



UNIVERSITY OF ZIMBABWE

FACULTY OF ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING



**SPATIAL SOIL EROSION HAZARD ASSESSMENT
AND MODELLING IN MBIRE DISTRICT,
ZIMBABWE: IMPLICATIONS FOR CATCHMENT
MANAGEMENT**

BY

FARAYI DUBE

MSC. THESIS IN IWRM

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In collaboration with

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MANAGEMENT**

BY

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**A thesis submitted in partial fulfilment of the requirements for the degree of Master of
Science in Integrated Water Resources Management of the University of Zimbabwe**

JULY 2011

DECLARATION

I, **Farayi Dube**, declare that this research report is my own work. It is being submitted for the partial fulfilment of the degree of Master of Science in Integrated Water Resources Management (IWRM) in the University of Zimbabwe. It has not been submitted before for any degree or examination in any other University.

Date: _____

Signature: _____

The findings, interpretations and conclusions expressed in this study do neither reflect the views of the University of Zimbabwe, Department of Civil Engineering nor of the individual members of the MSc Examination Committee, nor of their respective employers.

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LIST OF SYMBOLS AND ABBREVIATIONS

AGNPS	Agricultural Non-Point Source Pollution Model
ANSWERS	Areal Non-point Source Watershed Environment Response Simulation
AWF	African Wildlife Foundation
C	Cover Value
CONCEPTS	Conservational Channel Evolution and Pollutant Transport System
CREAMS	Chemical, Runoff, and Erosion from Agricultural Management Systems
C _s	Student Contrast
C _w	Contrast Weight
EGEM	Ephemeral Gully Erosion Model
EHU	Erosion Hazard Units
FAO	Food and Agriculture Organization (United Nations)
Fb	Mean Index of Soil Erodibility
GIS	Geographic Information System
GPS	Global Positioning System
HCEAC	House of Commons Environmental Audit Committee
Ib	Erosion Hazard Index
IES	Institute of Environmental Studies
IWRM	Integrated Water Resources Management
LGDA	Lower Gurnee Development Association
MDGs	Millennium Development Goals
MUSLE	Modified Universal Soil Loss Equation
P	probability value
RUSLE	Revised Universal Soil Loss Equation
SADC	Southern Africa Development Community
SLEMSA	Soil Loss Estimation Model for Southern Africa
SPI	Stream Power Index,
SSSA	Soil Science Society of America
STI	Sediment Transport Index
SWCS	Soil and Water Conservation Society
TWmap	Total Weight Map
USGS	United States Geological Services
USLE	Universal Soil Loss Equation
W ⁻	Negative weight
W ⁺	Positive Weight
WEPP	Water Erosion Prediction Project
WI	Wetness Index
WRB	World Reference Base
X	Soil Loss Ratio
ρ	Spearman's Rho

DEDICATION

To my parents, Nelia and Augustine

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ABSTRACT

Soil erosion is a natural geomorphological process resulting from water and land interactions but accelerated to become an environmental hazard by human activities such as clearing of forests for cultivation, poor farming practices and encroachment into marginal lands. Mbire District is no exception, with soil erosion manifesting in the form of gullies causing onsite adverse impacts on agricultural land, settlements and engineering structures. The main objective of this study was to assess soil erosion hazard and gully erosion occurrence in Mbire District, Zimbabwe and assess the implications for catchment management.

In this study an improved method of the Soil Loss Estimation Model for Southern Africa (SLEMSA) for soil erosion hazard assessment was used in a GIS to identify the spatial extent of potential erosion hazard for the District. The association between distribution of gullies and flood hazard, landcover, soil and terrain variables was assessed at Mushumbi Pools which forms part of Wards 4, 9, 12 and 17 of the district. Ten factors were linked to gully occurrence namely; landcover, soil type, slope, elevation, distance from river, distance from road, Sediment Transport Index (STI), Stream Power Index, (SPI) Wetness Index (WI) and flood hazard. Using factors showing significant correlation with gully occurrence, a gully erosion hazard map was developed by means of Weight of Evidence Modelling.

Results from the SLEMSA model show that Mbire District has a low and moderate erosion hazard covering 72% of the district, with pockets of high hazard occurring in areas with a combination of steep slopes, low erodibility soils, high settlement density and cultivation. Out of the 17 wards in Mbire District, 10% or more of the area of each of the Wards: 1, 2, 3, 5 and 6 was in the very high erosion hazard class. Results also show that out of the ten factors affecting gully erosion studied, seven were significantly correlated ($p < 0.05$) to gully occurrence namely; landcover, soil type, elevation, flood hazard, distance from river, STI and SPI. Three factors namely slope, WI and distance from road were not significantly correlated ($p > 0.05$) to gully occurrence. The gully erosion hazard map showed that 90% of the very high hazard class is within a distance of 250 meters from rivers. Model validation indicated that 75% of the validation set of gullies were in the high hazard and very high hazard class. The model had a prediction accuracy of 74.7 %.

In this study **it is concluded** that the SLEMSA model can be applied to assess erosion hazard in the District but cannot predict occurrence of gully erosion and Weight of Evidence Modelling has great potential in gully erosion hazard mapping. **It is recommended** that further studies could be done to establish the actual quantities of soil lost and its deposition into hydrological structures. Catchment management targeted at soil conservation may have to focus on areas with high settlement density and cultivation, especially if cultivation is expanding into fragile lands. For planning purposes, it is recommended that highly erodible soils should be allocated to landuse activities such as wildlife management which do not reduce vegetation cover. It is also recommended that policy makers have to address increases in settlement densities along rivers.

Key words: GIS, Gully Erosion, Mbire District, SLEMSA Soil Erosion Hazard, Weight of Evidence Modeling

CHAPTER 1: INTRODUCTION

1.1 Background

Soil erosion by rainfall and runoff, has been recognized as the major cause of land degradation worldwide and is increasingly becoming a major problem in many communal lands of Southern Africa (Boardman, 2006; Symeonakis *et al.*, 2009). The increasing soil erosion rates in Southern Africa are ascribed to increased clearing of forests for cultivation, poor farming practices and encroachment into marginal lands (Valentin *et al.*, 2005).

Fundamental on-site impacts of soil erosion include loss of agricultural land and loss of topsoil leading to reduction in food production (Pathak *et al.*, 2005), while off-site effects include siltation of rivers and reservoirs and deterioration of water quality (Sirviö *et al.*, 2004 and Whitford *et al.*, 2010). These impacts exacerbate poverty levels in Southern Africa, which largely relies on rain water for its agricultural production (Wani *et al.*, 2009). The efforts to eradicate poverty, which is one of the Millennium Development Goals (MDGs), can only succeed when soil erosion is kept to a minimum (HCEAC, 2007). Furthermore climate change prediction suggest that for Southern Africa, there will be a change towards a more high rainfall intensities, which will lead to increases in soil erosion rates in the future (Amore *et al.*, 2004). Therefore, planning of land and water conservation is essential. This requires knowledge of the potential erosion hazard and an understanding of the factors that cause soil erosion. The knowledge will contribute to the development of specific guidelines for the selection of the control practices best suited for the particular needs of each site. In addition, control of sedimentation in reservoirs requires that all the potentially significant sediment sources be known and characterized.

Globally it has been estimated that about 1.1 billion hectares of land is affected by soil erosion (Pathak *et al.*, 2005), with annual global loss of agricultural land due to erosion estimated at 3 million hectares (Woreka, 2004). By the year 1993 about a million hectares of agricultural land

were affected by severe gully erosion in Zimbabwe (Anderson *et al.*, 1993), with 29 million hectares of land affected in the African continent annually (Woreka, 2004).

Human activities such as deforestation, overstocking and poor agricultural practices are cited as the most triggers and accelerators of the otherwise natural process of soil erosion (Valentin *et al.*, 2005). It is reported that for Zimbabwe the demand for land is forcing people to settle along riverbeds, in mountainous areas and fragile lands exacerbating soil erosion problems in the country (SADC – ELMS and WSCU, 2000).

Soil erosion by water is expressed either in the form of splash, sheet, rill, streambank or gully erosion. Gully erosion under many circumstances has been reported to be the main source of sediment at the catchment scale (Valentin *et al.*, 2005).

An understanding of the processes and factors affecting sheet and rill erosion has enabled development of both physical and empirical models which have proven to be useful and applicable to a variety of conditions. These models include, the 1965 Universal Soil Loss Equation (USLE) by Wischmeier and Smith which was modified and adapted to other conditions through modified versions such as MUSLE (Williams and Berndt, 1977) and RUSLE (SWCS, 1993) for sediment yield and the Soil Loss Estimation Model for Southern Africa (SLEMSA) (Elwell, 1978). These models can be fully integrated into a Geographic Information System (GIS) environment to produce spatial erosion potential over large areas (Poesen, 2003). A number of studies have been done using these models ((Woreka, 2004; Wei, *et al.*, 2006, Romero-Diaz *et al.*, 2010) and for Zimbabwean conditions the SLEMSA proved to be a better tool compared to the alternatives because it requires few input data (McFarlane and Whitlow, 1990; Leanaers, 1990; Mambo and Archer, 2007), which can be readily available.

The weakness of studies done using the models mentioned above is that they do not integrate gully erosion yet soil losses and sediment production by gully erosion are far from negligible in the environments they occur (Poesen, 2003). The main reason of neglecting gully erosion is that it is often considered difficult to study and predict (Valentin *et al.*, 2005). For any holistic soil erosion hazard assessment, gully erosion should be considered. In addition, given the costly, labour intensive and often unsuccessful methods of gully erosion reclamation, catchment

management with a target of minimizing gully erosion problems can only be possible if the susceptibility of gully erosion can be mapped in advance. It is therefore important to apply modelling approaches because prediction expertise used for estimation of soil loss is regarded as a suitable tool in depicting the nature of the factors governing erosion (Morgan, 1995). Models have been developed in predicting gully erosion for example the Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1980), the Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995). Also the Ephemeral Gully Erosion Model (EGEM) (USDA-SCS, 1992) and the Conservational Channel Evolution and Pollutant Transport System (CONCEPTS) (Langendoen et al. 1998). The main disadvantage in all these models is that they require much data and are costly to undertake and they are not applicable over large areas (Valentin *et al.*, 2005). For Zimbabwe very little efforts have been done in trying to understand the driving forces of gully erosion using regression analysis (McFarlane and Whitlow, 1990; Dondofema, 2007). A GIS based statistical technique called Weight of Evidence Modelling (Bonham-Carter *et al.*, 1988) has the potential of modelling gully erosion hazard. Weight of Evidence Modelling is said to be more realistic compared to predictors selected and weighted through a method of multivariate analysis such as logistic regression (Ghosh *et al.*, 2011)

1.2 Problem Statement

There is generally little understanding of the interaction between the natural and anthropogenic factors affecting soil erosion and the magnitude of soil erosion hazard in Mbire District. For the purposes of landuse and water resources planning there is a need for improved understanding of the spatial variation of soil erosion hazard, soil erosion processes *i.e.* sheet, rill and gulley erosion and their link with environmental factors at the local and catchment scale.

1.3 Objectives

1.3.1 Main Objective

To analyse soil erosion hazard in Mbire District as a function of environmental factors, as well as assess its magnitude as an environmental threat to water resources in Mbire District of Zimbabwe.

1.3.2 Specific Objectives

1. To assess the spatial variation of erosion hazard in Mbire District using an improved method for erosion hazard mapping based on the empirical model SLEMSA.
2. To analyze the influence of flooding, landcover, soil and terrain variables on the distribution of gullies.
3. To determine the spatial distribution of gully erosion hazard using Weight of Evidence Modelling.

1.3.3 Specific Research Questions

1. What is the extent of soil erosion hazard in Mbire District?
2. Does flooding, landcover, soil and terrain variables have an influence on the distribution of gullies?
3. Can high gully hazard areas be predicted using Weights of Evidence Modelling in Mbire District?

1.4 Scope and Limitations

This study focused on soil erosion and attempted to give answers on a district scale to the questions; where is erosion occurring? Why is it happening? And how serious is it? Soil erosion is within a broad subject called land degradation. The study attempts to provide information useful for best response strategies for sustainable catchment management for soil conservation and landuse planning. Though it is important to assess the fate of the eroded soil particularly in hydrological structures such as rivers and reservoirs this study was limited to assessment of the potential sources of sediments and the factors affecting these sources. For soil erosion hazard assessment using the SLEMSA model, the research relied on a 2008 Landsat satellite image mainly because recent cloud free images were not available. In addition Weight of Evidence Modelling for gully erosion hazard was done only for a subset of the district, the given time frame did not allow for the collection and analysis of the data for the whole district.

1.5 Justification of the Study

This study uses Mbire District in the Manyame Catchment of Zimbabwe as a case study. Mbire District due to its erosion prone soils which are mostly sodic and the prevalence of tsetse flies (*Glossina spp.*), was originally a wildlife zone. However due to population pressure some areas were opened for settlement (Kusena, 2009). The opening up of these areas for settlements has led to the increase in cultivation (IES, 2009). The farming practices include seasonal encroachment into flood-prone areas (Chenje, 2000), stream bank and riverbed cultivation in search for residual moisture. Poor cultivation practices expose the soil to erosion by water. Land use in the district is influenced by the degree of flooding, with cultivation and settlements intensifying along rivers (Fritz *et al.*, 2003; AWF, 2010). Flooding is prominent in the area partly due to the proximity of the area to the Zambezi River with operations of the reservoirs within the Zambezi (namely; Kariba, Cahora Bassa, Luangwa and Kafue Dams) causing throw back. In addition flooding occurs due to flows generated upstream of the District. Soil erosion in the District is prominent; distinctly gully erosion is causing onsite adverse impacts on agricultural land, settlements and engineering structures (IES, 2009). Due to the district's proximity to the Cahora Bassa Dam the resultant sediment can have a significant contribution to sediments into the reservoir since according to Sanjay *et al.* (2002), erosion occurring within short distances to downstream reservoirs contributes the most sediments. The sediments reduce reservoir storage capacity and affect the dependent ecosystem Sanjay *et al.* (2002). Given the increasing cultivation and settlements, it is imperative to establish the nature of their relationship among other land uses and terrain variables with soil erosion. Furthermore, since the area is generally flood prone, this makes it again highly crucial to establish the nature of the link specifically between gully erosion and flood hazard. Such information is indispensable in sustainable land use planning and synchronisation of the reservoirs within the Zambezi Basin.

1.6 Report Layout

The report of this study is presented in six chapters. Chapter 1 gives an introduction to the study by highlighting the background to the soil erosion problem and its importance at the global and local scales. The chapter also presents the problem statement, objectives and justification for carrying out the study. Chapter 2 covers a review of literature on soil erosion and describes theoretical underpinnings of the methods. The chapter also discusses techniques of assessment of

soil erosion and their weaknesses. Chapter 3 presents the study area showing the location of the study area, climate, and soils and describes the problem of soil erosion in the study area. Materials and methods are discussed in Chapter 4; this consists of data collection, methods adopted to achieve objectives and the analysis procedures. Chapter 5 presents results and discussions for each objective. Finally the conclusion and recommendations derived from the study are presented in Chapter 6.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This Chapter presents a review of literature on accelerated soil erosion as an environmental hazard, forms of soil erosion and how soil erosion is related to environmental factors. The review will also focus on methods of soil erosion hazard assessment with emphasis on the methods to assess the main processes of soil erosion which are splash, sheet, rill, gully and streambank erosion and spatial erosion hazard assessment techniques. The review will address theoretical principles of the analysis methods. Finally, the review tackles the need for coming up with holistic conservation strategies for soil erosion in catchment management.

2.2 Soil Erosion

Soil erosion is a geomorphological process of landscape development (Felix-Henningsen *et al.*, 1997). However it is accelerated by the removal of vegetation cover and improper landuse to become an environmental hazard. There are basically two natural forces causing soil erosion these are wind and water. Under subtropical areas water erosion far much outweighs the effects of wind erosion due to high intensity of rainfall in these areas (Igwe *et al.*, 1999).

Water erosion occurs when raindrops strike unprotected (bare) soil surfaces or when runoff water flows across erodible and unprotected soils at a rate sufficiently rapid to detach soil. The main types of water erosion are gully, rill, sheet, splash, and streambank (Unger *et al.*, 2006). Basically the process of water erosion involves three types of soil movement. These are detachment of individual particles from the soil mass, transport of detached particles across the surface and deposition of transported particles as they fall out of suspension at the new site (Unger *et al.*, 2006).

Splash erosion is the loosening and splattering of small soil particles caused by impacting raindrops on a wet soil surface. The distance to which the particles are moved by the splash is

relatively small, and the particles may or may not be removed when runoff occurs. The raindrop, however, is a complete erosive agent within itself and little or no water erosion occurs when soil surfaces are protected by ample cover (Unger *et al.*, 2006). Unger *et al.* (2006) further stresses that raindrop impact usually is the force that initiates most water erosion.

Sheet erosion is the removal of a fairly uniform, thin layer of soil from the land caused by raindrop splash or water flowing across the surface. Raindrops provide most of the energy for detaching soil particles and over-surface flow is the primary transport mechanism (Troeh *et al.*, 1991).

Rill erosion results in numerous small channels caused by intermittent water flow during or immediately after a rain or when snow melt occurs. Rills usually are several centimetres deep with relatively-steep sides, occur most frequently on recently-tilled land, and do not interfere with and can be eliminated by normal cultural operations (SSSA, 1997).

Gully erosion is a more severe form of erosion and is identified as relatively deep permanent steep-sided recently-formed water courses which experience ephemeral flows during rainstorm existing on valley sides and on valley floors where there was no well-defined channel previously (Morgan, 1995). 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 (Morgan, 1995).

Streambank erosion is the scouring of soil materials and cutting of streambanks by water flowing in streams. Areas impacted by stream bank erosion usually are relatively small, but soils of those areas often are highly productive, thereby resulting in significant productivity losses (Troeh *et al.*, 1991).

2.3 Dynamics of soil erosion

Soil erosion is the main source of sediment that pollutes rivers and fills reservoirs. A decrease in soil quality invariably leads to a decrease in water quality, and often in air quality. Globally, about 1.1 billion hectares of land is affected by erosion (Pathak *et al.*, 2005), with annual global loss of agriculture land due to erosion estimated at 3 million hectares (Woreka, 2004). According to Pathak *et al.* (2005) a continuation of high soil 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.

The main factors affecting soil erosion particularly sheet and rill erosion have been discussed by various authors world over (Valentin *et al.*, 2005; Wei *et al.*, 2006; Boardman, 2006; Romero-Diaz *et al.*, 2010) and for Zimbabwe (Elwell, 1978; McFarlane and Whitlow, 1990; Leenaers, 1990; Mambo and Archer, 2007). The main findings indicate that the rainfall amount and intensity, topographic factors such as slope and slope length and vegetation cover are the factors affecting splash, sheet and rill erosion. An understanding of the processes and factors affecting sheet and rill erosion have enabled development of both physical and empirical models which have proven to be useful and applicable to a variety of conditions for example the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965), which has been adapted to other conditions through modified versions such as MUSLE (Williams and Berndt, 1977), RUSLE (SWCS, 1993) for sediment yield and the Soil Loss Estimation Model for Southern Africa (SLEMSA) (Elwel, 1978). GIS based models are also available such as Areal Non-point Source Watershed Environment Response Simulation (ANSWERS) (Beasley *et al.*, 1980), Agricultural Non-Point Source Pollution Model (AGNPS) (Young *et al.*, 1987) and the WaTEM/SEDEM (Van Rompaey *et al.*, 2001). These models are based on grid cells and were developed to estimate runoff quality, with primary emphasis on sediment and nutrient transport.

The models have revolutionised soil erosion management particularly in that they can be applicable over large geographic areas (Stocking, 1988). The SLEMSA Model has been used in Southern Africa for example it has been used to assess erosion rates in Botswana, South Africa and Malawi (Mkanda, 2000). In Zimbabwe SLEMSA has been applied in-small scale farming areas (Elwell, 1978). These studies concluded that SLEMSA is a useful tool for determining erosion hazard, particularly the improved version for erosion hazard assessment over large areas. (Stocking *et al.*, 1988) Therefore this review will concentrate on the least understood form of erosion, gully erosion yet it is the most permanent in areas it does occur and the main contributor of sediments in rivers and reservoirs at the catchment scale (Valentin *et al.*, 2005; Pathak *et al.*, 2005).

2.3.1 Environmental impacts of gullies

Gully erosion is geographically a widespread problem (Lal, 1992) and is the worst stage of soil erosion. For semi-arid regions, characterized by vulnerable landscape and flash floods gullies are quite substantial and their effects cannot be overlooked (Pathak *et al.*, 2005). About a million hectares of agriculture land are affected by severe gully erosion in Zimbabwe, with the figures rising to 29 million hectares of land in the African continent annually (Anderson *et al.*, 1993). Gullies have a potential to cause substantial impacts on water quality, aquatic ecosystems and infrastructure. At the catchment scale, they result in high sediment yields which in turn, cause downstream sedimentation and deterioration of water quality (Prosser and Winchester, 1996; Whitford *et al.*, 2010). Gullies can affect catchment hydrology typically resulting in higher flood peaks and reduced baseflow persistence (Rutherford *et al.*, 1996). Gully erosion is often associated with the changes in catchment hydrology brought about by anthropogenic factors such as forest clearing and agricultural or grazing and land uses that lead to poor groundcover (Sidorchuk, 1999). Gully erosion is more difficult and expensive to control than sheet and rill erosion. It is also more spectacular than inter-rill erosion. Contrary to sheet and rill erosion, the damage done to land by gully erosion is said to be permanent (Pathak *et al.*, 2005).

2.3.2 Factors affecting gully erosion

Most of the gullies are formed due to human activities. Some of the major causes of gully formation are overgrazing due to high cattle population, 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. Gully erosion is affected by several factors. Some factors determine the potential hazard while others determine the intensity and rate of gully advancement. The factors affecting gully erosion can be categorized into two groups: anthropogenic and physical factors (Pathak *et al.*, 2005).

Physical factors

Gullies are formed by increased runoff which acts as a cutting agent. The main physical factors which affect the rate and amount of runoff are rainfall, topography, soil characteristics, and profile.

Rainfall

Rainfall is obviously an important factor. For a given condition, there is direct relationship between the rainfall and runoff. Big storms can cause severe gulling. Intense rains coupled with soils prone to sealing and crusting, generate high runoff volume and concentrated flow (Lal, 1992; Pathak *et al.*, 2005). The force generated by the runoff flow causes gully erosion especially in semi-arid regions characterized by scanty vegetation cover. However at micro catchment level the effect of rainfall cannot be expressed because rainfall does not differ much on a small spatial area (Boardman, 2006).

Topography, shape and size of watershed

The size and shape of a drainage area as well as the length and gradient of its slopes have a major effect on the runoff rate, volume and flow velocity. The Wetness Index (WI) (Beven and Kirkby, 1993) and the Stream Power Index (SPI) have been developed to cater for the effects of topography and drainage area contributing to a gully. WI (Eqn 2.1) sets catchment area in relation to the slope gradient. The WI gives the spatial distribution and zones of saturation or variable sources for runoff generation.

$$WI = \ln(\alpha / \tan(\beta)) \quad \text{Eqn. 2.1}$$

Where: α = upslope contributing area

β = the local surface gradient.

The larger the watershed, the greater the amount of runoff, large watersheds have greater chances of gully erosion than small watersheds (Sulebak *et al.*, 2000). The shape of the watershed has strong relationship with the time of concentration and peak runoff rate. If the time of concentration is high, peak runoff rate will be low. The stream power index is the product of catchment area and slope and it gives the spatial distribution of concentrated surface runoff (Sulebak *et al.*, 2000).

The steeper the slope, the higher the velocity and erosive power of the runoff, this is one of the most important factors of gully erosion. Also, if the slope length is long, the possibility of gully formation is high (Pathak *et al.*, 2005). An index was developed to account for the effect of slope length on sediment transport called Sediment Transport Index (STI) (Sulebak *et al.*, 2000). The STI accounts for the effect of topography on erosion. The two-dimensional catchment area is

used instead of the one-dimensional slope length factor as in the Universal Soil Loss Equation and SLEMSA Model

Soil properties

Soil type affects the occurrence of erosion in an area. Some soils are more prone to gully erosion than others. A soil with a coarse texture, highly permeable surface horizon with an abrupt transition to slowly permeable subsoil is normally prone to gully erosion. For example, sodic soils are more susceptible to gully erosion due to their dispersive nature (Ford *et al.*, 1993). Sodic soils have a highly dispersible clay fraction and are highly impermeable; this makes them highly susceptible to piping and to erosion (Thompson and Purves, 1978; Ford *et al.*, 1993).

Vegetative cover

Vegetative cover intercepts rainfall, maintains soil structure and infiltration and provides resistance to runoff flow. Forested areas experience less erosion in the form of gullies than bare soil (Harvey, 1992; Zheng, 2006). Deforestation makes the soil bare and vulnerable to the erosive power of raindrops and runoff. Zheng (2006) concluded that erosion rates in the deforested areas were from 797 to 1682 times greater than those in the forested land prior to deforestation.

Floods and Erosion

Floods can promote soil erosion, EI-Swaify *et al.* (1982) describes classic cases of flooding and associated soil erosion in Tanzania, Severe short duration flash floods caused a considerable silting with 1,100 tons of sediment being removed from Morogoro Township. Floods can also cause sediment deposition particularly in flood plains with the clay and silt rich sediments being resistant to erosion and thus causing gully occurrence in these areas to be minimal.

Anthropogenic factors

Improper land use

According to Pathak *et al.* (2005), due to the increasing demand for agricultural land, people cut trees, burn litter and grasses, and cultivate annual crops on hillsides without using appropriate conservation measures. After a few years, the productivity of the soil is lost because of sheet, rill and gully erosion, and the land is abandoned. This kind of cultivation is repeated by farmers on

other hillsides until the land loses its productivity there as well. Thus, the whole area may be completely destroyed by gulling as the gully heads advance to the upper ends of the watershed.

Overgrazing

High cattle population and overgrazing constitute a major factor for gully formation in Africa. Uncontrolled overgrazing leads to denudation of vegetation. Cattle grazing in and around active gullies extend the nick point and dimensions of the gullies. Overgrazing removes much of the soils protective vegetative cover and trampling compacts the soil, thus the infiltration capacity of the soil is reduced. The increased runoff due to reduced infiltration produces new gullies or enlarges old ones (Morgan, 1995; Pathak *et al.*, 2005).

Burning

Burning is another widely practiced system of pasture renovation. It leads to a rapid denudation and exposure of land to torrential rains (Pathak *et al.*, 2005).

Improper land development

Often the land development works, viz., construction of water storage structures, drains and bunding, are not done properly. Consequently failure of hydraulic structures or breaching of bunds occurs often resulting in sudden release of high volume of water. This results in the formation of gully particularly on steep lands (Pathak *et al.*, 2005).

Road construction, livestock and vehicle trails

Road construction through steep lands, without adequate provision for drainage, is a major cause of gully erosion. Inadequate drainage systems for roads such as small number of culverts, insufficient capacity of road ditches, are some of the causes of gulling. Although the road-caused gully erosion may occur anywhere in the world, the problem is particularly severe in developing countries due to neglect in maintenance and the lack of provision for safe outlets for excess runoff (Pathak *et al.*, 2005). Gullies are also formed on livestock and vehicle trails that run along hillsides. Unplanned land use can disturb the natural drainage ways. Non-availability of water supplies in the rural communities necessitates villagers to walk to the springhead. Sunken footpaths made up-and-down the slope become the focus of concentrated flow that eventually turns into gullies. This leads to the development of new footpaths that also turn into gullies later on (Pathak *et al.*, 2005).

2.4 Determination of erosion hazard

2.4.1 Splash, sheet and rill

According to Stocking *et al.*, (1988) a soil loss model is a way of bringing together the various factors and processes in erosion in such a way that they most faithfully reproduce what occurs in reality and soil loss is predicted accurately. However soil erosion is a result of complex factors and interrelationships and usually a perfect model with universal applicability and extension to any combination of circumstances is unattainable. A number of soil loss estimation models have been developed both empirical and physical models are available for assessing soil erosion. One of the earliest models of soil loss is the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1965). This model was modified to the Revised Universal Soil Loss Equation RUSLE (SWCS, 1993). Another modified form of the USLE, Soil Loss Estimation Model for Southern Africa (SLEMSA) (Elwell, 1978) has been developed for Zimbabwean conditions. It combines basic data with use of locally-available data and an emphasis on some of the most important interactions in tropical environments especially that between vegetation cover, raindrop interception and rainfall erosivity.

The SLEMSA framework (Figure 2.1) has been used to develop a useful method for soil erosion hazard assessment (Stocking *et al.*, 1988). The modified method for erosion hazard assessment modifies the crop physical system to incorporate vegetation cover and this is the main distinction with the original SLEMSA model. Also interpretation of the erosion hazard is in Erosion Hazard Units (EHU) and not in tonnes per hectare per year as in the original SLEMSA Model.

2.4.2 Factors in erosion hazard assessment using the SLEMSA model

For erosion hazard assessment the relief factor, accounts for all the influences of the topography and shape of the land; the rainfall factor expresses the energy transfer and splash from the action of rain drops, and the input to overland flow of water. It also consists of the vegetation factor which integrate the protective effect of vegetation over a wide range of land uses and farming systems; and finally the soil factors which include the resistance of soils to erosion and transport (Stocking *et al.*, 1988).

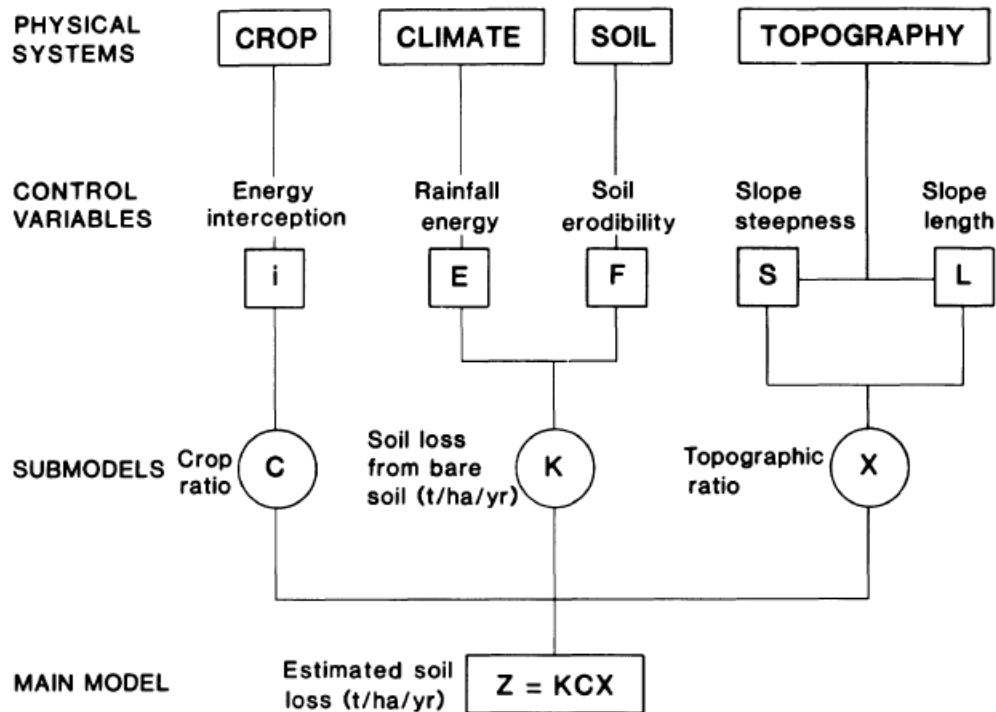


Figure 2.1: The SLEMSA Model - from Elwell and Stocking (1982) in Stocking *et al.* (1988)

Strength of the SLEMSA model

The SLEMSA model ensures that curvilinear relationships such as erosion and vegetation cover are accommodated and it provides a more realistic way of combining factors, other than by simple addition. It also gives adequate relative weighting to the factors and thus addressing the more important interactions (Stocking *et al.*, 1988; Leenaers, 1990).

Limitations of the SLEMSA model

The main limitation of the SLEMSA model is that it assumes that each factor in erosion has equal weight and importance, which is not true because under tropical conditions erosion rates are far more sensitive to changes in vegetation than to changes in soil type (Stocking *et al.*, 1988). Secondly, the technique uses the ordinal or ranking scale of measurement where erosion is implicitly linearly related to the rank of the variable. This ignores, for example, the important exponential relationship between vegetation cover and erosion (Elwell and Stocking, 1976 in Stocking *et al.*, 1988), meaning that a change in cover from 10 to 20% is proportionately far

more effective in reducing erosion than a change from 70 to 80%. Thirdly, it assumes that erosion hazard is the sum effect of each variable, ignoring known complex interactions.

2.4.3 Modelling gully erosion

A number of methods have been of use in modelling gully erosion; these include use of multi-temporal aerial photos and multi-temporal Digital Elevation Models (DEM) (Nachtergaele and Poesen, 1999; Wijdenes *et al.*, 2000; Shibru *et al.*, 2003). Gully erosion surveys based on aerial data have a great potential and results of the ephemeral gully erosion surveys based on high-altitude stereo aerial photos done in Belgium fit reasonably well with the results of other surveys carried out in the field in the Belgian loess belt (Nachtergaele and Poesen, 1999). Applying these techniques for erosion assessment in Zimbabwean conditions is hampered by the absence of DEMs and aerial photos for multiple dates. Satellite imagery have been useful in gully mapping, assessment and monitoring (Dondofema, 2007; Mulowoka, 2008).

Models have been developed in predicting gully erosion for example the Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1980), the Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995). Also the Ephemeral Gully Erosion Model (EGEM) (USDA-SCS, 1992) and the Conservational Channel Evolution and Pollutant Transport System (CONCEPTS) (Langendoen *et al.* 1998). The main disadvantage in all these models is that they require much data and are costly to undertake and they are not applicable over large areas (Valentin *et al.*, 2005) This therefore makes gully erosion the least understood process. For Zimbabwe very little efforts have been done in trying to understand the driving forces of gully erosion (McFarlane and Whitlow, 1990; Dondofema, 2007). Moreover most gully reclamation efforts done are successful only at the farmers scale (Valentin, *et al.*, 2006; Boardman, 2006) with very little achievements at the catchment scale. Efforts to contain gully erosion in the communal areas have achieved very little, and often the approaches undertaken to control erosion have proven to be failing (Anderson, 1993). For catchment management there is need to identify primarily the factors affecting gully erosion as a gateway for gully hazard modelling. A GIS based statistical technique called Weight of Evidence Modelling (Bonham-Carter *et al.*, 1988) has the potential of doing the job with ease, and will be the basis for

determining the relationship of gully erosion with environmental factors and modelling gully erosion hazard.

Weight of Evidence Modelling of gullies

Weight of evidence modelling is based on a statistical bayesian bivariate approach, and was originally developed for mineral potential assessment (Bonham-Carter *et al.*, 1988; Agterberg *et al.*, 1990). Several authors have applied the Weight-of Evidence method to mineral potential mapping using GIS in many countries (Alok and Hale, 2000; Emmanuel *et al.*, 2000; Harris *et al.*, 2000; Venkataraman *et al.*, 2000; Asadi and Hale, 2001). Weight of evidence modeling application has been also useful in landslide susceptibility mapping (Lee *et al.*, 2002; Mathew *et al.*, 2007; Bui *et al.*, 2008; Barbieri and Cambuli, 2009; Regmi *et al.*, 2010). The method has also been used for habitat quality assessment (Romero-Calcerradaa and Luqu, 2006). Because the weight of evidence approach is a probabilistic model relying on factors affecting a particular phenomenon, it is applicable to a variety of phenomena as long as the evidential themes are available. Furthermore weight of evidence modelling is said to be more realistic compared to predictors selected and weighted through a method of multivariate analysis such as logistic regression (Ghosh *et al.*, 2011). The distinction in this study is the application of a GIS based weight of evidence method to gully erosion susceptibility mapping.

Advantages of Weight of Evidence Modelling

The method calculates the weighted value of the factor statistically and thus avoids the subjective choice of weighting factors. Also in a GIS these multiple weighted maps can be combined by writing a script. The other advantage is that input maps with missing data (incomplete coverage) can be accommodated in the model. Furthermore under-sampled data do not significantly impact the results and finally the method provides a technique to avoid the use of data that are inter-correlated through testing for independence (Regmi *et al.*, 2010).

Weaknesses of Weight of Evidence Modelling

The main shortcomings of the model are that the weight is dependent on the number of gully pixels used on the modelling process. The method overestimates or underestimates weights if the area of a factor class is very small and the gullies are not evenly distributed. Moreover the method creates a number of possible combinations of the conditionally independent factors. To

determine what combination of factors is appropriate, assessment of the performance of each combination is necessary, which is a lengthy process. Furthermore the weight values calculated for different areas are not comparable in terms of the degree of hazard. This is possible only if the weights are standardized or converted to probability values (Regmi *et al.*, 2010).

Statistical description of Weight of Evidence Modelling

The theory behind weight of evidence modelling has been explained by Bonham-Carter *et al.* (1994); Van-Western (2003) and Barbieri and Cambuli (2009) among other authors. The weight of evidence method is based on the Bayes theorem and on the concepts of prior and posterior probability, for assessing the relations between the spatial distribution of the areas affected by gullies and the spatial distribution of the analyzed gully susceptibility factors (or parameters). It is therefore possible to calculate the degree of influence that each factor had, and will have in the future, on the development of gullies. If a part A_g of the studied area is affected by gullies, the prior probability (P_g) of finding a gully within total studied area (A_t) is:

$$P_g = \frac{A_g}{A_t} \quad \text{Eqn 2.2}$$

Where: P_g = prior probability of gully occurrence

A_g = gully area

A_t = total study area

This initial estimation can be then increased or decreased depending on the relations between analyzed factors and gullies. The probability of finding one of the factors examined in the study area (P_f) is given by:

$$P_f = \frac{T_f}{A_t} \quad \text{Eqn 2.3}$$

Where: P_f = probability of gully occurrence of one of the factors

T_f = total area occupied by a certain class of a certain factor

For the whole area surveyed, the probability of finding a gully in the areas occupied by the n class of the j parameter ($P\{A_g/T_f\}$) is the ratio between the probability of finding a gully inside

the territory occupied by the n class of the j parameter and the probability of finding an area occupied by the n class of the j parameter in the whole territory:

$$P\{A_g/T_f\} = \frac{P(T_f \cap A_g)}{P_f} = \frac{P(T_f/A_g)}{P_f} \times P_g \quad \text{Eqn 2.4}$$

Similarly, the posterior probability of finding a gully in the areas not occupied by the n class of the j parameter ($P\{A_g/\overline{T_f}\}$) is:

$$P\{A_g/\overline{T_f}\} = \frac{P(\overline{T_f} \cap A_g)}{\overline{P_g}} = \frac{P(\overline{T_f}/A_g)}{\overline{P_g}} \times P_g \quad \text{Eqn 2.5}$$

Where: $\overline{T_f}$ = areas not occupied by the factor and

$\overline{P_g}$ = is the area not occupied by gullies.

In this method positive and negative weights (W^+ and W^-) are assigned to each pixel of the factor maps. The weights are calculated by the following equations:

$$W^+ = \ln \frac{P\{T_f/A_g\}}{P\{T_f/\overline{A_g}\}} = \ln \left(\frac{\frac{T_f \cap A_g}{A_g}}{\frac{T_f \cap \overline{A_g}}{\overline{A_g}}} \right) = \ln \left(\frac{\frac{\text{Gully area in class}}{\text{Total gully area}}}{\frac{\text{Stable area in class}}{\text{Total Stable Area}}} \right) \quad \text{Eqn. 2.6}$$

$$W^- = \ln \frac{P\{\overline{T_f}/A_g\}}{P\{\overline{T_f}/\overline{A_g}\}} = \ln \left(\frac{\frac{\overline{T_f} \cap A_g}{A_g}}{\frac{\overline{T_f} \cap \overline{A_g}}{\overline{A_g}}} \right) = \ln \left(\frac{\frac{\text{Total gully area in other class}}{\text{Total gully area}}}{\frac{\text{Total Stable area in other class}}{\text{Total Stable Area}}} \right) \quad \text{Eqn 2.7}$$

The positive weight (W^+) is directly proportional to the influence that the n class of the j parameter has on gully development. For each factor, W^+ is used for those pixels of a factor (represented as a class in a multi-class map) to indicate the importance of the presence of the factor for the occurrence of gullies. If W^+ is positive the presence of the factor is favourable for the occurrence of gullies, and if W^+ is negative it is not favourable. The negative weight (W^-) is used to evaluate the importance of the absence of the factor for the occurrence of gullies. When W^- is positive the absence of the factor is favourable for the occurrence of gullies, and when it is not the absence is not favourable. Weights with extreme values indicate that the factor is useful for the susceptibility mapping, while factors with a weight around zero have no relation with the occurrence of gullies.

The advantage of using the log-linear model over the ordinary probability expression is that the weights are easier to interpret than probability factors. Because a positive weight implies that the (evidential theme-training points) association is greater than would be expected due to chance, it is relatively easy to understand the results. The calculation of the posterior logit is easy to follow (and program) because adding weights together is similar to the intuitive approach for combining evidence based on common sense (Romero-Calcerrada and Luque, 2006).

To analyze the influence of several parameters on the distribution of gullies in the area, the weights of each parameter are expressed as odds and summarized, as these parameters are mutually statistically independent:

$$\ln O_T\{A_g|T_{f1}^k \cap T_{f2}^k \cap T_{f3}^k \dots \cap T_{fn}^k\} = \sum_{i=1}^n W_{fi}^K + \ln O_g \quad \text{Eqn 2.8}$$

Where k can take the sign + or - depending on the presence or absence of this parameter.

For Eqn. 2. 8 to apply the binary patterns, of the factor should be conditionally independent from each other. The condition of independence is satisfied by Eqn. 2.9.

$$N\{F_1 \cap F_2 \cap G\} = \frac{N\{F_1 \cap G\}N\{F_2 \cap G\}}{N\{G\}} \quad \text{Eqn 2.9}$$

The left side of Eqn. 9 is the observed number of occurrences in the overlap zone of Factor 1 and Factor 2. The right side is the predicted number of occurrences in this overlap zone.

The difference between the positive (Eqn. 2.6) and negative (Eqn. 2.7) weights, as computed for each class of each parameter analyzed, is a good indicator of its relation with gullies:

$$C_w = W^+ - W^- \quad \text{Eqn 2.10}$$

Where C_w is contrast of each factor class

The contrast factor is 0, when the gully pattern and map class pattern overlap only by the expected amount due to chance. It is positive when there is a positive association between the two patterns and negative when there is a negative association between the two patterns. The Studentized value of Contrast (C_s) is a useful measure which serves as an approximate test of the spatial association between the occurrence of gullies and the influencing factor. It tests whether

C is significantly different from zero. (Bonham-Carter, 1994, Asadi and Hale, 1999; Carranza and Hale, 2002).

CHAPTER 3: DESCRIPTION OF THE STUDY AREA

3.1 Location of study area

The study area is the Mbire District of Zimbabwe located in the Manyame Catchment and occupying the Middle Zambezi Valley, between 30.60° and 31.20° East and 15.60° and 16.40° South (Figure 3.1). In this study, spatial coordinates are presented either in geographic or UTM coordinates system, the district falls within UTM Zone 36K. Mbire District has 17 wards (Figure 3.2) and it covers an area of approximately 4700 km². The study is divided into two parts, the first part focusing on sheet and rill erosion hazard for the whole district and the second part focusing on gully erosion modelling at Mushumbi Pools which forms part of Wards 4, 9, 12 and 17 of the district (Figure 3.3). The later covers an area of 30.7 km² and was selected because it has high gully activity. Mbire District is characterized mainly by the former floodplains of the Zambezi river basin, at an average altitude of 400 meters above sea level, and drained by the rivers Mwanzanutanda, Angwa, Manyame, Musengezi and Kadzi.

Mbire District is surrounded on most sides by wildlife areas. The western boundary is in the Chewore Safari Area while a significant part of the southern boundary is adjacent to the Doma Safari Area. Both of these areas are hunting concessions and settlements are not permitted. In the east, part of the District is adjacent to the Mavuradonha Wilderness Area in the Muzarabani District. Along the Mozambican border the District is adjacent to the Magoe District. People and wildlife coexist in the district, which is characterized by two contrasted habitats: a dense human settlement with crop lands, and a wooded savannah. Settlements are limited to areas along the major rivers and parts of the Cahora Bassa lakeshore (AWF, 2010).

A map of Spain divided into 17 numbered regions. Region 1 is the northernmost, colored light yellow. Region 2 is a large red area on the west coast. Region 3 is a light tan area to the east of region 2. Region 4 is a large yellow area in the northeast. Region 5 is a small orange area in the far northeast. Region 6 is a small orange area in the southeast. Region 7 is a small brown area in the southeast. Region 8 is a light tan area in the south. Region 9 is a light green area in the south. Region 10 is a light green area in the south. Region 11 is a light green area on the west coast. Region 12 is a bright green area in the center. Region 13 is a dark green area in the northeast. Region 14 is a dark green area in the southeast. Region 15 is a dark grey area in the southeast. Region 16 is a dark green area in the south. Region 17 is a dark green area in the center. A north arrow is located in the top right corner.

Farayi Dube - June 2011

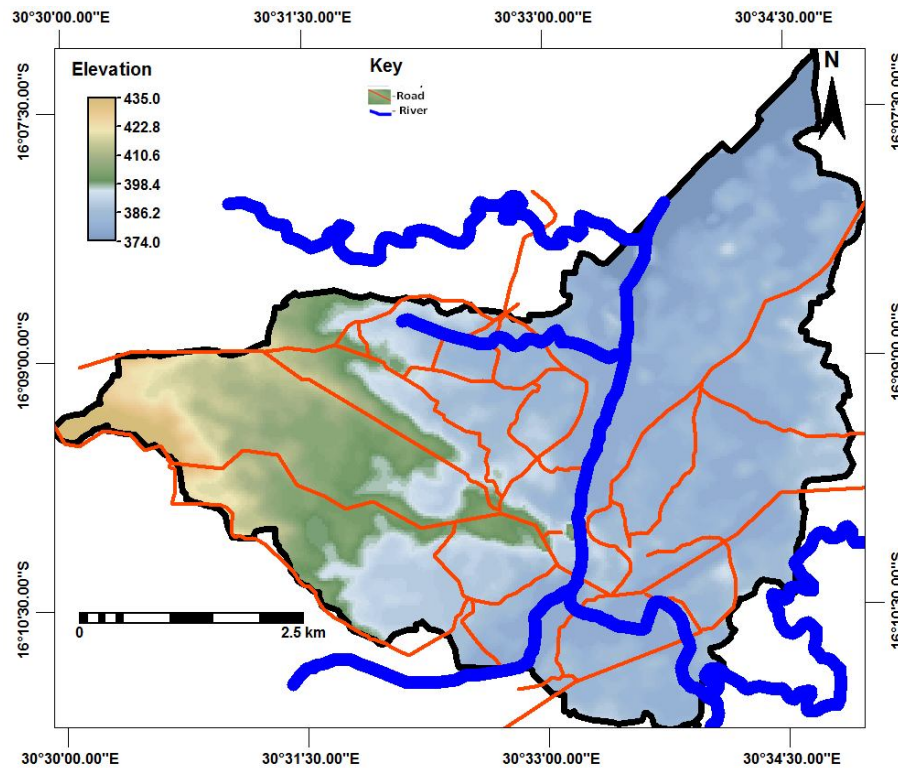


Figure 3.3: Location of gully erosion study area showing rivers and roads- Mushumbi Pools

3.2 Climate

Mbire District is in Zimbabwe's Natural Agro-ecological region IV (Figure 3.4). The climate is dry tropical, with low and very variable annual rainfalls of approximately 650-700 mm but it is highly variable with one year in four being below 500/550 mm and one in four being above 800/850 mm. The rainy season lasts a little over 100 days per annum between November and March. The rainfall is characterized by high intensities with around 40 days on which rain will fall this leads to high soil erosion rates. The district has a mean annual temperature of 25 °C. The months; October and November, which precede the arrival of the rains, are the hottest months with maximum temperatures of over 40 °C, whereas June and July have a minimal temperature around 10 °C (Fritz *et al.*, 2003; AWF, 2010).

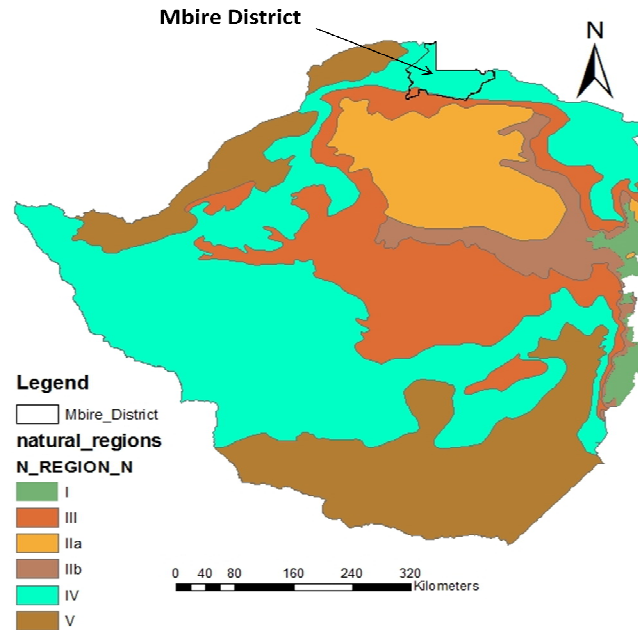


Figure 3.4: Location of Mbire District in relation to Natural Regions of Zimbabwe

3.3 Soils

Mbire District has a diversity of soils (Figure 3.5), however a significant part of the district is characterized by calcic solonetz soils, and these soils are sodic (FAO, 2006). Sodic soils have a highly dispersible clay fraction and are highly impermeable; this makes them highly susceptible to piping and to erosion (Thompson and Purves, 1978). Nyamepfene (1991) points out that the use of such soils for agriculture should be done with care and well thought management because poor management of these soils results in massive land degradation. Observations in the area show that land management is lagging behind degradation and soil erosion particularly gully erosion (Figure 3.6) has become an environmental concern.

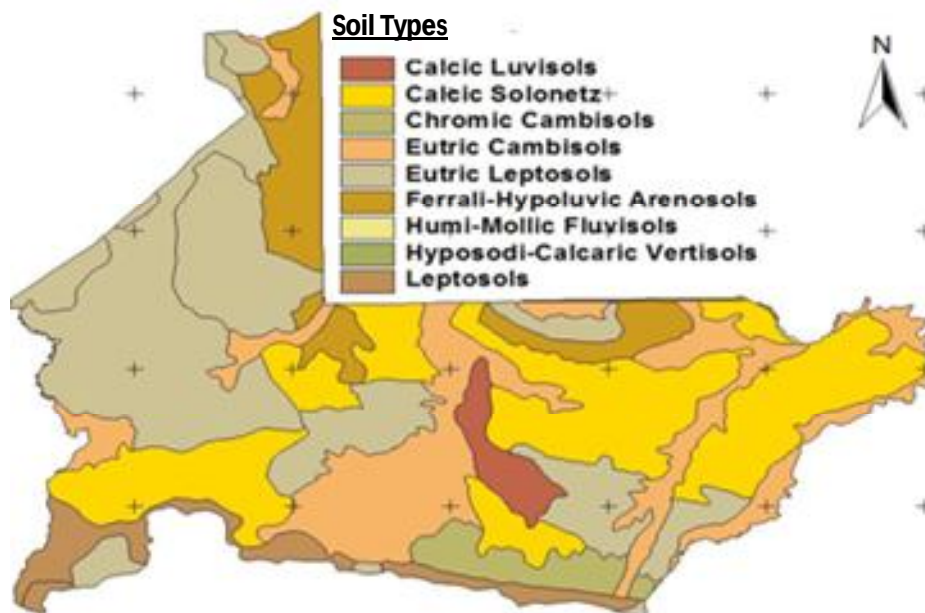


Figure 3.5: Mbire District Soils (FAO, 2006)



(a)



(b)

Figure 3.6 (a & b): Gullies in Mushumbi Pools (Mbire District)

3.4 Flooding

Mbire District experience occasional localised flooding, the floods result from reservoir operation related floods from Kariba Dam and Cahora Bassa Dam which create a throwback effect. This is in addition to floods generated in the area upslope of the escarpment and brought

to the valley by the tributaries of the Zambezi River which are Manyame, Mwanza-mutanda, Angwa, Kadzi, Musengezi and Dande Rivers.

3.5 Population and settlements

Archeological evidence shows that there were communities established in the Dande Valley by the 5th century AD, a history broadly comparable to the rest of the region with a predominantly agricultural economy, where the communities selected alluvial soils along watercourses (Pwiti, 1996). Historically, human population was very low in the district due to high tsetse fly (*Glossina sp.*) infestations that cause sleeping sickness to humans and trapanosomiasis to livestock. However in the late 1970s to early 1980s a regional tsetse fly control programme funded by the European Union managed to substantially reduce the tsetse fly infestation thereby making the area habitable (Kusena, 2009). According to a baseline study conducted by Lower Gurube Development Association in October 2008, the District had a total of about 116,000 inhabitants and about 21,500 households (LGDA, 2009). These people are mainly settled along main rivers (Figure 3.7) where farming is their dominant activity growing mainly cotton, small grains and maize (Biodiversity Project, 2001; AWF, 2010). Livestock populations are relatively low and grazing around settlements, although cattle numbers have been increasing recently. The uninhabited areas still cover a large proportion of the District. Over the recent past human population has been increasing and there is more demand for agriculture land and forest resources leading to a significant decline of forests (Kusena, 2006). Cash crop production has created even more demand for agriculture land and demand for fuel wood and timber has promoted deforestation. Such developments are incompatible with the natural ecosystem (Murombedzi, 1999) particularly the soils of the area because deforestation makes the soil vulnerable to erosion by water.

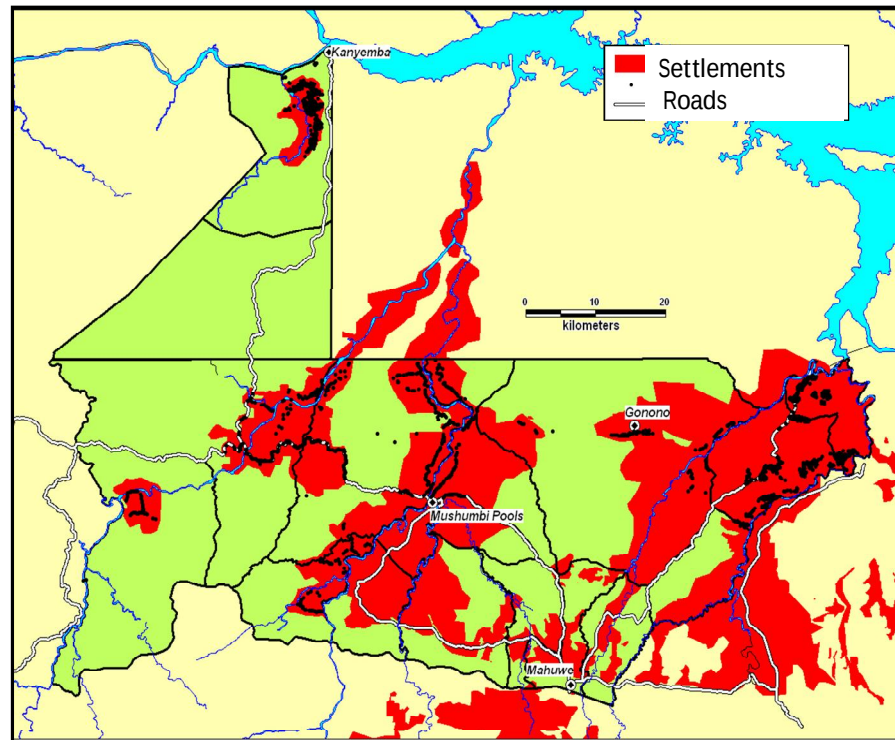


Figure 3.7: Distribution of settlements in Mbire District (AWF, 2010)

3.6 Flora and Fauna

The uninhabited areas still cover a large proportion of the Mbire District (83% of the study area), and contain a remarkable species richness, with more than 40 large mammal species, 200 bird species and 700 plant species (Biodiversity Project, 2001). The main forests in the area include the riverine woodlands and dry forests dominated by Mopane (*Colophospermum mopane*), *Brachystegia spp.* and *Acacia spp.* (Fritz *et al.*, 2003).

CHAPTER 4: MATERIALS AND METHODS

4.1 Introduction

This chapter describes the data collected, methods and analysis used to assess soil erosion hazard and the factors influencing gully erosion and finally model gully erosion hazard in Mbire District.

4.2 Data collection.

4.2.1 Data collection for erosion hazard assessment using the SLEMSA model

For assessing erosion hazard the following data were collected: Mbire District boundary map, ASTER Digital Elevation Model (DEM) with 30 m resolution from the website of Global ASTER Gdem. (<http://www.gdem.aster.ersdac.or.jp/>). 2008 rainfall data was utilized for generating erosivity values. The soil map of Mbire District was extracted from the Food and Agriculture Organization (FAO) World Reference Base (WRB) (FAO, 2006). For the purposes of landcover classification, a cloud free September Landsat TM image (Path 170 Row 071) of September 12, 2008 was obtained from the website (<http://glovis.usgs.gov/>). GPS coordinates were collected for the different landcover types for the purpose of ground truthing of the classified landcover types.

4.2.2 Data collected for the determination of factors influencing gullies and for gully hazard Modelling

Gullies were digitized from June 2007 spot image (© 2011, Cnes/Spot image) made available by Google Earth (© 2011 Google) and validated with field observations by obtaining geographical coordinates of the gullies. The landcover factor was also derived from digitizing various landcover types from the Spot image. The distance from nearest river and road was calculated from rivers and roads/paths digitized from the Spot image. The factors of slope, Stream Power

Index (SPI), Sediment Transport Index (STI) and Wetness Index (WI) were derived from the Aster DEM resampled to 2.5 m for the study area.

4.3 Methods and Data Analysis

4.3.1 Assessing the spatial variation of erosion hazard in Mbire District

Running the SLEMSA model for erosion hazard mapping

Basing on the theoretical description of the improved method of the SLEMSA Model (Stocking *et al.*, 1988) discussed in Chapter 2, the following factors were considered in the Model; relief (S & L), soil erodibility (Fb), vegetation cover (C) and erosivity of rainfall (E). These factors were discussed in detail in Section 3 of Chapter 2. A GIS database was created for Mbire District containing attributes and data necessary to run the SLEMSA model. GIS Layers viz. Mbire boundary map, drainage network, soil, landcover, digital elevation data from DEM and rainfall was spatially organized with the same resolution and coordinate system with a grid size of 30 x 30 m using ILWIS GIS software.

Determination of Erosivity (E)

For each grid square (30 x 30 m) the mean annual rainfall (mm) was determined using local records. The rainfall kinetic energy (E) in J/m^2 , was determined from the rainfall. Since there are no automatic rain gauges existing in the study area direct calculation of E was not possible. Given that Mbire District experiences high rainfall intensities, the following equation was adopted:

$$E = 18.84 * P \quad \text{Eqn. 4.1}$$

Where P = Total Annual Rainfall

Data for rainfall at a station in Mushumbi Pools recorded 759 mm annual rainfall for the year 2008 and was input in the equation to produce an E value of 14, 299.56 J/m^2 .

Determination of the Mean Index of Soil Erodibility (Fb) for the grid square

The Fb values are obtained from Tables by (Stocking *et al.*, 1988) depending on soil type. The soil Map of Mbire District was used (FAO, 2006). Fb values were assigned per each grid.

Determination of Erosion Hazard Index (I_b)

Using E and F_b the Erosion Hazard Index, (I_b) was determined (I_b is the same as K in the SLEMSA Model). This index refers to a standard plot of bare soil, 4.5% slope, 30 meters long and is obtained from the following formula:

$$I_b = \exp[(0.4681 + 0.7663F_b) \ln E + 2.884 - 8.1209F_b] \quad \text{Eqn. 4.2}$$

Determination of the Cover values, (C)

For the purpose of obtaining vegetation cover values, the landcover map was digitally classified; classification was done through use of a cloud free Landsat TM image (Path 170 Row 071) of September 12, 2008 obtained from (USGS, 2011) (courtesy of the U.S. Geological Survey). The Image was classified using Hybrid classification system in a GIS environment ILWIS to generate the landcover map. The operation “cluster” in ILWIS was used to generate 15 classes utilizing the image’s band 1, 2, 3 and 4. Manually similar classes were grouped together basing on landcover point map generated from GPS points collected from the research site. Four landcover classes were isolated, namely Water, Riparian & Evergreen Forest, Dry land Forest and Cultivation. The isolated landcover types were representative of the area and sufficient for the Model SLEMSA requirements. The Landcover map was used in deriving the interception (I) values for the district. I values of the landcovers were; 100% for evergreen forest, 90% for dryland forest and 20% for cultivation (adopted from Orr *et al.*, 1998). Equation 4.3 and Equation 4.4 by Morgan (1995) were used to determine the cover values

$$\text{for } I \leq 50, C = \exp(-0.06 \cdot I), \quad \text{Eqn. 4.3}$$

$$\text{for } I > 50, C = (2.3 - 0.01 \cdot I) / 30 \quad \text{Eqn. 4.4}$$

Where: I = Interception

C = Vegetation Cover

The 2008 cover value map was developed.

Determination of Soil loss Ratio (X)

The values of Soil Loss Ratio (X) were calculated from average slope (maximum 20%) using Equation 3.5. The slope was obtained from an ASTER DEM with 30 m resolution.

$$X = L^{0.5}(0.76 + 0.53S + 0.076S^2)/25.65 \quad \text{Eqn. 4.5}$$

Where: X = Soil Loss Ratio

L = Slope Length

S = Percentage Slope Steepness

The slope length was estimated to be a constant 100 m (Stocking *et al.*, 1988).

Determination of the erosion hazard

Finally the Erosion Hazard in Erosion Hazard Units was calculated from the resultant I_b , C and X using Equation 4.6.

$$\text{Erosion Hazard} = I_b \times C \times X \quad \text{Eqn. 4.6}$$

The erosion hazard was subdivided into five classes basing on work done by Stocking (1987) cited in Leenaers (1990) as indicated below.

EHU $\leq$ 10: erosion hazard	= 1 (low)
10 < EHU $\leq$ 25: erosion hazard	= 2 (moderate)
25 < EHU $\leq$ 50: erosion hazard	= 3 (moderately high)
50 < EHU $\leq$ 100: erosion hazard	= 4 (high)
EHU > 100: erosion hazard	= 5 (Very High)

4.3.2 Analysis of the relationship between distribution of gullies and flood hazard, landcover, soil and terrain variables

Mapping of gullies and determination of gully morphological features

Mapping of gullies was done at Mushumbi Pools (Figure 3.3 of Chapter 3). Gullies to be used as a training set were digitized from spot images (© 2011, Cnes/Spot image) made available by Google Earth (© 2011 Google) and validated with field observations. The “add polygon” function in Google Earth was used to digitize gullies in the selected areas. The gully polygons were saved as KML files. The KML to Shapefile function in ArcGIS 9.2 tool box was used to convert the digitized gullies to Shapefile. Thus gully polygons digitised from the spot images were used for this study. The gully polygons were overlaid with the study area and converted to a binary Map (presence of gullies 1. and absence 0). Ground truthing was done for the identified

gullies together with recording of gully morphological features *ie.* gully length, width and depth. Furthermore recent gully activity was noted and their GPS coordinates were recorded and these were used as a validation set.

Creation of factor maps

Landcover

The landcover factor was derived from digitizing the landcover types visible from a Spot image (© 2011, Cnes/Spot image) made available by Google Earth (© 2011 Google). Main landcovers which were identified were Settlement (built up area), Cultivation (area covered by fields), Forested land (area covered by forest) and area covered by rivers.

Flood Hazard

Vertical distance to channel was used to derive a flood hazard map using a binary logistic relationship (Eqn. 3.7) between flooding condition and vertical distance to channel produced for a similar environment by Murwira *et al.* (2005). The logistic function was used to calculate probability of flooding (P) of an area being inundated with water.

$$P = \frac{e^{(2.764 - 0.958 * D_v)}}{(1 + e^{(2.764 - 0.958 * D_v)})} \quad \text{Eqn. 4.7}$$

Where: D_v = vertical distance to the closest channel.

Ground truthing of the developed flood hazard was done by recording points which are known to frequently flood by the local communities. After overlaying these points with the flood hazard map, most points fell in the high hazard classes showing a validity of 93.4%.

Determination of vertical distance to channel was done using an ArcView script in ArcView 3.2 GIS software with 2.5 m DEM and Flow accumulation Map as input parameters. The 2.5 m DEM was resampled from a 30 m resolution Aster DEM using the nearest neighbour classification. Probability of flooding was classified to produce 10 equal classes within the 0 -1 range of probability.

Soil type

Soil type map was generated from FAO world soil database (FAO, 2006). This was done through an operation called clip in ArcGIS 9.2, such that only the soils covering the study catchment

were utilized, Three main soil types were within the study area which are Eutric Leptosols, Calcic Luvisols and Eutric Cambisols.

Distance from road and distance from river

The Distance calculation operation in ILWIS was used to derive the distances. Since these factors are continuous, they were categorized using the values of the data at which the slope of the preliminary weight contrast graph breaks according to Regmi *et al.* (2010). For rivers the distance was grouped into 8 classes and for distance from road 7 classes using the same techniques by Regmi *et al.* (2010).

Terrain variables

The factors of slope, SPI, STI and WI were derived from Aster DEM with a 30 m resolution resampled to 2.5 m for the study area. Elevation was determined directly from the DEM and was classified into 3 classes. The slope was determined by systematic operations and methods outlined in ILWIS GIS software. The slope was calculated as a percentage and classified into 5 classes. The indices; Wetness Index (WI), Sediment Transport Index (STI) and Stream Power Index (SPI) were derived through an operation called “compound index calculation” in ILWIS GIS software. Input parameters are DEM and flow accumulation. Functionality of these indices is presented in Chapter 2. For WI, 4 classes were produced and for STI, 8 classes were produced and for SPI, 8 classes were produced. The classes were produced basing on preliminary plotting of the factors against the contrast values. The continuous data were categorized using the values of the data at which the slope of the weight contrast graph breaks.

Analysis

The various thematic maps of the training set were overlaid (crossed) with the gully map on the basis of the intersections outlined in Equation 2.6 and Equation 2.7 by using ILWIS GIS software. Positive and negative weights for each class of each parameter were calculated basing on the number of pixels in each class and parameter extracted from the resultant tables as indicated in Equation 4.10 and 4.11. The simplified flow chart of the statistical bivariate analysis is presented in Figure 4.1. Using the weight-of-evidence method, the spatial relationship and the contrast value between gully area and each gully contributing factor was derived.

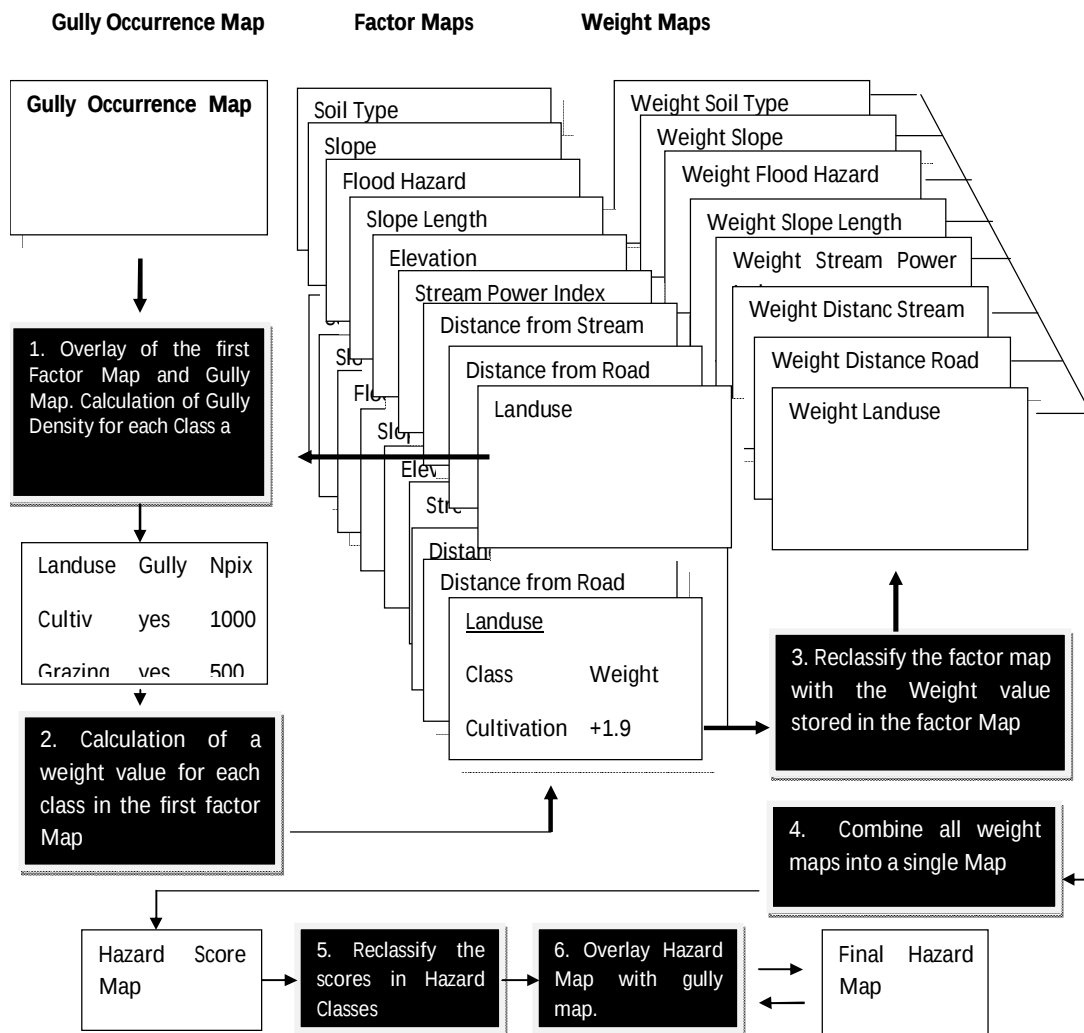


Figure 4.1: Statistical bivariate analyses modified from Van-Western (2003)

Calculation of weights for each predictive map or evidence map

For each factor there are four possible combinations (Table 4.1), of which the frequency expressed as number of pixels, can be calculated with a GIS (Van Western, 2003).

Table 4.1: Four possible combinations of a gully conditioning factor and a gully map

		<i>F - Potential Gully conditioning factor</i>	
		(Present)	(Absent)
G - Gully	(Present)	Npix ₁	Npix ₂
	(Absent)	Npix ₃	Npix ₄

$$W^+ = \ln \left(\frac{\frac{Npix_1}{Npix_1 + Npix_2}}{\frac{Npix_3}{Npix_3 + Npix_4}} \right) \quad \text{Eqn. 4.8}$$

$$W^- = \ln \left(\frac{\frac{Npix_2}{Npix_1 + Npix_2}}{\frac{Npix_4}{Npix_3 + Npix_4}} \right) \quad \text{Eqn. 4.9}$$

Where : *Npix* = number of pixels

W^+ = positive weight

W^- = negative weight

In order to calculate the weights using equations 4.8 and 4.9 the following columns were created in Microsoft office Excel:

Nmap = total number of pixels in the map

ngully = number of pixels with gullies in the map

nclass = number of pixels in the class

ngullyclass = number of pixels with gullies in the class

The values needed for the weight formulas are:

npix1 = ngullyclass

npix2 = ngully-ngullyclass

npix3 = nclass-ngullyclass

npix4 = nmap-ngully-nclass+ngullyclass

The weights were calculated as:

$$W^+ = \ln((npix1/(npix1+npix2))/(npix3/(npix3+npix4))) \quad \text{Eqn. 4.10}$$

$$W^- = \ln((npix2/(npix1+npix2))/(npix4/(npix3+npix4))) \quad \text{Eqn. 4.11}$$

The contrast weight (C_w) was calculated Eqn.4.12.

$$C_w = W^+ - W^- \quad \text{Eqn 4.12}$$

Where: W^+ = positive contrast of each factor class

W^- = negative contrast of each factor class

Since the factor maps used are not binary rather they are multiclass, this means C_w calculation will involve adding the negative weights of other classes to W^+ (Van-Western, 2003).

The Studentised Contrast (C_s) was then calculated, C_s is calculated as the ratio of C to its standard deviation. Values of C_s in the range $1.96 < C_s < -1.96$ indicate that the hypothesis that $C = 0$ cannot be rejected at 0.05 confidence level.

The association between a factor and the contrast value was assessed using the Spearman's Rank Correlation Coefficient. The Spearman correlation coefficient is for assessing correlation between ranked variables. The computation of the Spearman correlation coefficient was done using SPSS, Version 11.5 statistical software.

4.3.3 Mapping gully erosion hazard using terrain and landcover variables by means of weight of evidence modelling.

The GIS-based potential erosion hazard mapping process has four main steps:

1. Calculating weights for each predictive map or evidence map (covered in section 4.2.2);
2. Applying of conditional independence test;
3. Creating a total weight map
4. Model evaluation.

Testing Conditional Independence

Before summing up the weight map the factors were tested for conditional independence to ensure that the conditional independence outlined in Equation 4.13 is satisfied.

$$N \{ F_1 \cap F_2 \cap G \} = \frac{N\{F_1 \cap G\}N\{F_2 \cap G\}}{N\{G\}} \quad \text{Eqn. 4.13}$$

The left side of Eqn. 4.13 is the observed number of occurrences in the overlap zone of Factor 1 (F_1) and Factor 2 (F_2). The right side is the predicted number of occurrences in this overlap zone. This relationship leads to a contingency table calculation for the pair-wise testing of conditional independence. The conditional independence was tested by calculating χ^2 in Microsoft office Excel using Equation 4.14.

$$\chi^2 = \sum_{i=1}^r \sum_{j=1}^c \frac{(A_{ij} - E_{ij})^2}{E_{ij}} \quad \text{Eqn. 4.14}$$

where: A_{ij} = actual frequency in the i -th row, j -th column

E_{ij} = expected frequency in the i -th row, j -th column

r = number of rows

c = number of columns

A low value of χ^2 is an indicator of independence. As can be seen from the formula, χ^2 is always positive or 0, and is 0 only if $A_{ij} = E_{ij}$ for every i, j .

Creating a total weight map

The contrast of each factor class or type was summed to calculate the total weight map (TWmap).

$$TWmap = \sum Cw \quad \text{Eqn. 4.15}$$

Where: Cw = contrast of each factor class

Model Evaluation

Model validation was done by using randomly selected recent gully activity in the field. The recent gullies were those which were not identified from the spot image of 2007. The GPS Coordinates of these gullies were converted into a gully point map and was overlaid to a gully

hazard map. The accuracy of prediction of the model was determined from the area under the curve of cumulative percentage gully area against cumulative percentage study area (Regmi *et al.*, 2010.)

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Introduction

This chapter presents the findings from the study whose main objective was to assess soil erosion hazard as an environmental threat to water resources in Mbire District of Zimbabwe and discuss the implications for catchment management. Results and analysis are presented per specific objective in three sections and a summary of the chapter given in the fourth section. The first section gives results and discussions of the spatial variation of erosion hazard in Mbire District using an improved method for the empirical model SLEMSA for erosion hazard assessment (Stocking *et al.*, 1988). The second section covers an analysis of the influence of environmental factors on gully occurrence. The third section covers determination of gully hazard using weight of evidence modelling (Bonham- Carter, 1994; Van-Westen, 2003).

5.2 Spatial variation of erosion hazard in Mbire District

5.2.1 Soil erosion hazard

Figure 5.1 shows the spatial distribution of soil erosion hazard for Mbire District using rainfall data and landcover for the year 2008 derived from an improved method for erosion hazard assessment of the SLEMSA model (Stocking *et al.*, 1988). Where class 1 is low, 2 is moderate, 3 is moderately high, 4 is high and 5 is very high hazard. The maps of input parameters *i.e.* Erosion Hazard Index (Ib), Cover values (C) and the Topographic Ratio (X) are presented in Appendix 1 a, b and c respectively. It can be observed that Erosion Hazard Units (EHUs) vary from less than 10 EHUs to greater than 100 EHUs.

The southern boundary and the north-west part of Mbire District fall within the high hazard class. The southern boundary occupies the lower parts of the Zambezi Escarpment and the north-eastern part of the District is the Chewore mountain range thus due to high contribution of slope in these areas soil erosion is high. Generally a greater part of Mbire District has a low slope (see

map in Appendix 1d) making slope effects on erosion minimal. Nevertheless, a significant part of the District is occupied by very fragile sodic soils (FAO, 2006) and such soils are highly prone to erosion and have low erodibility values (see map in Appendix 1e).

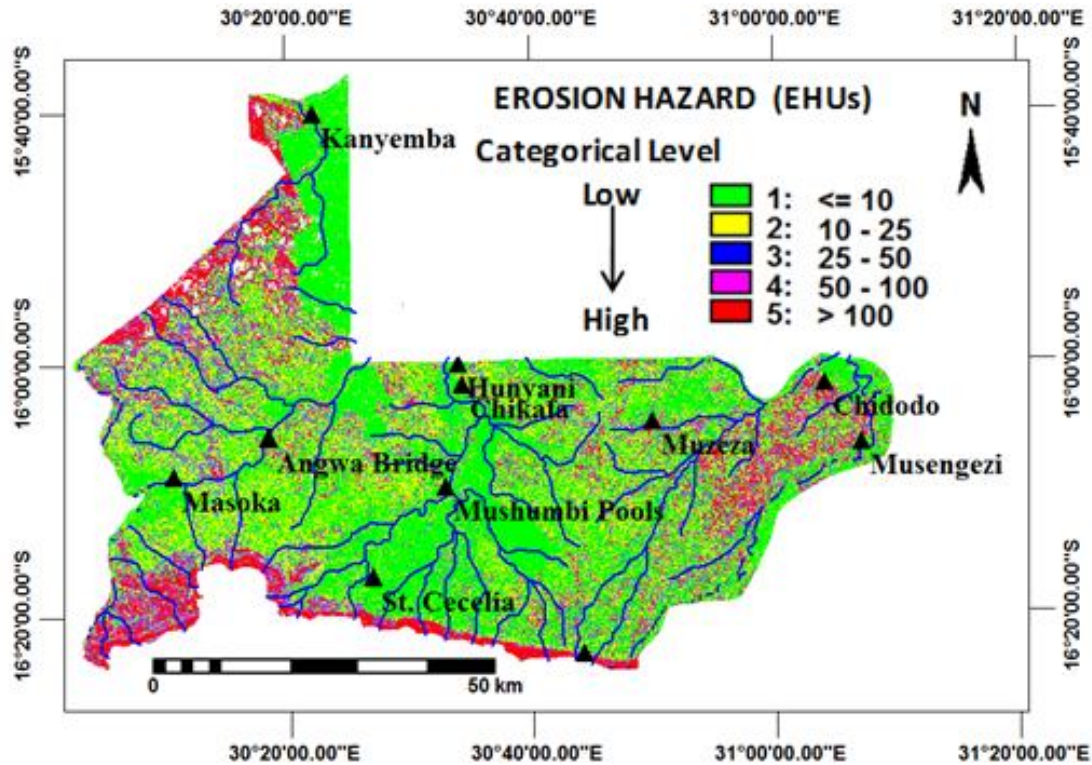


Figure 5.1: Spatial erosion hazard for Mbire District in relation to settlements and rivers

Figure 5.1 also illustrates spatial erosion hazard overlaid with major settlements and rivers. High erosion hazards are in areas with settlements such as areas around Chidodo, Musengezi, Masoka, and Angwa. An exception is the area around Kanyemba and Mushumbi Pools recording low erosion hazards. This indicates that settlements promote soil erosion.

Low erosion hazards around Kanyemba can be explained by the fact that Kanyemba has high vegetation cover than the other communal areas in the district. Mushumbi Pools regardless of high rates of gully erosion (IES, 2009), has low erosion hazard due to the gentleness of the slopes which counteract the high erodibility of the soil (Stocking *et al.*, 1988). Considering that the district has registered a significant increase in settlements and cultivation over the years (Fritz *et al.*, 2003; Kusena, 2009), continued increases in cultivation and settlements could

promote high erosion rates in the future. The results confirm the findings by Sharma *et al.* (2010) that disappearance of forest patches and intensification of cultivation practice in relatively more erosion-prone soil were the main factors contributing toward the increase in soil erosion.

Figure 5.2 illustrates the area covered by each erosion hazard class in the district. A greater part of the district is in the low erosion hazard class (≤ 10 EHU) covering 46% of the district followed by the moderate class ($10 < \text{EHU} \leq 25$) covering 25.7%, the moderately high class ($25 < \text{EHU} \leq 50$) covering 11.5%. The very high hazard (> 100 EHU) covers a greater area than the high hazard ($50 < \text{EHU} \leq 100$), with 9% and 7.6% coverage respectively.

A combination of low topographic ratio and high vegetation cover explains why a greater part of the district is within the low and moderate classes. High vegetation cover counteracts the effects of the low erodibility of the soil (Mkanda, 2000; Mulooka, 2008). This implies that Mbire District has generally low erosion hazard with pockets of high hazard occurring in areas with steep slopes and low landcover areas.

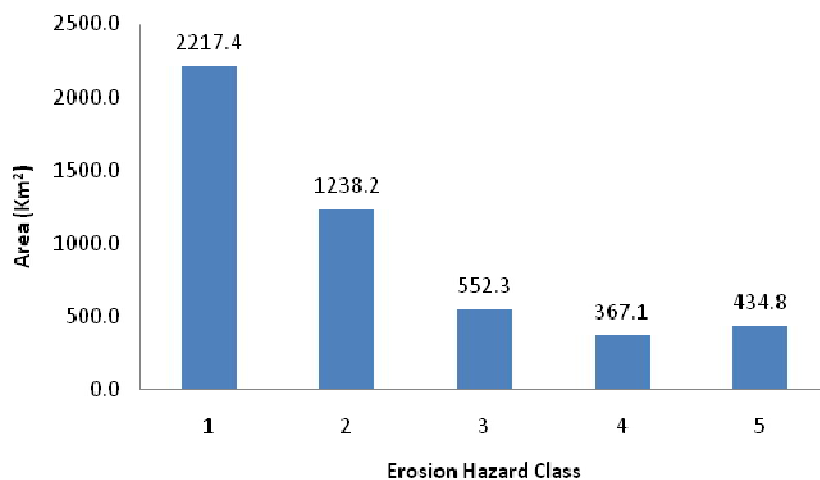


Figure 5.2: Coverage Area of each erosion hazard class for Mbire District

Figure 5.3 shows erosion hazard for each ward as a percentage of ward area, it was observed that in all the wards, the low hazard class (≤ 10 EHU) is the dominant class followed by the moderate class (10 - 25 EHU). For higher classes no pattern was observed with variations from ward to ward. However, looking at the percentage occurrence of the hazard classes, it is evident that

Wards: 7, 9, 10, 11, 13, 14 and 15 had the lowest erosion hazard because they have greater than 50% of the area in the low hazard zone. Wards: 1, 2, 3, 5 and 6 comprise above 10% of the area in the very high erosion hazard class, this indicates that these wards have the highest erosion hazard.

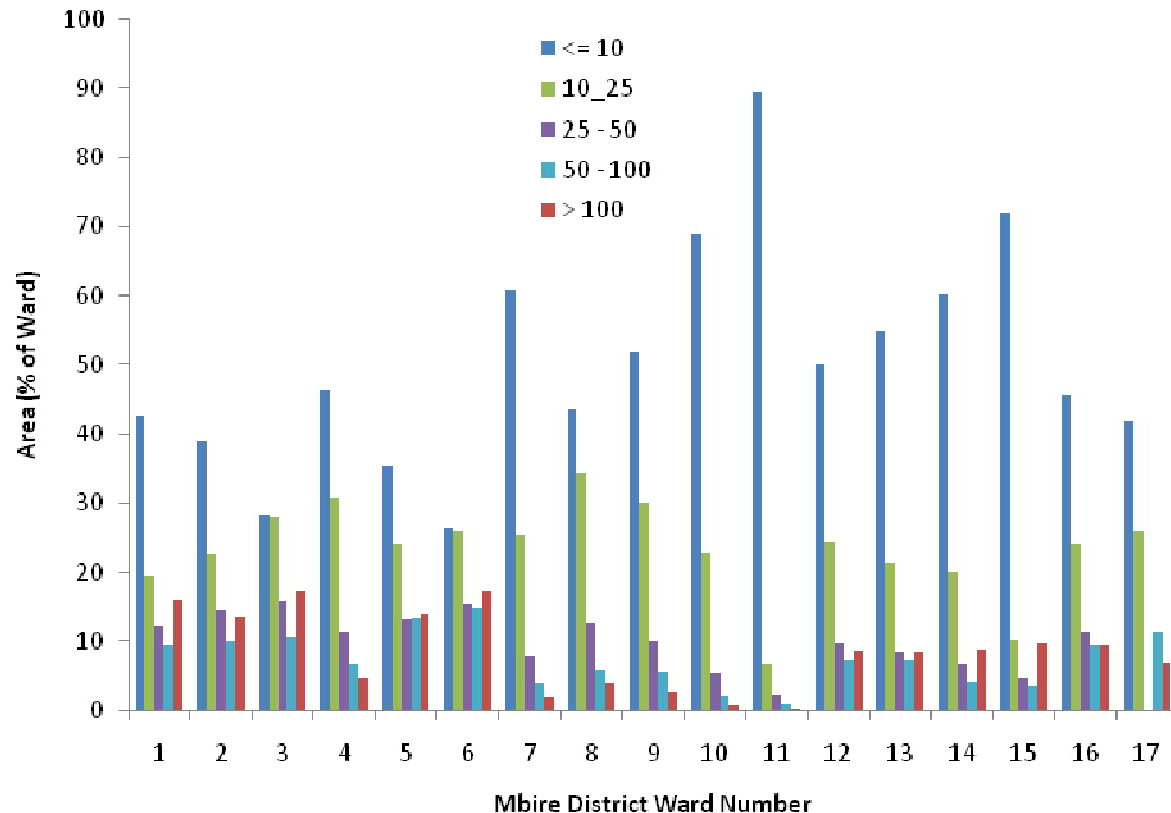


Figure 5.3: Erosion Hazard coverage as a percentage of ward area in Mbire District

5.2.2 Implications of findings

The use of GIS and remote sensing enabled the determination of the spatial distribution of the SLEMSA parameters. In this study tedious and costly field methods of obtaining landcover (Chakela and Stocking, 1988) have been replaced by the use of remote sensing derived landcover from satellite imagery. In this regard remote sensing and GIS can play a significant role in developing management scenarios and provide options to policy-makers for handling the soil

erosion problem in the most efficient manner through prioritisation of conservation at the district scale.

This study managed to produce spatial variability of erosion hazard for Mbire District singling out low hazard areas, which cover 46 %, moderate hazard areas covering 25.7 % with area covered by the moderately high, high hazard and very high hazard being 11.5%, 7.6% and 9% respectively. The areas covered by the last three classes need immediate attention from the conservation point of view. It was also evident that in Mbire District high erosion hazard occurs in areas associated with cultivation and settlements and in areas with fragile soils characterized by very low erodibility values, with very high erosion hazard observed when highly erodible soils are under cultivation. In areas which are forested the erosion hazard is moderate, however, the rate at which cultivation is replacing dryland forest is a likely threat (Kusena, 2009) and can cause erosion hazard in the future. It was therefore concluded that Mbire District has generally a low erosion hazard in the greater part of the district with pockets of high hazard occurring in areas associated with settlements and cultivation.

Catchment management targeted at soil and water conservation may have to focus on areas with high settlement and cultivation, especially if cultivation is expanding into fragile lands. For planning purposes, ideally highly erodible soils could be allocated to landuses which do not reduce vegetation cover such as wildlife. Expansion of agricultural practices into soils with low erodibility values may have to be avoided if feasible. Identification of the degree of hazard and the reasons for that hazard may be useful in broad-scale planning for the conservation and utilization of Mbire District land and water resources.

5.3 Influence of flood hazard, landcover, soil and terrain variables on occurrence of gullies

5.3.1 Introduction

Table 5.1 show the positive weights (W^+), negative weights (W^-) and contrast weight (C_w) together with the studentised contrast (C_s) and the spearman's rank coefficient (ρ) and its probability value. Evidential maps used to construct the positive (W^+) and negative (W^-) weights and in turn the contrast weight (C_w) of the factors affecting gully occurrence are presented in Appendix 2. The training sample gully map is also presented in Appendix 2.

5.3.2 Influence of landuse/landcover on gully occurrence

Table 5.1 show that there was a significant association between gully occurrence and landcover types; settlement, cultivation and forest ($C_s > 1.96$). A high positive contrast value is observed in land covered by settlement ($C_w = 1.139$), and an extremely negative value for areas covered by forest ($C_w = -6.277$). There was no significant association between land covered by rivers and gully occurrence ($C_s = 1.8$). These results show that there is a positive association between occurrence of gullies and settlements and there is a strong negative association between occurrence of gullies and the class forest. Cultivated areas have a negative association ($C_w = -0.254$) with gully occurrence, indicating that gully occurrence in the study area is not caused by cultivation. The presence (W^+) of the different landcover types is more important than the absence (W^-) of the landcover types, with all the (W^+) having a high magnitude than the (W^-) for example the class forest has a high W^+ (-6.1) but a very low W^- (0.1). This indicates that absence of these factors has no association with gully occurrence.

It is evident that removal of forests for the creation of settlements promotes gully development in the study area and thus increases in settlements could promote further gully erosion. The findings are in agreement with the knowledge that forested areas experience less erosion in the form of gullies than bare areas (Harvey, 1992; Zheng, 2006). Considering that the district has registered a significant increase in settlements over the years (Fritz *et al.*, 2003; Kusena, 2009; AWF, 2010), continued increases in settlements could promote high gully erosion rates in the future.

Table 5.1: Weight of evidence analysis showing: factors, factor classes, weights and spearman's rho (ρ)

Factor	Class/Type	W+	W-	Contrast (Cw)	Stud C (Cs)	Spearman's rho(ρ) & p value
Landuse	Cultivation	-0.141	0.046	-0.254	-2.743	N/A
	River	-0.162	0.036	-0.264	-1.829	
	Settlement	0.921	-0.285	1.139	12.281	
	Forested	-6.074	0.137	-6.277	-13.020	
Soils	Eutric cambisols	0.148	-0.936	0.541	5.678	N/A
	Calcic Luvisols	-1.975	0.393	-2.911	-23.357	
	Eutric Leptosol	-0.786	0.300	-1.629	-16.385	
Distance from River (m)	0 - 30	1.378	-0.036	1.332	11.628	-0.833 (p < 0.05)
	30 - 100	0.916	-0.030	0.863	8.222	
	100 - 250	1.065	-0.127	1.110	12.102	
	250 - 500	1.105	-0.233	1.256	14.265	
	500 - 1000	-0.252	0.178	-0.513	-5.360	
	1000 - 1250	-1.063	0.093	-1.238	-8.646	
	1250 - 1500	-2.090	0.073	-2.245	-11.396	
	1500 - 2000	-0.450	0.041	-0.574	-3.971	
Distance from Road (m)	0 - 50	0.283	0.039	0.228	2.287	-0.393 (p > 0.05)
	50 - 100	0.626	-0.014	0.623	6.450	
	100 - 150	0.843	-0.045	0.870	9.095	
	150 - 250	0.514	-0.009	0.507	5.502	
	250 - 500	0.535	-0.031	0.549	6.139	
	500 - 1000	0.518	0.007	0.494	4.749	
	1000 - 1500	-0.454	0.036	-0.507	-3.457	
Flood Hazard Probability	0 - 0.1	1.184	-0.017	1.239	10.010	-0.648 (p < 0.05)
	0.1 - 0.2	1.075	-0.009	1.122	8.331	
	0.2 - 0.3	0.722	-0.001	0.761	5.308	
	0.3 - 0.4	0.344	0.007	0.374	2.532	
	0.4 - 0.5	0.943	-0.009	0.990	7.802	
	0.5 - 0.6	0.436	0.007	0.466	3.462	
	0.6 - 0.7	0.868	-0.010	0.916	7.697	
	0.7 - 0.8	0.790	-0.015	0.843	7.964	
	0.8 - 0.9	0.398	0.022	0.413	4.161	
	0.9 - 1	-0.262	0.063	-0.287	5.002	
Elevation (m)	<385	0.379	-0.528	0.437	5.002	-1 (p < 0.01)
	385-395	0.630	-0.076	0.237	2.695	
	395-405	-2.272	0.134	-2.875	-16.407	
Slope (%)	0 - 2	0.208	-0.030	0.241	2.839	0.8 (p > 0.05)
	2 - 4	0.145	0.069	0.079	0.892	
	4 - 6	0.560	-0.011	0.574	6.114	
	6 - 9	0.816	-0.022	0.842	8.183	
	>9	0.795	-0.003	0.802	5.854	
Sediment Transport Index (STI)	<5	-0.326	0.120	-0.383	-4.508	0.857 (p < 0.01)
	5 - 10	0.573	-0.022	0.659	7.164	
	10 - 30	0.570	-0.010	0.643	6.781	
	30 - 100	1.037	-0.015	1.115	9.202	
	100 - 300	0.900	-0.002	0.965	5.992	
	300 - 600	2.211	-0.005	2.279	11.704	
	600 - 1200	1.578	-0.001	1.643	6.592	
	1200 - 6000	1.387	-0.002	1.453	7.057	
Stream power Index (SPI)	0 - 50	-0.059	0.112	-0.129	-1.511	0.905 (p < 0.01)
	50 - 100	0.576	-0.014	0.631	6.724	
	100 - 500	0.376	-0.003	0.420	4.757	
	500 - 1000	0.896	-0.012	0.949	8.064	
	1000 - 5000	1.069	-0.022	1.133	9.930	
	5000 - 10000	0.788	-0.001	0.831	4.810	
	10000 - 10000000	1.323	-0.016	1.380	10.651	
	>10000000	1.502	-0.004	1.548	8.555	
Wetness Index (WI)	0 - 12	-0.234	0.136	-0.338	-3.988	0.8 (p > 0.05)
	12 - 15	0.252	-0.086	0.370	4.362	
	15 - 24	1.182	-0.017	1.231	9.978	
	> 24	1.065	-0.001	1.098	5.224	

*The factors marked 'N/A' (Not Applicable) have classes which cannot be ranked

5.3.3 Influence of soil type on gully occurrence

The influence of soil type on gully occurrence can be observed in Table 5.1. For all soil types there was a significant association with gully occurrence ($C_w \neq 0$). In the case of eutric cambisols the contrast value was higher ($C_w = 0.541$). Also the influence of the absence of eutric cambisols ($W^- = -0.9$) were pronounced than the influence of the presence of the factor ($W^+ = 0.15$). A negative association was observed for calcic luvisols and eutric leptosols ($C_w = -2.911, -1.629$) respectively. This implies that gully erosion occurrence is positively associated to the soil type eutric cambisol and in areas with this soil type there is high gully erosion.

Cambisols experience low infiltration rates during a heavy rainstorm, when the rain falling on the surface of these soils far exceeds infiltration it gives rise to runoff and results in losses of soil by erosion. Luvisols have high clay content thus resistant to soil erosion and leptosols are quite shallow and gully development is not pronounced (Nyamapfene, 1993).

5.3.4 Influence of distance from river on gully occurrence

Observation of Table 5.1 show that there was a significant negative correlation ($p < 0.05$) ($\rho = -0.833$) between occurrence of gullies and the distance from rivers. There were significant associations ($C_s > 1.96$) of all the factor classes and gully occurrence. At lower distances there was a positive association ($C_w > 0$) of distance from river with gully occurrence but as the distance increases above 500 m the association becomes negative ($C_w < 0$). A very high negative contrast was observed at 1,250 m from the river ($C_w = -2.245$). This indicates that the further the place is to a river the less chances of that place experiencing gully erosion.

The findings can be explained by the fact that it is easier for a gully to develop on the bank of a river than on areas far from the river. This is a typical case for Mushumbi Pools where most of the gullies are attached to the main rivers; Manyame and Dande; these rivers provide an initial trigger to gulling due to bank erosion.

5.3.5 Influence of distance from road/path on gully occurrence.

Table 5.1 shows that there is no significant correlation of distance from road and occurrence of gullies ($p \Rightarrow 0.05$) ($\rho = -0.393$). Closer observation of the contrast values show that the classes are significantly different from 0 ($C_s \neq 0$) meaning that they are associated with gully

occurrence. A negative contrast at distances from path of above 1,000 m ($C_w = -0.507$) was observed however areas closer to the river show positive association.

The findings can be explained by the fact that areas far from roads and paths are less disturbed and thus are not likely to experience gully erosion (Pathak *et al.*, 2005). However since there was no significant correlation of distance from road and gully occurrence, this factor cannot be used for gully erosion hazard mapping.

5.3.6 Influence of flood hazard probability on gully occurrence

For the factor flood hazard probability (Table 5.1) there was a significant negative correlation ($p < 0.05$) ($\rho = -0.648$) with gully occurrence. There were also significant associations ($C_s \neq 0$) of the entire flood hazard classes and gully occurrence. Positive contrast values have been observed for low probabilities *ie.* for flood hazard probability class ≤ 0.1 and class 0.1 - 0.2, ($C_w = 1.239$, 1.122 respectively). However at flood hazard probability higher than 0.9 there is a negative association ($C_w = -0.287$). This indicates that gully erosion decreases with an increase in flood hazard.

The findings can be attributed to the fact that areas frequently flooded experience more sediment deposition (Ritchie *et al.*, 2004) and thus gully occurrence in these areas is unlikely, and the opposite is true for less flooded areas. In Mushumbi Pools high flood prone areas occupy the flood plains and these flood plains accumulate sediments deposited by the main rivers during a flood event, the likely sources of these sediments are the areas upstream well above the Zambezi escarpment.

5.3.7 Influence of Elevation on gully occurrence

The factor elevation (Table 5.1), had a significant negative correlation with gully occurrence ($p < 0.05$) ($\rho = -1$). At higher elevation (>395 m) there was a negative association with gully occurrence ($C_w -2.875$) and low lying areas have a positive association with gully occurrence ($C_w > 0$). This means that low lying areas have high gully activity as compared to high elevation areas.

The findings can be explained by the fact that high elevation areas form the boundaries of the watershed, and in these areas there is low accumulated runoff, but for low lying areas an accumulation of runoff is substantial to cause gully erosion.

5.3.8 Influence of Slope on gully occurrence

For the factor slope (Table 5.1), there was an insignificant positive correlation between slope and occurrence of gullies ($P > 0.05$) ($\rho = 0.8$). However all slope classes were significantly associated with gully occurrence ($C_s > 1.96$) except for the class 2-4 % which is not significantly associated with gully occurrence ($C_s = 0.842$). On the other hand, slopes gentler than 4% were found to be less associated with gullies in the area. This indicates that as slope increases gully occurrence increases however the relationship is not significant.

The findings are attributed to the fact that Mushumbi Pools has a relatively flat terrain with no steep slopes and making slope less influential on gully occurrence. The results show that slope does not have a direct contribution to gully occurrence in the area.

5.3.9 Influence of Sediment Transport Index (STI) on gully occurrence

Table 5.1 show that there was a significant positive association between gully occurrence and the Sediment Transport Index (STI) ($p < 0.01$) ($\rho = 0.857$). There was also a significant association between the factor classes and gully occurrence ($C_w \neq 0$). At STI of less than 5 there was a negative association ($C_w = -0.38$). Higher positive association ($CW = 2.28$) were observed for STI between 300 and 600. This indicates that gully occurrence increases with an increase in Sediment Transport Index.

The results can be explained by the fact that STI accounts for the effect of topography on erosion, it utilizes the two-dimensional catchment area such that the effect of slope length can be accounted for, high slope lengths means sediments can be transported for longer distances before they are deposited and likewise shorter slope lengths reduces the movement of sediments. The findings are similar to the findings of the work done by Moore *et al.* (1988) and Pathak *et al.* (2005) that topographic non-uniformity within small catchments is a major factor controlling the spatial variability of soil water and the location and development of gullies.

5.3.10 Influence of Stream Power Index (SPI) on gully occurrence

Table 5.1 show that there was a significant positive correlation between gully occurrence and Stream Power Index ($p < 0.01$) ($\rho = 0.905$). There was a significant association of all the factor classes and gully occurrence ($C \neq 0$) except for SPI class <50 ($C_s = -1.511$). This indicates that gully occurrence increases with an increase in Stream Power Index.

The findings can be explained by the fact that SPI is a product of catchment area and slope. It indicates the areas of concentrated runoff (Morgan, 1995) and thus the higher the SPI the higher the chances of a gully occurring.

5.3.11 Influence of Wetness Index (WI) on gully occurrence

Observation of Table 5.1 show that there was an insignificant positive association ($p > 0.05$) ($\rho = 0.8$) between gully occurrence and WI. However, all the factor classes are significantly associated with gully occurrence ($C \neq 0$). At WI values less than 12, a negative association was observed ($C_w = -0.34$), for WI values greater than 12 there is positive association ($C_w > 0$). This indicates that gully occurrence increases as Wetness Index increases. However, the results show that Wetness Index does not have a significant contribution to gully occurrence in the area.

This can be explained by the fact that at low WI there is less runoff water generated and as the WI increases it promotes gully development. This is because WI sets catchment area in relation to the slope gradient.

5.3.12 Implications of findings

The use of weight of evidence analysis has enabled an understanding of the factors affecting gully occurrence. It has been made clear by these findings that different classes of an evidential theme or factor associate differently with gully occurrence, making it apparent that no single factor can explain gully occurrence in the study area alone, rather it is affected by a combination of factors, some factors are more associated with gully occurrence than the others this confirms the findings by Lal (1992), Morgan, *et al.* (1997) Pathak *et al.* (2005). For the factors studied, it was observed that fewer gullies occur in cultivated areas and soil type has an influence on gully erosion. Furthermore it was concluded that there is a significant positive correlation between, Sediment Transport Index and Stream Power Index. There is a significant negative correlation between gully occurrence and the factors: flood hazard, distance from river, elevation.

Correlation of Wetness Index and slope with gully occurrence though positive, it was not significant. Also correlation of gully occurrence with distance from road though negative it was not significant. Therefore these factors should not be considered for gully erosion hazard modelling.

For sustainable gully erosion control and management, it is imperative for catchment managers to make sure that forests should remain intact. This comes as a realization that forested areas regardless of topography have negative association with gully occurrence. Where development of forested areas into settlement is inevitable proper planning of landuse may have to take centre stage, avoiding physically vulnerable areas. Since settlements have the highest gully activity reforestation of these areas may play a significant part in reducing runoff and reinforcing the soil. Also for the success of soil reclamation in addressing the effects of gully erosion the factors affecting gully erosion may have to be the primary consideration.

5.4 Gully erosion hazard determination using Weight of Evidence Modelling

5.4.1 Gully Erosion Hazard

Figure 5.4 shows the total weight map (TWmap) which is a result of summing the weight contrast (Cw) values presented in Table 5.1. The chi-square test indicated that the factors; landcover, soil type, distance from river, flood hazard, Sediment Transport (STI) and Stream Power Index (SPI) were conditionally independent from each other, making all of these factors useful for weight of evidence modelling. The factors; slope, distance from road and Wetness Index (WI) were not incorporated in the weight map mainly because these factors had no significant correlation with gully occurrence.

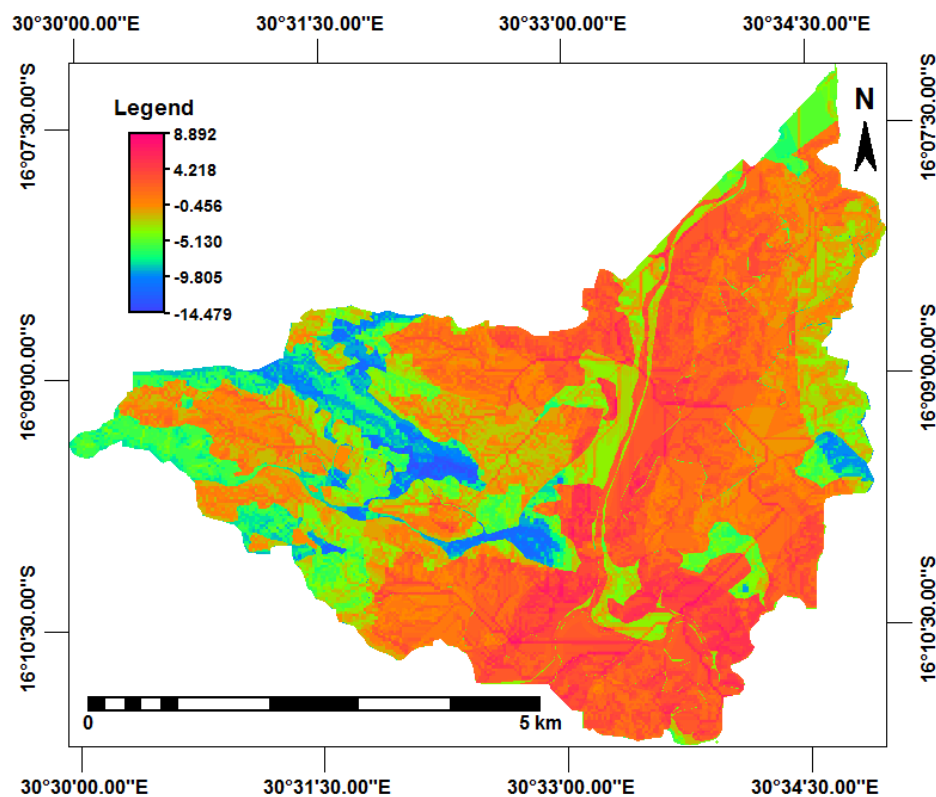


Figure 5.4: Total Weight map resulting from the summation of the factor contrast values – Mushumbi Pools

The total weighted map was converted into four classes. The classes were based on the change in gradient in the frequency distribution curve of the cumulated weight presented in Appendix 3 with a change in gradient signifying a change in class. Four classes were identified namely; very high hazard, high hazard, low hazard and very low hazard resulting in a gully erosion hazard

map (Fig. 5.5). The very high hazard zone has a value of weight ranging from 4 to 10, the high hazard has a value of weight ranging from 0 to 4, the low hazard has a value of weight ranging from -5 to 0, the very low hazard has a value of weight ranging from -14 to -5. In terms of area covered by each hazard class; 15.6% of the area falls within the very low hazard class, 33.1% in the low hazard, 43.4% in the high hazard and 7.9% in the very high hazard.

Observation of Figure 5.5 shows that most of the very high hazard zones are primarily located in the areas close to rivers. It was also observed that 90% of the very high hazard class is within a distance of 250 m from rivers, this can be explained by the fact that settlements in Mbire District are concentrated along rivers (Fritz *et al.*, 2003; Kusena, 2009), This implies that the development of settlements along rivers in Mbire District is a significant contributor of high erosion hazard in these areas. Increases in settlement density in these areas are likely to cause further gully erosion increases in the future. Furthermore since most of the high hazard areas are close to rivers it means that sediments generated from these gullies will certainly get into the rivers thereby causing siltation problems within the rivers and Cabora Bassa Dam downstream.

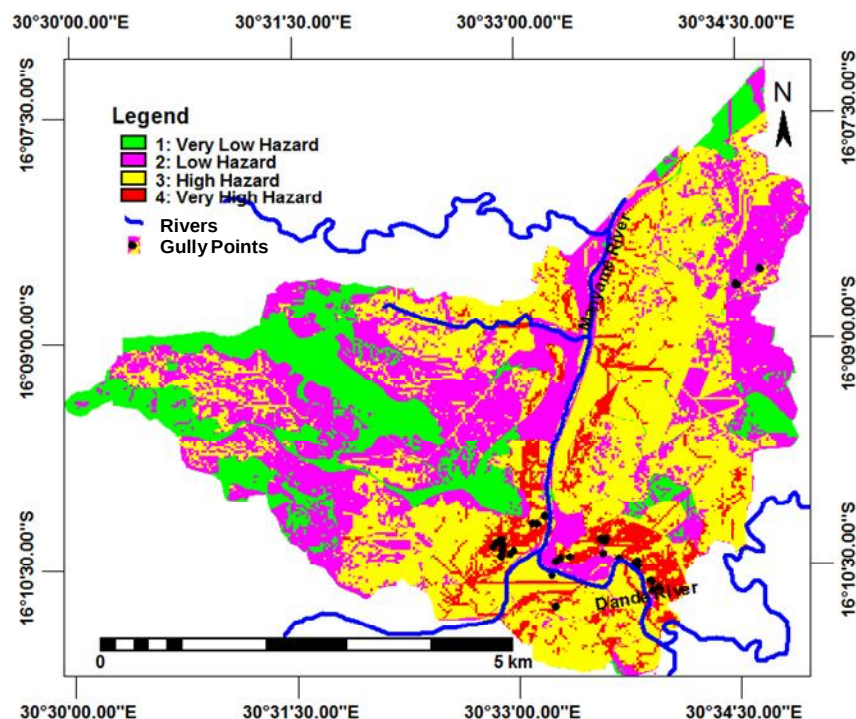


Figure 5.5: Map of gully erosion hazard classes, together with the main rivers and gully points observed in the field -Mushumbi Pools

5.4.2 Model validation and accuracy assessment

Model validation was done by testing the model using randomly selected recent gully activity in the field (Gully points presented in Figure 5.5). For the recent gullies identified in the field 45% of the gully points were in the very high hazard class, 30 % were in the high hazard, 25 % were in the low hazard class and no gully was observed in the very low hazard class. Combining the very high hazard and high hazard classes indicates that 75% of the gullies were in the high and very high hazard classes.

The accuracy of prediction of the model was determined from the area under the curve of cumulative percentage gully area against cumulative percentage study area (Figure 5.6) and it was found that the model has an accuracy of 74.7 %. This accuracy level is closer to the accuracy obtained by Regmi *et al.* (2010) of 78.4%. However it is quite lower than accuracy levels of 84.6% obtained by Mathew *et al.* (2007). To achieve such a high accuracy more factors should be incorporated and also using different factor combinations can result in a more accurate classification.

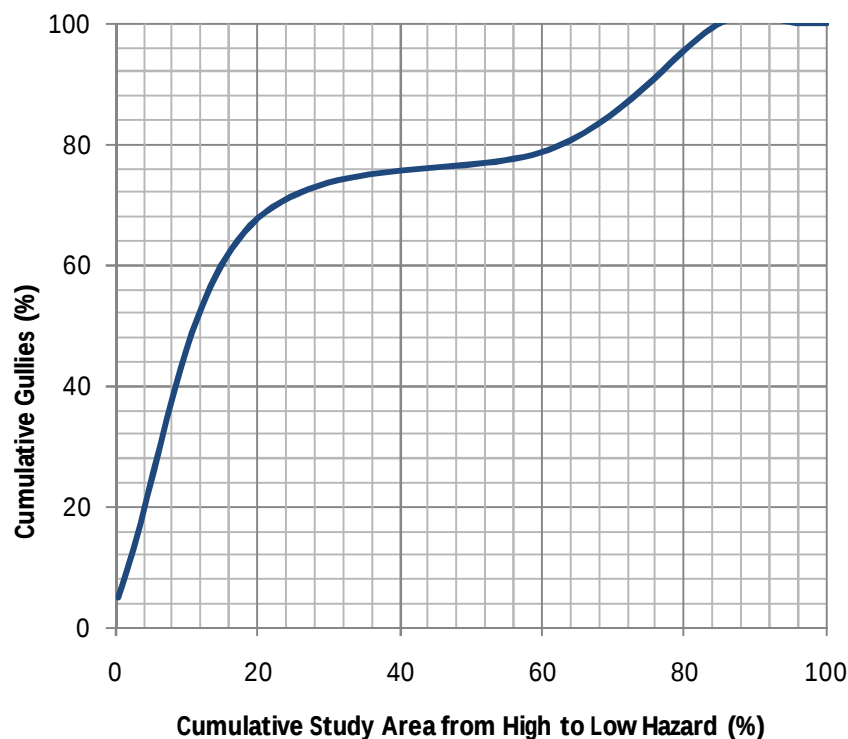


Figure 5.6: Accuracy assessment of the model using cumulative study area against cumulative gully area

5.4.3 Implications of findings

The Weight of Evidence Modelling technique has produced a valid gully erosion hazard Map. The predictive capability of the weight of evidence model in this study suggests that landcover, soil type, distance from river, flood hazard, Sediment Transport (STI) and Stream Power Index (SPI) can be useful in creating an optimum and valid map of gully erosion hazard. An observation of the spatial distribution of the very high erosion hazard class has shown that very high gully hazard is within very short distances to rivers. In Mbire District settlements are concentrated along rivers (Fritz *et al.*, 2003; Kusena, 2009). This implies that the development of settlements along rivers in the District is a significant contributor of high erosion hazard along rivers. An increase in settlement density in these areas is likely to cause further gully erosion increases in the future. Furthermore since most of the high hazard areas are close to rivers it implies that sediments generated from these gullies may get into rivers (Prosser and Winchester, 1996; Sanjay *et al.*, 2002; Sirviö *et al.*, 2004; Whitford *et al.*, 2010) thereby causing siltation problems within the river system and in the Cahora Bassa Dam downstream. However when areas close to rivers have a high flooding probability gully erosion hazard is minimal. It was therefore concluded that very high gully erosion hazard is along rivers and is mainly caused by high settlement density.

Policy makers may have to address increases in settlement densities along rivers. The main reason for having settlements along rivers is the need for access to water, therefore the provision of water sources in remote parts of the District may reduce settlement pressure and thereby reducing gully erosion in the long run.

Though high accuracy levels were achieved in this study, there is potential of achieving even higher accuracies. This may be achieved through incorporation of more evidential themes and also using different factor combinations. In this study the main limitation was unavailability of a high resolution soil map this therefore means incorporating such a map in the analysis can result in better results.

5.5 Results relevance to IWRM

Integrated Water Resources Management (IWRM) is a systematic process for the sustainable development, allocation and monitoring of water resource use in the context of social, economic and environmental objectives and the main basis of IWRM is that the many different uses of finite water resources are interdependent. Integrated management means that all the different uses of water resources are considered together (Cap-Net, 2005). These uses include, drinking, agriculture, and the environment. Water allocations and management decisions in IWRM consider the effects of each use on the others so that a balance can be made (Al Radif, 1999). In Mbire District an unregulated increase in settlements along rivers has potential of affecting other water uses such as water for the environment.

The findings from this study have demonstrated that high settlements density along the rivers: Manyame and Dande and their tributaries contribute to gully erosion in these areas. Such that the resultant sediment is deposited in the river system thereby causing siltation, this reduces water available to the riverine ecosystems. This is more important for Mbire District in that it is a wildlife zone with greater part of the district's revenue coming from wildlife. Wildlife relies on the river system for their water needs. From a study in the district by Fritz *et al.* (2003) it was shown that increases in settlements have reduced wild mammals' access to water thus effects of river siltation can worsen the situation particularly during the dry season when the river system is the only source of water. Furthermore the resultant sediments can find their way into the Cahora Bassa Dam downstream thereby reducing its water storage capacity. Consideration of all these issues in an IWRM plan and Strategy for Mbire District may lead to sustainable water resource utilization in the district.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

The aim of this study was to analyse soil erosion hazard in Mbire District as a function of environmental factors, as well as assess its magnitude as an environmental threat to water resources in Mbire District of Zimbabwe. The main conclusion derived from this study is that soil erosion is high in areas with settlements, and when settlements are in close proximity to rivers, gully development takes precedence and the resultant sediments have potential in causing river and reservoir siltation. The specific conclusions derived are as follows:

1. A greater part of Mbire District has low soil erosion hazard with pockets of high hazard occurring in areas associated with steep slopes, low erodibility values, settlements and cultivation.
2. There is a significant correlation between gully occurrence and environmental factors; landcover, soil type, elevation, distance from stream, flood hazard, Sediment Transport Index (STI) and Stream Power Index (SPI). There was no significant correlation between gully occurrence and distance from road, slope and Wetness Index (WI).
3. Weight of Evidence Modelling has great potential in gully erosion hazard modelling and it established that very high gully erosion hazard is along rivers and is mainly associated to high settlement density and in areas with soil type eutric cambisols.

6.2 Recommendation

The specific recommendations emanating from this study are:

1. Catchment management targeted at soil conservation may have to focus on areas with high settlement and cultivation, especially if cultivation is expanding into fragile lands. For planning purposes, ideally highly erodible soils could be allocated to landuses which do not reduce vegetation cover such as wildlife management.
2. For sustainable catchment management targeting gully erosion control and management the factors which significantly affect gully erosion may have to be the primary consideration.
3. Policy makers also need to address increases in settlement densities along rivers. The main reason for having settlements along rivers is the need for access to water, therefore the provision of water sources in remote parts of Mbire District can reduce settlement pressure along rivers and thereby reducing gully erosion in the long run.

Further studies should be done to establish the fate of the eroded soil, in terms of quantities and its deposition into hydrological structures.

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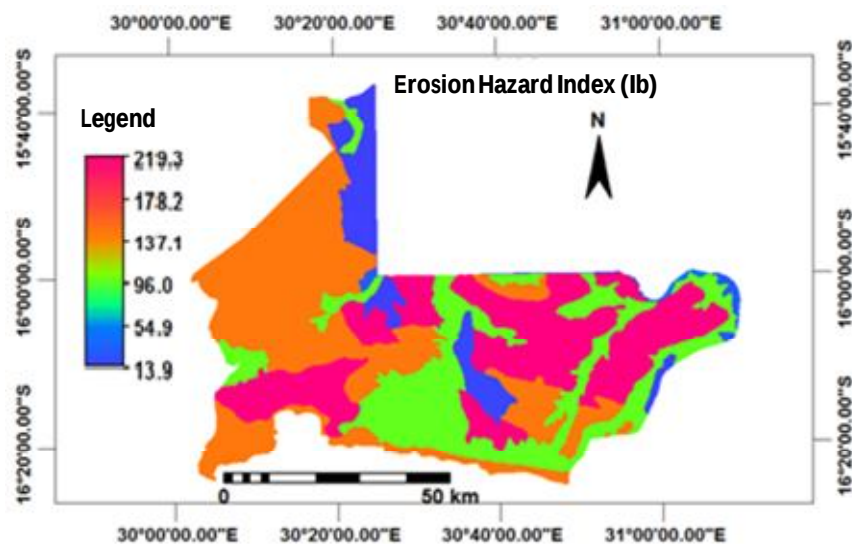
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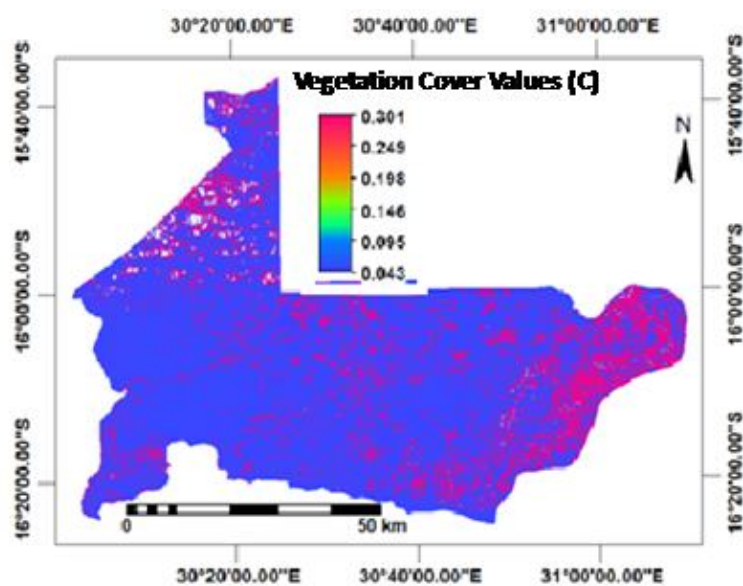
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APPENDICES

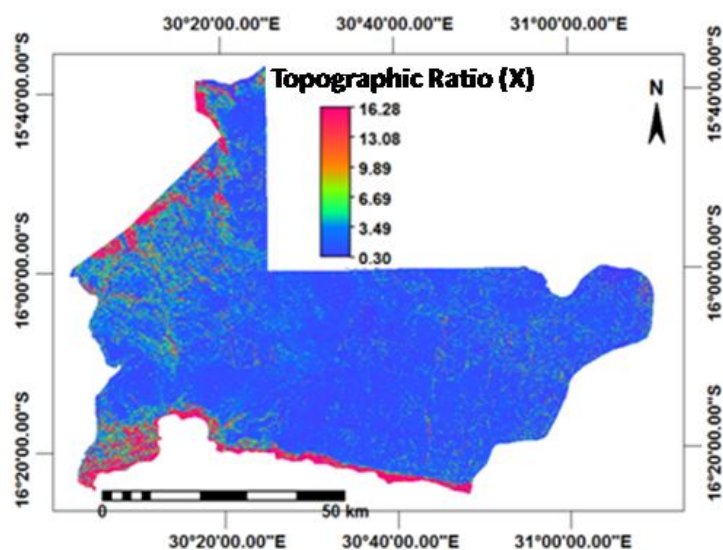
APPENDIX 1: Parameters used in the SLEMSA model



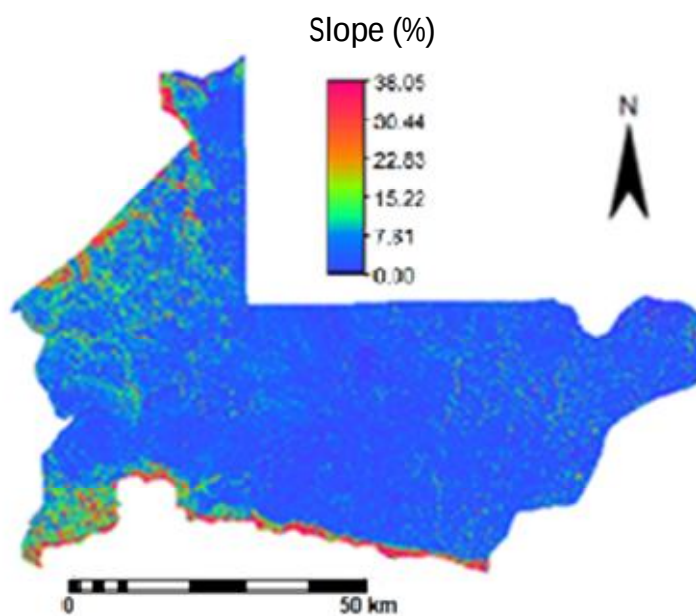
Appendix 1 a: Erosion Hazard Index (Ib) for Mbire District



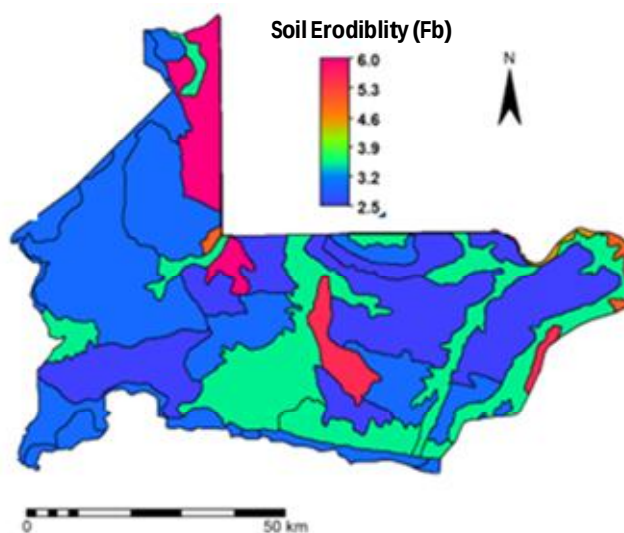
Appendix 1 b: Cover Values (C) for Mbire District



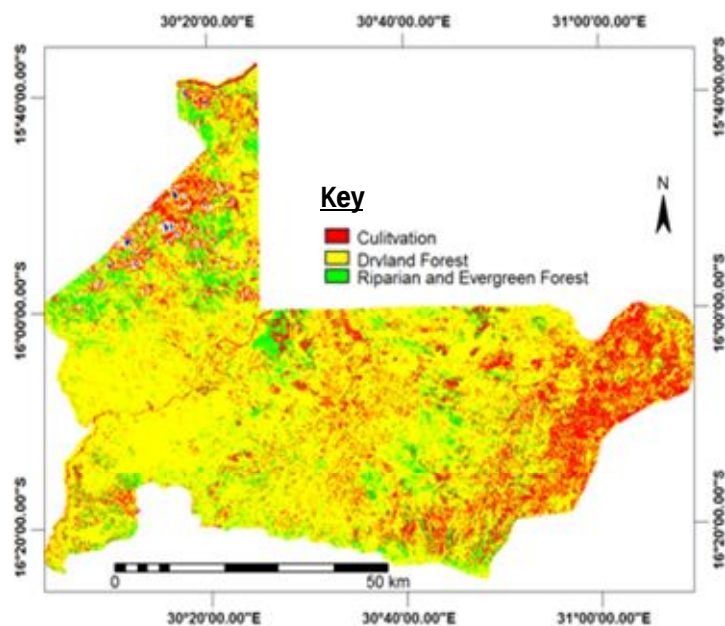
Appendix 1 c: Topographic Ratio (X) for Mbire District



Appendix 1 d: Slope map for Mbire District (%)

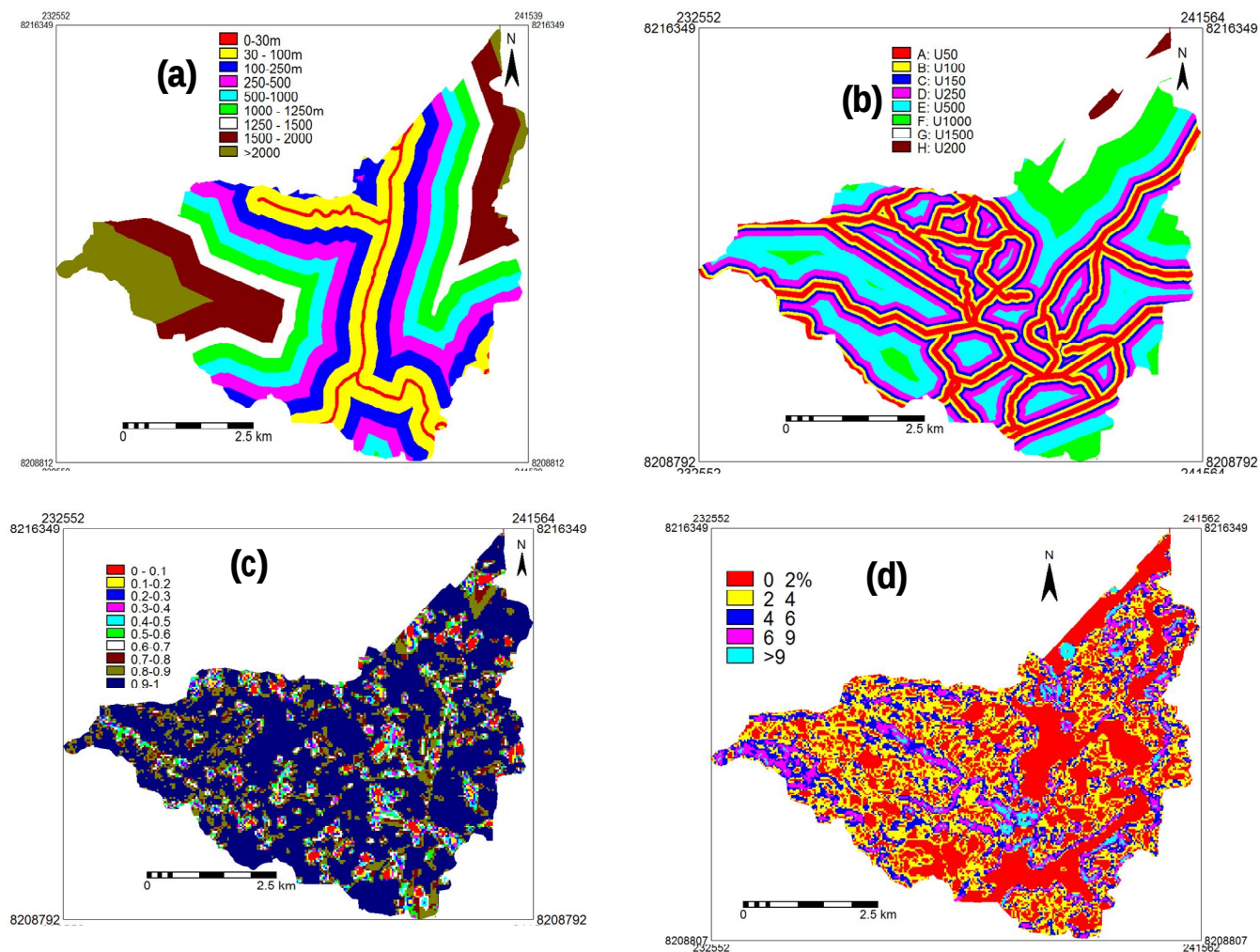


Appendix 1 e: Soil erodibility (Fb) for Mbire District

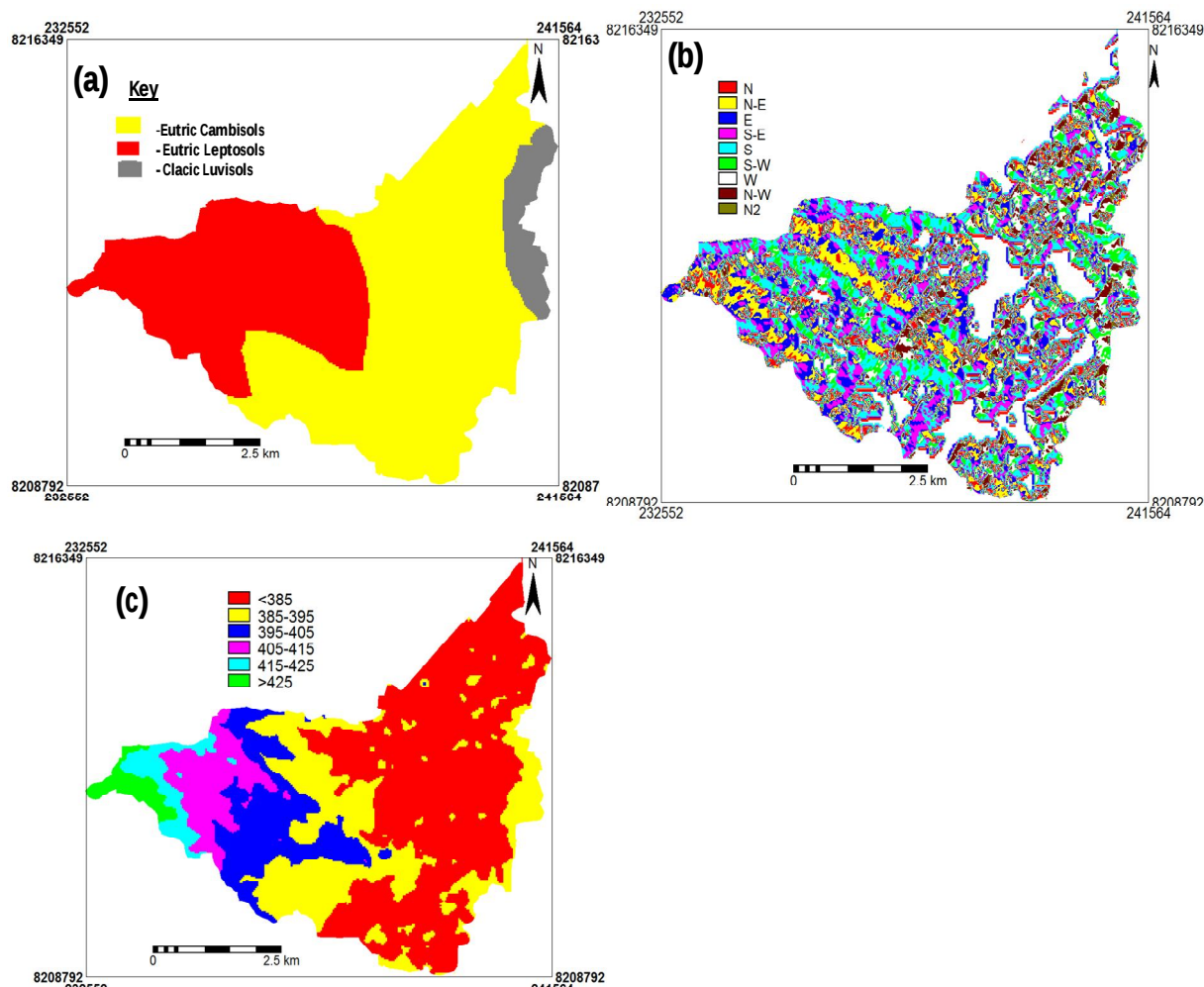


Appendix 1 f: September 2008 Landcover Map for Mbire District

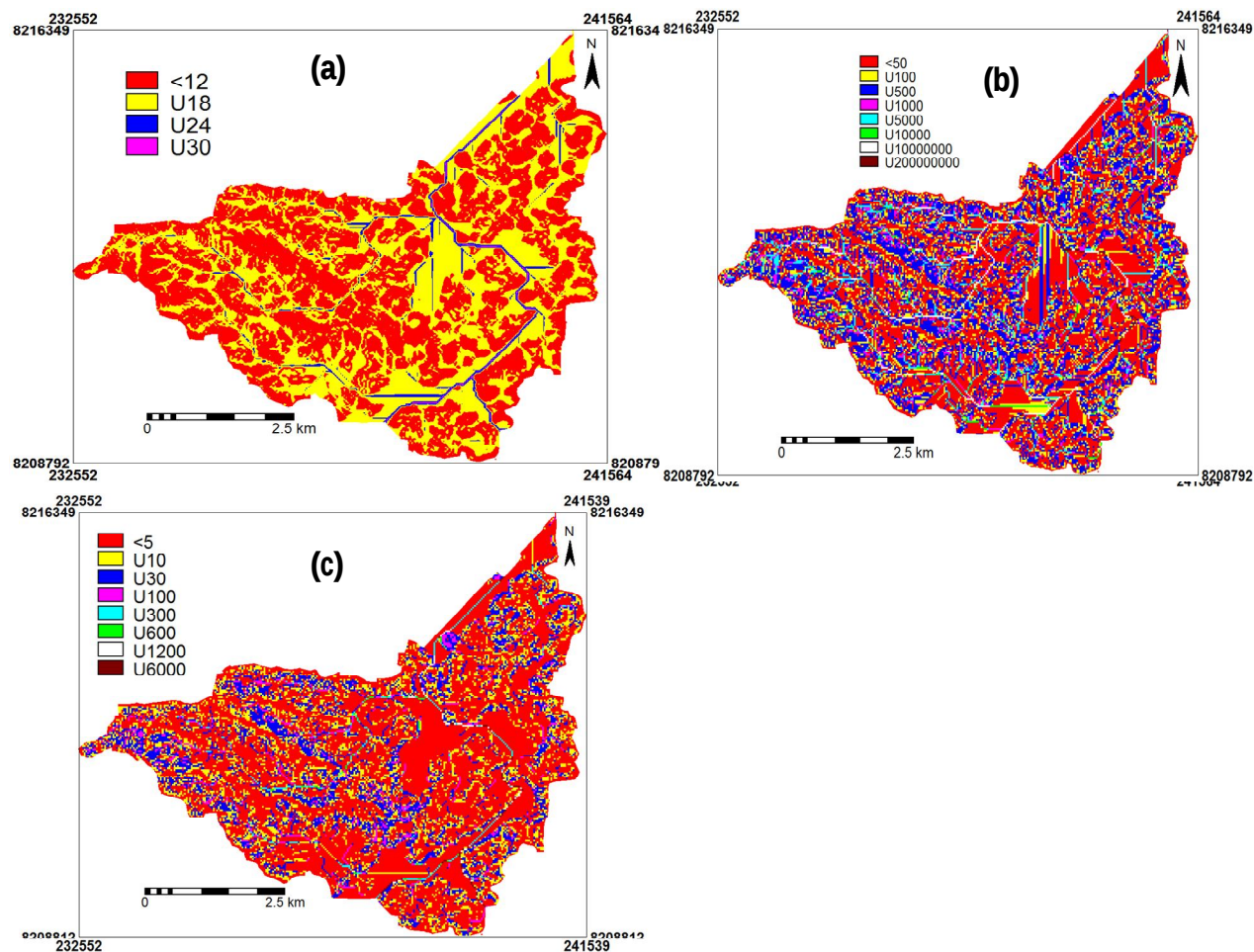
APPENDIX 2: Evidential themes used in Weight of Evidence Modelling



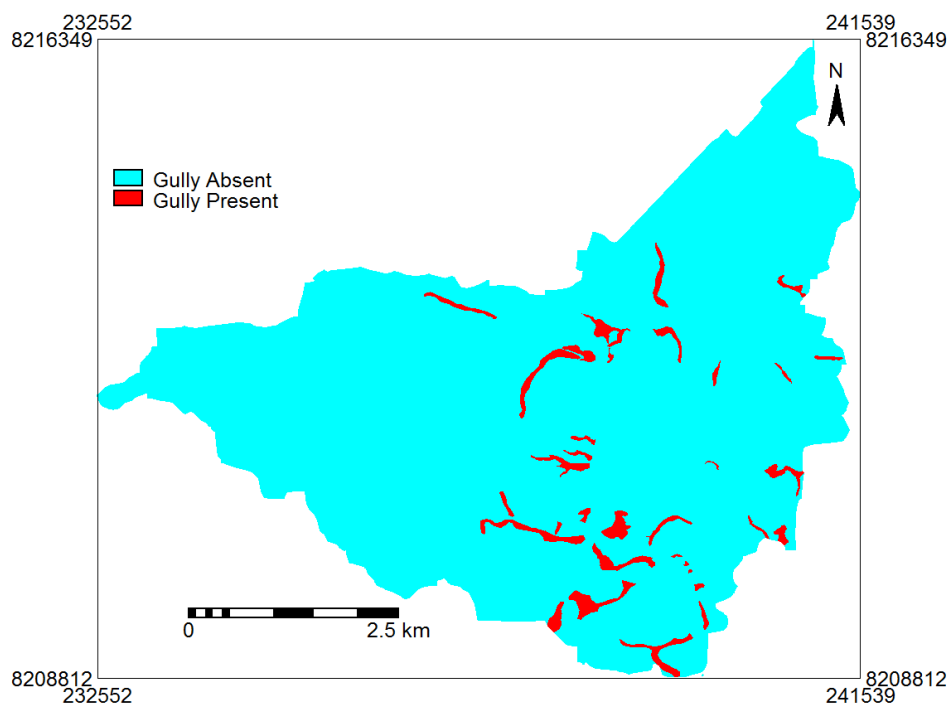
Appendix 2 a: Maps showing (a) Distance from stream, (b) Distance from road, (c) Flood hazard Map, & (d) Slope



Appendix 2 b: Maps showing (a) Soils, (b) Aspect & (c) Elevation

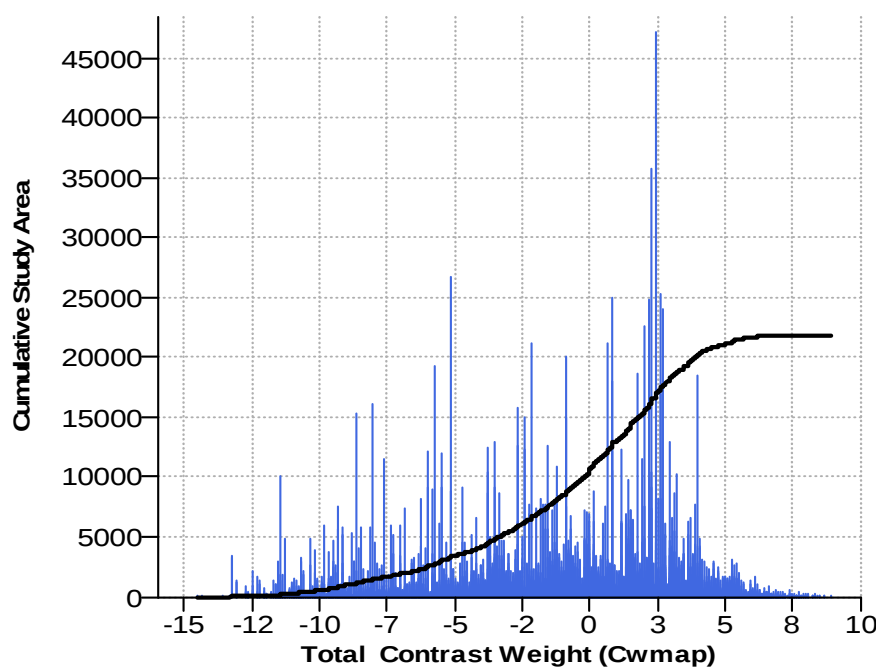


Appendix 2 c: Maps showing (a) Wetness Index, (b) Stream Power Index & (c) Sediment Transport Index with U indicating Upper boundary



Appendix 2 d: Binary Map of gullies at Mushumbi Pools digitized from 2007 spot image used as training sample

APPENDIX 3: Frequency Distribution curve of cumulated Contrast Weight



Appendix 3: a Frequency distribution curve of the cumulated weight