DEVELOPMENT OF A DESIGN TOOL FOR SOIL CONSERVATION SYSTEMS IN SOUTH AFRICA

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ABSTRACT

Soil erosion is a major problem both in South Africa and globally. Soil erosion reduces the productivity of land and has major environmental, as well as economic impacts. South Africa, in particular, experiences considerable challenges in combatting soil erosion owing to a combination of factors. Examples of these factors include low vegetal cover as a result of arid climatic conditions, as well as intense thunderstorm activity. As more data and computing power become available, it is important that approaches to the design of soil conservation structures and design tools be updated to reduce soil erosion.

In this document, the literature is reviewed in order to obtain an overview of mechanical soil conservation measures in South Africa, soil loss estimation models currently used and design approaches to the determination of contour bank intervals. Literature showed that site-specific evaluation is the preferable approach to determining contour bank intervals, rather than the use of empirical equations. It was also found that the Revised Universal Soil Loss Equation (RUSLE) held the most potential as a model, in terms of creating a design tool for the design of soil conservation systems. In the United States of America, software has been developed that applies the RUSLE to calculate soil loss and assist with soil conservation management. This computer program is called ‘RUSLE2’. This project involves the adaptation of this existing RUSLE2 software to South African conditions. The main aim of this project is to generate relevant climate files to allow the use of RUSLE2 in South Africa. This will include updating rainfall erosivity values for the country as these factors are still calculated using daily rainfall values rather than short duration rainfall values. The document also contains a project proposal, which gives a brief outline of the intended study.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Page

1. INTRODUCTION

Soil erosion is a process which involves the detachment of soil particles by erosive agents, such as water and wind, and their subsequent transport from their original location (Morgan, 2005). Although there are many forms of land degradation, soil erosion is a significant environmental issue, both internationally and particularly in South Africa (Le Roux *et al.*, 2008). In fact, according to Garland *et al.* (2000), previous studies have indicated that more than 70% of South Africa's surface area is affected by water erosion to some degree, with the predominant cause being poor agricultural practices.

Soil erosion has both on-site and off-site effects, which result in significant economic losses. On-site effects include loss and redistribution of soil in the field, breakdown of the structure of the soil and a decline in both nutrients and organic matter in the soil (Morgan, 2005). Another effect of soil erosion is a reduction in available soil moisture. This is the result of two main factors. Firstly, the runoff rate on eroded soils is generally higher than that of non-eroded soils, leading to less water entering the soil profile (Pimentel *et al.*, 1995). Secondly, according to Hudson (1994), the available water holding capacity of the soil is strongly influenced by the organic matter content. Therefore, as the organic matter is washed eroded, the soil water holding capacity decreases. These effects result in reduced soil fertility and arable soil depth, as well as increased susceptibility to drought. Ultimately, soil erosion results in decreased productivity, with an associated increase in fertiliser use to maintain yields (Morgan, 2005). Off-site effects include sedimentation, and hence a reduced life span, of dams. For example, the Welbedacht Dam on the Caledon River in South Africa lost 32% of its capacity to sedimentation in the three years following its construction (Russell, 1998). As most of the favourable dam sites in South Africa have already been used, the cost of building new dams is increasing because the new sites are less economically viable. According to Scotney and McPhee (1990), the annual cost of creating new water storage to compensate for that lost due to sedimentation was between R71 500 000 and R104 000 000 in 1990. The reduced capacity or blockage of rivers and drainage structures also leads to increased flooding risk (Morgan, 2005).

In many parts of South Africa, certain conditions exacerbate the problem of erosion and make the undertaking of soil conservation particularly challenging. These factors include "arid climatic conditions, intense thundershower activity with inherent high rainfall erosivity, shallow erodible soils, limited vegetation cover, and/or poor conservation management techniques" (Morgan, 2005). It is therefore of utmost importance that erosion control be improved, particularly in agricultural areas. In South Africa, responsibility is placed on land owners to reduce soil erosion on their land (Conservation of Agricultural Resources Act, 1983). Although standards are in place to conserve agricultural land, the methods must be continually updated as more information and computing power becomes available.

Many soil loss estimation models have been developed over the years to estimate how much soil is being lost from agricultural lands. Each of these models has its own applications, advantages and limitations. As computing power improves, these models will come to play an increasing role in soil and water conservation.

Before continuing, a few terms must be defined. Soil loss is the amount of soil which is relocated from its original position through the process of erosion (detachment, transport and deposition). In contrast, sediment yield is the amount of soil that is eroded minus the amount which is deposited before it reaches the point of interest (Renard *et al.*, 1996). The sediment yield is typically the amount of sediment leaving a catchment via that catchment's river (Morgan, 2005).

The objectives of this literature review are to:

(a) provide an overview of mechanical soil conservation methods in South Africa,
(b) review the main soil loss estimation models used currently in South Africa and internationally,
(c) investigate the design methods used to determine contour bank intervals, and
(d) present a brief project proposal for the adaptation of the RUSLE2 model for use in South Africa.

Chapter 2 contains a brief overview of the mechanical soil conservation methods used in South Africa. An analysis of empirical soil loss estimation models follows in Chapter 3 while design approaches for contour bank intervals are discussed in Chapter 4. Chapter 5 contains a discussion on the literature reviewed, as well as any conclusions made. Lastly, a brief project proposal is presented in Chapter 6.

2. MECHANICAL SOIL CONSERVATION MEASURES

In soil and water conservation, the various measures used to protect the soil are divided into three main categories: soil management measures, agronomic measures and mechanical measures (Morgan, 2005). Soil management measures include activities which improve the soil structure (e.g. promote infiltration) and encourage plant growth. Agronomic measures are those which use the vegetation to protect the soil and mechanical measures are those activities which change the topography and alter the pattern of runoff (Morgan, 2005). Examples of the various measures can be found in Figure 2.1.

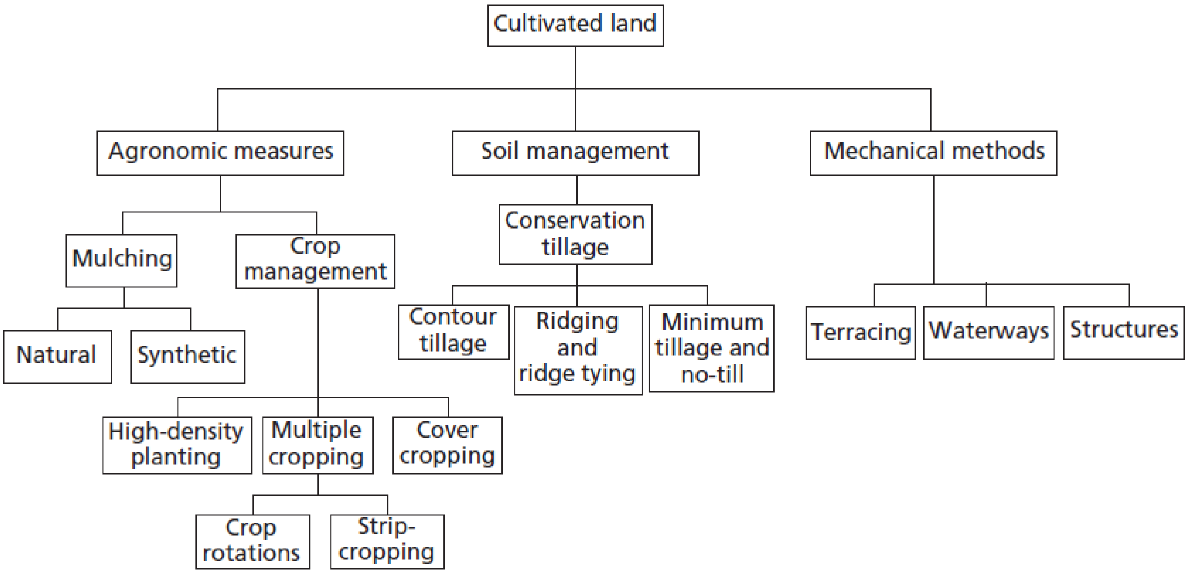


Figure 2.1 Soil conservation measures for agricultural land (Morgan, 2005; after El-Swaify *et al.*, 1982)

Mechanical measures are not necessarily required on some areas of land, however, it is often beneficial to install these engineering works from the start in order to provide a foundation on which agronomic or soil management measures can be based (Matthee, 1984). According to Morgan (2005), contouring has moderate control over detachment and strong control over transport in runoff erosion.

Contour banks and vegetated waterways are the mechanical conservation measures commonly used in South Africa in order to intercept and slow down surface runoff and convey it, with limited erosion, to a stable outlet. In this chapter, these two mechanical measures are defined and their role in runoff management is explained.

2.1 Contour Banks

A contour bank is also known as a terrace in South Africa. Contour banks are typically earth embankments and they are built across the main slope. Their purpose is to intercept runoff water (Matthee, 1984). According to ASABE Standard S268.5 (2012), contour banks have three major functions. These are to decrease soil erosion, retain moisture for utilisation by crops and to improve the quality of the water.

There are numerous ways in which contour banks reduce soil loss from a given area. Firstly, the contour banks shorten the distance over which surface runoff travels by splitting up the slope into shorter sections. This reduces runoff velocity and volume and hence decreases rill erosion. Secondly, the contour banks force tillage operations to be performed on the contour, rather than up and down the slope. Lastly, contour banks transport water to suitable outlet points at low velocities (Matthee, 1984). According to Huffman *et al.* (2011), contour banks "serve to retain runoff and increase the amount of water available for crop production." Contour banks intercept runoff flowing downslope and provide a greater time for more of the water to infiltrate the soil and become available for use by crops. Contour banks improve water quality by reducing the effective slope length. This means that the runoff has a lower velocity, and hence less energy with which to transport sediment, leading to cleaner runoff.

2.2 Vegetated Waterways

A vegetated waterway is "a shaped or graded channel that is established with suitable vegetation to carry surface water at a non-erosive velocity to a stable outlet" (USDA NRCS, 2012). Vegetated waterways are used where the duration of flow is less than the maximum inundation period that can be withstood by the grass, and the frequency of operation is low enough to maintain an adequate grass cover (USDA NRCS, 2007). According to USDA NRCS (2012), vegetated waterways have three main purposes. These are to:

(a) carry surface water from contour banks or other concentrations of water without causing scouring or flooding,
(b) reduce gully formation, and
(c) conserve or improve water quality.

In a typical runoff control plan, the contour banks intercept water flowing downslope, and lead it into either a natural waterway or an artificial grassed waterway (Matthee, 1984), as shown in Figure 2.2. The artificial grassed waterway then conveys the runoff to an established natural channel. Grassed waterways are usually wide and shallow, in order to limit the velocity of the water in the channel and thus to minimise soil erosion.

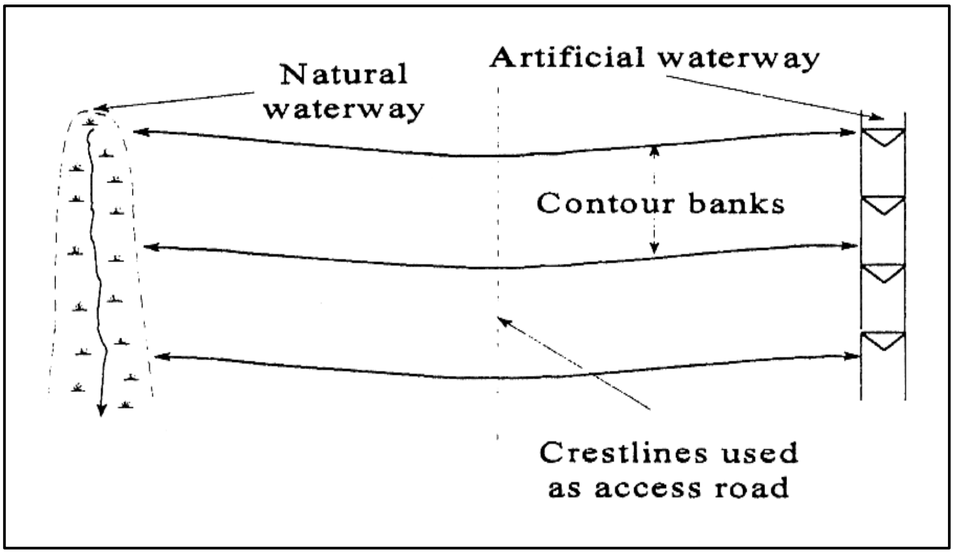


Figure 2.2 Components of a contour bank system (KwaZulu-Natal Department of Agriculture, 1998)

Now that the mechanical methods of conserving the soil have been explained, the next chapter will deal with methods of measuring the soil loss from these systems.

3. MODELLING SOIL LOSS USING EMPIRICAL METHODS

The estimation of soil loss is often required for planning and design purposes. Although it would be desirable to have complex deterministic models that simulate the erosion processes and provide accurate estimates of soil loss, this is often not practical or possible. This is due to the fact that these complex models require numerous input parameters, which are not practical for the average farmer or engineer to measure or obtain. These models also often require calibration and therefore cannot be easily or quickly applied to a number of different sites (Lorentz and Schulze, 1995).

For example, the WEPP model was developed by Foster and Lane (1987) and is a process-based, deterministic model (Smith, 1999). It is based on hydrological, hydraulic and sediment transport theory and promotes greater understanding of these processes. In order to compute net soil detachment and deposition, the WEPP model uses a steady state sediment continuity equation (Smith, 1999). Although the model has been used successfully in the USA (Flanagan *et al.*, 2007), it is a complex model. A large number of measurement parameters may not be available in many locations in South Africa (Smith, 1999). For these reasons, simple empirical methods have been found to be more effective in providing adequate estimates of soil loss for initial planning and design purposes. A number of these empirical models are discussed below.

3.1 Soil Loss Estimation Model for Southern Africa (SLEMSA)

The Soil Loss Estimation Model for Southern Africa (SLEMSA) was developed by Elwell (1978). According to Schulze (1979), SLEMSA "was designed to predict long term average annual soil losses from sheet and rill erosion for specific combinations of physical and management conditions". The SLEMSA algorithm is given in Equation 3.1. The standard field plot used in the calculations is a weed-free, bare, fallow field with dimensions of 30 m by 10 m. The slope of the standard fields plot is taken to be 4.5% and the soil is of a known erodibility. The soil erodibility and rainfall energy are incorporated into the variable K, below.

$$Z = KCX \tag{3.1}$$

where

Z = predicted mean annual soil loss [t.ha^{-1}.yr^{-1}] or Erosion Hazard Units [EHU],

K = mean annual soil loss from a standard field plot [t.ha^{-1}.yr^{-1}],

C = the ratio of soil lost from a cropped plot to that lost from bare fallow plot, and

X = the ratio of soil lost from a plot of length L and slope percent S, to that lost from the standard plot.

Experiments were conducted by Smithen and Schulze (1979) to compare results of SLEMSA and the USLE. The investigation showed that SLEMSA is highly sensitive to rainfall energy. SLEMSA has a very simple method of determining the crop factor, based simply on total canopy coverage. In comparison the USLE has various sub-factors which take into account canopy cover, mulch cover and the residual effect of land use. The investigation concluded that, in the catchment in question, SLEMSA gave estimates of soil loss which were approximately half of the USLE values. However, it was not proved which of these values were closer to the actual value of soil loss. It was stated that either model could be used to obtain an estimate of soil loss, and that the choice of model was a subjective one (Smithen and Schulze, 1979). SLEMSA was developed specifically for the Zimbabwean Highveld and according to Smith (1999), the estimations should only be used as a guide or rating when used outside of this area. A further limitation of SLEMSA is that it only calculates sheet erosion, and hence neglects rill erosion.

3.2 Universal Soil Loss Equation (USLE)

The Universal Soil Loss Equation (USLE), was first presented by Wischmeier and Smith (1965) in the USDA Agriculture Handbook No. 282. It was further developed by Wischmeier and Smith (1978) in the USDA Agriculture Handbook No. 537, and has become one of the most widely recognised and frequently applied empirical soil loss estimation methods, forming the basis for a number of other methods and equations (Lorentz and Schulze, 1995). The USLE is given in Equation 3.2.

$$A = R \cdot K \cdot LS \cdot C \cdot P \qquad (3.2)$$

where

A = long term annual average soil loss per unit area [t.ha^{-1}.annum^{-1}],

R = an index of annual rainfall erosivity [MJ.mm.ha^{-1}.h^{-1}.annum^{-1}],

K = soil erodibility factor [t.h.MJ^{-1}.mm^{-1}],

LS = slope length and gradient factor [dimensionless],

C = cover and management factor [dimensionless], and

P = conservation support practice factor [dimensionless].

Although the USLE was cutting-edge science at the time of its release, many weaknesses have been revealed with time and use. According to Smith (1999), one of the major disadvantages was that the database was restricted to the USA east of the Rocky Mountains. It was also limited to slopes with a gradient of 7% or less and soils with a low smectite content. Smith (1999) also stated that the USLE was never widely adopted in South Africa, due in part to the fact that it is assumed that empirical models do not perform well in conditions different to those in which the model is derived.

3.3 Revised Universal Soil Loss Equation (RUSLE)

The USLE was later revised and was presented as the Revised Universal Soil Loss Equation, RUSLE, by Renard *et al.* (1991b). The RUSLE is explained in detail in Agriculture Handbook No. 703 (Renard *et al.*, 1996) and it has the same form as the USLE. Both the USLE and RUSLE calculate erosion from sheet and rill erosion only, excluding erosion from gullies or concentrated flow. These equations give an estimate of the long term average annual soil loss and are not event based, although modifications have been developed to predict event based sediment yield (Lorentz and Schulze, 1995).

It has been noted by Kinnell (2010) that although the USLE and RUSLE are generally shown in the form of Equation 3.1, the model contains two steps. This is because the model is created with a standard runoff plot concept. The standard runoff plot is defined to have a slope of 9% and a length of 22.1 m. The plot is a tilled, bare, fallow area and tillage occurs up and down the slope. The first step in the USLE is to predict the erosion for the unit plot using Equation 3.3.

$$A_1 = RK \tag{3.3}$$

where

A_1 = long term average soil loss per unit area of the unit plot [t.ha^{-1}.annum^{-1}].

It must be noted that R and K are the only factors that have associated units. The remaining factors are then multiplied to the result from Equation 3.3 in order to give an answer relevant to the conditions at the plot of interest, as shown in Equation 3.4.

$$A = A_1 LSCP \tag{3.4}$$

where

A = long term average soil loss per unit area [t.ha^{-1}.annum^{-1}].

It must be remembered that the USLE is an empirical model. While the factors of the equation are physical factors in soil loss, they do not represent strictly physical interrelationships, but rather statistical interrelationships developed from a large database (Lorentz and Schulze, 1995). Although the RUSLE uses the same factors as the USLE, major updates were performed including improved input data and time-dependent variables. Each one of the five USLE factors is discussed in turn below.

3.3.1 Annual soil loss (A)

A represents the long term average annual soil loss for a given slope. It must be emphasised that soil loss is not the same as sediment yield. The A factor also averages the erosion along the slope, so erosion at specific points along the slope may differ from the computed average erosion.

3.3.2 Rainfall erosivity factor (R)

According to Smithen and Schulze (1982), values for the soil, topography, vegetation and management factors can be determined universally with the aid of available tables and nomographs (Wischmeier and Smith, 1978). However, the rainfall erosivity factor depends on the local climate and must be determined from location-specific data.

According to Wischmeier and Smith (1965), the R factor was developed from the analysis of large rainfall and soil loss datasets. It was found that with all other factors held constant, the soil loss was directly proportional to the product of the total storm kinetic energy (E) and the maximum 30-minute intensity of the storm (I_{30}). When using the metric system, rainfall kinetic energy is expressed in terms of J.m^{-2} per unit of time, while intensity is measured in mm.h^{-1}. The product of kinetic energy and intensity often results in values with large magnitudes. The product is therefore divided by 1000, and the solution gives the "units of erosivity" (Smithen and Schulze, 1982). In determining EI_{30} values for South Africa, only events in which the rainfall was greater than 12.5 mm, and separated from other periods of rain by more than 6 hours, were included. An exception to this threshold was if 6.3 mm of rain fell in 15 minutes, even if the total rainfall was less than 12.5 mm. The reason for this was to limit the cost and time required for calculations. In the study performed by Smithen and Schulze (1982), this threshold reduced the number of storms per year to a value seldom exceeding twenty. Wischmeier and Smith (1978) report that the introduction of the 12.5 mm threshold has little effect on the calculations. An additional threshold for the calculations was an intensity limit of 76 $mm.hr^{-1}$. It was found that the median drop size does not increase significantly above this threshold, and hence the energy of the rainfall event also remains constant (Carter *et al.*, 1974).

If the EI_{30} for all of the storms in a year are summed, the result is the total erosivity for that year. Using many years of record, an average erosion index for a station may be computed. In order to determine the erosion index for areas not represented by a station, iso-erodent maps can be generated, as shown in Figure 3.1. An iso-erodent is a line which joins points of equal erosion index values. The erosion index for points falling between iso-erodents can be found by interpolation (Wischmeier and Smith, 1965).

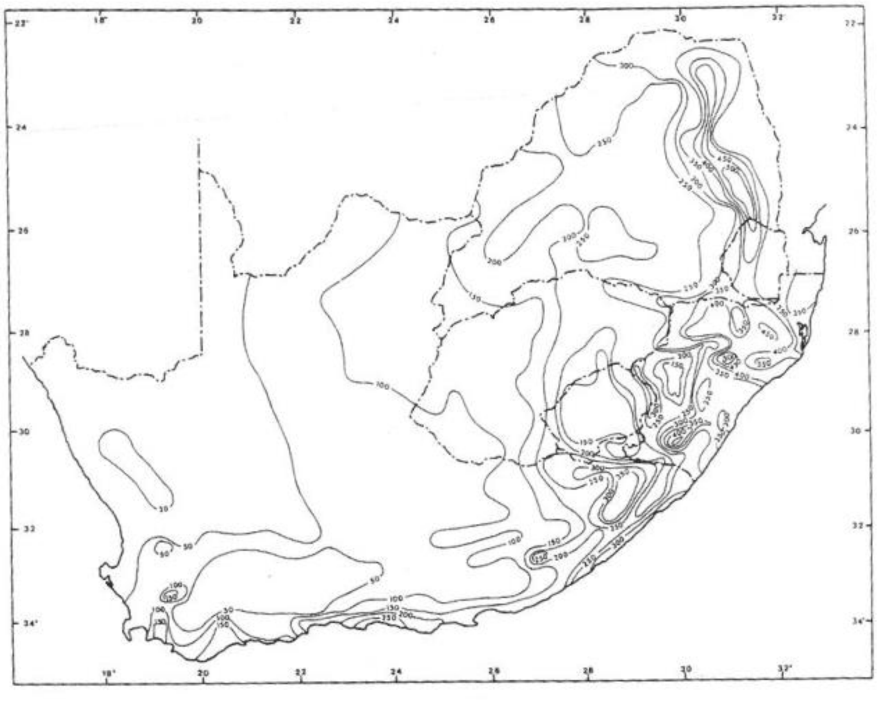


Figure 3.1 Isoerodent map of South Africa (Smithen and Schulze, 1982)

In South Africa, EI_{30} values were calculated for various stations in the country in 1982 by Smithen and Schulze (1982). Owing to the limited number of stations for which EI_{30} could be computed, the country was divided into fourteen relatively homogeneous regions and a key station was selected to represent each region. A regression analysis of EI_{30} against other rainfall parameters was performed. These parameters included total rainfall, effective rainfall, Modified Fournier's Index and the Burst Factor.

The 'total rainfall' is the simplest parameter. EI_{30} was simply related to total rainfall for a period of time. The 'effective rainfall' parameter excludes any events which are deemed non-erosive, *i.e.* events less than 12.5 mm separated by more than 6 hours. The Modified Fournier's Index (MFI) is given in Equation 3.5.

$$MFI = \sum_{i=1}^{12} \frac{{Pe_i}^2}{P} \tag{3.5}$$

where

Pe_i = effective rainfall amount for month *i* [mm], and

P = annual rainfall [mm].

It was assumed that a parameter which included rainfall intensity in some way would correlate well with EI_{30}. Maximum daily rainfall in a time period indicates intensity to a certain degree, and is readily available. Equation 3.6 gives the Burst Factor (BF) as presented by Smithen (1981).

$$BF = \sum_{i=1}^{12} \frac{M_i Pe_i}{P} \tag{3.6}$$

where

M_i = maximum daily rainfall for month *i* [mm].

Simple linear regression was used to determine the correlation between annual EI_{30} values and each of the parameters listed above. The parameters which gave the best prediction were determined for each station. It was assumed that the EI_{30} : rainfall relationships at the key stations represented the other daily rainfall stations in the respective homogeneous regions. The equations were then applied to daily rainfall records from 403 other stations across the country. An iso-erodent map was generated, allowing the determination of EI_{30} for any location in the country, as shown in Figure 3.1.

Originally, the equation used to determine the energy of the rainfall event, E, was that developed by Wischmeier and Smith (1958), as shown in Equation 3.7.

$$KE = 0.0119 + 0.0873 \log_{10} I \tag{3.7}$$

where

KE = kinetic energy of rainfall event [MJ.ha^{-1}.mm^{-1}], and

I = intensity of rainfall [mm.h^{-1}].

However, many different equations have been developed for different areas and under different conditions. For example, Hudson (1965) presented Equation 3.8 for tropical rainfall, based on Zimbabwean rainfall data.

$$KE = 0.298 \left(1 - \frac{4.29}{I}\right) \tag{3.8}$$

van Dijk *et al.* (2002) reviewed previous research and proposed Equation 3.9 as a universal equation.

$$KE = 0.283(1 - 0.52e^{-0.042I}) \tag{3.9}$$

According to Morgan (2005), this equation is fairly accurate in that it generally provides estimates within 10 % of measured values. However, it still has problems when applied to climates with a strong coastal effects, or areas which are semi-arid or sub-humid, where it overpredicts and underpredicts, respectively.

Just as there is debate about which energy equation to use, there are also questions raised as to whether EI_{30} is, in fact, an accurate representative of rainfall erosivity. Morgan (2005) argues that there is no clear reason why the I_{30} factor is the best parameter to relate to erosivity. In addition, the EI_{30} erosivity index assumes that even low intensity rainfall causes erosion. However Hudson (1965) showed that erosion occurs almost solely when rainfall intensities are above 25 mm.h^{-1}. He proposed a different erosivity index, KE > 25, which is simply the sum of the kinetic energy of the storm in the time increments when the rainfall intensity is greater than 25mm.h^{-1}. Although this index is better suited for tropical climates, it would be possible to alter the threshold for more temperate climates, *e.g.* KE > 10. Hudson's index is also relatively simple and does not have very stringent data requirements (Morgan, 2005).

It must be noted that the erosivity index is usually calculated on an annual basis. However, this does not take into account the seasonal patterns of both rainfall erosivity and vegetal cover. The temporal resolution of the erosivity index is particularly important when erosive rains fall on areas with low cover (Le Roux *et al.*, 2008). Le Roux *et al.* (2008) have updated the rainfall erosivity values since 1982. However, this update was still performed using daily rainfall records, rather than short duration records. The map of the updated rainfall erosivity values by Le Roux *et al.* (2006) is shown in Figure 3.2.

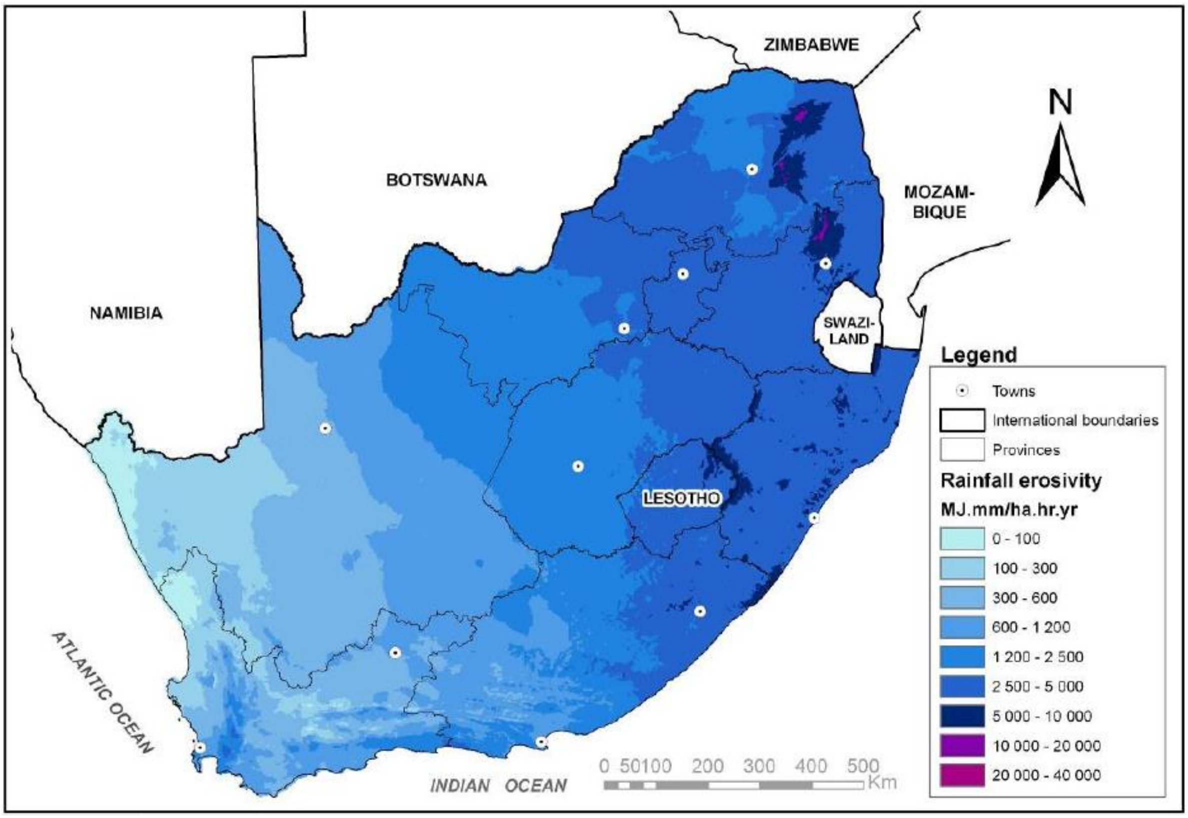


Figure 3.2 Rainfall erosivity map of South Africa (Le Roux *et al.*, 2006)

3.3.3 Soil erodibility factor (*K*)

Formally, soil erodibility is the "change in the soil per unit of applied external force or energy" (Renard *et al.*, 1996) and it has the units t.h.MJ^{-1}.mm^{-1}. This gives the amount of soil removed by one "erosivity unit". In practical terms, it can be thought of as how easily soil is detached by erosive forces such as rainsplash and runoff. It takes into account soil properties and accounts for the influence that they have on soil loss. These properties include detachment, transport, deposition, infiltration into the soil and roughness due to tillage (Renard *et al.*, 1996). The *K* factor can be determined by different methods, depending on the amount of information available.

The *K* factor may be determined from a simple knowledge of the type of soil. Both the Binomial Soil Classification (MacVicar *et al.*, 1977) and the Taxonomic Soil Classification (Soil Classification Working Group, 1991) systems may be used. For each soil type, the former Department of Agricultural Technical Services (DATS) has assigned an erosion potential class (*e.g.* high, low, moderate) (Department of Agricultural Technical Services, 1976). The erodibility factor, *K*, can then be determined from Table 3.1. An experienced user may refine the estimate of *K* by making field observations and studying the local conditions.

Table 3.1 Erodibility factors for various soil erodibility classes (Lorentz and Schulze, 1995)

Soil Erodibility Class	**Soil *K*-Factor**
Very High	> 0.70
High	0.50 – 0.70
Moderate	0.25 – 0.50
Low	0.13 – 0.25
Very Low	< 0.13

The *K* factor can also be determined using a particle size distribution analysis. Equation 3.10 is used to find the geometric mean of the particle sizes.

$$D_g = EXP[0.01 \sum (f_i \cdot \ln(m_i))] \tag{3.10}$$

where

D_g = geometric mean particle size [mm],

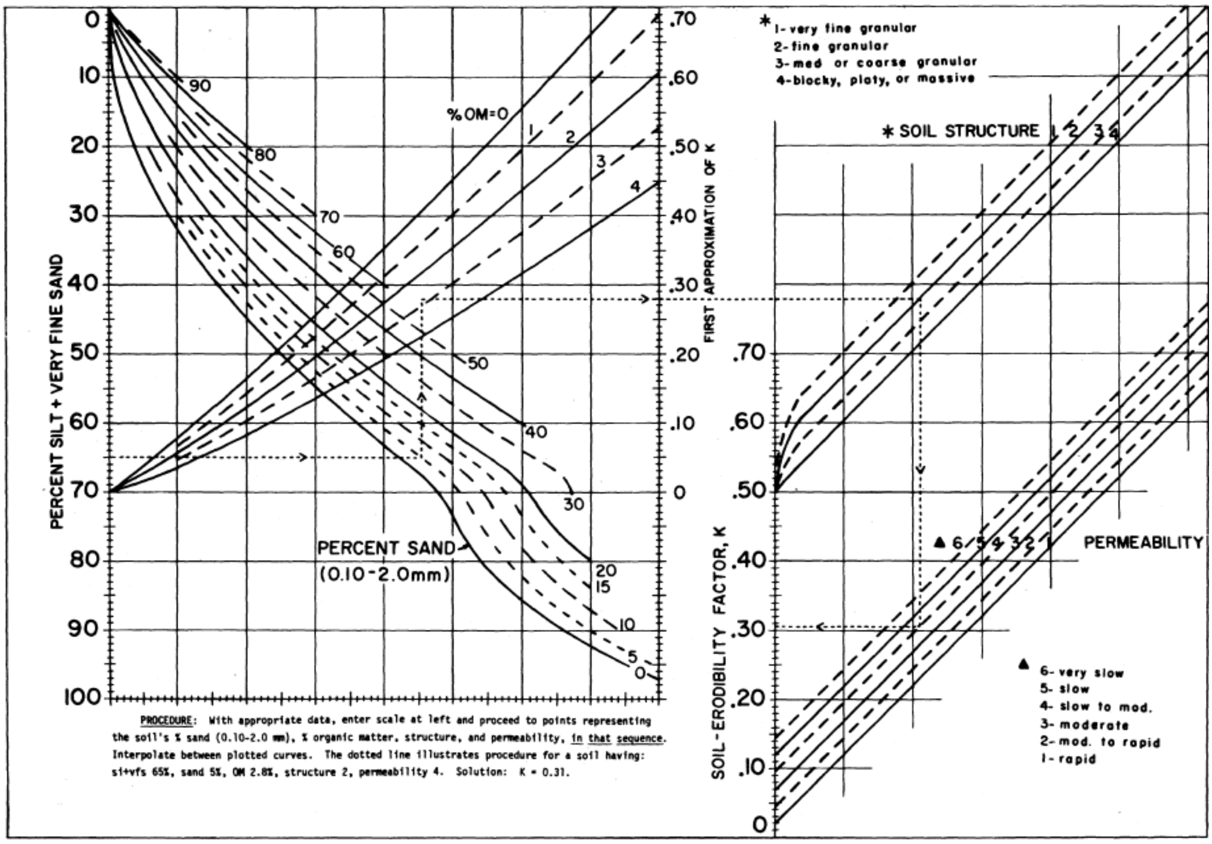
f_i = primary particle size fraction [%], and

m_i = arithmetic mean of the particle size limits of that size [mm].

The geometric mean is then used to estimate *K* using Equation 3.11 (Renard *et al.*, 1996).

$$K = 7.954\left\{0.034 + 0.0405exp\left[-\frac{1}{2}\left(\log(D_g) + \frac{1.659}{0.7101}\right)^2\right]\right\} \quad (3.11)$$

Wischmeier *et al.* (1971) developed a nomograph which takes into account many physical properties of the soil, as shown in Figure 3.3. These included the particle size distribution, the amount of organic matter in the soil, as well as the structure and permeability of the soil.



PROCEDURE: With appropriate data, enter scale at left and proceed to points representing the soil's % sand (0.10-2.0 mm), % organic matter, structure, and permeability, in that sequence. Interpolate between plotted curves. The dotted line illustrates procedure for a soil having: si+vfs 65%, sand 5%, OM 2.8%, structure 2, permeability 4. Solution: K = 0.31.

Figure 3.3 The soil erodibility nomograph to estimate K (Renard *et al.*, 1996)

If the fraction of silt does not exceed 70%, an approximation of K from the nomograph can be found using Equation 3.12 (after Wischmeier and Smith, 1978).

$$K = 0.01317[0.00021(12 - OM_{\%})M^{1.14} + 3.25(S_s - 2) + 2.5(P_s - 3)] \quad (3.12)$$

where

$OM_{\%}$ = % organic matter,

S_s = soil structure code,

P_s = permeability class, and

M = product of the primary particle size fractions

$$= [SS_{\%} * (SS_{\%} + Sa_{\%})]$$

and

$SS_{\%}$ = % silt plus very fine sand (0.002 - 0.1 mm), and

$Sa_{\%}$ = % sand (0.1 – 2 mm).

The permeability class can be determined from Table 3.2 and the soil structure code can be obtained from the nomograph in Figure 3.3.

Table 3.2 Permeability classes for different soil texture classes (Renard *et al.*, 1991a)

Texture Class	**Permeability Class, P_s**	**Saturated Hydraulic Conductivity (mm.h-1)**
Clay, Silty Clay	6	< 1
Silty Clay Loam, Sandy Clay	5	1 – 2
Sand Clay Loam, Clay Loam	4	2 – 5
Loam, Silty Loam	3	5 – 20
Loamy Sand, Sandy Loam	2	20 – 60
Sand	1	> 60

Although not applicable a field scale, Schulze and Horan (2007) have developed a map of South Africa showing the K factor. This map is shown in Figure 3.4.

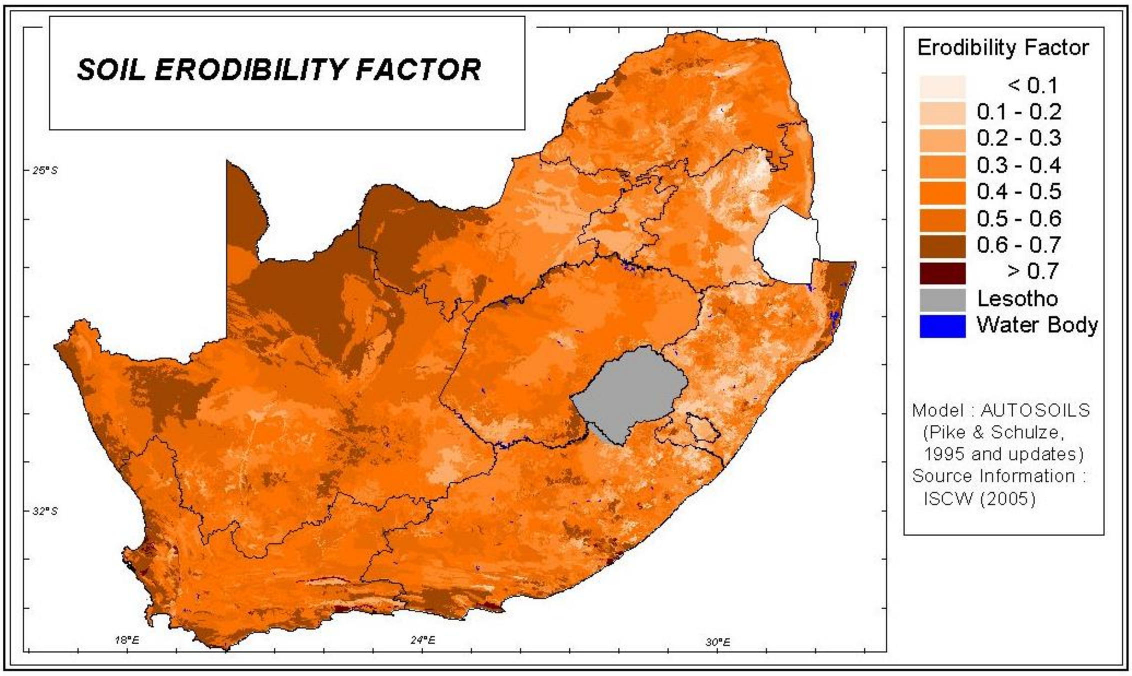


Figure 3.4 Soil erodibility map of South Africa (Schulze and Horan, 2007)

3.3.4 Slope length and steepness factor (*LS*)

The *LS* factor accounts for the topography in the area of interest. Two properties make up the *LS* factor. These are the length of the slope and the gradient of the slope. Slope length is defined as the distance from the source of the overland flow to either where the gradient decreases adequately for deposition to occur or where the flow enters a distinct natural or artificial channel (Lorentz and Schulze, 1995).

Erosion increases as the length of the slope increases (Renard *et al.*, 1996). It is best to measure the slope length in the field. Slope lengths determined using contour maps are often too long as the maps do not show the areas of water concentration where the slopes end. The slope length factor, L_s, is calculated using Equation 3.13.

$$L_s = \left(\frac{\lambda_1}{22.1}\right)^{m_{sl}} \tag{3.13}$$

where

L_s = slope length factor [dimensionless],

λ_1 = slope length [m], and

m_{sl} = a variable which is dependent on the ratio, βr, of rill (caused by flow) to interrill (caused mainly by rainfall impact) erosion.

m_{sl} is computed using Equation 3.14.

$$m_{sl} = \frac{\beta_r}{1+\beta_r} \tag{3.14}$$

The value of β_r is dependent on whether a slope is more susceptible to rill or interrill erosion. If the slope is moderately subject to both forms of erosion, then β_r can be calculated using Equation 3.15.

$$\beta_r = \frac{\sin S_{deg}}{0.0896\left[3.0(\sin S_{deg})^{0.8}+0.56\right]} \tag{3.15}$$

where

S_{deg} = slope angle [°].

If the conditions indicate that a slope is very susceptible to rill erosion (*e.g.* a steep slope that has just been tilled), the value of βr must be doubled. In the same way, if the rill erosion appears to have a much lower effect than interrill erosion (e.g. on gently sloping grasslands), the value of βr must be halved (Lorentz and Schulze, 1995).

An increase in slope steepness has a greater effect on soil loss than an increase in slope length (Lorentz and Schulze, 1995). The slope can be measured using a device such as an inclinometer. The equations for the slope steepness factor (S_{sf}), shown in Equations 3.16 and 3.17, were presented by McCool *et al.* (1987).

$$S_{sf} = 10.8\sin S_{deg} + 0.03 \qquad for\, S_{\%} < 9\% \tag{3.16}$$

$$S_{sf} = 16.8\sin S_{deg} - 0.50 \qquad for\, S_{\%} \geq 9\% \tag{3.17}$$

If the slope of interest is less than 5 m in length, Equation 3.18 should be used to determine the slope steepness factor.

$$S_{sf} = 3.0(\sin S_{deg})^{0.8} + 0.56 \tag{3.18}$$

In order to obtain the final *LS* factor, the L_s and S_{sf} factors must be multiplied together. If the slope is not uniform (i.e. concave or convex), the *LS* factor must be adjusted using tables available in the RUSLE guide developed by Renard *et al.* (1996).

3.3.5 Cover and management factor (*C*)

Lorentz and Schulze (1995) argue that the cover and management factor, *C*, may be the most significant factor in the calculating soil loss using the RUSLE. This is due to the large range of possible values that *C* may assume, its variation throughout the year and the difficulties often experienced in estimating it. Many methods exist for the calculation of *C*, and the choice of method depends on what information is available.

The *C* factor can be obtained using the SCS Runoff Curve Number, CNII. However, this relationship was created using experiments in South America and may not provide accurate results elsewhere. Its use requires caution and sound judgement. The relationship is shown in Equation 3.19.

$$C = EXP\left(\frac{CNII\ 97.5}{10.9}\right) \tag{3.19}$$

where

$CNII$ = SCS Runoff Curve Number.

The *C* factor can also be estimated for a given canopy cover, mulch cover and a knowledge of the management of the field. Two sub-factors are multiplied together to find an overall *C* value. The first sub-factor is a Soil Loss Ratio, *SLR1*, related to the canopy and mulch cover. The second sub-factor, also a Soil Loss Ratio (*SLR2*), is related to the management or residual effects such as tillage. SLR2 is more difficult to ascertain, and is dependent on factors such as whether the seedbed is ridged or compacted, and if a grass crop has recently been ploughed in. The *C* factor is determined for each growth stage on a time step specified by the user. On land such as pasture or veld, soil protection is relatively constant throughout the year and residual effects are not significant. In these cases, average annual values are provided by Wischmeier and Smith (1978).

The most complex method of determining *C* requires comprehensive information regarding the crop and its management. It involves the use of five sub-factors, namely:

(a) prior land use (PLU),
(b) canopy cover (CC),
(c) surface vegetation or mulch cover (SC),
(d) surface roughness (SR), and
(e) soil moisture (SM).

Each of these sub-factors must be calculated individually and each requires detailed information. The *C* factor changes continuously throughout the year as the crop develops through its various growth stages and certain cropping patterns/operations are followed. It is especially important to accurately determine the magnitude of *C* when the majority of erosive rainfall occurs as the crop can have a large erosion-reducing effect.

3.3.6 Conservation support practice factor (*P*)

According to Renard *et al.* (1996), the support practice factor is "the ratio of soil loss with a specific support practice to the corresponding loss with upslope and downslope tillage". These practices reduce the volume of runoff, as well as the rate of runoff by altering the pattern of flow, the slope of the land and the direction in which the runoff flows.

If only limited information is available, the *P* factor can be determined by the slope of the land and whether contour tillage and contour banks are used, as seen in Table 3.3. Both of these measures reduce soil erosion to some degree, the effectiveness of which depends on the steepness of the slope. Contour banks afford a higher degree of protection to the soil, when compared to only tilling on the contour, as they break the slope up into shorter pieces, while allowing deposition in the channel of the contour bank. *P* assumes a value of one for uncultivated lands, unless specific conservation practices are detailed.

Table 3.3 P factor when only slope is known (after Wischmeier and Smith (1978))

Land slope (%)	Contour tilled	Contour banks with grassed waterways
1-2	0.60	0.12
3-8	0.50	0.10
9-12	0.60	0.12
13-16	0.70	0.14
17-20	0.80	0.16
21-25	0.90	0.18

If more detailed information exists, a more complex method can be used to determine the P factor. On cultivated lands, the support practices covered include contouring, strip cropping, terracing and subsurface drainage. Contouring causes the runoff to flow around the slope, which decreases the slope significantly. This reduces both the detachment and transport capacity of the flow. The magnitude of the P factor in this case is determined by the slope of both the land and the furrows, as well as the height of the tillage ridges.

While the effects of strip cropping are complex and dependent on many factors, the estimation of the P factor for terracing is relatively straightforward. The P factor is determined using Equation 3.16. The benefit factor can be obtained from tables (Lorentz and Schulze, 1995).

$$P = 1 - B_d \cdot \left(1 - 0.1 \cdot EXP(2.4 g_t)\right) \tag{3.20}$$

where

g_t = slope of the terrace (%), and

B_d = benefit factor for deposition.

It can be seen that RUSLE takes into account all of the major factors affecting soil erosion. Many options exist to input information, depending on the level of data available. The next chapter looks at how contour intervals are calculated, and particularly how RUSLE can be used in that process.

4. DESIGN APPROACHES FOR CONTOUR BANK SPACING

There are many components in the design of a contour bank system. These include the determination of the correct contour bank spacing and layout of contour banks, the design of a suitable channel which has sufficient capacity, as well as the design of a cross-section which is stable and can be farmed if required (Huffman *et al.*, 2011). Except in the case of level contours, the channels should have continuous positive drainage along their entire length, and must convey the maximum flow at non-scouring velocities (ASABE Standard S268.5, 2012). According to Huffman *et al.* (2011), the most important factors in the design are "soil characteristics, cropping and soil management practices, and climatic conditions".

The spacing of contour banks is calculated in order to effectively reduce sheet and rill erosion. Two main approaches are used to calculate suitable contour bank spacing. These are the Vertical Interval Equation and site-specific evaluation.

4.1 Vertical Interval Equation

The present version of the Vertical Interval Equation (shown in Equation 4.1) is provided in ASABE Standard S268.5 (2012). A major drawback of this equation is that it does not directly take into account rainfall, soil or cropping systems. It also uses the original slope of the land, and so does not take into consideration the slope of the constructed terraces.

$$VI = XS + Y \tag{4.1}$$

where

VI = maximum vertical interval [m],

X = a variable ranging between 0.10-0.60, depending on rainfall characteristics (Matthee, 1984), or

= a variable ranging between 0.08-0.15 (van Staden, 1989), or

= a variable ranging between 0.12 and 0.24 (ASABE Standard S268.5, 2012)

Y = a variable ranging between 0.30 and 2.30, depending on soil erodibility, the crop and the cropping system, or

= a variable ranging between 0.60 and 1.20 (van Staden, 1989), or

= a variable ranging between 0.30 and 1.21(ASABE Standard S268.5, 2012), and

S = land slope [%].

In South Africa, the form shown in Equation 4.2 is commonly used (van Staden, 1989)

$$VI = \frac{S}{10} + 0.61 \tag{4.2}$$

The KwaZulu-Natal Department of Agriculture (1998) developed graphs to assist with the determination of contour spacing. An example of these graphs can be found in Figure 4.1. Three graphs were developed for low rainfall (MAP < 750 mm), medium rainfall (MAP between 750 and 900 mm) and high rainfall (MAP > 900 mm) areas respectively. The Vertical Interval of the contour banks is determined based on the slope of the land and the soil erodibility.

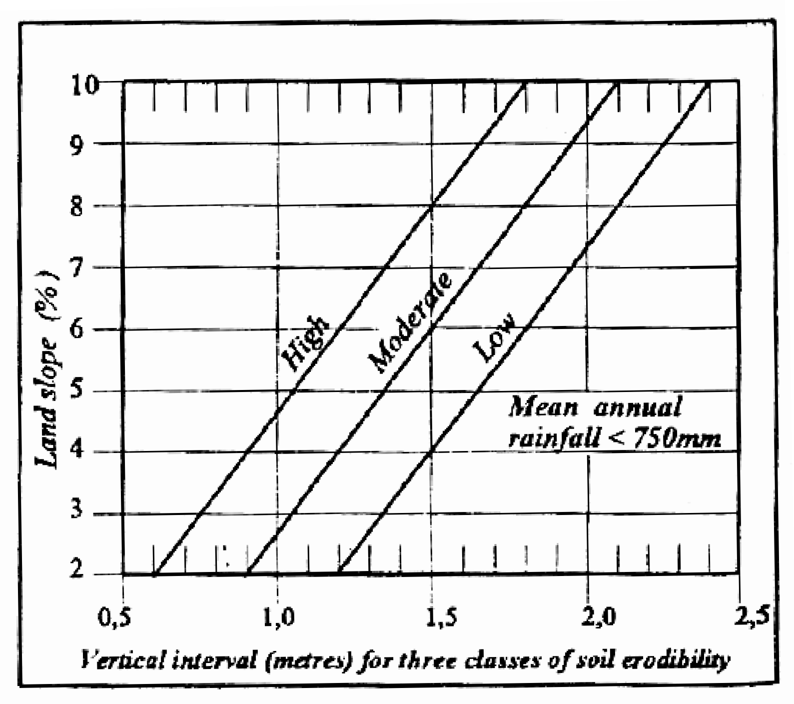


Figure 4.1 Graph for the determination of contour bank intervals in low rainfall areas (KwaZulu-Natal Department of Agriculture, 1998)

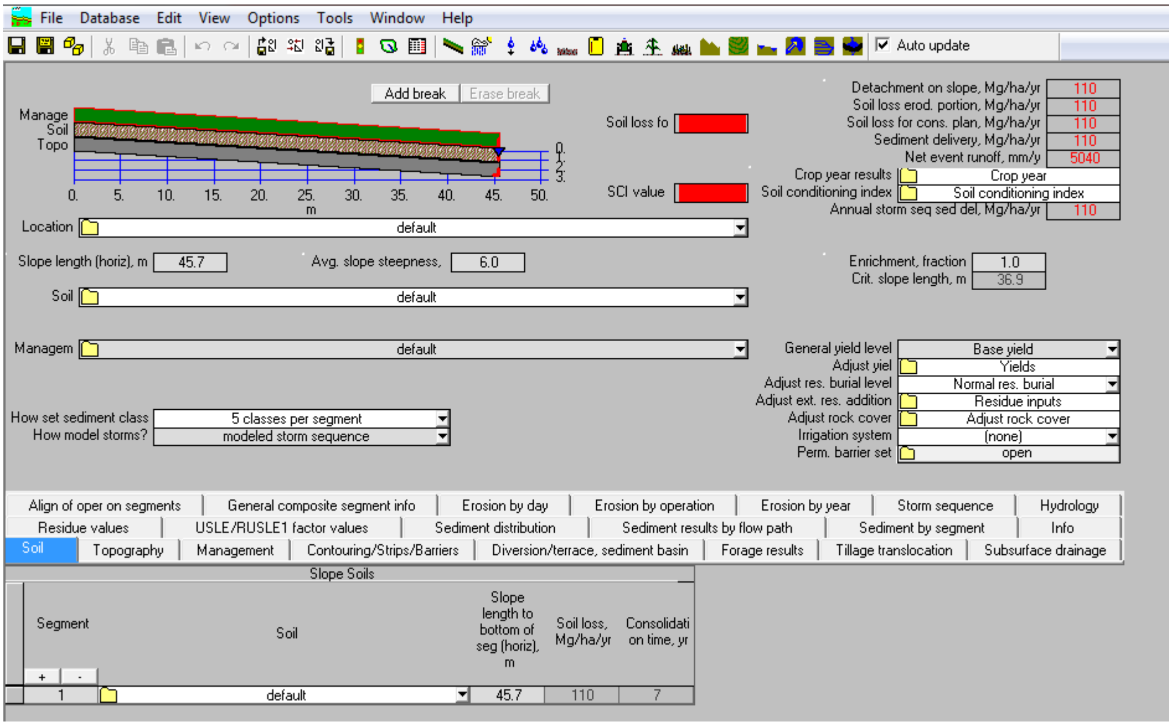
4.2 Site-specific Evaluation

The definition of Soil Loss Tolerance (also alternatively termed Permissible Soil Loss) is “the maximum rate of soil erosion that can occur and still permit soil productivity to be sustained economically” (Renard *et al.*, 1996). Soil loss tolerance does not only take into account the loss of productivity due to erosion, but also the rate of soil formation from parent material. It should also factor in the loss of nutrients and the economic cost to replace them. If the soil loss computed using the RUSLE is less than the value of the soil loss tolerance, erosion control is considered to be sustainable. A similar concept is that of Soil Life Expectancy. This is defined as “how long a soil can be subjected to a specific crop or practice before its sustained productivity is seriously affected by losses”(Matthee, 1984). The equation used to determine soil life takes into account the effective depth of the soil, the required soil depth for crop production, the rates of soil loss and formation, and the mass of the soil.

Additional soil loss limits have been put in place in certain areas for purposes other than cropland productivity, for example to improve offsite water quality. Renard *et al.* (1996) recommend that if the soil loss tolerance is for purposes other than maintaining cropland productivity, it should be specified for water quality concerns (T_{WQ}), economic planning (T_{EP}) and policy concerns (T_{POL}).

The preferred method of spacing is to use site-specific evaluation of the potential rill and sheet erosion of the proposed terraces. In the USA, this is commonly done using the Natural Resources Conservation Service (NRCS) erosion prediction software/technology (ASABE Standard S268.5, 2012). Site-specific evaluation aims to calculate the slope length, under given conditions, which will lead to a Tolerable Soil Loss (T). These T values vary according to the soil and can be found in databases specific to each county. The predicted soil loss of the planned terraces must not exceed the tolerable soil loss.

The NRCS uses the Revised Universal Soil Loss Equation (Version 2) to predict rill and sheet erosion. This models the various conditions of a terrace system, including factors such as slope, cropping system and climate (USDA NRCS, 2011). Figure 4.2 shows the input screen of the RUSLE Profile Module.



☑ Auto update

Soil loss fo 🟥

SCI value 🟥

Detachment on slope, Mg/ha/yr: 110
Soil loss erod. portion, Mg/ha/yr: 110
Soil loss for cons. plan, Mg/ha/yr: 110
Sediment delivery, Mg/ha/yr: 110
Net event runoff, mm/y: 5040
Crop year results: Crop year
Soil conditioning index: Soil conditioning index
Annual storm seq sed del, Mg/ha/yr: 110

Location: default

Slope length (horiz), m: 45.7
Avg. slope steepness,: 6.0

Enrichment, fraction: 1.0
Crit. slope length, m: 36.9

Soil: default

Managem: default

General yield level: Base yield
Adjust yiel: Yields
Adjust res. burial level: Normal res. burial
Adjust ext. res. addition: Residue inputs
Adjust rock cover: Adjust rock cover
Irrigation system: (none)
Perm. barrier set: open

How set sediment class: 5 classes per segment
How model storms?: modeled storm sequence

Slope Soils

Segment	Soil	Slope length to bottom of seg (horiz), m	Soil loss, Mg/ha/yr	Consolidation time, yr
1	default	45.7	110	7

Figure 4.2 Example simulation of the RUSLE2 Profile Module

Data requirements include the profile of the terraced land, climatic information (preloaded and based on location) and soils information, as well as the proposed crop and tillage system.

In South Africa, the process is much simpler. A nomograph has been developed by The Department of Agriculture and Water Supply (1990) in order to quickly and easily determine contour spacing. The nomograph is shown in Figure 4.3. The Department has also provided some basic soil loss tolerances based on soil type, as seen in Table 4.1.

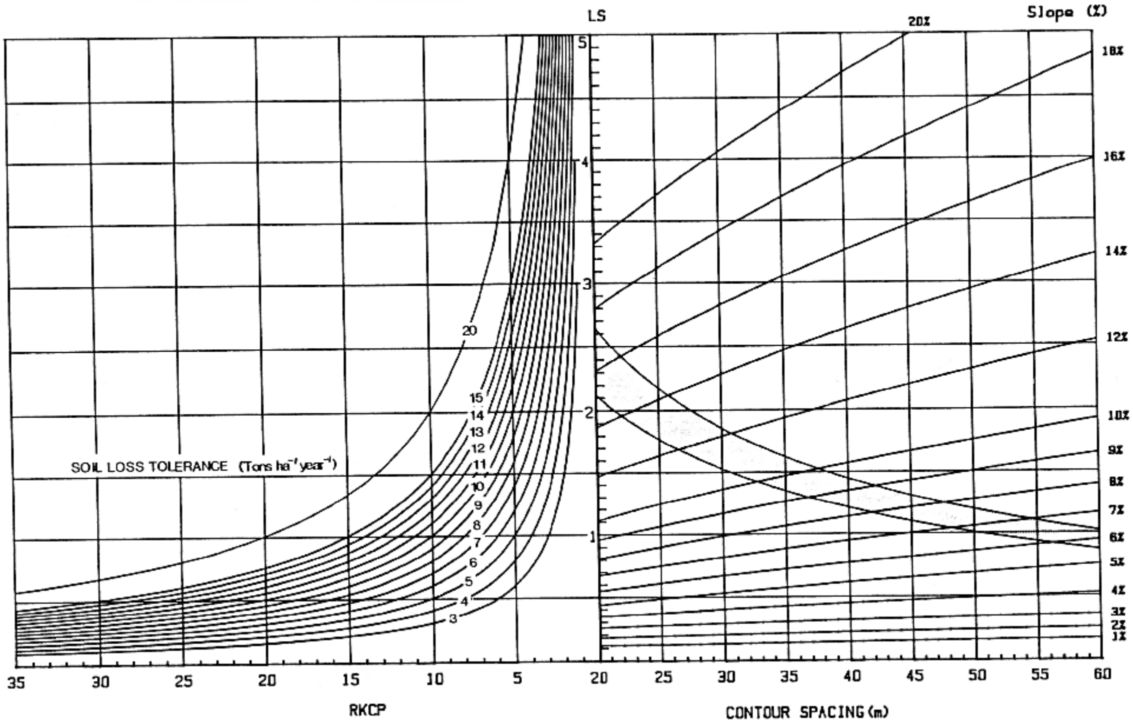


Figure 4.3 Contour spacing nomograph (van Staden, 1989)

Table 4.1 Suggested Soil Loss Tolerances (t.ha^{-1}.yr^{-1}) (van Staden, 1989)

Material underlying topsoil or E horizon	**Percentage Clay in B Horizon**				
	Undifferentiated	**0-6**	**6-15**	**15-35**	**Above 35**
Organic O Vertic A	9				
Yellow Brown Apedal Red Apedal Red structured B		6	7	8	9
E Horizon O Horizon Pedocutanic B Soft Plinthic B Neocutanic B Prismacutanic B Lithocutanic B		4	5	6	7
Hard Plinthite Rock		3	4	5	6

5. DISCUSSION AND CONCLUSIONS

This document contains a review of the mechanical measures used to reduce soil loss in South Africa, as well as design methods used in determining the vertical intervals of contour banks. It also includes an analysis of the different empirical soil loss models used both in South Africa and elsewhere in the world.

A review of the literature indicates that site-specific evaluation should be the preferred approach to the determination of contour bank spacing. The empirical equations used in South Africa are subjective and can be inaccurate, particularly on steep slopes. In addition to this, South Africa lacks detailed information on which factors to use under various conditions. As a consequence, contour intervals are found using a generalised empirical equation, or a simple graph which takes very few factors into account. A need is therefore present to provide a design tool which will allow engineers to accurately determine contour intervals for a specific site.

A review of empirical soil loss models showed that the RUSLE model is able to provide accurate results under a large range of conditions. It was found that the SLEMSA model did not provide accurate enough results when applied in areas other than that in which it was developed. It was able to provide comparative answers, but was not accurate in determining absolute values of soil loss. The USLE model was also found to be limiting, although efforts have been made to generate South African-specific factors. It appears, therefore, that RUSLE is the best model to work with as it is widely used and has significant improvements over USLE including greater data incorporation and increased flexibility.

Although rainfall erosivity values have been updated in recent years, the erosivity factor is still calculated based on daily rainfall values. Greater accuracy could be obtained using short duration rainfall data. The erosivity indices are also still being calculated on an annual time scale. Vegetation cover changes throughout the year, most dramatically in cultivated agricultural production systems. Soil loss would differ greatly depending on whether the majority of the erosive rainfall occurred during fallow periods, planting season or once the crop canopy was fully developed. It is therefore recommended that the rainfall erosivity be calculated on a monthly basis, and that the erosion for each month (with different erosivity and crop factors) be integrated over the whole year to obtain an overall soil loss. The RUSLE2 software utilises this approach, making it a suitable program for accurate results.

This literature review has met the objectives set out in the introduction. An overview of the mechanical soil conservation measures used in South Africa was given. The main soil loss estimation models used in the country were analysed, and it was found that RUSLE is the preferable model to apply in South Africa. This is because it is comprehensive in considering the factors causing erosion, while still simple enough to enable use with relatively accessible information. The design methods used to determine contour bank intervals were discussed and it was found that site-specific evaluation approach is preferable to the use of empirical equations. Lastly, a project proposal follows, which will give a brief outline of the proposed study.

6. PROJECT PROPOSAL

In this section, a project proposal is presented on creating climate files for use with the RUSLE2 program. The aims and objectives of the study are given, as well as a proposed methodology. A list of the required resources and equipment is given and the relevant health, safety, environmental and ethical considerations are discussed. Finally a project plan is presented, in which a timeline for the various tasks and milestones is provided.

6.1 Research Question

What is the impact of updated and refined design methods on the design of soil conservation systems in South Africa?

6.2 Aims and Objectives

The aim of this project is to provide a tool to assist engineers in the design of soil and water conservation measures and to update the rainfall erosivity data for South Africa, in order to improve the accuracy of soil loss estimates.

The specific objectives of the project are to:

(a) update the rainfall erosivity values for use in the RUSLE model in South Africa using longer and more detailed rainfall records,
(b) create South African climate files for use in the RUSLE2 program, and
(c) compare the new and old design approaches at selected sites.

This study will enable engineers to easily determine suitable contour bank intervals to prevent the exceedance of the tolerable soil loss from fields. By updating the erosivity values for South Africa, greater accuracy will be obtained both in the determination of contour bank intervals and also in estimating soil loss from existing fields and slopes.

6.3 Proposed Methodology

The study will begin with a detailed literature review. Methods used to determine contour bank spacing both locally and internationally will be analysed in order to determine the best method of developing a design tool for soil conservation structures. Methods for updating the rainfall erosivity factors in South Africa will also be investigated.

The project will include the following tasks:

(a) A comprehensive literature review will be undertaken.

(b) An update of the rainfall erosivity factors in South Africa will be performed, which will entail:
   i. obtaining the relevant rainfall data,
   ii. investigating different measures of erosivity,
   iii. applying the developed relationships to obtain rainfall erosivity values, and
   iv. validating the new values.

(c) The updated values determined in (b) will be incorporated into climate files for use in RUSLE2. Data required includes:
   i. monthly erosivity,
   ii. monthly precipitation,
   iii. monthly temperature, and
   iv. the 10 year – 24 hour precipitation amount.

(d) A comparison of the contour bank spacing obtained using the developed design tool with the spacing obtained using the traditional empirical equation methods will be performed.

The goal of this study is to provide a design tool for engineers, field technicians and soil and water conservation specialists, which utilises the most up-to-date information possible in order to provide accurate results.

6.4 Resources and Equipment

This project is a desktop study and will be carried out at the University of KwaZulu-Natal. The resources and equipment required to complete the study are listed in Table 6.1.

Table 6.1 Resources and equipment required for project

No.	Resources and Equipment	Source	Application
1	Desktop computer	UKZN	Research and model development
2	Short-duration rainfall data	SAWS	Updating rainfall erosivity information
3	Vehicle	UKZN	Transport
4	Bursary	NRF	Living/research expenses

6.5 Health, Safety, Environmental and Ethical Considerations

As this project will be a desktop study, there should be no health, safety, environmental or ethical considerations for the actual project. However, if the design tool is applied, there will be some environmental effects. A greater accuracy in contour bank determination will maintain soil loss within tolerable limits. This will prevent excessive erosion taking place and will hence maintain soil productivity, as well as reduce sediment loads in streams. This will have a general positive effect on the environment and will also reduce siltation of reservoirs.

6.6 Project Plan

Table 6.2 Project plan

Start date	End date	Task
1 January 2014	31 March 2014	Draft literature review and project proposal
1 April 2014	30 April 2014	Final literature review and project proposal
1 May 2014	1 August 2014	Corrections to literature review and project proposal Model research
1 August 2014	11 August 2014	Presentation
11 August 2014	30 October 2014	Update rainfall erosivity values
1 November 2014	31 December 2014	Creation of climate files
1 January 2015	31 January 2015	Model application
1 February 2015	31 March 2015	Analysis
1 April 2015	30 June 2015	Final write-up and thesis submission
1 July 2015	31 August 2015	Write papers

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