

12 A spatial assemblage model for the estimation of gross erosion and sediment yield using remote sensing and geo-data-base operations

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12.1 Introduction

In an attempt to set up and operate a Geo-Information System (GIS) for erosion and sediment yield studies as a part of land evaluation procedures, the following considerations were made:

- Make optimal use of the surveying techniques using remote sensing imagery and aerial photo interpretation. For the quantification (i.e. transformation) of data contained in mapping units and of data pertaining to climate, vegetation, etc., make use of existing, common methods. Accept empirical methods when necessary (regional rates, extrapolation of field data, soil physical constants, results of regression).
- Make optimal use of existing simulation models for the assessment of the transformations.
- The approaches should be applicable to various scales.
- Accept region-specific elements (climate, relief, soils, land use, developments).
- Use a common data base for all land evaluation procedures and keep the geodata base adjusted to other requirements.
- Overruling of automated results should be possible at the various stages.

Considering all the intricacies of the erosional and sediment transport processes, one wonders whether it is worthwhile to attempt to use an assemblage of various methods at different levels of sophistication for the prediction of erosion and sediment yields. However, the success of hydrological models for not too small catchments, the availability of satellite data and the computer facilities to handle distributed data are stimulants in continuing the approach described here.

We are not yet in a position to evaluate the results. The work done so far has rather exposed weaknesses in components of the assemblage. Earlier such defects were known, but conveniently overlooked. Now, at least we know where to direct our research and development efforts in trying to build a reasonably trustable, semi-automated methodology.

The approaches are being tested in three different but sloping areas:

1. NW Argentina, including Andes ranges;
2. Central Highlands of Sri Lanka;
3. Kasserine area, Tunisia.

12.2 Main outline of the assemblage

The chart of Figure 12.1 gives the main procedures leading to a map with gross erosion rates and a map with estimated sediment yields. There are three more or less independent types of input:

- climatic data;
- vegetation and land-use data;
- physiographic and geomorphological data.

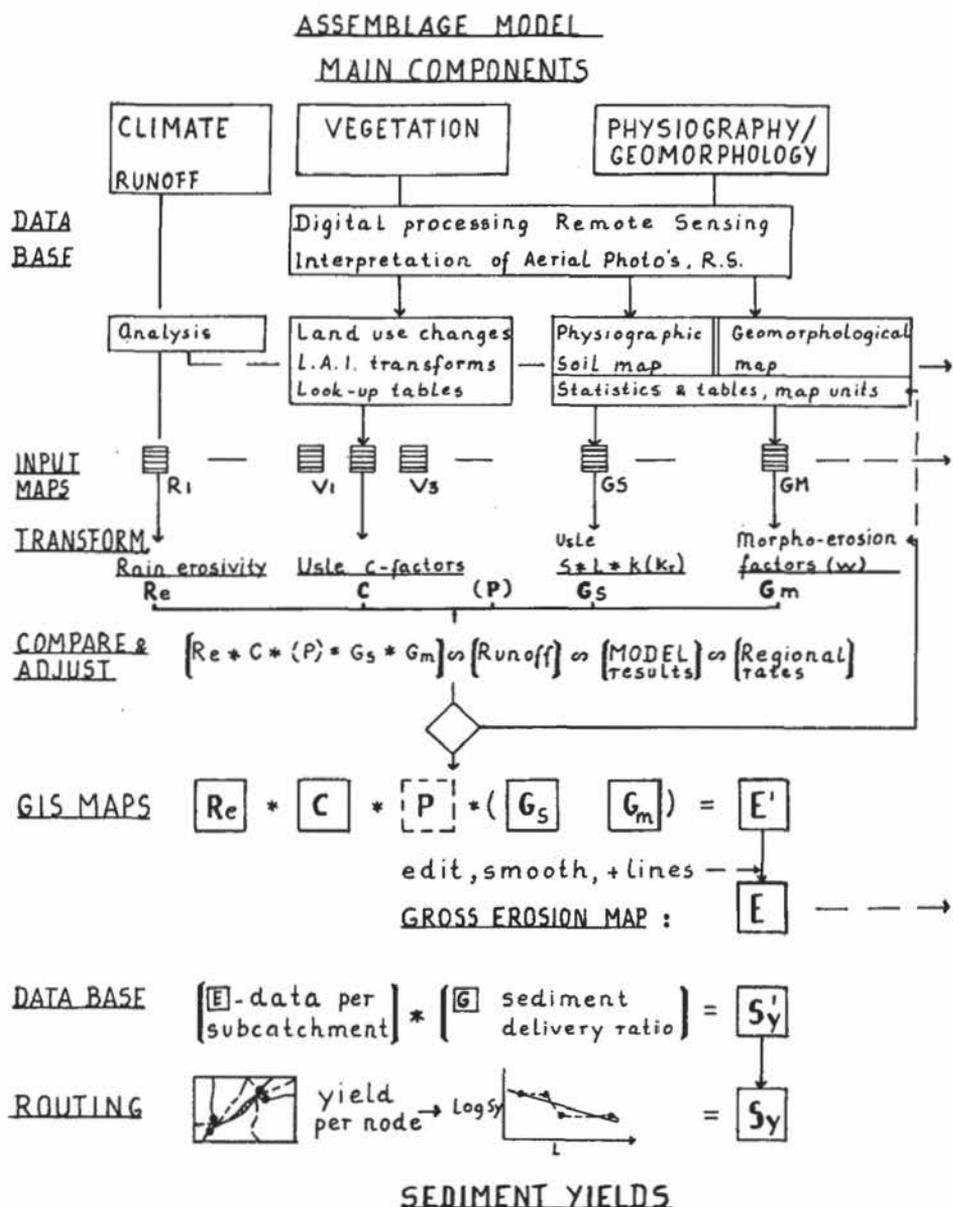


Figure 12.1 Erosion & sediment yield.

12.2.1 Data base

First a data base has to be compiled containing the basic raw data and treated data, as is illustrated in the charts below. Important components are thematic maps such as a physiographic map, a soil map, a geomorphological map or their combinations made in the conventional way. The maps are stored in the data base after digitalization (GIS). The vegetation-land use map may often consist of Leaf Area Index (LAI) transforms made from Landsat, with additional digitized land-use interpretations from aerial photographs or other sources.

12.2.2 Transformations

The rainfall data, prepared in the data base, will be transformed into a rainfall Erosion Index (EI) for the production of the gross erosion map. For other procedures in the land evaluation different maps will be produced, as is indicated in the charts of Figures 12.1-12.4.

Station values are plotted and with interpolation procedures, considering possible orographic effects, EI isolines are generated, digitized and converted to raster (pixels of the same size as resampled Landsat). The result is called the (Re) map in the GIS.

The vegetation map has to be transformed into a map showing the cover (C) factor of the USLE approach, or another index if so desired. This may be done by using two Landsat tapes, one for the dry period and one for the wet season. After LAI or NMI transforms a look-up table with C-values is made. The physiographic and geomorphological information is split up into tables which show the soil (K) and slope (L.S) factors of USLE per mapping unit and tables containing weighting constants (W) for areas under gullying, landslides, eroding channel networks. In mountainous terrain, an amalgamation of the physiographic and geomorphological data may be useful.

12.2.3 Comparison

Before the tables containing the (C) factors and the soil and geomorphological data are applied to generate GIS maps, trials are made for selected parts of the studied area (usually the best known or most important parts).

At this stage model simulations should be made, using the data prepared in the data base (not the GIS). So far, we have used the ANSWER model of Beasley et al. (Purdue) and Morgan's et al. (Silsoe) model. These model results are compared with those of the multiplied tables, with field observations and regional or known local erosion rates. The comparison will usually lead to an adjustment of the contents of the tables.

12.2.4 Gis maps

A sheet and rill erosion map (Gs) and a morpho-erosion map (Gm) can now be generat-



Map 1 Map Showing erosion classes in kg/ha resulting from GIS operation based on Morgan's model. Black and white reproduction of a colour map; dark units low erosion, light toned units higher erosion. Kandy area, Sri Lanka.

ed and the contents added, whereafter multiplication follows with the rainfall erosivity map (R_e) and the cover factor (C) map, according to the USLE algorithm, yielding the E1 map.

Our experience shows that this map needs editing:

- overlooked errors, erosion classification of parts where no erosion occurs such as towns, depositional areas, etc.;
- smoothing operations for better presentation.

Map 1 shows the erosion map resulting from GIS operations using Morgan's model (black and white reproduction from original colour screen)

12.2.5 Sediment yield

The map showing the gross erosion (E map) is a basic document for the estimation procedures of the sediment yield. Boundaries of subcatchments and channel networks are digitized and the statistics concerning the gross erosion are asked from the GIS. Similarly, information from the $G_s + G_m$ maps is derived and sediment delivery ratios per unit from the data base are applied to the subcatchments on a weighted area basis.

These results are presented in the form of sediment yields per subcatchment to the major river network. A simple graphical procedure – as yet – is used for routing the amounts downstream, taking into consideration link lengths of channels where flood-plain deposition occurs and where incision takes place. It is the intention to replace the graphical procedure by a proper routing model.

12.3 Remarks concerning the components

12.3.1 Climate

Most operations in the data base, illustrated in Figure 12.2, can be performed using well-known methods. The following problems were met during the application of the procedures in our test areas:

- The intensity-frequency-duration data of point rainfall is difficult to obtain. One may have to resort to empirical ratios of short to long duration rainfall. The runoff and erosion models often require short-term rainstorm input. To find an 'average standard storm' in the various seasons is no easy matter. Perhaps use of probability density functions of daily rainfall may be helpful.
- In other erosion models monthly or yearly runoff is required. We find a big gap between the Thornthwaite and Mather water balance methods and the physical model (such as SWATRE of Feddes et al., ILRI, for example) which require formidable input. We are trying out the results of the former method, using 10-day periods.
- The determination of the EI_{30} index is a major effort, for which basic data may be lacking anyhow. In the Andes test area an empirical adjustment of the Fournier index was used, but the correction is based on a station in the foothills. In Sri Lanka the value for one station, as estimated by Joshua, was used and variations within the area had to be estimated, introducing error. In the Tunisian area, a semi-arid region, one has the nagging doubt that the EI index may not be useful at all, because most of the erosion seems to occur during events of heavy rainfall with long recurrence intervals. Runoff data, if available for at least some small catchments, should be used fully, as indicated on the chart of Figure 12.2. The derived values of the input parameters after calibration are helpful in estimating those parameters in other areas. We find that, in absence of runoff data, peak runoff rates as determined by the slope area method (Manning's formula applied to channels) give reasonable results, if grouped and averaged per geomorphological unit.

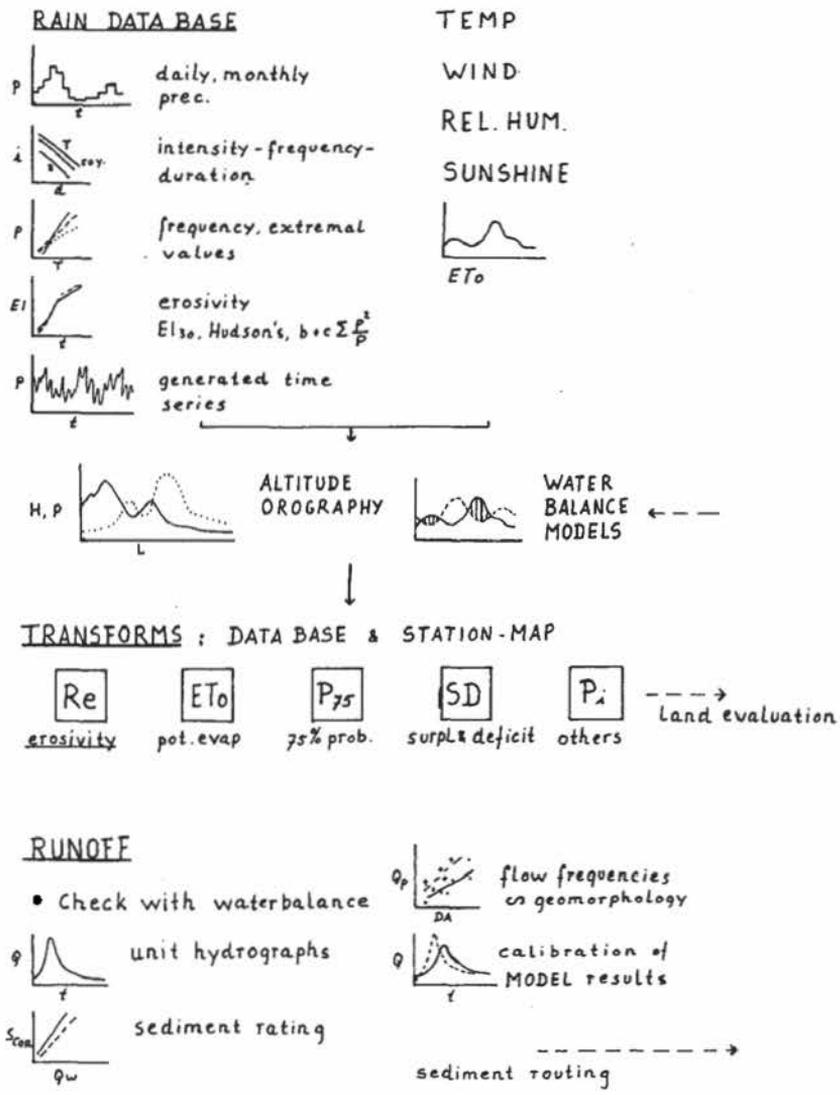


Figure 12.2 Climate.

12.4 Vegetation and land use

The remote sensing image processing is grouped under this heading because optimal benefit is made of the Landsat imagery for estimating the cover factor and for the assessment of the changes which may have taken place in the area (Figure 12.3).

It is generally not possible to derive sufficient information with regard to practice factors and even type of land use from the satellite data. Aerial photo interpretation and fieldwork is required, but the imagery may serve as a base map. Various techniques are possible to produce the best base maps. In hilly areas an intensity transform may provide a sort of relief map, essential for location, and filtered images using high-pass

- IMAGE PROCESSING
- restoration
 - atmospheric corr.
 - geometric corr.
 - image to image registration

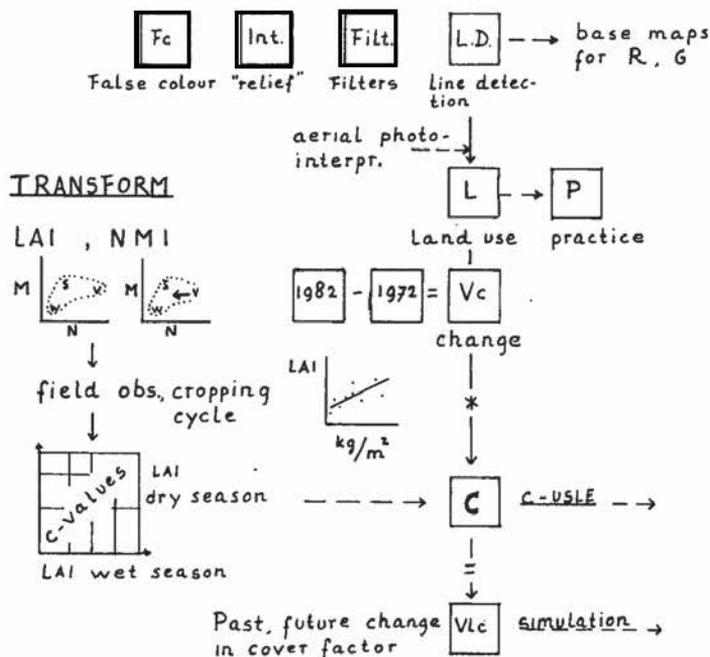


Figure 12.3 Vegetation - land use.

filters may enhance the drainage networks while in some regions line elements (roads, field boundaries, etc.) may be enhanced by other filters. The land use and practice maps are often compiled by plotting various parts of the region on different imagery.

It is commonly accepted that LAI transforms (b7-b5/b7α5) or the physically more acceptable NMI transform, are associated with vegetation densities in the field. In a general sense this is true for the test areas, but only up to a point. In Tunisia, for example, the correlation was not very satisfactory for open and dense forest stands. In the Sri Lankan area it was difficult to separate certain tea lands from paddy lands and some grasslands on the LAI image, but the corresponding (C) factors, as estimated in the field, are quite different.

In the Argentina test area large-sized fields in certain parts change to small parcelling in adjoining ones. From the small parcels mixed spectral signatures are registered. Different from the large parcels, but the ultimate cover factor may not differ very much in the large and small fields. For natural vegetation there seems to be no abundance of data in a form useful for relating the real densities in the field with the transforms of Landsat.

In our studies, LAI transforms were used and the (C) values in the look-up table, composed of the wet season and dry season scenes, were based on identifying known locations and estimates of (C), based on field knowledge. Because the (C) factor is of great importance in the estimation of erosion, much more research effort should

be directed to the application of remote sensing in this domain.

Map 2 illustrates the difference of the LAI in the dry season and the wet season in the Argentine area.

12.5 Physiography and geomorphology

To avoid semantic difficulties: with physiographic units here is meant essentially genetical units which are subdivided on the basis of relief forms which have typical soil associations, usually in the form of catenas. Sheet and rill erosion are related to the physiographic units. The geomorphological units here are also genetical units (fluvial,

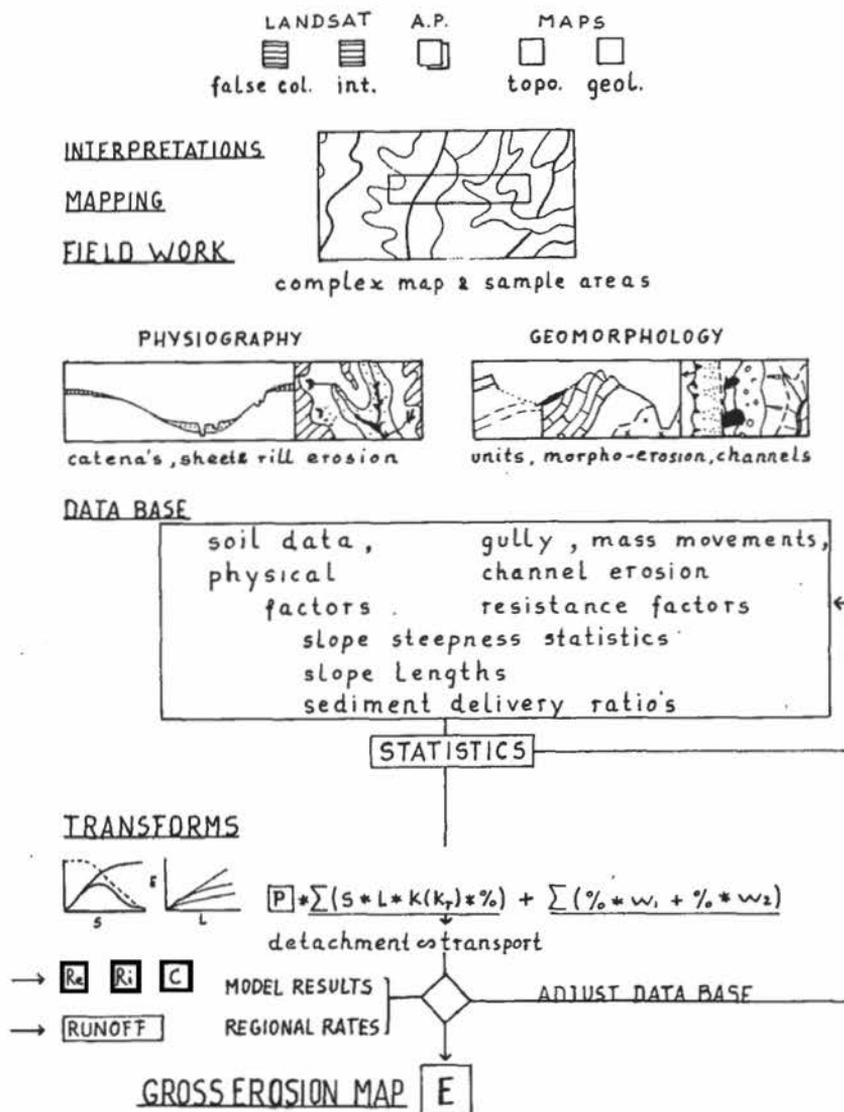
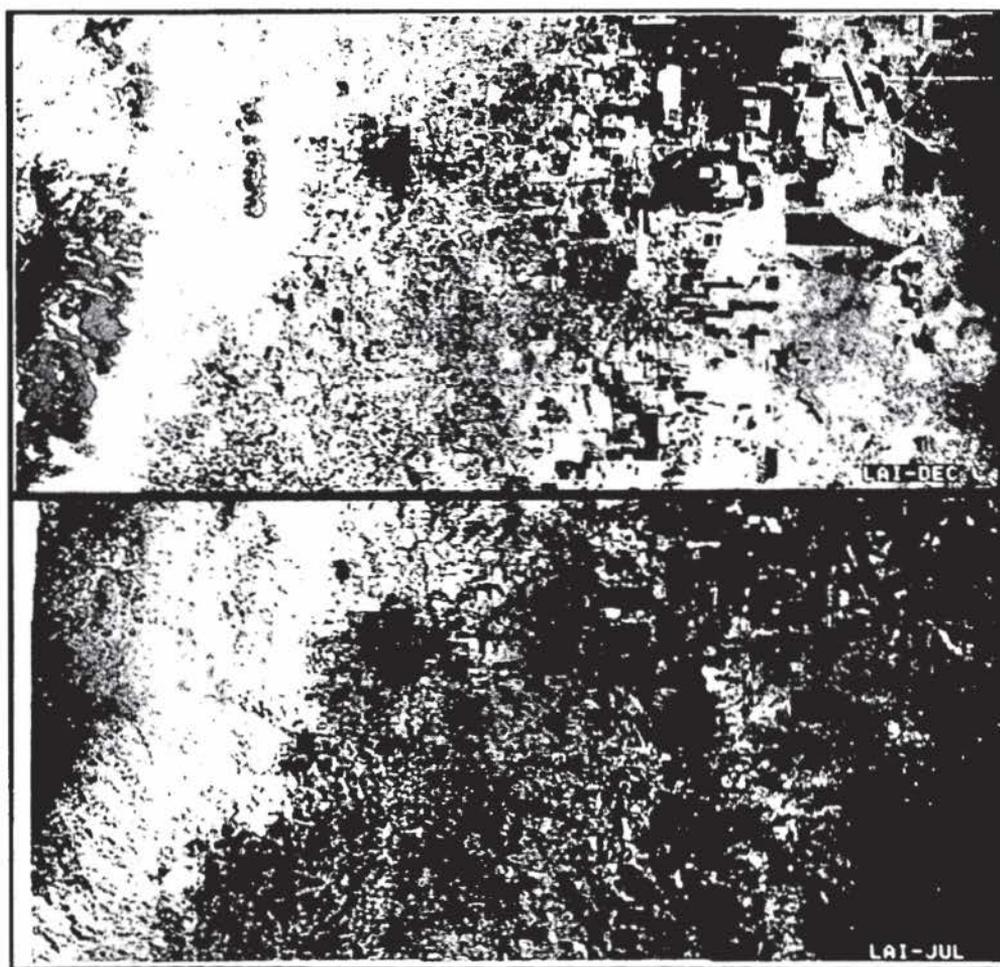


Figure 12.4 Physiography & geomorphology.

denudational, structural, karst, etc.), subdivided according to local relief, drainage density and pattern and to sequences. The information per geomorphological unit contains lithology, slope distributions, overland flow lengths, channel characteristics, surface resistance factors and the so-called 'morpho-erosion' forms. With the latter here is meant gully systems, landslides (soil flows, debris avalanches, slumps, etc.) and severe channel erosion. (Figure 12.4).

At reconnaissance or even semi-detailed scales, boundaries of the physiographic units and the geomorphological units usually coincide or can be made to coincide if one sacrifices formal legend conventions to some extent for the sake of a practical way of filling up a data base with relevant information (attributes). Sediment delivery ratios are estimated for each physiographic/geomorphological unit.



Map 2 Leaf Area Index transforms from Landsat b.5 and b.7 of the wet season (December) and the dry season (July), used for the look up table to produce the C factor map (USLE). Dark tones correspond to low LAI values, light tones to high values. On the left side the evergreen forest of the first ranges change into the arid zone (extreme left, dark toned, west of the clouds on the December image). Note the change in LAI in the drier plains in the east. Area NW Argentine.

Reasons for the split-up of the two types of information are:

- The GIS maps with the soil information will be used in other land evaluation procedures different from the maps with the geomorphological information.
- Too much information per mapping unit on a single map base leads to unwieldy legends and mistakes.
- The nature of the erosional processes is different in terms of causes, intensity per unit area and frequency (rate of work per event and magnitude of the event).
- For the sheet and rill erosion estimates, reasonably accurate approaches have been developed and applied to various parts of the world. This is not so for the morpho-erosional processes, for which quantitative estimates on a subjective basis have to be made.

12.6 Transformation

The physiographic information.

USLE factors (K), (L) and (S) are assigned to the elements of the associations of the mapping units. The (Gs) value for a mapping unit is determined by:

$$G_s = \Sigma(S.L.K(K_r).\%)$$

where (K_r) is a resistance factor to be used in case slopes are steeper than the 22% limit of the (S) function of the USLE, as will be discussed below. (%) is the proportion of the area of the element in the unit.

This algorithm assumes no transport limitation and no deposition, which have to be considered in studies of catchments or units with catenas. This may be done by:

- Estimation of runoff by water balance methods for each element and unit;
- Application of the algorithms such as used by Morgan et al. The chart of Figure 12.5 shows how the input maps can be processed using the IGIPS software according to Morgan's site model. The test area in Sri Lanka was used.
- Use of the ANSWERS model (see below) for 'averaged' subcatchments in the mapping units.

The initial (Gs) value may be altered to incorporate transport limitations and deposition.

Earlier we mentioned some problems in transforming vegetation data into USLE cover factors. Actually, for most transformations difficulties are encountered, which is no wonder when one considers the physical dimensions of the input and the desired output. In sloping areas (i.e. hilly or mountainous areas) one runs into difficulties with even the best tested method, the USLE approach, notably with the slope function.

12.7 Effect of slope steepness in hilly terrain

There is very little known on the effects of slopes steeper than about 12° (22%) on sheet and rill erosion. In our test areas, however, many units have slopes much steeper than 12°, and to our knowledge no procedures exist to estimate the USLE (S) factor. It is useful to list the existing slope functions in order to judge if or till what steepness they may be extrapolated.

example: Sri Lanka. Model by Morgan et al.

DATA BASE

G-units	Vegetation	Meteo
field observations sampling	L.A.I.	Rainfall
χ^2 , Tuckey statistics		Evapotransp.
GIS	K 0-.42	C 0.003-.30
MAPS	Rd 1.2-1.5 ⁹ /cm ³	Rv 1830-2120
	Inc 10-35%	ETd 970-1520 m.m.
final units	Fc 25-33%	ETd 900-1400 m.m.
	Rd 4-10.10 ⁻² m	Ke 9300 J/m ²
	S 0-30°	Rd 11.4-13.3 m.m.

$$DET = K * (Ke * e^{-0.05 Inc})^2 \quad (* ST) \text{ (stoniness)}$$

$$Rc = (ETd / ETa)^{0.5} * 10 * S * Bd * Fc$$

$$DF = Rv * e^{-Rc/Ra}$$

$$G = C * DF * \sin S * 10^{-3}$$

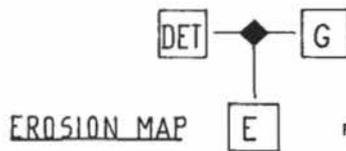


Figure 12.5 GIS operations & model algorithms.

In use are:

- polynomial functions (USLE)
- tractive force formulae
- modified versions
- power formula

$$E = 0.43 + 0.3s + 0.04s^2$$

$$E = \sin s \text{ (= velocity gradient)}$$

$$E = \sin^{exp} s \text{ (exp. varies from 1.05-2.5)}$$

$$E = s^{exp} \text{ (exp varies from 0.7-2.0, mostly 1.35-1.5)}$$

$$E = (s-s_c)^{exp} \text{ (} s_c \text{ is critical steepness below which is no erosion occurs, exp. varies from 2-2.5)}$$

- linear relationships

$$E = c.s \text{ (} c \text{ = constant)}$$

- Horton function

$$E = \sin s / \tan^{0.3} s$$

Except Horton's function, no others take into account a decrease for very steep slopes. This is required for the simple reason that rainfall, and thus overland flow, per unit of slope must vary with $\cos(s)$, assuming vertical rainfall. This leads to:

- modified version

$$E = \sin^{1.5} s \cdot \cos s$$

or
$$E = \sin s \cdot \cos s.$$

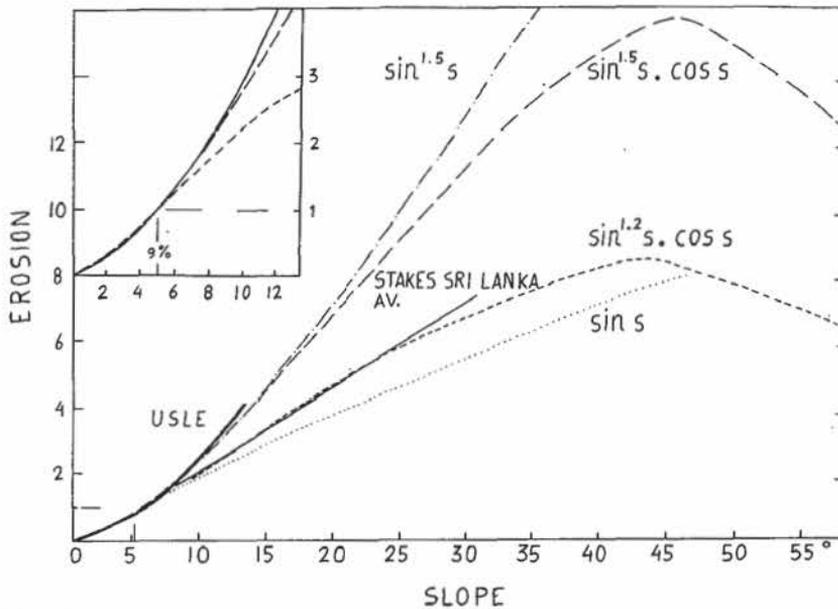


Figure 12.6 Comparison of slope functions, which are normalized for 9% (USLES).

The graphs of Figure 12.6 show some of the above functions, normalized for 9% = unity, in order to maintain compatibility with the widely used USLE numerical values for the factor (S). Before a function is adopted, field evidences may be examined.

12.7.1 Field evidences for the slope function.

As stated above there is, to our knowledge, very little information present in a form useful for detecting the slope function. For the sake of comparison the following data is shown:

- Renner's histogram used by Horton, Figure 12.7.a.
- The graphs of Fletcher and Beutner based on thickness of top horizons eroded (Figure 12.7.b). Note the wide variation.
- Polynomial functions would describe the observed phenomena. The same is true for the laboratory determinations of some Canadian soils up to 30° slope steepness (Bryan).
- New data by Ziadi (Figure 12.7.c) for the Kasserine area in Tunisia, using the same classes as Renner.
- Stake measurements in the highlands of Sri Lanka by Dissanayaka (Figure 12.7.d) for a rainy season (points represented are randomly drawn from a larger population of measurement data).

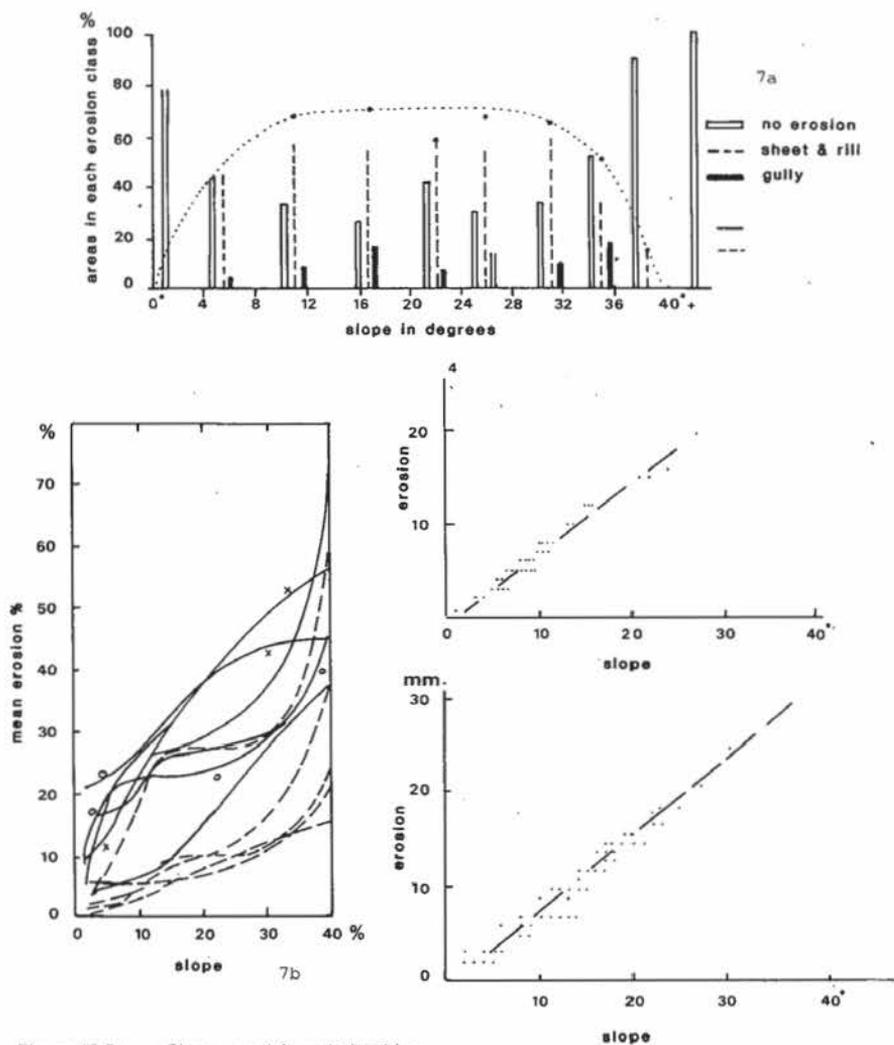


Figure 12.7 a - c Slope - erosivity relationships.

a. Idaho, USA (Renner, in Leopold, Wolman and Miller, 1964).

b. Upper Gila Watershed, USA (Fletcher and Beutner, 1941) desert soils, brown soils at higher altitude.

c. Kandy Highlands, Sri Lanka (Dissanayake, 1977) erosion stakes.

SLOPE STEEPNESS & EROSION

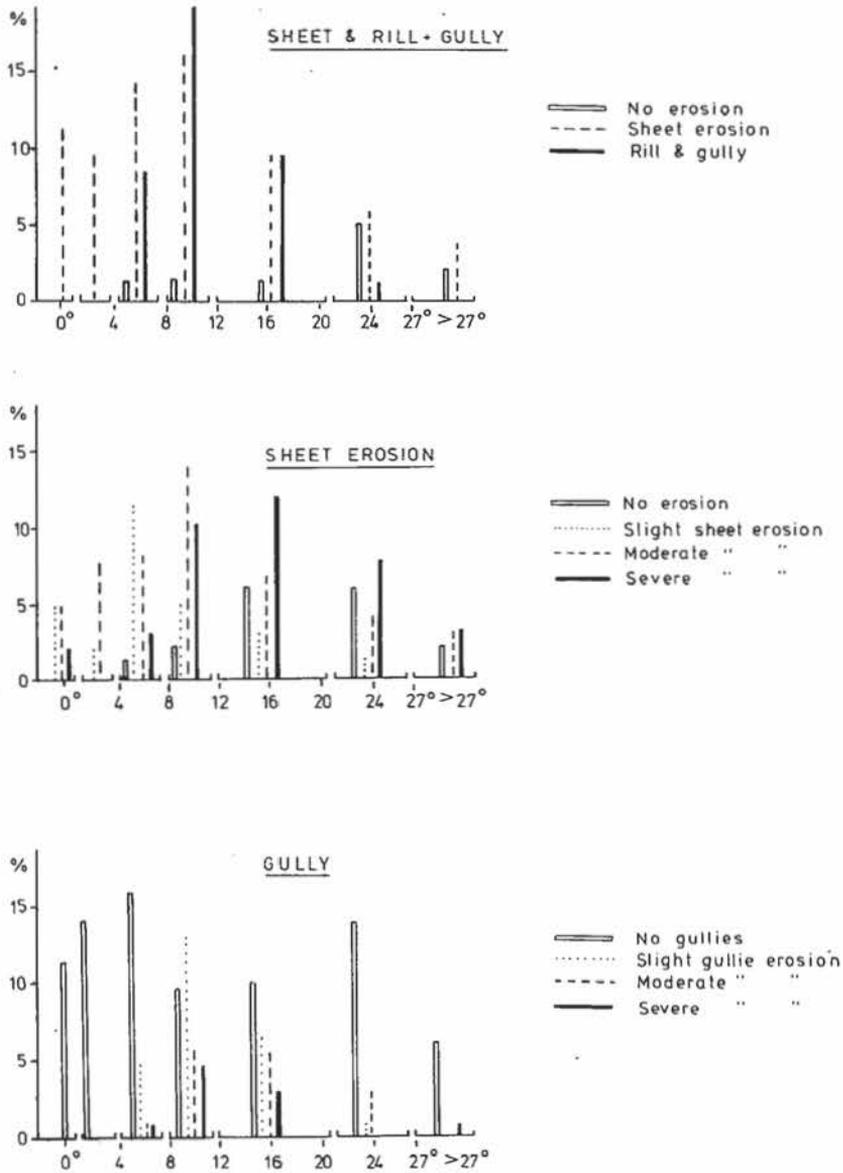


Figure 12.7 d Kasserine, Tunisia (Ziadi, in prep.) field estimates.

12.7.2 Evidence from sediment yields of mountain catchments

If the slope functions could be extended to steep slopes, very high sediment yields would be expected from mountainous terrain. The literature yields meager results, and mutual comparison is difficult. Some readily available data is shown in the table of Figure 12.8.

Figure 12.8 Sediment yields from mountain catchments.

author	area	remarks	ton/km ² /y	mass wasting important x present-
Ahmed 1960	N. Pakistan	Sed.yields large catchments,	500-3500	x
Kadomura 1980	Japan		500-13250	x
Meijerink 1977	Java, Merau River	Fly River	10000- \geq 25000	xx
Pickup et al. '81	Papua New Guinea,	0.37-4.05 mm/y	670-7400	x
Geiger 1957	Rocky Mountains	av.sed.yields	260	
	NW. U.S.A.	31 stations av.sed.yields	60	
	California	6 stations av.sed.yields	370	-
	(zone along lower Mississippi	14 stations, lowland	5940)	
FAO 1954	Añdes. N. Argentina	rel. degree top soil loss	slight-mod.	
UNESCO 1974	Andes. N. Argentina.	rel. degree top soil loss	only small pockets severe	
Fournier 1960	Andes. N. Argentina	empirical formula	60- \geq 1000	
Strakhov 1967	Andes. N. Argentina	empirical formula	\leq 50-240	
FAO 1975	S. Marocco		\leq 500-1000	
Lal et al. 1977	Himalaya, Sutley River, Bhakra reservoir		1500	-
Meijerink, 1974	Himalaya Aglar River		\geq 2000	-
Irrigation Dept.	Sri Lanka, Mahaweli at Kandy		400-800(?)	

Except in regions with rapid tectonic uplift where mass wasting is an important if not dominant process, the rates do not seem to be excessive. It should be noted that some figures are estimates and that sediment delivery ratios are not available. A tentative conclusion is that there is no basis for an a priori extrapolation of the slope functions.

12.7.3 Evidence from erosion and vegetation on steeper slopes

Again there seems to be no abundance of data. The table of Figure 12.9 shows some values (mainly derived from M. Jansson's review). Consideration of the USLE suggests that the value of (S) cannot be very high in cases where the soil loss on steep slopes

Figure 12.9 Vegetation and erosion on steep slopes.

author	region	soil	annual rainfall	Slope %	Cover	soil loss t/km ²
Starkel 1972	Murpur, Punjab		1092	25	grass 80% bare	545 1026
Temple 1972	Tenguru, Tanzania	deep red volc.soil	1070	32	grass, cut for hay maize banana + mulch coffee, clean weeded	0 m ³ /km ² 1200 m ³ /km ² 50 m ³ /km ² 2240 m ³ /km ²
Fournier 1967	Lake Alastra Madagaskar		978 978	20 30	grass 20% cover grass 100% cover	1200 2.6
Glymph 1954	Pullman, Wash.	Palouse silt loam	528	30 30	perennial grass bare, untilled	17.9 4950
Ashida et al. 1981	Japan			18 18 44	cultivated, bare planted ?	2000-4000 t/km/y 1000-2000 t/km/y 5,000

is low. The contents of the table show of course also the great influence of the cover factor.

12.7.4 Adopted slope-erosion relationship for sheet and rill erosion

From the above the following observations may be made:

- In the slope range up to 10° (17%) it makes little difference which equation is used (see Figure 12.6).
- The $\sin s \cdot \cos s$ function is perhaps the most satisfactory one from a physical point of view, but gives too low values for the gentler slopes.
- The function $\sin^2 s \cdot \cos s$ may be a reasonable compromise.
- The field data (Arizona, Tunisia, Sri Lanka) suggest region-specific relationships. The decline of erosion at steep slopes is related to increasing resistance of the surface to erosion on steep slopes. It is likely that the relationship is dependent on the erosional history. In semi-arid regions with hundreds or thousands of years of (accelerated) soil erosion the maximum erosion may be reached at 15-20°. In recently deforested humid tropical regions, the maximum may be reached within the range of 25-40°.

In order to maintain compatibility with the USLE procedures, the factor (k) may be used to describe the increasing resistance to rain erosion on steep slopes. To avoid confusion, we term the resistance factor k_r .

The factor (k_r) is dependent on slope steepness and the (k_r) (s) relation, which is region-specific, could perhaps be assessed from field measurements of elements which can be readily determined in the field, such as thickness of lithosol, stoniness, frequency of rock outcrops.

In Figure 12.10 a compound resistance factor is shown, based on a weighted s_1 m of the elements, in the form of an accumulative frequency curve. That curve is used to calculate (k_r) as a continuation of the USLE (k) factor, valid for the soils on the

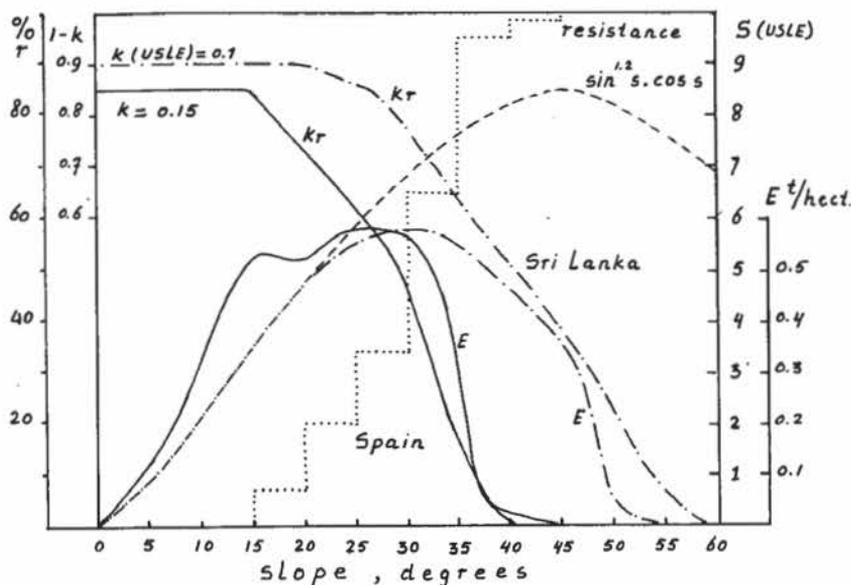


Figure 12.10 Slope function $\sin^{1.2} s \times \cos s$, and resistance factor (k_r) compatible with USLE s soil factor (k), derived from cumulative frequency of accumulated resistance elements per slope class. Erosion (E) in tons/unit area, results from $k(k_r) \times (S)$.

gentler slopes. Also shown in Figure 12.10 is an estimated and smoothed (k_r) (s) function for the test area in Sri Lanka, based on stoniness of former tea lands and adjusted for preliminary erosion rates, as estimated for root-exposure measurements on old tea bushes.

The resultant erosion (E) = $k(k_r) \cdot s$ is shown.

This approach, although empirical, results in decreasing erosion rates at steep slopes and may be accurate enough for a first evaluation. More research is required.

12.8 Transformation of the geomorphological information

The morphometrical information contained in the data base (frequencies of slope steepness, slope lengths) and the surface resistance factor, as derived from sampling in the units, is used for the transformation described above.

Of major concern in certain areas is the erosion and sediment yield contribution of the morpho-erosional processes such as gullying, sliding and channel erosion. The tables of Figures 12.11 and 12.12 give an overview of the possible range of magnitude and contribution. Included are short-term data (10 weeks, New Jersey) and long-term observations (34 years, California). As is well known, much sediment may be derived from only small parts of the catchments suffering from such erosion. However, not each and every gullied area, for example, is in an active state.

Estimates of the intensity per unit area may be made in several ways:

- If sediment yield data are available of some catchments, the rates may be assessed by estimating the contribution of sheet and rill erosion. The remainder is distributed over the parts affected by active morpho-erosion.

Figure 12.11 Debris/mudflows and landslides effect on sediment yield.

author	area	yield ton/km/y	
Pierson (1980)	N. Zealand	100-1,000xQ _s	surface wash rates
Ikeya (1981)	Japan	7,500 ton/km ²	
Rapp	Tanzania	650 ton/km/y	total yield
Meijerink (1977)	Java, sedimentary rocks	≥ 25,000 ton/km/y	
	volcanic rocks	10,000 ton/km/y	
Gerasimov, & Zvonkova (1974)	Caucasus	290,000 ton/km	
	S. Caucasus	200,000 ton/km	
	S. Kazakhstan	50,000 ton/km	
Swanson, Swanson & Woods (1981)	New Zealand	40,000 ton/km/y	
	B. Colombia, N. Zealand	11- 100 m ³ /km/y	forested
		111- 2,200 m ³ /km/y	clearcut
		282-15,600 m ³ /km/y	road, right of way
Kelsey et al. (1981)	N. California, earthflows 309 debris slides 544	853 ton/km/y	44% of gross erosion 1% of area

Figure 12.12 Gully erosion rates.

author	area	mm/year	
Kelsey et al. (1981)	Nw. California	0.37	584 t/km/y 36% of gross erosion 4% of area
Yair et al. (1980)	S. Israel	very low	
Campbell (1977)	Alberta, Canada	4.51	
Gerson (1977)	Israel	2 -10	
Robinson (1977)	W. Iowa USA	5 -18	
Gong & Xiong (1980)	Loess, China	3.3-13	
Schumm (1956)	N. Dakota	20 -38	
	N. Jersey	10 -35	
Hadley & Schumm (1961)	U.S.A.	15 -45	
Strakhov (1967)	world, small catchments, up to 85 mm		
Trimble (1974)	Piedmont plateau USA very severe sheet erosion destroyed by gullyng	1.3-2.9	
Piest (1974)	Iowa, gully erosion 20% of total yield, percentage of gullied area 0-10% (?)	6.6	

- Field estimates of gully growth and active landslide volumes may be obtained using information with regard to age and frequency of occurrence from local inhabitants and comparing volume growth from old large-scale aerial photography and maps.
- In some regions where most of the coarse material in the rivers is supplied by morpho-erosion, estimates of the bed load may be attempted using particle size distributions, flow parameters and channel sections.

These estimates give also approximate results, but may provide an insight into the geographical variation and give an idea of the minimum rates.

It is evident that any improvement in estimation methods will have to be adopted.

The actual transformation in the GIS consists simply of multiplying areas affected by a factor representing the average intensity in tons per unit area (i.e. a GIS pixel).

12.9 Trials, comparison and generation of the gross erosion map

As is shown in the chart of Figure 12.4, before the transformation of the input maps (Re), (C), (Gs) and (Gm) into the gross erosion map (E), first the provisional results for a number of units are studied and compared with estimates obtained by other means such as mathematical models, regional or local rates.

12.9.1 Use of mathematical models

The models which we have used so far are the ANSWERS catchment model, developed by Beasley & Huggins, Purdue, and the simpler site model of Morgan, Morgan & Finney, Silsoe.

The ANSWERS model is particularly suited, being fully deterministic in nature, and the (C) map and derivatives of the (Gs) map can be used as such as input in the model. The model produces:

- amount of erosion or deposition per pixel in the catchment;
- hydrographs of the surface runoff and the sediment concentration;
- sediment transport and sedimentation (with grain sizes) in the channel.

Because of lack of gauging data in the test areas, the calibration of the model we could do was limited to (a) peak flows with a recurrence interval of about 1 year, using estimated short-duration rainfall of the same frequency, and (b) using rainfall rates which do not result in noteworthy runoff and sediment transport in the rivers.

12.9.2 New automatic recorder

Very recently a cheap, small-sized fully automatic recording instrument is available. For river gauging the instrument is simply anchored to the bed at a suitable channel section, and can be left without any maintenance. Water-level readings are made at selected time intervals (minutes, hours) and stored in a built-in memory. The same type of instrument is used for rain gauging (prototype by ITC, commercial instrument by Siemens, Netherlands). A major bottleneck is thus removed for calibration of the modelled runoff in catchments in the various mapping units. Work is in progress to include sediment sampling.

12.9.3 Use of regional or local rates

Sediment yield data becomes more and more available in most parts of the world.

With the information of the (Gs) and the (Gm) maps it is possible to estimate the general levels of gross erosion, using the sediment delivery ratios estimated earlier. Furthermore, sometimes quantitative field estimates of erosion can be made from tree-root exposures, sediment surveys in small reservoirs, and so on.

12.9.4 Generation of the gross erosion map

Comparison of erosion rates, estimated in various ways, usually points out deficiencies in the tables of the (Gs) and the (Gm) data base. After corrections the gross erosion can be generated and edited, using once again image processing techniques and addition of drainage networks and topography.

12.10 Concluding remarks

It is too early to comment on the accuracy of the results obtained in the test areas, and the strength of the assemblage for simulation tasks beyond what is obvious to everyone. However, the following remarks can be made:

- Existing methods for estimation of erosion can be easily adopted by Geo-Information Systems, provided versatile facilities (hardware and software) are available to digitize, edit, transform and display the data.
- Vegetational, geomorphological and soil surveys, making use of interpretations of aerial photography and remote sensing (the conventional ITC-approach) are, together with climatic data, the basic sources of input information.
- Mathematical/physical models, preferably of a deterministic nature, can and should be an integral part of the data base and GIS operations. Either the GIS input maps can be processed according to model algorithms or the model results give improved values of factors for the transformations of the input maps.
- Adopted GIS formats and data-base procedures facilitate efficient multidisciplinary teamwork of specialists in the various fields.
- The forbidding strictness of the computer operations exposes weaknesses in the nature of the transformations, which in practice were usually covered by intuitive or empirical-associative approaches of the surveyor-specialist.

The assemblage, discussed here, takes a lenient view to the latter approach, but clearly indicates where improvements are required.

Acknowledgements

It is not for the sake of politeness that we thank and mention persons. Without their support we could never have reached the stage we are in now.

Three persons following M.Sc. courses at ITC did most of the work in the three test areas. They are V.M. Sayago (Argentina), whose persistence in compiling the information for all the transforms has to be admired; B. Emaruchi (Sri Lanka), who elegantly found a way to process the maps through the model of Morgan et al.; and K. Ziadi (Tunisia), whose precise field sampling and statistical analysis gives such

interesting results.

The many operations in the data base (frequency analysis, water budgets, statistics) could be made thanks to the participation and software of N.H.W. Donker (Geomorphology Group).

P. Stefanovic and D. Boonstra from the Cartography Department assisted in the digitalization and the conversion. The transformations of the maps in the GIS was done by B.G.H. Gorte and T. Bouw of the Computer Department with the versatile IGIPS (GIS) software which was developed by their department. Other transformations were done by Stefanovic using powerful cartographic software.

G. Reinink of the Image Processing Laboratory found a clever way of presenting the results using the remote sensing software, apart from his assistance in other processing, when needed.

The ANSWERS model was kindly given to us by D.B. Beasley, and the SWATRE model by R.A. Feddes.

The task of getting the hydrological models on the ITC VAX into operation with good graphical output was performed in a virtuouse manner by R.X. Portier.

Finally, the colleagues at ITC, far more knowledgeable in soil, erosion, vegetation than we, advised us on the best estimates for the conversions, but they cannot be held responsible for the way we tried to follow it up.

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Discussion

P-Hernandez: Can you give any idea about the estimate of accumulative errors?

Meyerink: The calculations are checked after each stage, thus if rates are not realistic then the parameters are adjusted; if a sensivity analysis is carried out then the results may change dramatically.

Jungerius: How reliable is the map shown?

Meyerink: The map is reliable as it was based on many systematic, very detailed observations.

Bennema: What are the assumptions used in the model, and why are some parameters not taken into account; for example if pesticides were being used, what would be their influence on the soil cover and subsequently on the runoff; it appears that some parameters are taken to be the same over a number of years.

Meyerink: We have been working on a small scale and maps of this nature have little relevance at farm level; however we have calibrated our data against field observations and know which data are still needed if we want to apply the methodology on a large scale.