A critique of soil erosion modelling at a catchment scale using GIS

by

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Glossary

A	Mean annual soil loss (ton.ha^{-1}.yr^{-1}) (of USLE)
ANSWERS	Areal Non-point Source Watershed Environmental Response Simulation
ARS	Agricultural Research Service
ATS	Department of Agricultural Technical Services
C	Cropping – Management Factor (of USLE)
C	Crop factor (of SLEMSA)
COM	Component Object Model
CSIR	Council for Scientific and Industrial Research
CSIR – SAC	Council for Scientific and Industrial Research – Satellite Applications Centre
DEM	Digital Elevation Model
DHI	Danish Hydrologic Institute
DWAF	Department of Water Affairs and Forestry of South Africa
EI_{30}	Rainfall-erosivity factor
ESRI	Environmental Systems Research Institute
EUROSEM	European Soil Erosion Model
GeoWEPP	Geo-spatial interface for WEPP
GIS	Geographical Information System
GUI	Graphic User Interface

K	Soil Erodibility Factor (ton/MJ/mm) (of USLE)
K	Erodibility Factor (tons.ha^{-1}.yr^{-1}) (of SLEMSA)
L	Slope Length (of USLE)
LISEM	Limburg Soil Erosion Model
LS	Slope and Length of Slope Factor (of USLE)
MAP	Mean Annual Precipitation
MSMP	Mpumanlanga Soil Mapping Project
NCS	KwaZulu-Natal Nature Conservation Service
P	Erosion Control Factor Practice (of USLE)
R	Rainfall and Runoff Erosivity Index (MJ/ha/mm/yr) (of USLE)
RUSLE	Revised Universal Soil Loss Equation
S	Slope steepness (of USLE)
SADC	South African Development Community
SEAGIS	Soil Erosion Assessment using GIS
SDR	Sediment Delivery Ratio
SLEMSA	Soil Loss Estimator for Southern Africa
TWP	Thukela Water Project
UIMS	User interface management systems
UNESCO	United Nations Educational, Scientific and Cultural Organisation
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation
WEPP	Water Erosion Prediction Project
WMA	Water Management Areas
X	Topographic Factor (of SLEMSA)
Z	Mean annual soil loss (tons.ha^{-1}.yr^{-1}) (of SLEMSA)

Disclaimer

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Gregory Dennis Breetzke

Chapter 1: Introduction

1.1 Problem description

The problems with modelling a dynamic and physical process such as soil erosion are not new. Research studies have resulted in many attempts to examine the measurement errors; scale problems; data collection, frequency and magnitude difficulties fraught in soil erosion modelling. The most significant problem lies in the scale of approach of the erosion model. In order for developers and planners to effectively plan a conservation strategy the size of the area has to be large enough to warrant an expensive intervention plan. A catchment is considered the minimum sized area required. GIS is the tool that allows soil loss estimation, previously limited to erosion plot studies, to be extrapolated from erosion-plot scale, to this catchment scale. From a GIS and town and regional planning point of view such soil loss figures are vital in order for land-use and management planning strategies to be effectively employed at these regional scales, and from an agro-ecological point of view, in providing appropriate conservation and management practices at the various scales of development.

The inherent problem lies in the fact that the soil loss models, upon which this extrapolation from point to regional or catchment scale have been based e.g. Universal Soil Loss Equation (USLE), Soil Loss Estimator for Southern Africa (SLEMSA), are often grounded in theory built on the spatial scale of a hillslope or erosion plot. These models are seen as desirable in developing countries as they are not data intensive and the input parameters required for the models are relatively simple compared to other erosion models. Catchment scale erosion models such as the Areal Non-point Source Watershed Environmental Response Simulation model (ANSWERS) have been fully integrated into a GIS but they are incredibly data intensive and as such are not desirable to developing countries for which data quality and accuracy are contentious issues. A planner's or consultant's focus of investigation is often adopted in developing countries wherein the chosen methodology must be rapid to apply and where immediate tangible results are required resulting in prompt outputs that would lead to agricultural development meeting the short-term conservation needs of the mostly rural population.

The side effects of this problem include the difficulty in validation of the extrapolated model results to a catchment scale. A generation and comparison of soil loss estimation using any erosion model/s remain an interesting albeit mute point in any research where results cannot be validated. Sediment yield figures and comparisons to erosion plot studies are seen as the most comprehensive means whereby catchment scale studies can be validated but both these methods are fraught with error.

1.2 Research extent and logical design of the paper

1.2.1 The main research question

This study is aimed at reviewing soil erosion modelling at a catchment scale using GIS. GIS is a powerful tool aiding in data management, analysis and manipulation and GIS modelling allows researchers to view the real world in simplified terms by modelling complex and dynamic environmental processes such as soil erosion.

The study will provide answers to the following additional research questions:

i) How can the differences between soil erosion models be quantified using GIS?

ii) Can GIS-based erosion models be extrapolated to an area bigger than the erosion plots upon which the models are based? The erosion models to be used in the study will be selected and introduced in later chapters.

iii) How can models be 'improved' using GIS to produce results that are 'closer to reality'? What is the sensitivity of the model results to changes in its input parameters?

iv) It is possible to validate a catchment scale, GIS-based erosion model?

1.2.2 The structure of the study

This study is structured into three broad sections:

1. The first part of this study examines the history, causes, influences and effects of land degradation, and in particular, that of soil erosion in South Africa. Soil loss is particularly acute in South Africa and has many economic, social and political implications and ramifications on society, yet despite the obvious practical importance of the issue at hand, very little research has been done concerning the spatial application and identification of erosion losses in South Africa. Chapter 2 sketches a broad overview of soil loss in South Africa and details the various soil erosion models that are prominent. The soil erosion models chosen for the purpose of this study are outlined and examined in more detail. In Chapter 3, GIS is introduced into the study. Various GIS software utilities offering tools for hydrological and erosion modelling are investigated. The modelling software that is selected for the study is examined more thoroughly.
2. The second part of the study focuses on the practical application of determining soil loss estimations using GIS. Chapter 4 provides comprehensive background information regarding the study site. The physical and human environment is examined in detail. Chapter 5 focuses on the calculation of soil loss estimation using GIS. Various GIS related topics are discussed concerning spatial modelling and a thorough description of the process followed in generating the results is provided.
3. The third, and final, part of the study focuses on the results and the critiquing of the results as well as validation attempts in soil erosion research. Chapter 6 initially examines the results that have been obtained during the course of the second part of the study and then investigates the sensitivity of the various input parameters by altering an input parameter and comparing results. The numerous futile attempts at validating the various different model results are provided and this is superceded by a general critique of the results based on a GIS perspective and more briefly, a soil science perspective. Chapter 7 concludes the study by initially addressing the original research questions and subsequently outlining the

conclusions reached based on the research conducted during the course of the study.

1.3 Chapter overview

This table provides an overview of the chapter's within the study. The logical flow of the paper will hopefully be illustrated to the reader.

Table 1.1: Chapter Overview

Chapter	Contents
1	An **introduction** to the study, with short descriptions on the problem description, research aims and objectives of the study.
2	**Soil erosion models** are examined and the selected erosion models used for the study are outlined
3	**GIS and erosion modelling** are coupled together in this chapter and the relevant GIS modelling software is investigated
4	The **practical and theoretical background** for the study site is provided. A comprehensive explanation of the physical and human environment is provided.
5	A comprehensive **calculation of soil loss in the Wagendrift catchment** is illustrated using two different soil erosion models
6	The **results** of the study are discussed and **critiqued.** The results are compared and attempts are made to validate the models results.
7	The original research questions are addressed and the advantages and disadvantages of using GIS in catchment scale erosion modelling are investigated. **Conclusions** and recommendations are made.

Chapter 2: Soil erosion models

2.1 Introduction

Chapter 2 begins with an examination of soil erosion in a South African context. The political, environmental and societal factors related to soil erosion in South Africa are investigated. Various theoretical soil erosion models are identified, and the two models chosen for use in this study are elaborated upon. The theoretical and practical limitations, and differences between the selected models are discussed.

2.2 Soil erosion in South Africa

Soil is basic to all lifeforms. It is the primary means of food production, directly supporting the livelihood of most rural people and indirectly everyone; it is an essential component of terrestrial ecosystems, sustaining their primary producers (micro-organisms, herbivores, carnivores) while providing major sinks for heat energy, nutrients, water and gasses (Wild, 1993 cited in Stocking, 1994). Weathering, the water balance, organic matter accumulation, erosion and sedimentation, and human actions all control soil development and degradation; thus, soils reflect both natural processes and human impacts (Renschler & Harbor, 2002). Soil erosion, as one of the main processes in land degradation, is the single most immediate threat to the world’s food security (Stocking, 1994). It can roughly be divided into a two phase process:

1. The detachment of individual particles from soil aggregates

2. The transportation of particles by erosive agents - wind or water.

These transported particles are eventually deposited to form either new soils; to fill lakes and reservoirs or get carried to the ocean. In South Africa, it is estimated that 20 to 30 billion tonnes of sediment are carried to the ocean every year (Lorentz & Howe, 1995). As a result of the diverse nature of soil erosion the rates of national and continental soil erosion are virtually impossible to measure accurately. According to (Garland, Hoffman & Todd, 1999) the most quoted South African rates of annual erosion include Midgley's (1952) figure of 363 million tonnes (3t $ha^{-1}yr^{-1}$), Schwartz and Pullen's (1966) value of 233 million tonnes (1,9t ha^{-1} yr^{-1}) and Rooseboom's (1976) estimate of 100-150 million tonnes (0,82-1,22t ha^{-1} yr^{-1}). These figures however are based on the sediment yield of main rivers in South Africa, the accuracy of measurement of which has been questioned by many researchers, including Annandale (1988).

According to Verster *et al*., (1992, cited in Lutchmiah, 1999) more than 1,5 million households in South Africa are directly dependent on agriculture, an activity that utilises about eighty percent of the total surface area of the country. Soil, in supporting this very important and essential activity thus becomes the most fundamental natural resource sustaining economic development and human well being in South Africa (Lutchmiah, 1999). This would therefore add value to Verster's *et al*., (1992) assertion that "soil erosion may well be the greatest environmental problem facing South Africa."

The environmental problem becomes evident through the on-site and off-site effects of soil erosion. According to Sampson (1981) these on-site effects range from increased acidity in the soil and increased soil compaction to the loss of organic matter and soil structure. On-site damage to soil resources does hinder crop productivity through decreased yield, although the exact relationship has been less than thoroughly established (Stocking & Peake, 1985). The off-site effects can be seen in the silt accumulation in dams and reservoirs as well as damage to canals, irrigation schemes and other infrastructure.

To understand soil erosion in a South African context it is important to be aware of the political, social and economic factors affecting land users in this country.

2.2.1 Political factors

> *"In South Africa apartheid policies ensured that 42% of the people lived on 13 % of the land (the "homelands"). This overcrowding resulted in severe erosion. As the land became increasingly degraded and thus less productive, subsistence farmers were forced to further overuse the land. The intensive agriculture and overgrazing that followed caused greater degradation. Soil erosion can be seen as both a symptom of underdevelopment (i.e. poverty, inequality and exploitation), and as a cause of underdevelopment. A reduced ability to produce, invest one's profit and increase productivity, contributes to increasing poverty, and can lead to desertification, drought, floods, and famine. On commercial farmlands, overstocking, mono-cropping, and the ploughing of marginal lands unsuitable for cultivation have led to soil erosion and desertification. Frequently these practices have been unwittingly encouraged by the state offering subsidies which made it profitable to exploit the land in the short-term."* (Collins, 2001).

"These small producers cause soil erosion because they are poor and desperate, and in turn soil erosion exacerbates their condition" (Blaikie, 1983), this quote from Blaikie sums up the political economic approach to erosion investigations in southern Africa.

2.2.2 Environmental economics of erosion

As mentioned earlier, the soil erosion resulting from agricultural land use is associated with environmental impacts (Clark II *et al*., 1985) and crop productivity loss (Lal, 1988; Pimentel *et al*., 1995), which makes the understanding of the erosion process not only important to guarantee food security (Daily *et al*., 1998) and environmental safety (Matson *et al*., 1997, cited in Sparovek *et al*., 2001), but also to ensure economic prosperity. Erosion impacts heavily on the national economy as loss in productivity in both the commercial and subsistence sectors has national costs in, for example, food imports, lower exports, relief supplies and extra agricultural investment (Stocking, 1984). As South Africa exports approximately R8,5 billion of food annually, comprising mostly sugar cane, maize and fruit (Tradepartners, 2002), it is easy to see the economic impacts that soil erosion has.

2.2.3 Social factors

The ultimate impact of erosion is its effect on society (Stocking, 1996). With South African society heavily dependent on agriculture as a primary source of food and sustenance, the effects of soil erosion on, in particular, the subsistence land users in South Africa should be monitored. The social welfare costs are less tangible than perhaps the economic costs of erosion, nevertheless these costs accrue as the decline in productivity on rural subsistence farms often causes migration of young males to seek work in towns, or change patterns of labour. Diet, disease and malnutrition are all indirect costs of the degradation of the land through erosion (Stocking, 1984). For a developing country, these social impacts add further burdening to the national economy.

2.3 Soil loss erosion models

Soil erosion is the outcome of a large number of causative factors of varying importance, which interact in a complex manner (Elwell, 1981), making the modelling of such a physical process incredibly difficult and, to a large extent, subjective. What is a model? A model is a representation of reality; it never claims to be reality but attempts to mimic reality as much as possible. In the dynamic and ever-expanding science of soil erosion, models are the closest and only aspects that we have to try and predict soil loss. Researchers have developed soil erosion models to describe how an erosion system functions and how the system responds to change, these models can then be used for farm planning, site-specific assessments, project evaluation and planning, policy decisions or as research tools to study processes and the behaviour of hydrologic and erosion systems (Foster, 1990; De Roo, 1993).

All soil erosion models are of the predictive type in that they rely on the prediction of outcomes given a set of conditions (deMers, 2000). When predicting erosion, decisions need to be made regarding the temporal and spatial scales required of the model. At the temporal scale decisions need to be made regarding whether the prediction should be for a year, a day, a storm or for short time periods within a storm; and spatially whether the calculated soil loss should be determined for a field, a hillslope or a drainage basin (Morgan, 1995). These differences in temporal and spatial perspectives will influence the processes which need to be included in the model; the way they are described and the type of data required for the model's validation and operation (Morgan, 1995). The predictive model should also satisfy the conflicting requirements of reliability, universal applicability, easy usage with a minimum amount of data, comprehensive in terms of the factors included, and the ability to take into account changes in land-use and conservation practice (Morgan, 1979). We shall next examine a few prominent soil erosion models and evaluate them on the basis of the above-mentioned facets.

2.3.1 WEPP

The Water Erosion Prediction Project (WEPP) is a process-based continuous simulation erosion model that simulates climate, infiltration, water balance, plant growth and residue decomposition, tillage and consolidation, surface runoff, erosion, sediment transport, and decomposition, as well as winter processes (Renschler & Harbor, 2002). WEPP technology is based on fundamental hydrologic and soil erosion processes and is designed to replace the widely used USLE (DeBano & Wood, 1990). The input parameters include information about rainfall, soil, plant growth and decomposition, tillage implements characteristics and slope shape; the outputs may be produced on a storm-by-storm, monthly, annual or average annual basis (Verbist, 2001). The spatial scale of application ranges from tens of meters for hillslope profiles, and up to hundreds of meters for small watersheds (Flanagan *et al*., 1995). WEPP is a theoretically based model that is implemented as a set of computer programmes using an interface, GeoWEPP, which is discussed in Chapter 3.

2.3.2 EUROSEM

Chisci & Morgan (1988) proposed a framework for a European soil erosion model to be based on the best existing European knowledge of soil erosion, at the European Community Workshop held in Brussels in 1986. The result has been the development of The European Soil Erosion Model (EUROSEM). EUROSEM is developed as a distributed event-based model that, in addition to predicting total runoff and soil loss produces hydrographs and sediment graphs for each event (Morgan *et* al., 1998). Although a theoretical erosion model, attempts are being made to develop a graphical interface for EUROSEM in order to make the model more user-friendly.

A primary goal of the physically based EUROSEM model has been the prediction of areas particularly sensitive to human actions (Rafaelli, Montgomery & Greenberg, 2001). This has been the main attraction of these types of models to land-use planners and environmentalists, who can then create land-use schemes and management proposals to lessen the effect of erosion in these areas.

2.3.3 USLE

'The Universal Soil Loss Equation (USLE) is an erosion model designed to predict the long time average soil losses in run-off from specific field areas in specified cropping and management systems" (Wischmeier & Smith, 1978). It is a relatively simple *a priori* model. "Despite (or perhaps because of) the simple regression approach, the USLE has proved to be a practical and accessible model that has been used and misused (Wischmeier, 1976) at various scales worldwide" (Renschler & Harbor, 2002).

2.3.4 RUSLE

In the mid- to late- 1980's the Agricultural Research Service of the United States Department of Agriculture (USDA-ARS) developed an improved USLE-based model for the northeastern areas of the United States of America (USA) (Smith, 1999). This was called the Revised Universal Soil Loss Equation (RUSLE). According to Smith (1999), RUSLE can best be described as a software version of a greatly improved USLE, which draws heavily on USLE data and documentation. The main differences being that RUSLE incorporates more data than USLE, it corrects errors in the USLE analysis and fills gaps in the original data and, most importantly, RUSLE is much more flexible than USLE and allows for the modelling of a greater variety of systems and alternatives (Smith, 1999).

2.3.5 SLEMSA

"In response to the poor predictive ability of the USLE in Zimbabwe (then Rhodesia), the Rhodesian Multidisciplinary Team on Soil Loss Estimation, under the leadership of Elwell (1977), developed the Soil Loss Estimation Model for southern Africa (SLEMSA) for estimating long-term mean annual soil loss from sheet erosion on arable land" (Hudson, 1987). SLEMSA is a relatively widely used soil loss model in African environments (Elwell & Stocking, 1982, cited in Smith, 1999). It should be seen as a modelling technique or framework, rather than mechanistic descriptions of the erosion system, and makes no claims of universality (Smith, 1999).

2.4 Erosion models selected for this study: USLE and SLEMSA

The USLE and SLEMSA erosion models were selected for use in this study for the following reasons: USLE because of its worldwide usage and reputation, it also requires a limited amount of data needed to perform a detailed scale erosion analysis (Rojas, 2002). SLEMSA because it was developed in southern Africa on the basis of the USLE and is an attempt to adapt the USLE model to an "African regional context". An additional appeal of SLEMSA is that it can also make use of limited data and allows for the progressive improvements of the model as more data becomes available. The relative simplicity of the input requirements, as well as the ease with which estimates of soil loss are made, makes SLEMSA a further appropriate method by which erosion assessments could be made (Hudson, 1987). The scale of application in this study is at a watershed scale, as, according to Kelley (1990), of all the scales possible - villages, provinces, countries – the only "natural" project area is that of a watershed because it allows planners to focus on all the effects of downhill runoff in a given area and to plan accordingly to control or contain it.

2.5 A history of USLE and SLEMSA erosion studies in southern Africa

According to Smith (1999) most of the soil erosion prediction research that has been conducted in South Africa has been conducted using a parametric or 'grey-box' type of model. This is mostly because of the complex and large number of measurement parameters for climate and soil and management practices required in other process-based, deterministic models. The large majority of studies conducted in South Africa have been done using the USLE, RUSLE and SLEMSA models (Smith, 1999).

The USLE has been applied in southern Africa conditions and these studies include those of Wendelaar (1978, as quoted by Elwell, 1996) in Zimbabwe, Crosby, McPhee and Smithen (1983) and Crosby, Smithen and McPhee (1981). According to Smith (1999), a couple of studies were conducted to provide local input data with respect to the different parameters in USLE. The most work that was done was conducted by the KwaZulu-Natal Department of Agriculture to calibrate USLE factors from standard run-off plots at various sites in the province. According to Smith (1999), the former South African Department of Agriculture promoted the use of USLE in the 1980's but it was never widely implemented due to the perception that the results of empirical models outside the range of conditions they were developed for were usually poor.

According to Smith (1999) erosion studies in which the SLEMSA model was used in southern Africa include those of Schulze (1979) in Richards Bay in South Africa, Grohs and Elwell (1993) in Zimbabwe, Stocking, Chakela and Elwell (1988) for the South African Development Community (SADC), Abel and Stocking (1987) in Botswana and Paris (1990) in Malawi. SLEMSA was also applied in the study site, by the former Department of Agricultural and Technical Services (1976) and by Schulze (1979). Hudson (1987) conducted an erosion study using SLEMSA in the mountainous Drakensberg area of South Africa, on the periphery of the study site. Smith (1999) has found that results derived from SLEMSA should be seen as relative values and much more verification and calibration of parameter estimates are required before the model could be routinely applied in soil conservation planning.

2.6 Calculation of soil loss using USLE

The USLE was first conceived in 1965 under the guise of Agricultural Research Service (ARS) scientists W. Wischmeier and D. Smith. At present, it has been the most widely utilised soil loss equation for the last 40 years. Essentially, the USLE breaks up the erosion process into 6 factors which are each calculated or determined using tables, nomographs, and various other sub-equations and algorithms. The USLE is a statistical model and requires relatively few input parameters which add to its universal appeal.

Various researchers have applied the USLE to their local conditions in order to gain an estimation of erosion in their countries (Rojas, 2002; Crosby, McPhee & Smithen, 1981; Ogawa *et* al., 1997; Mongkolsawat *et* al., 1994) and have achieved mixed results. These results indicate the variability of the USLE to conditions other than that of the eastern part of the USA where the plot studies, which initiated the development of the equation, where held. In this study, data and methods, for determining the input parameters for the USLE, have been obtained from South African researchers who have modified the sub-factors to South African conditions.

The USLE is a factor model; the sub-factors which make up the equation each have their own description and evaluative purposes. The equation is as follows:

$$A = R * K * LS * C * P$$

where

A = The mean annual soil loss (in ton.ha^{--1}.yr^{-1})

R = Rainfall and Runoff Erosivity Index (in MJ/ha/mm/yr)

K = Soil Erodibility Factor (in ton/MJ/mm)

LS = Slope and Length of Slope Factor

C = Cropping – Management Factor

P = Erosion Control Factor Practice

The following sections describe these factors in more detail.

2.6.1 Rainfall and Runoff Erosivity Index

The rainfall and runoff erosivity index (*R*) for a given location is expressed in MJ/ha/mm/yr (Wischmeier & Smith, 1978). The erosion index for a given storm is a product of the kinetic energy of the falling raindrops and its maximum 30-minute intensity (Engel, 2002). The sum of these EI values over a year divided by 100 give the annual *R* factor (Engel, 2002).

2.6.2 Soil Erodibility Factor

The soil erodibility factor (*K*) is the soil loss rate per erosion index unit (in ton/MJ/mm) for a specified soil as measured on a unit plot (Wischmeier & Smith, 1978). A unit plot can be defined as a standard condition of bare soil, recently tilled up-and-down slope with no conservation practice and on a slope of 9° and 22 m length (Morgan, 1995).

2.6.3 Slope and Length of Slope Factor

The factors of slope length, *L*, and slope steepness, *S*, are combined in a single index which expresses the ratio of soil loss under a given slope steepness and slope length to the soil loss from a standard condition of a 9° slope, 22 m long, for which *LS* = 1.0 (Morgan, 1995). Nomographs can be used to obtain this factor (Wischmeier & Smith, 1978) or the factor can be calculated from the following equation:

$$LS = (x / 22.13)^n (0.065 + 0.045 s + 0.0065 s^2)$$

where

x = slope length (m)

s = slope gradient (%) and

n = 0.5 for a slope > 5%, 0.4 for slope between 3.5 - 4.5%, 0.3 for a slope l - 3.5%, and 0.2 for a slope less than 1%.

All things being equal, the steeper the slope, the greater the soil erosion, soil erosion is more severe on long slopes than on short ones as the velocity of the water increases on long, unobstructed downhill stretches (Kelley, 1990).

2.6.4 Cropping – Management Factor

The vegetation cover, and especially ground (surface) cover, is perhaps the most important modelling factor as it represents conditions that can be managed to reduce erosion (Smith, van Zyl, Claassens, Schoeman & Laker, 2000). The Crop and Management factor is the ratio of soil loss from one area with specified cover and management to that from an identical area in tilled continuous fallow (Wischmeier & Smith, 1978). *C* values for a particular area are calculated from soil loss ratios representing six cropstage periods (rough fallow, seedbed, establishment, development, maturing crop and residue/stubble) and three levels of canopy cover at the mature stage (Stocking, 1994).

2.6.5 Erosion Control Factor Practice

The values for the support practice (P) factor are the most uncertain of all the factor values in the USLE (Renard *et al*., 1993). This is mainly as a result of the varying erosion control practices in existence worldwide together with its questioned applicability in all farming conditions. P is the ratio of soil loss with a support practice like contouring, strip cropping, or terracing to that with straight-row farming up and down the slope (Wischmeier & Smith, 1978).

2.7 Calculation of soil loss using SLEMSA

SLEMSA was developed largely from data from the Zimbabwe highveld. According to the model's creator Elwell (1996), the SLEMSA framework is a systematic approach for developing models for estimating sheet erosion from arable lands in southern Africa. The model is based upon a body of experimental data supplemented by data extrapolation in which process relationships are assumed (Stocking, 1980). It is also designed to incorporate the practical advantages of empirical methods with the greater flexibility of introducing variables that have not been individually monitored (Stocking, 1980). Elwell (1978) acknowledged that this compromise would lead to a loss of accuracy but argued that for a developing country, such as Zimbabwe (and indeed South Africa!) immediate answers of the right order of magnitude were needed urgently in order to plan for conservation.

The SLEMSA model is still in its infancy stage, and it is hypothesised that when fully developed, it will have required less than one sixth the capital and one third the labour of that needed to develop the USLE to an equivalent degree of proficiency (Elwell, 1981). It's definitive appeal lies in its relative ease of use and limited data requirements. According to Stocking (1980) SLEMSA has various other advantages for developing countries, in that:

- it combines reasonable accuracy without the need for excessively elaborate and expensive field experiments
- flexibility is maintained by the use of rational and easily-measurable parameters such as rainfall interception
- refinement and up-dating of information can be incorporated as and when new data become available

As is indicated in Figure 2.1, the SLEMSA model divides the soil erosion environment into four physical systems: crop, climate, soil and topography. Major control variables are then selected for each system on the basis that they should be easily measurable and the dominant factor within each system (Stocking, 1980). These control variables are subsequently combined into three sub-models; the bare soil submodel, topographical submodel, and the crop submodel. The main model is then simply the three submodels multiplied together. The SLEMSA equation is as follows:

$$Z = K * C * X$$

where

Z = the mean annual soil loss from the land (in $tons.ha^{-1}.yr^{-1}$)

K = Erodibility Factor (in $tons.ha^{-1}.yr^{-1}$)

X = Topographic Factor

C = Crop factor

The following sections describe these factors in more detail.

2.7.1 Erodibility Factor

The erodibility factor (*K*) is the annual soil loss ($tons.ha^{-1}.yr^{-1}$) from a standard conventionally tilled field plot 30m by 10m on a 4,5% slope for a soil of known erodibility, *F*, under a weed free fallow (Stocking, 1980). The erodibility factor is determined from the rainfall energy and soil erodibility control variables.

2.7.2 Crop factor

The crop factor (*C*) is the ratio of soil loss from a cropped plot to that lost from bare fallow land (Stocking, 1980). It is derived from the energy interception factor, *i*, which is determined by the crop type, yield and emergence date for crops, natural grasslands, dense pastures and mulches (Mughogho, 1998).

2.7.3 Topographic Factor

The topographic factor (*X*) is the ratio of soil loss from a field slope of length, *L*, in meters and slope percent, *S*, to that lost from a standard plot (Stocking, 1980).

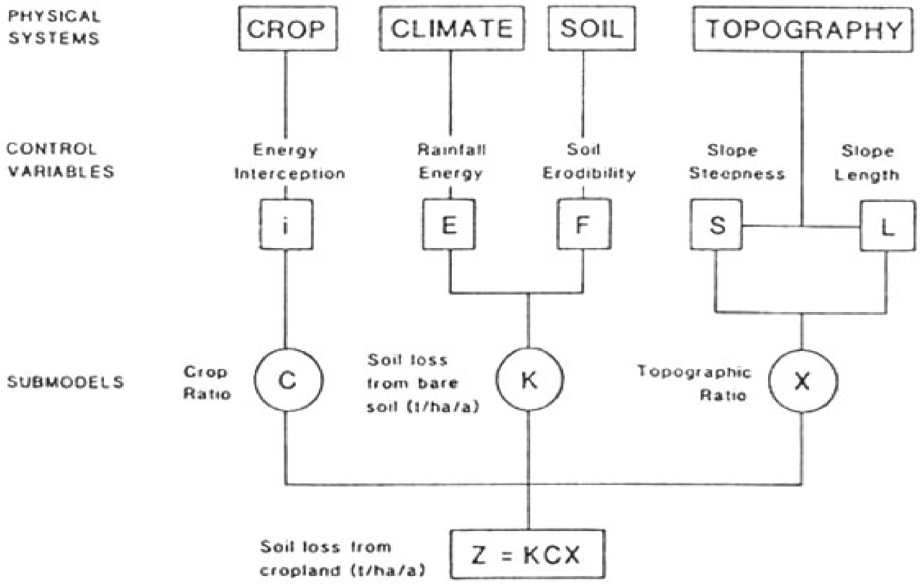


Figure 2.1: Structure of SLEMSA (Elwell, 1981)

2.8 Limitations of the USLE and SLEMSA models

The erosion models selected for this study, namely USLE and SLEMSA, have various theoretical and practical limitations as well as numerous inherent differences between them. In this section the main practical and theoretical limitations of these models are examined, and the differences outlined enlight of the study that will be undertaken subsequently.

2.8.1 Practical limitations of the USLE and SLEMSA models

2.8.1.1 Problems associated with absolute boundaries

Both USLE and SLEMSA are aimed at determining soil loss on arable land below 20% slope (Bonda *et al*., 1999). In developing countries such as South Africa, in rural areas, where poverty is rife and land is at a premium, cultivation of crops occurs on slopes that are well above the 20% slope limitation (Bonda *et al*., 1999), resulting in inaccurate results based on conditions not representative of the model. Both models were additionally designed to estimate soil loss for seasonal rainfall and not single or monthly rainfall, however there are some places where annual rainfall amounts are very low or very high hence these "outliers" may not give good predictions of soil loss in such areas (Mughogho, 1998).

2.8.1.2 Lack of SLEMSA literature for the estimation of regional input parameters

A major practical limitation, particularly of SLEMSA, is that South African regional input parameters are not available in any SLEMSA literature. This may be because of the relative newness of the model's development or because of the general lack of funds in establishing field observations to satisfy this demand. This often results in very subjective assumptions based on land-use practices and farming methods.

2.8.1.3 Scale limitations

A major limitation of not only USLE and SLEMSA but of most erosion loss models is scale-related. The hillslope erosion models such as SLEMSA or USLE have often been used in erosion hazard mapping at regional and national scales, despite the fact that they were developed as conservation planning tools for farmers (Bonda *et al*., 1999).

> *"Problems of scale can obfuscate the magnitude of soil loss critical in understanding erosion and sedimentation. For example, only 10 percent or less of the calculated soil lost from a hillslope may actually be transported out of a drainage basin. The remainder is simply moved and deposited somewhere between the hillslope and the large drainage basin. Thus, most soil loss estimation techniques, including the USLE and*

SLEMSA model, fall short in their ability to capture scale issues associated with erosion hazard assessment" (Bonda *et al*., 1999).

The issue of scale will be discussed at length in Chapter 6.

2.8.2 Theoretical limitations of the USLE and SLEMSA models

It is somewhat of a wonder from both an academic and a practical viewpoint that the USLE's appeal has had the support and longevity that is has. Many criticisms have been levelled against this empirical model, yet it continues to be treated as the definitive soil loss estimation model worldwide. A few theoretical limitations of both models are briefly explained.

2.8.2.1 Lack of factor interdependence

A major theoretical problem with the USLE and SLEMSA models is that soil erosion cannot be adequately described merely by multiplying together factor values. Both models rely on the false assumption that the factors in erosion can be treated separately (although SLEMSA does attempt to accommodate this problem to a certain extent) (Stocking, 1980), and disregard the considerable interdependence between the variables which is not taken into account. For instance, rainfall influences the *R* and *C* factors and terracing the *L* and *P* factors (Morgan, 1995). Other interactions, such as the greater significance of slope steepness in areas of intense rainfall, are ignored (Morgan, 1995).

2.8.2.2 Applicability of model

The theoretical basis of the USLE model was developed on terrain in the eastern half of the USA. The model has not been comprehensively tested and calibrated to determine its exact practicality in a South African environment.

2.8.3 The differences between USLE and SLEMSA

As mentioned earlier, SLEMSA was developed on the basis of the USLE; it would therefore be logical that there would be some similarities but also distinct differences between the two models. These differences between the USLE and SLEMSA models will obviously be portrayed in the results obtained in the study. It is, however, important to understand these differences from the outset in order to be able to interpret which result can be deemed the most applicable to the study site.

The main differences between the two empirical models, according to Hudson (1993) are the following:

- The *P* factor of the USLE is left out in SLEMSA because it is felt that the effects of local conservation practices can be allowed for in factors *L* or *S* within the topography system, or erodibility *F* in the soil system;
- The other factors in the USLE are quantified by methods in SLEMSA which are simpler to calculate or require less data. For example:
    - *R* (in USLE) is replaced by *E* in SLEMSA, and is a measure of the total kinetic energy of the rainfall, which is easier to calculate from rainfall records than *EI* (from USLE).
    - *C* (in USLE) is replaced by a different *C* in SLEMSA and is determined from *i*, the density of crop cover which is measured in the field at 10-day intervals over the 180-day growing season. *C* is expressed as a ratio of the soil lost from a cropped plot to that lost from a bare fallow. SLEMSA can be used to estimate the soil loss from rangeland using a lightly different sub-model to relate *C* to *i*.
    - *K* (in USLE) is replaced by *F* in SLEMSA which is a soil erodibility index and based on soil type. SLEMSA also attempts to address the complexities of vegetation and management by incorporating management effects into soil erodibility on the basis that ploughing, residues, and other standard management practices basically affect the susceptibility of the soil to erosion (Stocking, 1994).

- *LS* (in USLE) is replaced by *X* in SLEMSA calculated in a very similar manner but with slightly different equations

Lastly, from a non-technical viewpoint, SLEMSA uses the topographic factor developed for the USLE, adjusted to reflect a standard plot with 4.5% slope on a 30m long plot, instead of the 22m long, 9% slope plots used for the USLE (Bonda *et* al., 1999). Additionally, validation of findings are made easier in SLEMSA where findings can be tested against a single year's soil loss data provided that the values of the control variables are accurately measured on the site (Elwell, 1996), this is in sharp contrast to the USLE which requires 30 years necessary to validate results (Soil Conservation Society of America, 1976).

2.9 Chapter Summary

Soil erosion is a long lasting problem in South Africa. It has political, environmental, economic and societal implications for the country as a whole and it is important that potential erosion areas are identified and conserved. Soil erosion models are used as a means of quantifying the susceptibility of an area to erosion. There are many such erosion models that have been developed. The two most important models, which were selected for use in this study, are the USLE and SLEMSA models. Both these models are not without practical and theoretical limitations but both are well-established models, which have been previously used, in southern Africa.

Chapter 3: GIS and erosion modelling

3.1 Introduction

We have witnessed from Chapter 2 the nature and extent of soil erosion in South Africa. The predominant soil erosion models used to quantify this phenomenon have also been identified and the selected soil loss estimation models to be used in the study, namely USLE and SLEMSA, have also been elaborated upon. This chapter investigates the unique role that GIS can play in soil loss estimation. It examines the nature of GIS, and investigates predominant GIS modelling software used to estimate soil loss.

3.2 GIS Technology

> *"GIS technology is to geographical analysis what the microscope, the telescope, and computers have been to other sciences.... (It) could therefore be the catalyst needed to dissolve the regional-systematic and human- physical dichotomies that have long plagued geography"* (Abler, 1988)

There have been many attempts to try and find a definitive explanation to what a GIS is and does. Perhaps these many attempts illustrate the magnitude of the task at hand. GIS is not simply a definable subject that can be confined to a specific field of study. According to Burrough (1986) a GIS is: ‘ a system for capturing, storing, checking, integrating, manipulating, analyzing and displaying data which are spatially referenced to the Earth.’ The components that make up a GIS include that of computer systems and software, spatial data, data management and analysis procedures and lastly people and geographically referenced data.

GIS has been called an "enabling technology" because of the potential it offers for the wide variety of disciplines which must deal with spatial data (Cowen, 1997). GIS not only has the ability to integrate various different technologies but also has the capability of integrating these various scientific disciplines into one concise system. This is the appeal of GIS particularly to soil loss estimation. The most important aspect of GIS related to the scientific discipline of soil erosion is that of the spatial element. Before the conception of computer-based GIS, soil loss estimations were limited to statistical charts and tables outlining figures. Add to that the spatial component that defines a GIS and you have an illustrated map of potentially high-risk erosion spots that would be interpretable by the average farmer. This map is produced as a result of the ability of GIS technology to represent the real world as spatial objects and subsequently model these objects according to an equation, algorithm, or nomograph. Figure 3.1 illustrates the 4 subsystems which govern a GIS.

DATA PROCESSING SUBSYSTEM

- Data acquisition - from maps, images or field surveys
- Data input - data must be input from source material to the digital database
- Data storage - how often is it used, how it is updated

DATA ANALYSIS SUBSYSTEM

- Data retrieval and analysis - may be simple responses to queries, or complex statistical analyses of large sets of data
- Information output – displaying the results as maps or tables. Or the information is fed into some other digital system.

INFORMATION USE SUBSYSTEM

- Users may be researchers, planners, managers etc.
- Interaction is needed between GIS group and users to plan analytical procedures and data structures.

MANAGEMENT SUBSYSTEM

- Organisational role - GIS section is often organised as a separate unit within a resource management agency offering spatial database and analysis services
- Includes staff, procedures and maintenance

Figure 3.1: GIS subsystems (Adapted from Cowen, 1997)

3.3 GIS spatial modelling

Spatial models have been in use for a long time, but only recently has the functionality of GIS been incorporated into physical and empirical models to reproduce reality in a spatial way. Erosion-based spatial models are used by most governmental agencies at all levels to set regulations for erosion control practices for agriculture, construction, and forestry operations (Rojas, 2002), as well as to increase and synthesise our knowledge of soil erosion and conservation science (Morgan, 1995).

Soil loss estimation involves the modelling of a spatial system. But what is the purpose of a spatial model? In GIS, spatial modelling is used to analyse phenomena by identifying explanatory variables that are significant to the distribution of the phenomenon (i.e. in the case of erosion modelling; e.g. climate, soil type, vegetation) and providing information about the relative weight of each variable. A second purpose of spatial modelling answers "what-if" questions by evaluating alternative hypothetical situations (Chou, 1997). In this way GIS is able to provide techniques for conducting spatial analysis and developing a spatial perspective on the research conducted (Cowen, 1997). In the next section we will briefly examine the path that GIS modelling software has taken since its conception as well as identify various GIS erosion modelling software currently available.

3.4 GIS erosion modelling software

According to Eastman (2001), GIS modelling software has followed somewhat of an evolutionary path, beginning when modelling tools were macro languages (e.g., Arc/Info *AML*, ERDAS *EML* and IDRISI *IML*); followed by the development of the map calculator (which is excellent for the implementation of models that can be expressed as equations using the operations typically associated with a scientific calculator); followed by the development of two new modelling approaches called the Component Object Model (COM) client/server model and the graphical modelling medium. Both these models offer not only the ability to automate complex tasks, but the promise of profoundly changing the nature of GIS modelling itself (Eastman, 2001). COM, in particular offers the capability to create complex models with customised interfaces based on the capabilities of the host GIS software (Eastman, 2001). Each of these modelling software utilities offers the user a platform from where model estimations can be made.

Attempts have been made to make erosion-modelling software exist either as a stand-alone application or in conjunction with a variety of other software interfaces. There are typically three types of GIS modelling applications, they are:

- Third-party application
- Browser interface
- Stand-alone application

Arc/Info and ArcView GIS, developed by the Environmental Systems Research Institute (ESRI), are the most commonly used GIS software packages for soil erosion modelling. A few examples of the three above-mentioned modelling types are provided which illustrate the increasing popularity of GIS software developers to integrate soil erosion modelling software with existing GIS platforms.

3.4.1 Spatial Analyst, hydrologic and watershed delineation extensions

The most common and simplest way of estimating soil erosion using ArcView GIS is via the spatial analyst, hydrologic and watershed delineation extensions. These extensions exist as add-ons to the ArcView GIS software developed by ESRI. The Spatial Analyst extension is used to create the grid themes such as the Digital Elevation Model (DEM), from which the slope-length, and other factors in the USLE, can be determined. The Hydrologic and Watershed delineation extensions are used to calculate the flow accumulation grid formerly, and latterly, to delineate the watershed boundaries. A major advantage of ArcView GIS is its ability to spatially break down factor values into finite grid cells which allows the USLE to show spatial trends in the erosion estimates (Haws, 2000).

3.4.2 ANSWERS

ANSWERS is the acronym for Areal Non-point Source Watershed Environmental Response Simulation model. This event-oriented, distributed parameter model is designed for erosion, sediment and water quality control planning on complex, agricultural watersheds. The model divides catchments into square elements (grid cells) and uses the connectivity of the cells (derived from slope aspect values) and a continuity equation to route flow to the catchment outlet (Beasley & Huggins, 1982). The ANSWERS model uses flow-routing algorithms and GIS maps to predict erosion and run-off (Flanagan, Renschler & Cochrane, 2000).

3.4.3 GeoWEPP

GeoWEPP is an acronym for the Geo-spatial interface for WEPP (Water Erosion Prediction Project model described in Chapter 2). GeoWEPP utilises digital geo-referenced information such as digital elevation models (DEM) and topographical maps to derive and prepare valid model input parameters and defaults to start site-specific soil and water conservation planning for a small watershed with a single soil and land use for each sub-catchment (Renschler, 2002). Web-based model interfaces for WEPP have also recently been developed in 2002 and thus far have proved to be successful provided appropriate and accurate DEM data is available (Flanagan, Renschler & Cochrane, 2000). An accurate DEM is required since "the primary layer required in a GIS to delineate hillslopes and channels is a topography map." This delineation results in an essential input parameter for the model.

3.4.4 LISEM in PCRaster

PCRaster is a GIS that consists of a set of computer tools for storing, manipulating, analysing and retrieving geographic information (van Deursen, Wesseling, Burrough & Karssenberg, 2002). It includes

1) an Environmental Modelling language
2) a program Gstat for Geostatistics, and
3) modules for GIS functions.

The Limburg Soil Erosion Model (LISEM) is an example of a physically based hydrological and soil erosion model that has been fully developed in PCRaster.

LISEM is written in a prototype GIS modelling language currently developed at the University of Utrecht; the language comprises all PCRaster commands and currently includes only 200 lines of code (De Roo *et al.*, 1994). This is another major advantage of incorporating an erosion model in a GIS modelling software application as the 'source code' of the model then resides on the comprehensible abstraction level of one or two lines of source code, a GIS command, per process (e.g. interception, infiltration and sediment routing) (De Roo *et al*., 1994). This allows for manipulation of the code should the model extend its functionality in any way. Customisation per application is also then easily made possible.

3.4.5 SEAGIS

The SEAGIS (Soil Erosion Assessment using GIS) extension is a GIS-based application for soil erosion risk assessments. The Danish Hydrologic Institute (DHI) – Water and Environment, is currently marketing SEAGIS. SEAGIS operates according to the process outlined in Figure 3.2.

Firstly, the source erosion for each model is calculated. This is calculated through the multiplication of each factor in the USLE and applies to the soil eroded from each grid cell. From the source erosion grid, the transported erosion is determined, by multiplying the source erosion with a delivery ratio. The delivery ratio is estimated as a function of the amount of water expected to run through a given cell, the slope and the likelihood of deposition of material further down in the catchment (Lea, 1992). The transported erosion describes the amount of eroded soil reaching the catchment outlet. The application has been made as an ArcView GIS extension. It requires the basic ArcView and Spatial Analyst extension to run.

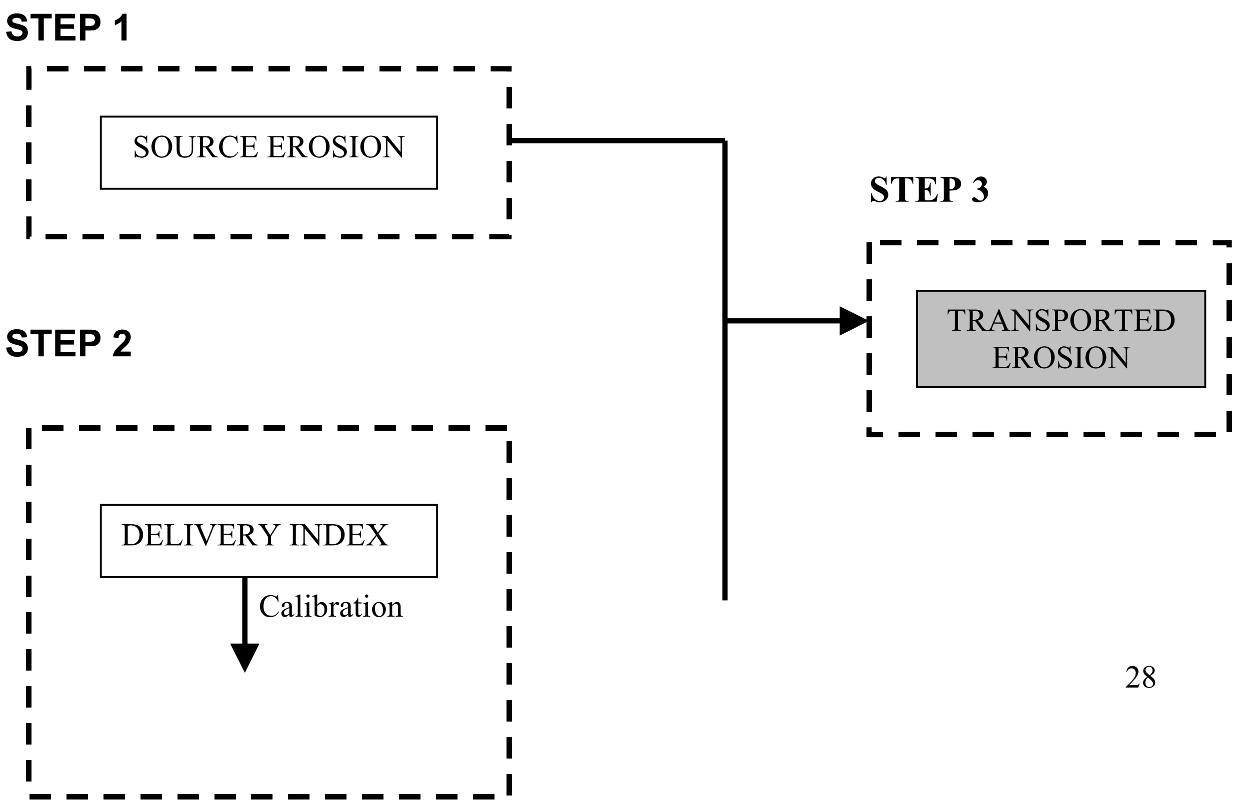


Figure 3.2: SEAGIS process of soil loss estimation (SEAGIS Documentation and User Guide, 1999)

3.5 Modelling utility selected for this study - SEAGIS

The SEAGIS modelling system is an example of a third-party application and exists as a separate extension to the ArcView GIS software package. The software requires the user to generate grids for each soil erosion model factor chosen for the application. Map algebra and data analysis on the grids are conducted using the ArcView GIS package that, in effect, acts as the host for SEAGIS.

It was decided to use SEAGIS in the study for three reasons; firstly, because it is a relatively new software utility sold by one of the leading developers in hydrological modelling software in Europe, namely DHI – Water and Environment; secondly, it offers an easy-to-use interface and is compliant with licensed ArcView software and thirdly, and most importantly, SEAGIS has tested applicability and has been used in various areas as a concrete tool in the accurate assessment of erosional hazards in a variety of environments including, among others, the Philippines (FMB-DENR, 1998).

3.6 Investigation of the Graphic User Interface (GUI) of SEAGIS

GIS user interface design is a cumbersome exercise in which detailed programming skills are required and most often the tools provided are only remotely suitable for designing user interfaces for dealing with geographic data (Egenhofer, 1995). GIS user interface design tools such as ArcView GIS, allow system designers the opportunity to build customised GIS user interfaces rapidly and at a high level, without the need to invest into learning low-level graphics programming, much like most user interface management systems (UIMS) require (Egenhofer, 1995). It is the role of the software designer, especially with emphasis on modelling applications, to ensure that the GUI's of erosion models are simple, clear and concise.

Foster, Lyon, Lown & Yoder (2002) proposed many principles of interface design. The SEAGIS GUI is described according to these principles.

- *Work with user objects*

*SEAGIS bases the interface on the user's objects (*soil, residue, vegetation, etc.*), and not on the model's objects (*homogenous segments, overland flow elements, etc.*)*

- Reduce information overload

SEAGIS conceals irrelevant same-level and low-level data; the interface deals with each factor in the erosion equations in different interfaces, thereby reducing the amount of information of the GUI at any one time.

- *Minimise input*

In the SEAGIS application the user enters all the information in only one dialogue box per factor value and only what is needed as input is stated in the dialogue boxes.

- Support interaction among diverse users

SEAGIS provides descriptive/iconic inputs and hides details from less experienced/technical users. There is only one level of use for the user; the GUI is aimed at those knowledgeable in the field of soil erosion theory.

- Ensure that the model is complete at all times

The model requires that the user specifies the input parameters directly through the interface or no results are obtained.

- Adapt to user work style

SEAGIS doesn't allow the user to specify the start-up configuration, default objects and any other configurations in the software. The model has a standard work style which comes as regulation with the software.

3.7 Chapter Summary

GIS is a tool that is invaluable in the estimation of soil loss through modelling. It is evident that the development of hydrological and erosion modelling tools are at the forefront of GIS software development. The selected modelling utility for the study is the ArcView GIS software extension called SEAGIS. The SEAGIS extension doesn't comply on all accounts with the "principles of interface design" specified by Foster *et al.*, (2002), but is still an emerging product that has been successfully calibrated and used in various studies worldwide.

Chapter 4: Theoretical background

4.1 Introduction

Chapter 4 provides the theoretical background for the study. The chapter includes a thorough background description of the physical and human environment in which the study occurs. Cognisance is paid, in particular, to the topography, climate, vegetation, and soil and land coverage characteristics of the physical environment; while within the human environment, issues such as land-use history, socio-cultural conditions and development plans and projects within the study site are examined.

4.2 Physical Environment

In this section the physical environment in which the study site occurs is comprehensively examined. The physical characteristics of the study catchment, namely, geographic location, soil characteristics, vegetation, climate and drainage, among others, all play contributing roles in soil erosion. These and other characteristics are therefore important in the study and are examined hereafter.

4.2.1 Geographic location

The study area extends over the Bushman’s River in the KwaZulu-Natal province of South Africa, 15 kilometres from the bordering country of Lesotho (Figure 4.1). It extends from 29º 30' 36" S, 29º 8' 24" E to 29º 52' 48" S, 29º 5' 24" E and has a surface area of approximately 341,4 km^2.

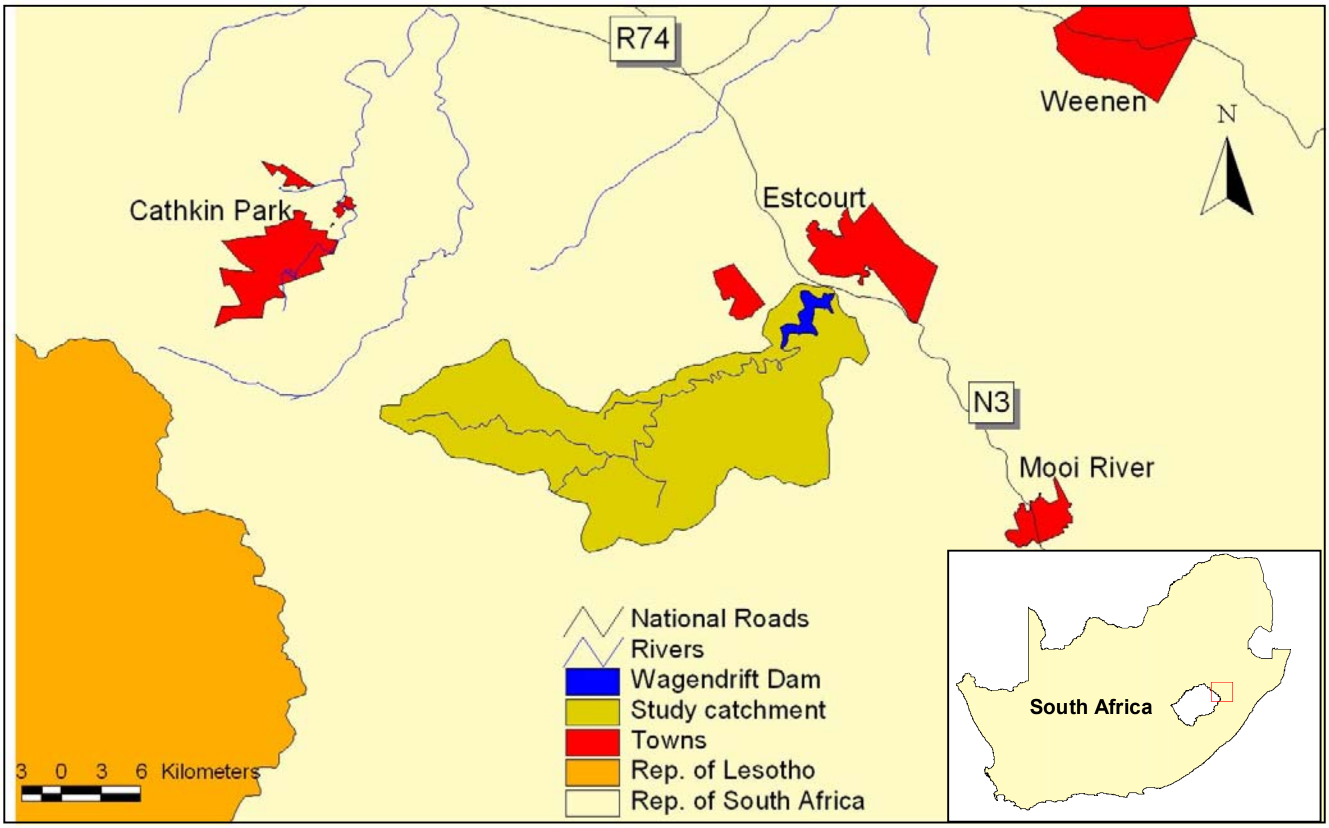


Figure 4.1: Location of the catchment/study site

4.2.2 Flora and wildlife

The catchment is located on the peripheral region of the Natal Drakensberg mountain range. The Drakensberg mountain range region harbours numerous endemic faunal and floral species; includes two of the seven major floristic regions of southern Africa; has the largest concentration of Bushman rock art in the sub-continent, and is representative of the post-Gondwana Cretaceous African erosion surface (Hudson, 1987).

The area is characterised by a large amount of wildlife. Among the mammals that roam the area are bushbuck, caracal, impala and zebra. Over 200 different species of birds are found within the catchment. The Little Tugela and Bushman's river, which are the main tributaries of the catchment, are famous for trout fishing, especially of the scaly *Barbus* *natalensis* and the brown trout *Salmo trutta* variety (Wagendrift Reserve Information Brochure, 2002).

4.2.3 Topography

The altitude of the catchment ranges from 1160m (above mean sea level) at the Wagendrift Dam, at the outlet of the catchment, to 2080m at the Giant's Castle Reserve at the western corner of the catchment. This insidious rise in elevation is evident in the Digital Elevation Model (DEM), which was created by the author, and provided in Figure 4.2. River valley plains and terraces dominate the central topography. The catchment area is characterised by high elevations, deeply incised valleys and long, steep slopes mainly covered by grassland. The geology of the area consists mainly of shales and sandstones of the Beaufort Group (Bijker, 2001). The most characteristic feature of the catchment are the stream valleys that rise sharply from the stream channels, indicating the strong incising path that the stream is cutting into the river channel. This illustrates the strong erosive potential of the Bushman River, and alludes to the siltation of the Wagendrift Dam which will be elaborated on later in the chapter.

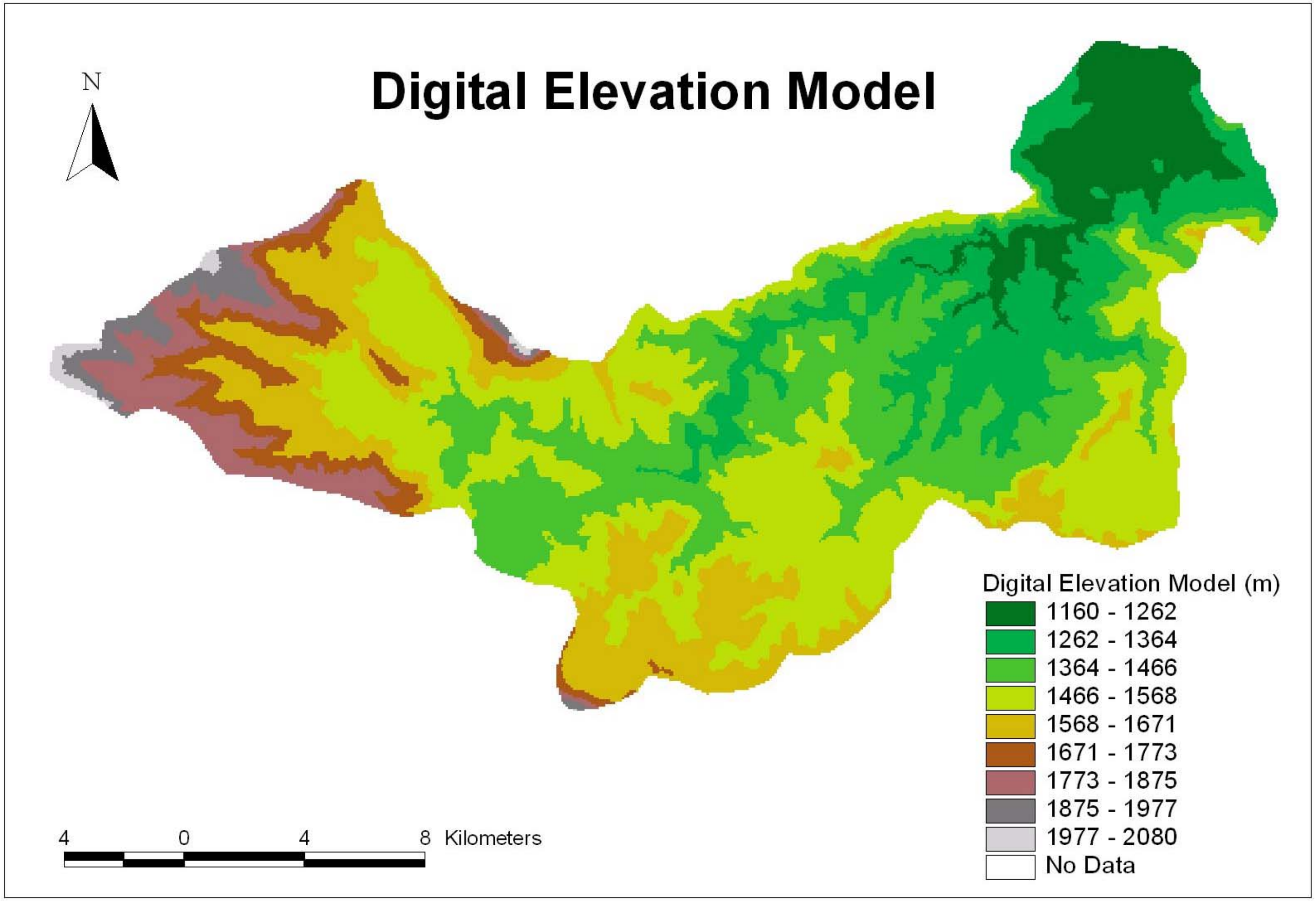


Figure 4.2: Digital Elevation Model (DEM) of the catchment

4.2.4 Climate

The catchment receives an annual average rainfall of 932mm. The catchment's rainfall displays a relatively steady pattern over the last fifty years, with the intermittent periods of high rainfall followed by periods of low rainfall. Rainfall is concentrated in the summer months (November - March) with the winter's months (May – August) receiving as low as 10mm of rainfall per month. The coefficient of variation of the mean annual rainfall is 18%, which is a reflection of the low variation of the catchments rainfall over the last 50 years.

Figures 4.3 and 4.4 indicate the mean monthly rainfall and the annual rainfall chronology for the catchment. The latter figure illustrates the variability of the rainfall. KwaZulu-Natal did, however, experience numerous floods in the 1990's. These periods of intense rainfall have significant implications in terms of run-off and erosion.

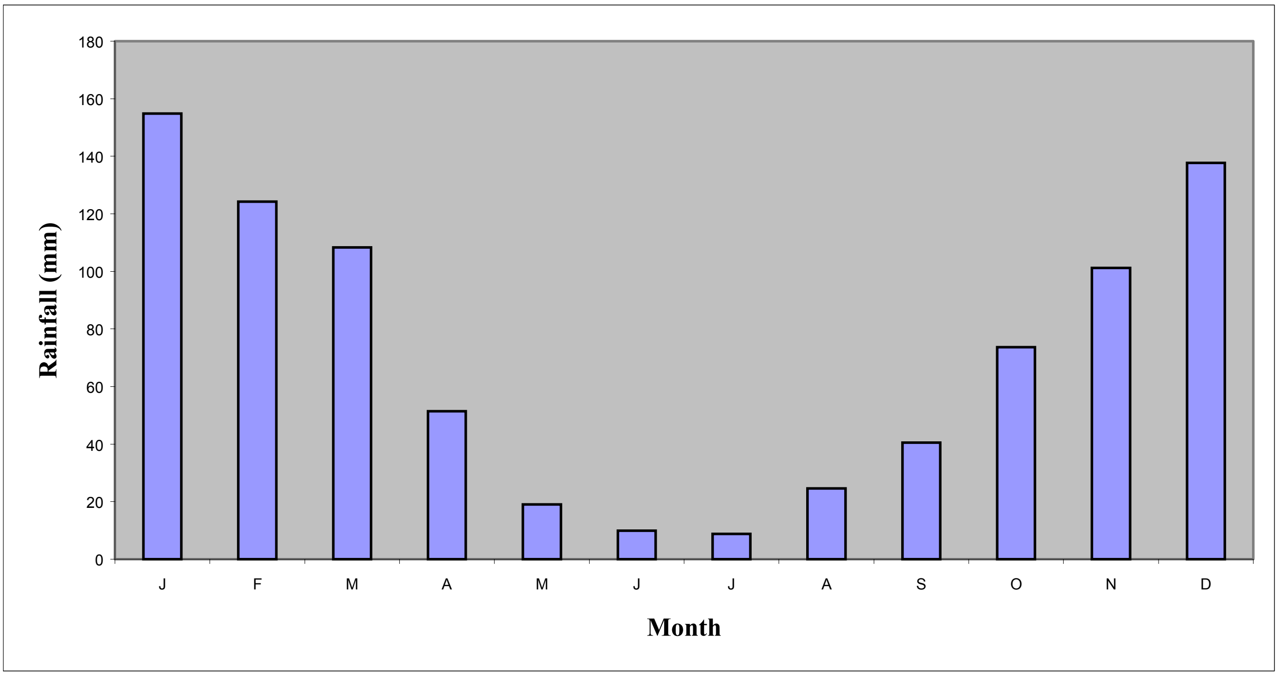


Figure 4.3: Mean monthly rainfall for the catchment (1950 – 2000)

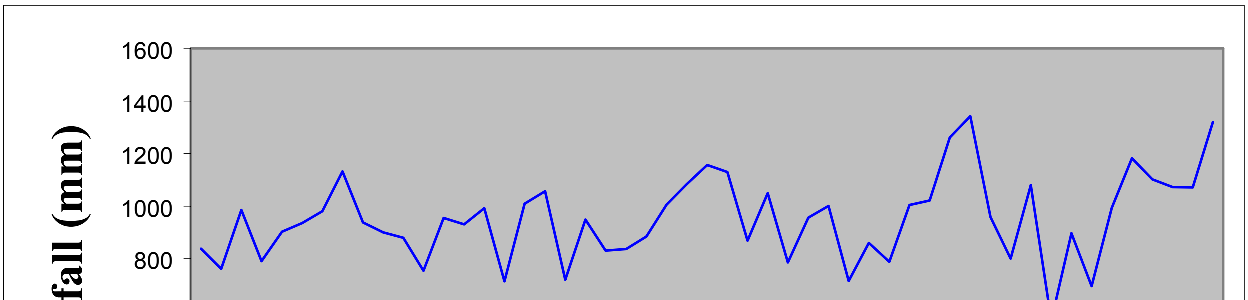


Figure 4.4: Annual rainfall chronology for the catchment (1950 – 2000)

4.2.5 Water Features

The most notable water feature in the catchment is the Wagendrift Dam which lies at the outlet of the catchment. A picture of the dam wall is shown on Figure 4.5 below.

Figure 4.5: Wagendrift Dam wall at the outlet of the catchment

The Wagendrift Dam is a man-made dam that was built to supply the rural town of Estcourt with water supply. Estcourt is approximately 7 kilometres away from the dam. The construction of the dam is described as a multiple double curvature arch dam. It is the first of its kind constructed in the world and was completed in 1964. The Wagendrift Dam was designed to contain 60 million cubic meters of water, which is far in excess of the foreseeable demand (Estcourt, 1998).

Table 4.1: Details of the Dam (Report from Department of Water Affairs and Forestry, 1999)

Statistics		
Full Supply Level	Above sea level	1179.58m
Gauge Plate Reading	At full supply	30.46m
Evaporation Area	At full supply	508.38ha
Shore length	At full supply	23km

Survey Date	Capacity (million m^3)	% Rise in sediment
1963 1983 1999	59.957 58.455 55.899	0.0 2.50 6.77
Average rate of sedimentation per year I.e.		0.19% (303 5294 tons/yr)
Survey frequency		15 years

An important detail in this report is the relatively high sedimentation rate. The average rate of sedimentation per year is 0.19%. There are numerous perennial rivers in the catchment draining to the Wagendrift Dam at the catchment outlet. The Wagendrift Dam itself is built on the Bushmen's River which has its source in the Giant's Castle area of the Natal Drakensberg Park. From Wagendrift, the Bushman's River flows through the town of Weenen before it joins the Tugela River. Numerous pans, and wetlands are also evident in the catchment and serve to provide the local inhabitants with drinking and cleaning water, or for any other purpose that can be deemed usable by the locals.

4.2.6 Land Coverage

The following table shows the percentage of land coverages of the catchment:

Table 4.2: Percentage land coverages of the catchment (Land Types according to the CSIR - SAC, 2001)

Land Coverage	Area (km^2)	%
Unimproved grassland	278.2	81.5
Forest Plantations	18.7	5.5
Thicket and scrubland	16.4	4.8
Cultivated: temporary – commercial dryland	6.3	1.9
Cultivated: temporary – subsistence dryland	5.8	1.7
Urban built-up land – residential	5.6	1.6
Waterbodies	5.6	1.6
Cultivated: temporary – commercial irrigated	2.2	0.7
Indigenous Forest	1.5	0.4
Improved Grassland	1.1	0.3
Total	341,4 km^2	

NOTE: These land cover types are in accordance with the land classification of the CSIR's – Satellite Application Centre of South Africa. A comprehensive explanation of each land cover type according to the CSIR - SAC guidelines are provided in Appendix 1.

The area is predominantly covered in unimproved grassland. According to the Council for Scientific and Industrial Research (CSIR) (2001) the unimproved grassland land coverage type consists of indigenous species of grassland growing under natural conditions while the improved grassland includes either exotic or indigenous grassland that has been grown under man-made conditions for grazing or some other purpose. Section 4.2.7 deals in more detail with the characteristics of the grassland vegetation type. The high proportion of grass coverage in the area puts the catchment at risk for numerous types of erosion. Footpath erosion is evident in the catchment as a result of the large amount of cattle tracks. Overgrazing and the resulting loss of vegetative cover have resulted in various forms of sheet, rill and gully erosion often creating impressive erosional features.

The forest plantations in the area are owned by Mondi Forests Pty (Ltd). Mondi Forests use the forest for timber, pulp logs, saw logs and other products. Mondi Forests Division currently owns and manages about 638 000 hectares of forest in South Africa and yields 6,4 million tons of wood annually (Mondi Limited, 2002). Only a small fraction of the land coverage is occupied by indigenous forest. There is restricted access to all the forested areas in the catchment making field observations in these areas difficult (see Figure 4.6).

A small portion of the catchment (only 5% ≈ 14,3 km^2) is designated as subsistence and/or commercial agriculture. These consist of the 6 white-owned commercial agricultural holdings in the catchment and the countless rural and informal settlements where subsistence agriculture is practiced. These settlements are known to accelerate erosion in South Africa (Garland *et al*., 1999).

Figure 4.6: Authorised entry to the forest plantations in the catchment

4.2.7 Vegetation

The catchment's dominant vegetation type is southern tall grassveld, which is characterised by alternating tall and short grasslands, interspersed with thorn tree woodland (NCS, 2002). Along the drainage lines *Podocarpus* species are common, and scattered on the higher altitudes; the *Protea* species occur with *Acacias* lower down the valley in most Drakensberg environments (Bijker, 2001). Calpurnia *woodii*, a yellow flowered shrub, which grows to three metres in height, occurs in some areas of the catchment. Major plant community differentiation in the area is usually related to climate (rainfall and temperature) associated with altitude (Bijker, 2001).

Physiognomic classification of the catchment vegetation types:

i) Short *Themeda triandra* grassveld

The Highland sourveld and Dohne sourveld covers the vast majority of the catchment. This is a dense, tough grassland veld type with a high carrying capacity in summer but which becomes fibrous and unpalatable in winter (Acocks, 1988). The soils of this veld type are chiefly acid, leached types, differing according to their parent materials (Acocks, 1988).

ii) Southern Tall grassveld

The Southern Tall Grassveld is a veld type that is characterised by scattered thorn trees and shrubs. Soils characteristic of this type of veld have erodible subsoil as well as a shallow topsoil (300 – 450 mm), which makes erosion very severe on this veld type (Acocks, 1988). An issue of concern is the loss of Southern Tall Grassveld, which is poorly conserved in KwaZulu-Natal with only 0,9% being formally conserved and 12% of this conserved in the Midmar Game Reserve (South African Government Gazette, 2000).

iii) *Themeda-trachypogon* highlands grassveld

This highlands grassveld is dominated by relatively short bunches of grasses up to 1,09m high (Acocks, 1988). The soils of this veld type are relatively deep, but shallow soils occur on steep slopes and on the crest of undulations (Adcocks, 1988). The soils are typically acid and leached which makes their fertility low, but their physical properties favourable (Acocks, 1988). This grass type is very similar to the short *Themeda triandra* grassveld and occurs sporadically in the catchment.

iv) Mountain *Podocarpus* forest

The mountain forest region of the catchment is characterised by the *Podocarpus henkelii* or Henkel's Yellowwood. These trees usually grow to between 20 to 40 metres in height and grow in rich and well-drained soil (Hooper, 2001).

v) Subalpine fynbos

Subalpine fynbos varies from 1 to 3m high, and changes in density from an open shrub community, associated with grassland, to dense shrub (Acocks, 1988). This type of vegetation was most often identified in the catchment along the rivers, in the gulleys and on steep slopes and on rock outcrops.

Figure 4.7: An example of the Southern Tall grassveld in the catchment. (Notice also the some small gullies and a fluvial fan on the green hillside)

4.2.8 Soil

South African soils, in general, are very fragile and susceptible to erosion (Lutchmiah, 1999). Physical factors such as geology, climate and steep slopes as well as poor management practice and lack of adequate monitoring and enforcement contribute significantly to the loss of productive topsoil in South Africa (Yeld, 1993 cited in Lutchmiah, 1999).

The catchment falls within the Estcourt Formation soil group. The Estcourt Formation is described as comprising dark-grey shale (often carbonaceous), siltstone and fine and medium to coarse-grained sandstone and is common in the northern section of KwaZulu-Natal (Turner, 2000). There are 4 major soil forms that are evident within the catchment:

1. Red-yellow apedal, freely drained soils

These soils refer to red and/or yellow soils belonging to one or more of the following South African soil forms: Inanda, Kranskop, Magwa, Hutton, Griffin, Clovelly. These soil forms are generally well drained and are not usually associated with high levels of erosion should the land be managed well (van der Waals, *pers.comm.*).

2. Plinthic catena: Upland duplex and margalitic soils rare

A large portion of the study site is occupied by a catena, which in its perfect form is represented by (in order from highest to lowest in the upland landscape) the South African soil forms of Hutton, Bainsvlei, Avalon and Longlands forms (Mpumanlanga Soil Mapping Project (MSMP), 2001). The valley bottom in the catchment is occupied by one or other gley soil (e.g. Rensburg, Willowbrook, Katspruit, Champagne forms). These soils are not very well drained and are prone to erosion should canopy cover be reduced (van der Waals, *pers.comm.*).

3. Plinthic Catena: Upland duplex and/or margalitic soils common

This soil is similar to the previous mentioned plinthic catena but which has, in upland positions, margalitic and/or duplex soils that together cover more than 10% of the total area (MSMP, 2001). These soils are prone to erosion and do not drain well. Both these plinthic catena soils tend to be rather shallow and are characterised by a topsoil which immediately overlays a hard rock horizon, making it further prone to erosion especially in high rainfall areas (van der Waals, *pers.comm.*).

4. Glenrosa and/or Mispah forms

"These soil forms are consistent with pedologically young landscapes that are not predominantly rock and not predominantly alluvial or aeolian and in which the dominant soil forming processes have been rock weathering, the formation of orthic topsoil horizons and, commonly, clay illuviation, giving rise typically to lithocutanic horizons " (MSMP, 2001).

5. Miscellaneous land classes

The last class refers to land types with a soil pattern difficult to accommodate elsewhere, at least 60% of which comprises pedologically youthful, deep (more than 1 000 mm to underlying rock) unconsolidated deposits.

4.3 Human Environment

In this section the human environment in which the study site occurs is comprehensively examined. The human characteristics of the study catchment, namely, landuse history, overgrazing, burning, socio-cultural conditions and development plans and projects, all play contributing roles to the soil erosion in the study site. These characteristics are therefore important in the study and are examined hereafter.

4.3.1 Landuse History

The large majority of the mostly, Zulu-speaking population were moved into the area as part of the "betterment" schemes of the old apartheid government. A study by Watson (1996), found that subsequent to their arrival in the catchment in the 1950's, eroded and sparsely vegetated surfaces were very localised and these surfaces increased dramatically during the first few years after their settlement. According to Watson (1996) this trend was halted somewhat in the mid-1970's during a wet spell which lead to better cultivation of crops but has since been exacerbated by the deforestation, annual dry season veld burning and the overstocking of cattle. This overgrazing of the natural grasslands, the burning practices, deforestation and slashing of scrubs for agricultural land use and fuel wood in these marginal areas are examples of inappropriate land use practices which contribute to the gradual deterioration of the land (Verstappen, 1983).

The area's erosional activity, seen by Watson (1990, cited in Watson, 1996) reveals that the area was repeatedly accelerated by landuse changes associated with the following events: -

(i) the Late Iron Age introduction of sheep, goats and cattle;
(ii) the late 18th Century introduction of maize;
(iii) the settlement of European small-scale market farmers during the second half of the 19th Century; and commencing at the turn of this century
(iv) large scale intensive, increasingly mechanised commercial agriculture, and
(v) intensification of subsistence production achieved by shortening fallow periods, cultivating marginal lands and overgrazing in the increasingly overcrowded and overstocked "native reserves"/"homelands" in which traditional African landuse was confined.

Visual observation of the catchment has alluded to the seriousness of the erosional features evident in the catchment. According to the KwaZulu-Natal Nature Conservation Service (NCS) *pers. comm.* (2002) the eroded areas in this vicinity are caused by badly planned drainage of runoff water from roads passing higher up the slope, this erosion is further exacerbated by the uncontrolled grazing of domestic stock. Attempts have been made to stem this tide of erosion; Figure 4.8 illustrates the mini-diversion channels or barriers currently being erected on all the secondary roads in the region.

Figure 4.8: Conservation measures to prevent run-off from transport roads

An erosional feature that has alerted the nature conservationists in the area is the silting up of the Wagendrift Dam. According to the NCS *pers. comm.* (2002), this siltation is being caused by sediment being washed down from badly managed commercial and subsistence farmlands higher upstream, where overgrazing and erosion are taking place. This sediment is then blocking up the entrance to the Wagendrift Dam. This is not a new problem in the KwaZulu-Natal province as according to Garland *et* al., (1999), the Hazelmere dam has lost more than 25% of its original design capacity since its completion in 1975 (Russow & Garland, 1998), and the Inanda Dam in the early 1990's was accumulating 3,5 million tonnes of material per year (1,3% of storage capacity). A field survey conducted by the author (Appendix 2) found that while most of the commercial farmers had been informed of the serious nature of the situation a lack of action and urgency was evident.

4.3.2 Burning

Fire has been seen as being a valuable management tool in the area; with the occasional burning of the grassland the rural inhabitants are forced to graze their stock on fresher unused grass, giving time for the burnt grass to renew itself. The KwaZulu-Natal Department of Agriculture and Environmental Affairs has outlined "Veld Burning Guidelines" for farm owners, landowners and land users, aimed at guiding the burning process and specifying the correct time and the correct method to use. These guidelines are seen as vital to the sustainability of the region for if the veld is burnt too early, the soil surface is left bare and erosion will occur. If the veld is burnt too late, after regrowth has commenced, the root reserves of the plants will be depleted (Singh, 1999). According to Garland *et* al., (1999) vegetation burning is a controversial land management tool with various researchers advocating the acceleration of erosion with burning (Scott, 1981) while other investigations (van Wyk, 1980) suggest limited effect of burning on erosion.

4.3.3 Overgrazing

Cattle are the main form of food and nourishment for the vast majority of the inhabitants in rural KwaZulu-Natal. Not only does cattle provide their owners with food and milk, but they are also seen as a symbol of wealth and prestige among the Zulu people. The vast amounts of cattle in the study area have resulted in the area being severely overgrazed. Erosional features associated with cattle tracks are prevalent throughout the catchment mostly caused by the compaction of the soil along the cattle tracks and footpaths. Visual observation of the cattle tracks lead to evidence of many large-scale erosion features along these tracks.

4.3.4 Socio-cultural conditions

The catchment is rich in cultural heritage. One point in the catchment named Makabeni Hill is listed as the site of the first known settlement in southern Africa (NCS, 2002). Archaeological excavations on Makabeni Hill have produced artefacts which indicate an early Bantu settlement in the form of a 'citadel' with 49 terraces and an encompassing wall, approximately 580m in circumference. Carbon dating of material has suggested that the area was occupied in about the eleventh century AD (NCS, 2002).

According to Statistics South Africa (1993), the catchment lies in magisterial district number 56 of KwaZulu-Natal. This district encompasses the rural towns of Weenen, Klipdrift, Estcourt and Bergville. From a tribal point of view, the catchment lies within an intersection of four rural tribes in the area, the Dlamini, Abambo, Hlubi and Mhlungwini tribes. According to the inhabitants in the area there is sporadic fighting between these tribes as a result of crop and cattle theft. The catchment is home to approximately 30 000 inhabitants most of whom live in conditions of extreme poverty. The catchment lies in one of the poorest areas of South Africa with the majority of inhabitants living in the lowest income bracket of the country (Municipal Demarcation Board, 2002). Basic sanitation, electricity, and running water are scare among the population, most of who rely solely on the rivers in the catchment for food, water and as a cleaning and sanitation aid.

There is a strong Zulu cultural tradition in the catchment, with the large majority of inhabitants living in traditional Zulu huts. There is also a strong reliance on subsistence agriculture, with maize and sorghum being the most common crop. Polygamy is prevalent often leading to a large number of huts being built on a small piece of land as each wife has her own hut according to Zulu tradition. This increases the stress on the land as the number of people being directly dependant on the same piece of land increases; this point is illustrated in Figure 4.9 below.

As mentioned previously, the catchment is also home to 6 white-owned commercial agricultural holdings. According to a survey conducted by the author on these holdings, farmers typically farmed very few crops and focused mainly on dairy farming. Numerous problems were experienced by these farmers, including theft of livestock, crops and even the fencing of their property. All these factors culminated in farmers placing less emphasis on the scale of production and concentrating on increasing productivity on the small-scale. The catchment provides a typical reflection of the cultural history of South Africa, with the huge disparities in incomes and distribution of wealth between the white minority and black majority, being evident almost upon your arrival in the catchment.

Figure 4.9: Example of the traditional Zulu huts and adjoining fields

4.3.5 Development plans and projects

The study area is located in the upper Thukela catchment in the KwaZulu-Natal province of South Africa. The Thukela Catchment is one of 12 Water Management Areas (WMA) of South Africa as identified by the Department of Water Affairs and Forestry of South Africa (DWAF). WMA's were created with the aim of enhancing the development of strategies to facilitate the management of water resources in South Africa (DWAF, 1999). The ultimate goal being the assurance that all people in South Africa have adequate and equitable access to water. There are currently 3 DWAF Water Projects running within the catchment, these are the Emanjokweni Project, the kwaDlamini Project and the Bhekabezayo Project (Municipal Demarcation Board, 2002). The two former projects are aimed at improving the poor infrastructure in the area; the latter is a sustainability project.

The study catchment as well as many catchments in the region are currently part of a large-scale project named the Thukela Water Project (TWP). The primary aim of the TWP is to increase the delivery rate of raw water to the Vaal River System (located in the northern provinces of South Africa), via the Drakensberg Pumped Storage Scheme, by 15 m^3/s. According to The Department of Water Affairs and Forestry (2002), the towns of Estcourt, Weenen, Colenso, Winterton and Bergville will be affected by one or more of the components of the TWP. In addition to its primary aim, the TWP aims to align and place infrastructure, such as roads, electricity transmission lines, telecommunication lines and buildings, in a manner that benefits the rural communities of the area in the long term. As an estimated 74% of the population of the Thukela Region is rural and relatively poor, this project is seen as being vital to boost the local economy through the investment of capital amounts and the creation of temporary and permanent employment opportunities. Lastly, there are currently seven further projects underway in the region being run by the South African Department of Public Works. Five of which are aimed at improving the local road infrastructure. E.g. upgrading existing roads, while the other two projects are aimed at building an administration building and a market stall respectively. An accurate assessment of areas of possible high and low erosion potential could prove essential in the development and building of the proposed infrastructure.

4.4 Chapter Summary

The Wagendrift catchment is a vast and diverse catchment located in the central midlands of the KwaZulu-Natal province of South Africa. The area is one of the poorest areas in South Africa, with the majority of inhabitants relying solely on the land for sustenance. This places extreme stress and pressure on the land and hydrology to continually provide food and water for the locals. The high number of government and private projects in the area illustrates the need for economic and social development in the area.

Chapter 5: Calculation of soil loss in the Wagendrift catchment

5.1 Introduction

Chapter 5 describes the GIS methodology followed in the creation of the soil loss maps in firstly, the USLE model (Section 5.2), secondly, the SLEMSA model (Section 5.3) and lastly, an 'adjusted' USLE model (Section 5.4). The practical section of the study was conducted using the GIS software products, ArcView, SEAGIS and IDRISI. The database requirements for the processing of the models are provided in Appendix 3. Individual GIS files were built for each factor in the USLE and SLEMSA models and combined by cell-grid modelling procedures in ArcView, using SEAGIS, to predict soil loss in the spatial domain (Mati *et al*., 2000). The contrasting results and a critique of the results that are produced are provided in Chapter 6.

5.2 Soil loss estimation: USLE model

5.2.1 Creating a Rainfall Erosivity Index (*R*) grid

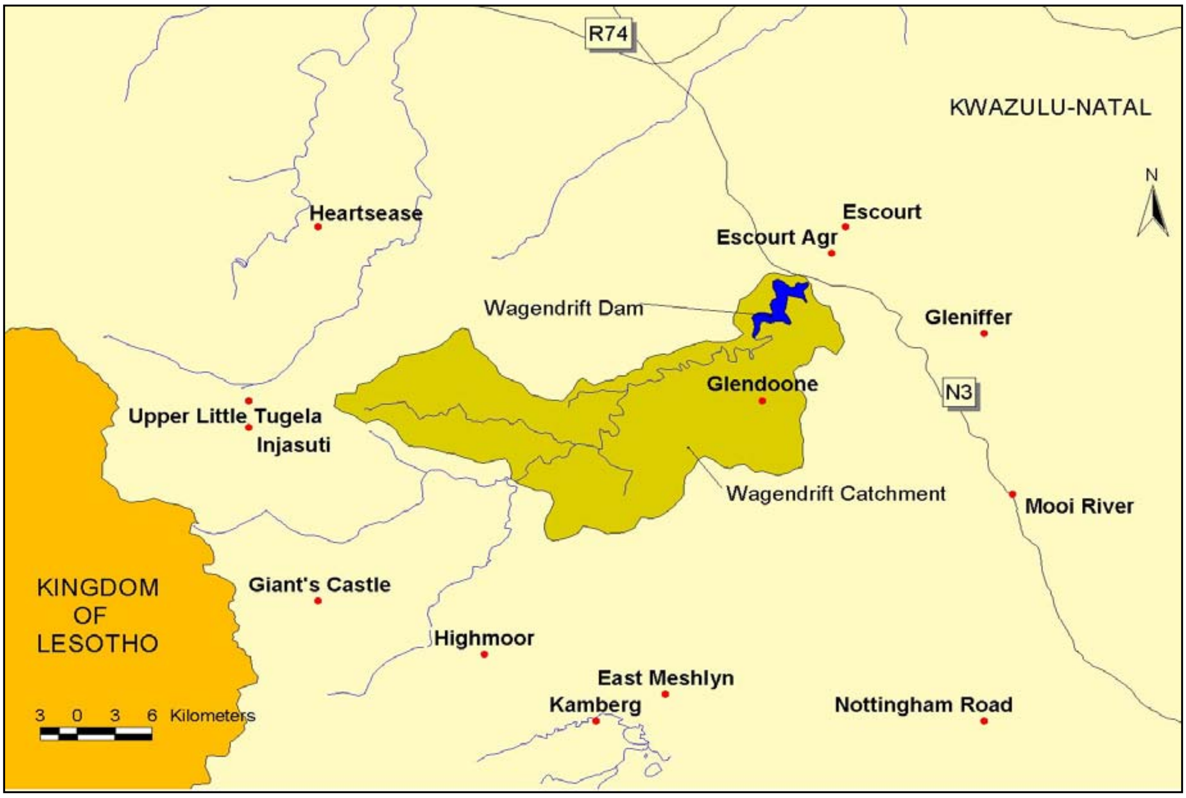
For the creation of the rainfall erosivity (*R*) grid, a grid of Mean Annual Precipitation (*MAP*) of the study area was created. In order to get a representative *MAP* grid of the area, rainfall measurements of 13 rainfall stations (Figure 5.1), in and immediately surrounding the study catchment, were interpolated. The South African Weather Bureau provided basic rainfall data for the 13 rainfall stations. The following rainfall stations were used in the spatial analysis:

Table 5.1: Rainfall stations used in the creation of the *MAP* grid

No.	Station Name	Station Code	Mean Annual Rainfall
1	Glendoone	0268548 1	844.3
2	Upper Little Tugela	0267788 0	1105.3
3	Mooi River	0268882 4	699.1
4	Nottingham Road	0268862 X	894.9
5	Estcourt Agr	0268631 X	775.6
6	Injasuti	0267789 2	1099.8
7	East Meshlyn	0268441 0	954.1
8	Giant's Castle	0267887 7	1053
9	Highmoor	0268199 7	1272.7

10	Gleniffer	0268845 0	712
11	Estcourt	0300690 1	736.1
12	Kamberg	0268352 1	1064
13	Heartsease	0299900 4	911.6

Cubic or third order surface trend analysis was used to create the *MAP* isohyetal map (see Figure 5.2), based on an average of 30 years of rainfall data. Polynomial third-order surface analysis was chosen for interpolation since there are a large number of valleys and hills in the catchment. Multiple regression techniques have also successfully been used in the past to describe the spatial distribution of mean annual precipitation over South Africa (Dent, *et al.*, 1988, cited in Lynch, 2002).



Using the *MAP* grid, two options were investigated for the creation of the *R* factor grid; the first of these was to set the *R* factor as a constant value, the second option was to calculate the *R*-factor from a region specific formula. The latter option was selected in order for the variant rainfall distribution pattern within the catchment to be more accurately assigned values. Wischmeier and Smith (1978) provide various rainfall-erosivity factor (EI_{30}) formulas, but these formulas are specific to regions within the United States. A study by the former Department of Agriculture and Water Supply (1984), aimed at investigating the adaptation of the USLE for South African conditions, found more precise determinations of the rainfall-erosivity factor (EI_{30}) for South African conditions. In this study, rainfall-erosivity factor equations for various regions of South Africa were developed. These equations are shown in Table 5.2 below and were based on computed EI_{30} values for the rainfall stations indicated in the third column. The applicability of these equations/formulas could be extended to the regions indicated in the map areas shown in Figure 5.3.

Table 5.2: Calculated rainfall-erosivity (EI_{30}) equations for South African regions (Dep. Agriculture and Water Supply, 1984)

MAP AREA	EQUATION	STATION
A	R = 0.23 P - 47.61	D. F. Malan Airport
B	R = 0.38P - 25.36	Upington
C	R = 0.80P - 371.16	Port Elizabeth
D	R = 0.25P - 18.67	Grootfontein
E	R = 0.54P - 166.83	J. B. M. Hertzog
F	R = 1.12P - 730.97	East London
G	R = 0.32P - 15.34	Kimberley
H	R = 0.68P - 135.54	Pietersburg
I	R = 0.41P - 38.51	Pretoria
J	R = 0.69P - 289.29	Jan Smuts Airport
L	R = 0.65P - 245.42	Louis Botha Airport
M	R = 0.88P - 420.46	Mount Edgecombe
N	R = 0.65P - 192.46	Richards Bay
O	R = 0.42P - 38.79	Makatini
P	R = 0.37P - 11.93	Newcastle
Q	R = 0.48P - 136.55	Cedara
R	R = 0.40P - 35.62	Kokstad
S	R = 0.65P - 145.36	Ladysmith
T	R = 0.63P - 153.72	Estcourt
U	R = 0.64P - 239.68	Waterford
R = EI_{30} P = Annual Rainfall		

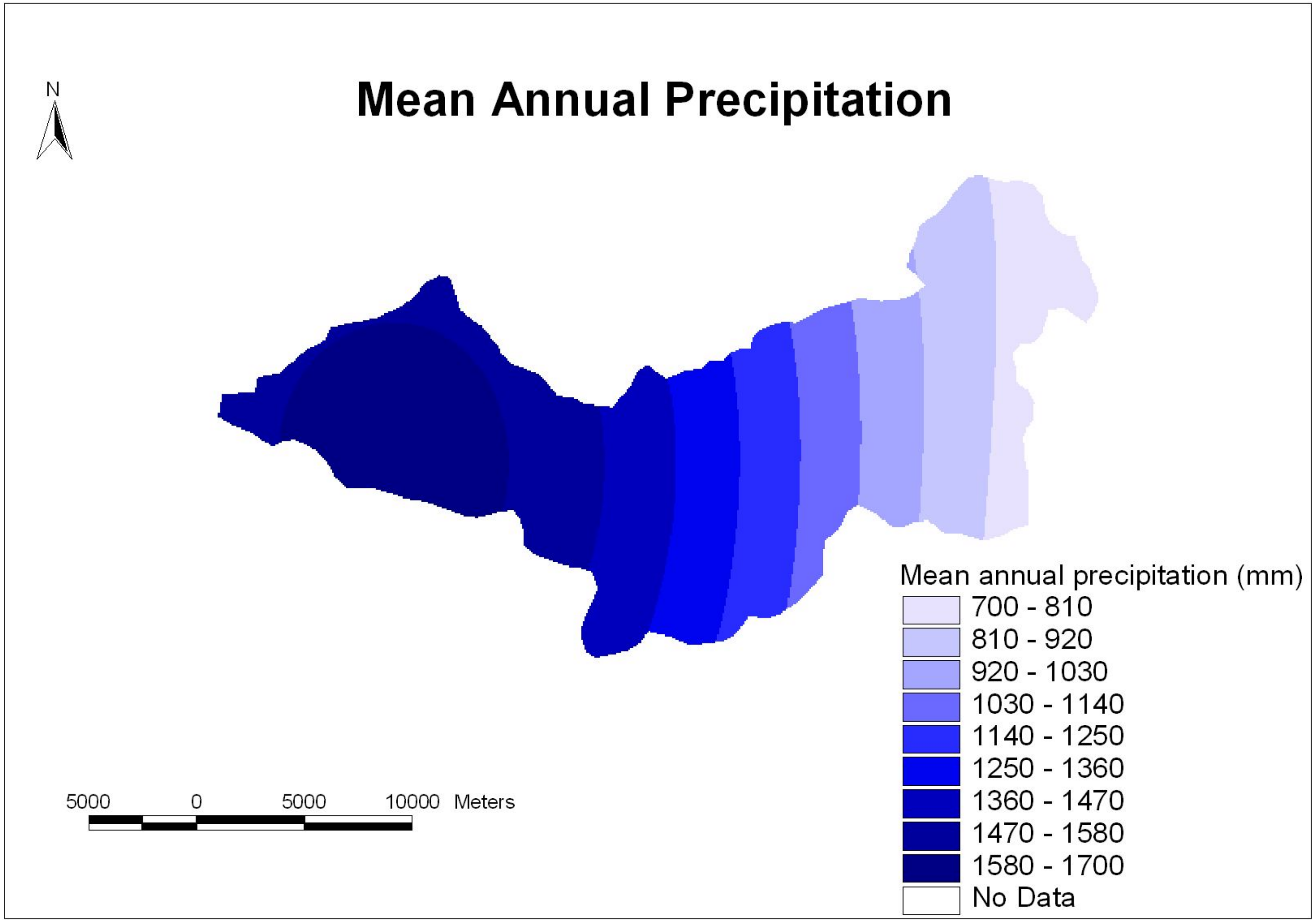


Figure 5.2: Mean annual precipitation map of the study site

The catchment is located predominantly in the Estcourt area, as indicated on the map (Area T) (see Figure 5.3 below). It is for this reason that the *MAP* grid was then multiplied by the equation of Map Area T above. The calculation is shown below:

R = 0.63 *MAP* - 153.72 at T Map Area

where

MAP = mean annual precipitation grid (in mm)

The resultant map is shown in Figure 5.4.

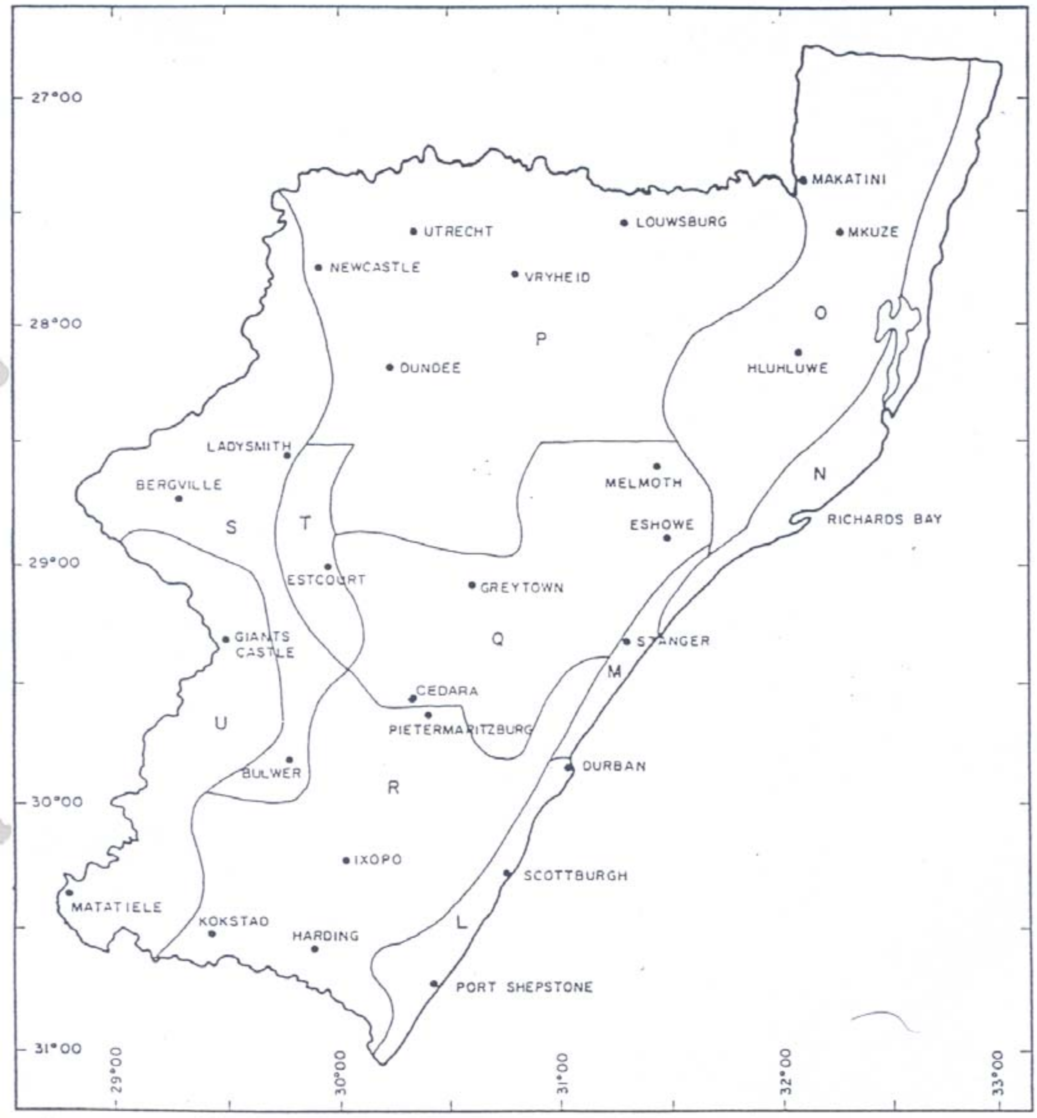


Figure 5.3: Rainfall erosivity regions in KwaZulu-Natal, South Africa, with study site indicated (Dept of Agriculture and Water Supply, 1984)

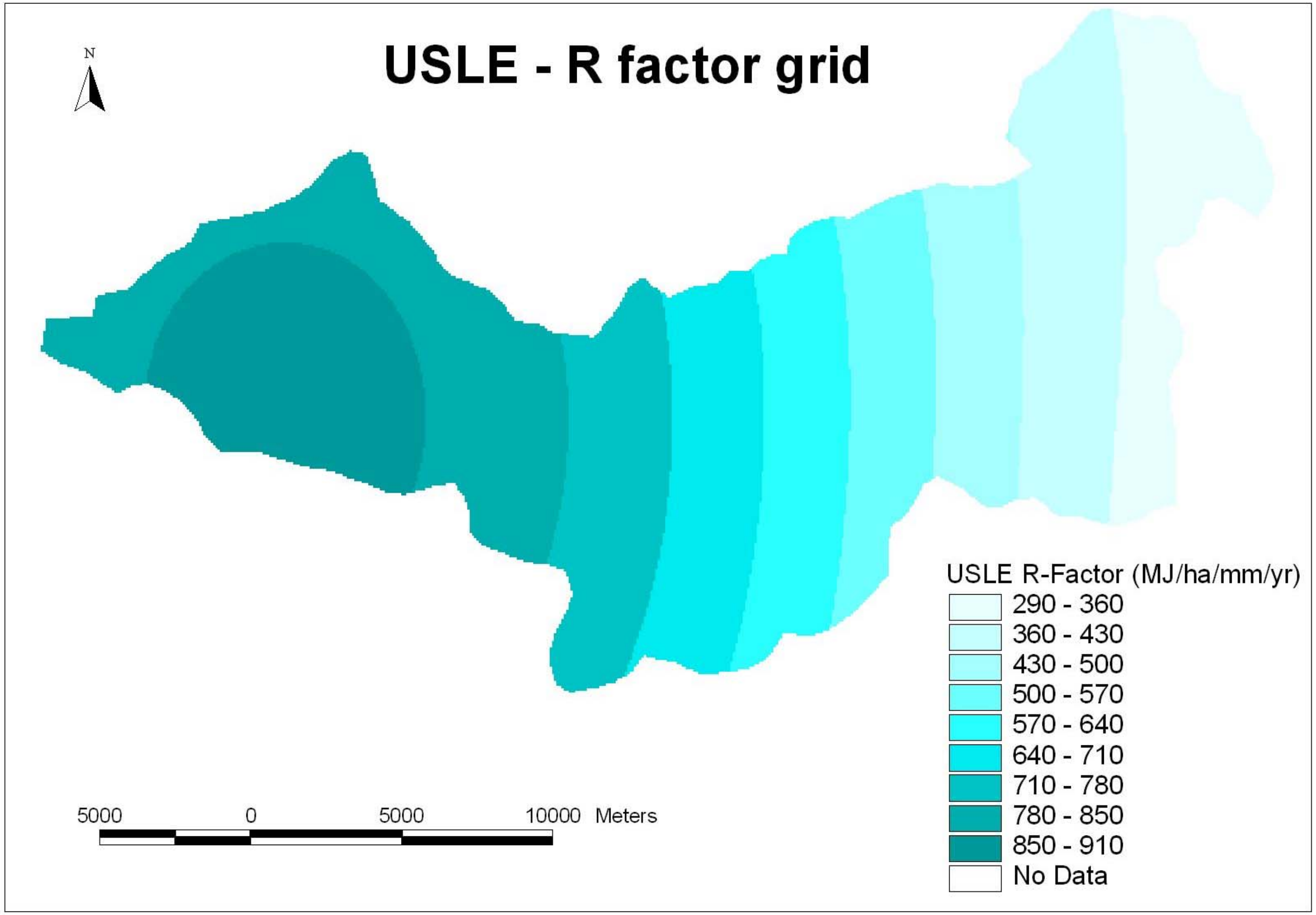


Figure 5.4: USLE *rainfall erosivity* factor grid

5.2.2 Creating a Soil Erodibility Index (*K*) grid

Various options were investigated for the creation of the soil erodibility index grid of USLE. Among the methods investigated were the assignment of *K* factor values to soil types using soil maps or geological maps. The problems encountered here was that the area of concern has not been comprehensively surveyed thus limiting the accuracy of data obtained from such maps. In addition it was felt that fieldwork would provide a more hands-on and up-to-date means of obtaining such data. The erodibility factor *K* (in ton/MJ/mm) is a function of the texture, structure, organic matter and permeability of the soil. The erodibility factor for USLE was calculated according to the nomograph method outlined in Wischmeier & Smith (1978) and shown mathematically below in equation 5.1. With regard to South African soils, the Department of Agriculture and Water Supply (1984) state that *K* values can be assigned to South African soils according to the nomograph method with "reasonable confidence". This method has also previously been used in South African soil loss estimation research, most notably by McPhee & Smithen (1984).

$$K = [2.1 * 10^{-4} * (12 - OM) * M^{1.14} + 3.25\,(s - 2) + 2.5\,(p - 3)] / 759 \qquad (5.1)$$

where

K = erodibility factor (in ton/MJ/mm)

OM = organic matter content (%)

M = texture product

s = structure class

p = permeability class.

The texture product M is calculated according to:

$$M = \%\ \text{silt} \times (\%\ \text{silt} + \%\ \text{sand}) \qquad (5.2)$$

It was decided to calculate the *K* factor per field observation point in the catchment and interpolate the results using the interpolator, Inverse Distance Weighting. In order to get an accurate description of the soil texture (%sand, % silt, % clay) in the catchment's widely distributed landscape, distributed sampling methods were used to capture 95 soil samples in the area. According to Fridah (2002) distributed sampling is the preferred sampling method when attempting to avoid sample aliasing within a region

These 95 soil samples were subsequently examined and a fine particle analysis was performed on the samples in order to get the % sand, % silt, and % clay for each sample. The principle employed for this analysis was not the direct measurement of the particle diameter, but an approximation of it via its settling velocity. This is based upon Stoke's Law, which states that the velocity of fall of a sedimentary particle through a viscous medium is directly proportional to its diameter (Briggs, 1977). Therefore larger particles fall more rapidly than smaller, and coarse materials settle out before fine material (Briggs, 1997). For each sample the percentage organic matter was also calculated according to the method specified in Carter (1993).

As mentioned previously, for each observation point, a soil sample was taken together with brief notes regarding the surrounding environment (a summary of the sample is provided in Appendix 4). After subsequent consultation with soil experts (*pers. comm.* Van der Waals), and governed by the USDA structure and permeability tables (shown below), each soil sample was categorised into structure and permeability classes.

Table 5.3: Soil structure classes

Class	Description
1	Very fine granular
2	Fine granular
3	Medium or coarse granular
4	Blocky, platy or massive

Table 5.4: Soil permeability classes

Class	Description

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

Once determination of the percentage factors, referred to above, and the structure and permeability codes had been determined, the texture of the soil was ascertained with the use of the USDA textural triangle (Appendix 5).

These percentage factors and figures were used as input parameters in equations 5.1 and 5.2. The *K* factor's generated for each observation point in the catchment were used as variable for the erodibility grid map composed using the local estimator, Inverse Distance Weighting. This grid map was subsequently summarised to create a table containing the mean *K* values per soil type in the catchment, and a grid was created with the mean *K* values as the variable. The resultant *K* factor map is illustrated in Figure 5.5.

5.2.3 Creating a Topographic Factor (*LS*) grid

The topographic *(LS)* factor grid for USLE was created according to the RUSLE model since the equations used in the calculation of the RUSLE's, *LS* factor, takes rill erosion into account.

The topographic factor consists of two sub-factors: a slope gradient factor and a slope length factor; both of which are determined from the DEM. According to the SEAGIS User Guide (1999) two methods exist for deriving the slope length factor from the DEM. It can be either calculated as the horizontal length of each cell or it can be measured from each high point in eight flow directions. The boundaries of slopes are determined according to a user specified cut-off value. The cut off value in this study was specified at 50% to give an accurate representation of the possible deposition occurring after initial downslope erosion in the catchment.

The input requirement for the creation of the topographic grid is a filled DEM. Filling a DEM can be described as identifying any sinks or cells that have a lower elevation value than the surrounding cells and giving them a higher elevation value (Jennings, 2001). When the sinks are filled the area is given an average value which is calculated using the value of the neighbouring cells (Jennings, 2001). Using the equations shown below, the slope gradient and slope length factors were calculated from the DEM and combined to result in the topographical factor grid. The result is shown in the Figure 5.6.

Slope length factor

$$L = (x/22.13)^{m} \text{, where} \tag{5.3}$$

L = slope length factor

x = length of slope (in m)

m = $\beta/(1+\beta)$, where β is the ratio of rill erosion to interrill erosion.

Values for β can be computed from:

$\beta = (\sin\theta/0.0896)/[3.0(\sin\theta)^{0.8} + 0.56]$, where θ = slope angle

Slope gradient factor

For slopes shorter than 15 feet (4.5 m): (5.4)

$S = 3.0(\sin\theta)^{0.8} + 0.56$, where

S = slope gradient factor

otherwise:

$S = 10.8\sin\theta + 0.03$, slopes steepness < 9 %

$S = 16.88\sin\theta + 0.03$, slopes steepness > 9 %

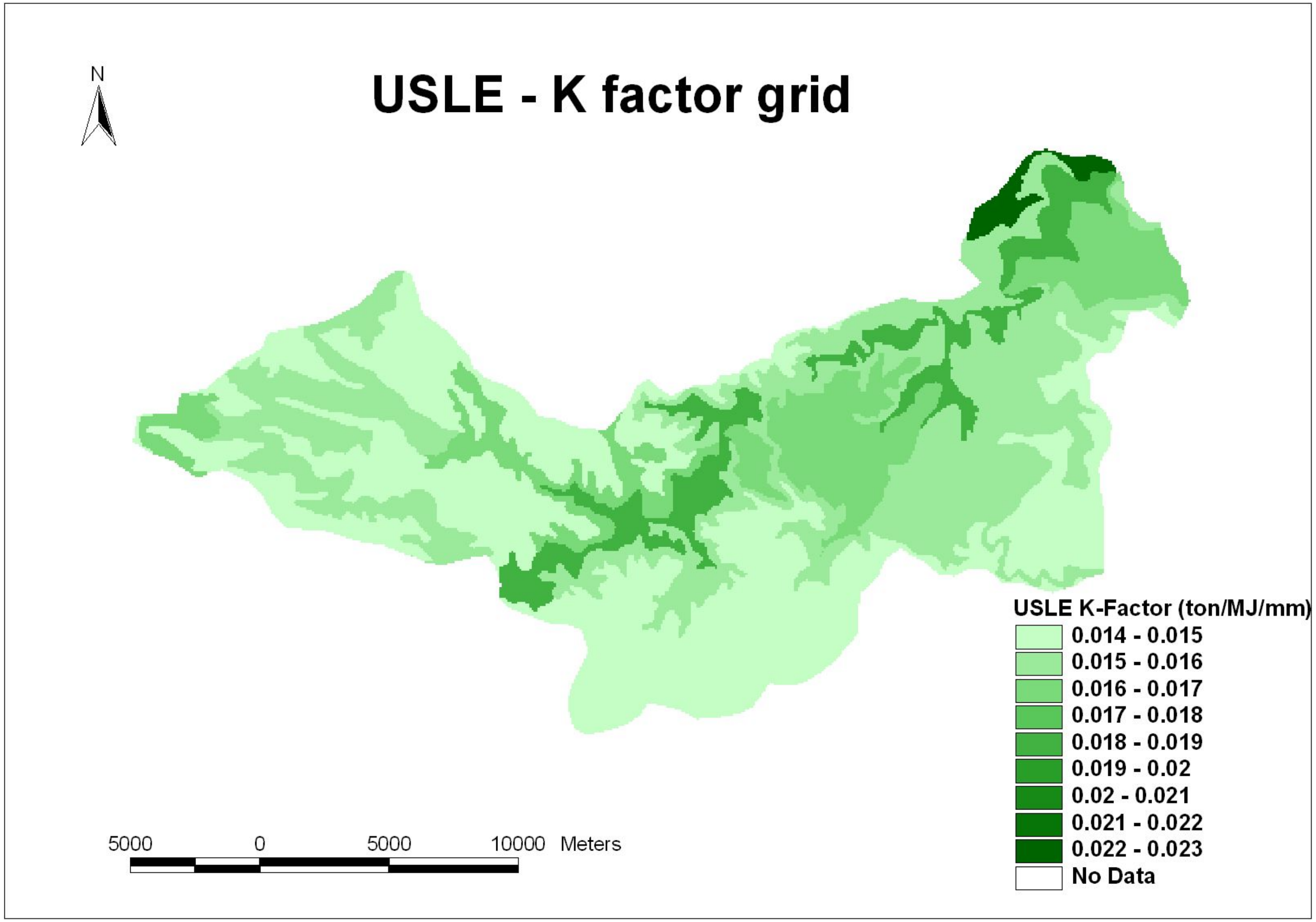


Figure 5.5: USLE *soil erodibility* factor grid

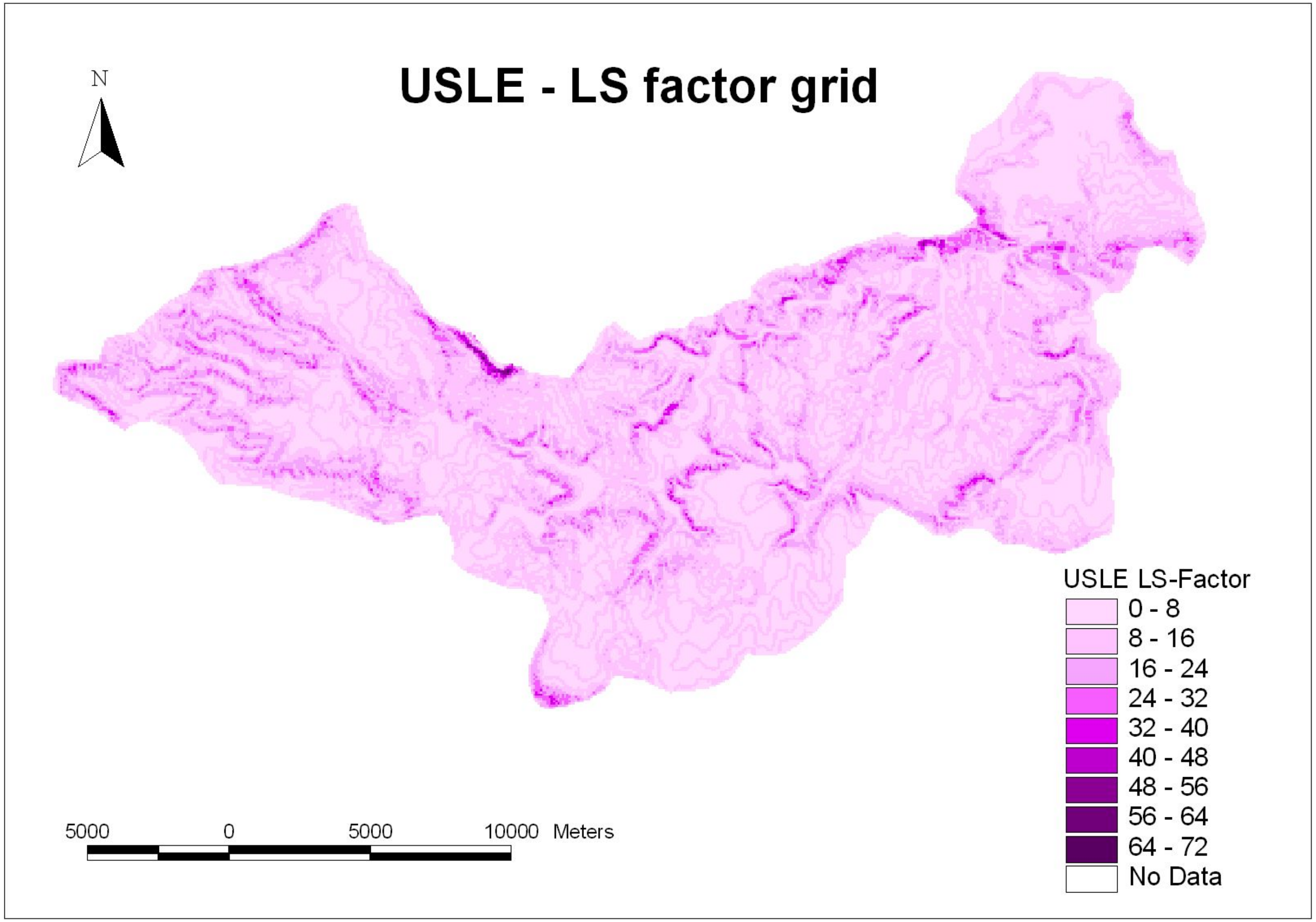


Figure 5.6: USLE *topographic* factor grid

5.2.4 Creating a Crop Management Factor (*C*) grid

The *C* factor is the crop/vegetation and management factor used to determine the relative effectiveness of soil and crop management systems in terms of preventing soil loss (Rojas, 2002). In order to determine the *C* factor values to be used in the USLE equation, a number of sources were examined. Wischmeier and Smith (1978) present extensive tables for evaluating crop and management effects (see Table 5.5 and 5.6), but these results are based on experiments conducted in the USA and as such will be prejudiced to an American environment. Roose (1977) produced *C* factor values for West Africa (see Table 5.7), but West African environments are also different to southern African conditions. Initially, however, the USLE *C* factors corresponding to each crop/vegetation condition were estimated using these sources. These figures were later used as comparative references to the modified values estimated through South African sources.

Efforts have been made in an attempt to generate *C* factor values for South Africa. According to Smith (1999), McPhee (1980) established good correlations between percentage canopy cover and leaf area index with respect to maize and soya beans; McPhee, Smithen, Venter, Hartmann and Crosby (1983) used rainfall simulator results to provide local input data with respect to two important parameters in the USLE, namely soil erodibility and mulch and canopy cover effects; and McPhee, Hartmann and Kieck (1983) used a rainfall simulator to determine soil erodibility and crop management factors under pineapple production. All of this information has proved invaluable for the successful implementation of USLE in South Africa, however; as yet no other extensive efforts have been made to determine *C* factors values for a wider range of crops and conditions (Smith, 1999). This lack of information proved problematic in the determination of exact *C* factor values for the study.

Table 5.5: C factor for permanent pasture, veld and woodland[1]. (Wischmeier & Smith, 1978)

Vegetative Canopy		Cover that contacts the soil surface						
Type and Height[2]	% Cover[3]		Percent Ground Cover					
		Type[4]	**0**	**20**	**40**	**60**	**80**	**95+**
No appreciable canopy cover		G	0.45	0.20	0.10	0.042	0.013	0.003
		W	0.45	0.24	0.15	0.091	0.043	0.011
Tall weeds or short brush with average drop fall height of 0.5m	**25**	G	0.36	0.17	0.09	0.038	0.013	0.003
		W	0.36	0.20	0.13	0.083	0.041	0.011
	50	G	0.26	0.13	0.07	0.035	0.012	0.003
		W	0.26	0.16	0.11	0.076	0.039	0.011
	75	G	0.17	0.10	0.06	0.032	0.011	0.003
		W	0.17	0.12	0.09	0.068	0.038	0.011
Appreciable brush or bushes, with average drop fall height of 2m	**25**	G	0.40	0.18	0.09	0.040	0.013	0.003
		W	0.40	0.22	0.14	0.087	0.042	0.011
	50	G	0.34	0.16	0.08	0.038	0.012	0.003
		W	0.34	0.19	0.13	0.082	0.041	0.011
	75	G	0.28	0.14	0.08	0.036	0.012	0.003
		W	0.28	0.17	0.12	0.078	0.040	0.011
Trees, but no appreciable low brush. Average drop fall height of 4m	**25**	G	0.42	0.19	0.10	0.041	0.013	0.003
		W	0.42	0.23	0.14	0.089	0.042	0.011
	50	G	0.39	0.18	0.09	0.040	0.013	0.003
		W	0.39	0.21	0.14	0.087	0.042	0.011
	75	G	0.36	0.17	0.09	0.039	0.012	0.003
		W	0.36	0.20	0.13	0.084	0.041	0.011

1 The listed C values assume that the vegetation and mulch are randomly distributed over the entire area.
2 Canopy height is measured as the average fall height of water drops falling from the canopy to the ground. Canopy effect is inversely proportional to drop fall height and is negligible if fall height exceeds 10 metres.
3 Portion of total area surface that would be hidden from view by canopy in a vertical projection (a bird's eye view).
4 G: cover at surface is grass, grasslike plants, decaying compacted duff, or litter at least 5cm deep
W: cover at surface is mostly broadleaf herbaceous plants (as weeds with little lateral root network near the surface) or undecayed residues or both.

Table 5.6: C factor for undisturbed forest land (Wischmeier & Smith, 1978)

Percent of area covered by canopy of trees and undergrowth	Percent of area covered by duff at least 5cm deep	Factor C[1]
100 – 75	100 – 90	0.0001 – 0.001
70 – 45	85 – 75	0.002 – 0.004
40 – 20	70 - 40	0.003 – 0.009

1 The ranges in listed *C* values are caused by the ranges in the specified forest litter and canopy cover and by variations n effective canopy height.

Table 5.8 shows the defined list of land covers in the catchment as well as their generated *C* factor values. The **national** percentage canopy cover, fall height and ground cover values per land coverage were obtained from Thompson's (1996) detailed classification. The **catchment's** percentage canopy cover, fall height and ground cover were determined based on Thompson's (1996) classification, aerial photo analysis, information from other studies conducted within southern Africa on specific crops and land cover types, (e.g. McPhee & Smithen, 1984) and field observation of the catchment. In this way mimicking a similar process done by another researcher (Donald, 1997), in determining appropriate *C* factor values for a South African catchment in which little local data is available. The *C* factor value used in the study is listed in the far right hand column of table 5.8.

Table 5.7: *C* factor values for selected cover conditions and cultural practices for West Africa (Roose, 1977)

Cover and Cultural Practice	Annual *C* Value
Bare Soil	1
Forest or dense shrub	0.001
Savannah, prairie in good condition	0.01
Overgrazed savannah or prairie	0.1
Crop cover of slow development or late planting 1st year	0.3 – 0.8
Crop cover of slow development or late planting 2nd year	0.01 – 0.1
Crop cover of rapid development or early planting 1st year	0.01 – 0.1
Corn, sorghum or millet	0.4 – 0.9
Rice with intensive fertilization	0.1 – 0.2
Cotton, tobacco (2nd cycle)	0.5 – 0.7

Groundnut	0.2 – 0.8
Palm tree, coffee, cocoa with cover crop	0.1 – 0.3

Table 5.8: *C* factor ranges defined for each land cover in the catchment (Adapted from Donald, 1997)

Land Cover	National			Wagendrift			
	% canopy cover	**Fall height metres**	**% ground cover**	**% canopy cover**	**Fall height metres**	**% ground cover**	***C* factor**
Forest	>70	>5	>80	>80	>5	>80	0.006
Forest Plantation	>75	>5	>80	>80	>5	>80	0.006
Waterbodies	0	0	0	0	0	0	0
Unimproved grassland	<10	0.5	40 – 100	<20	0.5	>60	0.038
Improved grassland	<10	NAC	60 – 100	>50	2	>60	0.008
Thicket, bushland, scrub forest and high fynbos	10 – 70	2 - 5	20 - 90	>50	2 – 5	>60	0.008
Cultivated: temporary, commercial dryland	<40	<1	GP	<40	<2	<20	0.43
Cultivated: temporary, subsistence dryland	<30	<1	GP	25	<2	0	0.17
Cultivated: temporary, commercial irrigated	<50	<1	GP	60	<2	<20	0.70
Urban/built-up land: residential	<40	0 - >5	<20 - 80	<20	0 - >5	<30	0.58

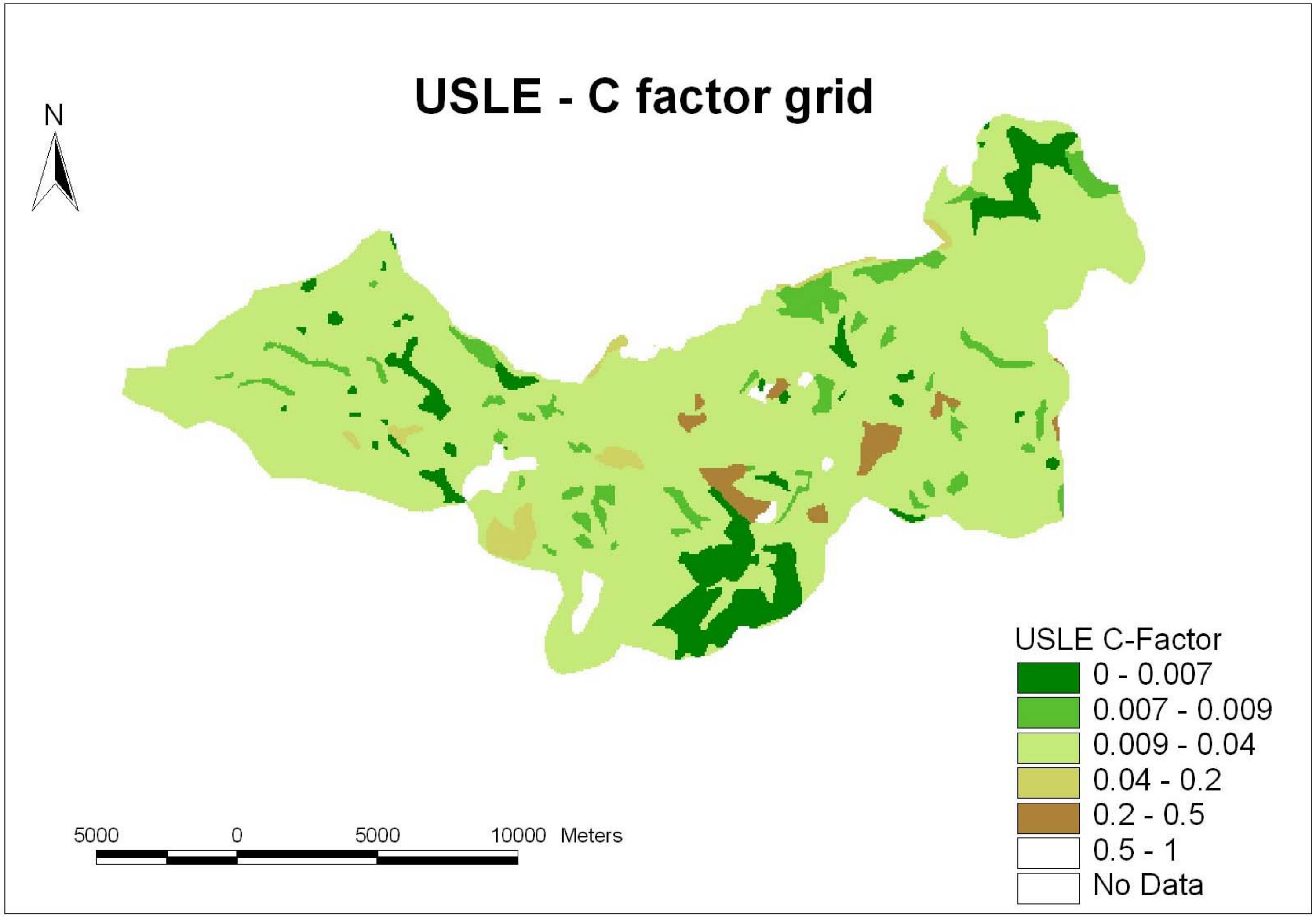


Figure 5.7: USLE *crop management* factor grid

5.2.5 Creating an Erosion Control Practice (*P*) grid

Information on the support practices or *P* factor values in the catchment (e.g. contour intervals, terracing, burning) was collected during fieldwork. According to McPhee & Smithen (1984), the only USLE support practice applicable to conditions in South Africa is contour tillage. *P* factor values extracted for the purpose of applying the USLE in South Africa are listed in Table 5.9 below:

Table 5.9: Support practice factor values for contour tillage on contoured lands in South Africa (McPhee & Smithen, 1984)

% LAND SLOPE	SUPPORT PRACTICE FACTOR VALUE *P*
0 – 3	0.6
3 – 8	0.5
8 – 15	0.6

Field examination of the land cover-mapping units revealed that the only form of erosion control being practiced in the catchment is on the "Cultivated land –temporary commercial" –type-mapping unit. There were examples of contour tillage on these mapping units, as is illustrated in the Figure 5.8 below, taken of one particular site of commercial farming. The average slope of this type of mapping unit lies between 0 – 3% and these areas were therefore assigned a support practice factor value of 0.6. The rest of the Wagendrift catchment was assigned the *P* factor value of 1, indicating no physical evident of erosion control in these areas. The map is shown in Figure 5.9.

Figure 5.8: Contour tillage on cultivated fields

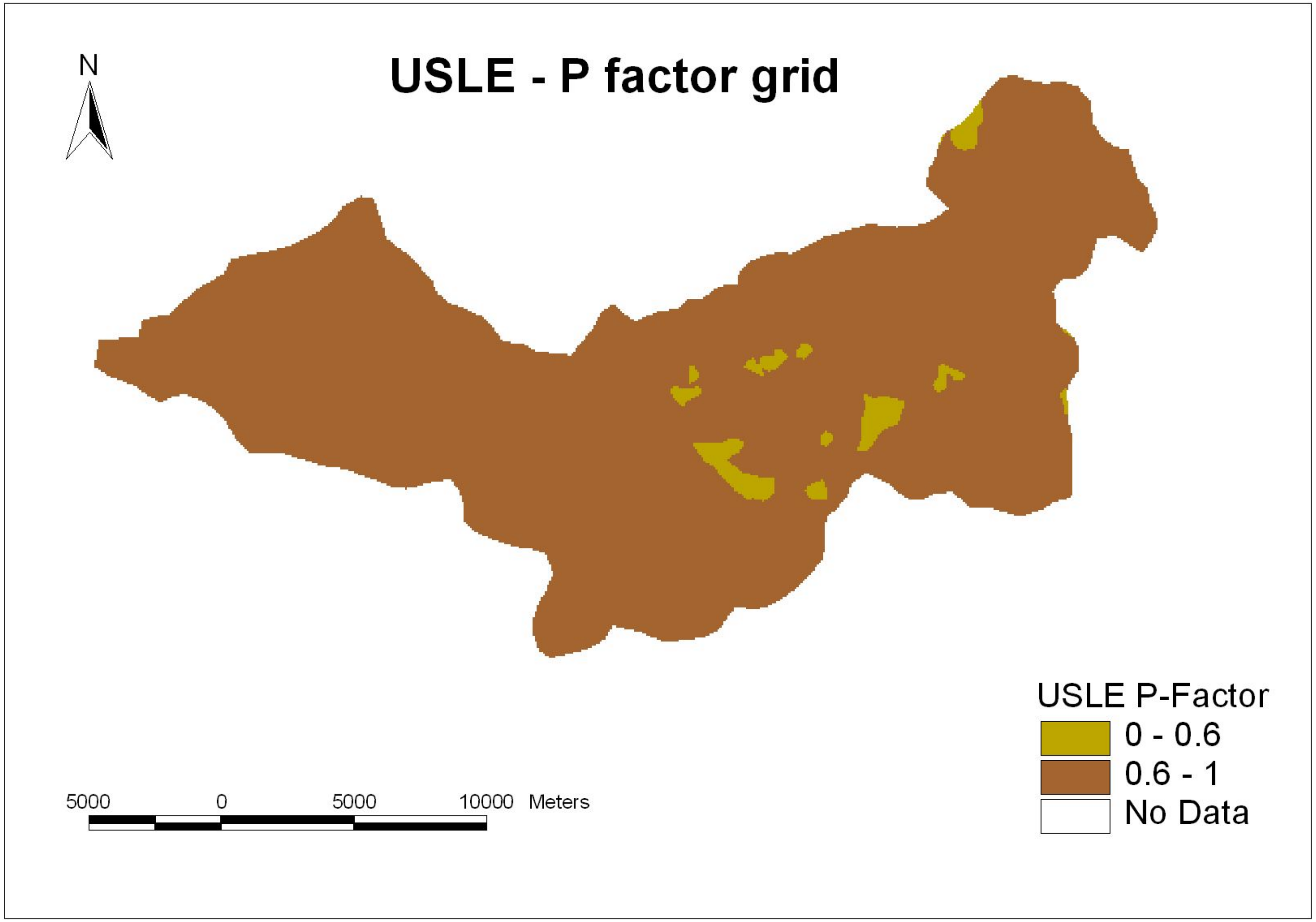


Figure 5.9: USLE *erosion control* factor grid

5.2.6 Creating the USLE Source Erosion grid

The USLE Source Erosion grid was created through the multiplication of each individual USLE factor grids. The resultant map is shown in Figure 5.10, the annual soil loss given is in tons.ha^{-1}.$year^{-1}$. It is recommended not to consider the results as actual values, but more as index values showing where we have a high potential soil loss. Investigations and/or simulations on a smaller scale in time and space should assess the actual amount, and will be discussed in Chapter 6.

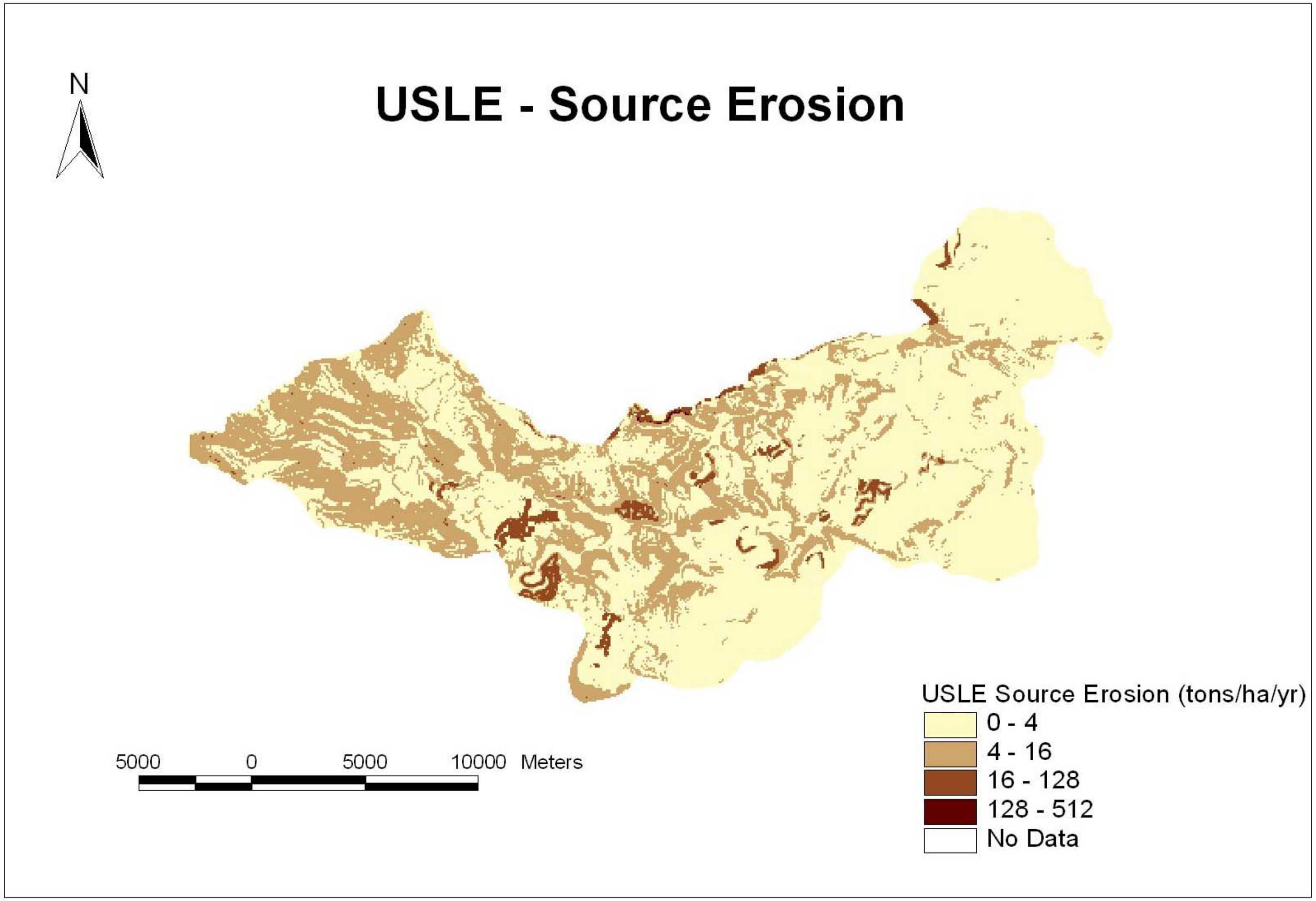


Figure 5.10: USLE Source Erosion grid – *non-linear legend*

5.3 Soil loss estimation: SLEMSA model

We have witnessed in the previous section the methodology followed in determining soil loss at a catchment scale using the USLE. In this section the same procedure is employed in determining the soil loss of the same catchment but this time using the SLEMSA model. The methodology used to determine the various factor grids for SLEMSA is detailed and the final source erosion grid is provided.

5.3.1 Creating an Erodibility Factor (*K*) grid

According to Morgan (1995) the value of *K* is determined by relating mean annual soil loss to mean annual rainfall energy (*E*) using the exponential relationship:

$$ln\ K = b\ lnE + a \qquad (5.5)$$

where E is in J/m^2, and the values of a and b are functions of the soil erodibility factor (F):

$$a = 2.884 - 8.2109\ F \qquad (5.6)$$

$$b = 0.4681 + 0.7663\ F \qquad (5.7)$$

As mentioned earlier *E* represents the kinetic energy of raindrops as they strike the soil or vegetation (Schultze, 1979). This *E* factor for individual storms in the USLE is expressed as the product of kinetic energy and the maximum 30-minute rainfall intensity (Schultze, 1979). Detailed rainfall recorder charts containing rainfall intensity data were not available from any of the 13 rainfall stations on or surrounding the catchment. However, in a study conducted by Schultze (1979), a rainfall erosivity equation was determined by using data obtained at the Ntabamhlope Research Station which is located 5,5 kilometres away from the catchment. According to Schultze (1979), this rainfall intensity and kinetic energy equation can be taken as being representative of Philips' (1973) Bioclimatic Region's 4, 6 and 8, of South Africa. The total catchment falls within these Bioclimatic regions. The equation generated by Schultze (1979) is shown below:

$E = 15{,}16\ MAP - 1517.67$ J. m^{-2} annum^{-1} at Ntabamhlope Research Station where

MAP = mean annual precipitation (in mm)

The MAP for the area, as mentioned in Chapter 3 is 932.58mm. Therefore the calculation of E is in the form of:

$E = 15{,}16\ (932.58) - 1517.67\ \mathrm{J.\ m^{-2}\ annum^{-1}}$

$E = 12620.2428\ \mathrm{J.\ m^{-2}\ annum^{-1}}$

The soil erodibility (F) of the soil is governed by its soil texture and soil type. The table below provides an estimate of the F value according to these factors:

Table 5.10: Input values for soil erodibility for use in SLEMSA (Elwell, 1978)

Soil erodibility (*F* factor)		
Soil texture	Soil type	*F* value
light	sands	4
	loamy sands	
	sandy loams	
medium	sandy clay loam	5
	clay loam	
heavy	sandy clay	6
	clay	
	heavy clay	

Subtract the following from the *F* value:

1	for light-textured soils consisting mainly of sands and silts
1	for restricted vertical permeability within one metre of the surface or for severe soil crusting
1	for ridging up-and-down the slope
1	for deterioration in soil structure due to excessive soil loss in the previous year (>20t/ha) or for poor management
0.5	for slight to moderate surface crusting or for soil losses of 10-20 t/ha in the previous year

Add the following to the *F* value:

2	for deep (>2) well-drained, light-textured soils
1	for tillage techniques which encourage maximum retention of water on the surface, e.g. ridging on the contour
1	for tillage techniques which encourage high surface infiltration and maximum water storage in the profile, e.g. ripping, wheel-track planting
1	for first season of no tillage
2	for subsequent seasons of no tillage

As mentioned in section 5.2.2, 95 soil samples were taken of the region and analysed in terms of particles size and percent organic matter. Using the results of the particle size analysis, and governed by the USDA textural triangle, the texture of each soil sample was determined. An individual soil erodibility value (*F*) was subsequently assigned to each sample point according to the specifications provided by Elwell (1978) and shown in Table 5.10. The derived soil erodibility values (*F*) were entered into equations 5.6 and 5.7 to determine variables *a* and *b.* The final *K* value per observation point was derived using equation 5.5 and input variables *E, a* and *b.* Similarly to the GIS methodology used for the derivation of the USLE *K* factor grid, the *K* factor's generated for each observation point in the catchment were used as variable for the erodibility grid map composed using the interpolator, Inverse Distance Weighting. This grid map was subsequently summarised to create a table containing the mean *K* values per soil type in the catchment, and a grid was created with the mean *K* values as the variable. The resultant map is shown in Figure 5.11.

5.3.2 Creating a Slope-Length Factor (*X*) grid

The slope-length factor grid (*X*) was created using equation (5.8). This equation has been used in previous southern African research to estimate the slope-length factor of SLEMSA, including those of Abel & Stocking (1987).

$$X = \sqrt{L} * (0.76 + 0.53 * S + 0.076S^2) / 25.65 \text{, where} \qquad (5.8)$$

where

X = topographic ratio

L = slope length, in metres (m)

S = slope steepness, in percent (%)

The slope length and slope steepness sub-factors were calculated from the filled DEM. These factors were subsequently substituted into the topographic ratio equation (5.8) above to produce the SLEMSA slope-length factor grid shown in Figure 5.12 below.

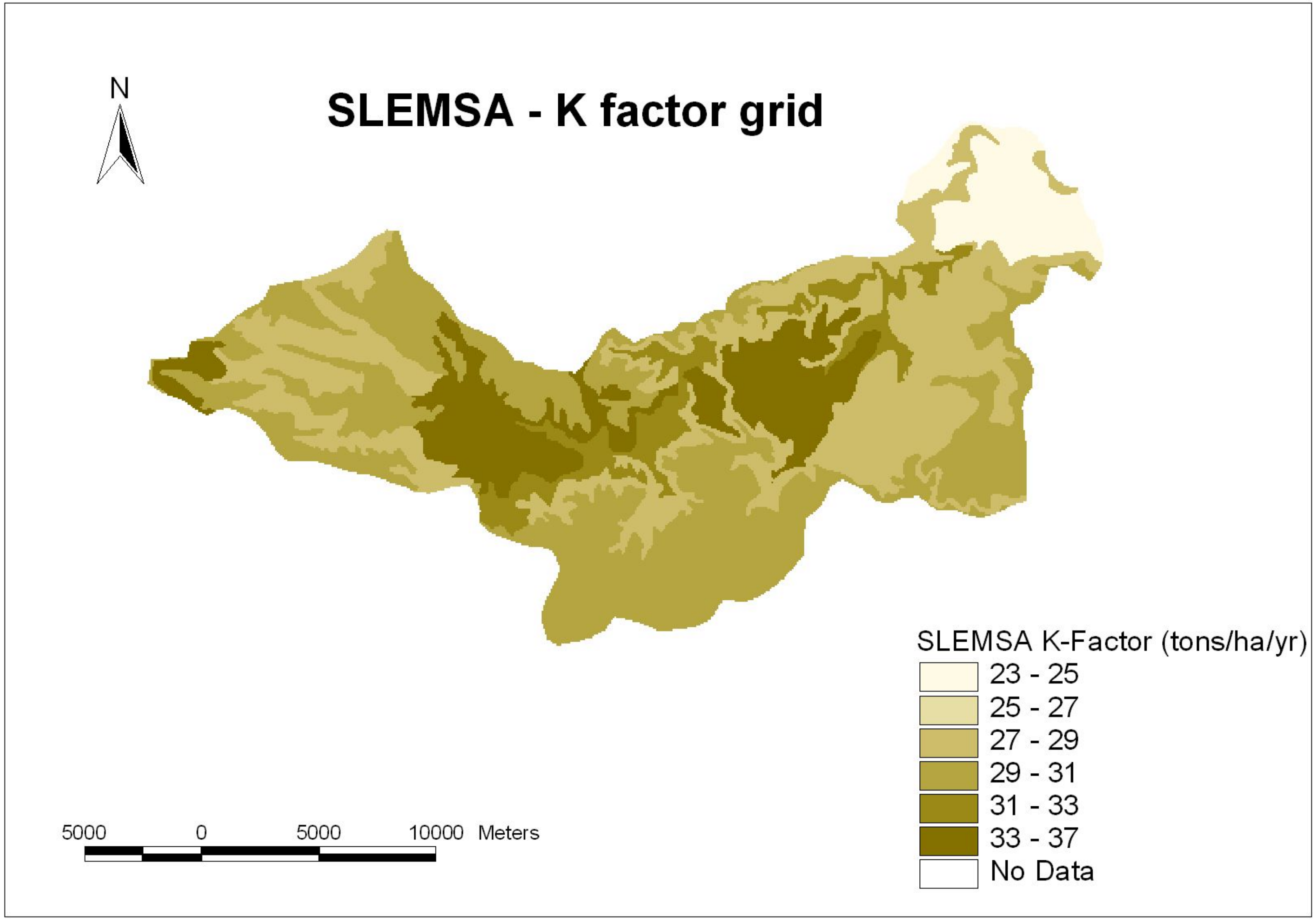


Figure 5.11: SLEMSA *erodibility factor* grid

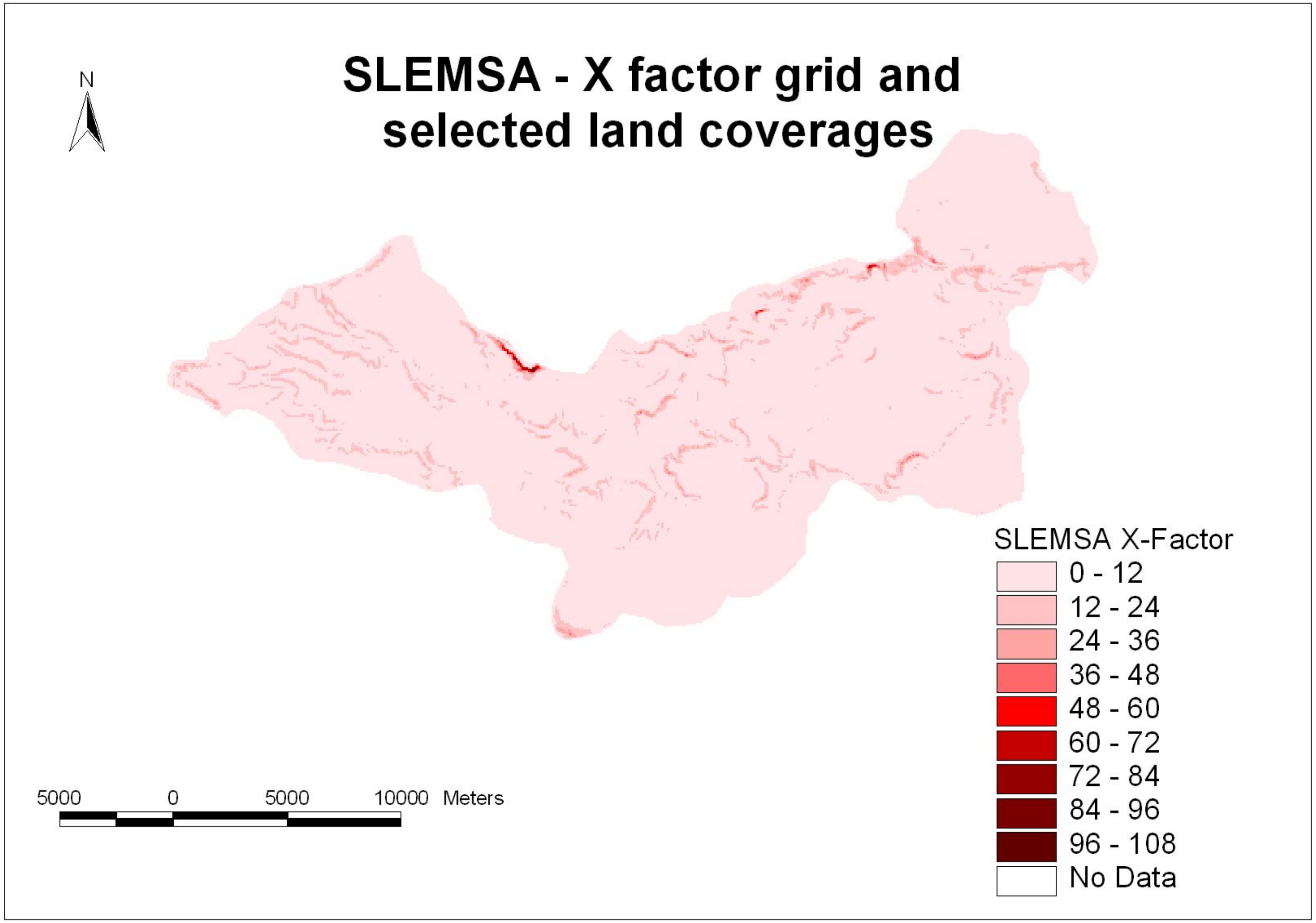


Figure 5.12: SLEMSA *topographic factor* grid

5.3.3 Creating a Crop Factor (*C*) grid

The SLEMSA crop factor, *C*, is estimated using the control variable *i* which provides an indication of the amount of rainfall that is intercepted by vegetation. The crop factor, *C*, is based on a Zimbabwean model originally developed for grassland by Elwell and Stocking (1976). The summary of the factor is shown below:

$$C = e^{(-0.06i)} \text{ when } i < 50\%$$

and

$$C = (2{,}3 - 0{,}01i)/30 \text{ when } i > 50\%$$

where

C = the ratio of soil loss from a crop having an interception value of i, compared to the soil loss from bare fallow

i = percentage rainfall energy intercepted by the crop

Studies have been conducted by a variety of researchers into the determination of SLEMSA *C* factor values for South Africa (Schultze, 1979; Department of Agricultural and Technical Services (ATS), 1976; Hudson, 1987; Elwell, 1977), but it was research done by Edwards (1967), into the plant ecology of the Tugela Basin, which encompasses the catchment, that was used as the basis in estimating the SLEMSA *C* values.

Table 5.11 provides a summary of the vegetation characteristics and associated *C* factor values of the catchment. The average percentage cover values for the physiognomic classes used in the study were adapted from Schultze's (1979) index (After Hudson, 1987). Validation of these observations was provided through research done by Elwell (1977), ATS (1967) and Edwards (1967). The derivation of the canopy cover values for natural vegetation and plantations were found to be the most difficult as there are no existing guidelines for estimating this cover type in the SLEMSA literature. This was not considered however to be too problematic since according to Bonda *et al*., (1999) ungrazed natural woodlands and plantations generally provide good protective cover and since the effect of cover is exponentially declining, the difference in the effect of cover becomes minimal above 50%. As such, there may be little difference in the soil loss beneath a 50% cover and beneath an 80% cover. In Table 5.11, the various vegetation-mapping units identified in the catchment, are correlated to a vegetation type identified by Edwards (1967).

Table 5.11: Vegetation characteristics and *C* factor values in the Wagendrift catchment (Adapted from Schultze, 1979)

Vegetation type according to Edwards (1967)	**Equivalent crop type after Dept. ATS (1976) and Elwell (1977)**	**Average % cover in rainy season ATS (1976)**	***C* value after ATS (1976)**	**Average % cover in rainy season Schultze (1979)**	***C* value according to Schultze (1979)**
Themeda-hyparrhenia *grassland in moist traditional phase*	Tall grassveld – average condition	45 – 75	0.057	60	0.057
Themeda-hyparrhenia *grassland but unimproved*	Tall grassveld – poor condition	<45	0.090	40	0.090
Themeda-trachypogon highlands grassveld dominated by relatively short bunches of grasses up to 3,5 ft high	Highland Sourveld – average condition	80	0.050	70	0.053
Mountain *Podocarpus* forest	Orchards, not cultivated, after second year	80	0.050	90	0.047
Subalpine fynbos and grassland	Highland sourveld – good condition	80	0.050	80	0.050

The C factor value by the former Department of Agricultural Technical Services (ATS) (1976), was included to provide some comparison with initial results.

These initial *C* factor values were then reviewed based on existing local knowledge of the catchment as well as through visual inspection via aerial photo analysis.

According to ATS (1976), since burning occurs within the catchment, the veld cover figures must be modified as follows: -

5% cover deducted for September burns in Tall Grassveld and Thornveld
5% cover deducted for August and September burns in Highland Sourveld
10% cover deducted for August burn in Tall Grassveld and Thornveld
10% cover deducted for November burn in Highland Sourveld
15% cover deducted for November burn in Tall Grassveld and Thornveld

According to Bainbridge (1983), spring burning has been the standard Drakensberg treatment for over 30 years. The spring season in South Africa traditionally begins in the first week of September, and therefore the deductions were made accordingly. For land coverage types, not specified in literature, a null value of 1 was ascribed. Using these modifications and the equations shown above, the final *C* factor values were calculated and are shown below.

Table 5.12: Final *C* factor values per veld, crop and land coverage type

Vegetation Type	Average % cover	*C* factor value
Themeda-hyparrhenia grassveld – average	55	0.058
Themeda-hyparrhenia grassveld – poor	35	0.122
Themeda-trachypogon highlands grassveld	75	0.052
Mountain *Podocarpus* forest	90	0.050
Philippia evansii fynbos and grassland	80	0.043
Urban built-up land – residential	N/A	N/A
Waterbodies	N/A	N/A
Cultivated: temporary – commercial dryland[1]	55	0.058
Cultivated: temporary – commercial irrigated[2]	70	0.053
Cultivated: temporary – subsistence dryland[3]	70	0.053

1 Typical cultivated: temporary – commercial dryland crops in the catchment are maize
2 Typical cultivated: temporary – commercial irrigated crops in the catchment are maize

3 Typical cultivated: temporary – subsistence dryland crops in the catchment are maize and vegetables (e.g. onions, potatoes, legumes)

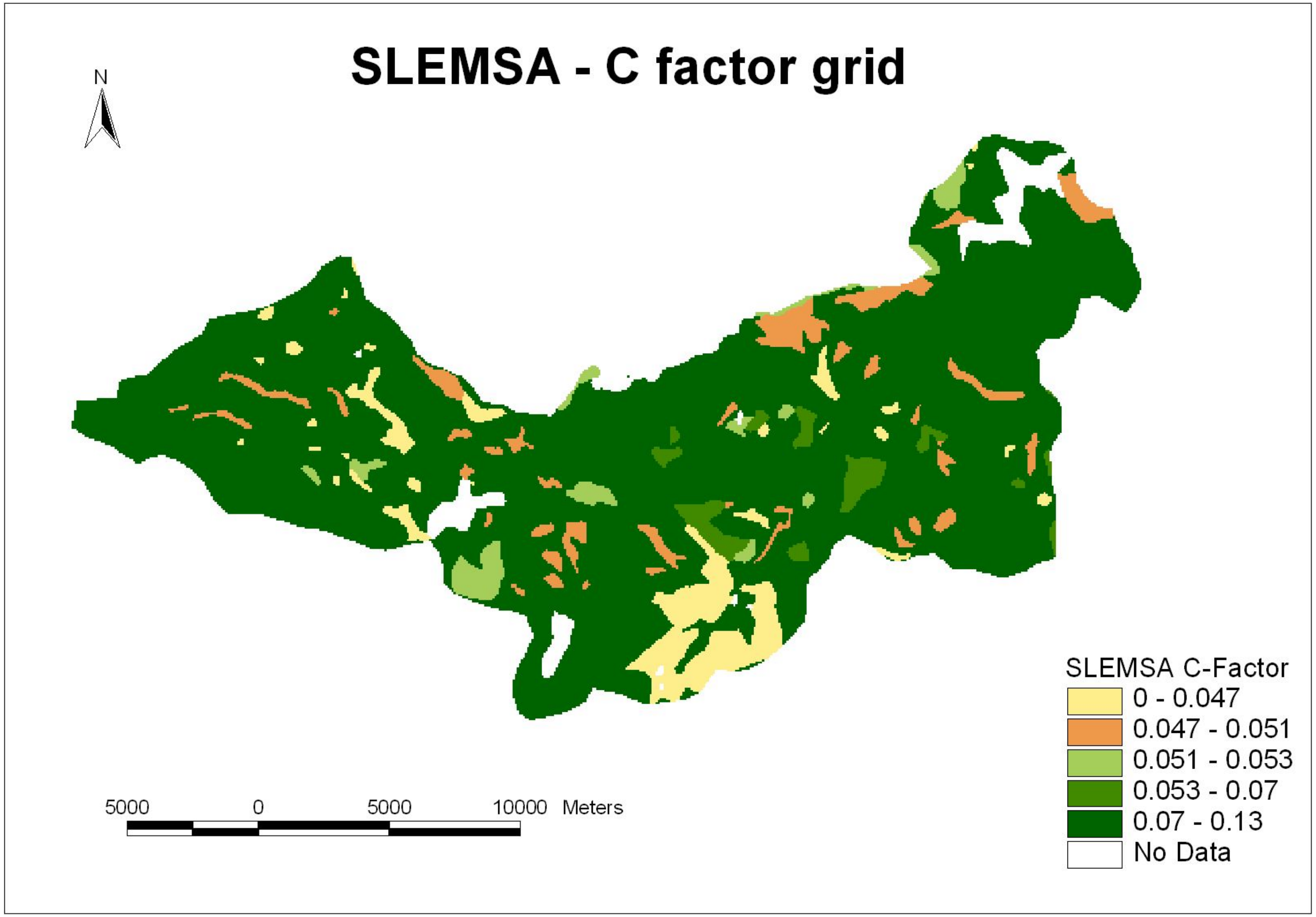


Figure 5.13: SLEMSA *crop factor* grid

5.3.4 Creating the SLEMSA Source Erosion grid

The SLEMSA factor value grids were multiplied to provide an estimation of soil loss in the spatial domain. The resultant map is shown in Figure 5.14, the soil loss is given in tons.ha^{-1}.year^{-1}. Once again it is important not to consider the results as actual values, but more as index values showing where there is a high potential soil loss.

5.4 Soil loss estimation: "adjusted" USLE model

This section outlines the methodology taken in developing 'another' result in the estimation of soil loss at a catchment scale. Once again the USLE is used as the base equation for determining the new result. In this instance however, one of the factor values of the USLE equation is re-calculated. The reason for doing this is to provide an indication of the range of results and indicate the variability of results that can be obtained from modelling soil loss at a catchment scale. In this instance the *R* factor in USLE is re-calculated based on sound scientific principles, as will be discussed below. The result of this third result/scenario is shown to be in stark contrast to the first USLE model result postulated earlier in Chapter 5. A short summary of how this contradictory result was created is explained below:

NOTE: The only factor that was changed for the latter model was the rainfall erosivity, *R* factor, of the USLE; all the other factors that were used in the first calculation of the USLE model were subsequently used in the new calculation and are hence not repeated here.

5.4.1 Creating a 'new' Rainfall Erosivity Index (*R*) grid

In developing countries, where comprehensive autographic rainfall data is scarce various other indices have been developed as a means of reducing the data requirements for calculation of the *R* factor in USLE models. Among the many indices developed are the Wischmeier and Ateshean indices together with those developed by Hudson and Lal (Arnoldus, 1981). The most widely accepted indice that provides a rapid way of approximating the rainfall factor value is the Modified Fournier's Index, which, according to Arnoldus (1981) is a tool that has adequate precision when applied to small-scale maps in South Africa. Smithen (1984) also found the Modified Fournier's Index to be a good predictor of the rainfall erosivity factor in areas of low intensity rainfall within South Africa. The Modified Fournier's Index is shown below:

$$R = \sum pi^2 / P$$

pi = monthly rainfall (in mm)
P = yearly rainfall (in mm)

Using the same precipitation data obtained from the 13 rainfall stations in and directly surrounding the catchment, another *R*-factor was calculated using this correlation equation. Based on the rainfall station data, the *R*-factor value was re-calculated using the Modified Fournier Index:

R-factor: 91151.98/853.9319 = 106.7438

The new *R* factor of 106.74 was applied as a constant to the Mean Annual Precipitation (*MAP*) grid. This value is very different to the value range of between 200 – 300 identified by Smithen & Schultze (1982) for the region, in their paper describing the spatial distribution of the rainfall erosivity factor in South Africa. It is also very different to the range of *R* factors calculated in the first version of the rainfall erosivity grid in Figure 5.4. The resultant map is shown in Figure 5.15, the annual soil loss is given here in $tons.ha^{-1}.year^{-1}$.

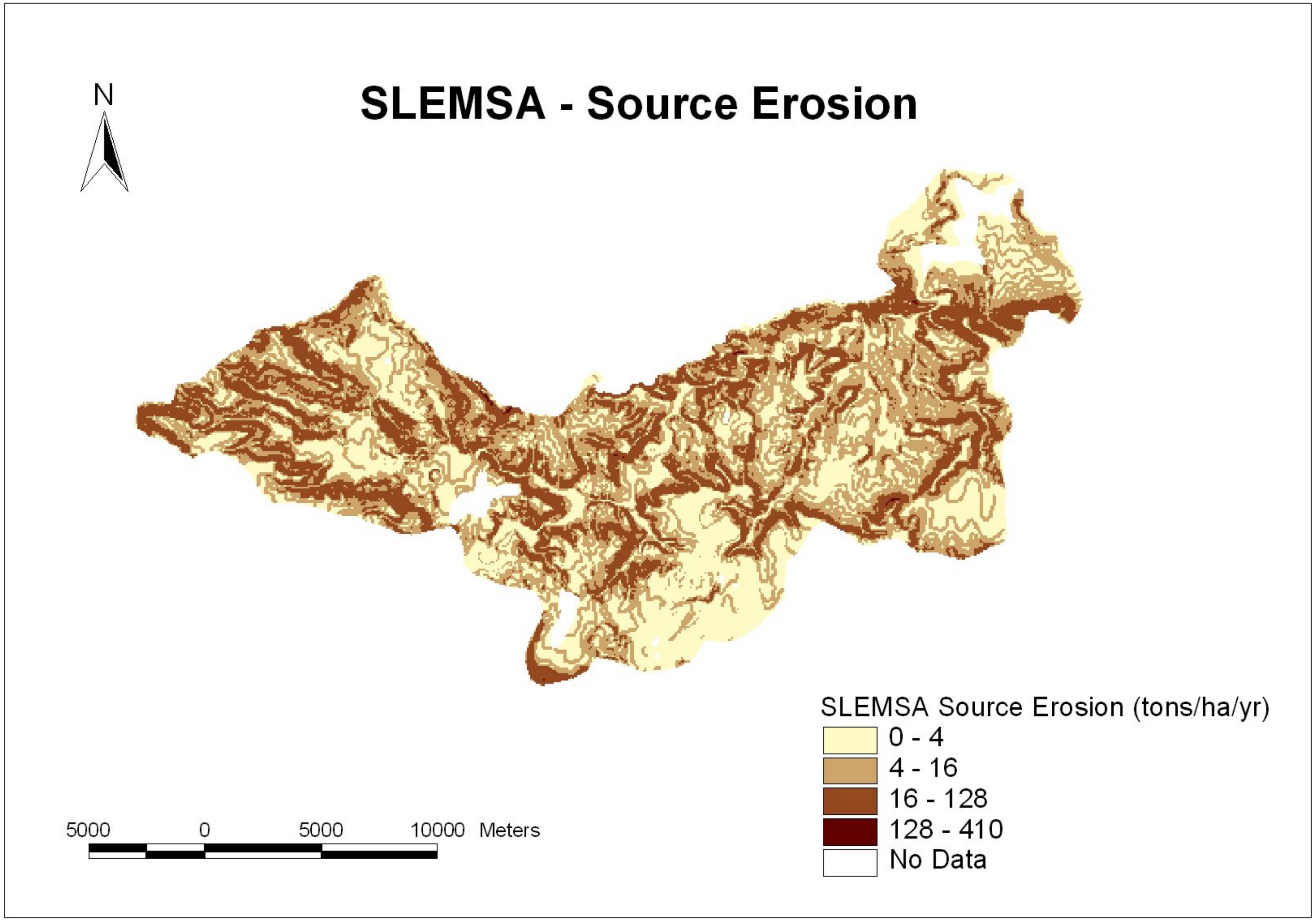


Figure 5.14: SLEMSA Source Erosion grid – *non-linear legend*

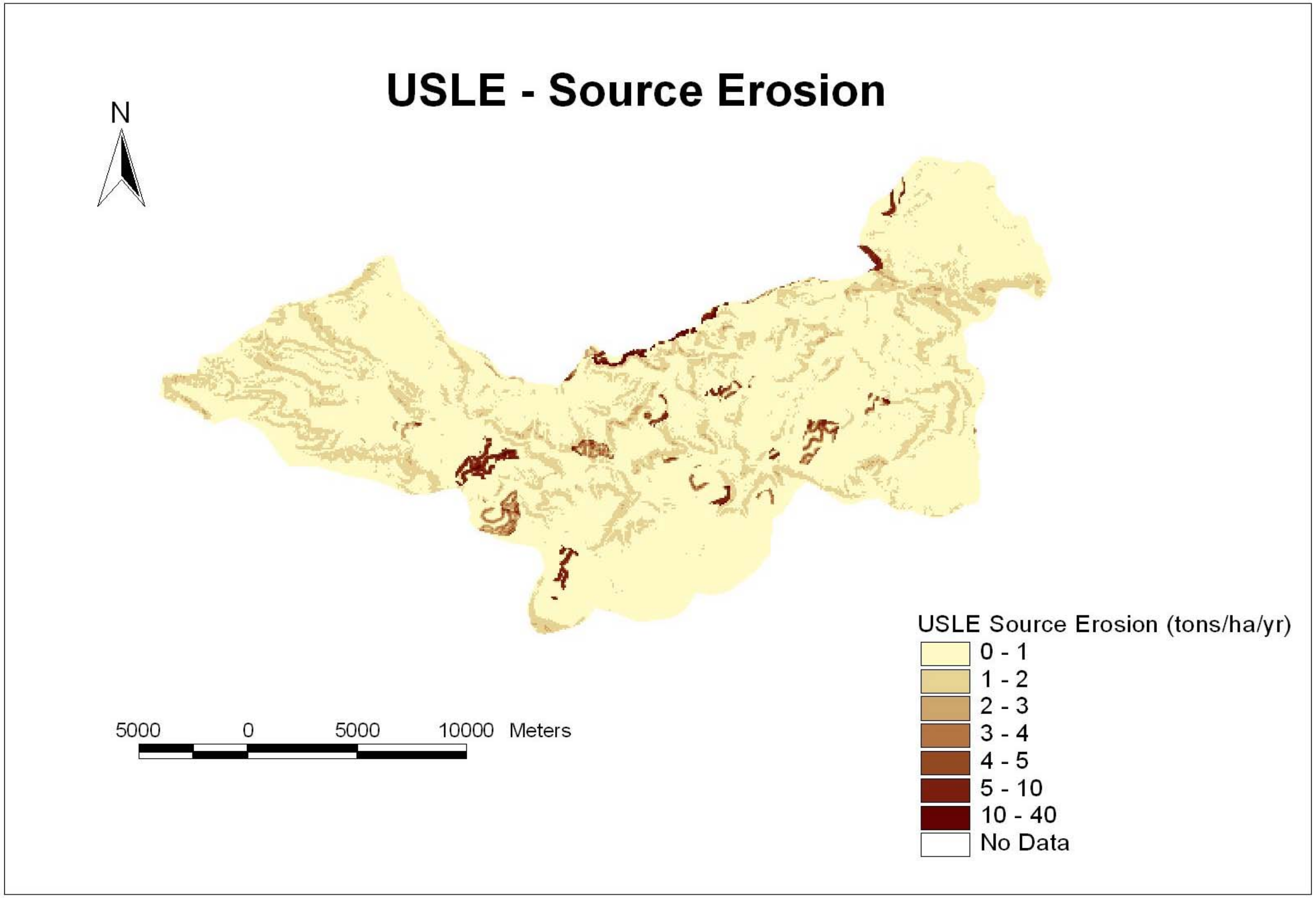


Figure 5.15: “Adjusted” USLE Source Erosion grid – *non-linear legend*

5.5 Chapter Summary

The two soil erosion equations identified in Chapter 2, USLE and SLEMSA; and the GIS software extension SEAGIS, outlined in Chapter 3 were collectively used to establish the nature and extent of soil erosion in the study site. The results of these models will not only be used to draw conclusions of the soil loss potential in the area but will also be contrasted against each other critically. A discussion on results and conclusions that can be drawn from these maps collectively, as well as further analysis, will be performed in Chapter 6.

Chapter 6: A critique of the results

6.1 Introduction

In this penultimate chapter, the results that have been obtained using the erosion models USLE and SLEMSA are critiqued. The catchment scale results have been generated using GIS software and have been displayed in the preceding chapter. Initially, a summary of the results are provided and briefly discussed. The numerous attempts at validating the different model results are provided and this is followed by a general critique of the results based on a GIS perspective and more briefly, a soil science perspective. From each perspective various topics of concern are raised which illustrate firstly, the variability of erosion modelling and secondly, the hesitancy at which GIS can be envisaged as the definitive, error free method of generating catchment scale erosion results.

6.2 Results

Table 6.1 indicates the main findings of the study. It provides the results of the study conducted using the two different erosion-modelling techniques, namely USLE and SLEMSA. The third model result, indicated as USLE* in Table 6.1 was generated using a different rainfall erosivity factor (*R*), which was explained in Chapter 5. The results of the study are provided in terms of mean annual soil loss (in tons.ha^{-1}.yr^{-1}) for each land use category. The reason for doing this is to highlight the uneven distribution of soil loss within the catchment and to hypothesise the causality of the high or low mean annual soil loss, based on the land coverage. An initial glance at the results indicates the variable results obtained using these three different models. The SLEMSA results illustrate the highest mean annual soil loss within the catchment, particularly on the unimproved grassland, thicket and scrubland and indigenous forest land cover types. While the USLE and 'adjusted' USLE results provide lower mean annual soil loss per land coverage, but are more easily comparable with each other than with the SLEMSA model.

Table 6.1: Mean annual soil loss predicted per land coverage of the study catchment

Land-coverage	Area (km^2)	Coverage (%)	Soil loss predictive approach (t.ha^{-1}.yr^{-1})		
			SLEMSA	USLE	USLE* (R = 106.74; explained below)
Unimproved grassland	278.2	81.5	15.6	4.1	0.7
Forest Plantations	18.7	5.5	2.8	0.5	0.1
Thicket and scrubland	16.4	4.8	13.6	1.5	0.2
Cultivated: temporary – commercial dryland	6.3	1.9	2.4	8.5	1.7
Cultivated: temporary – subsistence dryland	5.8	1.7	5.4	16.2	2.0
Urban built-up land – residential	5.6	1.6	N/A	N/A	N/A
Waterbodies	5.6	1.6	N/A	N/A	N/A
Cultivated: temporary – commercial irrigated	2.2	0.7	2.8	13.3	2.8
Indigenous Forest	1.5	0.4	30.7	2.1	0.2
Improved Grassland	1.1	0.3	4.3	0.6	0.1

6.3 Discussion

From the onset of the discussion it is important to note that the research data for this study was mostly obtained from sample points and it is imperative to realise that extrapolation from point to catchment and regional scales is problematic, and direct proportional conversions will undoubtedly result in over-estimations (Stocking 1987). This fact should be kept in mind when considering the discussion below and when attempting to validate the model (see section 6.4).

As mentioned earlier, Table 6.1 provides the main findings of the study. The most basic conclusion that can be drawn on the first impression of the table is that SLEMSA and USLE do not compare very well. The greatest discrepancies between the SLEMSA and the USLE models are shown in the land coverages of unimproved grassland, thicket and scrubland, and indigenous forest, with the SLEMSA model greatly exceeding the USLE models results. It is noticeable if one examines the thicket and scrubland and indigenous forest areas within the catchment, indicated on Figure 6.1, that part of the reason for these high values exhibited by these land coverages could be because they occur on the steepest regions within the catchment.

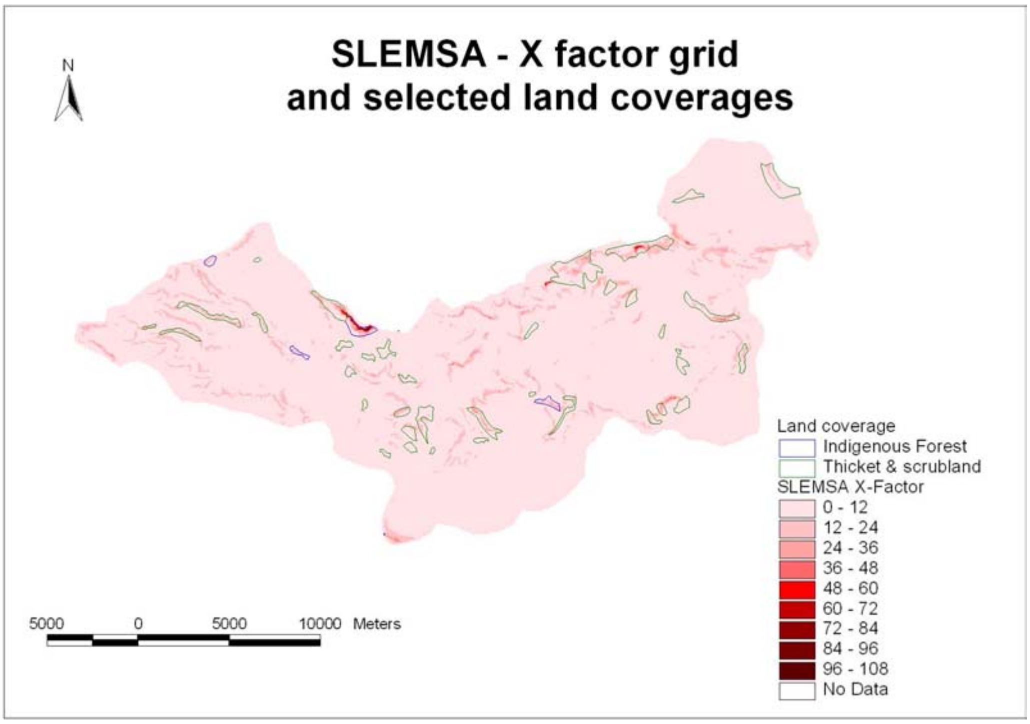


Figure 6.1: A review of selected land coverages with the SLEMSA X factor grid

The forests in the catchment are founded on steep slopes with shallow soil depth, but on stable slopes. While the grassland, and thicket and scrubland coverages, of the area, which also exhibit high soil loss values, occur on unconsolidated, colluvium slopes that are prone to paleo-landslides and mass movements making the incidences of visible soil erosion and loss more prevalent throughout the catchment. The area is frequently characterised by paleo-landslides of high frequency-low magnitude type (Meiklejohn, *pers. comm*). The fact that the thicket and scrubland, and indigenous forest coverages takes up such a small percentage of the catchment, i.e. only 16,4 km^2 and 1,5 km^2 respectively, and yet is on the steepest land, could account, in part, for the high soil loss found in those land coverages of the SLEMSA model.

The biggest factor discrepancy between the two models lies between the soil erodibility factor, *K*, of USLE and the erodibility factor, *K*, of SLEMSA (Figure 6.2). These two factor grids cannot be directly compared to one another, based on

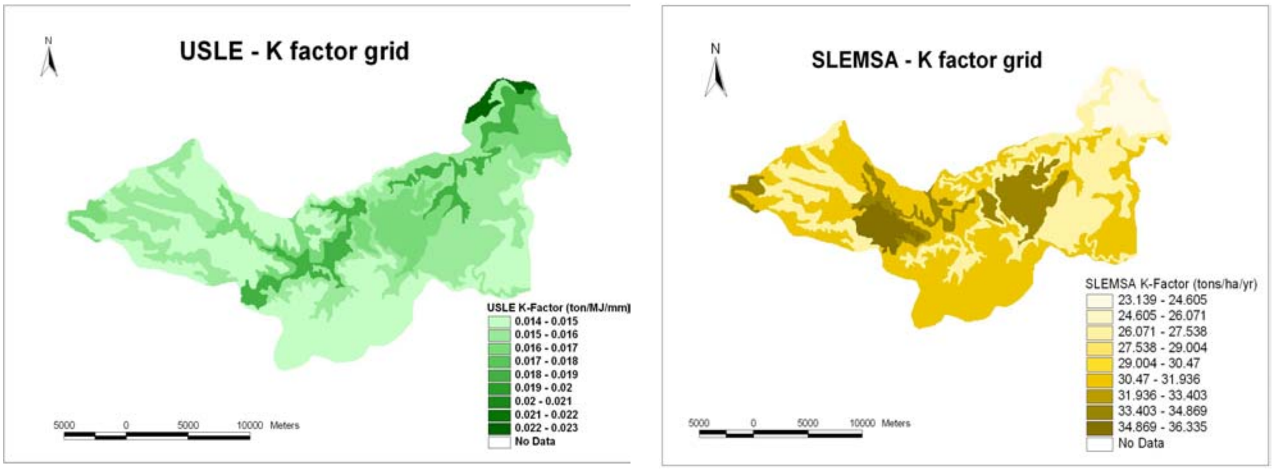


Figure 6.2: A comparison between the USLE and SLEMSA K factor grids

inherent theoretical differences, but a few interesting points are evident. For instance, the patterns of each grid are in conflict. Areas of high soil erodibility in the USLE K factor grid are corresponded with areas of low erodibility in the SLEMSA K factor grid.This pattern tends to reoccur throughout the catchmnet. An explanation for this discrepancy could be the fact that within the SLEMSA K factor grid, the erosive ability of the rainfall is coupled with the soil type in determining a K value. In USLE, the K factor refers only to the erodibility of the soil.

These two discrepancies between the two models could account for the extreme results in the study when compared with the rest of the findings. These discrepancies are further validated by a study conducted by Hudson (1987), in which she investigated the applicability of SLEMSA in mountainous terrain in South Africa, she found that estimates of soil loss were very sensitive to variations in both slope steepness and rainfall energy and that estimations of soil loss using SLEMSA were 20 times larger than actual measurements.

Another fact that could perhaps attempt to explain the high annual soil loss obtained using the SLEMSA model in this extremely mountainous catchment in the Natal Drakensberg lies in the lack of effective integration of certain requirements within GIS soil modelling software to soil erosion parameters. Rock mass strength, and the geomorphological history of the area, (which in part determine the rock mass strength) are factors that can affect soil loss from a catchment. A shortcoming of GIS modelling software is its inability to accommodate these necessary factors within a spatial model. A shortcoming of both the USLE and SLEMSA models is the inability to incorporate these factors and the effect they have on for instance, land coverage, within the models. Another shortcoming of these empirical models, particularly when linked with GIS is the tendency to lump the model calculations and therefore oversimplify the erosion process.

The USLE and 'adjusted' USLE results seem to indicate a more realistic outlook on the state of soil erosion in the catchment. Once again the unimproved grassland land cover types provide a high figure but the majority of high values occur on lands identified as cultivated commercial or subsistence farmlands. These reasonably high figures could be explained by studies conducted by Elwell (1981), which found that estimates using USLE were up to 100% too high for cropped plots in southern Africa. The results display a rather worrying tale for conservation strategists, the main reason being that a high amount of soil loss occurs on the unimproved grassland. This is grassland that is not currently being man-managed for grazing, hay or turf production (CSIR- SAC, 2001), and as such is vulnerable to the large amount of cattle grazing in the area. This overgrazing reduces the vegetation cover and also induces cattle tracks, which also contributes to erosion in the area.

6.4 Validation of results

Validation of results determines the accuracy and reliability of the research. The above-mentioned methodology provides an indication of the problems faced with researchers in validating model results based on the simple fact that soil loss model results can be so variable.

6.4.1 Validation of the results using sediment yield

The first option investigated for the validation of the results for this study was field observation of eroded sites within the catchment. After comprehensive field observation of the research area no obvious sites of deposition from eroded soils were found, and where deposits do occur it is practically impossible to accurately date them (Hudson, 1987). According to Hudson (1987) the only form of contemporary erosional features on which to possibly base field corroboration was gully erosion and slope degradation but that was in itself inconclusive. It thus became apparent that the only viable methods of field corroboration – in the time available for this study – would be to either compare sediment yield data with the predicted soil loss values and/or to compare results of erosion plot studies conducted in adjacent catchments in KwaZulu-Natal with the predicted soil loss values in the study catchment. The fact that little within-catchment deposition occurs, suggests that adoption of these methods is feasible (Hudson, 1987).

According to Hudson (1993) a valid estimate of run-off and soil loss from a catchment can only be obtained from measurements at the outlet of the catchment. Sedimentation yield figures of the Wagendrift Dam at the outlet of the catchment and sediment yield results at a scale of 1:250 000 obtained from the Department of Water Affairs and Forestry of South Africa were used in an attempt to accurately validate the model results through sediment yield. The last sediment survey of the Wagendrift Dam took place in December 1999, the total volume capacity of the sediment in the Dam was found to be 4 057 225 m^3, which is 6.77% of the gross capacity (59 957 000 m^3) of the Dam (DWA, 1999). The average rate of sedimentation per year in the Dam is 0.19%, which would make the amount of sediment being deposited into the Wagendrift Dam being 114539.6 m^3 per year by the present year 2003. Using a standard weight per volume of 2,65 tons/ m^3 (Brady, 1974) this equals 303529.94 tons/year. This figure is provided that ALL the sediment that is run-off from the catchment is deposited in the dam, which is highly unlikely!! When one compares this figure with the total soil loss for the catchment generated in the study from the various models we can see that the USLE figure of 255493,44 tons/year compares favourably while the other models yield indifferent totals of 43343.48 tons/year for the 'adjusted' USLE model and the SLEMSA figure of 888672.83 tons/year.

This method of catchment scale validation however is error prone. Firstly, it is not an accurate procedure to validate with sediment yield data obtained at a watershed scale because the USLE does not include deposition and delivery ratios (Hudson, 1993). A study by Garland, Hoffman & Todd (1999) has found that differences between sediment yield and soil loss figures could be very high indeed. Measurements by Scott & Schulze (1991) and Scott & Van Wyk (1992) in South Africa suggest that "at a site" soil loss within a catchment could be up to 5 times greater than sediment yield from the same catchment over the same period. Garland *et al*., (1999) concluded however, that soil loss and sediment yield values probably bear a stable relationship to each other. In terms of the SLEMSA model it is important to distinguish once again between the model results and sediment yield as measured in rivers and dams. The reason for this is that SLEMSA, like USLE, does not take into account the possible deposition of the soil at the end of a slope and not necessarily into a river system. SLEMSA is therefore, essentially a model of soil removal (Schultze, 1979), making any comparison with sediment yield data, highly inaccurate.

6.4.2 Validation of the results using erosion plot studies

The second method of validation that was investigated was one based on results of erosion plot studies conducted in adjacent catchments in KwaZulu-Natal. According to Garland, *et al*., (1999) average annual soil losses on bare, weed-free plots with 9% slopes at Cedara Research Station, KwaZulu-Natal, ranged between 23 and 200 $t.ha^{-1}$ (Department of Agriculture, 1991). Soil loss from a small fallow catchment at La Mercy in KwaZulu-Natal reached 115 $t\ ha^{-1}\ yr^{-1}$ in 1981. Van Wyk *pers. comm.* (cited in Hudson, 1987) conducted soil loss research in two catchments adjoining the study site catchment and observed soil losses of 1,8 $tons.ha^{-1}.yr^{-1}$ and 0,4 $tons.ha^{-1}.yr^{-1}$ respectively on open grassland. According to Garland *et al*., (1999) measured values of soil loss from undisturbed veld in the Drakensberg ranged from 0,02 $tons.ha^{-1}.yr^{-1}$ (Garland, 1988) to 0,75 $tons.ha^{-1}.yr^{-1}$ (Haylett, 1960). The variation can be accounted for by local slope, vegetation, rainfall and soil conditions. Examples of this variation can be found through studies whose values for grazed land ranged from 0,6 $tons.ha^{-1}.yr^{-1}$ (Scott, 1951) to 1,7 $tons.ha^{-1}.yr^{-1}$ (Haylett, 1960). These erosion plot results are summarised in table 6.2.

Table 6.2: Summary of erosion plot studies conducted in adjacent catchments or catchments of similar environmental conditions to the study catchment

Predicted soil loss rate	Researcher/s	Erosion plot type	Erosion plot Size
23 - 200 tons.ha^{1}.yr^{-1}	Department of Agriculture (1991)	Weed-free plots	22m * 2m
0,02 tons.ha^{-1}.yr^{-1}	Garland (1988)	Undisturbed grassland	22m * 2m
0,6 tons.ha^{-1}.yr^{-1}	Scott (1951)	Grazed grassland	90ft * 6ft
1,7 tons.ha^{-1}.yr^{-1}	Haylett (1960)	Grazed grassland	12ft * 25ft

These study results can be compared to the values obtained in the three different soil loss prediction methodologies referred to in table 6.1. A summary of the table results relevant to the erosion plot studies is shown below:

Table 6.3:Mean annual soil loss predicted for 'Improved' and 'Unimproved grassland'

Land coverage	Soil loss predictive approach (to.ha^{-1}.yr^{-1})		
	SLEMSA	USLE	USLE* (R = 106.74)
Unimproved grassland	15.6	4.1	0.7
Improved grassland	4.3	0.6	0.1

The model results obtained through the study appear to be the most consistent with erosion plot studies conducted by researchers using the USLE and the 'adjusted' USLE model. Both these models provide results which are well within the range of soil loss estimates provided for by the various researchers on the grassland, land coverage type. Validation or model corroboration on land coverages other than grassland is questionable at best since erosion plot studies by definition are consistent with plots on land defined as weed-free fallow, grassland, or exhibiting an agricultural crop type. Since the range of land coverages within the catchment extend from forest plantations to thicket and scrubland an extrapolation of erosion plot results to these land coverages would be unscientific.

The fact that runoff plots are expensive and usually ineffective, and worldwide the vast majority of plots have produced little or no usable or worthwhile information (Hudson, 1993), must also raise the question as to whether it is even accurate to validate the models results with erosion plot studies at all. According to Hudson (1993) the difficulties in collecting erosion plot data of sufficient accuracy and reliability are so great and so numerous that only large experimental programmes conducted at great expenses over a long period of time can really meet this objective. *It has to be remembered that the USLE was based on a data base of approximately 10 000 plot years, and it is unrealistic to imagine that local variations for different regimes of soil or climate can be constructed from the results of a handful of plots for a year or two. "* (Hudson, 1993). There is however no viable alternative which exists for erosion plots as the major form of data input to predictive equations of soil loss (Stocking, 1987).

With this in mind one may argue that any form of validation of this catchment scale erosion study is not scientifically sound yet according to Zobeck, Parker, Haskell & Guoding (2000) the USLE, which is a field-scale water erosion model (Wischmeier and Smith, 1978) has been used in conjunction with GIS to estimate water erosion for a 600,000 ha region in Ontario (Snell, 1985), a 61,000 ha watershed in Idaho (Prato *et al*., 1989), and a 1400 ha watershed in New Brunswick, Canada (Mellerowicz *et al*., 1994). A modified version of the USLE was used with GIS to estimate erosion in an 8.6 million hectare region in northern Thailand (Liengsakul *et al*., 1993). If the validity of a 34100 ha catchment-scale erosion study is brought in question than the validity of an 8.6 million hectare region in northern Thailand must surely surpass all scientific validation. Moreover, the preoccupation in most soil erosion investigations of quoting the total mass of sediment removal in an area or catchment is absurd. "Does it really matter that 55 000 tonnes/km^2 is eroded from the loess plateau of China? Automatically, many will say that it does matter. However, it remains unproven that this erosion affects yields and that stopping it will actually increase yields and make the living conditions of rural Chinese any better" (Stocking & Peake, 1985).

6.4.3 Validation of erosion modelling at a catchment scale

The accuracy of model predictions is usually tested, as seen above, by comparing predicted with measured values. This section will take the validation argument a step further and concentrate on the very legitimacy of GIS erosion modelling and more particularly on catchment-scale erosion modelling.

Erosion modelling is very error prone (Jetten *et al*., 1999) and has many weaknesses such as the oversimplification of reality and the tendency to ascribe model output as 'fact' (Stocking, 1984). According to DeMers (2000), the following three fundamental questions should be asked to provide 'validation' to the modelling process:

1. Do the data in the model truly represent the conditions we are attempting to model?
2. Have we combined the model factors correctly, to represent proper factor interactions, thus correctly describing or prescribing the correct decision-making process?
3. Is the final solution acceptable by the users and/or useful to them as a decision-making tool?

In response to the first question postulated above, the data in the model does not truly represent the conditions we are attempting to model. Most notably the data collected during the fieldwork and also through various data sources are accurate representations of the environmental conditions of that point in the catchment at which they were sampled. The 95 soil sample points that were used for the determination of the soil erodibility factor of USLE and the erodibility factor of SLEMSA are correct to, and only to, the exact soil at the location of the samples. A more accurate result could have been obtained from a soil or geological map of the area but since the area has not been comprehensively surveyed the data extracted from these maps would be questionable. The scales of these maps are also too small to provide the detail required for such a study. The extrapolated data does not represent the heterogeneous nature of the catchment and the conditions that we are attempting to model. Extrapolation of that data, through interpolation, to a catchment scale would be incorrect based solely on the diverse nature of any quaternary river catchment.

Secondly, both the USLE and SLEMSA models are statistical and empirical models that have "universal applicability". The various factors within these models were combined correctly and the various factor interactions have been followed according to the methodologies specified in the various handbooks and guidelines outlined by the developers of these models.

Lastly, as to whether the final solution will be deemed acceptable by the users or useful to them as a decision-making tool is one of interpretation. The problem faced within this application is whether ANY model result is true or can be deemed to be nearer the truth than any other model result. Any result that we have determined could be deemed acceptable by decision-makers depending of their objectives of the research. Should the objective of the researcher be to give an indication of the serious nature of soil erosion in the Wagendrift catchment, then the results of the SLEMSA model would appear to be valid and accurate and would serve as a sound scientific base from which to lobby for developmental programmes to be put in place within the catchment to end the scourge of erosion within the catchment. Should the objective be to clear one's conscious regarding the state of soil erosion in a poor, rural region in the Natal Drakensberg, then the 'adjusted' USLE erosion map might suffice.

6.4.4 Validation of the USLE and SLEMSA

The overall problem of the USLE and SLEMSA models lies in the fact that statistical models, as a whole, typically yield a picture of erosion that is heavily biased by modern anthropogenic impacts and the limitations of too little data collected over too short a time frame (Finlayson & Montgomery, 2002). Notwithstanding this fact however, the USLE is only valid where the factor values for the equation have been experimentally determined, that pertains only to cropland east of the Rocky Mountains in the United States (Abel & Stocking, 1987). As this study has been conducted in a catchment in an extremely mountainous region of South Africa the question of applicability must arise. Whereas numerous studies have been conducted investigating the use of USLE in South African conditions, most notably, Donald (1997), McPhee & Smithen (1984) and Crosby, McPhee & Smithen (1983), all researchers propose that USLE could be applied to South African conditions provided input data for local conditions could be developed. Studies conducted in Zimbabwe by Elwell (1981) found that USLE and its factor values were found to be inappropriate under local conditions and estimates varied from 50% too low for bare fallow soils to 100% too high for cropped plots. The attraction of the USLE in this particular study however, is that the USLE as compared to dynamic simulation models is a relatively simple statistical soil erosion model, which is easy to parameterise, and thus requires less data and time to run (Sun & McNulty, 1997). Factors which are all very attractive when considering the time frame of the study and the, at times, extremely limited data resources in South Africa.

Various conclusions have been drawn regarding the accuracy of results from the SLEMSA model with Garland (1982) concluded that SLEMSA could at best provide comparative results and Smith (1999), adding that values derived from SLEMSA should be seen as relative values and much more verification and calibration of parameter estimates are required before the model could be routinely applied in soil conservation planning. Hudson (1987) also determined that estimations of soil loss using SLEMSA were 20 times larger than actual measurements. The methodologies used in her study – nearly always small-sized soil loss and run-off plots – are well known to produce erosion rate measurements that are far higher than actual net loss from a hillside (Stocking, 1987). Since the estimations hypothesised in this study are at a catchment scale it is nearly impossible to estimate the discrepancies between the calculated soil loss values and the actual rate of soil loss in the catchment. The relative simple input requirements and as well as the ease at which estimates of soil loss are made with the model made it an appealing choice for the author. To compare an internationally acclaimed soil loss predictor model with a locally developed model added to its appeal.

6.5 Critique of results - A GIS perspective

6.5.1 Assumptions

"Models are only as good as (and often much worse than) the assumptions upon which they are based" (Stocking, 1984)

Technical journals are attempting to raise the standard of field experimentation by rejecting articles for publication that do not have a suitable statistical analysis and a reasonable timespan (Hudson, 1993). I would like to include within these technical journals the additional pre-requisite of detailed information regarding the limitations, assumptions and specific objectives of the research made by researchers involved in modelling soil erosion. These may include information regarding *per se*:

- The methodology used to extrapolate from detailed case studies to the region or catchment, as well as the capability to extrapolate data recorded at individual points to a catchment scale
- Data collection method (frequency and magnitude)
- Details of the validation process (the technique and scale of measurement must be quoted)
- The data output (for whom is the GIS analysis result generated for, economists, decision-makers etc)

Such clarity would further illustrate the assumptions that the reader can make regarding the authenticity of the research design.

6.5.2 Scale

The inherent problems of any soil loss prediction result is whether or not you can take measurements of land degradation from one scale and extrapolate the results to another scale? The immediate scientific response to this question would be no. Strictly speaking the total amount of soil loss on a standard 22 by 2 metre field plot, is applicable to, and only to, that field plot. This is however, not a viable solution to GIS specialists, and other industrial workers for whom the design of decision support systems and information systems are the output for such a study. They require the results to extend over an area of a certain size in order for effective conservation strategies to be put in place. Rates of erosion however, measured at the field scale will, when extended to the scale of the catchment, grossly overestimate the total amount of sediment leaving the catchment (Stocking, 1987). The reason for this being the fact that the field scale erosion studies occur on land a fraction of the size of a catchment, the soil being eroded at a catchment scale is often re-deposited when the slope angle decreases. In the field scale erosion calculation, the re-deposition of eroded soil particles is not accounted for based on the small size and definitive boundaries of the erosion plots. These eroded particles are then used in the calculation of the total erosion within the field scale plot. As Stocking (1984) states:

> *"Small, bounded plots give the highest measured soil losses per unit area. This is because each soil particle that is detached by erosion and starts to move is caught and weighed. As the area for assessment increases, there is greater likelihood of storage of sediment within the bounded area. In real field conditions as much as 90-95 percent of eroded soil is redeposited elsewhere within the landscape"*

Scale is a crucial issue in soil erosion modelling and policy support because it influences model development and selection, as well as data availability and quality (Renschler & Harbor, 2002). The choice of scale of your project will obviously influence the choice of model that will be used for your study, for a catchment scale project the most notably developed soil erosion model would be the ANSWERS model which has been fully integrated into a GIS. This model is a distributed parameter, event-oriented planning model that subdivides the watershed into a uniform grid of square cells (Dillaha, Wolfe, Shirmohammadi & Byne, 2001). Within each cell, the model simulates interception, surface retention/detention, infiltration using Holtan's method, surface runoff, and percolation (Dillaha *et al*., 2001). However, just as scale influences your choice of erosion model and policy support it also influences the data requirements and quality for you model. The catchment scale ANSWERS model is incredibly data intensive and requires a large amount of detailed information which is a big disadvantage in developing countries where parameter specific data is more often than not unobtainable. For smaller scale projects (e.g.

hillslope) the researcher is spoilt for choice for erosion models, most of which can be manipulated to accommodate the particular environment in which the project is taking place. The problem however lies in the small-scale nature of the study area, which, as mentioned earlier, is not conducive to conservation strategists for whom the economies of scale hold true.

Scientists are well aware of scale problems and expect robust models to explicitly deal with variability, as well as with the issue of how data on erosional processes at one scale can be extrapolated to processes operating at other scales (Poesen, Boardman, Wilcox & Valentin, 1996). At different scales, different groups of processes are dominant, so the effective focus of the model also changes (Renschler & Harbor, 2002). For example, at the scale of the single erosion plot, the timing and volume of overland flow is critical and at coarser scales, topography, soil vegetative patterns and other factors become more important (Zobeck *et al*., 2000). "In this approach, different models are required at varying scales to accommodate the particular processes dominating at the level simulated" (Zobeck *et al*., 2000).

Multiscale approaches are presently one of the focal points of the GIS research community (Molenaar, 1998). This is due to the rising awareness that many processes, including soil erosion, can only be monitored and managed if they are understood in their geographic context (Rojas, 2002). One of the major challenges in soil erosion modelling, which has become even more important with increasing use of models linked to GIS, is the mismatch between the small spatial and temporal scales of data collection and model conceptualisation, and the large spatial and temporal scales of most intended uses of models (Renschler & Harbor, 2002). The ANSWERS model operates at the spatial scale of a grid cell and within the temporal scale of a single storm, whereas the USLE and SLEMSA models tend to operate at the hillslope or field plot spatial scale in theory but in a GIS, results are extrapolated to a catchment scale. With this in mind Renschler & Harbour (2002), proposed a diagram that aligns spatial and temporal properties which are important for the dominant processes at the indicated scale.

According to this diagram, SLEMSA, which is only valid at the hillslope scale, cannot account for watershed degradation problems that include sedimentation and changes in stream baseflow (Bonda, *et al*., 1999). The spatial and temporal properties important for the generation of SLEMSA results would be all the properties that 'fall in line' under the 'Hillslope' heading in the diagram.

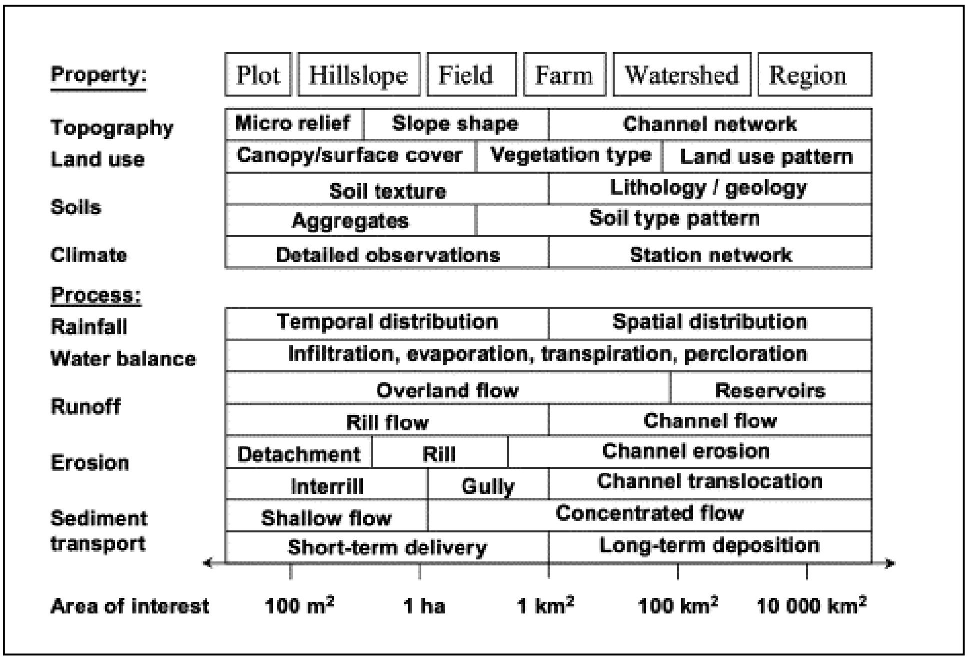


Figure 6.3: Scales of interest, spatial, and temporal variable properties important for dominant processes at an indicated scale (Renschler & Harbor, 2002).

In conclusion, the problem with scale and erosion modelling is two fold – on the one hand by estimating potential soil loss at a catchment scale the spatial error in the application is propagated. According to Jetten, *et al*., (1999) the reason for this being that at a catchment scale the input maps are often created from a limited amount of field data and with a lot of assumptions and therefore highly subjective; there are also many methods of interpolation that are equally valid but give different results. All these problems mean that there is a greater opportunity for concatenation and amplification of any errors and uncertainties in the input data within the model (Jetten *et al*., 1999). On the other hand however catchment-scale applications are able to treat heterogeneous catchments of varying size and perhaps most important of all predictions of future erosion at a scale smaller than catchment (e.g. a single field), no matter how reliable, are of limited value for developing future soil conservation strategies (Jetten *et al*., 1999). For the foreseeable future, both scales of model have a role to play.

6.5.3 Addressing the problems of scale

Upscaling model results, using GIS, to different scale levels has been seen as a method of scaling up erosion estimates from field to the catchment scale but Moore *et al* (1993, cited in Zobeck *et al*., 2000) have warned against such an approach and identified four major scale-related problems that must be dealt with if such an approach is to be taken. They are:

(i) Element size in which homogeneity is assumed;
(ii) The method of analysis used to derive the attribute values;
(iii) Merging data with different resolutions, accuracies and structures, and
(iv) Scale differences between model process representation and data available for model parameterisation.

According to Bonda *et al*., (1999), in order to address the scale issue in erosion modelling, effective regional values for each application should be developed in terms of land cover (which should be limited to those that can be identified with regional characterisation tools such as satellite imagery with ground verification) and topographic factors (which should use a single effective hillslope length applicable to the whole catchment even though in a catchment there may be many different hillslope lengths). Other solutions proposed by Bonda *et al*., (1999) include cross-checking models results against those of other estimate models and developing an erosion hazard scoring system, similar to the one developed for Zimbabwe by Elwell (1977); this scoring system takes into account population pressure as well as topographic factors, climatic factors and cropping practices. Since the methods mentioned above, (including SLEMSA and USLE) have their own limitations, there is no consensus as to the proper method of erosion hazard assessment at the regional scale. While there are benefits to cross-checking the results of for instance SLEMSA with other methods, erosion hazard assessment remains a difficult task with no clearly superior method. (Bonda, *et al*., 1999).

The problem with scale invariably brings up the question proposed by Stocking (1996), and that is: “If the assessment of the seriousness of soil erosion rates is so fraught with methodological and practical uncertainties and if experimental results of erosion rate are so difficult to interpret and subject to exaggeration, do we even need to measure erosion and is there no alternative strategy of soil conservation?"

6.5.4 Data accuracy and reliability

The main GIS problem associated with validating spatial process models is lack of appropriate data (Heywood *et al*, 1998). In determining if models and data are accurate and reliable, a common approach is to compare model results with observational data; however model predictions rarely match observations exactly; does this mean that models are insufficiently reliable?? (Renschler & Harbor, 2002). Issues relating to data accuracy and reliability occur at the beginning of the modelling process, according to Stocking (1987), in land degradation research; the data collection itself is probably the major source of error. Resulting in using incorrect data as input and then comparing to results that also have errors.

A study conducted by Renschler and Harbor (2002) found that variations in input resolution affected model results and that in their study the coarser data overestimated erosion loss compared to higher resolution data. They found that the data resolution also affects the average annual storm runoff and sediment yields, as well as the details of where erosion is predicted to be occurring, all of which have significant management implications.

6.6. A soil science perspective

6.6.1 Assumptions made

"Soil erosion is bad, but it's badness depends on who you are, how you study it, and what information you care to select" (Stocking, 1996)

The major assumption, from a soil science perspective, that was made while conducting the research concerned the calculation of the soil erodibility factor of USLE and the erodibility factor of SLEMSA. For both of these factors, data, which was collected at various points within and around the catchment, were extrapolated to the whole catchment, from point to regional scale. Up to 95 soil samples were taken within and around the catchment and these sample points formed the basis of the calculation of the soil erodibility factor grid of both models. Strictly speaking the parameters obtained from these points and used in analysis e.g. % organic matter, % sand, %silt and % clay, are applicable to, and only to, the exact site at which the samples was taken. Although this point negates the obvious fact that it is practically impossible to sample an infinite number of points in the whole catchment in order to accurately determine the soil properties for the whole catchment, it still indicates that the data (extrapolated to the whole catchment) used in the model does not truly represent the heterogeneous conditions in the catchment. Similarly, in establishing the crop management factor values, it was assumed that the vegetation coverage, ascertained from the Council for Scientific and Industrial Research (CSIR), prevailed throughout the catchment, even when land-use maps and land coverage maps showed the area to be either under cultivation or conservation. The supervised or unsupervised classification of satellite imagery to establish land coverages in the area is in itself a process subject, in part, to interpretation.

Zobeck *et al*., (2000) also found that the map scale of the soil map used in the determination of the erodibility of soil could be a major factor in the resulting erosion potential of an area. He compared erosion prediction results using two different soil maps, one with a minimum mapping unit of 2 ha and the other with a minimum mapping unit of 625 ha and found a 15% difference in the erosion potential of an area based on the scale of the soil map used. While this fact may not necessarily be applicable in this study it does beg the question as to how different the models outputs would have been had 200 soil sample points been taken as opposed to 100.

6.6.2 Data measurement, reliability and accuracy

The capability to measure accurately is central to all scientific explanation (Goudie, 1981, cited in Stocking, 1995). "Measurement is never neutral, never a pure service for science or policy. To quote Weatherall (1968): 'Man, as a scientist, is inescapably part of any experiment he conducts' (Extracted from Stocking, 1987).

The misuse and abuse of the USLE since its conception in 1978 lead to its authors publishing an article expanding upon the ways in which the USLE are to be used in the future. Among the main warnings issued by Wischmeier and Smith is the extrapolation of equation factor values into unmeasured areas. The biggest problem associated with the extrapolation of data to unmeasured areas lies in the fact that the data in unmeasured areas cannot be said to be reliable and truthful enough to base results upon. Therefore the extrapolation of the *K* factor values, upon which the soil erodibility grids of both models were based, cannot be said to be reliable and truthful. To take this argument a step further, according to Roose *pers. comm.*, (1980, cited in McPhee & Smithen, 1984) there can be no single *K* factor value for any soil because the soil characteristics on which *K* depends can be changed by land use in the long term and by soil moisture, compaction and surface sealing in the short term. The question of the reliability and truthfulness of the data must therefore come into consideration.

What is the truthful result of the study? Which result is the truthful one? This fact can be left open to the interpretation of the reader. The problem can be illustrated further by comparing sediment loss maps produced by Strakov (1967) and Fournier (1960), and UNESCO (1975), all using the same data of sediment transport in rivers and reconnaissance surveys. The true map is the map that subscribes to your point of view.

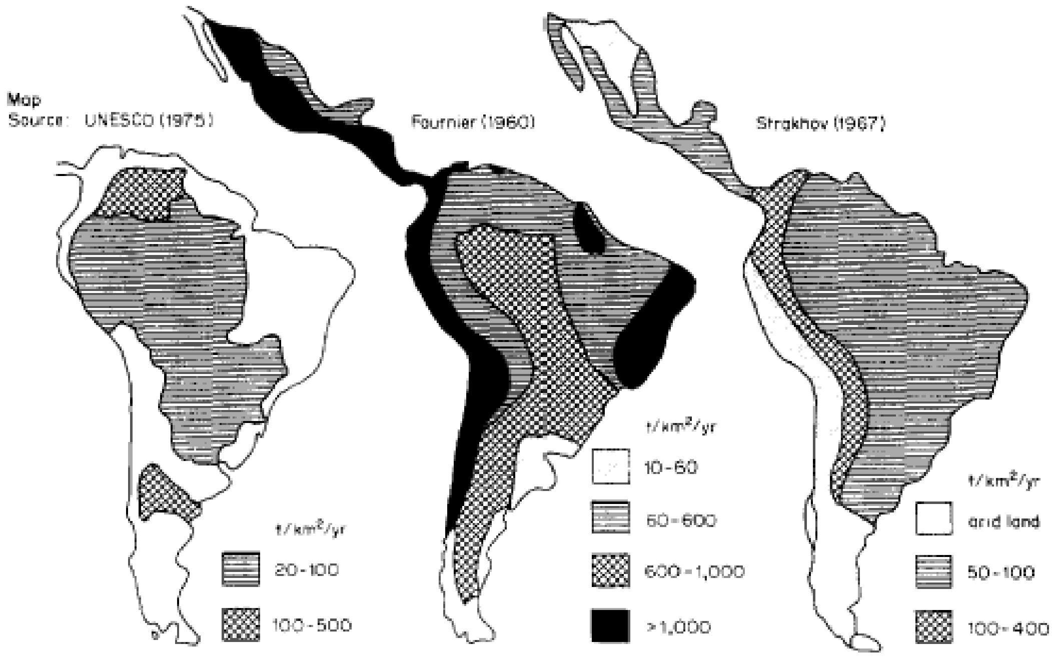


Figure 6.4: Sediment loss maps for South and Central America

6.6.3 Frequency/Magnitude problem

Edwards (1985, cited in Stromquist, 1991) analysed the importance of extremes, he lists the number of years when annual soil loss due to one single event was more than certain proportions of the total. On average, he found that, in about one year in three, a single rainstorm would cause more than 75% of the total soil loss. The problem when dealing with soil loss estimation is that the processes of land degradation occur at varying rates and with varying degrees of severity (Stocking, 1987). At different scales, different groups of processes are dominant. Against such variation in rates and frequency of process, the measurement of variables of land degradation must concern itself with the frequency of observations, the spacing and regularity of observations and the overall sampling frame in time (Stocking, 1987).

6.7 Discussion and Implications

6.7.1 The correct result?

Stocking (1987) rightly puts it: "Faced with contradictory measurements which are you to believe? The one that proves your preconceptions? Or the most complicated and apparently technically superior measurement? Or the one that gives the neatest, cheapest or most satisfying solutions?" It is unscientific for the author to ascribe any of the models results as fact. In such a diverse and complicated field as soil erosion modelling the resultant figure must be questioned on grounds of authenticity and assumption (Stocking, 1984). Meaning how authentic are the results? Are they accurate representations of reality? What assumptions have been made or decisions taken in order to come up with a hard figure (or in this instance, map)? Which is the correct figure (map)? (Stocking, 1984).

According to Stocking (1995) the different results the author obtained in the study could be accounted for by the different 'role players' in the soil erosion field. The role players include aid agencies, who provide finance for the Wagendrift Dam; the KwaZulu-Natal Nature Conservation Board, who is in charge of the environmental management of the catchment; the Department of Water Affairs and Forestry; seeking to promote specific land-uses for the catchment; politicians playing to their various constituencies, individual government officers looking after their careers; scientist advisers, looking for further funds; and lastly, the rural population. The correct policy to adopt in response to the threatened siltation of the Wagendrift Dam is the policy that satisfies the needs of the particular policy maker. Not surprisingly policy makers will pick the result to suit their needs – there is a fine range of results to suit all tastes and prejudices! (Stocking, 1995). With the variability of results using USLE just demonstrated, the importance of establishing an authentic research design outlining the precise methodology followed by the researchers in determining a definitive soil loss figure becomes all the more essential.

6.7.2 Role of conservation

"Soil conservation from a developing country's perspective is a minefield for the unwary." (Stocking, 1988).

Conservation of this catchment in the KwaZulu-Natal midlands is of vital importance to nature lovers' and to the cultural heritage of South Africa. The sub-catchment is home to no less than 3 nature reserves including the Moor Nature Park, Wagendrift Nature Reserve and the Giant's Castle Nature Reserve. The benefit of basing my study on the catchment scale is that a catchment approach to soil and water management can be adopted in the conservation of the region. According to Kelley (1990) this approach refers to the fact that while a large and badly eroded catchment can be selected for development, the work carried out in the conservation of the catchment can be carried out gradually, one sub-catchment at a time and according to Kelley (1990) the work can be spread over a number of years, depending on the availability of funds and trained manpower.

Conservation measures in South Africa, in particular the rural areas of South Africa, are very often based upon the cultural traditions and knowledge of the inhabitants (Critchley, 2000). This often creates an incorrect perception among the scientific relating to its process, development and degradation as being the work of God, they also saw erosion as only in the form of rills and gullies, whereas scientists and conservationists refer to all forms of soil loss from winds and/or water. Similarly a study by Lindskog and Tengberg (1994, cited in van Dissel & de Graaff, 1998) found that the Fulani in northern Burkina Faso did not believe that they themselves could influence the process, and accepted land degradation as an act of God (Allah). From these viewpoints it is easy to understand that changing the perception of soil erosion, its causes and cures, must be seen as the first step in the conservation process (van Dissel & de Graaff, 1998). The problem is further exacerbated by the fact that the value of money in developing countries such as South Africa is different from developed countries. Stocking (1988) found that monetary incentive schemes set up by the Tanzanian government in the 1980's which included incentives aimed at destocking and tree-planting in the region failed as the local subsistence farmers found no need for money, the cattle were a symbol of there wealth.

As the problem of soil erosion is extensive in the grassland areas of the catchment, typically overgrazed, a multi-disciplinary approach as specified by Mati *et al*., (2000) is required to identify solutions that are applicable at a reconnaissance scale for the rehabilitation of these degraded lands in the catchment. It must not however be overlooked that in many parts of the troubled catchment the indigenous knowledge, perceptions and traditions of the rural farmers regarding soil erosion have led to more than amicable conservation measures being put in place. An example of this was shown in Figure 4.8 where mini-terraces have been constructed on the sides of all secondary roads in the catchment to prevent run-off from the roads after rainfall.

6.8 Chapter Summary

The focus of this penultimate chapter was not so much on the results of the models used in the study but on the validation process used in this and other soil loss estimation studies. Initially both the USLE model and the 'adjusted' USLE model (with a newly created rainfall erosivity grid) compared favourably with sediment yield data and various other erosion plot study results conducted within the vicinity of the study catchment, although both validation methods were shown to be fraught with errors and are open to question. The SLEMSA model had soil loss values per land coverage greatly exceeding the sediment yield figures as well as the erosion plot study results. The validity of catchment scale soil loss studies were brought into question especially with regard to the scale effects. The implications of the research focussed on the importance of researchers to include data limitations, model assumptions and project objectives within their research design so as not to depict the research results as fact but rather as a proxy of reality.

Chapter 7: Conclusion

7.1 Introduction

In this final chapter the study is concluded by initially reviewing the four original research questions that were postulated in Chapter 1. The findings generated through the completion of the study are correlated to these questions in order to find out whether any definitive answers were found, and if they are found, what implications do they have for GIS. The chapter finally concludes with a look at the advantages and disadvantages that have been discovered through the course of the study, of using GIS to model soil loss erosion.

7.2 Addressing the original research questions

The first research question postulated whether or not GIS could be used to quantify differences between soil erosion models. It has been found that GIS **can** be used as a tool in quantifying the differences between theoretical soil erosion models. A quantitative summary of the results that were obtained by calculating the soil loss from the catchment using the soil loss models, USLE [(*)] and SLEMSA are provided in table 7.1.

As mentioned in Chapter 6, the basic conclusion to this research question is that based on my research findings, USLE and SLEMSA do not compare very well. The average SLEMSA soil loss estimation being larger than the USLE model results as well as larger than the ‘adapted’ USLE soil loss calculation. There are a variety of possible causes for these discrepancies between the soil loss calculations, which were highlighted in the previous chapter. These study results are consistent however, with prior research in the KwaZulu-Natal province of South Africa, where variable results have been obtained regarding the use and accuracy particularly of the SLEMSA model, with Garland (1982) concluding that SLEMSA could at best provide comparative results in South African conditions, and Hudson (1987) finding that use of SLEMSA in mountainous terrain could provide soil loss that were 20 times larger than actual measurements.

Table 7.1: Soil loss calculation summary

Land Coverage	Gross erosion per land coverage type per year (tons.yr^{-1})		
	SLEMSA	**USLE**	**USLE***
Unimproved grassland	816991.2	214242.3	36019.9
Cultivated: temporary - commercial dryland	2992.3	10373.3	2071.1
Cultivated: temporary - commercial irrigated	1228.2	5950.8	1260.5
Cultivated: temporary - semi-commercial/ subsistence dryland	5924.6	17861.4	2767
Forest	8614.7	608.8	84.6
Forest plantations	9904.8	1619	257.5
Improved grassland	882.7	124.6	25
Thicket & scrubland	42134.2	4713.2	855.9
Gross erosion in catchment (tons.yr^{-1})	888672.8	255493.4	43343.5
Catchment size (ha) (excluding Waterbodies and residential areas)	33020	33020	33020
Average rate per hectare (tons.ha^{-1}.yr^{-1})	26.91	7.74	1.31

The second research question asked whether or not GIS-based erosion models could be extrapolated to an area bigger than an erosion plot scale upon which the theoretical models are based. The numerous failed attempts at validation of the models results would seem to indicate that GIS can, has, and will continue to be used to extrapolate data from the erosion plot scale to a catchment scale, but whether this is scientifically sound remains a point of contention, and whether the results produced are accurate are also unsure.

The third research question posed asked whether or not GIS could be used to produce model results which are ‘closer to reality’ and in doing so determine the sensitivity of the model to its various input parameters. The research conducted showed that one of the benefits of using GIS in catchment-scale erosion studies is the ability to modify input parameters at ease and in doing so be able to determine the influence of various land use or land coverages to soil loss. The sensitivity of input parameters into the soil loss models can also be investigated and quantified as was illustrated in the ‘adapted’ USLE calculation where a revised R factor was determined for a soil loss calculation subsequent to the original USLE calculation. The results have shown a big difference visually, as is evident through a comparison of figures 5.10 and 5.15, and well as statistically, where tables 6.1 and 7.1 show the statistical difference between the soil loss calculations. In this way GIS can be used as a tool to not only illustrate the capricious nature of predictive soil erosion results but to also add a spatial dimension to the results thereby illustrating the spatial extent and variability of the outcome. The integration of soil erosion models with the technology of GIS results in the large amounts of spatial data, demanded by soil erosion models, being effectively stored, manipulated and analysed. GIS also displays spatial information in means useful for analysing the findings.

Lastly, the research question was asked as too whether it is possible to validate a catchment scale, GIS-based erosion study. There is no definitive answer to this question. Investigation of relevant literature has revealed many studies in which validation has ‘successfully’ been achieved by researchers but within my study I have shown that although many different validation methods are available, few if any are error free. Which also leaves the question as to which soil loss theory is correct, USLE or SLEMSA. If neither models result can be validated accurately then the correct result would be the one that achieves the researchers objectives.

7.3 The advantages and disadvantages of the GIS modelling of soil erosion

Soil loss calculations form an integral part of the planning and projects of governmental as well as private agricultural organisations. As land degradation becomes more evident with increasing changes in land use, it is becoming increasingly necessary to map and quantify soil erosion more extensively, covering entire catchments, with the aim of providing a tool for planning soil conservation strategies at a regional level (Mati *et al.*, 2000). The use of GIS and erosion models is one way of doing this. GIS is able to deal with the complexity of model input variables as well as simplifying the wide spatial domain at which these variables interact (Mati *et al.*, 2000). GIS therefore allows soil loss estimation, previously limited to erosion plot studies, to be extrapolated from this erosion-plot scale, to a catchment scale; from data-rich to data-poor areas. Moreover, GIS modelling provides the opportunity to evaluate various scenarios and impacts of land use changes. The catchment scale result is beneficial to decision-makers and conservationists in that a conservation strategy can be developed for a region. An indication of the amount of erosion that is occurring within a 2 by 22 metre erosion plot within the study catchment is of little, if any use, to decision-makers for whom the conservation of large areas is there focus of interest. The concern that arises here is that although GIS has been seen as the tool in which these conservation strategies can be developed, it must still be kept in mind that there are various theoretical and practical errors in accepting GIS-related erosion studies, particularly at a catchment-scale, as truth.

The benefits of integrating soil loss estimation research with GIS are very exciting. Integrating the USLE and SLEMSA models with ArcView GIS, together with SEAGIS, allowed for effective data input, analysis, visualisation and output, as well as allowing conservationists, and other interested parties, to access the results with little computer experience. Most importantly, the GIS grid spatial display and analysis utilities allow the USLE and SLEMSA models to be applied for individual cells (Sun & McNulty, 1997). The GIS approach allows land managers to identify problem areas and conduct risk assessment before making management decisions (Sun & McNulty, 1997). The most important aspect to non-GIS users is the output that is generated by the various erosion models. GIS significantly reduces the complex amounts of information to fit within the constraints of the erosion modelling software. It was also found to be a valuable asset in demonstrating the results of the modelling in ways that are more meaningful to scientists, managers, and stakeholders (Spitze *et al*., 2003).

“The economics of erosion and conservation have received much recent attention. If this debate is to make any advance into definite monetary costs and benefits of conservation, then the erosion-productivity relationships must be quantified” (Stocking, 1984). The erosion-productivity relationship is the relationship between soil erosion and soil productivity, in brief, soil erosion causes a loss in soil productivity, but the relationship between the two has been seen to be “inextricably linked”. The research I have conducted begs the question as to whether or not the erosion-productivity relationship can be quantified and if it can be quantified, how accurate would the resulting statistic be. If conservation measures are to be taken in response to these generated results, and these conservation strategies impact the economic returns of government parastatals and any other involved organisation then the amount of soil loss and subsequent loss of soil productivity must be known at a catchment scale. GIS as we have seen is currently the only means by which soil loss estimation can be made at a catchment scale. Time and financial constraints make catchment scale fieldwork an unviable option for most researchers; and any other scale would not produce results relevant enough to justify an expensive conservation strategy. But the generation of soil loss in three different models has found the process of generating absolute soil loss figures at a catchment scale to be variable to say the least.

It would seem that the results and conclusions of my research bring about more questions and hypotheses than definitive results and figures. That is perhaps precisely the point of conducting soil loss estimation research using GIS. The temptation lies in using the increasing technological advances in GIS computer software to the benefit of decision-makers without correctly identifying the theoretical GIS problems relating to modelling such a dynamic, spatial and complex process as soil erosion.

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Appendix 1: Council for Scientific and Industrial Research - Satellite Applications Centre (CSIR-SAC). Field guide for the National Land Cover 2000 database project.

FIELD GUIDE

1. FOREST & WOODLAND

All wooded areas with greater than 10% tree canopy cover, where the canopy is composed of mainly self-supporting, single stemmed, woody plants >5 m in height. Essentially indigenous tree species, growing under natural or semi-natural conditions (although it may include some localised areas of self-seeded exotic species). Excludes planted forests (and woodlots). Typically associated with the Forest and Savanna biomes in South Africa

1.1 Forest

Tree canopy cover > 70%. A multi-strata community, with interlocking canopies, composed of canopy, subcanopy, shrub and herb layers.

1.2 Woodland

Tree canopy cover between 40-70%. A closed-to-open canopy community, typically consisting of a single tree canopy layer and a herb (grass) layer.

1.3 Wooded Grassland

Tree canopy cover between 10-40%. An open-to-sparse canopy community, typically consisting of a single tree canopy layer and a herb (grass) layer.

2. THICKET, BUSHLAND, SCRUB FOREST & HIGH FYNBOS

Communities typically composed of tall, woody, self-supporting, single and/or multi-stemmed plants (branching at or near the ground), with, in most cases no clearly definable structure. Total canopy cover > 10%, with canopy height between 2 - 5 m. Essentially indigenous species, growing under natural or semi-natural conditions (although it may include some localised areas of self-seeded exotic species, especially along riparian zones). Typical examples are Valley Bushveld, Mopane bush, and tall Fynbos. Dense bush encroachment areas would be included in this category.

2.1 Thicket

Areas of densely interlaced trees and shrub species (often forming an impenetrable community). Composed of multi-stemmed plants with no clearly definable structure or layers, with > 70% cover. A typical example would be Valley Bushveld.

2.2 Scrub Forest

Vegetation intermediate in structure between true forest and thicket. A multi-layered community with interlocking canopies, with > 70% cover.

2.3 Bushland

Similar to "thicket", but more open in terms of canopy cover levels. Composed of multi-stemmed plants with no definable structure or layers, and with < 70% cover.

2.4 Bush Clumps

Scattered islands of thicket-like vegetation (i.e. > 70% cover) within a matrix of more open bushland or grassland.

2.5 High Fynbos (Heathland)

Fynbos communities between 2 - 5 m in height, > 70% cover, and composed of multi-stemmed evergreen bushes *typically* growing on infertile soils. The Proteaceae family typically dominates.

3. SHRUBLAND & LOW FYNBOS

Communities dominated by **low**, woody, self-supporting, multi-stemmed plants branching at or near the ground, between 0.2 - 2 m in height. Total tree cover < 1.0%. Low shrublands and heathlands are combined at Level 1 due to similar overall physiognomic structure and (in many cases) appearance on remotely sensed imagery. Examples would include low Fynbos, Karoo and Lesotho (alpine) communities.

3.1 Shrubland
Typically broad-leaved or bushes, frequently deciduous. A typical example would be vegetation from the Karoo biomes. Category also includes dwarf succulent shrublands.

3.2 Low Fynbos (Heathland)
Typically small-leaved (i.e. nanophyllous), sclerophyllous, evergreen plants growing on infertile soils. Proteaceae, Ericaceae and Restionaceae frequently dominate.

4. HERBLAND

Communities dominated by **low**, non-woody, self-supporting, non-grass like plants, between 0.2 - 2 m in height. Total tree cover < 1.0%. Typical vegetation examples are found in Namaqualand, and `weed' dominated degraded areas.

5. GRASSLAND

All areas of grassland with less than 10% tree and/or shrub canopy cover, and greater than 0.1% total vegetation cover. Dominated by grass-like, non-woody, rooted herbaceous plants. Typically associated with the Grassland Biome.

5.1 Unimproved Grassland
Essentially indigenous species, growing under natural or semi-natural conditions.

5.2 Improved Grassland
Planted grassland, containing either indigenous or exotic species, growing under man-managed conditions for grazing, hay or turf production, recreation (e.g. golf courses).

6. FOREST PLANTATIONS

All areas of systematically planted, man-managed tree resources, composed of primarily exotic species (including hybrids). Category includes both young and mature plantations that have been established for commercial timber production, seedling trials, and woodlots/windbreaks of sufficient size to be identified on satellite imagery. Unless otherwise stated, Levels 1 & 2 include clear-felled stands *within* plantations. Excludes all non-timber based plantations such as tea and sisal, as well as orchards used in the production of citrus or nut crops. Level 1 category will include associated land-cover/use's such as roads, fire-breaks and building infrastructure if these are too small to be clearly mapped off the satellite imagery.

7. WATERBODIES

Areas of (generally permanent) *open water*. The category includes natural and man-made water bodies, which are either static or flowing, and fresh, brackish and salt-water conditions. This category includes features such as rivers, dams (i.e. reservoirs), permanent pans, lakes, lagoons and coastal waters.

8. WETLANDS

Natural or artificial areas where the water level is at (or very near the land surface) on a permanent or temporary basis, typically covered in either herbaceous or woody vegetation cover. The category includes fresh, brackish and salt-water conditions. Examples include saltmarsh, pans (with non-permanent water cover), reed-marsh or papyrus-swamp and peat bogs.

9. BARREN LANDS

Non-vegetated areas, or areas of very little vegetation cover (excluding agricultural fields with no crop cover, and opencast mines and quarries), where the substrate or soil exposure is clearly apparent.

9.1 Bare Rock / Soil

Natural areas of exposed sand, soil or rock with no, or very little vegetation cover during any time of the year, including rocky outcrops, dunes and gravel plains.

9.2 Degraded Land

Permanent or seasonal, man-induced areas of very low vegetation cover (i.e. removal of tree, bush and/or herbaceous cover) *in comparison to the surrounding natural vegetation cover*. Category includes major erosion scars (i.e. sheet and gully erosion). Should be sub-divided by Level I vegetation classes i.e. **Degraded-Woodland**, and **Degraded-Grassland** wherever possible to allow reconstruction of full class extent. Typically associated with subsistence level farming and rural population centres, where overgrazing of livestock and/or wood-resource removal has been excessive. Often associated with severe soil erosion problems.

10. CULTIVATED LAND

Areas of land that are ploughed and/or prepared for raising crops (excluding timber production). The category includes areas currently under crop, fallow land), and land being prepared for planting. Unless mapping scales allow otherwise, physical class boundaries are broadly defined to encompass the main areas of agricultural activity, and are not defined on exact field boundaries. As such the class may include small inter-field cover types (i.e. hedges, grass strips, small windbreaks etc), as well as farm infrastructure. Subdivided into:

(i) **Subsistence/semi-commercial cultivation:** Characterised by numerous small field units in close proximity to rural population centres. Typically dryland crops produced for individual or local (i.e. village) markets. Low level of mechanisation.

(ii) **Commercial cultivation:** Characterised by large, uniform, well-managed field units, with the aim of supplying both regional, national and export markets. Often highly mechanised.

(iii) **Irrigated / Non-irrigated:** Major irrigation schemes (i.e. areas supplied with water for agricultural purposes by means of pipes, overhead sprinklers, ditches or streams), are characterised by numerous small farm-scale irrigation dams, close proximity to major water sources and/or centre pivot irrigation systems.

10.1 Permanent crops

Lands cultivated with crops that occupy the area for long periods and are not replanted after harvest. Examples would include tea plantations, vineyards, sugar cane and citrus orchards, hops and nuts.

10.2 Temporary crops

Land under temporary crops (i.e. annuals) that are harvested at the completion of the growing season, that remains idle until replanted. Examples would be maize, wheat, legumes, potatoes, onions, and lucerne. Lands cultivated with crops that occupy the area for long periods and are not replanted after harvest. Examples would include tea plantations, vineyards, sugar cane and citrus orchards, hops and nuts.

11. URBAN / BUILT-UP LAND

An area where there is a permanent concentration of people, buildings, and other man-made structures and activities, from large village to city scale. Small rural communities are often included within the surrounding land-cover category (i.e. subsistence / semi-commercial agriculture) if mapping scales do not permit identification of such settlements as individual features. Where mapping scales permit, the limits of the urban boundary are delineated to exclude open areas within the built-up region (i.e. vegetated or non-vegetated areas with few or no structures).

11.1 Residential

Areas in which people reside on a permanent or near-permanent basis. The category includes both *formal* (i.e. permanent structures) and *informal* (i.e. no permanent structures) settlement areas, ranging from high to low building densities, (including smallholdings on the urban fringe).

11.2 Commercial

Non-residential areas used primarily for the conduct of commerce and other mercantile business, typically located in the central business district (CBD).

11.3 Industrial / Transport

Non-residential areas with major industrial (i.e. the manufacture and/or processing of goods or products) or transport related infrastructure. Examples would include power stations, steel mills, dockyards and airports.

12. MINES & QUARRIES

Areas in which mining activity has been done or is being done. Includes both opencast mines and quarries, as well as surface infrastructure, mine dumps etc, associated with underground mining activities.

REFERENCE

Fleming, G. (2002). NLC 2000 – Illustrated Field Guide. http://www.csir.co.za/plsql/ptl0002/PTL0002_PGE100_LOOSE_CONTENT?LOOSE_PAGE_NO=7057944, Nov. 2002.

Appendix 2: Field survey questionnaire

QUESTIONNAIRE

Name (optional): ______________________________

Surname (optional): ______________________________

Physical Address (optional): ______________________________

____

Farm Number/Name (optional): ______________________________

Principle Statistics

Farming Unit Size

Hectares	X
<2	
2-4	
5-9	
10-19	
20-49	
50-99	
100-199	
200-299	
300-499	
500-999	
1000-1999	
2000-4999	
5000-9999	
10000+	

Dominant Farming Activities

Dominant Activity >75%	X
Field crops	

Horticulture	
Animals	
Forestry	
Mixed	

Land Utilisation by area

Field crop products

What field crops do you farm?

Field crop	X
Summer cereals	
Winter cereals	
Oil seeds	
Legumes	
Fodder crops	
Other field crops	

What types of summer cereals do you plant and how much is produced?

Type of summer cereal	How many hectares are planted	Production in metric tons (Optional)
Maize		
Grain sorghum		
Other _______________		

What types of winter cereals do you plant and how much is produced?

Type of winter cereal	How many hectares are planted	Production in metric tons
Wheat		
Barley		
Other _______________		

What types of oil seeds do you plant and how much is produced?

Type of summer cereal	How many hectares are planted	Production in metric tons (Optional)
Sunflower seeds		

Groundnuts		
Soya beans		
Other ______________		

What types of legumes do you plant and how much is produced?

Type of legumes	How many hectares are planted	Production in metric tons (Optional)
Dry beans		
Other ______________		

What types of fodder crops do you plant and how much is produced?

Type of fodder crops	How many hectares are planted	Production in metric tons (Optional)
Lucern		
Teff		
Other ______________		

What other types of field crops do you plant and how much is produced?

Type of fodder crops	How many hectares are planted	Production in metric tons (Optional)
Sugar Cane		
Tobacco		
Cotton		
Other ______________		

Horticulture products

What horticultural crops do you farm?

Horticulture	X
Vegetables	
Fruit	
Nuts	
Tea/coffee	
Other horticultural products: ______________________	

What types of vegetables do you plant and how much is produced?

Type of vegetables	How many hectares are planted	Production in metric tons (Optional)
Potatoes		
Tomatoes		
Cauliflower		
Cabbage		
Onions		
Beetroot		
Carrots		
Sweet Potatoes		
Green Beans		
Green Mielies		
Green Peas		
Pumpkins		
Other _______________		

What types of fruit do you plant and how much is produced?

Type of fruit		How many hectares are planted	Production in metric tons (Optional)
Citrus	Oranges		
	Lemons		
	Grapefruit		
	Naartjies		
Sub-tropical	Pineapples		
	Avocados		
	Bananas		
	Mangoes		
	Pawpaws		
Deciduous	Apples		
	Pears		
	Peaches		
	Plums		
	Grapes		

	Other _______________		

What types of nuts do you plant and how much is produced?

Type of nuts	How many hectares are planted	Production in metric tons (Optional)
Macadamia		
Pecan		
Other _______________		

What other types of horticultural products do you plant and how much is produced?

Type of horticultural products	How many hectares are planted	Production in metric tons (Optional)
Tea		
Coffee		
Other _______________		

Is erosion a problem on your farm?

YES	NO

What type of erosion are you exposed to on your farm?

Sheet erosion (the uniform removal of soil in thin layers from sloping land)	
Rill erosion (soil is removed by water from little streamlets that run through land with poor surface draining)	
Gully erosion (gully erosion is an advanced stage of rill erosion)	

Are you undertaking any measures to combat erosion?

YES	NO

If yes, what erosion control measures are you taking?

Diversion channels	

Terracing	
Conservation tillage	
Burning	
Contour strip-cropping	
Sediment ponds	
Farming on the contour (Contour cropping)	

If no, what are the reasons for not using soil conservation measures?

Reasons	Explanation
Lack of money	
Lack of labour	
Insecure land tenure	
Methods do not work	
Erosion is very slow	
Erosion is not serious	
Do not know methods	
Others	

What type of government incentives or other sources that would cause you to use soil conservation measures?

	Explanation
Labour assistance	
Money to built soil conservation measures	
Tech. support/education.	
Light earth-moving equipment	
Would never use method	

Appendix 3: Database requirements for processing the USLE and SLEMSA models

Data Group	Data Type	Source Type	Field Aliases	Field Type	Description
Hydrology	Annual precipitation	Polygons	Pa	Floating	Annual precipitation
	6 hour rainstorms	Grid		Floating	No 6-hour rainstorms per 2. Year
	Recipients	Grid		Integer	All recipients as a grid
	Monthly rainfall	Grid		Floating	
Base Map	Filled DEM	Grid			Filled digital elevation model
Land use	Land cover	Polygons	FieldID	Floating	Internal ID
			Lccd	Character	Key to land cover type
			LcID	Character	Name of land cover class
			Area	Floating	Area of polygon
	Soil	Polygons	SoilID	Character	Unique key to soil class
			SoilName	Character	Name of soil
			Texture	Character	Texture class
			Area	Floating	Area of polygon
	Soil Horizons	**Table**	SoilID	Character	Unique key to soil class
			SoilName	Character	Name of soil
			HorizNo	Floating	Horizon number
			HorizName	Character	Horizon name
			Depth	Floating	Depth of horizon in cm
			Texture name	Character	Name of texture in horizon
			Structure code	Floating	USLE structure code
			Permeability code	Floating	USLE permeability code
			Organic matter	Floating	Percent organic matter
			Clay	Floating	Percent clay
			Silt	Floating	Percent silt
			Very fine sand	Floating	Percent very fine sand

Appendix 4: Soil survey sheet

Sample Point Number:

GPS Number:

X co-ordinate:

Y co-ordinate:

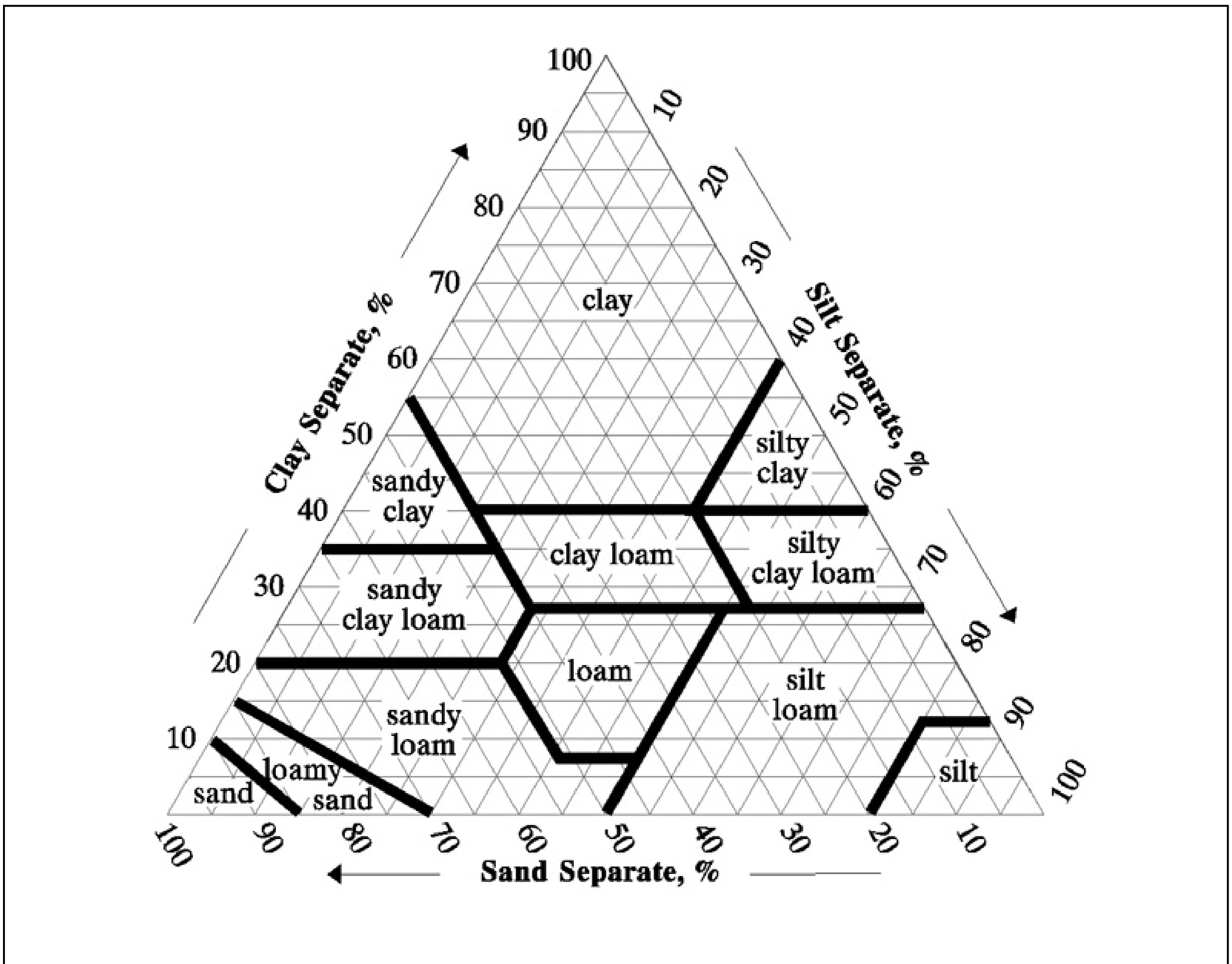
PROFILE										
PLACE										
VEGETATION										
BASAL COVERAGE	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
LANDFORM TOPOGRAPHY										
SOIL USE										
TEXTURE										
CONSISTENCY										
STRUCTURE	Very fine granular	Fine granular	Medium or coarse granular	Blocky, platy or massive						
ROCKS										
-AMOUNT										
-SIZE										
ROOTS										
- AMOUNT										
PERMEABILITY	Rapid	Moderate to Rapid	Moderate	Slow to Moderate	Slow	Very slow				
UNDERLYING MATERIAL										
EROSION LEVEL	Light	Moderate	Severe							
TYPE OF EROSION										
GENERAL COMMENTS										

Soil Sample No.	% sand	% silt	% clay	% ash	% Organic matter	Texture
1	44	43	13	94	6	loam
2	41	52	7	91.5	8.5	silt loam
3	29	58	13	96.5	3.5	silt loam
4	57	35	8	96	4	sandy loam
5	35	55	10	94	6	silt loam
6	37	50	13	97.5	2.5	loam
7	43	48	9	96	4	loam
8	75	20	5	94	6	loamy sand
9	75	20	5	91.5	8.5	loamy sand
10	53	33	14	93	7	sandy loam
11	52	35	13	97	3	loam
12	65	27	8	97.5	2.5	sandy loam
13	44	48	8	98.5	1.5	loam
14	41	41	18	93.5	6.5	loam
15	61	28	11	94.5	5.5	sandy loam
16	60	36	4	96	4	sandy loam
17	49	41	10	96	4	loam
18	66	30	4	99	1	sandy loam
19	24	61	15	96.5	3.5	silt loam
20	51	41	8	94	6	loam
21	44	48	8	94	6	loam
22	46	41	13	85	15	loam
23	29	59	12	93	7	silt loam
24	47	38	15	93.5	6.5	loam
25	44	43	13	95.5	4.5	loam
26	52	42	6	93.5	6.5	sandy loam
27	50	45	5	89.5	10.5	sandy loam
28	62	25	13	94.5	5.5	sandy loam
29	45	45	10	92	8	loam
30	43	51	6	92	8	silt loam
31	29	58	13	85.5	14.5	sandy loam
32	86	13	1	94	6	sand
33	54	33	13	96.5	3.5	sandy loam
34	59	36	5	88	12	silt loam
35	40	45	15	93.5	6.5	loam
36	67	29	4	87	13	sandy loam
37	44	48	8	92.5	7.5	loam
38	33	60	7	92	8	sandy loam
39	52	33	15	90.5	9.5	sandy loam
40	73	18	9	92	8	sandy loam
41	87	11	2	97	3	sand
42	63	30	7	97	3	sandy loam
43	83	16	1	93	7	loamy sand
44	44	43	13	93	7	loam
45	50	35	15	91.5	8.5	loam
46	36	55	9	91.5	8.5	silt loam
47	56	36	8	89.5	10.5	sandy loam
48	40	50	10	85	15	loam

49	51	46	3	89	11	sandy loam
50	81	15	4	88.5	11.5	loamy sand
51	40	53	7	91	9	silt loam
52	47	47	6	96	4	sandy loam
53	59	35	6	92	8	sandy loam
54	44	49	7	94.5	5.5	sandy loam
55	44	53	3	91.5	8.5	silt loam
56	68	27	5	95.5	4.5	sandy loam
57	24	52	24	96.5	3.5	silt loam
58	48	45	7	94.5	5.5	sandy loam
59	59	36	5	92.5	7.5	sandy loam
60	37	45	18	97.5	2.5	loam
61	42	51	7	95	5	silt loam
62	62	31	7	93	7	sandy loam
63	46	41	13	96	4	loam
64	59	40	1	96.5	3.5	sandy loam
65	24	66	10	95	5	silt loam
66	41	53	6	86.5	13.5	silt loam
67	47	36	17	94.5	5.5	loam
68	53	44	3	87.5	12.5	sandy loam
69	88	11	1	96.5	3.5	sand
70	96	3	1	95	5	sand
71	63	27	10	95	5	sandy loam
72	36	47	17	92.5	7.5	loam
73	44	48	8	94.5	5.5	loam
74	53	42	5	96.5	3.5	silt loam
75	44	48	8	94	6	loam
76	86	11	3	95.5	4.5	loamy sand
77	55	23	22	97	3	sandy clay loam
78	73	23	4	96	4	silt loam
79	51	36	13	97.5	2.5	loam
80	57	36	7	93	7	sandy loam
81	60	14	26	94.5	5.5	sandy clay loam
82	79	8	13	91.5	8.5	sandy loam
83	88	4	8	93	7	loamy sand
84	62	17	21	97.5	2.5	sandy clay loam
85	61	18	21	93.5	6.5	sandy clay loam
86	91	4	5	94.5	5.5	sand
87	80	6	14	92.5	7.5	sandy loam
88	79	7	14	95	5	sandy loam
89	85	5	10	94	6	loamy sand
90	74	7	19	93.5	6.5	sandy loam
91	77	5	18	89	11	sandy loam
92	60	20	20	94	6	sandy loam
93	90	2	8	93.5	6.5	sand
94	65	13	22	96.5	3.5	sandy clay

						loam
95	91	3	6	98.5	1.5	sand

Appendix 5: USDA Textural triangle



United States Department of Agriculture (USDA). (1972).