UNIVERSITY OF ZIMBABWE

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Masters Degree in Integrated Water Resources Management

Relationships between gully characteristics and environmental factors in the Zhulube Meso-Catchment: Implications for Water Resources Management

By

Farai Dondofema

Supervisors: **Dr A. Murwira**
Mr A. Mhizha

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ABSTRACT

The objectives of this study were to determine the accuracy of using satellite imagery and Orthophotos in gully identification and to test for significant relationships ($p<0.05$) between gully characteristics and environmental factors. The results showed that gully characteristics (depth, width and area) are significantly ($p<0.05$) explained by soil characteristics, environmental factors, slope gradient, sediment loadings and the erosive power of streams. Statistical analysis focused on the correlation and regression of soil chemical properties, vegetation type and gully characteristics and identification of susceptible areas. GIS and remote sensing techniques showed that 36% of major gullies were discernible using the Landsat TM imagery, 56% from the Spot panchromatic and 77% from the Orthophoto. There was an evident significant ($p<0.05$) relationship between gully depth and bulk density at r^2= 0.873 were the soil clay content was another soil property that showed a significant ($p<0.05$) relationship with gully development with its related minerals (Manganese, magnesium, Sodium and Calcium), indicating a decline in erosion with an increase in proportions. A significant ($p<0.05$) relationship between gully depths and slope gradient showed a resultant increase of r^2= 0.62. There was a significant ($p<0.05$) relationship between gully development and the erosive power of stream while sediment loadings of the streams indicated a non-significant effect on the gully depth with an r^2= 0.02 were $p<0.05$. It can be concluded that remote sensing and GIS techniques are applicable in gully identification, their accuracy levels varying greatly depending on the spatial, spectral and temporal resolution of the imagery used. The inherent susceptibility of soils to detachment and transport by various erosive agents was a function of soil properties including among others, physical and chemical soil properties. The effects of each soil property were different between sites thereby influencing the degree of vulnerability of any given soil to destructive erosion forces. In addition, the interactive effects of the topography, vegetation cover and rainfall factors greatly influenced erosive agents. Soil erodibility assessment using simulated stream erosive forces and sediment loadings revealed that sediment yield or the erosive power of the streams in the study area increased with increasing slope gradient depending on the clay content of the soils.

Key Words: gully, remote sensing, GIS, erosion, mapping

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LIST OF ABBREVIATION AND ACRONYMS

GIS	**Geographical Information System**
GPS	**Global Positioning System**
ESA	**European Space Agency**
DEM	**Digital Elevation Model**
TM	**Thematic Mapper**
USLE	**Universal Soil Loss Equation**
SDR	**Sediment Delivery Ratio**
NDVI	**Normalized Difference Vegetation Index**
PAR	**Photosynthetically Active Radiation**
ILWIS	**Integrated Land Water Information System**
STI	**Sediment Transport Index**
SPI	**Stream Power Index**

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DECLARATION

I……………………………. hereby declare to the Registrar of examinations at the University of Zimbabwe that the work contained in this thesis is the result of the author's original work. With the exception of such quotations or references that have been attributed to their authors or sources and that all photographs, sketches, maps, plans, overlays, graphs and pictograms were made or drawn by me except where I have acknowledged that someone else is the author. It is submitted for the Masters degree in Integrated Water Resources Management (IWRM), Department of Civil Engineering in the University of Zimbabwe, Harare. To the best of my knowledge, it has not been submitted before, for any degree or examination in any University.

Date……………………………………..

Name………………………………….... Signed…………………………………………….

DEDICATION

To **Brian. T. Murau:** (26 May 1974 to 16 May 2005).Thank you for your support, leadership and encouragement big brother. You will forever be remembered for all your great deeds Chitova, rest in peace till we meet again. Lamentations 3[v40] *"Let us search and try our ways, and turn again to the Lord."*

CHAPTER ONE: INTRODUCTION

1.1. Introduction

Gully erosion is one of the major problems affecting global agricultural productivity, although the problem of gully erosion is as old as settled agriculture, its extent and impacts on human welfare and the global environment are more now than ever before. A continuation of high gully erosion will eventually lead to a loss in crop production even though fertilizers and other inputs often result in increased yield in the short term. Gully erosion also leads to environmental pollution, as it is the main source of sediment that pollutes rivers and fills reservoirs. Problems caused by gully erosion and sediments include losses of soil productivity, water quality degradation, and less capacity to prevent natural disasters such as flooding of watercourses. Globally, about 1.1 billion hectares of land are affected by gully erosion. In the Zhulube Meso-catchment gully erosion and sediment yields from catchment are key limitations to achieving sustainable land use and maintenance of water quality in streams, dams and other water bodies. Through well-coordinated catchment management, a reduction in the sediment yield and delivery to the stream network and receiving bodies can be achieved.

Gully erosion is geographically a widespread problem (Cooke and Reeves 1976, Lal, 1992) and is the worst stage of soil erosion. It is common in the semi-arid region, characterized by denuded landscape and flash floods. An estimated 1 million hectares of land are affected by severe gully erosion in Zimbabwe. An additional 2 million ha are now susceptible to gully erosion in the semi-arid tropics. In Africa, about 29 million hectares of land are affected by gully erosion. Gully erosion is more difficult and expensive to control than sheet and rill erosion, it is also more spectacular than interrill erosion. Contrary to sheet and rill erosion, the damage done to land by gully erosion is permanent. Gully erosion also causes depreciation in land value by lowering the water table and depleting the available water reserves. Buildings and infrastructures are also undermined by rapidly advancing gullies.

Gully erosion problems have been on the increase in the recent past especially in developing countries such as Zimbabwe, where agriculture is a major economic activity for the indigenous population. An aerial appraisal on detailed analysis of 8500 aerial photographs of the severity of soil erosion in Zimbabwe showed that 18,000 km^2 was severely degraded, of this 15 300 km^2 was in communal Lands, while 2,700 km^2 was in the large-scale commercial farming enterprises (Whitlow, 1986). This illustrated that approximately half of communal land in Zimbabwe could be suffering irreparable gully erosion damage (Dregne, 1990). Land tenure policies that concentrate native Zimbabweans on marginal land are aggravated the erosion problems (Dregne, 1990). Approximately 4090 t/km^2/ year of topsoil are lost forming huge gullies in most of Zimbabwe's communal lands (Brough, 1990).

Some of the problems associated with gully erosion include loss of fertile topsoil, grazing land, dam siltation, eutrophication of surface water bodies and loss of aquatic biodiversity. Management practices to minimize gully erosion problems can be done if the magnitude and spatial distribution of the gullies are known, but practical field methods of determining gully erosion have the shortcoming of requiring a lot of resources apart from micro plot studies under a controlled system (Kirkby and Morgan, 1980).

Gully erosion determination at catchment scale poses a very big challenge since a catchment is normally heterogeneous with different biophysical characteristics, experiencing variable hydrological regimes spatially and temporally, thereby making erosion dynamics more complex. However, through use of erosion models, remote sensing and GIS reasonable estimates of soil erosion can be achieved. This research focuses on a methodology for the assessment of water-induced landform gullies with a hydrologic link to distinguish them from other disturbed land features such as clay pits, new development, and off road recreation. Remote sensing and GIS technologies were used to interpret groundtruthed aerial photography, SPOT and Landsat satellite imagery for potential gully features.

1.2 Problem statement

Continued expansion of gullies in the Zhulube Meso-catchment has contributed to the loss of agricultural land leading to increased siltation levels of the Zhulube dams. What is known about gully erosion in the Meso-catchment is that most rehabilitation methods implemented have not been successful; thus prompting the need to establish the factors associated with gully development. This study may lead to an in-depth understanding of this phenomenon, which can be used as support for decision making in gully rehabilitation exercises at Meso-catchment level.

1.3 General objective

To establish the relationship between gully characteristics, soil characteristics, slope gradient, vegetation types, stream erosive power and sediment loadings at Meso-catchment level.

1.3.1 Specific objective

1. To determine suitability of remote sensing and GIS techniques for gully characterization in a Meso-catchment.
2. To determine the relationship between gully characteristics, soil properties, slope gradient, stream erosive power, sediment loadings and vegetation types in the Zhulube Meso-catchment.
3. To evaluate the implications of the findings to water resources management

1.3.2 Detailed research questions

- Can we significantly characterize gully development using photogrammetric methods in a GIS?
- What is the relationship between slope gradient, soil characteristics, vegetation types and gully development?
- Is there a relationship between the erosive power of streams, their sediment loadings and gully development in the Meso-catchment?

1.4 Hypothesis

Null hypotheses 1 (H_0): Photogrammetric techniques and GIS cannot significantly characterize gully development in the Zhulube Meso-catchment.

Null hypotheses 2 (H_0): There is no relationship between slope gradient, soil characteristics, vegetation types and gully development.

Null hypotheses 3 (H_0): There is no correlation between the erosive power of streams, their sediment loadings and gully development in Zhulube Meso-catchment.

1.5 Study approach

To achieve the specific objectives a set of laid down procedures were followed and these included a desk study, followed by the data collection process, which entailed computer analysis and field data collection. After all the data had been collected they were subjected to statistical analysis to determine the relationships between the different type of data collected, cleaned and validate indicating the accuracy of the inferred results. After running these processes, it was evident that photogrammetric methods in a GIS can be used with a considerable level of accuracy depending on the spatial resolution of the satellite imagery. The results also indicated that there is a strong relationship between slope gradient, soil characteristics and gully development, with a very weak insignificant relationship coming about between gully development and the presence of vegetation. Finally, gully development showed a highly significant relationship with the erosive power of a stream but showing a weak relationship with gully characteristics. The study was conducted in the Zhulube Meso-catchment of the Mzingwane sub-catchment (20° 47′ S, 29° 22′ E), in Southern Zimbabwe, which covers twenty percent of the Matebeleland South and Midlands province the Mzingwane sub-catchment. Soils in the area vary from clays loams in the north to sandy soils in the south with a rugged high ground.

CHAPTER TWO: DESCRIPTION OF THE STUDY AREA.

2.1. Introduction

This chapter gives a description of the study area; it starts by introducing the broader study area at basin level, down to catchment level and then zooms in to the specific study area, which will be the main focus of this chapter.

2.2 Description of study area

This study was conducted in the Zhulube Meso-catchment, which falls within the Mzingwane sub-catchment, in the Limpopo river basin with coordinates of 20° 47′ south and 29° 22′ east. Figure 2.1 shows the geographical location of the Limpopo river basin with respect to other river basin in Southern Africa. The basin is located within four Southern African countries namely, Zimbabwe, Botswana, South Africa and Mozambique. The Mzingwane sub-catchment is part of the seven catchments in Zimbabwe. Four sub-catchments covering 20% of the Matebeleland South and Midlands Provinces were created from the main catchment.

Figure 2.1: Limpopo Basin map showing the location of study area (www.imwi.cgiar.org, 2005)

2.2.1 Specific study area

The study was situated in ward 1 of Insiza district, which is located in the Upper Mzingwane sub-catchment. The Insiza district is one of the six districts in Matebeleland North province and has 18 wards, 11 of which fall within Mzingwane catchment. The research work was conducted in the Zhulube village (Figure 2.2 and Figure 2.3).

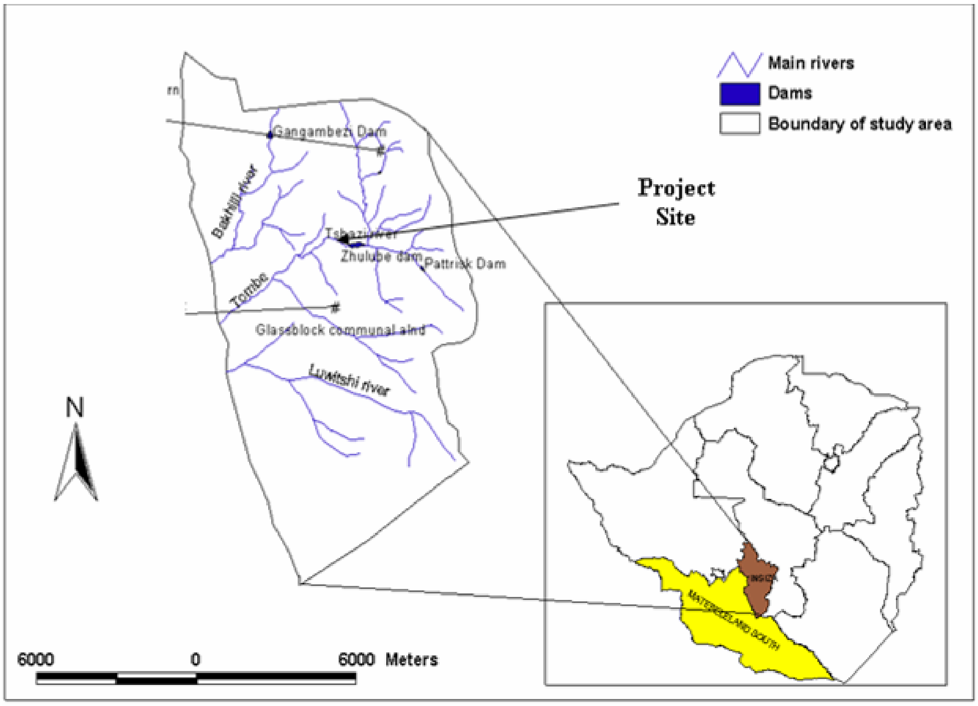


Figure 2.2: Map showing the Zhulube Meso-catchment

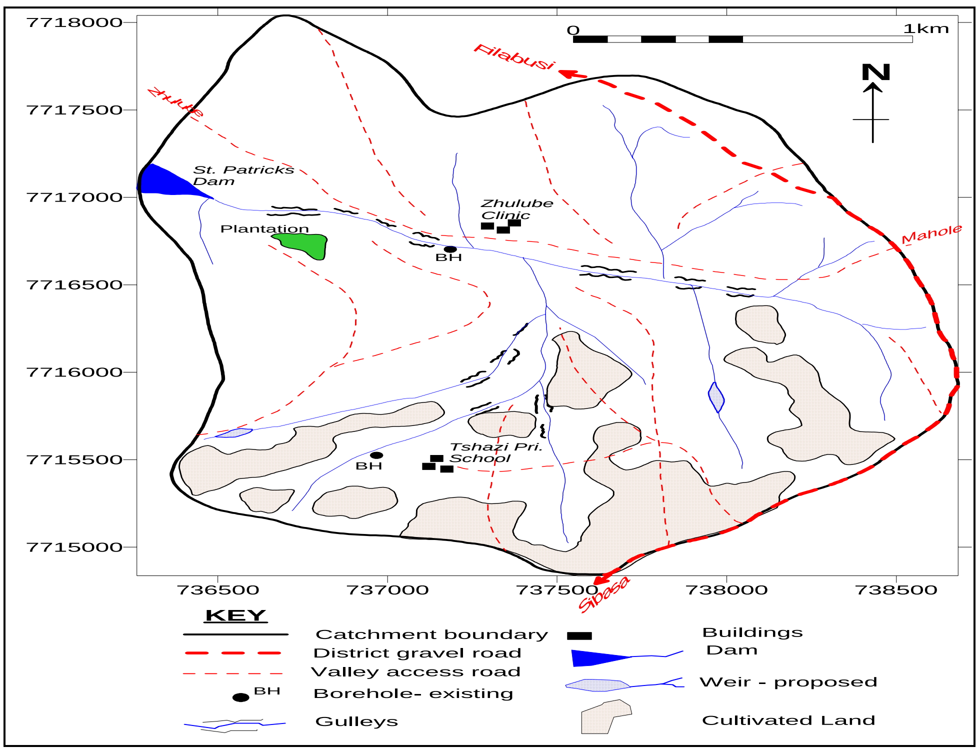


Figure 2.3: Sketch map of the Zhulube Meso-catchment (Filabusi-AREX, 2001)

Gullies are a common feature in the Zhulube Meso-catchment (Figure 2.3). Their formation can be attributed to physical factors and anthropogenic activities such as alluvial mining, poor agricultural practices and intensified grazing pressure in the area. The study area is significantly affected by overgrazing due to overstocking and the concentration of watering points in the area and which can affect water flow in the area during rainy season. A distinct site was the Gobalidanke gully (Figure 2.4 a & b), which shows high level of degradation, was the Gobalidanke gully.

2.3 The Gobalidanke gully

The Gobalidanke gully, which developed in the year 1983, is one of the prominent most gullies within the study area. The area was well vegetated and fenced off during the colonial era (1920 to 1979) when it was in a commercial farm under management of white farmers. Natives were not allowed to utilize the natural resources or graze livestock in the area and common bush vegetation comprising of *cyperus Flabeliformis* (imizi) and *Phragmites Mauritus* (umhlanga) was dominant. After independence (1981 to present), the area was under communal settlement leading to gradual changes in vegetation and soil degradation. Livestock started foraging in the area and anthropogenic activities in the form of alluvial gold mining and digging for fishing worms, which led to slow soil degradation, gully development and loss of vegetation cover. The ground became bare as a result of grazing pressure from livestock, resulting in high runoff collecting in the waterway leading to soil erosion and gully formation as in the case of the Gobalidanke gully (Figure 2.4 (a & b).

(a) (b)

Figure 2.4 (a & b): Pictures showing part of the Gobalidanke gully (a) and a gully at site 5.on the Tshazi river (b)

2.3.1 Description of catchment area

The Zhulube dam has a catchment area of 2000 hectares, characterised by 280 hectares, which are under cultivation taking up 14% of the total catchment area, and the rest of the catchment comprises of grazing and homestead areas.

2.3.2 Drainage

The drainage in the catchment consists of, 4 major streams flowing from the hills from north to south on slopes of between 5% and 7% steep. The Zhulube and Tshazi tributaries flow from the low lying plains in an east to west direction for a distance of about 8.1 km to dam. There are eight major waterways that constitute the drainage of the catchment as illustrated in Figure 2.5.

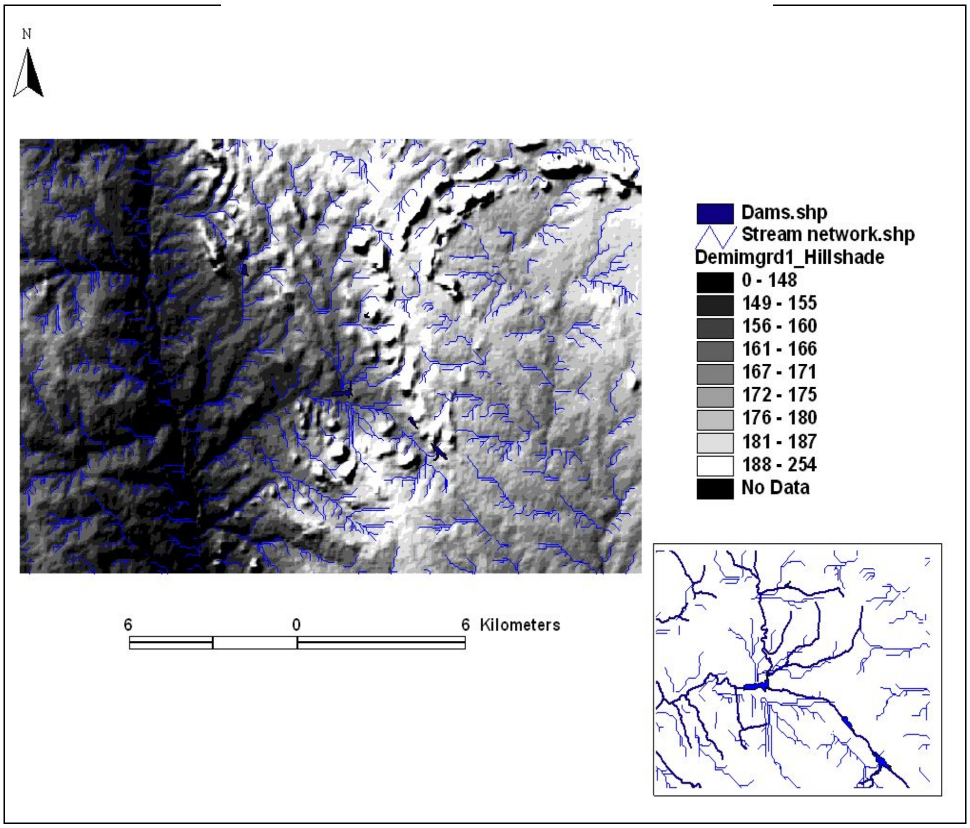


Figure 2.5: Drainage and stream networks in the Zhulube Meso-Catchment.

2.3.3 Soil

The study area soils vary from sands to heavy clays within the Meso-catchment area, with the southern parts of the catchment being dominated by sandy loam soils while the northeast areas close to the Zhulube clinic consist mainly of red soils.

2.3.4 Climate

The climate can be classified as semi-warm, sub-humid, with a summer rainfall regime, occurring in convectional storms of short duration and high intensity. The area has a mean annual rainfall of around 450 mm (Figure 2.6) and a mean annual temperature ranging from about 12^0C to 29^0C (Figure 2.7). The summer temperatures can reach 40° C (Filabusi meteorological station, 2001).

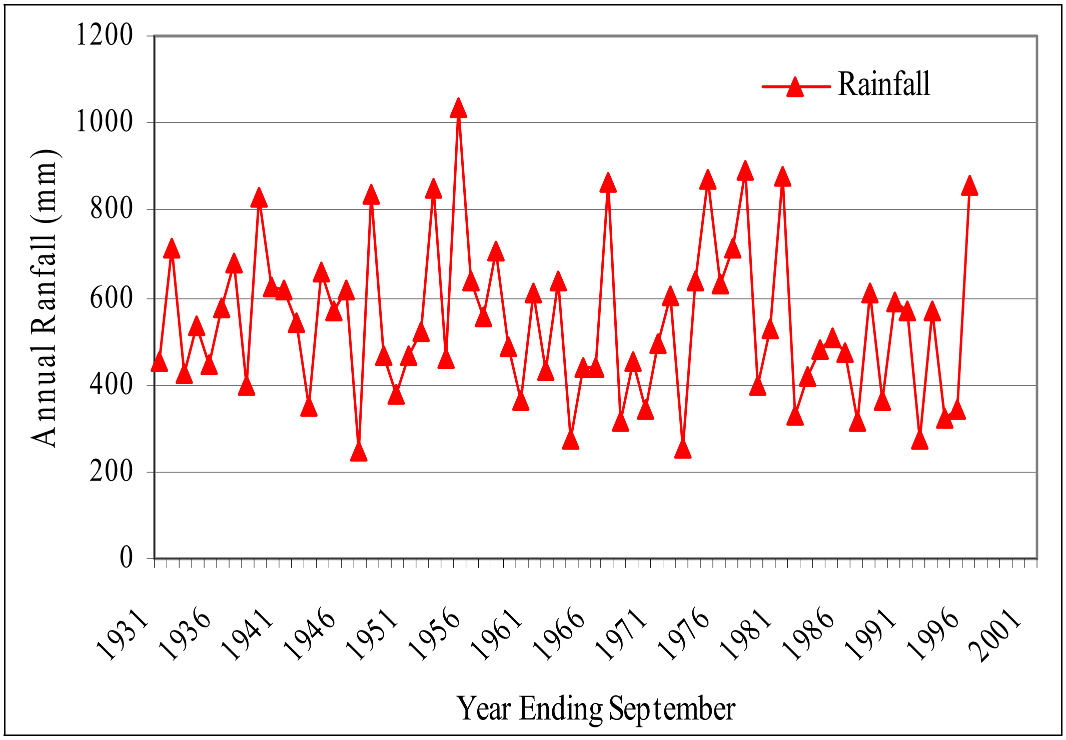


Figure 2.6: Annual Rainfall (Filabusi meteorological station, 2001)

From the data collected by the Filabusi meteorological station, the temperatures are lowest from June to July and highest in October.

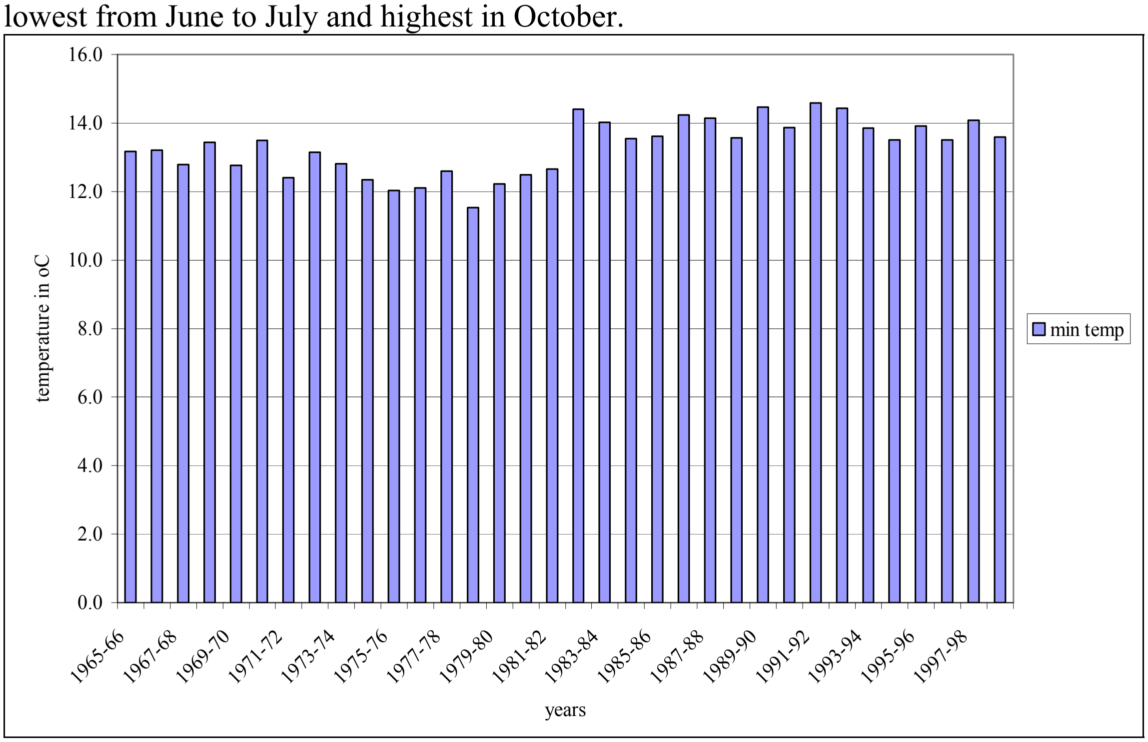


Figure 2.7: Mean temperature of the annual minimum daily temperature (Filabusi meteorological station, 2001)

2.3.5 Runoff

The upper Insiza sub-catchment experiences a higher mean annual runoff than the lower Insiza, mainly due to topographic and rainfall variations. A low mean annual rainfall of about 450 mm/year for both the sub-catchments also greatly affects the runoff coefficients variation, which range from 125 to 130.

2.3.6 Vegetation

The vegetation of the Zhulube Meso-catchment comprises of three classes that is Acacia woodlands, mopane woodlands and mixed woodlands as shown in Figure 2.8. The most abundant tree species in the area is the *Acacia* species and the *Mopane* (*Colophospermum mopane),* which become dominant in heavier soils. The grasses consist of both perennial and annual species with the proportions being a function of rainfall, wetter years have, increases in perennials as well as grazing pressure. Production of grass can vary tenfold from one year to the next in response to rainfall variability, the bulk of grass biomass coming from perennials. A limited proportion of the area consists of arable lands or fallow areas in various stages of recovery, with various parts of the study area especially on dryland, maize cropping persists because the subsistence farmers concerned about few other options (Walker *et al.,* 1981).

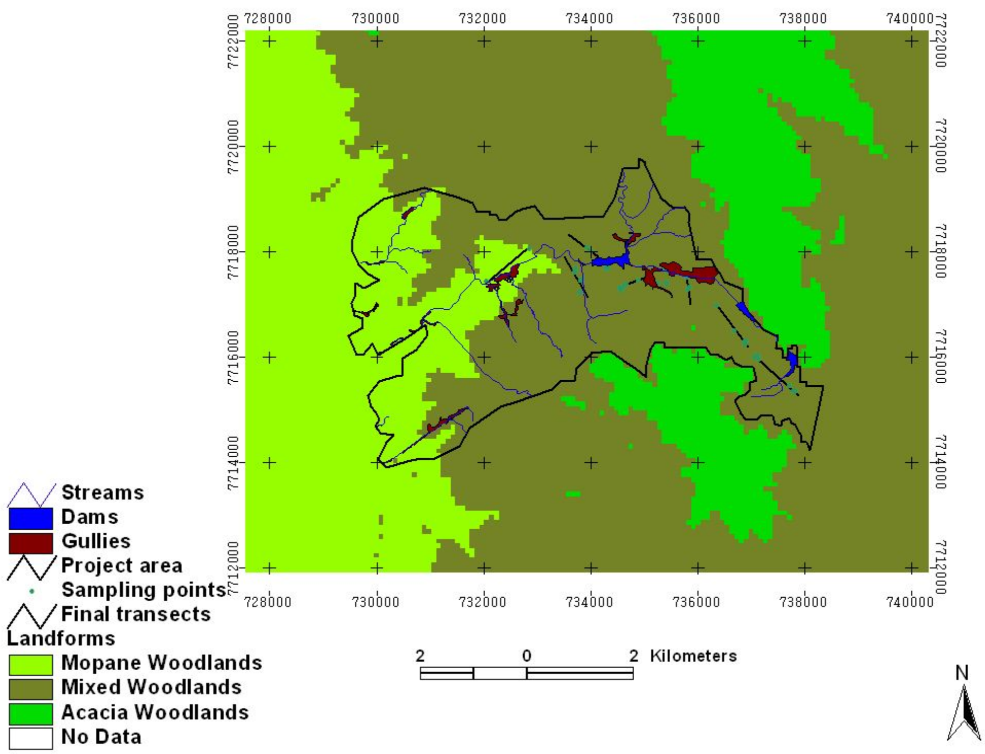


Figure 2.8: Vegetation classification in sampling area

2.4 Land use

Land use in the Meso-catchment is mainly a mixture of croplands, rangeland and woodland (Hearn *et al.*, 2001). Cropping includes commercial farming in the north, often under irrigation, and smallholder farming in the south. Irrigation in the south includes schemes managed by farmer committees, and household vegetable gardens using mostly drip kits (Maisiri *et al*., 2005 and Chigerwe *et al*., 2004).

2.5 Population

Table 2.1 summarizes the population data of ward 1 in Insiza. These population censuses were conducted in the years 1961/1962, 1969, 1982 and 2002; Table 2.1 below shows only the 2002 population.

Table 2.1: Population data for 2002 of Insiza (Veterinary office, Filabusi, 2002).

Location	Total Population	Population density (persons/km^2)	Total Households (Households)	Average household size (people)
Zhulube	768	30.4	96	8

2.6 Livestock

Table 2.2 shows the livestock quarterly statistics of Zhulube in relation to the Stocking Rates.

Table 2.2: Livestock data of Insiza ward 1 March 2006 (Filabusi Vet. Office, 2006).

Location	Grazing area (ha)	Number of Cattle	Number of Goats	Number of Sheep	Number of Donkeys	Total Livestock Units (LU)	Stocking rate Ha/LU
Zhulube	2000	408	425	20	92	362.3	5.5

Where an LU is an equivalent of 400kg live mass of an animal.

2.6.1 Effects of livestock grazing

The impacts of grazing on rangeland hydrology are the effects of livestock on parameters, which determine infiltration rate. These include the depletion of soil nutrients, resulting in low plant production, decreased plant cover due to heavy grazing; this result in acceleration of soil loss. (Pieper, 1994). The greatest nutrient losses result from alteration of plant community structure that influences overland flow, erosion, infiltration rates and nutrient turnover rates (Miller *et al.,* 1994).

CHAPTER THREE: LITERATURE REVIEW

3.1. Introduction

Gullies are "relatively permanent steep sided water courses that experience ephemeral flows during rainstorm" (Morgan, 1995). The size of the gullies varies from shallow 0.3 - 1 meter deep gullies to over 20 meter deep ravine gullies (Bergsma, 1996). Gullies normally have a distinctive propagating head, which is the morphological expression between stable and unstable gully regimes (Rebeiro-Hargrave, 2000) and where overland flow from the catchment above enters the gully. The most important processes of gully propagation are concentration and the incision of overland flow, gully wall collapse and piping (Morgan, 1995). Nevertheless, soil erosion studies in the past have mainly concentrated on sheet and rill erosion, since both forms of erosion can be studied through standard soil erosion plots (Poesen *et al*., 2003). The recent developments in both GIS techniques (Martínez-Casanovas, 2003) and photogrammetric techniques (Daba *et al*., 2003) have introduced new methodologies for gully erosion studies.

A complex interplay exists between anthropogenic and climatic variables, which induce spatial, and temporal variations in gully erosion distribution have been documented variously (Watson, 1996; Ferreira, 1997; Nachtergaele and Poesen, 1997). In particular, Faulkner (1995) and Harden (1997) identified the propensity of abandoned cultivated fields to high runoff and soil erosion. This is true especially in those areas where a combination of drought conditions and degraded soils tends to inhibit revegetation in wetter periods, rendering the areas highly vulnerable to extreme runoff generation and severe erosion. This should, however be evident in the context of soil and land management conditions in a given area.

In their study of abandoned agricultural terraces in Mediterranean Spain, Ruecker *et al.,* (1998) noted that protective vegetation cover was reestablished between 10 and 20 years after abandonment. They attributed this to the lower soil erodibility and the positive effect of agricultural terraces on vegetation succession. Similarly, Francis (1990) observed the regeneration of vegetation after field abandonment in central Spain, which she ascribed to local soil type and soil surface conditions at the time of abandonment. In the present study, given the high erodibility of the soils (Fox and Rowntree, 2001) and the absence of appropriate management mechanisms, the soil eroded faster than the vegetation cover could reestablish itself.

Finally, all the information collected will be applied in the development of methodologies for gully erosion hazard assessments. Both multivariate statistical techniques (Guzzetti *et al*., 1999; Luoto *et al*., 2001; Martinez-Casasnovas *et al*., 2003) and the "critical slope" concept (Kirkby *et al*., 2003; Morgan & Mngomezulu, 2003; Moyersons, 2003) will be applied in the assessments (Pellikka *et al*., 2004).

3.1.1. Definition of gully erosion

The Soil Conservation Society of America (SCSA) defines a gully as "a channel or miniature valley cut by concentrated runoff but through which water commonly flows only during and immediately after heavy rains; it may be dendritic or branching or it may be linear, rather long, narrow, and of uniform width" (SCSA 1982). Nevertheless gully erosion produces channels larger than rills, which carry water during and immediately after rain events and can be distinguished from rills, as gullies cannot be obliterated by normal tillage (Schwab *et al*. 1981). Thus, gully erosion is an advanced stage of rill erosion as much as rill erosion is an advanced stage of sheet erosion. It is often difficult to differentiate between large gullies and small river valleys. Gullies have intermittent storm water flows of shorter duration compared to rivers with seasonal flows. Gullies, contrary to river valleys, are cut out rapidly and are generally restricted to easily erodible soils.

3.1.2. Causes of gully erosion

Most of the gullies are formed due to a combination of hydrological and anthropogenic activities (SCSA 1982). Some of the major causes of gully formation are overgrazing due to high stocking rates, expansion of cultivation in steeper or marginal land, cultivation without taking care of surplus runoff water, deforestation due to clearing of vegetation, unsatisfactory waterways and improper design of culverts and other structures. Generally, a gully is caused by a rapid expansion of the surface drainage system in an unstable landscape (SCSA 1982). Gully development is influenced by several factors; some factors determine the potential hazard while others determine the intensity and rate of gully advance. Factors affecting gully development can be categorized into two groups: man-made factors (Improper land use, overgrazing, improper land development, road construction and livestock and vehicle trails) and physical factors (rainfall, topography, soil characteristics, profile characteristics and vegetative cover) (SCSA, 1982).

3.2. Classification of gullies

Several methods can be used for gully classification based on their different characteristics like size, drainage and discharge rate (FAO, 1977). Table 3.1 describes the gully classification criteria based on size classes (small, medium and large gullies), which is commonly used in manuals on erosion.

Table 3.1: Gully classes based on size (Frevert *et al*., 1955).

Gully classes	Gully depth (m)	Gully drainage area (ha)
Small gully	Less than 1	Less than 2
Medium Gully	1 to 5	2 to 20
Large gully	More than 5	More than 20

3.3. Gully classification based on shape

This classifies gullies according to the shape of their cross-sections (Figure 3.1).

- U-Shaped gullies are formed where both the topsoil and subsoil have the same resistance against erosion, because the subsoil is eroded as easily as the topsoil, nearly vertical walls are developed on each side of the gully.

- V-Shaped gullies develop where the subsoil has more resistance than topsoil against erosion; this is the most common gully form.
- Trapezoidal gullies can be formed where the gully bottom is made of more resistant material than the topsoil.

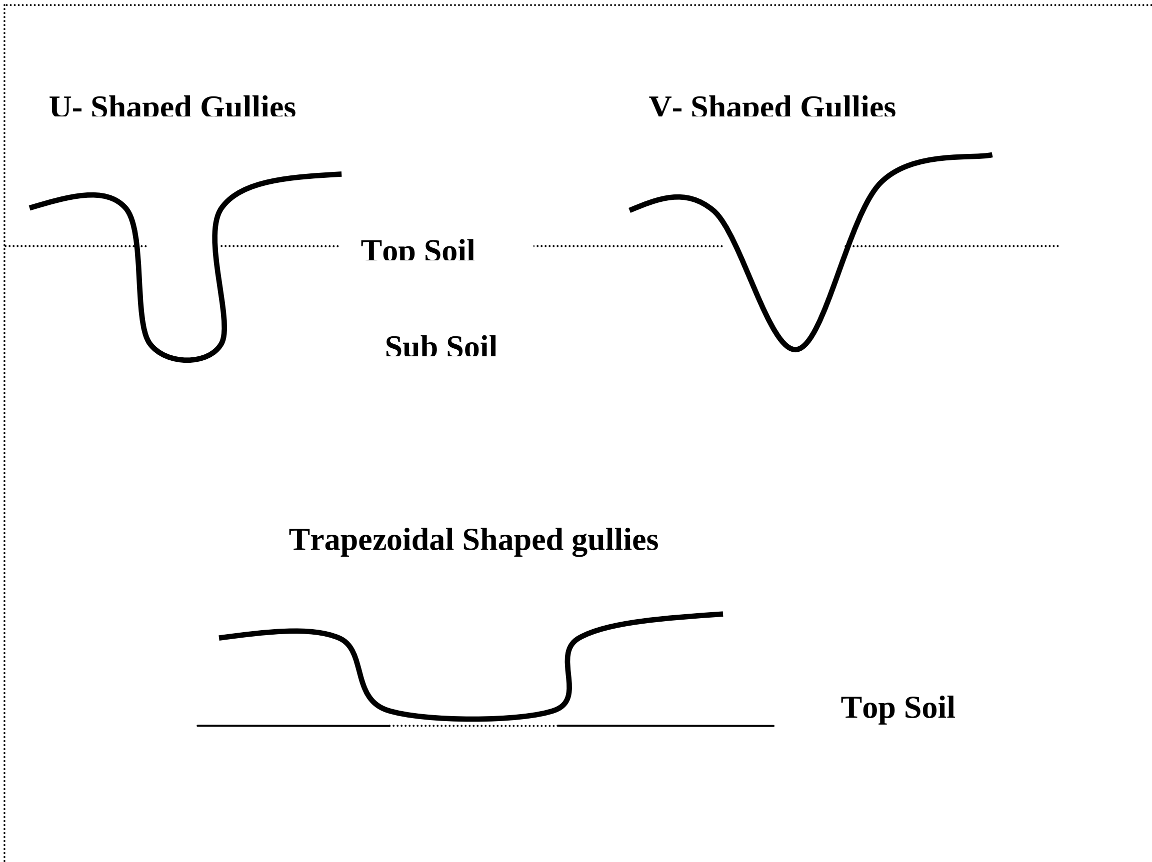


Figure 3.1: Gully classes based on shape of gully cross-section (Weidelt, 1976)

3.4 Land use and cover change

Land cover refers to the physical and biological cover over the surface of land, including water, vegetation, bare soil, and artificial structures (Van der Merwe *et al*. 2000). Natural scientists define land use in terms of syndromes of human activities such as agriculture, forestry, and building construction that alter land surface processes including biogeochemistry, hydrology, and biodiversity. Land use types (Table 3.2) were described for Southern Africa by Hoffman *et al*., (1999) as well as changes in land use type over the decade 1987 to 1997.

Table 3.2: Land Use Types (LUT) after Hoffman *et al*., 1999

Land use type	Definition
Cropland	Land used for the cultivation of crops, including fallow land (less than 10 years old; land use for annual field cropping), perennial field cropping; tree and shrub cropping.
Grazing land or veld	Land used for animal production on natural and includes planted pastures used for grazing. It also includes commercial wildlife ventures owned by individuals or farmer consortiums.
Commercial forest	Land used mainly for commercial wood production and in some cases, protection
Conservation area or state land	Declared national, provincial, and municipal conservation areas as well as state land.
Settlement	Includes both rural settlements and urban areas, roads and construction sites
Other	Predominantly mining areas and lakes or dams

Zimbabwe is in a transitional phase of land redistribution and land reform, with a developing country's population growth rate. A change in land use and land use intensity is a mixture of market forces, agro-economic considerations, and changing farm livelihood systems (Whitlow, 1988). What is important, however, is the field being gained by conservation farming systems notably within communal settlements; the expansion of rain fed crop production on high potential soils. In addition, the conversion of marginal cropland to pastures, all conducive to the sustainability of the natural resource base and low input food production.

3.5 Effects of changes in land use

Changes in land use and land cover date to prehistoric times and are a direct and indirect consequence of human actions to secure essential resources (Weidelt, 1976). This may first have occurred with the burning of areas to enhance the availability of wild game and accelerated dramatically with the birth of agriculture. More recently, industrialization has encouraged urbanization and the depopulation of rural areas, accompanied by the intensification of agriculture in the most productive lands and the abandonment of marginal lands. All of these causes and their consequences are observable simultaneously around the world today.

3.6 Effects of land use on rangeland hydrology

In recent years, physically based, distributed models as well as conceptual models have been frequently used to address the influence of land-use change and land use management on hydrology. Many studies have shown that hydrological models addressing the issue of land-use change need to be process based (Gutknecht, 1996) in order to address the effect of land-use change on runoff generation. In addition, the models need to consider the explicit spatial distribution of land use change and management in the catchment. Bronstert *et al.,* (2002) discusses the present knowledge and modeling capabilities to simulate the effect of land-use change on runoff generation.

However, independent of the chosen approach, data availability for calibration and validation still seem to hamper further progress in using hydrological models to predict the impact of land-use change and management and use the hydrological model for sustainable catchment management. The time series of discharge at the outlet of a catchment is still the most important data to calibrate and validate a hydrological model. Multi-response validation has been proposed as an option to increase the probability that the hydrological model correctly represents the processes in the catchment (Mroczkowski *et al.*, 1997) by including additional hydrological information like groundwater level and soil moisture.

3.7 Relationship between sedimentation and gully erosion

The ultimate destiny of all reservoirs is to be filled up with sediments (Sherry, 1959), the question that arises is how long will it take? In addition, as the sediments accumulate with time, will this adversely affect the water control goals within the catchment? Soil erosion is the first step in the sedimentation processes, which consist of erosion, transportation and deposition of sediment (Lal, 1990). A fraction of eroded soil passes through channel system and contributes to sediment yield while some of them deposit in water channels (Schwab, 1993).

The stream power is a measure of the rate of work done (Js^{-1}) by the stream in overcoming the resistance exerted on the flow by the bed and the fluid itself, and in transporting sediment. It should therefore serve as an index of the stream's ability to transport sediment. Since it is possible to make a separate calculation of the rate of work done in transporting sediments, it is possible to calculate the efficiency of the stream as a sediment-transporting agent.

3.7.1 Stream Power Index

The Stream Power Index:
W = As / tanB-- **Equation 1**
This is directly proportional to the stream power:
P = pgq tanB-- **Equation 2**

Were:
- **p** = density of water, **g** = acceleration due to gravity and **q** = overland flow discharge per unit width.

This is an indicator of erosive power of overland flow.

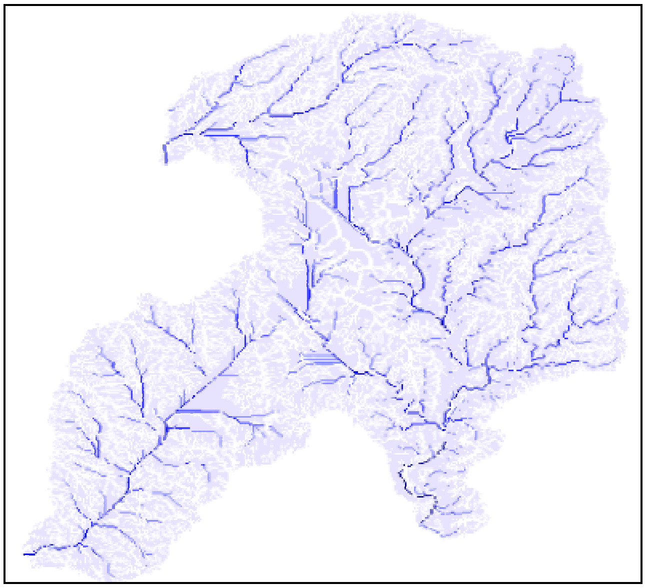


Figure 3.2 Stream power index (Minnesota GIS/LIS Consortium, 2001)

3.7.2 The Sediment Transport Index

The Sediment Transport Index:

T = [As / 22.13] ^0.6 * [sinB / 0.0896] ^1.3--------------------------------------- Equation 3

This index characterises the process of erosion and deposition, presents the effects of topography on soil loss and can vary along the length of a stream.

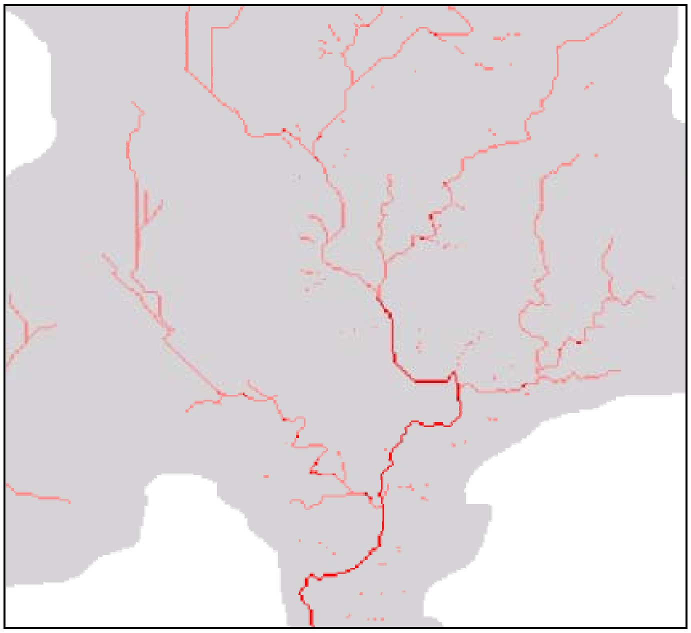


Figure 3.3: Sediment Transport Index (Minnesota GIS/LIS Consortium, 2001)

3.8 Applications of remote sensing in land cover detection

Satellite and airborne remote sensing techniques have become the most effective tool for the analysis of earth features. Remote sensing data has been used to solve complex environmental problems, investigate the impacts for global climate change, identify archeological sites, and solve geopolitical-political problems (Lillesand & Kiefer, 1994). However, spectrally based degradation assessment techniques are often of limited repeatability and do not operate well in semi-arid to arid environments (Pickup & Chewings, 1988; Ray, 1995). Many resources vary in space and time, and sampling these variations is difficult (Lyon *et al*., 1992). Remote sensing affords the user the opportunity to sample multiple dates and extrapolate point measurements collected in the field over large spatial scales (Lyon and McCarthy, 1995, Vincent, 1997).

There have been many uses of remote sensing to inventory and assess rangelands (Tueller, 1992). Change detection techniques similarly are often not viable without complex correction procedures, because factors such as background soil noise and changing moisture status can distort results (Guyot & Gu, 1994). Landsat TM imagery has been used to estimate rangeland plant productivity, and monitor change (Haas, 1992). The use of remote sensing data as input to an ecological model is important for rangeland assessment and monitoring. Landscape ecological models require spatially intensive data (Lobo *et al.,* 1998) and remote sensing provides this information, often at the fine spatial resolution and large extents needed for most landscape studies (Frohn, 1997).

Recent spectroscopic studies have shown that organic matter, soils types, grain size, soil moisture, and other parameters indicative of erosion and soil conditions can be determined from spectral data. The full reflective spectrum has in some instances been used to predict soil organic matter and other mineralogical and chemical soil properties based on multivariate statistics. Multivariate analyses of spectral data have been used as well to assess soil degradation, and soils swell potential. Tueller, (1973) explores the relationships between soil reflectance and surface moisture. Jensen *et al.,* (1997) proposed a successful method to retrieve organic carbon in xenomorphic soils, which highlights areas of accumulation and relative stability (sediment sinks).

Methodologies such as the spectral mixture analysis, also known as spectral unmixing, have been used to estimate the relative amounts of rock fragments and soil particles on the earth's surface. Since soil erosion leads to an increase in rock cover in source areas and the accumulation of soil material as colluviums elsewhere, rock content can be used as an indicator of degradation. Spectral unmixing of reflectance signatures has permitted the successful identification and spatial differentiation of soil substrates and biological crusts in sandy arid ecosystems. The spectral information used here not only depends on characteristic well-known spectral features at definite wavelengths, but on the detailed analysis of the albedo and shape of the full reflective spectrum in the (Visible Near Infra Red (VNIR) and Short Wave Infra Red (SWIR).

All remote sensing analysis follows a given order, which includes:

- Georeferencing
- Creation of Digital elevation models if using aerial photographs

- Orthorectification if using aerial photographs

These processes are explained in greater detail below.

3.9 Georeferencing

The purpose of georeferencing in this project is to incorporate geographically unregistered data in the form of aerial photography to a basemap with a known coordinate system. The resolution quality of aerial photography far exceeds that of other surface imagery such as Landsat satellite data, making it an invaluable tool for mapping gullies. Subtle surface features such as small-rills and gullies do not appear on Landsat images and are often difficult to detect in the field, but are readily visible in aerial photos. These features could easily be digitized into separate layers. However, aerial photos are not orientated in the compass directions, with no spatial reference information, and scale. Georeferencing address these problems, allowing alignment of geographically unregistered data to data that exists in geographical coordinates (Lillesand & Kiefer, 1994).

Aerial photos can easily be added to an existing data frame of any GIS, but because they contain no geographical registration information, they are assigned arbitrary coordinates. The question, then, is how to correctly align the air photos with the other layers in the data frame. This can be done using the Georeferencing tools. These tools allow the user to rotate, translate, scale, and even deform the aerial photos so that they match the existing map coordinate system. The user manually makes links between features that are visible in both the aerial photo and the existing map. Examples of possible common features are the corner of a building, the confluence of two streams, or the intersection of two roads. Making an accurate alignment is directly related to the user's ability to pinpoint these features- any error in doing so will result in a poor alignment. Of course, this method will only work if there are features common to both the aerial photo and the existing map (Tueller, 1973).

3.10 Digital Elevation Models (DEM)

For the Orthorectification of satellite images, aerial photographs and for the visualization of terrain conditions in three Dimensions (3D) a Digital Elevation Model (DEM) was generated from a variety of resources, figure 10 show the DEM generation process. In addition to the Orthorectification of remote sensed images, the DEMs are also utilized in support of the pre-planning and layout of transects surveys and gully sites. There is a variety of DEM source data available for developed areas and the suitability of this available data depends on the project specifications. In remote regions around the world, were little or no source data is available, the DEM can be produced by automatic DEM extraction from stereo satellite scenes. The DEM can also be provided from stereo digital aerial photography at various resolutions, depending on the quality and scale of the aerial photography. When cloud cover is affecting the quality of the images, the DEM is extracted from existing topographic maps or acquired by other remote sensing techniques like; radar interferometry. Final DEM data is provided in a variety of digital GIS and mapping formats, for utilization in GIS programs like ArcGIS (Jensen *et al.,* 1997).

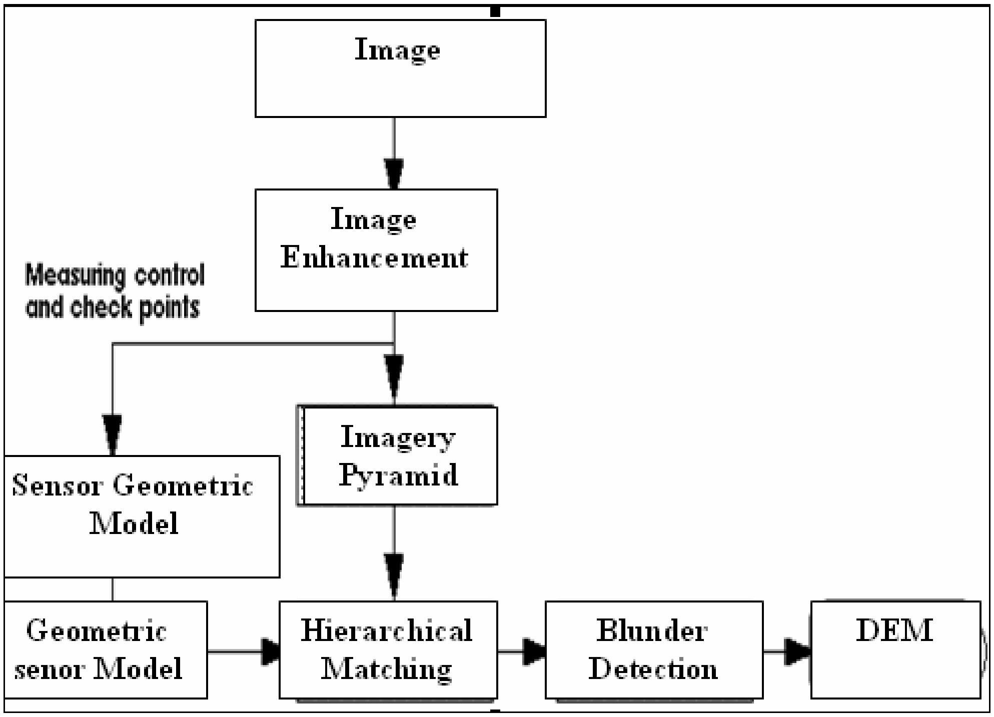


Figure 3.4: Creation of DEM

3.11 Orthorectification

Orthorectification is the process by which photographic distortions characteristic of aerial photographs (such as topography and perspective, flight direction, camera model, etc.), are systematically corrected producing images that are spatially accurate. Processed aerial photographs can provide highly accurate reference and planning data. For many projects, there is a value in the ability of a photograph to convey detailed and precise information about a particular site that is simply not available from maps or satellite imagery alone. Aerial photos were selected for the purpose of this study because of their ability to convey accurate and diverse information about the actual characteristics of a site. Special types of images such as satellite and aerial Orthophoto and others can be particularly useful for performing various types of Land cover or vegetation analysis (Ikonos, 2007).

This is achieved by carrying out processes 1 to 5 as shown in Figure 3.5 in a GIS on data acquired by satellite and airborne image sensors. These processes can correct for terrain distortions when the image sensor is not pointing directly at the Nadir location of the sensor. Low elevation angles of aerial photographs or images, imperfect terrain models, and variability of sensor azimuth and elevation angles within an image limit accuracy potential if aerial photo or image orthorectification is attempted. For this reason, when new high resolution aerial photography or satellite image data are acquired over rough terrain, high elevation angles of the sensor are required (Ikonos, 2007). Figure 3.5 shows the Orthorectification process of a remotely sensed image.

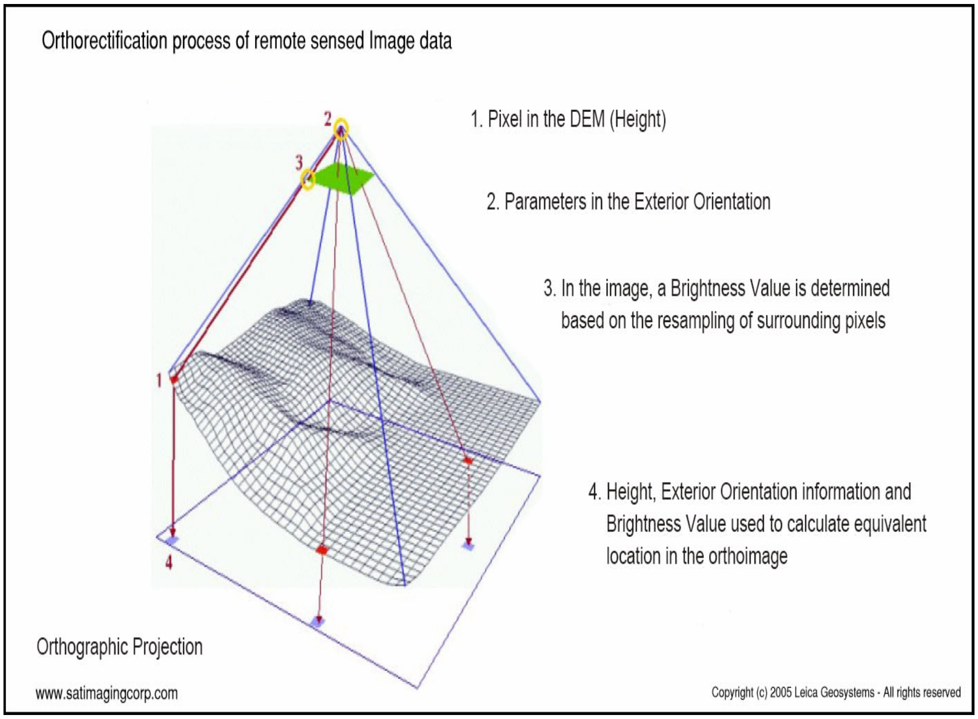


Figure 3.5: Orthorectification process (Ikonos, 2007)

3.12 NDVI applications in arid and semi-arid environment

The TM instrument on Landsat-5 and the ETM+ instrument on Landsat-7 observe the Earth with 7 different filters or "bands". Bands 1, 2, 3, 4, 5, and 7 on both instruments are sensitive to light energy from the sun reflected by the surface of the Earth. Each band is sensitive to a different part of the reflected solar energy. The length of the light waves defines the parts of the reflected energy. Thus, band 1 of the TM and ETM+ instruments record reflected light energy only in the range of 0.45 microns (μm - a micron is one millionth of a meter long) to 0.52 μm. The human eye sees reflected light in that band of wavelengths as the color blue; hence, band 1 is sometimes referred to as the *blue band*. In a similar manner, bands 2 and 3 of the TM and ETM+ instruments record reflected green and red light, respectively (Brooks, 1998).

The LANDSAT TM derived Normalized Difference Vegetation Index (NDVI) offers immense potential to study dryland ecosystems. Its relation with vegetation and rainfall in arid and semi-arid regions is both sensitive and complex. The physical basis of this relation is vegetation, mainly grown due to soil moisture availability as the result of the seasonal rainfall, which intercepts photosynthetically active radiation (PAR) and hence directly influences the aggregate of NDVI (Srivastava *et al.,* 1997, Potdar *et al*., 1993, Potter and Brooks, 1998). Landsat TM NDVI has been successfully used to study dryland ecosystem in Africa (Eklundh, 1998). However, it is still controversial (Leprieur *et al*. 1996).

To determine the density of green on a patch of land, researchers must observe the distinct colors (wavelengths) of visible and near-infrared sunlight reflected by the plants.

As can be seen through a prism, many different wavelengths make up the spectrum of sunlight. When sunlight strikes objects, certain wavelengths of this spectrum are absorbed and other wavelengths are reflected. The pigment in plant leaves, chlorophyll, strongly absorbs visible light (0.4 to 0.7 µm) for use in photosynthesis. The cell structure of the leaves, on the other hand, strongly reflects near infrared light (0.7 to 1.1 µm). The more leaves a plant has, the more these wavelengths of light are affected, respectively. With Landsat TM detectors, researchers can measure the intensity of light coming off the Earth in visible and near-infrared wavelengths and quantify the photosynthetic capacity of the vegetation in a given pixel (Landsat TM pixels are 30 x 30 meters) of land surface (Potter and Brooks, 1998).

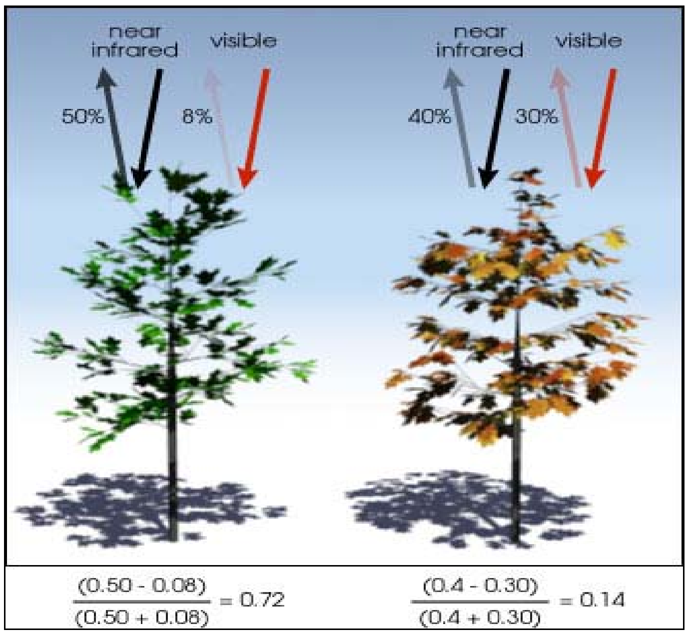


Figure 3.6: NDVI creation (Robert Simmon, 2001).

As depicted in figure. 3.6, NDVIs are calculated from the visible and near-infrared light reflected by vegetation. Healthy vegetation (left) absorbs most of the visible light that hits it, and reflects a large portion of the near infrared light. Unhealthy or sparse vegetation (right) reflects more visible light and less near infrared light. The numbers on figure 8 are representative of actual values, but real vegetation is much more varied. Nearly all satellite Vegetation Indices employs this difference formula to quantify the density of plant growth on the Earth: near-infrared radiation minus visible radiation divided by near-infrared radiation plus visible radiation. The result of this formula is called the Normalized Difference Vegetation Index (NDVI). Written mathematically, the formula is

NDVI = (NIR — VIS)/ (NIR + VIS) ------------------Equation 4 (Robert Simmon, 2001)

Were: NDVI is the Normalized Difference Vegetation Index

NIR is Near Infra Red

VIS is the Visible

Calculations of NDVI for a given pixel always result in a number that ranges from minus one (-1) to plus one (+1); however, no green leaves gives a value close to zero. A zero means no vegetation and close to +1 (0.8 - 0.9) indicates the highest possible density of green leaves (Lillesand & Kiefer, 1994).

3.13 Data cleaning and quality control

Little is known about data that is not collected by the user, information on how it was collected, what sources where employed, the relative quality of information elements and what type of quality control existed during the collection process are rarely noted. As spatial data is so widely used some measure of data quality is required to safeguard both the producer and the user of the geographic information. Spatial data that is captured can only be as good as the source maps from which it was captured.

Another significant issue to consider is that of precision, this is a term used in computing that often refers to the number of decimal places or significant digits in a measurement. Precision is not, however, the same as accuracy. It measures the exactness with which a value was expressed, whether the value is right or wrong. A large number of significant digits, therefore, do not necessarily indicate that the measurement is accurate. It is important to realize that a GIS may work at high precision, mostly much higher than the accuracy of the data itself.

Some data, can be time sensitive, for example, agricultural lands and production this affects the determination of land cover at a specific time, thus the need to consider data updates and or revisions. Changes may be made on a daily, monthly or periodic basis. Very few data structures can accommodate any reference to information revision, in addition, data sets may be collected at different times (Evans, 1972).

3.14 Sampling transect selection

Using GIS software packages it is possible to lay transects based on biological methods in an area before going to the research site. These sampling tools were developed to assist biologists in using GIS software packages to generate spatially explicit random or systematic sampling schemes to support resource monitoring, mapping, and research needs. In most cases the tools work either with polygons in themes or with graphics added to a spatially displayed view. Most of these tools also give the user an option to Sample entirely within a single polygon or shape, or distributed among several disjoint polygons or shapes. A number of user defined constraints and settings are usually available depending on the software being used (Loesch, 2005).

3.15 Soil Samples

To ascertain the effects of soil characteristics on gully development, soil samples are collected and analysed for chemical and physical properties and their reaction to rainfall and runoff. Soil sampling is a particularly difficult task when attempting to get a representative sample. Normally a 500-gram sample has to be submitted for laboratory analysis; this 500-gram sample may represent 2.5 hectares or more. If the area covered by the sample is not uniform, the chemical analysis may not accurately reflect the nutrient status of specific sites.

Factors that were considered when sampling soil include the depth and time of sampling. The current crop, past cropping, depth of ploughing and also the nutrient of interest affect proper sampling depth. Subsoil samples are important for most crops. Standard sampling times should be used due to the difficulty in comparing samples taken at different times. The fertility level of a field varied over the course of the year and interpreting results for samples taken at different times of the year would be very difficult.

Chemical analysis of soil samples from sodic patches that is soils with an abnormally high concentration of exchangeable sodium and have the capability of adversely affecting soil stability, plant growth and land use (Charman & Murphy, 2000). The geological parent material is rich in sodium containing minerals are a common occurrence in Zimbabwe and are often severely eroded as in the Meso-catchment (Thompson, 1965). Deflocculated characteristics of clay soils makes it mechanically unstable and is responsible for widespread sheet and gully erosion thus making clay dominated areas prone to gully erosion. This affects plant growth on clay and sodic soils mainly resulting in stunted pant growth and reduction in vegetation cover (Charman & Murphy, 2000). Bulk density is important for determination of effects of compaction by livestock and anthropogenic activities on soil properties, the bulk density calculation were done using equation 5.

$$\frac{\text{Mass of dry soil (g)} - \text{Mass of Rocks (g)}}{\text{Volume of dry soil (mL)} - \text{Volume of Rocks (mL)}} = \text{Bulk Density (g/mL or g/cm}^2\text{)}$$

....Equation 5

3.15 Chemical and physical Analysis

To determine the effects of soil chemicals on gully development a chemical analysis of the Meso-catchment's soils necessary to ascertain chemical and physical properties of the Meso-catchment soils. When the adsorption of sodium on the surface of clays exceeds 6% of the total CEC, the soil is sodic and subject to serious structural degradation (Rengasamy & Olsson, 1993). In simple terms, the inorganic (clay) and organic colloids in the soil (particles less than 2 µm) have a net negative charge on their surfaces and these negative charges attract positively charged ions (cations) from the soil solution in order to attain electrical neutrality.

The major cations in the soil are Ca^{2+}, Mg^{2+}, Na^{+}, $K^{+,}$ $H^{+,}$ and Al^{3+}, each of which can bond to the negatively charged sites to reduce electronegativity. Sodium is not as effective as other cations in neutralising the charge on the colloid, thus individual colloids continue to repel each other and stay in solution (Brady, 1990). The total negative charges on the soil are called the cation exchange capacity. The surfaces of clay particles in sodic soils typically exhibit a net negative charge, which was neutralized by a distribution of ions characterized by an increase in the cation concentration with increasing proximity to the surface and an opposing trend for anions (Rengasamy and Sumner, 1998).

3.16 Effects of livestock grazing

The impacts of livestock grazing on rangelands are varied and complicated; some effects are long lasting while others are temporary. Some livestock grazing effects are applicable to different spatial and temporal scales. Since several impacts often occur concurrently and that overall effects may be synergistic rather than additive, ecological impacts from livestock grazing are difficult to study or analyze with traditional reductionism methodologies (Noss and Cooperrider, 1994). Livestock grazing may simultaneously reduce plant cover, alter plant species composition, increase soil erosion, and decrease infiltration. The collective impact of all these processes may be far more severe than any impact in isolation (Noss and Cooperrider, 1994).

Grazing by livestock affects the hydrological status of the catchment through removal of plant cover, changing the composition of vegetation and trampling disturbances. As the cultivated areas have extended so, grazing lands have retracted more and more animals have had to be supported on less and less land (Miller *et al*., 1994). In addition, cropping has normally taken over the more productive areas leaving the marginal terrain for livestock. In addition, grazing lands seem to be overlooked and treated as 'common lands'. Implying that they are exploited by everyone and cared for by no one. They are typically overstocked and mismanaged (Pieper, 1994).

3.17 Conclusions

From this chapter it is evident that most developing countries, acknowledge the importance of gully erosion in reduction of water storage capacity of reservoirs but little research has been directed to quantifying and modeling the effects of this phenomenon. From the review of literature, it is also evident that a lot of factors some of which, mankind does not have control over, affect gully erosion but to effectively combat this misnomer there is need to maximize efforts on the reduction of man-induced effects. Literature also indicates that there are vast opportunities for applying technologies like GIS and remote sensing in detecting and characterizing areas that are susceptible or already affected by gully erosion, through loss of topsoil and siltation, thus aiding in decision-making. From the reviewed literature, there is evidence of greater possibilities of applying GIS and remote sensing technologies in assessment and monitoring of soil degradation especial if erosion induced.

In most case, gully erosion occurs covering large spatial extends, with a link to the rainfall and runoff patterns, making it difficult to monitor at a large scale. Thus making GIS and remote sensing data, which can cover large spatial and temporal scales important by reducing costs and time of implementation of such projects. This study contributes to the existing body of knowledge on the assessment and monitoring of erosion in arid to semi arid savannas, by showing how effective new technologies are in decision making and support. Another notable contribution is that this study lays down a guideline on possible methods of assessing gully erosion and its contribution to siltation of reservoirs in the Mzingwane sub-catchment and even to the whole of Africa.

CHAPTER FOUR: METHODS

4.1 Introduction

The methodology used in this study included two main procedures that are data acquisition and data handling. The data acquisition process consisted of stereoscopic interpretation of multitemporal satellite images and aerial photographs. Sequences of satellite images provided a time-series from which gully changes were mapped while aerial photographs increased the spatial resolution.

For the purposes of gully identification using remotely sensed imagery, the smallest scale images were selected from sequential aerial photographs and satellite images of various scales, which were used as the threshold for data extraction (Watson, 1990). The threshold for the smallest scale set of aerial photographs and satellite imagery used in this study was 1: 25 000, which is equivalent to 25m^2 on the ground. A scale of approximately 1: 25 000 was considered the most effective scale to use in Meso-catchment studies (Watson, 1990). Smaller scales lose detail and larger scales involve a sacrifice in terms of the synoptic view (Keech, 1980). Transparent overlay maps were prepared from the stereoscopic pairs in the photographic series. Ground survey for historical photographs is, by definition, impossible (Price, 1987); groundtruthing was however, done to determine the occurrence and characteristics of the vegetation and gully erosion classes.

4.2 Application of geoinformation techniques

4.2.1 Georeferencing and Validation

The scanned image was geo-referenced by tie points; this process involved picking four points randomly from the demarcated area on a scanned aerial photograph processed digitally on a computer screen by clicking on the screen and location of selected point and imputing the co-ordinates repeatedly three or four times so that the image becomes spatially registered with the new co-ordinates. During the geo-referencing, affine transformation was applied, with validation and verification of the digital data being carried out to check if the ground distances are the same as the one on the georeferenced aerial photograph before further processing. However, if some difference still exists the whole geo-referencing process was repeated all over again.

4.2.2 Digitising and database editing

On-screen digitising of the scanned georeferenced Orthophoto was done instead of table digitising. This process converts the digital data, which is having a two-dimensional co-ordinate system (eastings and northings), for each contour selected into numerical digital database. The three-dimensional database comprising of the eastings, northings and elevations was achieved by geocoding the numerical database with their respective elevation values from the topographic sheet. These three-dimensional co-ordinates were exported to Microsoft Excel, edited and saved as Comma Separable variable (CSV).

4.3 Selection of sampling transects

Sampling tools were used to select 10 transects incorporating the discernible range in plant species composition and physiognomy. The selection also considered the geological formations and soil zones within the study area. These tools were developed to assist biologists in using GIS software packages like ArcView to generate spatially explicit random or systematic sampling schemes to support resource monitoring, mapping, and research needs. Placing random transects is a more complex operation and the opportunity for user inputs has been expanded to try and cover most of the user needs. All the transects generated from this option are random both in the placement of the starting point and direction although these can be random placed within a specified direction by setting lower and upper azimuth limits for transects as illustrated in Figure 4.1.

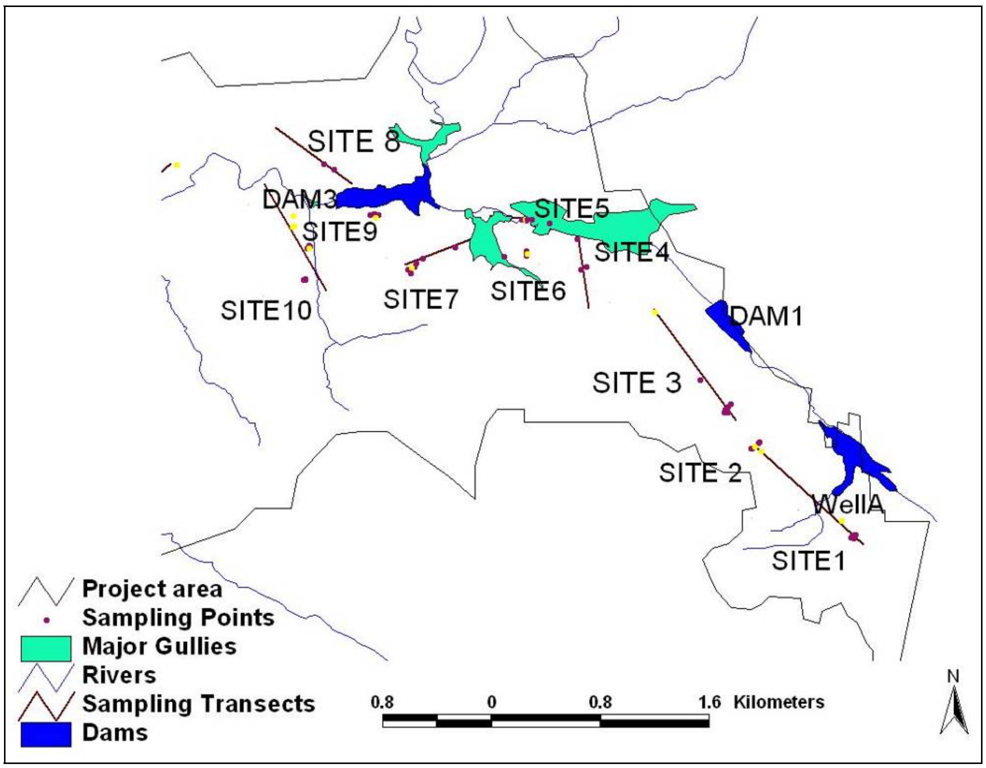


Figure 4.1: Sampling sites

4.4 Soil sampling, erosion and soil mapping

During the soil sampling process, the area was subdivided into homogeneous sections, from, which nine sampling sites were located. Between 10 and 20 sub-samples where combined from each area. Sub-samples were small enough that the composite sample was of a size that can be completely processed for analysis. Factors like vegetation cover, type and ground hardness determined the sampling depth.

To survey the changes in extent of gully erosion and to develop and implement policies for the control of accelerated erosion, three basic approaches need to be adopted as proposed by Morgan, (1993) to appraise the extent and nature of the situation. These are: (i) surveys of informed opinion, (ii) surveys of loss of original soil profiles and (iii) mapping of erosion features using aerial photographs or satellite imagery. Of these three options, satellite imagery picking up degradation indices spanning 15 years was used to map erosion in this study.

An excavated profile pit at the dam site, collapsed gully walls and supplement auger borings were used to demonstrate lateral changes in the soil as well as vertical ones, and are important for the full description of type soils and for the taking of soil samples for chemical and physical analysis. In this way, a picture was built up of the soil in a region and its relationship to the landscape in which it lies. Soils were mapped at a scale of 1:25,000 by, which the pattern of soils in individual fields could be identified.

4.7 Botanical methods

4.7.1 Vegetation mapping

Discrimination between vegetation classes was based predominantly on the pattern and presence of plant communities. These plant communities had similar aerial photographic characteristics in tone, texture, shadow and pattern. The rationale for using the landscape scale classification was that mapping trends in habitat fragmentation has important implications for conservation management (Odum and Turner, 1990).

Three broad vegetation classes were chosen to facilitate consistent and easy interpretation from the orthophotos and satellite images. Field verification of the mapped vegetation classes involved surveying transects through GPS data collection in the study area and the spatial extent of the area under study restrict the use of Landsat NDVIs.

The basal cover of all the herbaceous species were quantified by means of the point to tuft distance within the laid transect (Trollope and Tainton, 1988). Twenty points were systematically spaced over each transect and the presence of bare or occurrence of an herbaceous plant tuft was recorded. These were analysed to give the approximate herbaceous cover component of study area and associated gully areas.

Stunting is a conspicuous feature of the woody species on sodic soils and transects incorporated observed range in height of the dominant woody species. Individuals considered for analysis ranged from multi-stemmed coppice-clumps less than one-meter tall to single stemmed trees up to 10m tall. Within each transect all individuals of a species were grouped into 1m and greater than 2m height classes.

For each height class the bush density, canopy diameter, mean cross sectional area of the stem, that is the breast height of the stem was calculated. Tree height classes lower than 2 meters were classified as shrubs and the cross sectional area was recorded from the lowest browseable material. An importance value *Iv* for each species was calculated as follows:

$$Iv = \sum_{t=1}^{n}(HiNiAi)$$ -- **Equation 6**

Were H*i* is the height of species *I,* N*i* is the individual height class *I* and A*i* is the mean cross-sectional area of stem in height class *i.*

The tallest individual determines the number of classes (n) in a quarter, with all woody species growing being classified as sub-shrub, and for these only density was recorded while seedlings are not recorded, as they might not be recruited into the next height class.

4.7 Data cleaning and quality control

The collected data was cleaned to remove outliers that showed biased trends and were attributed to sampling error. The process of data cleaning and quality control was achieved by making sure the data was in the same formats. This process was done to assure that only necessary data would be used in the study.

4.8 Data manipulation, analysis and Management

The data-handling component of the study involved capturing the mapped vegetation and erosion data into the ArcView 3.2a, ArcGIS 9.1 Geographic Information System and Microimages TNT MIPS softwares. This spatial database platform was then used for spatial analysis and the generation of maps. Percentage changes of the erosion and vegetation cover variables over time were calculated to determine rates of change with respect to these parameters. Software packages used in the data analysis and production of this report include Microsoft (MS) Word 2000, MS Excel 2000, SYSTAT© 12, ILWIS, ArcGIS 9.1 and ArcView GIS version 3.2a. Digital versions of the report, graphics, GIS data (ArcView shape files), and data files and data forms are included on a CD in a pocket following the appendices.

4.9 Procedure for statistically analysing the research data

Statistical analysis of the research data included correlation determination and regression analysis for vegetation, slope gradient, gully and soil properties. These were considered as the overall procedures used in the analysis of the research data recorded in the experiment.

y = a + b1x1 + b2x2 + . . . +bnxn ……………………………………………Equation 7

Were:

Y is the dependent variable; Xi is the independent variable and I, and b1. . . bn are the regression coefficients.

Graphs were used to illustrate how the landscape has changed over the mapped time period, because of the small sample size and limited data, nonparametric statistical methods based on Spearman's Rank Order Correlation Coefficient were used to determine correlations between the erosion and vegetation variables, the significance was accepted at a 95% confidence level.

After exclusion of species, occurring in less than three sites (*Myetinus heterophylus, Acacia nilotica and Grewia flaviensis*); woody and herbaceous species were left in the data set. Seventeen soil variables were analysed for in the collected soil samples

(Appendix 4), two more variables that are percentage herbaceous cover (Appendix 3) and depth of sampling made the environmental variables nineteen for each site.

An ordination method was used that is the reciprocal averaging, which included analysis of species. The values for the vegetation characteristics were recorded for each site and divided by 50 a large arbitrary figure, thereby inactivating these attributes in the analysis and insuring that the extracted axes are determined by vegetation data alone.

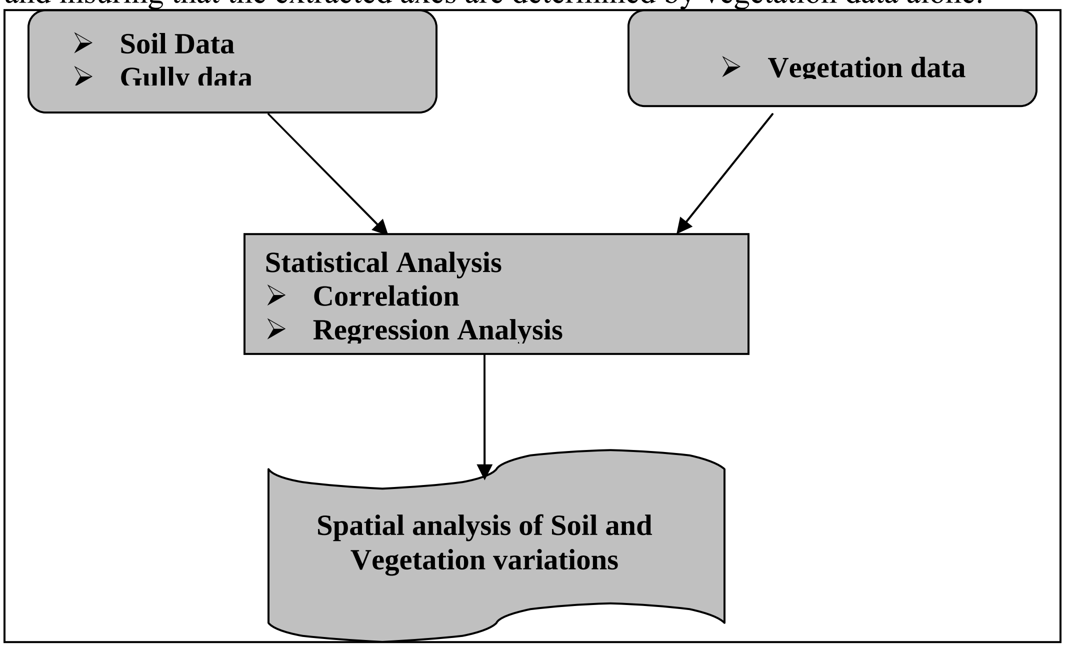


Figure 4.2: Procedure followed during statistical analysis of the different environmental Variables and vegetation data

Prior to the analysis the environmental data were scaled in such a way that the majority of the values for all variations lay in the same order of magnitude, as shown in Figure 4.1. This was done to alter the relationship between soil variations, but prevents the analyses from being dominated by those variables having large values. The influences of all environmental variables are thus made approximately equal.

The floristic data were normalised using the reciprocal transformation before inclusion into the analysis. All other woody species occurred as isolated individuals and were of doubtful ecological significance. These characteristics make these species unsuitable for multivariate analysis, so they were removed and considered separately. Computational limitations necessitated reduction in the amount of environmental attributes. The Pearson coefficient was calculated between all soil factors between sampling sites. The Spearman rank order correlation coefficient is computed by ranking all values of each variable, then computing the Pearson Product Moment Correlation coefficient, *r*, defined by equation 8, of the ranks.

$$R = \frac{\sum (X - \overline{X})(Y - \overline{Y})}{\sqrt{\sum (X - \overline{X})^2 \sum (Y - \overline{Y})^2}}$$

...Equation 8

CHAPTER FIVE: RESULTS AND DISCUSSION

5.1 Introduction

5.2 Remote sensing of gully development in the Zhulube Meso-catchment.

Figures 5.1 (a, b and c) shows gullies identified from three Landsat TM, SPOT and an Orthophoto. Figure 5.1(a), illustrates the gullies that were identified from the Landsat TM image of the Zhulube Meso-catchment. Interpretation of the Landsat TM image achieved 36% accuracy in gully identification; these results are explained by the fact that Landsat TM has a lower spatial resolution of 30 meters which is relatively too coarse for the gullies which are as narrow as 10 metres. This can be explained in terms of the spatial resolution dependent trend of gully identification. It can also be concluded that the average gully width of 17 meters can be detected by the Landsat TM sensors even if they are lower than the satellite's spatial resolution. The shadow effects of vegetation cover in the identification of gullies were evident resulting in a reduced accuracy and made it difficult to use satellite imagery to identify gullies within the area. Figure 5.1(a) also showed the occurrence of some gullies which were not visible in the other two sets of images and this can be attributed to the spectral capabilities of the Landsat TM image used which allows the increase in clarity of some features after band composites have been done.

Figure 5.1(b) illustrates the gullies that were identified from the SPOT panchromatic image of the Zhulube Meso-catchment. It can be observed that the SPOT panchromatic interpretation achieved 56% accuracy. These results are explained by the fact that SPOT has a high spatial resolution of 10 meters. From the SPOT image more information on the occurrence of the gullies becomes evident mainly due to its fine spatial resolution of 10m which is less than the average gully width of 17 meters within the study area. The smallest gully width was 6 meters, which is less than the spatial resolution but was identified because of its closeness to 10 meters. The shadow effects of vegetation cover in the identification of gullies were evident resulting in a reduced accuracy and made it difficult to use satellite imagery to identify gullies within the area.

Figure 5.1(c), illustrates the gullies that were identified from the Orthophoto image of the Zhulube Meso-catchment. It can be observed that the Orthophoto interpretation achieved 77% accuracy. These results are explained by the fact that the Orthophoto has a very high spatial resolution of 2.5 meters, thus identifying 77% of the sampled gullies within the study area. This can be explained in terms of the spatial resolution dependent trend of gully identification as in the case of the Orthophoto image. From the Orthophoto more information on the occurrence of the gullies becomes evident mainly due to its fine spatial resolution of 2.5 meters, with much is less than the average gully width of 17m within the study area. Figure 5.1(c) also shows a gully identification accuracy of 77%, which can be explained by the high spatial resolution of Orthophotos and the shadow effects of vegetation cover in the identification of gullies were evident resulting in a reduced accuracy and made it difficult to use satellite imagery to identify gullies within the area. This makes Orthophoto analysis the, most accurate method for gully identification in the study area.

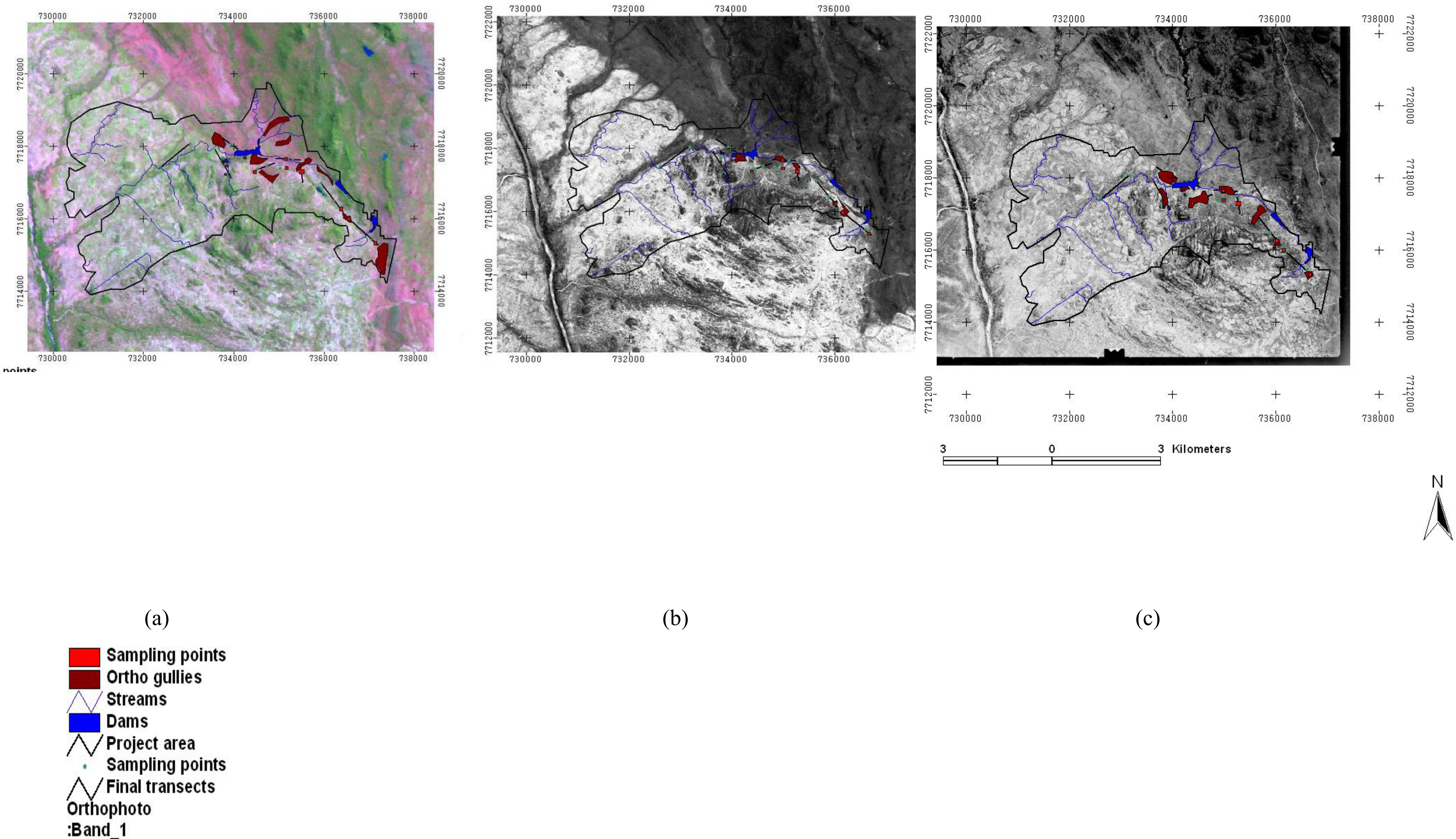


Figure 5.1 (a, b & c): Gully identification using Landsat satellite imagery (a), Spot Panchromatic imagery (b) and Orthophoto (c).

Table 5.1: Spearman Correlation Matrix of soil type, vegetation characteristics and gully erosion

	TREE DENSITY	BASAL COVER	GULLY DEPTH	GULLY WIDTH	GULLY LENGT	GULLY AREA
TREE DENSITY						
BASAL COVER	0.217					
GULLY DEPTH	-0.143	0.345				
GULLY WIDTH	-0.084	0.092	0.402			
GULLY LENGTH	0.521	-0.110	0.243	0.433		
GULLY AREA	0.101	-0.202	0.276	0.850	0.750	
GULLY VOLUME	-0.008	0.018	0.510	0.817	0.617	0.917
PH	0.256	-0.168	-0.545	0.017	0.085	0.220
Electrical Conductivity	0.109	0.321	-0.285	0.317	0.200	0.250
BULK DENSITY	-0.042	0.056	**0.873***	0.067	0.269	0.076
PARTICLE DENSITY	-0.250	-0.402	0.017	0.084	-0.176	0.235
CLAY	-0.048	0.010	**-0.748***	-0.026	-0.459	-0.139
SILT	-0.426	0.246	-0.051	0.329	-0.338	0.160
SAND	0.357	-0.181	0.343	-0.177	0.405	-0.025
TOT Nitrogen	-0.392	0.000	-0.245	0.162	-0.137	0.222
Nickel	-0.253	-0.143	-0.597	0.251	-0.243	0.192
Calcium	0.077	-0.237	-0.775	-0.354	-0.228	-0.203
Magnesium	-0.179	-0.336	**-0.809****	-0.305	-0.407	-0.203
Potassium	-0.448	0.048	-0.253	**-0.705***	**-0.827***	**-0.809***
Iron	-0.241	-0.304	**-0.798****	-0.243	-0.460	-0.184
Copper	-0.055	0.000	-0.639	0.159	-0.226	0.134
Zinc	-0.360	-0.032	-0.549	-0.210	**-0.723***	-0.345
Manganese	-0.079	-0.105	**-0.725***	-0.035	-0.261	-0.017
Sodium	0.300	-0.240	**-0.882***	-0.209	0.059	-0.033
Sodium Adsorption Rate	0.325	0.286	-0.353	0.310	0.393	0.318
ESP	0.367	0.221	-0.311	0.427	0.477	0.435
Stream Power Index	-0.134	0.505	0.385	**0.683***	0.083	0.433
Sediment Transport Index	0.118	0.073	-0.218	0.550	0.383	0.450
Slope	0.172	0.159	**0.645***	0.502	0.545	0.426

** Correlation is significant at the .01 level (2-tailed).
* Correlation is significant at the .05 level (2-tailed).

5.3 Relationship of gully erosion and vegetation characteristics within the Zhulube Meso-catchment.

Table 5.1 shows a correlation matrix between the gully characteristics, soil physical and chemical characteristics, erosivity of streams and terrain characteristics that were collected (Appendix 5 and 6). The bold numbers marked with asterix in the table are correlation coefficients of the different above-mentioned components that show significance at ($p < 0.05$) correlation relationships. Of interest to note is the relationship between the gully depth and most of the other components (Bulk density, clay, calcium, magnesium, iron, manganese and slope). Other interesting observations from Table 5.1 are the significant correlations between gully width and a couple of the other components (Potassium and Stream power index). To further validate these two notable trends regression plots were done to find out the relationships between the components as independent variables to gully depth and width.

5.4 Significance of difference in soil components

5.4.1 Relationship between gully depth and bulk density

The Pearson correlation analysis showed that the soil chemical characteristic, bulk density had a highly significantly ($p<0.05$) effect on gully depth. Figure 5.2 illustrates the relationship between gully depth and bulk density on scatter plot. The relationship shows linear increase in gully depth as the bulk density of a soil increases due to the vertical removal of soil mass by flowing water. This can be interpreted as meaning that the bulk density of the soil is contributing strongly to the size of gullies occurring in the Zhulube Meso-catchment, as bulk density affects pore space; thus an increase in bulk density (e.g. by compaction) reduces water storage and decreases infiltration and drainage capabilities. This is explained by the regression plot Figure 5.2, which indicates a linear relationship between increase in gully depth and an increase in the bulk density.

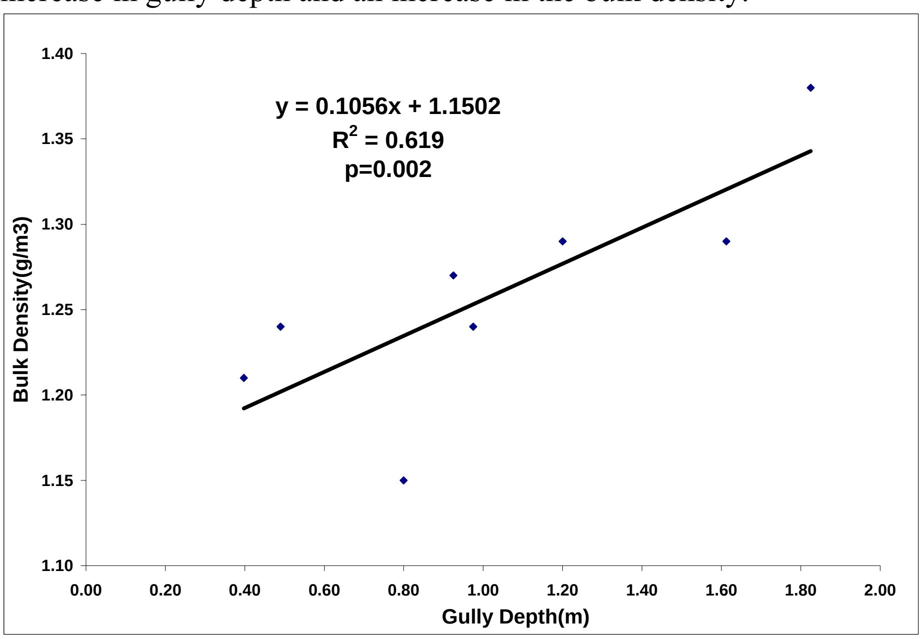


Figure 5.2: Significant ($p < 0.05$) relationship between Gully depth and bulk density

Figures 5.3(a) and (b) are two pictures showing sample sites two and nine respectively. These sites had the greatest disturbance by human beings and grazing livestock as evident by high soil bulk density values on these sites.

(a) (b)

Figure 5.3 (a) and (b): Gully walls of site 3 and 9.

Figure 5.3(a) shows an upstream moderate gully approximately 1.6 meters deep at sampling site 2 (Figure 4.1). This was one of the deepest gullies, which were being rehabilitated by stone filling and gabions. Continued lateral and vertical expansion of the gully indicates that the rehabilitation methods being used are not effective. It was evident that sodium and pH levels were significantly ($p<0.05$) high raising possibilities of sodic soil occurrence, which require a different rehabilitation regime. The vegetation survey showed that the site was poorly vegetated in terms of herbaceous basal cover and erosion levels are high. The tree densities of 260 plants per hectare on this site also indicated absence of adequate protection from incident rain and runoff. Figure 5.3(b), shows an upstream moderate gully approximately 1.83 meters deep at sample site 3 (Figure 4.1). From the picture, it is evident that the walls are collapsing thus leading to expansion of the gully both vertically and laterally.

This can be explained by observations, which point to the fact that this site was moderately vegetated with regard to the basal herbaceous cover component and showed moderately sized gullies and other forms of erosion. The results also show that site 3 (Figure 4.1) had a higher tree density than other sites; a look the collected vegetation data shows that even though there are adequate woody species around the gully with a tree density of 600 plants per hectare and a tree index of 3.6 is not enough to hold the soil from further erosion. Grass species whose roots are mainly concentrated in the A-horizon also offer very little resistance to the collapse of the gully walls. A closer look at the soil chemical components of the site indicates no significant ($p>0.05$) contribution by the chemical and physical constituents of the soil tested for, it thus can be suggested that the expansion of this gully might mainly be a cause of gully development and may also be related to anthropogenic factors.

5.4.2 Relationship between Gully depth and Clay properties

Figure 5.4 illustrates a significant negative relationship between gully depth and the percentage of clay within each sample site (Figure 4.1). From the plot, it is evident that as the clayey component of the sites increases the severity of erosion was reduced, mainly because of the resistance of clay minerals to erosion. Measured physical properties (clay) of soils are given in Figure 5.5(a, b, c & d). The clay content showed great inter-sites variation ranging from 2% to 8% between the sampling sites, indicating that the study area was dominated by sandy soils, which are weak and prone to erosion. It was evident that a slight increase in the proportion of clay within the soils causing significant ($p<0.05$) declines in gully depths across the sampling sites.

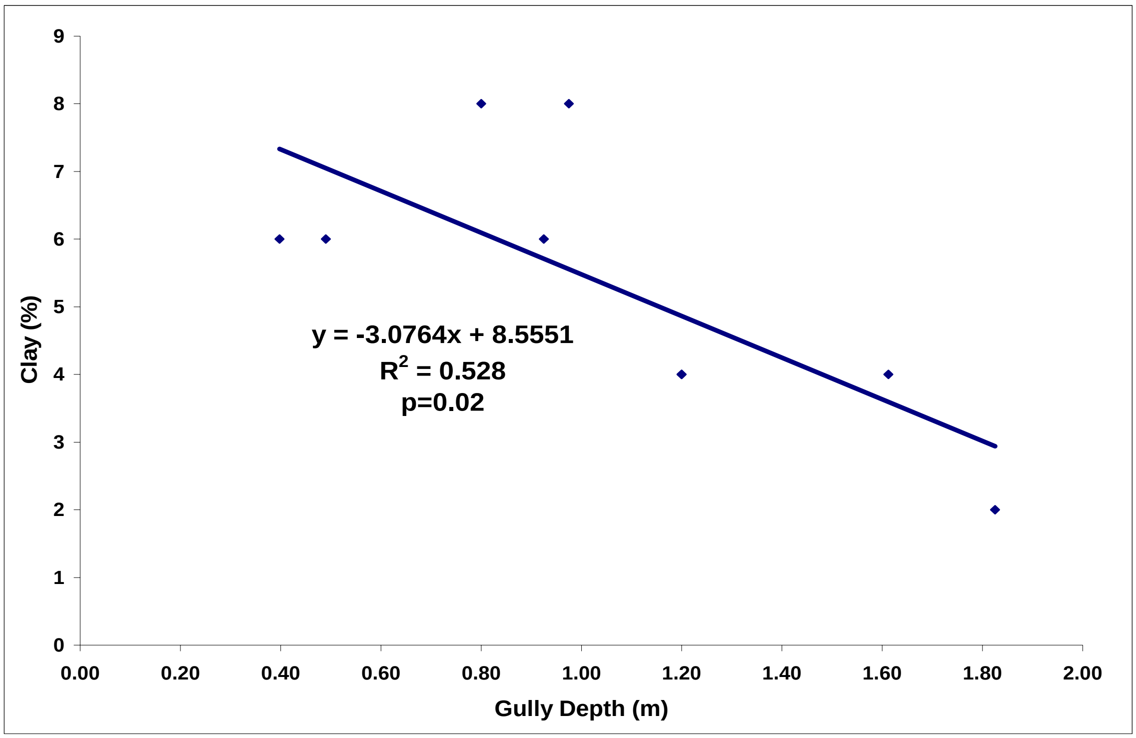
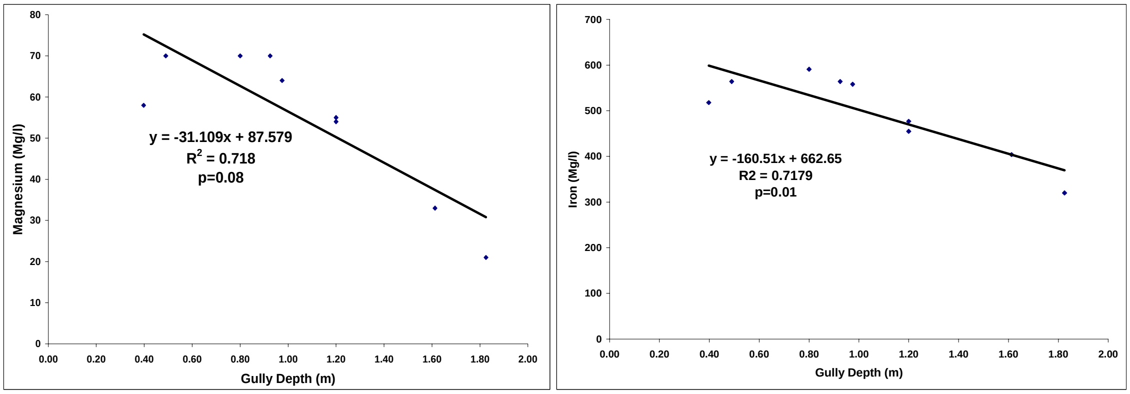
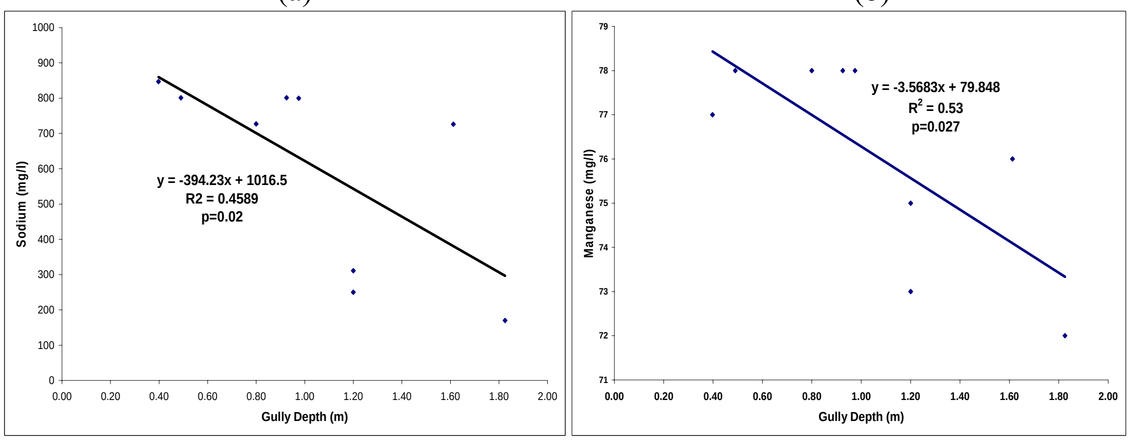


Figure 5.4: Significant ($p < 0.05$) relationship between Gull Depth and Clay content



(a) (b)



(c) (d)

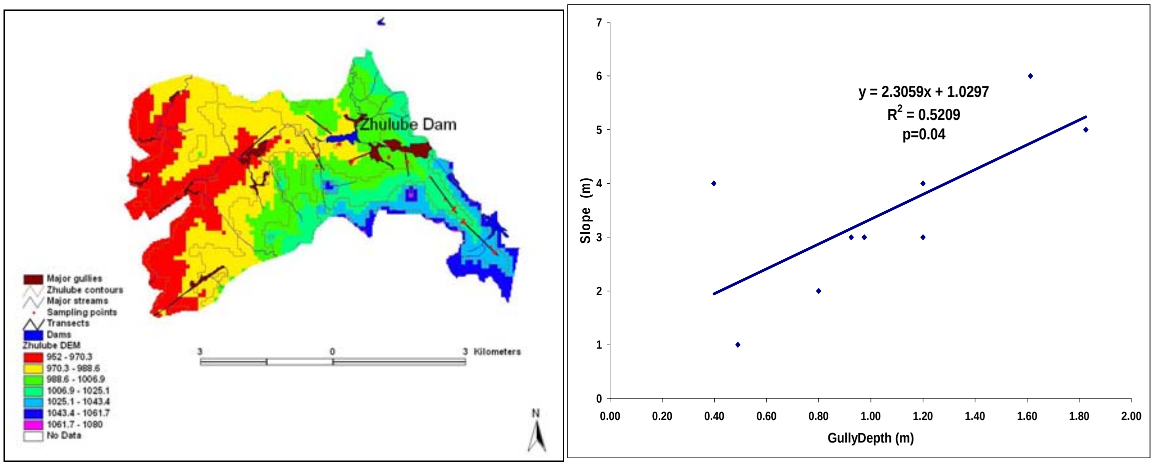
Figure 5.5(a, b, c and d): Significant ($p<0.05$) relationship between Gull Depth, Magnesium, Iron, Sodium and manganese.

From Figure 5.5(a,b,c & d), the trend shown by the four minerals that had a significant effect on the gully depth indicate a similar pattern, with all four chemical components presenting a negative significant correlation coefficient with the exception of sodium. This can be explained by the fact that magnesium, iron, manganese and sodium are major constituent of clay minerals, which include the layer silicates, the metal oxides and crystalline chain silicate minerals like kaolinite, Chlorite, illite and montimorilonite.

5.5 Significance of difference in slope gradient, stream erosive power, sediment transport ability and gully erosion.

5.5.1 Relationship between Gully depth and Slope gradient

Figure 5.6(a) shows the slope gradient of the Zhulube Meso-catchment and the possible severity of erosion can be estimated roughly by considering the degree of the slope and other related environmental factors. The regression in Figure 5.6(b) illustrates the analysis of gully depth and slope shows a positive significant relationship with a correlation coefficient $R^2 = 0.62$, this can be interpreted as a resultant increase in gully depth as the slope gets steeper, a result which is in line with literature (Minnesota GIS/LIS Consortium, 2001) as the erosive power of a flowing water body increases linearly with an increase in slope.

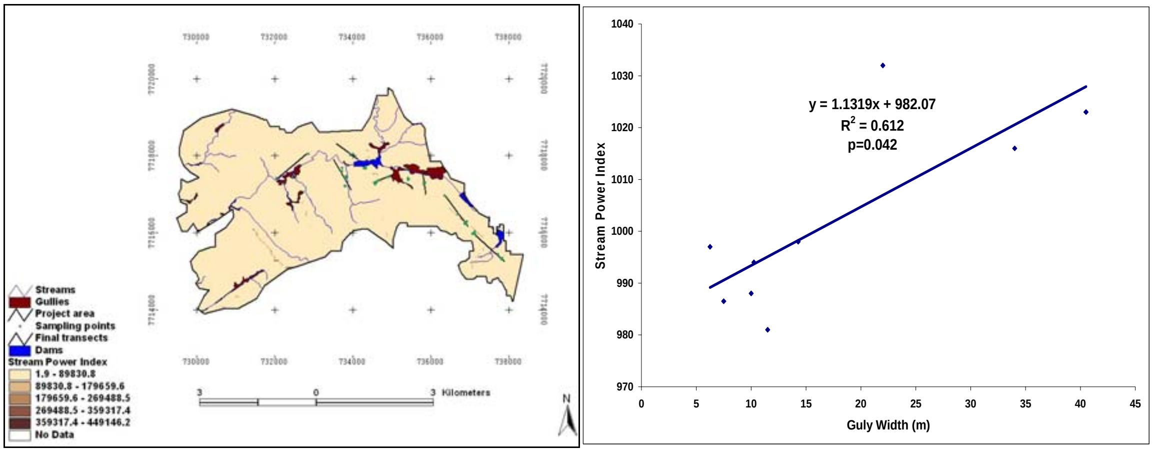


(a) (b)

Figure 5.6: Slope gradient and significant ($p< 0.05$) relationship between gully depth and slope gradient in the Zhulube Meso-catchment

5.5.2 Relationship between gully depth and stream power

Figure 5.7(a) Illustrates the power of the streams within the Zhulube Meso-catchment using steam power indices calculated from the digital elevation model. From Figure 5.7(a) shows that the streams within the study area have a generally weak stream power of 1.9 KJS^{-1}). Approximately 95% of the study area has weak stream power the most powerful flow 400 KJS^{-1} occurring close to the dams, illustrating low erosivity of the streams within the Zhulube dam’s catchment area. This further supports the hypothesis that the gullies within the study area result from the lateral movement of slow flowing water through sodic or poorly vegetated soils. In some areas especially close to the dam there is a significant ($p<0.05$) increase in stream flow power were evident there were average sized gullies indicating a weak link between stream flow and gully depth. The darker toned areas in Figure 5.7(a) indicate increasing stream power while the lighter tones indicate a decrease in the magnitude of stream power. Figure 5.7(b) illustrates a high positive correlation with gully depth, meaning that if the stream flow increases the gullies increase in their depths.



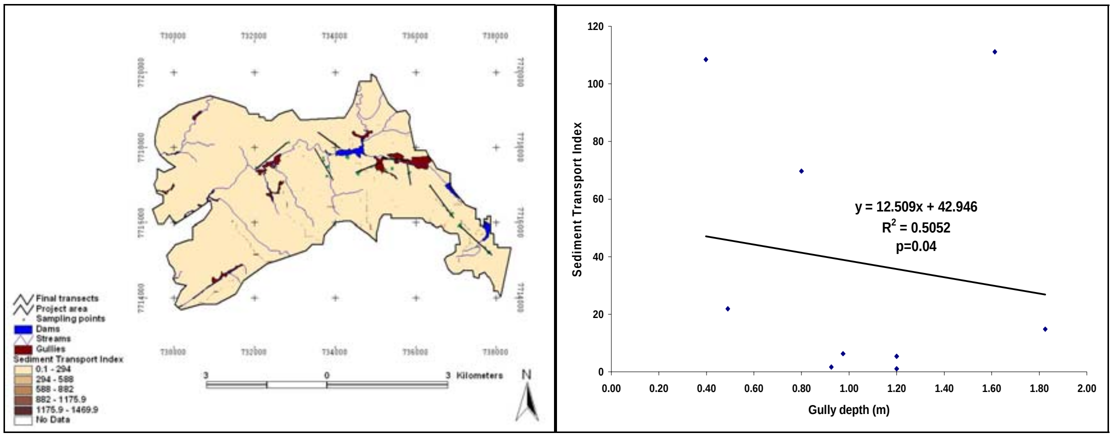
(a) (b)

Figure 5.7: (a & b): Stream Power Index and significant ($p < 0.05$) relationship between gully depth and stream power index

5.5.3 Relationship between gully depth and sediment loading

To quantify the possible soil loss to gully erosion and other less significant types of erosion in the Zhulube Meso-catchment the erodibility of the streams within the area as exhibited by the Sediment Transport Index needs to be related to the potential sediment load according to their elevation and possible power of flow. The sediment transport index indicated the potential of the streams to carry sediment and this is depicted in Figure 5.7(a), which indicates low sediment loads within the greater parts of the Meso-catchment but it is evident that the final sampling transects fall in close proximity to areas of high sediment transport indices, meaning around these areas the erosivity of the streams is high thus resulting in relatively deep gullies.

The is a significant ($p<0.05$) increase in sediment transport values at sites 2 and 9 (Figure 4.1), which show very high sediment loading values and these tallies with the field collected data as these were some of the deepest and broadest gullies in the study area. The sediment transport index as illustrated by Figure 5.8(a) indicates potential sources of sediment as dark colours while the lighter toned colours show areas of potential sediment deposit within the catchment. Figure 5.8(b) shows a regression plot of the gully depth and the Sediment transport index, the results illustrate a weak correlation between the depth of the gullies and the amount of sediment that is transported. These results indicate the presence of other methods of sediment transport of high activity during the earlier years after the construction of the Zhulube dam. The weak relationship between gully erosion and the sediment transport index also makes it difficult to estimate the time the Zhulube dam took to silt as the annual sedimentation rates do not show any constant trend.



(a) (b)

Figure 5.8 (a & b): Sediment transport index and a non-Significant ($p > 0.05$) relationship between Gully Depth and Sediment Transport Index

5.6 Implications to water resources management

For any meaningful intervention in reducing the impacts of gully erosion on livelihoods and dam siltation there is need to look at the factors that drive the process of erosion and suggest possible methods to reclaim affected areas or prevent further spread of erosion within any given area. The interaction of environmental factors and the erosive power of streams within any given catchment through analysis of Stream Power Index and the Sediment Transport Index can be used for planning purposes.

It is also important for a well-updated database to be put in place if gully erosion is to be managed or kept minimal; this can only be achieved by putting in place a monitoring strategy especially using imagery like Orthophotos, which had a higher accuracy in detecting areas affected by gully erosion. It was also beneficial if an updated database on the land use and stocking rates of the study area could be put in place.

Using the information obtained from environmental factors, physical and man made factors water resources management and decision-making and support can be enhanced, thus a decision that is more concrete can be made on the methods of gully reclamation and timing of the activities. This study also aims to identify possible gaps in water resources management that could lighten the work of most water managers on gully rehabilitation methods and possible prevention methods.

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

The general conclusion that can be drawn from the above-discussed study is that a significant relationship exists between vegetation types, soil characteristics (Physical and Chemical), and Slope and gully development. It can be further concluded that to come up with a lasting solution for gully rehabilitation within the Zhulube Meso-catchment there is need to first consider the effects of vegetation, soil characteristics, slope and anthropogenic factors. Remote sensing and GIS can be used to identify gully development in the Zhulube Meso-catchment but the levels of accuracy varies greatly as affected by factors like the spatial resolution of the image and the spectral resolution in the case of multi band images like Landsat. The panchromatic spot image also had a relatively high efficiency of discriminating gullies.

The inherent susceptibility of soils to detachment and transport by various erosive agents was a function of soil properties including among others, Physical properties, Chemical properties. The extent of each of these soil properties was different in different soils thereby influencing the degree of vulnerability of any given soil to destructive forces like erosion. The interactive effects of the topographic, vegetation cover and rainfall factors in turn influence these factors. From the study, it was evident that the slope gradient had a highly significant effect on the erosive power of stream. Sampling sites at lower slope gradients had reduced stream power and sediment loads than those located at areas with higher slope gradients like site. Vegetation did not have much effect on gully development pointing towards the conclusion that most of the sampling sites were located in the mixed vegetation class thus very minimal differences were evident across al sampling sites. Soil erodibility assessment using simulated erosive force (stream power index) and sediment loadings (stream power index) in the study site revealed that sediment yield or the erosive power of the streams in the study area increased with increasing slope gradient depending on the clay content of the soils. The higher the clay content the lower the erodibility factor as shown by the relationship between clay content and the gully depths.

5.1 Research needs and recommendations

There is need for more detailed process based soil loss estimation in order to get a more accurate estimate of soil loss from particular locations so that site-specific management options can be executed with better confidence. Furthermore, integrated soil conservation research is required to develop a comprehensive database for modeling of the various soil erosion parameters as well as to design and implement appropriate soil conservation measures. It was also important to assess the relative importance of the various erosion parameters that are responsible for degradation in the study area. There need to develop comprehensive databases initially at a small scale then for the whole basin, which are relevant to the specific conditions of any given area. This may include accumulation of more detailed data on climate, soil, vegetation, topography, geology and hydrology, land management and social aspects. It was necessary to carry out validations on the applicability of the most acceptable erosion models and soil conservation measures existing within the study area.

References

Anderson, I.P., Brinn, P.J., Moyo, M. and Nyamwanza, B. 1993. *Physical resource inventory of the communal lands of Zimbabwe – An overview*. NRI Bulletin 60. Chatham, UK: Natural Resources Institute.

Bergsma, E. (ed.), 1996. Terminology for Soil Erosion and Conservation. International Society of Soil Science, Grafisch Service Centrum, Wageningen, 313 pp.

Behnke RH, Scoones I. 1993. Rethinking range ecology: *Implications for range management in Africa. In Range Ecology at Disequilibrium*: New Models of Natural Variability and Pastoral Adaptation in African Savannas, Behnke RH, Scoones I, Kerven C (Eds). Overseas Development Institute: London.

Brady, N.C. 1990. The nature and properties of soils. Macmillan, New York. USA.

Brinkcate, T.A. & Hanvey, P.M., 1996: Perceptions and attitudes towards soil erosion in the Madebe community, Northwest Province, S. Afr. Geog. J., 78, 1, 75-82.

Broderick, D.M., 1985: A history of land degradation in the Tugela Basin, Natal, Isizwe, 8, 1-14.

Broderick, D.M., 1987: An examination of changes in the extent of erosion in agricultural areas in the Tugela Basin, Unpubl. MA thesis, University of Natal, Durban.

Bronstert, A.; Niehoff, D.; Bürger, G. (2002) Effects of climate and land-use change on storm runoff generation: *present knowledge and modeling capabilities*. Hydrological Processes, 16, 2, 509-529.

Bull, L.J. and Kirkby, M.J., 1997: Gully processes and modelling. Progress in Physical Geography 21, 354-374.

Calder, I.R., Hall, R.L., Bastable, H.G., Guston, H.M., Shela, O., Chirwa, A. and Kafundu, R. 1995. *The impact of land use change on water resources in Sub-Saharan Africa*: a modeling study of Lake Malawi. Journal of Hydrology, 170, 123-135.

Charman, P.E.V. and Murphy, B.W. Eds 2000. *Soils: Their Properties and Management*. Oxford University Press, South Melb.

Chenje, M., Sola, L., and Paleczny, D. (eds.), The State of Zimbabwe's Environment 1998, Government of the Republic of Zimbabwe, Ministry of Mines, Environment and Tourism, Harare, 1998.

Chicheste. 1980. Freebairn DM., Gupta SC., Microrelief rainfall and cover effects on infiltration. *Journal of Soil and Tillage Research (*05). 296-300

Chigerwe, J., Manjengwa, N., van der Zaag, P., Zhakata, W. and Rockström, J. 2004. *Low head drip irrigation kits and treadle pumps for smallholder farmers in Zimbabwe*: a technical evaluation based on laboratory tests. *Physics and Chemistry of the Earth*, 29, 1049-1059.

Cleaver, K. M. and G. A. Schreiber (1994). Reversing the Spiral. *The Population, Agriculture, and Environment Nexus in Sub-Saharan Africa*. Washington, D.C.: The World Bank.

Commercial Farmers Union, 2000. *Facts on land and the present situation*. Mimeograph, 25 pages

Cooke RU and Reeves RW. 1976. Arroyos and environmental change in the American Southwest. Oxford, UK: Oxford University Press.

Daba, S., W. Rieger & P. Strauss, 2003. Assessment of gully erosion in eastern Ethiopia using photo-grammetric techniques. Catena 50(2-4), pp. 273-291.

Dawn M. D 1990. "Forest Statistics for West Virginia 1975 and 1989", Forest Service Resource Bulletin NE-114 (1990) 172 pp. Northeast Forest Experiment Station, Radnor, PA 19087

DeFries, R. S., G. P. Asner, and R. A. Houghton, editors, 2004. Ecosystems and Land Use Change. American Geophysical Union, Washington, DC.

Dregne H.E., (1990) "Erosion and Soil Productivity in Africa", JSWC, 45: 431-36.

Du Plesis, M.C.F., 1986. Grondagteruitgang. *S.African. J. Nat. Science Tech*. 5(3), 126-138.

Dye, P.J. and Spear, P.T. 1982. The effect of bush clearing and rainfall variability on grass yield and composition in south-west Zimbabwe. *Zimbabwe Journal of Agricultural Research* 20: 103-117.

Dye, P.J. and Spear, P.T. 1982. The effect of bush clearing and rainfall variability on grass yield and composition in south-west Zimbabwe. *Zimbabwe Journal of Agricultural Research* 20: 103-117.

Edward C. Wolf, "Avoiding a Mass Extinction of Species", in Linda Starke, ed., State of the World 1988, W. W. Norton and Co., New York (1988) pp. 101-17.

Eklundh L., 1998.Estimating relations between AVHRR NDVI and rainfall in East Africa at 10-day and monthly time scales. International-Journal-of-Remote-Sensing 19 (3) 563-568.

Emmett WW. 1980. Overland flow. In *Hillslope Hydrology* Kirby MJ Ed. Wiley. Chichester. Erosion response of a disturbed sagebrush steppe Hillslope. *Journal of Environmental Quality (*11) 587-698.

Evans, I. S. 1972. Chapter 2 – General Geomorphometry, derivations of altitude and descriptive statistics. Pages 17-90 *in* R. J. Chorley, Editor. Spatial analysis in geomorphology. Harper & Row, Publishers. New York, New York, USA

Evans R. 1980. Mechanics of water erosion. In *Soil Erosion* Kirby MJ Morgan RPC "eds. Wiley.

Everitt, J.H. and D.E. Escobar. 1992. Airborne video systems for real time assessment of rangelands. Geocarto, 7(1):19-26.

FAO/UNEP, 1977. Methodology for assessment and mapping of desertification. In Desertification revisited. Proceedings of an Ad Hoc Consultative Meeting on the Assessment of Desertification, Odingo RS (Ed.). UNEP-DC/PAC: Nairobi; 123–178.

Faulkner H. 1995. Gully erosion associated with the expansion of unterraced almond cultivation in the coastal Sierra de Lujar, S. Spain. Land Degradation & Rehabilitation 6: 179–200.

Fitzpatrick, R.W., 1978: Occurrence and properties of iron and titanium oxides in soils along the eastern seaboard of South Africa, Unpubl. PhD. thesis, University of Natal, Pietermaritzburg.

Fitzpatrick, R.W., Boucher, S.C., Naidu, R. and Fritsch, E., 1994: Environmental consequences of soil sodicity. Australian Journal of Soil Research 32, 1069-1093.

Foley, J. A., R. DeFries, G. P. Asner, C. Barford, G. Bonan, S. R. Carpenter, F. S. Chapin, M. T. Coe, G. C. Daily, H. K. Gibbs, J. H. Helkowski, T. Holloway, E. A. Howard, C. J.

Food and Agriculture Organization of the United Nations (FAO). 1983. Guidelines for the Control of Soil Degradation. Rome: United Nations Environment Programme and FAO.

Ford, G.W., Martin, J.J., Rengasamy, P., Boucher, S.C., and Ellington, A., 1993: Soil sodicity in Victoria. Australian Journal of Soil Research 31, 869-909.

Fox RC, Nel EL. 1997. Pension payouts, periodic marketing and the continuance of urban dependence in rural South Africa. In Regional Development Planning and Management of Urbanization: Experiences from Developing Countries, UNCHS (Habitat) (Eds). UNCHS: Nairobi; 203–220.

Fox RC, Rowntree KM. 2001. Redistribution and reform: prospects for the land in the Eastern Cape Province, South Africa. In Land Degradation, Conacher A (Ed.). Kluwer Academic Publishers: Dordrecht; 167–186.

Francis C. 1990. Soil erosion and organic matter losses on fallow land: a case study from southeast Spain. In Soil Erosion on Agricultural Land, Boardman J et al. (Eds). Wiley: Chichester; 331–338.

Friedel, M.H., Pickup, G. & Nelson, D.J. (1993). The interpretation of vegetation change in a spatially and temporally diverse arid Australian landscape. *Journal of Arid Environments*, 24:241-260.

Frohn, R.C. 1997. Remote sensing for landscape ecology: new metric indicators for monitoring, modeling, and assessment of ecosystems. CRC Press, Lewis Publishers, Boca Raton, Florida, USA.

Garland G.G., Robinson J.R. & Pile K.G., 1994: Policy, perception and soil conservation -a case study from Cornfields, Natal, Human Needs, Resources & Environ. Rep. HSRC, Pretoria, Aug. 1-41.

Garland, G.G. & Broderick, D.M., 1992: Changes in the extent of erosion in the Tugela catchment, 1944-1981, S. Afr. Geog. J., 74(2), 45-48.

Gelmroth, H., 1981: Mapping of Soil Erosion from Aerial Photographs, Ministry of Agriculture, Division of Land Utilisation, Gaborone, Botswana.

Gichuki, F.N., 2003. Basin profiles: Towards the development of strategic research and development plans. Unpublished document, CGIAR, Rome.

Gifford, G.F. (1976). Applicability of some infiltration formulae to rangeland infiltrometer data. Journal of Hydrology 28(1): 1-11.

Gifford, G.F. (1978). Infiltrometer studies in rangeland plant communities of the Northern Territory. Australian Rangeland Journal 1(2): 142-149.

Gillespie, P.D., 1981: Development of gully erosion at the head of Bango Creek near Yass, New South Wales. Journal of the Soil Conservation Service of N.S.W. 37, 6-12.

Global Land Project. 2005. Science Plan and Implementation Strategy. IGBP Report No. 53/IHDP Report No. 19, IGBP Secretariat, Stockholm.

Goldberg, S. and R.A. Glaubig. 1987. Effect of saturation cation, pH, and aluminum and iron oxide on the flocculation of kaolinite and montimorilonite. Clays Clay Min. 35: 220-227.

Görgens, A.H.M. and Boroto, R.A. (1997). Limpopo River: flow balance anomalies, surprises and implications for integrated water resources management. In: *Proceedings of the 8th South African National Hydrology Symposium*, Pretoria, South Africa.

Goudie, A. et. Al. 1990. Geomorphological techniques (2nd edition). Chapters 43 and 44.

Gregory, K.J. and Walling, D.E., 1973: Drainage Basin Form and Process - a geomorphological approach. Edward Arnold, London.

Gutknecht, D. (1996) Abflussentstehung an Haengen – Beoachtung and Konzeption. Oestereichische Wasser- und Abfallwirtschaft, 48, 134-144.

Guyot, G. & Gu, X. (1994). Effect of Radiometric Corrections on NDVI-Determined from SPOT-HRV and Landsat-TM Data. *Remote Sensing of Environment*, 49: 169-180.

Haas, R. H. 1992. Landsat thematic mapper products for rangeland assessment. Geocarto, 7(1):27-33.

Hanson, C. L., Khlman, A.R., Erickson, C.J. and Lewis, J.K., 1970. Grazing effects on runoff and vegetation on western South Dakota rangeland. J. range Manage. , 23(6):415-420.

Hardy M.B. & Tainton N.M. 1993. Towards a technique for determining basal, cover in tufted grasslands. Afr J for Range Sci. 10:2:77-81. Distance measures, monitoring, precision.

Hermunen, T., A. Keskinen, M. Lanne, K. Masalin & T. Sirviö, 2004. Mwatate – Trading post with soil erosion. In: Pellikka, P., J. Ylhäisi & B. Clark (eds.): Taita Hills and Kenya, 2004. Expedition Reports of Department of Geography, University of Helsinki 40, Department of Geography, University of Helsinki. In print.

Hillel D. 1982. Introduction to Soil Physics. Academic Press. New York 017 pp

Hoffman, T., Todd, S., Ntshona, Z. & Turner, S., 1999. Land Degradation in South Africa. Final report. Dep. Environmental Affairs and Tourism.

Horton. Approach toward a physical interpretation of infiltration capacity. *Soil Science Society of America Proceedings (*4). 288-306.

Hurni H, .1996. Precious Earth: From Soil and Water Conservation to Sustainable Land *Management*. Berne, Switzerland: International Soil Conservation Organisation (ISCO) and Center for Development and Environment (CDE).

Jensen. J.R., Huguenin, R.L., M.A. Karaska, D. Van Blaricom. 1997. Sub pixel classification of bald cypress and tupelo gum trees in thematic mapper imagery. Photogrammetric Eng. Remote Sensing. 63(6):717-725.

Kamalu C (1994). The effects of slope length and inclination on the separate and combined actions of rainsplash and runoff. In *Conserving Soil Resources European Perspectives* Rickson RJ Ed. University Press. Cambridge.

Keech, M.A., 1980: Remote sensing in planning the control of erosion, in De Boodt, M. and Gabriels, D. (eds), Assessment of Erosion, John Wiley and Sons, Chichester, 419-425.

Kileshye Onema, J-M (2004).*A hydrological assessment of landuse changes and human's activities in semi-arid Zimbabwe: case study of the Insiza sub-catchment.* MSc. Water Resources Engineering and Management thesis (unpublished) University of Zimbabwe, Harare.

Kirkby, M. J. & Morgan, R. P. C. (Eds) (1980) *Soil Erosion.* John Wiley, New York, USA.

Kirkby, M.J., L.J. Bull, J. Poesen, J. Nachtergaele & L. Vandekerchhove, 2003. Observed and modelled distributions of channel and gully heads – with examples from SE Spain and Belgium. Catena 50(2-4), pp. 415-434.

Kloosterboer E.H. & Eppink L.A.A.J, 1989. Soil and water conservation in very steep areas. In *The Extent of Soil Erosion. Regional Comparisons* Baum E Wolf P Zobisch MA "Eds.

Kucharik, C. Monfreda, J. A. Patz, I. C. Prentice, N. Ramankutty, and P. K. Snyder. 2005. Global consequences of land use. Science 309:570-574.

Lal R 1981 soil-erosion problems on alfisols in western Nigeria .6. Effects of erosion on experimental plots geoderma 25 (3-4): 215-230

Lal R. 1992. Restoring land degraded by gully erosion in the tropics. Advances in Soil Science 17:123–152.

Leeper, G.W. and Uren, N.C. 1993. *Soil Science: An Introduction.* Melbourne University Press.

Leprieur. C., Y.H. Kerr, J.M. Pichon. 1996. Critical assessment of vegetation indices from AVHRR in a semi-arid environment. International Journal of Remote Sensing 17(13): 2549-2563.

Lillesand, T.M. & Kiefer, R.W. (1994*)*. Remote Sensing and Image Interpretation (3rd Edn). New York: John Wiley & Sons Inc. 750pp

.
Lobo, A., K. Moloney, O. Chic, and N. Chiarello. 1998. Analysis of fine-scaled spatial pattern of grassland from remotely sensed imagery and field collected data. Landscape Ecol. 13:111-131.

Loesch Chuck, 2005. DNR Sampling Tool (V2.8 November 09, 2005), Minnesota

Love, D., Jonker, L., Rockström J., van der Zaag, P. and Twomlow, S. 2004. The Challenge of Integrated Water Resource Management for Improved Rural Livelihoods in the Limpopo Basin – an introduction to WaterNet's first network research program. In: Abstract volume, *5th WaterNet-WARFSA Symposium*, Windhoek, Namibia.

Ludwig, J. (1986). Primary production variability in desert ecosystems. In: Whitford, W.G. (Ed.), Pattern and Process in Desert Ecosystems, pp. 5}17. Albuquerque: University of New Mexico Press.

Ludwig, J., Tongway, D., Freudenberger, D., Noble, J. & Hodgkinson, K. (1997). Landscape Ecology. Function and Management. Principles from Australia's Rangelands. Collingwood: CSIRO. 158 pp.

Luoto, M., M. Kuussaari, H. Rita J. Salminen & T. von Bonsdorff, 2001. Determinants of distribution and abundance in the clouded Apollo butterfly: a landscape ecological approach. Ecography 24, pp. 601-617.

Lyon, J.G., R.S. Lunetta, and D.C. Williams. 1992. Airborne multispectral scanner data for evaluating bottom sediment types and water depths of the St. Mary's River, Michigan. *In:* J.G. Lyon and J. McCarthy (Eds), Wetland and Environmental Applications of GIS. CRC Press, Lewis Publishers, Boca Raton, Florida, USA.

Maisiri, N. 2004. An on-farm evaluation of the effects of low cost drip irrigation on water and crop productivity compared to conventional surface irrigation systems. Masters thesis (Unpublished), Water Resources Engineering and Management Programme, University of Zimbabwe.

Martínez-Casasnovas, J.A., M.C. Ramos & J. Poesen, 2003. Assessment of sidewall erosion in large gullies using multi-temporal DEMs and logistic regression analysis. Geomorphology 58(1-4), pp. 305-321.

Matowanyika, J.Z.Z. 1998. *Land resources*. In: Chenje, M., Sola, L. and Paleczny, D. (Eds.). The State of Zimbabwe's Environment 1998. Government of the Republic of Zimbabwe, Ministry of Mines, Environment and Tourism, Harare, Zimbabwe.

Mazvimavi, D., 1998. Water availability and utilization in Zimbabwe, *Geographical Journal of Zimbabwe,* Vol. 29, 23-36.

McDonald, R.C., Isbell, R.F., Speight, and J.G., 1984: Land surface. In McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J. and Hopkins, M.S. (Eds) Australian Soil and Land Survey Field Handbook, Inkata Press, Melbourne, 68-82.

McDonald, R.C., Isbell, R.F., Speight, and J.G., 1990: Land surface. In McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J. and Hopkins, M.S. (Eds) Australian Soil and Land Survey Field Handbook, Inkata Press, Melbourne, 87-102.

Merzouk, A. and H. Dhman, 1998. Shifting land use and its implication on sediment yield in the Rif Mountains (Morocco). Advances in GeoEcology 31, 33-340.

Meyer, W. B., and B. L. Turner. 1994. Changes in Land Use and Land Cover: A Global Perspective. Cambridge University Press, Cambridge England; New York, NY, USA.

Morgan, R.P.C., 1993: Soil erosion assessment, Proceedings of a Workshop on Soil Erosion in Semi-Arid Mediterranean Areas, Taormina, Italy, 28-30 October 1993, Consiglio Nazionale delle Ricerche, Roma, 3-17.

Morgan, R.P.C., 1995. Soil Erosion and Conservation. Longman Group Ltd., Essex, England.

Morgan R.P.C. & D. Mngomezulu, 2003. Threshold conditions for initiation for valley-side gullies in the Middle Veld of Swaziland. Catena 50(2-4), pp. 401-414.

Moyersons, J., 2003. The topographic thresholds of hillslope incisions in southwestern Rwanda. Catena 50(2-4), pp. 381-400.

Mroczkowski, M, G. Raper, G. Kuczera (1997). The quest for more powerful validation of conceptual catchment models. Water Resource. Res., 33(10), 2325-2336.

O'Connor,-T.G. (2001), Effect of small catchment dams on downstream vegetation of a seasonal river in semi-arid African savanna. Journal-of-Applied-Ecology [J.-Appl.-Ecol.] 2001 vol. 38, no. 6, pp. 1314-1325

Odum, E.P. and Turner, M.G., 1990: The Georgia landscape: a changing resource, in Zonneveld, I.S. and Forman, R.T.T. (Eds), Changing Landscapes: An Ecological Perspective, Springer-Verlag, New York, 137-164.

Oldeman LR, Hakkeling RTA, Sombroek WG. 1990. World Map of the Status of Human-induced Soil Degradation: An Explanatory Note (2nd edn). ISRIC & UNEP: Wageningen & Nairobi.

Olderman, L.R., 1991 "The extent of human-induced soil degradation", World Map of the Status of Human-Induced Soil Degradation, International Soil Reference and Information Centre, Wageningen/United Nations Environment Programme, Nairobi (1991) 27-33.

Orkin, F.M. & Njobe, B., 2000. Employment trends in agriculture in South Africa. Statistics South Africa.

Palmer, A.R. & Avis, A.M. (1994). The description, mapping and evaluation of recent change in the contemporary vegetation patterns.Mid-Fish River Zonal Study. Pretoria: Land and Agriculture Policy Centre 54 pp.

Patterson, R.A. 1994. On-site treatment and disposal of septic tank effluent. PhD thesis. Department of Resource Eng. & Agronomy and Soil Science. University of New England. Armidale

Pickup, G. and Chewings, V.H. (1988). Estimating the distribution of grazing and patterns of cattle movement in a large arid zone paddock: an approach using animal distribution models and Landsat imagery. International Journal of Remote Sensing 9(9): 1469-1490.

Poesen, J., J. Nachtergaele, G. Verstraeten & C. Valentin, 2003. Gully erosion and environmental change: importance and research needs. Catena 50(2-4), pp. 91-133.

Poesen JW. 1997. Gully erosion: after event field survey. Volume of Abstracts for the IVth International Conference on Geomorphology, Bologna, Comitato Glaciologico Italiano: Torino; 285.

Potdar, M.B., S.S. Pokharna, V.N. Sridhar. 1993. Response of vegetation in the Thar Desert to monsoon rainfall: An investigation using NOAA AVHRR and meteorological data. Journal of arid environments 25(1): 19-26.

Press F& Siever R. 1986. Earth Freeman. New York NY 234 pp. Rose CW. 0877. Research progress on soil erosion processes. In *Soil Erosion Research Methods* LalR "ed. Soil and Water Conservation Society.

Price, M., 1987: The analysis of vegetation change by remote sensing, Progress in Physical Geography, 10, 473-491.

Pyrczak, Fred. (2002). Success at statistics: A Work text with humor (2nd Ed.). Los Angeles: Pyrczak Publishing.

Quirk, J.P., and C.R. Panabokke. 1962. Incipient failure of soil gates. J. Soil Sci. 13:60–69.

Ramsey, R.D., Black, T.A., Edgley, E., and Yorgason, N.1999. Use of GIS and remote sensing to map potential Columbian sharp tailed Grouse Habitat in southern Idaho. A final report to the USDI/BLM, Malad field Station, Idaho. Task O. 06 AA N°:1422-D910-A3-0210.

Ray, T.W. (1995). Remote Monitoring of Land Degradation in Arid/Semi-arid Regions. Ph.D. Thesis, California Institute of Technology.

Reenberg A, Nielsen TL, Rasmussen K. 1998. Field expansion and reallocation in the Sahel: land use pattern dynamics in fluctuating biophysical and socio-economic environment. Global Environment Change. 8:309–327.

Renard, K.G., Foster, G.R. Weesies, G.A., MC Cool, D.K. and Yoder, D.C. 1996. Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE), USDA/ARS.AG Handbook #703. Washington, D.C.

Rengasamy, P and Olsson, K.A. 1993. Irrigation and Sodicity. *Aust. J. Soil Res.* 1993. 31:821-37.

Rengasamy, P. and Sumner, M.E., 1998: Processes involved in sodic behaviour. In Sumner, M.E. and Naidu, R., (Eds) `Sodic soils - distribution, properties, management and environmental consequences'. Oxford University Press, New York, 35-50.

Richards, K.S. 1982. Rivers: Form and process in alluvial channels. Chapters 3 and 4.

Rienks, S.M., Botha, G.A. and Hughes, J.C., 2000: Some physical and chemical properties of sediments exposed in a gully (donga) in northern KwaZulu-Natal, South Africa and their relationship to the erodibility of the colluvial layers. Catena 39, 11-31.

Rebeiro-Hargrave, A., 2000. Large Scale Modelling of Drainage Network Evolution in a Tectonically Active Environment. Ph.D. Thesis. University of London. 323 pp.

Romme, W.H. (1982). Fire and landscape diversity in subalpine forests of Yellowstone National Park. *Ecological Monographs*, 52: 199}221.

Rouse, J.W., Smith, M.O. & Adams, J.B. (1973). Monitoring vegetation systems in the Great Plains with ERTS. *Third ERTS Symposium*, *NASA SP*, 351 39}317.

Ruecker G, Schad P, Alcubilla M, Ferrer C. 1998. Natural regeneration of degraded soils and site changes on abandoned agricultural terraces in Mediterranean Spain. Land Degradation & Development 9: 179–188.

Ruddiman, W. F. 2003. The anthropogenic greenhouse era began thousands of years ago. Climatic Change 61:261-293.

Rukuni, M. 1994. Report of the Commission of Inquiry into Appropriate Agricultural Land Tenure Systems. Volume II: Technical Reports. Government Printers, Harare.

SARCCUS, 1981: A System for the Classification of Soil Erosion in the SARCCUS Region, Department of Agriculture and Fisheries, Pretoria.

Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jaerel, W.M., Virginia, R.A. & Whitford, W.G. (1990). Biological feedbacks in global desertification. *Science*, 247: 1043}1048.

Schwab GO, Frevert RK, Edminster TW and Barnes KK. 1981. Soil and water conservation engineering. 3rd edition. New York, USA: John Wiley & Sons Inc. 525 pp.

Scoones I. 1995. New directions in pastoral development in Africa. In Living with uncertainty: New Directions in Pastoral Development in Africa, Scoones I (Ed.). Intermediate Technology Publications: London; 1–36.

Scotney, D.M. & Dijkhuis, F.J., 1990. Changes in the fertility status of South African soils. *S. Afr. J. Sci*. 86, 395-402.

SCSA. 1982. Resource conservation glossary. Ankeny, Iowa, USA: SCSA.

Sherry, S. 1959. Experimental measurement of runoff and soil erosion in wattle plantations in Natal. Proceedings of the Third International African Soil Conference 1: 677-683.

Simanton J.R, Weltz MA & Larsen HD. 1991. Rangeland experiments to parameterize the water erosion prediction model] vegetation canopy cover effects. *Journal of Range Resources Conservation District Management* (33).165-171

Srivastava, S.K. et al. 1997. Interlinkages of NOAA/AVHRR derived integrated NDVI to seasonal precipitation and transpiration in dryland tropics. International Journal of Remote Sensing. 18(14): 2931-2952.

Stocking M, Murnaghan N. 1986. Land Degradation: Guidelines for Field Assessment. OGD, University of East Anglia: Norwich.

Summerfield, M. 1991. Global geomorphology. Chapters 8 and 15.

Tadesse, T. Coleman, P. O'Neill, T. Jackson, W. Crosson, and C. Laymon (1997). Comparison of Soil Moisture Determination under Different Crop Coverages Using Remote Sensing and Conventional Methods. Proc. 13th Conf. on Hydrology, AMS, Long Beach, CA, 8 362-365.

Taguira, F, "Soil erosion and conservation techniques for sustainable crop production in Zimbabwe", JSWC, 47 (1992) pp.370-4 (EROS--4/17/95).

Tainton, N.M. 1988. A consideration of veld condition assessment techniques for commercial livestock production in South Africa. *Journal of the Grasslands Society of Southern Africa* 5: 76-79.

Tanser, F.C. (1997). The application of a landscape diversity index using remote sensing and geographical information systems to identify degradation patterns in the Great Fish River Valley, Eastern Cape Province, South Africa. MSc. thesis, Rhodes University, Grahamstown. 167 pp.

Teague WR, Trollope WSW & Aucamp AJ 1981 Veld management in the semi-arid bush-grass communities of the Eastern Cape. Proceedings Grassland Society Southern Africa 16: 23-28.

Theocharopoulos, S. P., D. A. Davidson, J. N. McArthur, and F. Tsouloucha. 1995. GIS as an aid to soil surveys and land evaluation in Greece. Journal of Soil and Water Conservation 50: 118-124

Thomas DSG, Middleton NJ. 1994. Desertification: Exploding the Myth. Wiley: Chichester.

Thompson, M. P., Joe, H. and Church, M., 1987, Statistical Modeling of Sediment Concentration: Environment Canada Report for Sediment Section, Water Survey of Canada, Water Resources Branch, Inland Waters Directorate, and Environment Canada IWD-HQ-WRB-SS-88-1.

Tongway, D. (1990). Soil and landscape processes in the restoration of rangelands. *Australian Rangeland Journal*, 12: 54}57.

Trollope, W. S. W., Trollope, L.A. & Bosch, O J H. (1990). Veld and pasture management terminology in southern Africa. J. Grassld. Soc. Sth. Afr. 7(1): 52-61.

Tueller, P.T. 1973. Secondary succession, disclimax, and range condition standards in desert shrub vegetation. In: Proceedings of the Third Workshop of U.S/Australia Rangelands Panel. Tucson, Arizona, USA.

Turner II, B. L., W. C. Clark, R. W. Kates, J. F. Richards, J. T. Mathews, and W. B. Meyer. 1990. The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere over the Past 300 Years. Cambridge University Press with Clark University, Cambridge; New York.

Turner, M.G. & Gardner, R.H. (Eds) (1991). Quantitative Methods in Landscape Ecology: The Analysis and Interpretation of Landscape Heterogeneity. New York: Springer. 536 pp.

Van der Merwe, A.J., 1995. Wise land use: The basis for sustainable growth and develop-ment in South Africa. *Proc.* A*RC-ISCW Wise Land Use Symp.* 2-15. Pretoria, South Africa.

Van der Merwe, A.J., de Villiers, M.C., Barnard, R.O., Beukes, D.J., Laker, M.C. &. Berry, W.A.J., 2000. Technical report on guidelines on the management and rehabilitation of acid and fertility declined soils in South Africa. *Proc.*

Van Olphen, H., 1977: `An introduction to clay colloid chemistry'. (Second Edition). John Wiley & Sons Inc., New York.

Vincent, R.K. 1997. Fundamentals of geologic and environmental remote sensing. Prentice-Hall, Upper Saddle River, New Jersey, USA.

Watson, H.K. and Macdonald, I.A.W., 1983: Vegetation changes in the Hluhluwe-Umfolozi Game Reserve Complex from 1937 to 1975, Bothalia, 14 (2), 265-269.

Watson, H.K., 1990: A Comparative Study of Soil Erosion in the Umfolozi Game Reserve and Adjacent Kwazulu area from 1937 to 1983, Unpublished PhD thesis, University of Durban-Westville.

Weaver, A.v.B., 1988: Changes in land use and soil erosion in South African and Ciskeian portions of the Yellowwoods drainage basin between 1975 and 1984, Earth-Science Reviews, 25, 501-507.

Weaver, A.v.B., 1991: The distribution of soil erosion as a function of slope aspect and parent material in Ciskei, South Africa, Geo Journal, 23(1), 29-34.

West, N.E., F.D. Provenza, P.S. Johnson, and M.K. Owens. 1984. Vegetation change after 13 years of livestock exclusion on sagebrush semi desert in west central Utah. J. Range Manage, 37(3):262-269.

Whitlow, R., 1986: Mapping erosion in Zimbabwe: a methodology for rapid survey using aerial photographs, Applied Geography, 6, 149-162.

Zachar, D. 1982: Soil Erosion. Developments in Soil Science 10. Elsevier Scientific Publishing Company, Amsterdam.

Zar, J.D. 1999. Biostatistical analysis. 4th Ed. Prentice Hall, Upper Saddle River, NJ.

Appendix 1: Grass Survey Analysis

Grass Survey Analysis			
Site	**Score**	**Erosion Class**	**Basal Cover Component**
1	**3 to 5**	Moderately vegetated	Moderate
2	**6 to 8**	Poorly vegetated	High
3	**3 to 5**	Moderately vegetated	moderate
4	> **9**	Bare	Excessive
5	**3 to 5**	Moderately vegetated	moderate
6	**0 - 2**	well vegetated	negligent
7	**3 to 5**	Moderately vegetated	Moderate
8	**6 to 8**	Poorly vegetated	High
9	**3 to 5**	Moderately vegetated	moderate

Appendix 2: Tree Survey Analysis

Tree Survey Analysis	
Site	**Tree Index**
1	4.852
2	3.8108
3	3.63312
4	1.2943
5	9.0555
6	5.1814
7	4.3269
8	17.7983
9	6.477

Appendix 3: Gully Classification

Gully Classification					
Site	**Average depth [m]**	**Average width [m]**	**Average length [m]**	**Gully drainage area [ha]**	**Gully classes Score**
1	0.8	22	2.5	Less than 2	1
2	1.6125	40.5	14.175	1 to 5	2
3	1.825	34	22.25	1 to 5	2
4	0.975	14.275	2.575	Less than 2	2
5	0.3975	10.25	5.25	Less than 2	1
6	0.925	11.5	5.125	Less than 2	2
7	0.49	7.5	4.7	Less than 2	1
8	1.2	6.25	4	1 to 5	2
9	1.2	10	1	1 to 5	2

Appendix 4: Measured Environmental variables

Site	pH	E.C	Bulk Density	particle Density	Clay	Silt	Sand	Tot N	Ni	Ca	Mg	K	Fe	cu	Zn	Mn	Na	SAR	ESP
	CaCl2	*uS/cm*	*g/cm3*	*g/cm3*	*%*	*%*	*%*	*%*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*		
1	5.9	200	1.15	2.51	8	16	76	0.08	125	0.41	70	24	591	57	37	78	727	43.3	7.7
2	5.2	1955	1.29	2.34	4	10	86	0.06	20	0.13	33	11	404	9	21	76	726	63.1	16.5
3	5.2	37	1.38	2.49	2	6	92	0.04	15	0.09	21	8	320	6	10	72	170	18.5	5.8
4	6.9	439	1.24	2.46	8	16	76	0.06	59	0.57	64	14	558	44	32	78	800	49.8	10.2
5	7.6	531	1.21	2.38	6	4	90	0.05	37	0.41	58	14	518	19	22	77	847	55.4	11.7
6	7.7	254	1.27	2.58	6	12	82	0.12	94	1.39	70	14	564	43	30	78	801	47.4	9.4
7	5.2	157	1.24	2.4	6	8	86	0.05	17	1.39	70	14	564	43	30	78	801	47.4	9.4
8	5.7	187	1.29	2.46	4	8	88	0.06	16	0.18	55	29	477	7	27	75	311	20.9	3.7
9	5.1	101	1.36	2.4	4	6	90	0.04	16	0.13	54	25	455	5	27	73	250	17	3.2
10	7.6	206	1.05	2.12	8	8	84	0.07	79	1.04	67	17	550	31	29	77	598	36.3	7.0

Appendix 5: Gully variables

GULLY & GULLY CHANGE VARIABLES (Dependent)

Variab ?004)	*Zone*	*Code*	*Units*	*Data Source*	*Scale*
Gully Length	Body	L & Δ*L*	m	AP 1955, 1993, 2003 & 2004, GIS	Both
Gully Density	Grid	D & Δ*D*	m/ha	AP 1955, 1993, 2003 & 2004, GIS	Both
Gully Area	Body	A & Δ*A*	m^2	AP 1955, 1993, 2003 & 2004, GIS	Large
Gully Volume	Body	V & Δ*V*	m^3	AP 1955, 1993, 2003 & 2004, GIS	Large

GULLY BODY VARIABLES) (Independent)

Gully Body Variable	*Code*	*Unit*	*Data Source*	*Scale*
Average Gully Width & Depth	BoW, BoD	m	AP 2003 & 2004, GIS	Large
Gully Width/Depth Ratio	BoW/D	Index	AP 2003 & 2004, GIS	Large
Gully Width/Length Ratio	BoW/L	Index	AP 2003 & 2004, GIS	Large
Stream order (number)	BoO	Index	AP 2003 & 2004, GIS	Both
Distance to the nearest gully	BoDist	m	AP 2003 & 2004, GIS	Both
Aver. Slope Gradient of Gully Bed	BoSGBed	°	AP 2003 & 2004, GIS	Large
Aver. Slope Gradient along Gully Surface	BoSGSur	°	AP 2003 & 2004, GIS	Large

GULLY SYSTEM VARIABLES (Independent)

Gully System Variable	*Code*	*Unit*	*Data Source*	*Scale*
Number of gullies within a system	SyGN	Number	AP 2003 & 2004, GIS	Both
Length of gullies within a system	SyGL	m	AP 2003 & 2004, GIS	Both

(AP=Aerial orthophotographs, GIS=Geographic Information System Database including derivatives from different GIS operations, DEM = Digital Elevation Model & DRS = Diffuse Reflectance Spectroscopy, SPOT = SPOT-images)

Appendix 6: List of environmental variables used in Study

pH	pH
E.C	Electric Conductivity
BD	Bulk Density
PD	Particle Density
Clay	Clay
Silt	Silt
Sand	Sand
Tot N	Tot Nitrogen
Ni	Nickel
Ca	Calcium
Mg	Magnesium
K	Potassium
Fe	Iron
Cu	Copper
Zn	Zinc
Mn	Manganese
Na	Sodium
SAR	Sodium Adsoption Rate
ESP	Exchangeable sodium percentage