the following landscape and soil units (between brackets: soil classification according FAO-UNESCO, (1994 and CPCS, 1967):

A. Landscape with schist and meta-volcanites.

- A1. Soils of the hills (Lithosol, Eutric Regosol, *Sol brun eutrophe tropical*).
- A2. Soils of the ironcaps (Lithosol, *Sols minéraux bruts d'apport éolien*, *Sols peu évolués lithiques et régosoliques*).
- A3. Soils of the valleys (Eutric Fluvisol, *Sol peu évolué d'apport alluvial*).
- A4. Rock outcrops.

B. Landscape with granite and migmatite

- B1. Soils of the ironcaps (see A2).
- B2. Soils of the valleys (Dystric Regosol, *Sols minéraux bruts d'apport alluvial*; Eutric Fluvisol, *Sol peu évolué d'apport alluvial*).
- B3. Rock outcrops.

The results on soil loss data of LUCOSO units, each covering more than 2% of the study area, are given in Table 3. For description of soil units as outcome of dBase (Table 4).

Soil loss calculated according SLEMSA appeared to be always higher than calculated according USLE. To illustrate soil distribution, land use and erosion hazard, those maps are given of the central part of the area in figure 6. For description of land use units, see Table 5.

Table 3. Soil loss according USLE and SLEMSA and erosion hazard classification.

LUCOSO	Area	Soil	Land use	Soil loss (tons/ha/yr)		Erosion hazard
(Unit nr.)	(%)	(Code)	(Code*)	USLE	SLEMSA	USLE
8	5.7	A150	CB	4.9	12.8	3
9	2.6	A150	CBH	1.3	3.4	1
12	2.0	A150	PH	0.8	2.1	1
23	4.0	A240	P	5.8	19.6	3
25	4.3	A312	AV	4.2	18.2	3
37	2.6	A340	AV	4.1	16.0	3
45	2.8	B121	CV	2.7	5.0	2
57	2.4	B140	P	4.2	23.6	3
61	6.8	B211	AV	7.0	17.7	3
67	8.5	B213	AV	9.3	26.7	3
75	4.0	B230	AV	10.4	18.9	4
79	2.4	B230	CV	8.6	15.6	3

* For explanation of codes: see Table 5.

7. Discussion

The maps in figure 6 illustrate the pattern of erosion hazard. There is some resemblance of erosion hazard with the soil map, but it is more the combination of soil and land use with the specific SOTER characteristics, such as slope length, soil structure and texture of the topsoil, which determine the erosion hazard class. Due to the classification of erosion hazard, there is a general simplification, especially in the landscape with granite and migmatite (B).

Table 4. Description of soil mapping units of study area (Fig. 6).

Code	%	Average slope	Surface gravel	Surface blocks	Drainage cond.*	Depth (cm)	Texture 0-30 **	Texture 30-60	Texture 60-120
A130	100	4.5	44	27	W	27	cl		
A150	87	2.1	48	5	W	31	sl	l	
	7	11.0	32	8	I	19	sil/c		
	6	3.0	18	10	I	94	sl	scl	scl
A210	100	3.6	37	6	R	10	sl		
A222	54	2.0	27	7	W	78	sl	cl	cl
	46	2.1	27	7	R	10	sl		
A230	100	18.3	39	12	R	10	scl		
A240	100	3.6	26	9	W	39	scl	scl	
A312	93	1.9	19	8	W	32	scl	scl	
A313	100	3.0	2	1	R	85	ls	ls	ls
A314	82	1.6	13	4	W	48	sl	scl	
	18	2.8	25	7	W	25	ls		
A330	100	1.3	14	9	W	63	scl	cl	c
A340	100	1.3	25	4	W	75	scl	scl	cl
B110	100	2.0	50	15	R	10	sl		
B121	100	2.0	45	12	R	29	sl		
B122	78	3.4	43	7	R	19	sl		
	22	3.0	15	8	W	100	sl	sl	sl
B130	100	32.0	58	28	R	11	scl		
B140	100	4.5	26	21	W	41	ls	sl	
B211	84	2.0	21	5	W	37	sl	sl	
	9	1.7	7	1	W	99	sl	sl	sl
	7	2.8	55	10	R	2	sl		
B213	92	2.0	8	3	W	98	ls	sl	sl
B230	91	1.3	8	2	I	95	sl	l	cl

* Drainage condition: rapidly (R), well(W), imperfectly(I); ** Soil texture: silty(si), sandy (s), loam / loamy (l), clay (c).

The classification of erosion hazard applied in this study needs further elaboration.

However, the main aim of the study was to test GIS and Remote Sensing for estimation of erosion hazard. GIS, used for combination of soil and land use as well as combination with land cover, appeared to be an essential tool. An interesting application of GIS is the estimation of slope length by isodistance lines from the drainage ways. At the moment, that was the goal. However, the present visual interpretation of graphs should be replaced by geostatistical methods to calculate slope length. Moreover, the average distance of mapping units to the drainage way itself may be used in models to calculate runoff contribution from more distant units to those more near to the drainage way.

It has to be taken in mind, that the SOTER system was compiled for small scale mapping. Estimation of land use and vegetation was found to be difficult according to the classification and model input data given in the manual. Adaptations were necessary to apply the system at scale 1:30,000. It is advisable to take physiognomic vegetation properties as an entry to classification of land use and vegetation.

Database management and SWEAP were appropriate to carry out the soil loss calculations. The present appraisal is a per unit calculation of soil loss for average rainfall conditions; the influence of runoff coming from units upslope is not accounted for.

Table 5. Description of land use units (Fig. 6c).

Code	Description	Trees	Shrubs	Grass	Agric. fields	Bare land
P	Pasture (*pâturage*)	3	7	14	38	76
CV	Intensively cultivated high fertilization level (*champs de village*)	4	5	6	60	85
CB	Extensively cultivated (*champs de brousse*)	6	7	13	46	75
AV	Valley bottom with fruit trees	9	7	10	40	75

If we compare the results on soil loss and erosion hazard with those derived for exploratory scale by OLDEMAN *et al.* (1991), the degree of degradation estimated by these authors seems to be exaggerated. The area north of Ouagadougou was characterized by the following indication: Wt3.5/Wd3.3 g/a, where Wt stands for loss of topsoil and 3.5 for strong degree of degradation (50-100% of the area affected); Wd is indicating terrain deformation/mass movement, 3.3 is strong degradation (10-25% of the area affected), g/a indicates the cause by overgrazing/agricultural activities. At small scale, we would prefer to go one step back in degree of degradation.

Conclusions

The application of GIS and remote sensing together with dBase, is promising for assessment of erosion hazard. Remote sensing with multispectral satellite data was useful for soil survey and for estimation of density of land cover.

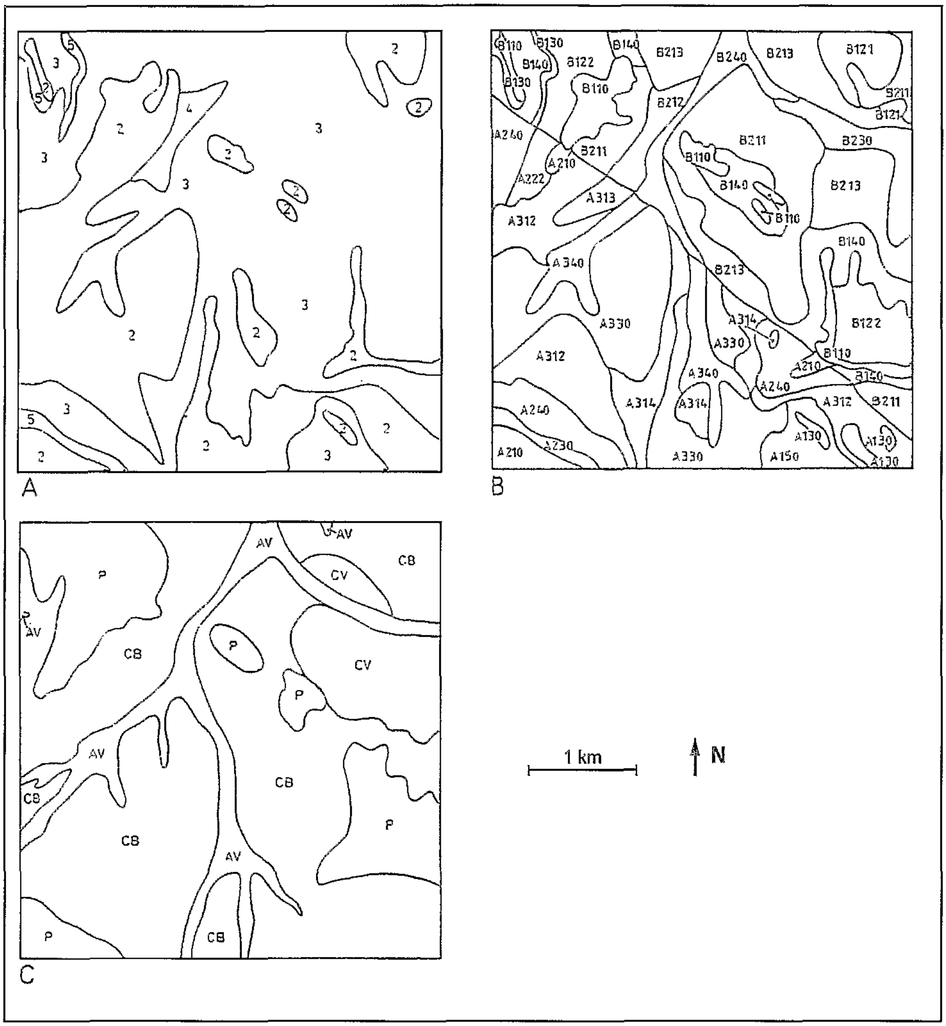


Figure 6. Erosion hazard (A), soils (B) and land use (C) in central part of the study area.
Erosion hazard classes (USLE): 0: < 0.3; 1: 0.3-1.5; 2: 1.5-4; 3: 4-10;
(tons/ha/yr) 4: 10-20; 5: 20-50; 6: 50-150; 7: > 150.

Slope length estimation using isodistance from the drainage ways and moreover the average distance from the drainage way per mapping unit are aspects, which have to be further studied to improve erosion hazard estimation. For example, the models should include the contribution of runoff from upslope units for erosion hazard estimation.

The medium scale approach was useful to test the validity of exploratory scale assumptions on SOTER characteristics. The study of key areas will improve the exploratory scale surveys on degradation.

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