SOIL EROSION ASSESSMENT USING GEOGRAPHICAL INFORMATION SYSTEMS (GIS)

(A CASE STUDY FROM ALORA, SOUTHERN SPAIN).

BY

BRIAN J. MHANGO

Wageningen Agricultural University
Wageningen (The Netherlands)

International Institute for
Aerospace survey and
Earth Sciences
Enschede (The Netherlands)

SOIL EROSION ASSESSMENT USING GEOGRAPHICAL INFORMATION SYSTEMS (GIS)

(A CASE STUDY FROM ALORA, SOUTHERN SPAIN).

BY

BRIAN J. MHANGO.

Wageningen (Netherlands), February 1995.

Thesis submitted in partial fullfilment for the Degree of Master of Science in Geographical Information Systems at Wageningen Agricultural University (Wageningen, Netherlands) and the International Institute for Aerospace Surveys and Earth Sciences (Enschede, Netherlands).

<u>BOARD OF EXAMINERS</u>:

Professor Dr. Ir. M. Molenaar (WAU)
Drs J.C. de Meijere (ITC)
Dr. G. Epema (WAU)

<u>supervisors</u>:

Dr. W.G. Wielemaker.
Professor Dr. Ir. M. Molenaar.

CONTENTS

ACKNOWLEDGEMENTS

My stay in the Netherlands has been of mixed fortunes and completion of my studies has been in part subject to these.
I count myself fortunate to have reached this far given that my funding was not guaranteed. I missed my family: Rachael, Chipo, Pelina, Stella and my brothers. Their communication with me did add some inspiration .
Drs J.C. de Meijere was very influential to my success in having to extend to an M.SC.
course having, originally not been registered for the this course. In other words, I should long been home in Zambia at this stage.
I am thankful to the Zambia Agricultural Extension Research Project (ZAREP) for awarding me the scholarship to study.
I am in a special way indebted to Dr. K. Munyinda who did encourage me to have a closer look at GIS.
Thesis writing brought its own desparations particularly when one starts from a kind of fuzzy idea. Whether this fuzziness has been cleared at this stage should hopefully be clear in this treatise. I am grateful to Dr. G. F. Epema who was my director of studies at Wageningen Agricultural Unoversity.
Drs J. C. de Meijere was my course director from the International Institute for Aerospace Surveys and Earth Sciences (ITC) and, to him I am genuinely indebted.
However, in the course of it all I gained reasonable insight from my supervisors: Dr. W.G. Wielemaker and Professor Martien Molenaar.
Coming to soil erosion, I had invaluable assistance from Ir. Leo Eppink all the way. On ARC/INFO and Digital Elevation Models I am grateful to John Stuiver and Ir. Sytze de Bruin.
I am thankful to all my course mates some of whom I will not forget, they made case studies of every ARC/INFO command.
These are obviously too many to mention. I hope, hereafter all will be equally inspiring particularly in the field of GIS.

Brian John Mhango.

February, 1995.

LIST OF FIGURES

LIST OF TABLES

PLATES

CHAPTER I INTRODUCTION

1.1 INTRODUCTION

This study emanates from an integrated fieldwork by the departments of Soil Science & Geology, Tropical Crop Science, Irrigation and Soil & Water Conservation and, Land Surveying and Remote Sensing of Wageningen Agricultural University (WAU) under the concept of "Sustainable Land Use" in the Lower Guadalhorce valley, Andalucia, southern Spain. The primary objective of integration was to allow for an understanding of how each discipline viewed the real world, and come up with parallel units (bio-physical and socio-economic) that are studied by each discipline under the notion that all objects studied by each discipline are a part of a large entity or system hence, soils and land use/cover can be conceived as phenomena within a parallel hierarchy (Annex 1).
Furthermore, the fieldwork was a basis for gaining an insight of the relationships between soil, landscape and land use based on field methodologies for the description, analysis and mapping of landscape, soils and land use at different levels. The integrated approach was expected to result in devising procedures for inter-disciplinary processing of data such as building of databases, aggregation and desaggregation of data, and development of a classification system for landscape, soil and land use information.
A notable problem in the study area as typical to most semi-arid environments is soil erosion. Soil erosion is a hazard mostly associated with agriculture in both tropical and semi-arid environments. This inevitably necessitates fundamental research in soil erosion if sustainable land use is to be realised in the lower Guadalhorce valley. The history of soil erosion in the area dates back to the 8th century with some serious events in the 13th century (5).
Erosion in the study area is severe and on aerial photographs erosion features such as gullies and landslides can be distinguished.
An understanding of soil erosion processes forms the basis for prevention of soil erosion and proper planning for soil conservation measures. This may possibly lead to sustainable land use. Soil erosion is a spatial-related phenomenon hence the use of Geographical Information Systems (GIS) as supportive tools to implement databases that can be manipulated to answer queries on soil erosion is invaluable. This study advances an inductive approach (bottom-up approach) to model soil erosion using the Revised Universal Soil Loss Equation (RUSLE). Moore's sediment transport capacity index is evaluated along side the Revised Universal Soil Loss Equation.
The sediment transport capacity index is used here in that it addresses the three-dimensional aspect of landscapes with respect to zones of net erosion and deposition.

The RUSLE as the acronmy suggests was purely chosen as an improvement on its forerunner, the Universal Soil Loss Equation (USLE) and its claimed capabilities to account for the Slope-Length factor much more accurately even for nonuniform slopes. RUSLE is a lumped, empirical erosion model and, as such, conducive for inductive research. The model is enshrined in the erosion theories (chapter III) which consider so-called steady-state sediment transport limiting cases predicted by the theories.
The three-dimension oriented approach of the RUSLE to calculate the LS factor makes it particularly attractive for implementation in a GIS through Digital Elevation Models (DEMs).
Being an inductive approach, the analysis is that of 'from-the-specific to the-general'. The specific here refers to point data and the general refers to bio-physical entities that constitute the landscape at a given aggregation hierarchy and scale.
The bottom-up approach being advocated in this study implies that aggregation and generalization rules must be defined to present erosion information at coarser scales.
The implementation of such rules in a GIS necessarily means that we define appropriate geometric and thematic data structures, and database manipulations. This entails design procedures that can be translated from both spatial and conceptual models to internal structures that can be implemented in computers for efficient operation of the database.
This treatise has six chapters in all and notable are chapters III, IV and V. Chapter III deals with concepts of erosion modelling. Chapter IV discusses materials and methods applied in this study and chapter V dwells on database design and implementation.

1.2 PROBLEM DEFINITION

Although most erosion research has been at detailed scales, results of such research rarely concern needs for generalizing and/or aggregating such data for presentation at lower resolutions (small scales).
It is a well known fact that we can neither measure all properties for example, soil properties at a particular location in space and in time nor can we measure even a single property at all points in space and time. It is costly to carry out detailed investigations both in time and monetary terms thus coarse scales implicitly address these problems. But this is at a cost in terms of accuracy of data and information presentation and reliability.
This is the justification for detailed investigations through sample areas (or inductive research).
The question then, is: how can we aggregate and generalize soil erosion from high resolution data to coarser scales ? What would

be the rules to achieve desired results ?
Erosion is modelled in this study using terrain characteristics as prime model input data which can be modelled in a GIS.

This is possible from database point of view through analysis of underlying spatial data structures in particular through classification or generalization and aggregation subject to capabilities of a GIS and the database management system.
According to Burrough (1986), information analysis in geographical information processing can be summed up as an exercise in resolving spatial data into patterns that we can understand. This intuitively leads to formulation of rules for aggregating and generalizing or classifying of spatial information.

1.3 RESEARCH OBJECTIVES

The general objectives of this study are estimation, or better, simulation of soil loss (erosion hazard) in a sub-catchment of the lower Guadalhorce, and analysis of the effects of terrain characteristics, and soil on generalization and aggregation of soil erosion information from high resolution data for presentation at small scales.
As stated in the problem definition, objectives of this study equally include formulation of inductive conceptual approaches for modelling soil erosion. This calls for an understanding of existing modelling concepts and identification of relevant terrain objects of analysis for soil erosion that are mappable at given resolutions. Consequent to the above objectives is an evaluation and understanding of the effects of aggregation and generalization on the model simulation results.
Another fundamental objective is implementation of the model in a GIS that encompasses a spatial and a thematic database which can be accessed, transformed, manipulated and permits analyses to answer specific queries about soil erosion in the lower Guadalhorce.

1.4 RESEARCH LIMITATIONS

In this study some model input data is from previous studies in the area and in places some input data is derived using theoretical principles. The RUSLE is an improvement of an empirical model the professed Universal Soil Loss Equation (USLE) which applies data at plot level and is concerned with rill and interrill erosion.
The USLE is a site specific model and is so far, well attested in the United States. The factors that account for erosion at coarser scales amongst others include gully erosion which is not accounted for in the model. Soil erosion is a phenomenon that

should ideally be modelled using stochastic models since there is always a random element associated with measured values. The model applied in this study is deterministic which in itself is a limitation. On the other hand, the model results are simulation results and do not refer to actual measured soil loss in the field.

Furthermore, not all observation points formed complete data sets necessary for simulating soil loss particularly, those of previous studies.
Although Global Positioning System (GPS) readings for positional accuracy purposes were taken during fieldwork, these have not been made available in this study. Only two landscape units were well covered by the sample area, the old river terrace remnant and the glacis. These form the basis for generalization and aggregation in this study. The sample size (N = 42) is equally limiting in this study. Desaggregation of these units to facets resulted in fewer observations per object of analysis and curtailed meaningful statistical analyses. Thus an approach of reselection and reclassification using other terrain characteristics without stratification was unavoidable.
This means that spatial bio-physical entities are lumped irrespective of their morphographic properties to increase the sample size. Implicitly, bio-physical entities are treated as if they were discrete (non-fuzzy) entities.
Some soil characteristics are not fully evaluated, for example, the effect of calcium carbonate ($CaCO_3$) on soil erodibility. There are two schools of thought on this property and paradoxically in opposite directions. One school claims that it has a positive effect while the other claims that it has a negative effect on the soil's resistance to erosion. It seems some threshold value exists at which one of them is true while the other is not. This threshold was difficult to establish in this study.
This study does not account for propagation of errors in the input variables of the model due to measurement errors, interpolation errors and, spatial and temporal variations that may be associated with the variables. The model is applied idealistically assuming so-called steady-state conditions, and whether it simulates the true and acceptable results for the study area remains a subject for validation.

CHAPTER II. THE STUDY AREA

2.1 LOCATION

Alora is in the province of Malaga which is part of Andalucia, the southern region of continental Spain (Fig. 2.1).
The study area is about 15 km north of Alora.
Alora is aproximately 20 km NW of Malaga. The study area can be located on topographic sheet 16-44 No. 1052 Ardales/Alora (1:50,000 series) within UTM coordinates 470810,480810,470820 and 480820.

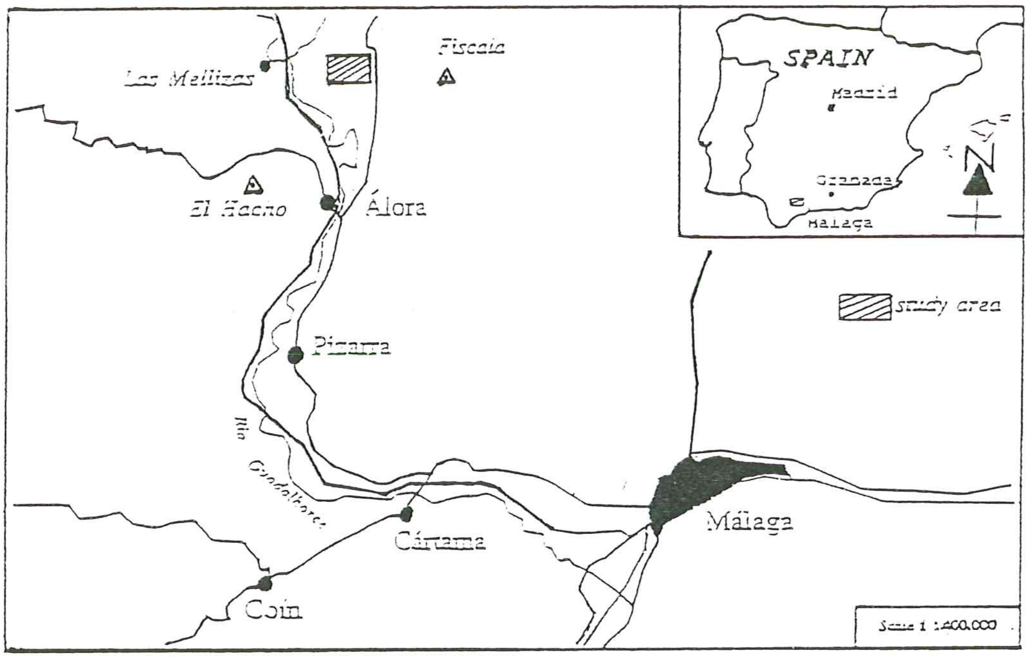


FIG. 2.1 LOCATION MAP OF THE STUDY AREA.

2.2 CLIMATE

The study area according to Koppen-classification (3,18) has a mediterranean climate with warm dry summers and cool humid winters.
Rainfall ranges from 500 to 700 mm per year, most (about 75%) falling in winter.

Frost occurence is said to be rare. High temperatures are common in summer and, in July and August temperatures may exceed 40°C.
Table 2.1 is climatic data of Alora and neighbouring meteorological stations. Temperature data is from Casarabonela 15 km SW of Alora and evapotransipiration data is from Alora and Malaga.

2.3 HYDROLOGY

The river Guadalhorce with its tributaries so-called rios and small rivulets called arroyos form the major drainage of the catchment. The drainage pattern is reminiscent to the so-called dendritic drainage pattern.
According to Spaan and Sterk (1992) the length of the river Guadalhorce is 154 Km and flows from Estrema del salinas 25 Km north-east of Antequera through the Embalse del Guadalhorce 15 Km west of Antequera into the Mediterranean sea.
The whole catchment is said to cover approximately 3160 Km^2.
The above catchment area consititutes the Upper and Lower Guadalhorce, the "Guadalhorce Alto" and the "Guadalhorce Bajo" respectively.
The Upper Guadalhorce debouches into three large manmade lakes upstream of El Chorro. The lakes have a catchment area of 1700 Km^2 and a water bearing capacity of 390 hm^3 (18).

2.4 GEOLOGY

The study area is situated in the so-called Sistema Betico (Cordilleras Betica) which is characterised by a wide and irregular mountain range in the southern part of Andalucia (3,5,18).
The Betic Cordilleras is one of the morphological-tectonic regions of the Iberian peninsula formed as a consequence of collision between Africa and Europe (3,5).
The collision of the two continents is thought to have occured during the Alpine (Tertiary) phase of mountain building (about 60-40 m.y.b.p.). The study area is said to be situated in the external zone (or subbeticum) of the Betic Cordilleras, an area of low relief.
The whole study area is under marls or flysch deposits.

TABLE 2.1 CLIMATIC DATA OF MALAGA, ALORA AND CASARABONELA (After Spaan & Sterk, 1992).

	J	F	M	A	M	J	J	A	S	O	N	D	Year
P (mm)	68.1	57.6	70.6	54.0	30.8	9.6	1.8	4.0	26.8	55.7	69.8	82.3	531.1
ETo (mm)	55.8	67.2	93.0	123.0	163.3	186.0	207.7	189.1	147.0	89.9	60.0	55.8	1438.8
T°C	12.9	12.4	13.7	16.0	18.4	21.7	26.2	26.2	22.4	19.4	14.6	11.6	17.7
Tmax (°C)	22.2	23.0	23.0	24.7	28.9	31.3	35.2	35.9	31.7	29.0	23.4	21.6	-
Tmin (°C)	4.2	4.4	4.4	5.3	6.5	9.2	14.0	15.5	12.5	9.3	6.8	4.9	-

P = mean precipitation.
ETo = mean reference evapotransipiration.
T = mean temperature.
Tmax = mean absolute maximum temperature.
Tmin = mean absolute minimum temperature.

2.5 SOILS

The mediterranean region did not have the Quaternary rejuvenation of soils due to ice ages as found in northern Europe.
Erosion by ice and deposition of young material (Moraines, Cover Sands, Loess) was absent in Andalucia (18). Consequently, there are many soils that are older than the Holocene (more than 1 m.y.b.p.).
The soils of the study area are said to have been derived from Tertiary marls and clays also known as flysch deposits. The flysch was folded and due to erosion, soil texture of surface soils varies. On sandstones remnants of old (red) soil formation are found (2,5). Erosion is said to be faster than soil formation.
The soils are strongly weathered, characterised by low Cation Exchange Capacity (CEC) and low Base Saturation (BS) but, lack marked clay deposition (illuviation) with depth.
According to the USDA soil moisture classification criteria the soil moisture regime is Xeric, that is, mean annual summer and winter soil temperatures differ by 5°C or more at a depth of 50 cm or at a lithic or paralithic contact, whichever is shallower. Five soil orders are prevalent in the study area namely: Entisols, Inceptisols, Alfisols, Ultisols and Vertisols. In this study soils of the first two orders seem to dominate.(20)
Hijmans (1991), places the dominant soils of the study area in the following proportions: Entisols (30%), Inceptisols (26%), Ultisols (14%), Alfisols (14%) and Vertisols (11%).

2.6 NATURAL VEGETATION AND LAND USE

Natural vegetation in terms of spontaneous plant communities is said to be rare in Andalucia. Oak forests have been the natural vegetation of the area but these have degraded to so-called matorral, dense thickets of woody, shrubby plants with evergreen stiff and thick leaves. The mountains sustain pines whereas along rivers elm groves are said to occur.
There are mainly four major land use types in the study area namely; rainfed tree crops, rainfed arable land, irrigated land and rainfed grassland besides natural vegetation (3).
Main crops include: olives, almonds, cereals and citrus. Rainfed tree crops are mainly found on the moderately deep calcareous gravelly loam soils. Rainfed arable cropping and grass lands are on clay soils.

CHAPTER III EROSION MODELLING: THEORY AND CONCEPTS

3.1 EROSION MODELS

A model simulates the effect of an actual or hypothetical set of processes and forecasts one or more possible outcomes (Kirby, 1992). Moore et. al. (1993a) claim there are at least two reasons for developing models:

(i). to assist in the understanding of the system that the model is meant to represent, that is, as a tool for hypothesis testing; and

(ii). to provide a predictive tool for management.

Hillel (1986) as reported by Moore et. al. [9], is said to have identified four principles that should guide model development:

1. Parsimony: "A model should not be any more complex than it needs to be and should include only the smallest number of parameters whose values must be obtained from data";

2. Modesty: "A model should not pretend to do too much", "there is no such thing as **THE** model";

3. Accuracy: "We need not have our model depict a phenomenon much more accurately than our ability to measure it"; and

4. Testability: "A model must be testable" and we need to know "if it is valid or not, and what are the limits of its validity".

However, many models are said to violate these guidelines. It is doubtful whether or not the Revised Universal Soil Loss Equation is an exception to the violation of the above guidelines. Erosion prediction methods are packages of scientific knowledge that effectively transfer technology from the researcher to the user. They are also convenient tools for extrapolating Information where specific field situations have not been studied in research (29). Foster (in Lal, 1988) cites four models for erosion assessment namely, the Universal Soil Loss Equation (USLE), Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS), the Productivity Index (PI) Model and the Erosion Productivity Impact Calculator (EPIC).

De Roo (1993) cites over 33 models inclusive of some of the above for erosion modelling. Amongst these the USLE is seemingly the forerunner. Whatever the case, erosion models are principally classified as either being deterministic or stochastic.
They are further distinguished between conceptual and empirical. Stochastic models are models in which any of the variables included in the model are regarded as random variables having a distribution in probability. If all variables are regarded as free from random variation, the model is deterministic (13).
A model is said to be conceptual if the physical processes acting upon the input variable(s) to produce the output variable(s) are considered in terms of physical laws.
On the other hand, empirical models by strict definition are based on observation and experiment, and not on theory (13).
The approach in this study suggests a kind of deterministic-conceptual model. Suryana et al. (1994, personnal communication) mention of an inductive model which they contrast with a deductive model. This classification of erosion modelling seems to be scale-dependent and does not necessarily supersede the main categories cited in this thesis. Most of the models used in erosion studies are said to be empirical grey-box type (Table 3.1).

TABLE 3.1 TYPES OF EROSION MODELS (After Morgan, 1986).

TYPE	DESCRIPTION
PHYSICAL	Scaled-down hardware models usually built in the laboratory; need to assume dynamic similitude between model and real world.
ANALOGUE	Use of mechanical or electrical system analogous to System under investigation, e.g. flow of electricity to simulate flow of water.
DIGITAL:	Based on use of digital computers to process vast quantities of data.
(a) Physically -based	Based on mathematical equations to describe the processes involved in the model, taking account of the laws of conservation of mass and energy.
(b) Stochastic	Based on generating synthetic sequences of data from the stastistical characteristics of existing sample data, useful for generating input sequences to physically-based and empirical models where data is available for a short period of observation.
(c) Empirical	Based on identifying statistically significant relationships between assumed important variables where a reasonable database exists. Three types of analysis are recognised: **black-box:** where only main inputs and outputs are studied; **grey-box:** where some detail of how the system works is known; **white-box:** where all details of how the system operates are known.

Casasnovas (1994) states that erosion modelling strategies can be grouped into erosion hazard mapping and erosion feature-and-degree mapping.

The erosion hazard maps show the expected rates of soil loss in the near future by means of qualitative or quantitative classes through prediction models such as the USLE. The erosion feature and degree mapping is for showing erosion features (sheet, rill, gully, mass movements) and their activity or stability and degree of development.
In the latter case the landscape is classified into units having similar intensity or frequency of a particular combination of erosion features. Casasnovas distinguishes soil erosion modelling within the two approaches.
The Revised Universal Soil Loss Equation applied in this study ascribes to the first approach. The erosion feature approach seems to be an approach advocated at coarser scales of mapping and is said to be highly subjective.
Annex 2 gives a number of major erosion models and hydrological distributed cathment models.

3.2 SOIL EROSION: THEORY AND CONCEPTS

There is no strict differentiation between what is called a soil erosion model and the theory or concept of soil erosion in literature. However, theory should be seen here as to mean the processes that are postulated or thought to operate regarding soil erosion. In this sense, a model does not precede theory but, is rather a consequence of theory. On the other hand, a model embodies a theory hence perhaps the interchangeable use of the two terms in literature. It is not the intention of this study to improve on these definitions.

3.2.1 Definition of Soil Erosion

Loosely, soil erosion can be defined as loss of topsoil, in particular, from agricultural fields. Moore (1975) defines soil erosion as the wearing away and loss of topsoil mainly by action of rain and wind.
A comprehensive definition is given by Morgan (1986) who defines soil erosion as a two-phase process consisting of the detachment of individual particles from the soil mass and their transport by erosive agents such as running water or wind. When sufficient energy is no longer available to transport the particles, a third phase, deposition is said to occur.
Rose et. al. (1983) present these processes as in Fig. 3.1.

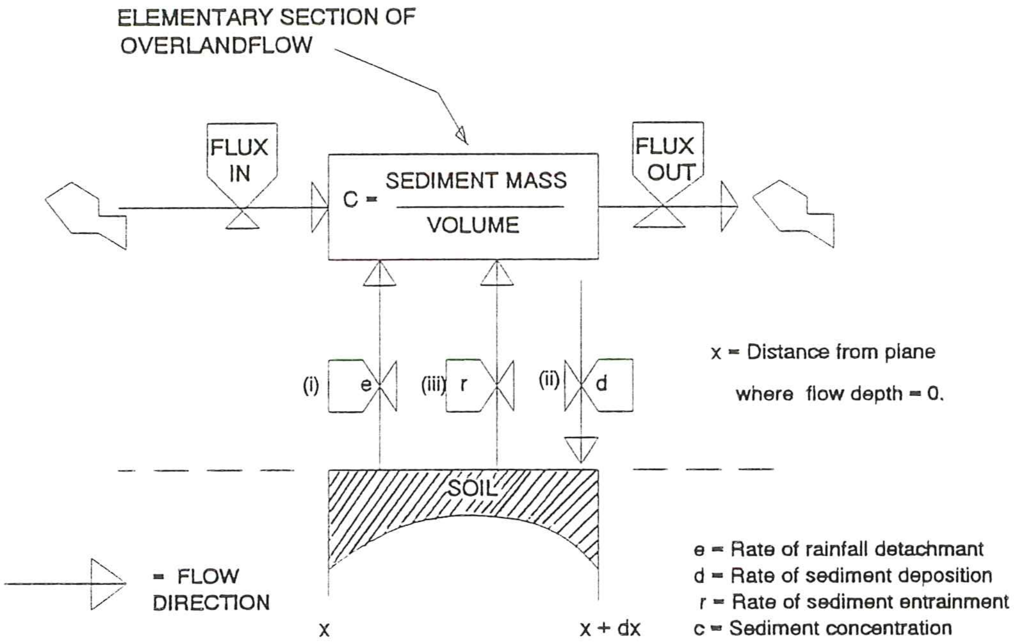


FIG. 3.1 EROSION AND DEPOSITION PROCESSES

Processes (i) and (ii) are said to increase sediment concentration, whereas process (iii) decreases sediment concentration. All the three processes can occur simultaneously at different rates as denoted by e, d, and r above. Flux-in and flux-out refer to sediment volume of overland flow parallel to the soil surface.

3.2.2 Soil Erosion Theories and Concepts

Moore and Wilson (1992) mention three theories that present the "State-of-the-art" in erosion studies:

(i) Water Erosion Prediction Project Theory;
(ii) Hairsine-Rose Theory; and
(iii) Catchment Evolution Theory.

These theories are further categorized into models namely, physically-based (or process-oriented) models, dynamic models and steady-state models. The three theories are briefly discussed here. The RUSLE used in this study is based on these theories (17).

3.2.2.1 The Water Erosion Prediction Project (WEPP) Theory

This theory is said to be process based and is intended to replace the Universal Soil Loss Equation (USLE) this year (1995). The concept divides erosion into an interrill component that represents detachment and transport by raindrops and a very shallow flow, and a rill component representing net erosion or deposition in rills. Rill detachment is modelled as a function of so-called excess hydraulic shear. The theory is compressed into a steady-state sediment continuity equation for a rill given as:

$$\delta q_s/\delta_s = D_f + D_i$$

Where q_s is the sediment flux ($kgm^{-1}s^{-1}$);

D_i is interrill sediment delivery rate to the rill ($Kgm^{-2}s^{-1}$);

D_f is the net erosion or deposition rate in the rill ($Kgm^{-2}s^{-1}$).

The effects of shallow flow hydraulics on delivering sediment to the rills are lumped with the rainfall kinetic energy and adjusted by the expression:

$$D_i = K_i I_e^2 CgCcSf\ (Rs/W).$$

Where K_i = interrill erodibility ($KgSM^{-4}$);

I_e = effective rainfall;

Cg = ground cover factor;

Cc = canopy cover factor;

Sf = slope factor ($= 1.05 - 0.85e^{4 \sin a}$); e = $\log_e$ and a is the slope of the land surface towards the rill;

Rs = spacing between rills (m per rill); and

W = rill width (m).

The net erosion or deposition rate in the rill (Df) is given by:

$$Df = \phi(T_c - q_s).$$

Where T_c = sediment transport capacity in the rill ($Kgm^{-1}s^{-1}$);
ϕ = ßVs/q for net deposition in the rills (i.e. when $T_c < q_s$) or
ϕ = D_c / T_c for net soil detachment in the rills (i.e. when $T_c > q_s$);
q = water flux ($Kgm^{-1}s^{-1}$);
Vs = sediment settling velocity (ms^{-1});

Dc = detachment capacity of rill flow ($Kgm^{-2}s^{-1}$); and

ß = 0.5 for rainfall conditions (1.0 for snow melt conditions).

Df is positive when there is net erosion and negative when there is net deposition. The detachment capacity of rill flow is expressed as:

$$Dc = Kr\tau \ (1-\tau_0/\tau) \text{ for } \tau > \tau_0 \text{ and } Dc = 0 \text{ for } \tau < \tau_0.$$

Where τ = flow shear stress acting on the soil particles;
τ_0 = threshold shear stress; and
Kr = rill erodibility parameter (sm^{-1}).

The sediment transport capacity is represented by an approximation of the so-called Yalin sediment transport equation given by:

$$Tc = K_t\tau^{3/2}.$$

Where Tc is the transport coefficient ($m^{1/2}s^2Kg^{-1/2}$). Water Erosion Prediction Project (WEPP) performs its internal calculations on per rill area basis (17).

3.2.2.2 Hairsine-Rose Theory

This is equally a process-based model recognizing raindrop impact and surface flow as main causes of erosion of surface soils. The theory treats rainfall detachment, entrainment (detachment by overland flow), rainfall re-detachment and re-entrainment of deposited sediment and deposition as separate processes (23). The model is represented by a so-called one-dimensional sediment continuity equation given by:

$$\delta q_{si} + \delta (C_i h) \delta S \delta L = r_i + r_{di} + e_i + e_{di} + r_{gi} - di$$

Where q_{si} (= qCi) is sediment flux ($Kgm^{-1}s^{-1}$) in the direction of flow (s);

q = water flux (i.e. specific discharge);

C_i = sediment concentration Kgm^{-3};

h = depth of overland flow (m);

r_i = rainfall detachment;

r_{di} = rainfall re-detachment;

e_i = rainfall entrainment;

e_{di} = rainfall re-entrainment; and

di = deposition.

In each case **i** refers to each of **n** sediment settling velocity classes, each class having an equal mass of soil.

3.2.2.3 Catchment Evolution Theory

This theory differentiates between the sediment transport behaviour in channels and on hillslopes through a coupled flow and sediment continuity equation. Channel initiation is modelled as a threshold process that has no linear relationship to both slope and discharge.
The governing sediment continuity equation and the so-called channel indicator function are highly complex and certainly beyond the scope of this thesis. Interested readers are referred to the cited literature.

3.3 TOPOGRAPHIC INDICES

The main model in this study is said to account for both zones of net erosion and zones of net deposition but rather implicitly through the slope-Length factor.
In order to account for deposition and erosion processes explicitly, a topographic index, "sediment transport capacity index", is used in this study. Moore et.al. (1993b) give three indices for characterising the terrain namely, the wetness index (**W**), the stream power index (λ) and the sediment transport capacity (τ). All three can be calculated using the slope (ß) and the so-called flow accumulation or "specific catchment area" (**As**). These indices can be derived from Digital Elevation Models (DEMs). The stream power index is a measure of erosive power of the overland flow. The wetness index characterises spatial distribution zones of surface saturation and soil water content. In this study, only the sediment transport capacity is determined since it characterises erosion and deposition processes.
The sediment transport capacity is analogous to the **LS**-factor in the Revised Universal Soil Loss Equation (RUSLE) and applicable to three-dimension landscapes (10). The three terrain characteristics are given by the following equations:

Wetness index (W) = $Ln\ (A_s/\tan ß)$;

Stream power index (Ω) = $A_s Tanß$; and

Sediment transport capacity index:

$$(\tau) = (A_s/22.13)^m (Sinß/0.0896)^n.$$

Where **As** = specific catchment area ($m^{-2}m^{-1}$);
ß = slope angle in degrees; and
m = 0.6 and n = 1.3.
The assumption in these equations is that A_s is directly proportional to **q** (discharge per unit width), and that steady-state conditions prevail (17,22).

3.4 EROSION MODELLING AND GEOGRAPHICAL INFORMATION SYSTEMS

Literature separates Geographical Information Systems and soil erosion.

In other words, the two are their own disciplines.
It is clear from literature that where both are being discussed keywords are: **linking**, **using** and **applying** for example, "linking the Universal Soil Loss Equation to a Geographical Information System".

It is unlikely that one may find a GIS purely designed for handling erosion modelling, this does not of course preclude the possibilities. At least the author's literature search did not reveal one such Geographical Information System. It is perhaps prudent to first define what is meant by Geographical Information Systems (GIS) since soil erosion has been defined earlier on. There is consensus in literature about the definition of Geographical Information Systems. Taken in the broadest sense, a Geographical Information System is any manual or computer based set of procedures used to store, and manipulate geographically referenced data (25). A somewhat comprehensive definition is given by the National Center for Geographic Information Analysis (30) which defines GIS as "a computer database management system for capture, storage, retrieval, analysis and display of spatial (logically defined) data." Others define GIS as a spatial Information System. A spatial information system is an information system that integrates and displays thematic and spatial (geometric, topological) data.

Erosion being a spatial related phenomenon, Geographical Information Systems are said to provide the technology to store and manipulate the spatial relational data demanded by erosion models.

According to Burrough (1986), Geographical Information Systems are the result of linking parallel developments in many separate spatial data processing disciplines (Fig. 3.2).

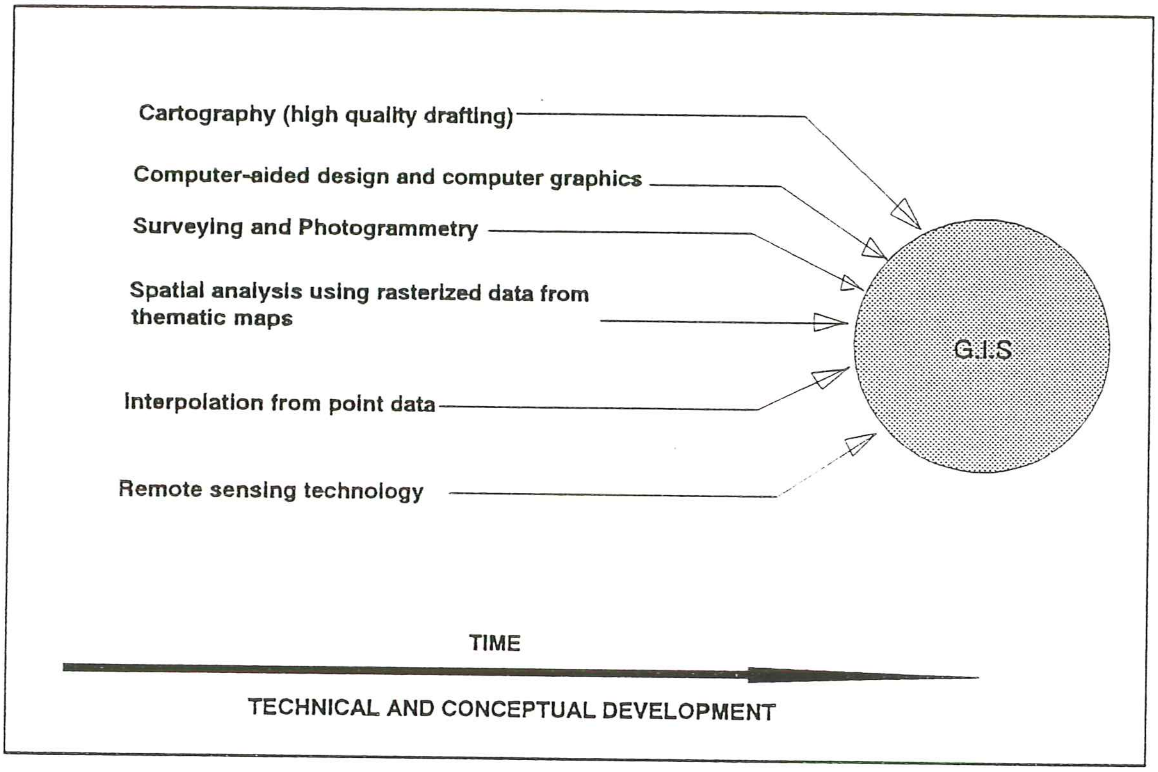


FIG. 3.2 GEOGRAPHICAL INFORMATION SYSTEMS AS THE RESULT OF LINKING PARALLEL DEVELOPMENTS IN SEPARATE SPATIAL DATA PROCESSING DISCIPLINES.

It is clear in literature that erosion modelling should be based on terrain features. These are objects representing the real world and are called spatial entities.

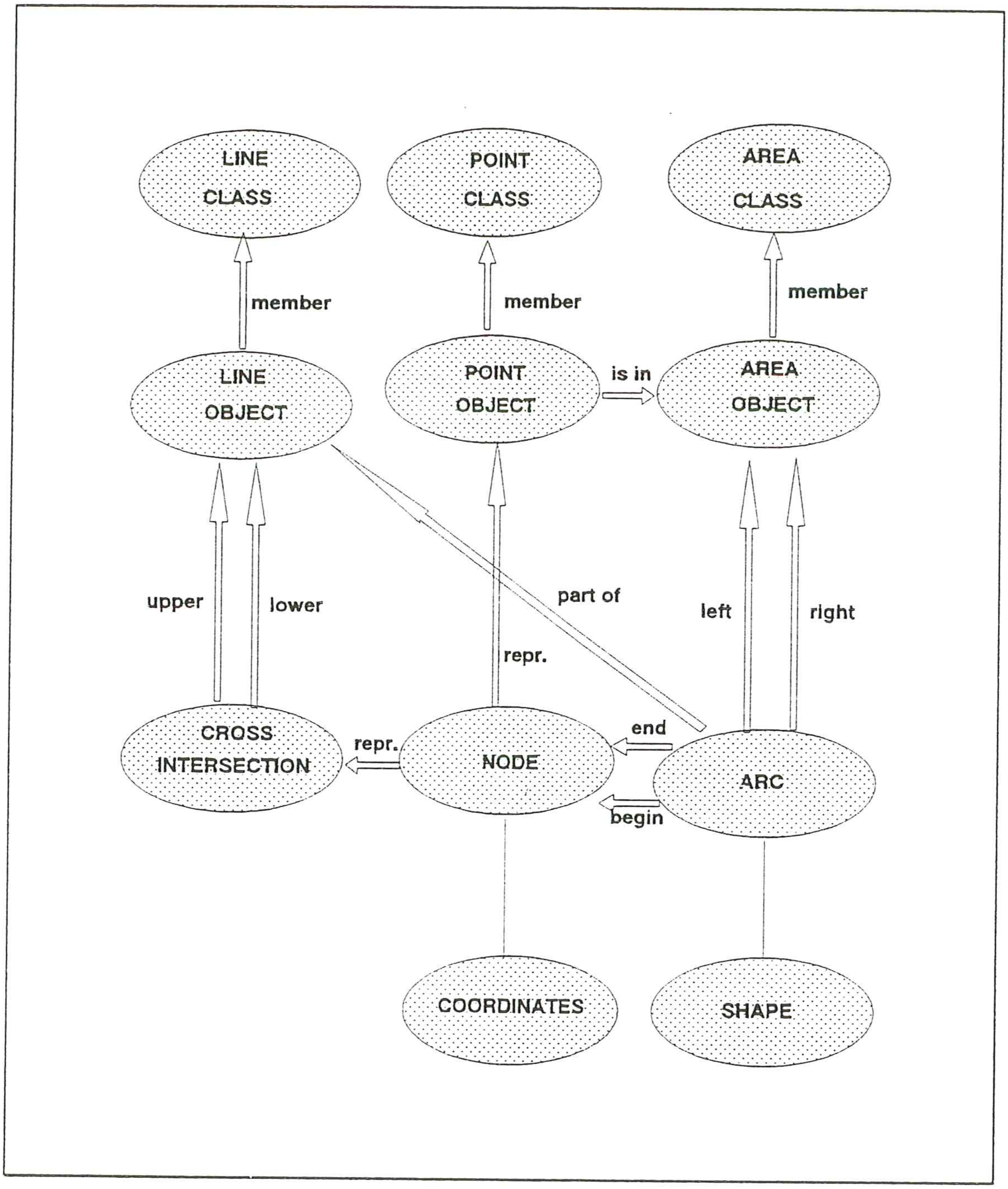
According to Molenaar (1991), three feature types can be distinguished in case of two-dimensional terrain descriptions: area features, line features and point features.

However, computers need to be instructed on how exactly spatial patterns should be handled and displayed (32). This is the concern of so-called data structures, for example, Molenaar's Formal Data Structure (FDS) for single-valued vector maps (Fig. 3.3) or so-called topologic data models.

Burrough further distinguishes two representations of terrain features in a computer namely, explicit and implicit representations.

He defines explicit representations as representations of features by a set of points on a grid or raster, and implicit representations as representations of features by a set of lines defined by starting and end points, and some form of connectivity (vectors).

Both representations are used in this study.
The explicit presentations are derived from the implicit representations through the grid module of ARC/INFO. The latter seems typical of Molenaar's Formal data Structure (Fig. 3.3). Erosion studies largely concern line and area objects (features) which are aggregated and generalized from one scale of mapping (resolution) to another.



repr. = represents

FIG. 3.3 FORMAL DATA STRUCTURE (FDS) FOR SINGLE-VALUED VECTOR MAP (After Molenaar, 1991); (IMPLICIT REPRESENTATION OF TERRAIN FEATURES).

Van Oosterom (1993) presents geographical data types in a hierarchy (Fig. 3.4). According to this hierarchy the distinction of raster and vector data is the concern of spatial geometric representations.

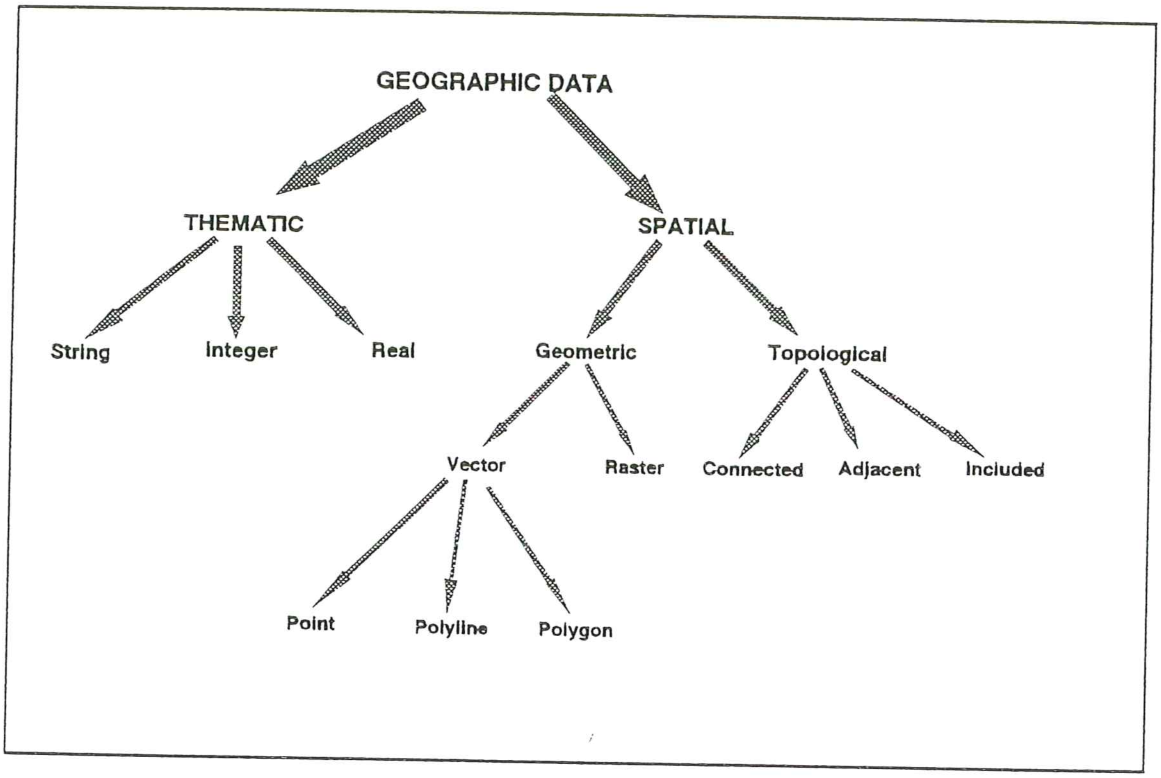


FIG. 3.4 THE HIERARCHY OF GEOGRAPHICAL DATA TYPES

It can be argued, however, that GIS does not generate new scientific knowledge of the domain we are modelling.
In other words, we will not understand soil erosion processes by merely linking soil erosion models to Geographical Information Systems. The advantages of applying GIS are obvious and, amongst others they include:

(i). dissemination of expertise in an efficient way;

(ii). assisting in organizing and synthesizing knowledge and information; and

(iii). provision of a framework with which to capture and store spatial data.

3.5 DIGITAL ELEVATION MODELS (DEMs)

According to Moore et. al. (1993b), and Zevenbergen & Thorne (1987), it is possible to calculate a number of topographic attributes by applying a second-order, finite-difference scheme centred on the interior node of a moving 3 X 3 square-grid network (Fig. 3.5a & 3.5b) using Digital Elevation Models.

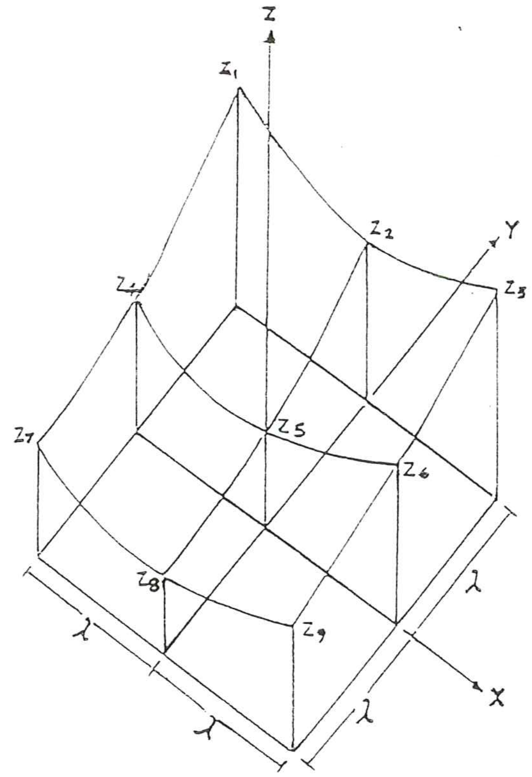


FIG. 3.5a 3 x 3 ALTITUDE SUBMATRIX

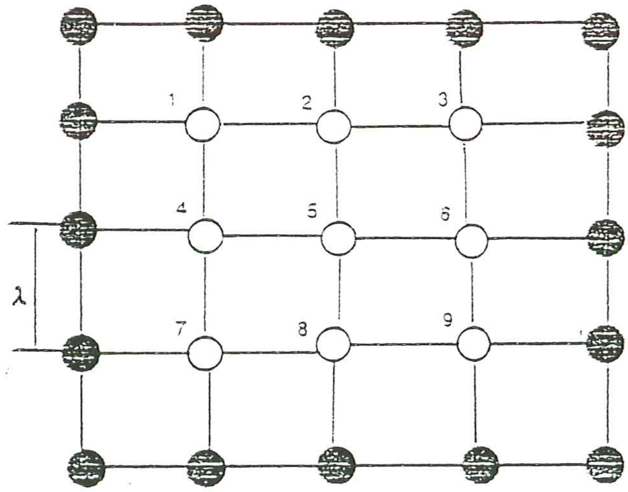


FIG. 3.5b 3 X 3 GRID-SUBMATRIX

The grid-spacing of this network is λ (Fig.3.5a and 3.5b). By simplification Moore et. al. derived the following equations:

$f_x = \delta z/\delta x$; $f_y = \delta z/\delta y$; $f_{xx} = \delta^2 z/\delta x_2$; $f_{yy} = \delta^2 z/\delta y^2$;

$f_{xy} = \delta^2 z/\delta x \delta y$ eqn [1]; and

$P = f_x^2 + f_y^2$, $q = P + 1$ eqn [2].

Zs are elevations of the models (Fig. 3.5a); then the central finite-difference forms of the partial derivates for the central node, node **5** are computed as follows:

$$f_x = \frac{Z_6 - Z_4}{2\lambda};\quad f_y = \frac{Z_2 - Z_8}{2\lambda};\quad f_{xy} = \frac{-Z_1 + Z_3 + Z_7 - Z_9}{4\lambda^2};$$

$$f_{xx} = \frac{Z_4 + Z_6 - 2Z_5}{\lambda^2};\quad f_{yy} = \frac{Z_2 + Z_8 - 2Z_5}{\lambda^2}. \qquad \text{eqn [3].}$$

The maximum slope, ß (degrees), aspect, ψ (measured in degrees clockwise from the north), and profile curvature (m^{-1}) of the mid-point in the moving grid are calculated using the following relationships:

$$ß = \arctan (P^{0.5}).$$

$\psi = 180 - \arctan (f_y/f_x) + 90 (f_x / |f_x|)$ and profile curvature

$$(\omega) = \frac{f_{xx}\mathrm{Cos}^2\phi + 2f_{xy}\mathrm{Cos}\phi\mathrm{Sin}\phi + f_{yy}\mathrm{Sin}^2\phi}{q^{0.5}\mathrm{Cos}V} \qquad \text{eqn [4].}$$

Where **V** is the angle between the normal to the surface and the section plane and ϕ is the angle between the tanget of the given normal section and the X-axes. Profile curvature is a measure of water flow and sediment transport processes where as plan curvature is a measure of convergence or divergence, and hence the concentration of water in the landscape. For profile curvature (ω):

$$\mathrm{Cos}V = 1,\ \mathrm{Cos}\phi = f_x / (pq)^{1/2} \text{ and}$$

$$\mathrm{Sin}\phi = f_y/(pq)^{1/2}.$$

so that $\omega = \dfrac{f_{xx}f_x^2 + 2f_{xy}f_xf_y + f_{yy}f_x^2}{pq^{3/2}}$ eqn [5].

Similarly, Zevenbergen and Thorne (1987) present what they call an appropriate surface presented by a partial quartic equation (Fig. 3.5a) given by:

$$Z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I \quad \text{eqn [6]}.$$

Where A to I are nine parameters determined from the nine elevations of the 3 X 3 submatrix by lagrange polynomials.
If the surface of the nine submatrix elevations is of the lower order than equation 6, the appropriate coefficients are said to be equal to zero. However for a quadratic surface the coefficients A, B and C will be equal to zero and if the surface is plain A to F coefficients are equal to zero (31). Accuracy of representing a surface by equation 6 depends on the size of the so-called grid mesh distance.

The nine parameters are given as follows:

$$A = [(Z_1 + Z_3 + Z_7 + Z_9)/4 - (Z_2 + Z_4 + Z_6 + Z_8)/2 + Z_5]/\lambda^4 ;$$

$$B = [(Z_1 + Z_3 + Z_7 + Z_9)/4 - (Z2 - Z8)/2]/\lambda^3;$$

$$C = [(-Z_1 + Z_3 - Z_7 + Z_9)/4 + (Z_4 - Z_6)/2]/\lambda^3;$$

$$D = [(Z_4 + Z_6)/2 - Z_5]/\lambda^2;$$

$$E = [(Z_2 + Z_8)/2 - Z_5]/\lambda^2;$$

$$F = (-Z_1 + Z_3 + Z_7 - Z_9)/4\lambda^2;$$

$$G = (-Z_4 + Z_6)/2\lambda;$$

$$H = (Z_2 - Z_8)/2\lambda; \text{ and}$$

$$I = Z_5.$$

Z_1 to Z_9 are the nine submatrix elevations numbered systematically as shown in figure 3.5a. Z_5 is the centre point such that $x = y = 0$ and λ is the distance between matrix points in the row and column directions and must be in the same units as Z.
The topographic indices are calculated by differentiating equation 6 and solving the resulting equation for the central point of the 3 X 3 submatrix (x=y=0).
The slope is the first derivative of Z with respect to S where S is the aspect direction (θ); and

$$\text{slope} = \delta Z/\delta S = G \cos\theta + H \sin\theta \quad [7].$$

Since, at the origin $\cos\theta$ is equal to $-G/(G2 + H2)^{1/2}$ an $\sin\theta$ is equal to $-H/(G2 + H2)^{1/2}$, slope is given by $-(G2 + H2^{1/2}$.
The negative sign indicates that the direction, θ, is downslope and is by convention ignored (31). The maximum slope direction or aspect is found by differentiating equation 7 to find its minimum so that:

$\delta Slope/ \delta\theta = -G\sin\theta + H\cos\theta = 0$; or

$\theta = \arctan(-H/-G)$.

The curvature for any direction is the second derivative of Z with respect to S, and is given by:

$$\omega = \delta^2 Z/\delta S^2 = 2(D\cos^2\Phi + E\sin^2\Phi + F\cos\Phi\sin\Phi).$$

The two directions of meaningful curvature are in the direction of slope ($\Phi = \theta$), giving profile curvature, and transverse to the slope ($\Phi = \theta + \pi/2$), giving planform curvature.
The use of grid-based DEMs to derive these terrain parameters makes GIS a versatile tool for modelling and assessing erosion.

CHAPTER IV: MATERIALS AND METHODS

4.1 FIELD MATERIALS AND METHODS

Prior to the fieldwork, photo-interpretation of the study area primarily to delineate major and minor landscape units and facets was done on the 1 : 25 000 and the 1 : 5 000 aerial photographs respectively with a Topcon stereoscope. The photographs were used as basemaps in the field to characterise and describe the land units that were distinguished during the photo-interpretation phase. Soil and site data were collected along a catena (toposequence) covering a sample area of nearly 20 hectares. Soil samples of the A-Horizon's upper 15 cm were collected at 42 observation points using more or less a rigid grid of 20 X 20m for laboratory analyses. At each site slope length and steepness were estimated and recorded. The slope length was noted mostly by visual interpretation whereas slope steepness was recorded using an Abney Level. The majority of site attributes were by visual interpretation.
For the whole sub-catchment area a total of 150 observations including those of previous studies were available in this study. However, only the 42 observations are used for interpolation as they constituted complete data sets for model input variables.

4.2 LABORATORY METHODS

Laboratory analyses were done by the Department of Soil Science and Geology of Wageningen Agricultural University. Here only analyses of immediate interest to this study are mentioned, for full procedural explanations refer to van Reeuwijk (1993).

4.2.1 Parcticle size analysis

The samples were pretreated to remove organic matter by hydrogen peroxide (H_2O_2) and carbonates by a midly acid buffer of P^H 5. A shaking process with a dispersing agent ("Calgon "-type) followed to separate sand from the silt and clay with a 50 micron sieve. The sand was further fractionated by dry-sieving. The silt and clay fractions were determined by the so-called pipette method.

4.2.2 Soil moisture content

Determination of moisture content was done prior to particle size analysis on the basis of oven dry weight (at 105°C) and multiplied by a moisture correction factor. The moisture correction is given by:

$$\frac{100 + \%\ \text{moisture}}{100}.$$

4.2.3 Oragnic carbon

Organic carbon was determined by the Wakley-Black method through oxidation of a mixture of potassium dichromate and sulphuric acid without external heating.

4.2.4 Carbonates

Carbonate content was determined by the piper method using an excess of hydrochloric acid to dissolve the carbonate.
This is said to dissolve both the calcite and other carbonates and the result is also known as the calcium carbonate equivalent.

4.3 STATISTICAL METHODS

The variables for the model determined at each observation point were first scaled to distinguish nominal and ordinal data from interval and ratio scale data. Ordinal and nominal data are usually concerned with qualitative analysis. The discrimination of the data in this way permits the proper use of so-called summary statistics. According to Bregt et.al. (1992) for example, for spatial interpolation of point data most techniques such as kriging, splines, trend surface analysis, fourier models and distance weighting methods can only be used with interval and ratio data whereas spatial interpolation with Thiessen polygons can be applied to nominal and ordinal data. The data was then summarised statistically using the SPSS version 5.0 program.
This formed part of the basis for generalization and aggregation procedures. In this study 30 variables were either on the nominal or ordinal scale and only 15 were on interval or ratio scale. Table 4.1 is the distribution of model variables in this study across the four measurement scales.

Table 4.1 DISTRIBUTION OF VARIABLES ACROSS MEASUREMENT SCALES.

Measurement scale	Variable
Nominal	parent material, slope form, crest form, horizon symbol, structure type, morphographic name.
Ordinal	moisture condition, drainage, gravel, stones, boulders, rock, crust, cracks, sheet erosion, rill erosion, gullies, land use code, hue dry, value dry, chroma dry, chroma moist, hue moist, value moist, texture, structure grade, structure class, HCL reaction.
Interval	depth, % gravel, % stones, % mottles, % slope, slope length, %sand, % silt, % organic matter permeability, erodibility, erosivity, Carbonate content.
Ratio	none

4.4 MODEL INPUT DATA

Input data into the models is distinguished between primary and secondary data as shown in Table 4.2 below.

Table 4.2 MODEL INPUT DATA CATEGORIES

Physical System	Primary data	Secondary data
Soil	texture, structure, drainage, organic matter, % sand, % silt, % clay, % very fine sand, carbonate content, % gravel, % stones, depth, colour, A-Horizon properties.	erodibility
Terrain	crop factor, practice factor, slope , slope length, elevation.	slope form, DEM, slope aspect, stream power index, wetness index, sediment transport capacity.
Climate	rainfall amount	runoff, peak discharge, erosivity.

4.4.1 DERIVATION OF VARIABLES FOR THE REVISED UNIVERSAL SOIL LOSS EQUATION (RUSLE) MODEL.

The variables in the RUSLE are given by the equation **A = RKLSCP** where:

R = the rainfall erosivity;
K = soil erodibility;
L = slope length;
S = slope steepness;
C = crop factor;
P = practice factor.

4.4.1.1 The rainfall factor (R)

The rainfall factor in this study is derived using so-called pluviograms (Annex 3a and 3b) of 3 February and 5 October 1972 and empirical relations to derive R.
The pluviograms are for determining total kinetic energy and the 30 minute energy intensity index (EI_{30} or I_{30}) tables 4.3a and 4.3b (after Coenders et. al., 1994).
The average annual R factor is given in table 4.3c. Rainfall kinetic energy is given by :

$$E = 11.87 + 8.73 \log_{10} I \quad (3,33).$$

Table 4.3a Total Kinetic Energy of 24-hours Precipitation of 3 February and 5 October 1972.

Duration (hours).	Rainfall (mm).	Intensity (mm/h)	E (J / m^2.mm)	E (J /m^2).
1.9	12.6	6.6	19.0	239
1.4	10.0	7.1	19.3	193
0.3	0.2	0.7	10.5	2
0.2	0.1	0.5	9.3	1
0.3	0.3	1.0	11.9	4
		Σ E (J / m^2) 3 February 1972		439
Duration (hours).	**Rainfall (mm).**	**Intensity (mm/h)**	**E (J / m^2.mm)**	**E (J /m^2).**
0.3	3.7	12.0	21.3	79
0.1	0.2	2.0	0.3	0
0.4	1.0	2.5	15.4	15.4
1.6	13.8	8.6	20.1	277
0.7	0.9	1.2	12.6	1.3
0.1	1.0	10.0	20.6	20.6
1.2	3.9	3.3	17.1	21
		Σ E (J / m^2) 5 October 1972.		425

Table 4.3b Total EI_{30} of 3 February and 5 October 1972.

Duration (hrs)	Rainfall (mm).	I_{30} (mm / h).	E (J /m^2.mm)	(J / m^2)
3.8	19.6	11.7	18.2	356.7
			Σ EI_{30} 5 October 1972	8347
Duration (hrs)	Rainfall (mm).	I_{30} (mm / h).	E (J /m^2.mm)	(J / m^2)
1.9	12.6	8.0	19.0	239.4
			Σ EI_{30} 3 February 1972	1915

Table 4.3c Average Annual Rainfall Factor R in Alora (3).

METHOD	P_a	P_{24h}	P_{1h}	P_{6h}	R
$R = 1.11*10^{-3}*P_a*P_{24h}*P_{1h} + 660$	510.2	58.1	24.2		1429
$R = 0.373*P_{6h}^{2.2}$				39.9	1243

The first method is used for calculating the R factor as it is the approximate estimator for sub-humid and semi-arid enviroments.

4.4.1.2 Soil erodibility factor (K)

The soil erodibility factor was calculated for each observation point using Wischmeier and Smith's nomograph (Annex 4) and the equation:

$$100K = 2.242\ [(2.1M^{1.14} * 10^{-4}\ (12 - a) + 3.25(b - 2) + 2.5\ (p - 3)].$$

where M = (% silt + % very fine sand)* (100 - % clay);
a = % Organic matter (2*OC);
b = soil structure code (Annex 4);
p = soil permeability class (Annex 4).

Soils of the study area have coarse fragments both on the soil surface and in the soil profile (*Plate 1*)
The K factor was corrected for coarse fragments on the soil surface by a correction factor (F) derived from the equation:

$$F = 1.026 - 0.025 * Coar + 2.534 * 10^{-4}\ Coar^2 - 1.026 * 10^{-6} Coar^3$$

Where F = the correction factor to be multiplied with the K above.
Coar = the maximum of coarse fragments in the A-horizon or % surface covered with stones or rock (14).

4.4.1.3 The Slope Length and Slope Factor (LS)

Slope length was determined from the equation: $L = (\lambda/22.13)^m$ (Eppink, 23, 56).
Where L = slope length;
λ = field determined slope length (m);
m = is a variable exponent according to Wischmeier and Smith (1978) and is determined as follows:
m = 0.3 for slopes ranging from 1-3 %;
m = 0.4 for slopes < 3-5 %;
m = 0.5 for slopes > 5 %.

The slope gradient was determined by the formula:

$$S = 0.0065*s^2 + 0.04554*s + 0.065\ (37).$$

Where s = slope gradient in % for slopes of between 2 and 20 % and for steeper slopes $S = (s/9)^{1.35}$.

In this study values derived from the DEM are also used.

4.4.1.4 The Crop Factor (C)

The crop factor is determined by the relation of soil loss on bare soil and the soil loss on the specific soil type with a given cover which varies with climatic conditions. In the study area citrus, wheat (*Plate 2*), sunflower, olives and almonds (*Plate 3*) are the principle crops.
The average annaul C-factors for some of these crops are given in Table 4.4 (3).

Table 4.4 Average annual C-Factors of principle crops in Alora

Crop	Olives	Almonds	Sunflower	Wheat
C-Factor	0.90	0.90*	0.47	0.46

* Estimated value.
The C-factor varies with crop growth stage.

4.4.1.5 The Practice or Management Factor (P)

This factor has been estimated to be around 0.80 in the study area and has been treated as a constant as it is not well documented.
This factor is a cropping support factor showing effects of practices on soil conservation. The practices include improved tillage such as contour tillage, terracing and strip cropping. According to Wischmeier and Smith (1978), P values are as given in Table 4.5.

Table 4.5 P-Factors for some selected Practices.

slope %	contouring or terracing	strip cropping
1-2	0.60	0.30
3-8	0.50	0.25
9-12	0.60	0.30
13-16	0.70	0.35
17-20	0.80	0.40
21-25	0.90	0.45

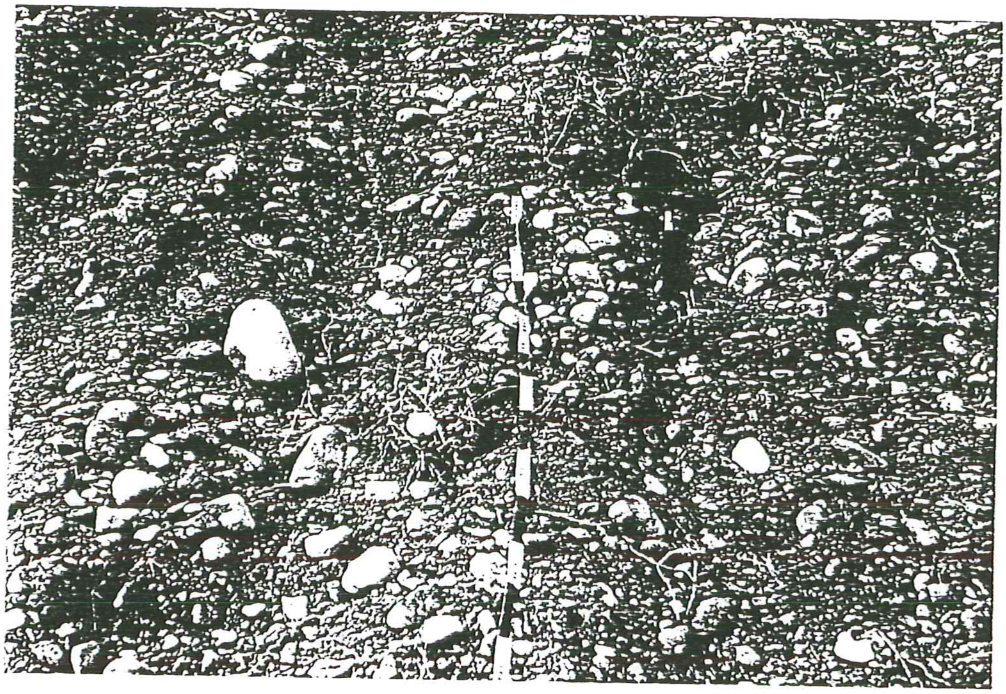


PLATE 1: Stones on soil surface (vicinity of observation no. 219)

PLATE 2: Wheat on an erosion glacis

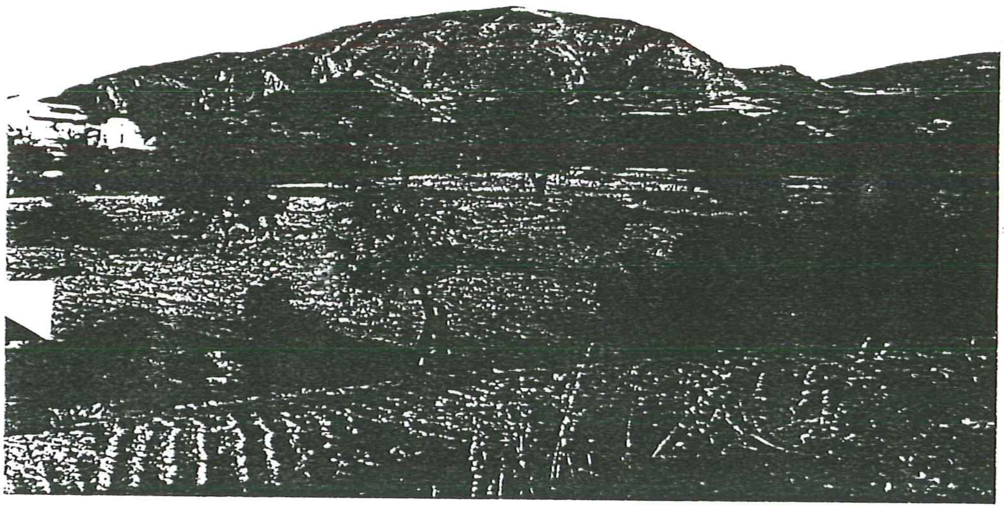


PLATE 3: *Olives and Almonds (on an old river terrace remnant)*

4.5 SEDIMENT TRANSPORT CAPACITY INDEX (τ)

Sediment transport capacity index is given by:

$$\tau = (As/22.13)^m (\sin\beta/0.0896)^n$$

The variables in the model are **As** and **ß**. The slope (in degrees) is calculated at each observation point using the grid module of ARC/INFO by gridding a point coverage and assigning the slope in degrees.
The specific catchment area is treated as the square of the cell size λ (Fig 3.5b and 3.5b, Chapter 3). The values **m** and **n** are 0.6 and 1.3 respectively.

4.6 AGGREGATION AND GENERALIZATION STRATEGIES

The author proposes use of some concepts of spatial mapping for aggregation strategies advocated by Forbes et. al. (1981) at Cornell University in the United States. These include **Map scale, Minimum Legible Area , Average Size Delineation (ASD)** and the **Index of Maximum Reduction (IMR).**
The minimum legible area(in **ha**), here abbreviated as **MLA** at any given scale is given by:

$$(1/RF)^2 \,/\, 2.5 * 10^8$$

Where RF is the scale number. The MLA is said to be the smallest area that can be represented on a map at a given scale of mapping. The ASD is defined as the arithmatic mean of the sizes of the delineations in a portion of map measured in cm^2 of map sheet.
The Index of Maximum reduction is a factor by which the scale of a map can be reduced before the ASD would be equal to the MLA, that is, before more than one half of the map would become illegible and is computed as the square root of the ratio of the ASD to the MLA (0.4cm^2) by the formula:

$$IMR = \sqrt{(2.5*ASD)}.$$

An IMR of 2.0 is said to be optimal, that is, ASD = 1.6 cm^2. A delineation size of 1.6 cm^2 is referred to as an optimum legible delineation. The concepts are presented in annex 5. The optimum legible delineation size is scale independent.
These indices should permit proper decisions on aggregation of spatial (area features) units as we progress from fine scales to the coarser ones.
This process yields what we may call "aggregate-units".

Agregating for example, facets to a specific landscape unit can easily be resolved using these criteria on condition that full neighbourhood relationships exist at the immediate lower scale before aggregating, otherwise, thematic and/or heuristic criteria takes precendence.
The lumping and generalization of point data is entirely statistically achieved using interpolation methods in-built in ARC/INFO by stratifying terrain units according to morphographic names, in each case treating terrain units as discrete entities (non-fuzzy objects).
There is implicit generalization in the aggregation process. In order to define fairly homogenous terrain units the author proposes use of statistically significant terrain and soil parameters as thematic definers of the resulting "aggregate-terrain units."
For variables that are neither on the interval or ratio scales the use of semi-variograms or so-called **spatial difference probability functions** are ideal (18). However, these have not be used in this study. Instead so-called summary statistics have been preferred to rationalize aggregation and generalization.
The concepts of Forbes et. al. seem identical to Turner et. al.(1989)'s concepts of **diversity, dominance** and **contagion** in characterising landscape patterns.

CHAPTER V: DATABASE DESIGN AND IMPLEMENTATION

5.1 INTRODUCTION

Database design is concerned with the logical structure of the database (6). The process of designing a database can be divided into two phases: logical design and physical design. Logical design is the integration of all application requirements in a database structure that supports the views and processing needs of the applications. Physical design refers to the evaluation of alternative implementations and choosing storage structures, query mechanisms and access methods Navathe & Schkolnick, (1978).
According to Date (1990), database design has three levels: external, conceptual and internal. These levels are defined as follows:

(i). **external level:**
the way the data is viewed by individuals;

(ii). **conceptual level:**
representation of the entire information content of the database in structures which show how data is logically stored in a computer.

(iii). **internal level:**
the way the data is physically stored in a computer.

The three levels are indetical to Molenaar's spatial and conceptual data modelling, logical data modelling and physical data modelling respectively. Purely from a thematic point of view, Bowman et. al.(6), define database design as deciding on the tables that should belong to the database and the columns that should belong to each table. According to Elmasri and Navathe (1989) the processes in database design are typical of figure 5.1.
Implementation of the database is obviously, how the database is finally realised.
Geographical information describes phenomena on the landscape that are related by their spatial location and some intrinsic attributes that distinguish them from their surroundings. Digital (or numeric) representations of these phenomena are stored in computers sequentially and are related by their location in the computer's "memory".
To reduce geographic information to digital representations that are understandable by computers, it is necessary to impose some form of locational referencing system, often referred to as **data structures** (ESRI,1991).

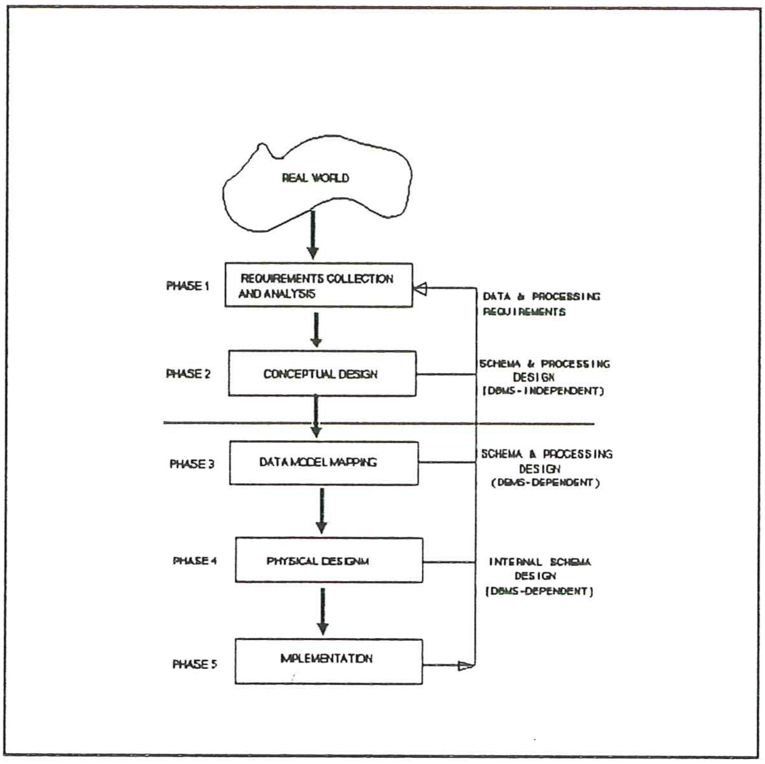


FIG 5.1 DATABASE DESIGN PROCESSES

This study is implemented in an ARC/INFO environment, and thus, is subject to ARC/INFO's data structure model.
ARC/INFO as a GIS is characterised : by its data model, the GIS functions that it performs, its modular design, its ability to integrate many types of input data, its macro programming language (AML), and an open architecture which allows it to be linked to other relational database management systems (Marble, 1990).
ARC/INFO's topological relationships are said to be recorded at the level of geometric (or topological) primitives: nodes, arcs and polygons; and spatial relationships are defined by a conceptual data model at terrain object level.
Spatial data in ARC/INFO is modelled akin to the formal data structure of Molenaar (1991).

5.2 ENTITY RELATIONSHIP MODELLING (CONCEPTUAL DATABASE MODEL)

There are two database design aids namely, **entity relationship modelling** and **normalisation.** These are guidelines rather than rigid rules.
The entity relationship modelling concept uses **entity**, **relationship**, and **attribute** to represent data.

Entities are objects or features in the real world with an independent existence; **relationhips** describe associations among entities; and **attributes** are the properties that describe the entities and relationships (8). These concepts are said to be representable graphically using so-called schema diagrams which provide a high level of abstraction. Although the ER schema captures many of the constraints and semantics of a database, some importatnt abstraction concepts are said to be difficult to to express using the basic ER model. This data structure, however, is said to answer queries on topologic relationships between terrain objects.

The primary components of ARC/INFO are ARC and INFO. Arc is for storing coordinate data and performing operations on this type of data, INFO is a relational database management system (DBMS) and stores and performs operations on attributes, that is, descriptive non-coordinate data.

ARC/INFO is linked to Oracle Relational Database Management System (RDBMS) and the latter provides flexibility for data manipulation. Oracle permits structured querying and procedural operations for automatic data processing. The formal data structure implemented in ARC/INFO is shown in Figure 5.2.

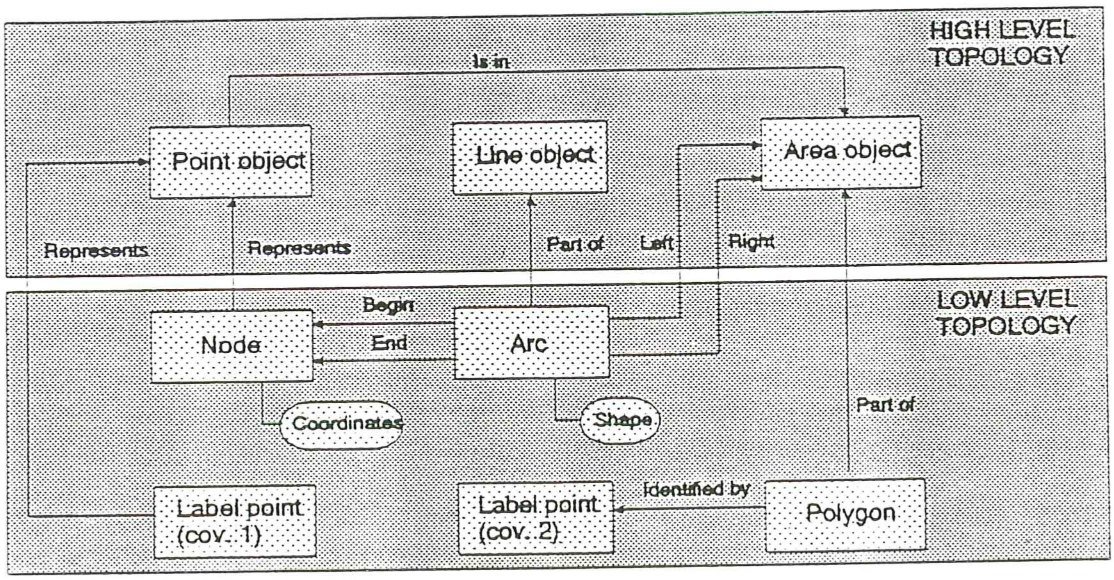


FIG. 5.2 FORMAL DATA STRUCTURE IN ARC/INFO (1).

In this study the author ,hence, uses the so-called **Extended Entity Relationship Model (EER-model)** approach of Fernandez & Rusinkiewicz (1993) with some minor modifications.
This model removes the limitations imposed by the basic entity relationship model.
The extended entity relationship model (EER Model) incorporates various forms of generalization and specialisation including subsets and unions (11).
The relevant conceptual database model (EER Model) implemented in this study is given in figure 5.3. This model conforms to ARC/INFO's formal data structure (FDS) figure 5.2.
The black dots in figure 5.3 indicate obligatory relationships, for example, it is obligatory that a sample is associated with a horizon.

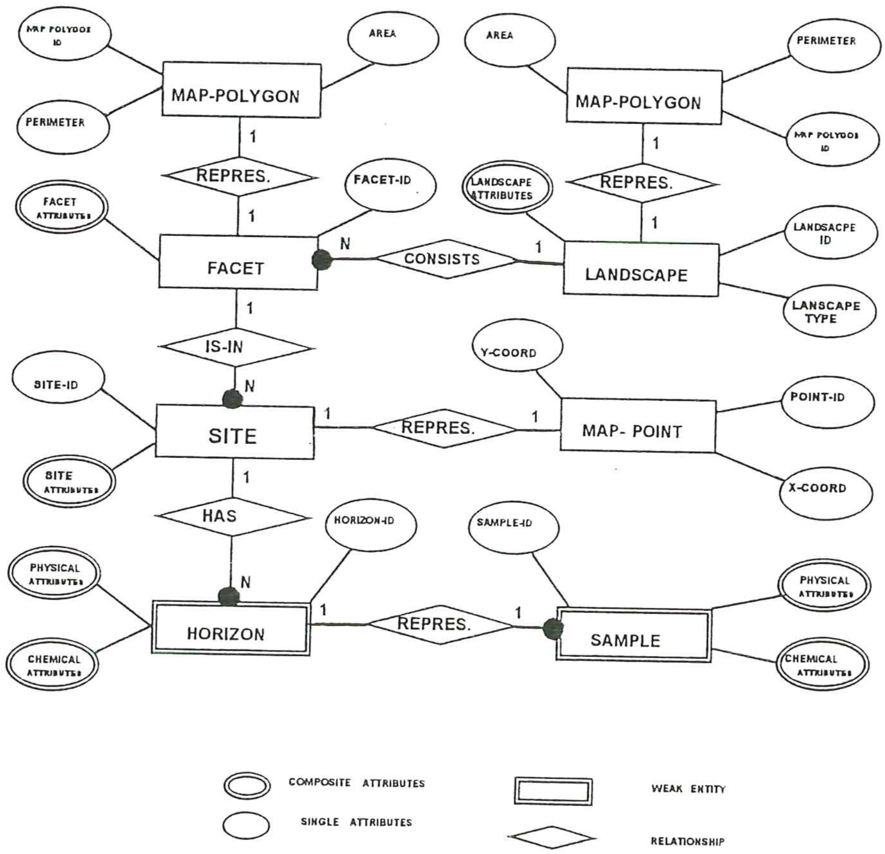


FIGURE 5.3 EXTENDED ENTITY RELATIONSHIP CONCEPTUAL MODEL

There are five entities which are thought to be sufficient for erosion modelling in the present case study. For clarity the entities are here defined. There seems to be no clear-cut definition of landscape in literature. Godron (1981) defines landscape as a kilometre wide area with a cluster of interesting stands or ecosystems repeated in a similar form.
Harris (1968), defined landscape as a stretch of country as seen from a particular vantage point. To a critical reader the vagueness of these definitions is obvious. However, in this study, the landscape unit is a delineation of the terrain (at 1 : 25 000) according to geology and geomorphology, for example, hilly to rolling dissected terrain on tertiary marls. A facet is a process response unit or a recognisable geomorphic unit occuring within a landscape; a unit of minimum variability in soil forming factors with respect to geology and geomorphology (Wielemaker, in (5)). A horizon in pedology (soil science) is defined as a layer of soil material approximately parallel to the land surface differing from adjacent genetically related layers.
This study concerns only the A-horizon (topsoil). The author has taken liberty to define the remaining entities as was perceived during fieldwork. A site, is a specific location (in X,Y,Z) where a soil sample was collected, although X,Y coordinates are sufficient to identify a site. This definition is rather strict, since strictly speaking the attributes of a site were not specific to that point, for example, land use code meant the landuse in the vicinity or in proximity to the site. The soil sample refers to the soil material that was collected for laboratory analyses.

5.3 NORMALISATION AND DATABASE INTERGRITY CONSTRAINTS

The database building blocks (Tables!) were derived through the normalisation process. Five primary tables were defined as a consequence of normalisation: **Landscape table, Facet table, Site table, Horizon table** and **Soil sample table**. Although these tables are sufficient in themselves, they do not suffice for asssessment of soil erosion. To supplement these tables, two extra tables (secondary tables) were defined: **Soil loss table** and **Soil erodibility table**. These tables were directly created in oracle including the horizon and sample tables.
The remaining tables are within the ARC/INFO environment since they are directly linked to the respective coverages.

The EER schema (figure 5.3), shows the entities and their degrees of relationship. From this schema the following constraints apply in the database:

(i). A landscape may have more than one facet, however, a facet cannot belong to more than one landscape unit.

(ii). A site is located only in one facet and its relationship with the landscape is through the facet.

(iii). Each horizon is associated with one specific site; it is obligatory that a horizon so defined belongs to a specific site.

For consistence with the purpose of this study and in compliance with the sample collection procedures:

(iv). A soil sample must be associated with exactly one horizon and vice versa.

Given these constraints and the degrees of relationships; the following so-called skeleton tables were defined, and for brevity, only primary and foreign keys are given. In the case of foreign keys, only where applicable.

LANDSCAPE TABLE (<u>Landscape-id</u>,------------------------------).

FACET TABLE (<u>Facet-id</u>, landscape-id,-----------------------).

SITE TABLE (<u>Site-id</u>, facet-id,---------------------------).

HORIZON TABLE (<u>Horizon-id</u>, site-id,------------------------).

SAMPLE TABLE (<u>Sample-id</u>, horizon-id, ---------------------).

The primary keys are underlined in each table. The secondary tables are linked to primary tables that have most relevant thematic meaning defining a given secondary table.
For example, it is far reasonable to link the soil loss and erodibility tables *items* to the site table since the interpolation process begins here. In other words, its point data that is being generalised or rather interpolated to the subcatchment at each next higher level of aggregation.
On the other hand, presentation of graphical displays are viable through clasification or reclassification processes so that, for exampmle, each facet can be represented by one value of erodibility or soil loss.

The thoroughness of such generalizations is dictated by summary statistics of the variable being measured and criteria proposed in Chapter IV.

5.4 AGGREGATION AND GENERALIZATION

It is obviously necessary to define aggregation and generalization before discussing how these concepts are implemented in the present study. Wielemaker (1994; in (5)), claims that in GIS, reduction in spatial detail is called aggregation and the reduction in thematic detail defines generalization.
He further states that GIS permits implementation of different strategies for generalization, aggregation, simplification and translation of information.
In this study the aggregation starts at the point data values through stratification by facets for the first level of generalization bearing in mind that facets are treated as discrete terrain units. All points falling within a facet were statistically analysed to determine the mean soil loss and sediment transport capacity values. The means are classified and assigned to each facet as representative values.
For the sediment transport capacity index only two classes are recognised: the net deposition class and the net erosion class.
Facets yielding the values within a certain soil loss class are aggregated (merged) if they share full neighbourhood conditions. Where a facet or landscape unit does not meet the minimum legible area criterion it is disolved through a series of ***Reclassification*** processes in the ***Local*** function of the grid module of ARC/INFO to merge it with one of its neighbours with which its soil loss values are approximate.
Figure 5.4 shows an example of a reclassification process in ARC/INFO's grid module.
Spatial interpolation was achieved through kriging of gridded point coverage. When gridding the point coverage the resultant grid is assigned a specific variable values that will then be the subject of analysis in the gridding procedure.
There are only two levels of aggregation in this study, point to facet, and facet to landscape unit. At the given scales of analysis, the ***minimumm legible area*** (**MLA**), the ***average size delineation*** (**ASD**) and ***index of maximum reduction*** (**IMR**) are given in table 5.1.

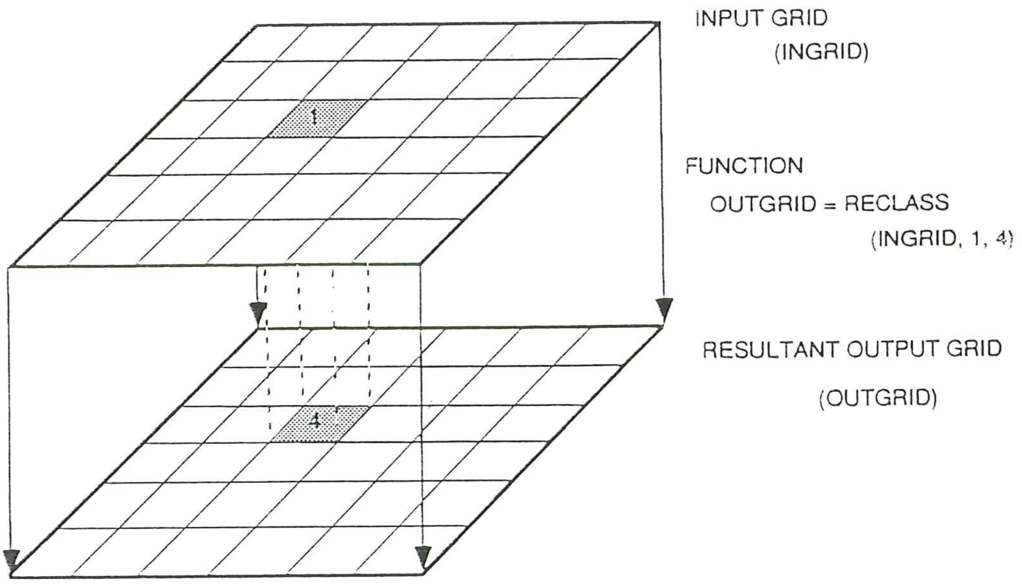


FIG 5.4 RECLASSIFICATION IN THE GRID MODULE OF ARC/INFO.

TABLE 5.1 MAP SCALES AND MINIMUM MAPPABLE AREA CRITERIA

	Point data	Facet	Landscape
SCALE/RES.	20 x 20 m	1 : 5 000	1 : 25 000
MLA (ha.)		0.25	6.25
ASD (cm^2)		1.6	1.6
IMR		2.0	2.0

MLA = Minimum legible area
RES = Resolution
ASD = Average size delineation
IMR = Index of maximum reduction

5.5 DATABASE MANIPULATIONS AND SIMULATION PROCEDURES

Implementation in this study refers to how the functionalities of the model (EER model) are realised in the database.
Simulation refers to the processes (algorithmic procedures) that are programmed to produce desired output.
An output can be a single variable in the Revised Universal Soil Loss Equation or their combinations as may be desired.
In ARC/INFO the basic structure of the data is a coverage (or so-called data layer). The coverages have geometric and thematic attributes. Topology and thematic data are described in the relational tables via the geometric primitives.
ARC/INFO generates tables associated with the coverage automatically. These tables include:

- **Arc attribute table** (<coverage_name>.AAT>);
- **Polygon attribute table** (<coverage_name.PAT>);
- **Node attribute table**(<coverage_name>.NAT); and
- **Point attribute table**(<coverage_name>.PAT).

The tables have a system defined unique identifier and a unique identifier defined by the author (user-id) section 5.2. Attributes associated with each relevant table other than those automatically generated by ARC/INFO are added through the **Additem** functionality in the tables environment by invoking a given table through the **Select** command.
The relationship between tables is realised through the **relate** environment of ARC/INFO. The relate function permits linking of two tables, it is particularly important, where a display of reclassed data is needed. The classed data is in a look-up table. The simulation procedure was done in the grid module of ARC/INFO. Grid is a raster or cell-based geoprocessing system integrated with ARC/INFO.
The simulation processes are shown in figure 5.5.

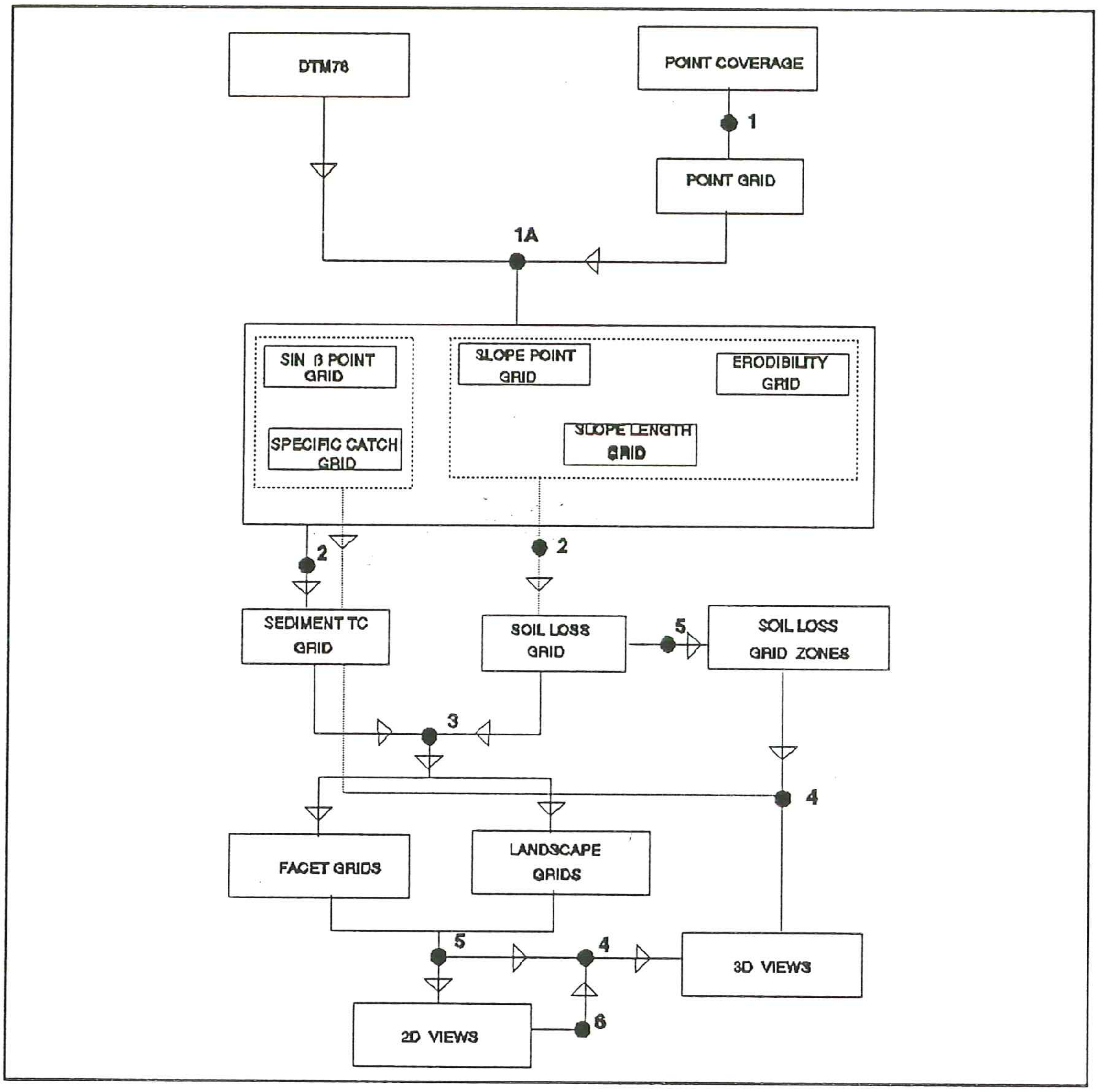


FIG 5.5 SIMULATION FLOW CHART

1 = Gridding process
1A = Gridding with map algebra
2 = Gridding with model
4 = Surfacedraping
3 = Surface interpolation (Kriging)
5 = Reclassification / Aggregating
6 = Polygonization

Dots indicate processes in the database.

To display a 3D-View of the facets or landscape units showing soil loss values of the soil loss grid, the following procedure is initiated in the grid module :

GRID: Mapex DTM78;
GRID: ap surface lattice soilossgrid;
GRID: ap surfacedefaults;
GRID: ap surfaceresolution 25;
GRID: ap surfaceobserver relative 145 30 1000;
GRID: ap surfacedrape gridpaint soilossgrid # linear # gray.

The above processes lead to calculation of visibility which is quite a slow process before surfacedraping is finally done.
To improve spatial resolution surfacedraping with the mesh and distance options are included in the above procedure.
The above procedure is for black and white displays and for colour displays the shadecolorramp command is used.
The surface resolution command gives the cell size.
The surface observer command handles the azimuth, altitude and distance. Kriging is always with respect to a point coverage.
The point coverage has data on which the interpolation is based. In this study only 42 points have soil loss values in the database. The soil loss values are added to the point caverage point attribute table, implying that kriging has to be done after a reselect process so that only points with data are used.
All these procedures are either done autonmatically (using the **AML** facility within ARC/INFO) or interactively.
Kriging is always preceeded with setting of cell sizes after specificattion of the reference Digital Elevation Model through the map extent command.

CHAPTER VI: RESULTS AND CONCLUSIONS

The soil loss simulation results in this study appear somewhat below expected values, for example, Clavaux and Heerbout (1994) report soil loss figures ranging from 40-70 ton/ha/year in olives. An avearge of 44.8 ton/ha/year is reported for Andalucia by the same authors. This study simulated an average of 27 ton/ha/year (about 60 % of the regional average).
The likely difference is perhaps in the models used. Clavaux and Heerbout used the Universal Soil Loss Equation and do not appear to account for surface stoniness in their simulations. Simulated soil loss figures in the subcatchment in this range from 3 to 72 ton/ha/year. Table 6.1 gives summary statistics of main inputs into the RUSLE model.

TABLE 6.1 SUMMARY STATISTICS OF MODEL INPUT VARIABLES

	Mean	S. deviation	Skewness	Range	Maximum	Minimum
SL	2.0	0.864	2.536	3.60	4.8	1.2
S	7.7	5.210	0.601	18.0	19	1.0
K	0.2	0.115	0.646	0.51	0.6	0.1
A	27	20.4	0.883	72.4	75	2.6

SL = slope length　　S = Slope (%)
K = Erodibility　　A = Soil loss (t/ha/y)

The coefficients of skewness of most of variables with an exception of slope justify a stratification approach for erosion assessment in this environment since most soil characteristics and terrain parameters do not depict a normal distribution. Thus trend analysis should be avoided.
The generalization strategies therefore should be stochastic oriented. The statistical analyses revealed some facts which are perhaps surprising and difficult to explain.
There is for example an inverse relationship between soil loss and elevation (r = -0.2833). Table 6.2 shows correlation coefficients of some selected soil and terrain characteristics.
Surface stoniness correlates well with erodibility since stones reduce the effect of raindrop impact. Soil moisture, clay content, % sand and % silt correlate equally well with erodibility and justify the basis of the erodibility nomograph (Annex 4).

TABLE 6.2 CORRELATION COEFFICIENTS OF SOIL AND TERRAIN VARIABLES

	Erodibilty	Soil loss	STC
Soil moisture	0.7689	0.2603	-0.4582
% Silt	0.7899	0.2762	-0.2263
% Clay	0.7904	0.3476	-0.3946
% Sand	-0.8443	-0.3211	0.3751
% Very fine sand	0.0942	-0.1606	-0.2269
Oragnic carbon	0.3279	0.0233	-0.0862
Altitude	-0.6565	-0.2833	0.3558
Slope steepness	-0.5138	0.0358	0.8120
% Surface stones	-0.8204	-0.3573	0.4853

Universal kriging is hence an appropriate technique for both generalization and aggregation in ARC/INFO's grid module given these observations.

The data available in this study does not permit meaningful analysis of the simulated soil loss values per facet or landscape unit. However, for a few selected facets it was observed that aggregation of point data led to underestimation of soil loss.

Stratifying the analysis into glacis and old river terrace remnant (geomorphic units) revealed similar consequences. This of course does not mean we should never undertake spatial aggregation. Perhaps future research should come-up with some decisions rules that can avoid excess underestimations.

The effects of kriging have not be fully explored by the author in this study but it is clear that kriging is a reliable means of aggregating spatial units from large scales to smaller scales for three dimensional terrain analysis.

6.1 RESULTS OF SPATIAL AGGREGATION USING MINIMUM MAPPABLE AREA

This is an easy process in ARC/INFO through the map algebra functions. At the scale of 1 : 5 000 the minimum mappable area criterion revealed that most facet were delineated correctly.

Thus there was not need to merge any of them purely from spatial resolution point of view.
However, at the landscape scale of 1 : 25 000 the minimum mappable area criterion dictated that most of the facets would merge. However, a few facets maintained self existence at this scale, implying that a facet in fact may be a landscape unit. This is perhaps alluded to in literatue where a facet sustains an *'is a'* relationship with a land element which has parent material as its major attribute.

6.2 FUTURE RESEARCH

There are two cardinal issues that emerge in this study. One concerns the fact that a facet may in actual fact qualify as a landscape unit from spatial resolution point of view.
What would this mean for aggregation strategies ? A nother is the use of Digital Elevation Models (DEMs) to assess soil erosion. The DEM (DTM78) used in this study has a cell size or so-called mesh distance of 25 m while the sampling distance in the field was 20 m. This means that DTM78 is not strictly appropriate in this study.
The sediment transport capacity index has not yield desired results in this study despite its wide publicity in literature. It is highly an ambiguos parameter to assess (see table 6.2). This may be due some uncertainities associated with the specific catchment area calculations in this study taken as λ^2 at each observation point.
It is advisable that prior knowledge of the data resolutions in a GIS that one wishes to use in their analysis be known. According to Tobler (1988, in (28)) one cannot add resolution to the data even, by merely picking a small lattice size.
The author is of the opinion that for fundamental research pursuits prior assessement of models data needs be ascertained to void excesses of data gaps.
This would possibly lead to accurate estiamations or simulations of soil loss.
Sampling should be stratified according to terrain mapping units as opposed to toposequence sampling particularly for variables that do not normally depict trend in the landscape.
Field methods of soil loss measurements must be encouraged to add improvements to theoretical models being used in erosion assessments and prediction.
For validation of the usefulness of topographic indices like the sediment transport capacity index, field sampling should be stratified according to zones of deposition and erosion.
In this study, samples in depressions yielded higher sediment transport capacity indices. Whether this is as would be expected is not clear to the author.

REFERENCES

[1]. Casasnovas, Jose A.M. Hydrographic Information Abstraction for Erosion Modelling at Regional Level: A Database Perspective In a GIS Environment (A Case Study in the Anoia-penedes Region, NE-Spain). M.Sc. Thesis, WAU-ITC, July 1994.

[2]. Clavaux, M. and Heerebout, W. Erosion Calculation and Prediction in the Mediterranean Area by means of GIS. M.Sc. Thesis WAU. Landbouwuniversiteit Wageningen, August 1994.

[3]. Coenders, B., Coorens, S., During, A., Eykelenburg, V. van and M. van Jole (eds). "Hola Campesino", Report on Soil Conservation Aspects for the course: Sustainable Land Use in Alora, Spain. Wageningen: Dept of Irrigation and Soil & Water Conservation, Wageningen Agricultural University , August 1994.

[4]. Suryana, N., Molenaar, M. and Imeson, A. "An approach to building and handling uncertainty associated with the Inductive Erosion Model in Geographical Information Systems" 1994 (personal communication).

[5]. Wageningen Agricultural University. Introduction to the field training project "Sustainable Land Use" in Alora, Spain. 1994.

[6]. Bowman, Judith S., Emerson, Sandra L., and Darnovsky, Marcy. <u>The Practical SQL Handbook: Using Structured Query Language</u>, 2nd edition. Reading etc.: Addison-Wesley Publishing Company, 1993 , 453p.

[7]. ESRI. <u>Understanding GIS the ARC/INFO Method</u>. Redlands Inc.: Environmental Systems Research Institute, 1993.

[8]. Fernandez, R.N. and Rusinkiewicz, . "A conceptual design of a Soil Database for Geographical Information System", <u>International Journal Of Geographical Information Systems</u>, Vol.7, (6), 1993, 525-529.

[9]. Moore, I.D., Turner, A. Keith, Wilson, John P., Jenson, Susan K., and Band, Lawrence E. "GIS and land-surface-subsurface process modelling", <u>Environmental Modelling with GIS</u>. Oxford, New York.: Oxford University Press, 1993, pp 197-233.

[10]. Moore, Ian D., Gesseler, P.E., Nielsen, G.A. and B.A. Peterson, "Terrain Analysis for Soil Specific Crop management", ASA-CSSA-SSSA, Madison, 1993, 27-57.

[11]. Oosterom, Peter van. Reactive Data Structures for Geographical Information Systems, Ph.D. Thesis, Leiden University, Netherlands, February 1993.

[12]. Reeuwijk, L.P. van. Procedures for Soil Analysis., ISRIC: Wageningen, 1993,109p. Technical Paper No.9.

[13]. Roo, A.P.J. de, Modelling Surface Runoff and Soil Erosion in Catchments Using Geographical Information Systems, Utrecht.: Faculteit Ruimtelijke Wetenschappen, Universiteit Utrecht, 1993, 295p.

[14]. Berg, Maurits van den. SWEAP: A Computer Program for water Erosion Assessment applied to SOTER. SOTER Report 7, UNEP-ISRIC, 1992, 27p.

[15]. Bregt, A.K., Stoorgel, J.J., Bouma, J. and A. Stein. "Mapping Ordinal Data in Soil Survey: A Costa Rican example." Journal of Soil Science, Vol.56 (2), 1992, 525-531.

[16]. Kirby, M.J., Naden, P.S., Burt, T.P. and D.P. Butcher. Computer Simulation in Physical Geography, 2nd Edition. Chichester. New York etc.: John Wiley & Sons, 1992, 180p.

[17]. Moore, Ian, D. and J.P. Wilson. "Length-Slope factor for the Revised Universal Soil Loss Equation: Simplified Method of estimation", Journal of Soil & Water Conservation, Vol. 47 (1), 1992, 423-428.

[18]. Spaan, W., and Sterk, G. Selection and design of soil and water conservation measures in a catchment, Course Instruction K200-508 ,Dept of Irrigation and Soil and Water Conservation, Wageningen Agricultural University, 1992.

[19]. Stroosnijder, L. and L.A.A.J. Eppink. Principles of Soil and Water Conservation. Lecture Notes of course K200-500/510. WAU. Dept of Irrigation and Soil & Water Conservation, September, 1992.

[20]. Hijmans, Robert J. Agriculture in the Lower Guadalhorce Watershed. May 1991, Dept of Crop Science, Wageningen Agricultural University.

[21]. Molenmar, M. "Status and problems of geographical information systems: The necessity of a geoinfomation theory", ISPRS Journal of Photogrammetry and Remote Sensing, vol. 46 (1991) 85-103.

[22]. Moore, Ian D., and Grayson, Rodger B. "Terrain-based catchment partitioning and runoff prediction using vector elevation data", Water Resources Research, vol.27, (1991) no.6, 1177-1191.

[23]. FAO. Guidelines for Soil profile Description. Rome.: FAO, 1990, 70p.

[24]. Webster,R. and Oliver, M.A. Statistical Methods in Soil and Land Resource Survey. Oxford: Oxford University Press, 1990, 316p.

[25]. Aronoff, Stan. Geographical information Systems: A Management Perspective. Ottawa: WDL Publishers, 1989, 294p.

[26]. Elmasri, Ramez. and Navathe, Shamkant B. Fundamentals of database Systems. Redwood City: The Benjamin /Cummings Publishing Company , Inc., 1989, 802p.

[27]. Turner, Monica G., O'Neill, Robert, V., Gardner, Robert H., and Milne, Bruce T. "Effects of changing spatial scale on the analysis of landscape pattern", Landscape Ecology, vol. 3 (1989) No.3/4, 153-162.

[28]. Mounsey, H. and R. Tomlinson (eds). Building Databases for Global Science. London. New York.: Taylor & Francis, 1988, 419p.

[29]. Lal, R. (ed). Soil Erosion Research Methods, Ankey.: Soil & Water Conservation Society, 1988, 244p.

[30]. NSF. The National Center for Geographical Information Analysis: A Prospectus, Technical report, National Foundation Science Foundation, March 1987.

[31]. Zevenbergen, L.W. and C.R. Thorne. "Quantitative Analysis of Land Surface Topography", Earth Surface and Landforms , Vol. 12; 1987, 47-56.

[32]. Burrough, P.A. Principles of Geographical Information Systems for Land Resources Assessment, second edition. London. New York.etc.: Edward Arnold, 1986, 309p.

[33]. Morgan, R.P.C. Soil Erosion and Conservation, Essex.: Longman Group UK Limited, 1986, 289p.

[34]. Rose, C.W., Williams, J.R., sander, G.C. and Barry, D.A. "A mathematical model of soil erosion and deposition processes: theory for a plane land element', Soil Sci. Soc. of America, vol.47, (1983), 1 , 1991-1000.

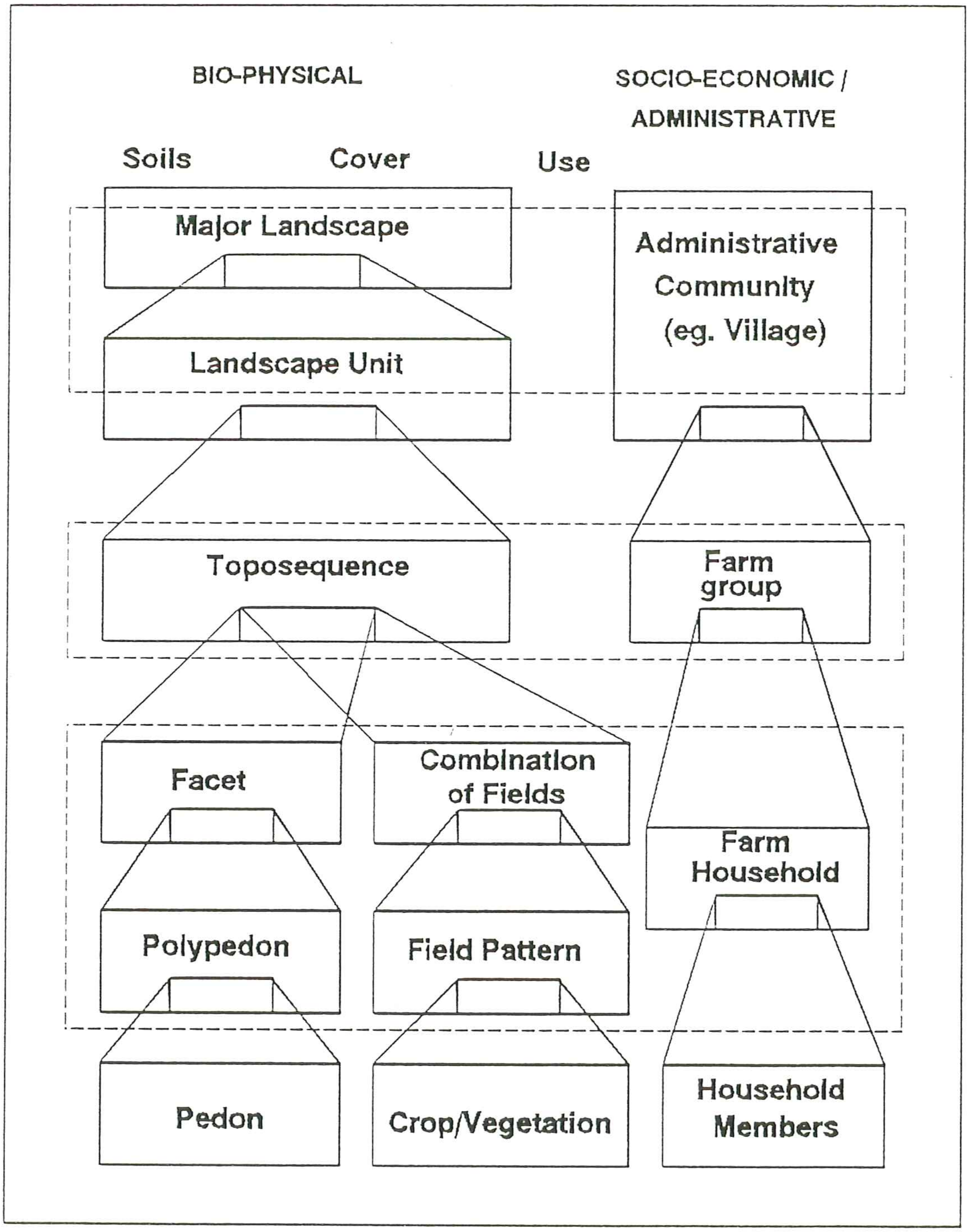
[35]. Forbes, T., Rossiter,D. and A. van Wambeke. Guidelines for Evaluating the Adequacy of Soil Resource Inventories . Washington DC:. USDA-SMSS, Technical Monograph NO.4, 1981, 50p.

[36]. Navathe S. and Schkolnick, M. "View representation in logical database design", Proceedings of ACM-SIGMO International Conference on Management of data., Austin, Texas, 1978, 144-156.

[37]. Wischmeier, Walter H. and Dwight D. Smith. Predicting Rainfall Erosion Losses: A Guide to conservation Planning, Washington.: USDA, 1978, 58p.

[38]. W.G. Moore. A Dictionary of Geography, London: Adam & Charles Black, 1975, 260p.

ANNEX 1: PARALLEL HIERARCHIES OF BIO-PHYSICAL AND SOCIO-ECONOMIC SYSTEMS.



ANNEX 2: COMMON SOIL EROISON AND HYDROLOGICAL DISTRIBUTE MODELS

ACRONOMY	MODEL NAME	REFERENCE YEAR	TYPE	PROCESSES
USLE	Universal Soil Loss Equation (Wischmeier & Smith)	1958-1978	LEFT	E
MUSLE	Modified Universal Soil Loss Equation (William & Berndt)	1957-1977	LEFE	E
RUSLE	Revised Universal Soil Loss Equation (Renard et. al.)	1987	LEFT	E
MUSLE	Modified Universal Soil Loss Equattion 1987; Hensel & Bork	1987	DECT	E
SLEMSA	Soil Loss Estimator for Southern Africa (Stocking)	1981	LEFT	E
CREAMS	Chemical Runoff and Erosion from Agricultural Management Systems (Knisel)	1980	LOCTV	ENRP
EPIC	Erosion Productivity Impact Calculator (Williams et.al.)	1984	LOFT	ERNC
WEPP	Water Erosion Prediction Project (Nearing et. al.)	1989	DPSTVfe	ER
ANSWERS	Aerial Nonpoint Source Watershed Response Simulation (Beasley et. al.)	1977-1980	DPCVfd	ER(N)
KINEROS	Kinematic Erosion Simulation (Smith)	1981	DPCVfe	ER
EROSEM	European Soil Erosion Model (Morgan et. al.)	1991	DPCVfe	ER

KEY:

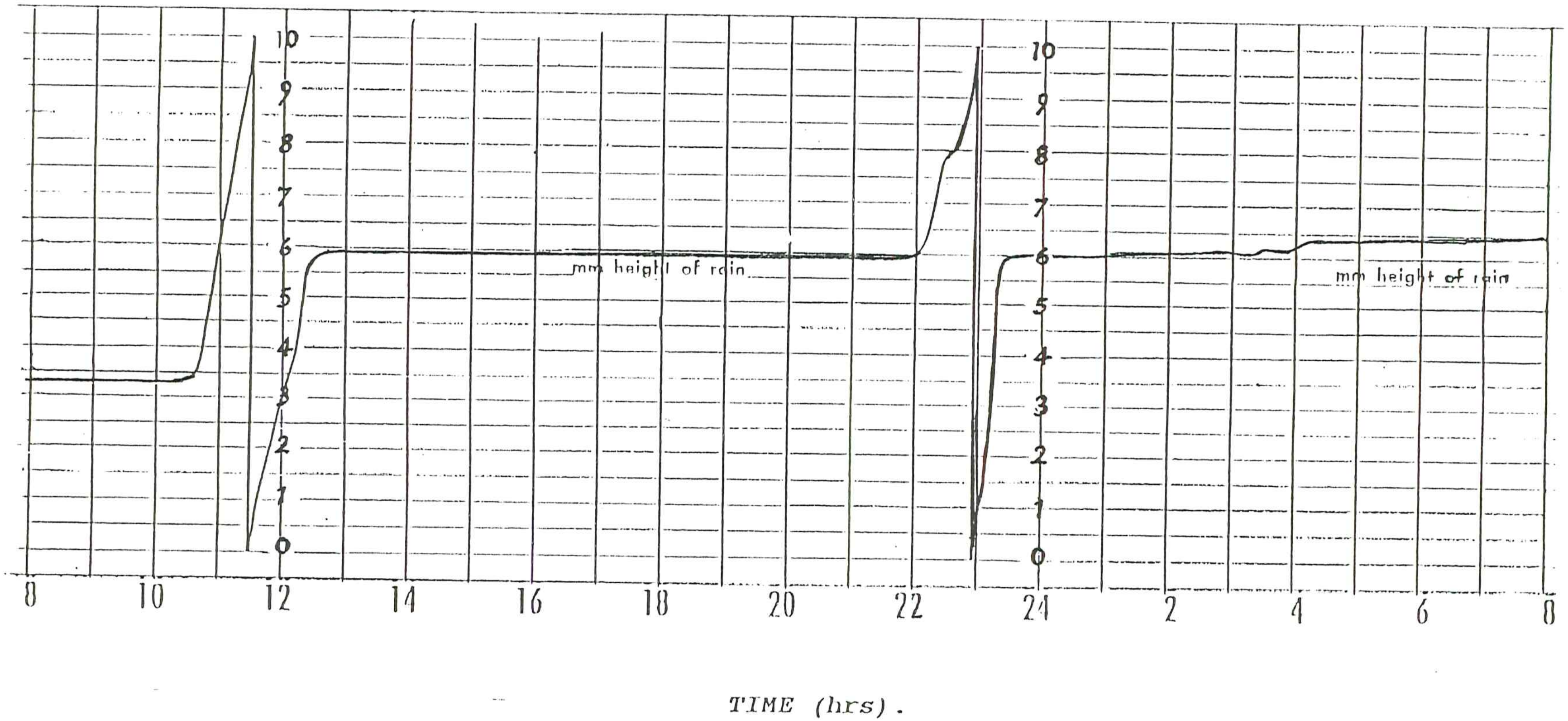
Type:

D/L	**Distributed/Lumped**
P/O/E	**Physical-based/Conceptual/Empirical**
C/F/S	**Catchment/Hillslope/Field**
V/T	**Event/Continous**
fe/fd	**Finite element/Finite difference**

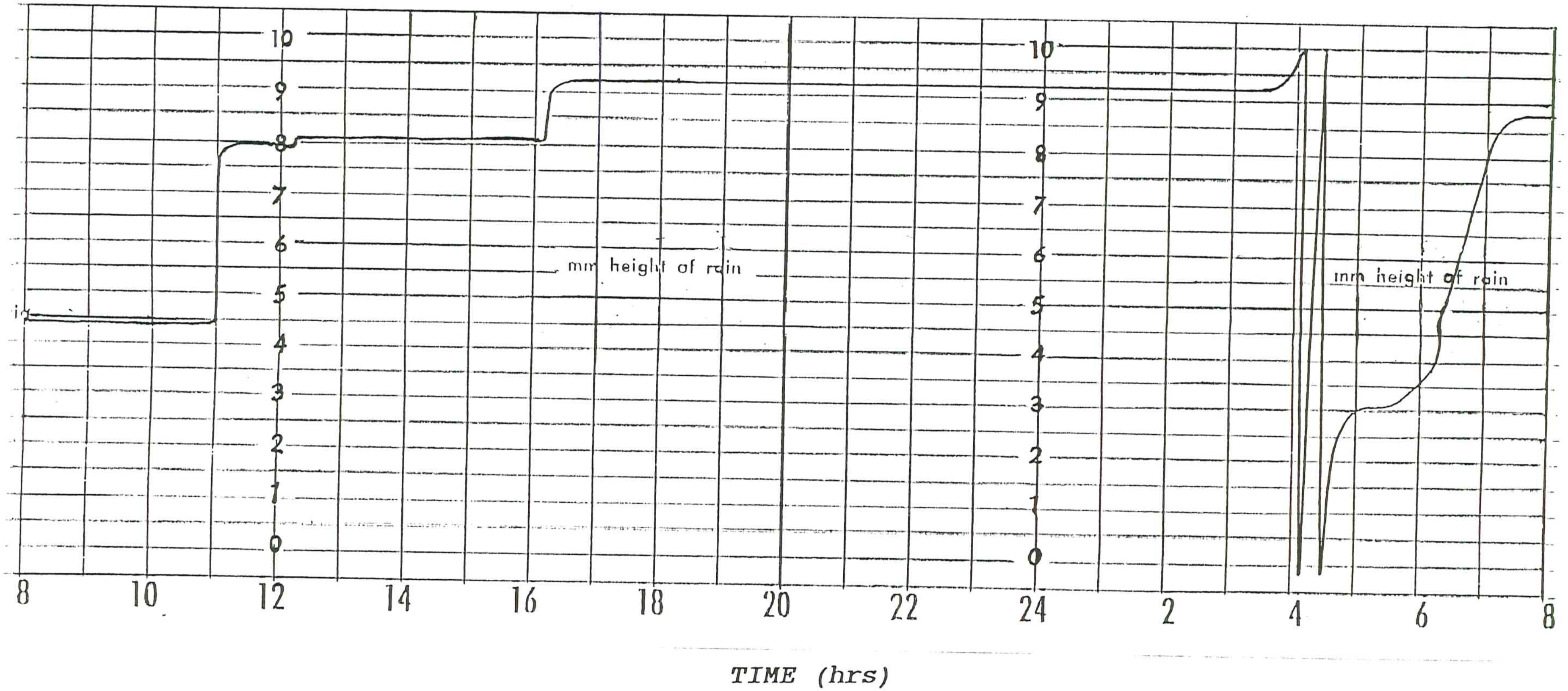
Process:

E	**Erosion**
R	**Runoff**
N	**Nutrients**
P	**Pesticide**
C	**crop growth**

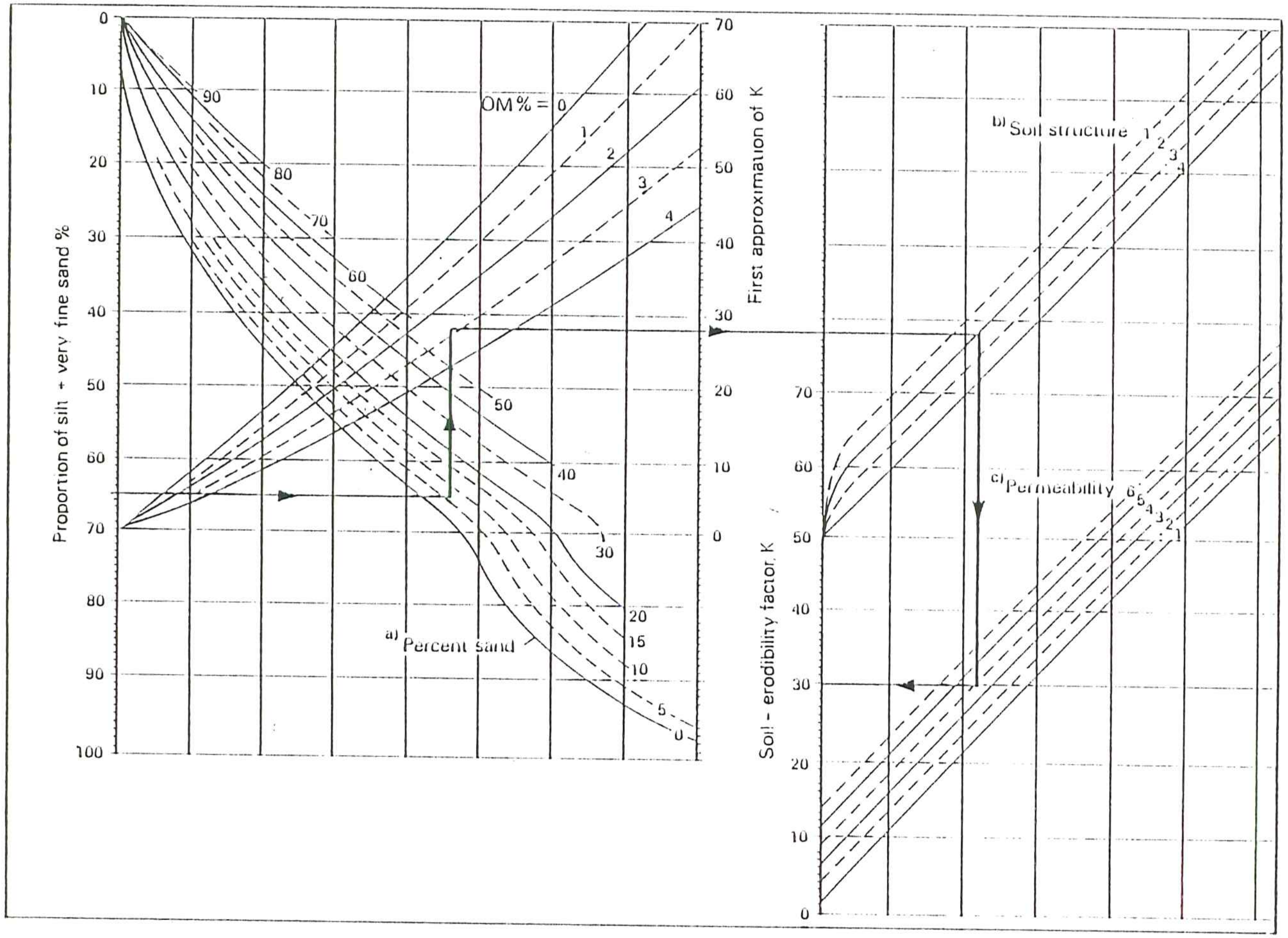
ANNEX 3a: PLUVIOGRAM FOR 3 FEBRUARY 1972



ANNEX 3b: PLUVIOGRAM FOR 5 OCTOBER 1972



ANNEX: 4 NOMOGRAPH FOR ESTIMATING SOIL ERODIBILITY (Wischmeier & Smith, 1978)



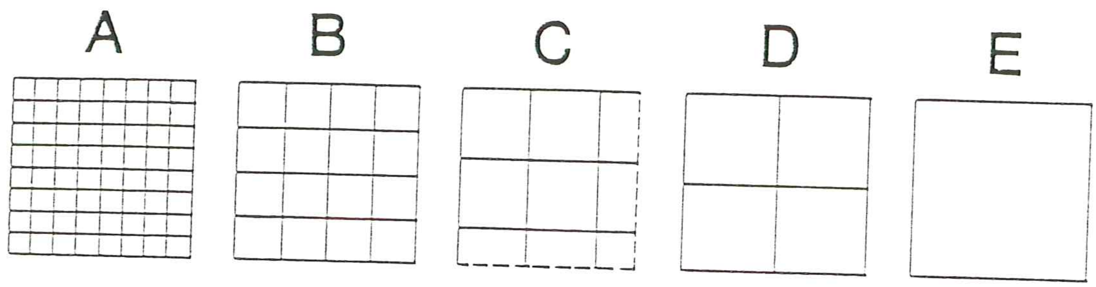
KEY:

Structure classes
1 = Very fine granular
2 = Fine granular
3 = Medium or coarse granular
4 = Blocky, platy or massive

Permeability classes
1 = Rapid
2 = Moderate to rapid
3 = moderate
4 = Slow to moderate
5 = Slow
6 = Very slow

Note: Sand taken as particles with diameter 0.1-2.0 mm.

ANNEX: 5 MAP DELINEATION SIZE AND LEGIBILITY



	A	B	C	D	E
ASD:	0.1	0.4	1.0	1.6	6.4 CM2
IMR:	0.5	1.0	1.58	2.0	4.0

(ASD = average size delineation)
(IMR = index of maximum reduction)

AREA A: ASD = ¼ of the minimum legible delineation
AREA B: ASD = minimum legible delineation
AREA C: minimum acceptable IMR
AREA D: ASD: = optimum legible delineation
(4 times the minimum legible delineation)
AREA E: ASD = 4 times the optimum legible delineation
(16 times the minimum legible delineation)