Spatial and temporal extent of land degradation in a communal landscape of KwaZulu-Natal, South Africa

by

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Abstract

Land degradation in communal rangelands is one of the problems that lowers land productivity, a central point for livelihood and economic benefits in rural areas. Therefore, monitoring spatial and temporal extent of land degradation offer a means of understanding the nature and causes of this phenomenon. Land degradation can be quantified by evaluating land cover changes over a period of time. Using five datasets of historical aerial photographs dating back to 1945, the current study employs GIS and Remote Sensing techniques to reconstruct the history of spatio-temporal extent of land degradation in the light of land cover changes and conversion in Okhombe, a communal area in a mountainous region of KwaZulu-Natal, South Africa. However, due to the mountainous terrain nature of the area which greatly affects the geometric accuracy of aerial photographs, this study first evaluated the potential of several georectification techniques in order to optimize geometric accuracy for change detection analysis. To achieve this, four different georectification methods were evaluated while the numbers of Ground Control Points (GCPs) used by the models were altered to assess their effects on the georectification accuracy. Of the four georectification methods, the spline transformation method yielded the highest accuracy when the highest number of GCPs was used, and this approach was thus used to georectify the rest of the historical aerial photographs used in this research. Once georectified, major land cover types were interpreted, digitized and mapped for the respective periods. The 'Landcover Change Modeler for Ecological Sustainability' in IDRISI was used to analyse landscape changes. Results showed that at a catchment scale, the spatial and temporal patterns of land degradation (with bare soil surfaces as the main indicator) did not change significantly, despite some other land cover types having changed notably due to land use management interventions and other factors. The major trend evidenced with bare soil surfaces was a slight increase that occurred between 1976 and 1992, a period that experienced low rainfall in the region. The results also demonstrated the roles of land cover changes and conversions in influencing patterns of land degradation. Furthermore, the study has also shown how landscape characteristics and effects of land use management such as slope and access gates influence prevalent patterns of land degradation in communal areas.

Preface

The experimental work described in this thesis was carried out in the School of Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, from January 2008 to September 2009, under the supervision of Professor Onisimo Mutanga.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

Declaration 1 - Plagiarism

I, Victor Mugabo Bangamwabo, declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.

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Declaration 2 - Publications

DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part and/or include research presented in this thesis (include publications in preparation, submitted, *in press* and published and give details of the contributions of each author to the experimental work and writing of each publication)

Publication 1: Bangamwabo, V.M. [1], and Mutanga, O.[2], (in preparation), Evaluating aerial photograph georectification techniques in a mountainous environment of eastern KwaZulu-Natal province, South Africa

The work was done by the first author under the guidance and supervision of the second author. The work is intended to be submitted to the Computers and Geosciences Journal.

Publication 2: Bangamwabo, V.M.[1], Mutanga, O.[2] and Salomon, M.[3], (in preparation), Spatio-temporal patterns of land degradation in the light of land cover conversions / changes in a communal landscape of KwaZulu-Natal province, South Africa

The work was done by the first author under the guidance and supervision of the second author. The third author assisted with field work and data interpretation. The work is intended to be submitted to the Land Degradation and Development Journal.

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Signed: ……………………………………..

Table of contents

List of tables

Appendices

List of figures

For my dear parents

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Abbreviations

ANOVA: Analysis of Variance

DEAT: Department of Environmental Affairs and Tourism

DEM: Digital Elevation Model

DTM: Digital Terrain Model

DWAF: Department of Water Affairs and Forestry

ESRI: Environmental Systems Research Institute

GCPs: Ground Control Points

GIS: Geographic Information Systems

GPS: Global Positioning Systems

HLURB: Housing and Land Use Regulatory Board

LCM: Land Change Modeler

MLP: Multi-Layer Perceptron

TIFF: Tagged Image File Format

RMSE: Root Mean Square Error

RPC: Rational Polynomial Coefficients

UNCCD: United Nations Convention to Combat Desertification

Chapter 1

General introduction

1.1 Background

In the last half of the 20th century there were dramatic land cover changes (Coxhead and Ragnar, 2007) accompanied by increasing environmental problems such as land degradation. Wessels *et al*. (2007: 272) describe land degradation as being 'one of the most serious global environmental issues of our time'. Land degradation in communal rangelands is one of the problems that lower land productivity which is crucial for livelihood and economic benefits in rural areas. (Hoffman *et al*., 1999; DEAT, 2008; Vetter, 2005; Meadows and Hoffman, 2002; Garland *et al.*, 1999). With adverse land conditions such as low vegetation cover, productive land in some communal areas has been impaired as a result of severe levels of land degradation (Palmer *et al.*, 2001). Land degradation is mainly manifested in the form of loss of vegetation cover that results in increased soil erosion (Kakembo, 2001; Valentin *et al.*, 2005) and bush encroachment threatening grazing and arable land (DEAT, 2008; Garland *et al.*, 1999; Meadows and Hoffman, 2002).

Various definitions of land degradation based on the nature of study (e.g. soil degradation and vegetation degradation) can be found. DEAT (2008: 3) defines land degradation as being 'the reduction or loss of biological or economic productivity of agricultural land, woodlands and forest that mainly results from human activities'. For instance, the loss of grassland vegetation resulting to bare soil surface can be referred as a physical description of land degradation. From this definition, land degradation can be attributed to land cover modification, a continuous process that alongside human influences such as livestock grazing, is driven by climate, geology, topography, and vegetation characteristics (Hester *et al.,* 1996; Garland *et al.*, 1999). Complex interactions of these factors, however, make landscape change a non-uniform process in nature which often results in prevalent land degradation in communal areas. Other characteristics of degraded lands include changing of productive land cover types into bare soil surfaces, rills and gullies (Valentin *et al.*, 2005; Meadows and Hoffman, 2002), bush encroachment (DEAT, 2008; de Villiers *et al.*, 2002), loss of indigenous vegetation and dispersal of invasive alien plants (Versveld *et al.,* 1998;

Meadows and Hoffman, 2002; de Villiers *et al.,* 2002) as well as the loss of biodiversity (Meadows and Hoffman, 2002). As Versveld *et al.,* (1998), Meadows and Hoffman (2002), and de Villiers *et al.* (2002) highlight, the state of land degradation in South African communal areas takes all these forms.

The increase in land degradation and high susceptibility of productive land to degradation in South African communal areas has been blamed on high livestock and population densities, communal land tenure, rainfall (DEAT, 2008; Meadows and Hoffman, 2002), steeper slopes (Meadows and Hoffman, 2002; Wessels *et al*., 2007), and often associated with high levels of poverty (Wessels *et al*., 2007). Moreover, DEAT (2008) and Valentin *et al.* (2005) state that poor land use planning and land use changes are further key contributing factors, whereas Meadows and Hoffman (2003) highlight roles played by poverty and apartheid land use management as being significant. Okhombe, a communal area located in a mountainous region of KwaZulu-Natal province in South Africa (see Figure 2.2), is one such area showing most of the above-mentioned characteristics regarding land degradation. For instance, land tenure type and land use interventions that have been implemented in Okhombe over the past century have had significant influences on land degradation (Tau, 2005). Sonneveld *et al*., (2005) highlight that land degradation in Okhombe is characterized by development of bare soil surfaces, gullies and rills, with most of these features dominating the midslope, upperslope, footslope, and the river valley. In a national review of land degradation conducted by the Department of Environmental Affairs and Tourism in 1997 and 1998, the Okhahlamba Local Municipality that Okhombe falls under, was reported to have a 'severe' degradation index, the worst on the scale of four levels (i.e. Insignificant, Light, Moderate, and Severe) on a combined degradation index scale mainly based on soil and vegetation conditions (Hoffman *et al*., 1999). While communal areas are reported to have high rates of land degradation (e.g. in Meadows and Hoffman, 2002), often little is known about historical trends of land cover and associated land degradation trends and impacts of identified factors controlling such degradational changes over the years, particularly at local scales. As an environmental problem that is spatial in nature, trends in land degradation can be spatially and temporally assessed by studying changes in land cover to verify if changes that have occurred are indeed components of degradation. In the case of Okhombe, an intermix of the major land use management interventions implemented over the past 60 years and the physical characteristic of the landscape (particularly with its mountainous topography) present an intriguing opportunity to study the resultant trends of land degradation.

The ability to determine the extent of land degradation at a given time requires having an insight of its spatial extent, while its spatio-temporal extent provides the degree and rate of change (DEAT, 2008). The means of measuring spatio-temporal extent of land degradation are generally to determine and measure spatial extent of its features (such as vegetation cover and bush encroachment), and study soil properties amongst others. As tools that enable comprehensive spatio-temporal investigation of land cover features, Geographic Information Systems (GIS) and Remote Sensing can be used to study and quantify the state and change rate of land degradation using land degradation features as indicators.

Given that communal areas are vulnerable to land degradation if future climatic conditions deteriorate (Meadows and Hoffman, 2003), there is a need to sustainably manage this phenomenon. In this regard, the application of GIS and remote sensing is becoming increasingly important. In addition, advancements in the analytical knowledge and technology of these tools are offering valuable opportunities to study land degradation. Time series data obtained from satellite imagery has provided data and opportunities to develop land cover change models (Kaufmann and Seto, 2001) for estimating past and future land cover conditions. These tools have been widely used to study changes in savanna environments, shrub encroachment, and urban environments, amongst others (Laliberte *et al.,* 2004; Zhan *et al.,* 2002; Palmer and van Rooyen, 1998). However, the use of satellite imagery in studying dynamics of land degradation *per se*, is affected by various factors that include spatial resolution and availability of imagery appropriate to monitor change for longer periods (Serneels *et al.,* 2001; Friedel, 1997). To overcome these limitations, aerial photographs are used since their availability predates the acquisition and existence of satellite imagery. this provides the ability to detect landscape trends that are longer as highlighted by Kakembo (2001); Hester *et al.,* (1996); Fensham *et al.,* (2007) and Akbari *et al.,* (2003).

Aerial photographs have extensively been utilized as sources of information for map production since the early 1900s when the first aerial photographs were taken (Lillesand *et al.,* 2004). This affirms views by Meadows and Hoffman (2002) and Valentin *et al.* (2005) that a long history of environmental dynamics in an area of concern should not be overlooked when attempting to study and monitor land degradation. By individually scanning and inputting existing hardcopy paper aerial photographs into a GIS, these are then georectified in order to establish their geographical locations before any mapping tasks such as digitizing and further analysis are performed. It is only after such procedures that land degradation and its changes can be mapped to quantify its spatial and temporal extent.

The significance of accurately georectifying aerial photographs is an important procedure (Lillesand *et al.,* 2004) that assigns correct map coordinates to features of interest (e.g. land degradation features such as bare soil surfaces and gullies) and attempts to minimize positional errors (Rocchinia and Di Rita, 2005). Generally, such errors have implications and that become more prominent when multiple image data covering the same geographical location but taken at different dates is overlaid for assessment. For instance, errors occur during land cover change analysis whereby positional error may have significant effects on accuracy of the results. The degree of these discrepancies depends primarily on components of the georectification process applied during this procedure. These include the type of georectification technique or model employed, whose accuracy is conversely affected by topographic variations and the number of ground control points used to fit the georectification model within a GIS.

When studying land degradation, remote sensing and GIS techniques are used to analyse aerial photographs and thus provide a useful platform in determining areas most and least affected by land degradation, spatial patterns of the detected changes, the change rate of land degradation and spatial dispersal of land degradation in relation to other land cover types. With the resultant information, explanatory analysis of detected spatial and temporal extent of land degradation can be conducted to better aid the understanding of this process (Wessels, *et al*., 2007; Sonneveld *et al.*, 2005). At a local scale, historical investigation of these changes highlight the significance of how understanding these changes may inform rangeland resource management for the present and future of communal areas like Okhombe. However, mountainous terrain such as that of Okhombe present methodological challenges (i.e. geometric distortions resulting from the choice of georectification techniques and parameters employed) that are grave enough to negatively affect accuracy of any change detection analysis, particularly when a large number of aerial photograph scenes are used. In this regard, investigating the performance of georectification techniques as well as evaluating factors influencing their accuracy is critical for the adoption of suitable techniques for mountainous environments like Okhombe (see Figure 2.2).

Okhombe presents a good case to study changes in spatial extent of land degradation as it possesses an appreciably long history of different major land use management interventions, some partially aimed to contain this problem but were unsuccessful. For instance, the Betterment Scheme implemented in the 1960s is widely regarded to have failed to meet its intended aim of minimizing land degradation. More recently, the National LandCare Programme implemented in 1999 as part of a community based natural resource management project and efforts to combat land degradation by employing camp rotation and herding as methods of communal grazing system also did not produce intended results and grazing systems and practices employed are not environmentally sustainable (Tau, 2005). Furthermore, associated with these interventions was the effect of change in grazing patterns imposed by erected fences that livestock would often have to cross (through access gates) to access the rangeland. An important observation about Okhombe is that as the landscape changed, the spatial locations of fences and access gates were also shifted, presenting new spatial patterns of various land cover types and potentially changing patterns of land degradation.

The present research attempts to determine and study how landscape and land degradation in particular, has been altered over the years in Okhombe using GIS and Remote Sensing techniques. Bare soil surfaces are used as the primary indicator of degraded land (although gullies and woody vegetation are also considered to some extent) while other land cover changes describing the land degradation phenomenon are employed as a means of identifying trends in land degradation. Furthermore, change prediction capabilities provided by GIS and remote sensing tools are used to predict future patterns of land degradation. Four different time periods which encountered these land use interventions and considerable variations in rainfall conditions are investigated in this study. These include the pre-Betterment Scheme period (1945), the period following the implementation of the Betterment Scheme (1962), prolonged period after the Betterment Scheme (1976 to 1992), and the period after the LandCare project (2004). With the above background in mind, the following specific aim and objectives are to be addressed in the study.

1.2 Aim and objectives

The main objective of this research is to assess the spatial and temporal extent of land degradation in Okhombe communal area in the mountainous region of KwaZulu-Natal province, South Africa. To achieve this aim, the following main objectives are addressed:

- To evaluate the accuracy of different georectification techniques in a mountainous environment.
- To map land cover change and indicators of land degradation from 1945, 1962, 1972, 1992, to 2004.
- To predict future land cover conditions and patterns of land degradation based on transition states of the detected changes in land cover.

1.3 Research question

How and to what extent has land degradation changed in Okhombe since 1945 and what are the likely future patterns?

1.4 Contributions and significance of this research

The current study is part of a wider research entitled '*Cattle keeping in a changing landscape*' investigating changes in the communal grazing area of Okhombe from the ecological/physical environment, economic and socio-political perspectives. The impacts that have occurred since the early 1900s are investigated in order to address challenges faced in cattle grazing management in communal areas.

By employing GIS and Remote Sensing techniques, the current study answers the 'physical environment' aspect of the wider research to reconstruct the history of landscape change in Okhombe since 1945 and thus investigate the possible causes of the detected changes in land degradation patterns, particularly in relation to climatic conditions and major land use management interventions. Furthermore, these tools enabled integration of available data and knowledge to understand patterns of identified trends and forecast future spatial conditions using a stochastic Remote Sensing model. This is conducted at a catchment scale, representing an entire community with a history of homogeneous land use management strategies and biophysical conditions as described in Chapter Two.

1.5 Outline of the thesis

This thesis is presented in five chapters and structured mainly around two chapters that form two publishable papers to be submitted to peer reviewed journals. These are Chapter Three covering an evaluation of georectification techniques for a mountainous area of KwaZulu-Natal, South Africa and Chapter Four addressing the spatial and temporal patterns of land degradation in the light of land cover conversions and changes in Okhombe. Each of these two chapters has major sections presenting the introduction, literature review, methodology, results discussions, and topical conclusions of the respective chapter.

Prior to these chapters, in Chapter Two a general description of the study area is presented, and aspects relevant to the study are highlighted.

In Chapter Three, the rationale of this chapter is motivated and methods and experiments employed in this are outlined. These entail identification and selection of the optimal georectification technique used in this study to georectify numerous scenes of aerial photographs used to achieve the aim of the thesis. Results of the accuracy of the various georectification criteria employed for identifying and selecting the optimal georectification technique ultimately used in this research are presented and discussed.

In Chapter Four, the literature on land degradation and land cover conversion in communal areas of South Africa is briefly reviewed. Application of GIS and remote sensing techniques used to assess past land cover change and predict future land cover conditions are reviewed in the context of this study. The data pre-processing procedures (e.g. digitizing) and procedures conducted for change detection and future change prediction analysis are outlined. Results of this chapter are presented and then discussed using bare soil surface as the primary indicator. To aid this discussion, correlation analysis between locations of identified bare soil surfaces and slope, and then distance to access gates are utilized. Furthermore, ancillary data such as past rainfall data and existing literature, particularly that on Okhombe, are also used for the discussion and interpretation of the results.

In Chapter Five the main aim, objectives, and findings of this thesis are reviewed. The limitations of the study are highlighted and recommendations provided.

Chapter Two
Description of the study area

Okhombe is a communal settlement that falls under the jurisdiction of the Amazizi Traditional Administrative Council, and the Okhahlamba Local Municipality in the province of KwaZulu-Natal. Figure 2.2 shows the location of the study area. Currently, Okhombe is recognised as a ward consisting of six sub-wards. Situated at the foot of the Northern Drakensberg Mountain range, a Cultural and Natural World Heritage Site, Okhombe is within 10 to 20 km of the north-eastern border of Lesotho. The altitude varies from about 1200 to 1800 m and the area receives a mean annual rainfall of about 800 to 1000 mm, with summer months (November to March) receiving about 70 % of this rainfall. The mean annual temperature is 14 ^{o}C. In winter, the mean annual temperature reaches 5 ^{o}C with frost and snow occurring almost every winter (Temme, 2008). Rainfall has fluctuated slightly over the past 60 years with a general increase in rainfall from 1945 towards the late 1950s, while the early 1980s experienced a dry spell (Figure 2.1).

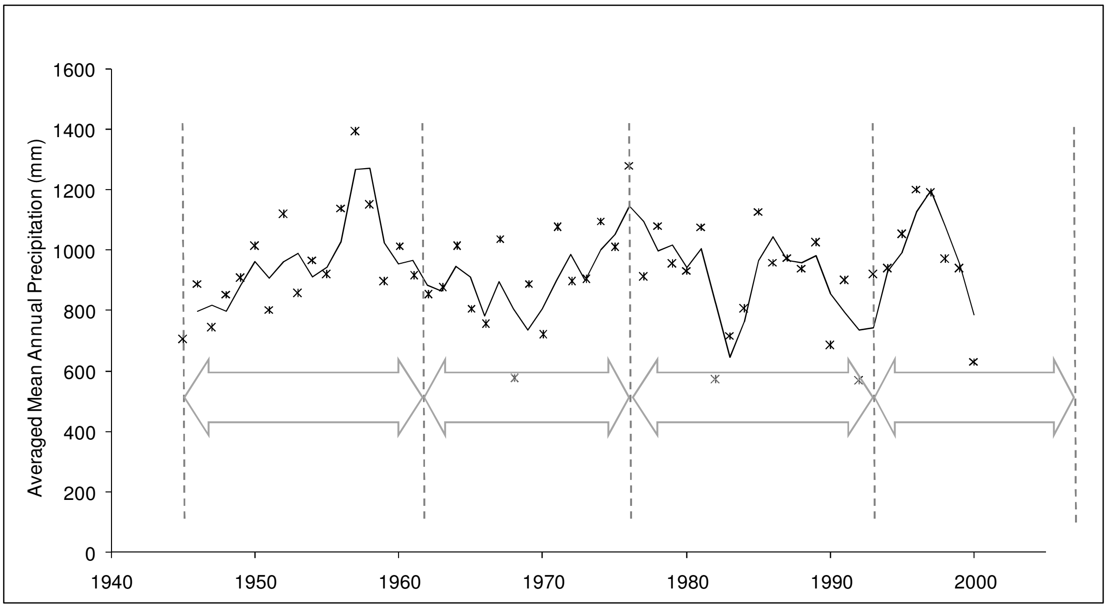

Figure 2.1 Graph showing a moving average trendline of mean annual precipitation at two rainfall stations located near Okhombe from 1945 to 2000. The arrows show the four time periods traversed by this research. (Rainfall data extracted from The Daily Rainfall Data Extraction Utility compiled by ICFR and BEEH).

Based on slope and parent rock material, Sonneveld *et al*. (2005) distinguished five different landscape units, namely the River Valley (1250 to 1300 m), Footslope (1300 to 1330 m), Midslope (1330 to 1360 m), Upperslope (1360 to 1425 m), and the Plateau (1425 to 1500 m). According to the Bioresource Groups inventory compiled by Camp (1999), the River Valley, Footslope, Midslope, and the Upperslope have a slightly homogeneous mean annual rainfall ranging from 901 to 1100 mm, while the Plateau receives a higher mean annual rainfall above 1100 mm. At these elevation variations, Okhombe has underlaying parent rock materials of the Beaufort Group consisting of sandstone and mudstone on the plateau; mudstone and shale on slopes; and shales, sandstone, and basalt on lower elevation (Sonneveld *et al.*, 2005; Tau, 2005). Soils in Okhombe, derived from basalt rock materials, are described as being acidic, highly leached, and structureless (Tau, 2005). Slope steepness varies from 0.01 to 69 % (i.e. in slope percentage) on steep hill slopes. Given such high elevation variation characterized by steep slopes, soil characteristics, and high rainfall, the landscape in Okhombe is vulnerable to erosion.

Vegetation is mainly grassland and described as being Southern Tall Grassland and Highland Sourveld according to Acocks' vegetation classification (Acocks, 1988). However, patches of shrub and forest are found mainly along upper riparian areas. A variety of grass species, both palatable and unpalatable, are found in the area during the summer and winter months, respectively.

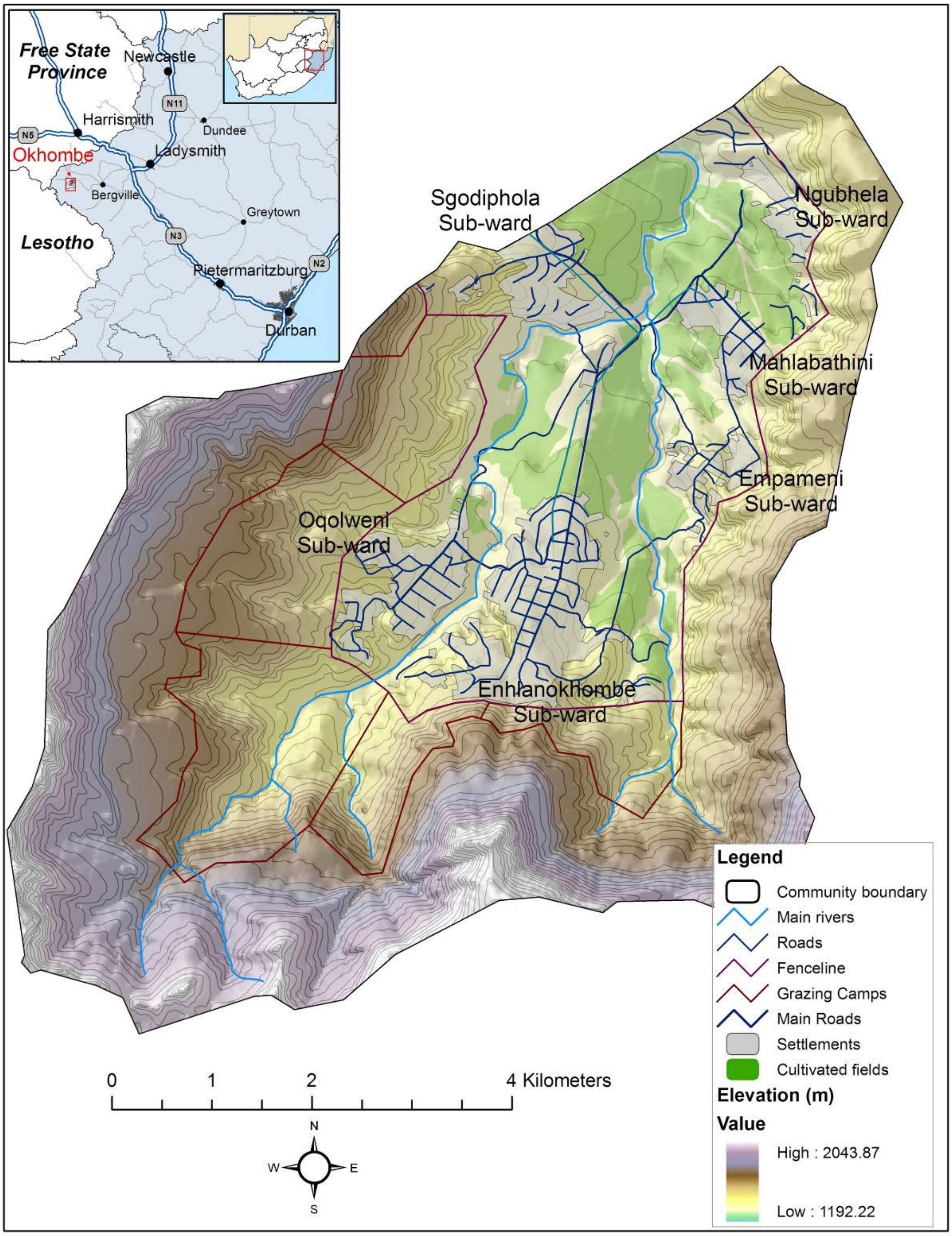

Figure 2.2 Locational map of Okhombe showing the elevation at 20 m contour intervals and spatial locations of the major land use types.

Land use management in Okhombe has been affected by a number of external interventions. The Betterment Scheme was implemented in Okhombe in the 1960s to combat land degradation (DEAT, 2008; Sonneveld *et al.*, 2005). The programme was initiated in communal areas by the apartheid regime in an effort to halt land degradation. Since its implementation, this programme has played a significant role in shaping the present spatial patterns of land use and land cover in Okhombe. For instance, today, the main settlement areas are mostly situated along lowlands and on low hill slopes while rangelands are located on higher elevation away from cultivated fields that occupy the valleys.

Livestock keeping is one of the commonly practised livelihoods and a cultural practice in Okhombe. Thus rangeland has always been considered to be an important natural resource. In summer, lowland areas are generally used for cultivation and grazing of milking cows, while hill slopes and rangeland on the upper plateau are used for grazing. During some winter months (from May to September) grazing activities by all cattle is confined within lowland areas due to the decline in nutritive forage in upslope rangeland. These prevailing patterns of land use have presently been strengthened by later land use management interventions such as the National LandCare Programme intended as a community based sustainable poverty alleviation program (DWAF, 2008).

More recently, the Okhombe Monitoring Group, a group consisting of community members trained to monitor rehabilitated areas in an effort to combat soil erosion has conducted considerable work showing a decline of soil erosion following installation of rehabilitation measures (Everson *et al.,* 2007).

Although there are numerous settlements surrounding the Okhombe ward, land use management in Okhombe has always been uniformly conducted at a ward scale thus promoting a focused manner of land use management within this ward. This manner of land use management and strategies has been strengthened by a fence-line erected in some places to demarcate Okhombe. One of the main purposes of this fence-line is to prevent cattle theft and from going to the neighbouring communities.

Chapter Three
Evaluating aerial photograph georectification techniques in a mountainous environment of eastern KwaZulu-Natal province, South Africa

3.1 Introduction

Georectification methods range from a complex orthorectification method to polynomial transformation methods. Leica Geosystems (2003), Shaker *et al.* (2005), and Rocchinia and Di Rita (2005), describe orthorectification as being a process which gives a precise geographical location to ground objects on the rectified images as they appear on the earth's surface regardless of the topographic effects. To achieve this, digital elevation models (DEM) or digital terrain models (DTM) are incorporated in this process to correct positional errors resulting from topographic relief displacement (Leica Geosystems, 2003; Lillesand *et al.,* 2004; Rocchinia and Di Rita, 2005). Orthorectification products are thus widely accepted as being ideal reference data to use for map production and geographic analysis in GIS (Okeke and Karnieli, 2006; Cots-Folch *et al.,* 2007; Leica Geosystems, 2003; Rocchinia and Di Rita, 2005; Hurskainen and Pellikka, 2004), because this method achieves near-perfect georectification accuracy.

Despite the ability to yield high accuracy, orthorectification is not commonly used because it has more costly, sophisticated computational, and specialized user requirements (Hughes *et al.*, 2006). For instance, running an orthorectification process in two of the commonly used image processing softwares (namely ERDAS Imagine and ArcMap) is often not possible since some of the processing requirements are often not available to users. In ERDAS Imagine for instance, fiducial marks, recorded GCPs, camera calibration reports needed for the camera model properties within the software environment, and an accurate DEM are required (Leica Geosystems, 2003), while in an ArcMap environment, the Rational Polynomial Coefficients (RPC) provided by the vendor along with the imagery and an accurate DEM are required (ESRI, 2007). An alternative to this method, are the polynomial transformation based georectification techniques which can be employed within these two software environments if the above requirements are not available. Polynomial transformation techniques have been used increasingly in recent years mainly due to the popularity of desktop GIS which is generally affordable (i.e. software and hardware equipment) and not very sophisticated to use.

Polynomial transformation techniques make use of matching control points on the target image to their identified locations on reference data and then rectifying the image based on least square fitting algorithms (ESRI, 2007). Polynomial transformation algorithms that are commonly used range from the simpler first-, second-, and third-order polynomials to the more complex curvilinear mathematical transformation algorithms such as the spline transformation, commonly known as 'rubbersheeting' (ESRI, 2007; Hughes *et al.,* 2006).

3.1.1 Problems associated with polynomial transformation techniques

While each polynomial transformation technique is based on unique mathematical algorithms, accuracy performance varies from technique to technique as has been reported by various researchers whose studies are reviewed below. Rocchinia and Di Rita (2005) report that higher order polynomials, based on more complex transformation models, yield better rectification accuracy than lower order polynomials. Higher order polynomials such as the second- and third-order polynomials allow for curving of rectified images and can thus be more efficient than the first-order polynomial as reported by Shaker *et al.* (2005), Rocchini and Di Rita (2005), and Hughes *et al.* (2006). However, distortions build up on and in close proximity of GCPs used for the first-, second- and third-order polynomials (Yanalak *et al.*, 2005) but remain unchanged for the spline transformation (Doytsher, 2000; ESRI, 2007) even when the required minimum number of GCPs is exceeded. To achieve this, spline transformation preserves the exact locations of the matched control points regardless of their number (Doytsher, 2000; Herwitz *et al.,* 2000). This is attained through curving, stretching, shrinking, and reorienting of the target image as GCPs are accurately matched to their location on the reference data (ESRI, 2007). Doytsher (2000) outlines that the spline transformation approach has an ability to improve data quality by retaining the data continuity throughout the database or image data. Hughes *et al.* (2006) and Xie *et al.* (2003) mention that spline transformation can correct topographic distortions for local scale image data and yield accurate results similar to orthorectified products.

While image georectification is regarded as being an important process, several landscape change detection studies using remote sensing and GIS (such as Hudak and Wessman, 1998; de Castro, 2005) used mostly the first- and/or second-order polynomials during georectification. Some of these and several other studies such as those of Seppe (2004) and Okeke and Karnieli (2006) rarely state the georectification methods used and/or fail to report on georectification accuracy attained during the procedure. It is also evident that only a few studies have revealed and compared accuracy performance attained by different georectification techniques including the spline transformation.

3.1.2 Factors affecting georectification accuracy

Apart from assessing the performance of various georectification techniques, it is imperative to understand the factors that influence their performance. These factors include the number of Ground Control Points (GCPs) used, the topography of the environment of focus, and the map scale (i.e. global and local scales) used. In addition, the complexity of mathematical transformation algorithms on which polynomial transformation techniques are based plays an important role (Hughes *et al*., 2006; Yanalak *et al.*, 2005).

3.1.3 The number of Ground Control Points (GCPs) and georectification techniques

The number of GCPs used during georectification is widely considered to be a significant factor that influences georectification accuracy. Rocchinia and Di Rita (2005) and Hughes *et al.* (2006) show that there is improved georectification accuracy with an increased number of GCPs for the first-, second-, and third-order polynomials. It can thus be assumed that georectification accuracy attained by a certain polynomial transformation model is a function of the number of GCPs applied by the model. However, Shaker *et al.* (2005) report that the number of GCPs used by a georectification technique does not significantly affect georectification accuracy in an even topography, and they maintain that a modest number of GCPs be utilized in such an environment.

3.1.4 Topography of the study area and georectification techniques

Topography has been reported to significantly affect accuracy performance attained by the first- and second-order polynomials. For instance, Shaker *et al.* (2005) investigated the effect of elevation on rectification accuracy using a comparison of various transformation techniques. These researchers found the second-order polynomial obtained the lowest Root

Mean Squared Error (RMSE) value for even topography and was ideal for use at global scale (Shaker *et al*., 2005; ESRI, 2004). In addition, Rocchinia and Di Rita (2005) and Shaker *et al.* (2005) demonstrated that the overall RMSE attained by different polynomial models tended to be slightly similar in flat environments and varied as the polynomial order increases in mountainous areas. Furthermore, Hughes *et al*. (2006) state that higher order polynomials can produce relatively more satisfactory results in mountainous settings. This is attributed to the inability of lower order polynomials to effectively curve, stretch, shrink, and wrap the target image to compensate for elevation difference introduced by topographic variation, a characteristic that is more prominent as the polynomial order increases and in the spline transformation method (Hughes *et al.*, 2006).

In view of the above, there is evidence that inconsistent results are achieved regarding the effects of several environmental variables on georectification accuracy. In addition, there is paucity of information on the effect of the number of GCPs used have on georectification accuracy attained by the spline transformation technique in mountainous environments. Furthermore, this is despite the ability of the spline transformation technique to wrap, shrink, stretch, curve, and reorient the target image while preserving the exact locations of the matched control points (Doytsher, 2000; Herwitz *et al.,* 2000), a characteristic that linear polynomial techniques lack.

In the light of the above background, the performance of various techniques is evaluated in this study to aid selection of the appropriate techniques and criteria for the final georectification of historical aerial photographs of a mountainous environment. For this chapter, the hypothesis was that georectification accuracy increases with increased georectification polynomial order (i.e. from the first-, second- then third-order polynomial and even higher with spline transformation), based on the transformative characteristics of individual georectification methods used. The first-, second- and third-order polynomials and spline transformation methods were comparatively tested for georectification accuracy superiority using ArcMap, a commonly used image processing software.

Guided by two main methodological factors, namely the number of GCPs and the polynomial model used which determine georectification accuracy, the following experiments were undertaken in order to:

- Establish the effect of the number of GCPs on different georectification transformation methods on georectification accuracy using independent control points.
- Evaluate the georectification accuracy of different georectification transformation methods using a fixed number of GCPs.
- Evaluate the georectification accuracy obtained by using a varying number of GCPs on spline transformation.

3.2 Methods and materials

3.2.1 Measuring georectification accuracy

Appropriate evaluation of positional errors occurring after georectification is a key component of judging the degree of discrepancy the number of GCPs, the polynomial method used, and the topography have on overall georectification accuracy. Generally, georectification accuracy is quantified using the RMSE expressed as (according to Slama *et al.*, 1980):

$$\text{RMSE} = \text{sqrt}\{\Sigma[(x_i - X_i)^2 + (y_i - Y_i)^2]/n\} \quad (3.1)$$

where x_i and y_i are coordinates of the GCPs when the polynomial transformation functions is applied, and X_i and Y_i coordinates of the same points on the reference, whereas n represents the number of coordinate pairs used

The limitation of this method is that it does not represent the actual positional error but the consistency of the transformation model when different GCPs are used to georectify an image. Therefore, the RMSE calculates the transformative ability of the georectification model fitted based on the locations of GCPs, rather than the actual positional error (s) occurring elsewhere within the image. This is well demonstrated when spline georectification method, a true rubbersheeting method, is used, whereby an RMSE value of zero is obtained whenever the required minimum number of GCPs for this model is met, yet enormous positional error is evidenced elsewhere in the image.

To overcome this and be able to more accurately measure georectification performance when different criteria are selected, a method used by Hughes *et al.* (2006) employing independent test points is used to evaluate georectification accuracy, whereby the resulting RMSE values represent discrepancies in locations of independent test points. These independent test points have identifiable locations on both the target and reference image and are independent of the locations of GCPs (Shaker *et al.,* 2005). When GCPs are used and a particular polynomial model is fitted, the geographical locations of independent test points are altered and thus positional errors elsewhere within the image can be quantified (Hughes *et al.,* 2006 and Shaker *et al.,* 2005). For this method, the residual distances between locations of independent test points before and after georectification are calculated (i.e. residual distance differences between locations of individual test points before and after the georectification process on the rectified and reference image) to get a mean error value for the set of independent test points used. The results represent positional error resulting from the transformative ability of a particular transformation model and the number of GCPs used to fit the model. The following equation used to derive the mean positional error:

$$\text{RMSE} = \text{sqrt}\{\Sigma[(r_1)^2+(r_2)^2+(r_3)^2 +\ldots(r_n)^2]/i\} \qquad (3.2)$$

where r is the residual distance between the locations of the independent test points for the first to the n^{th} coordinate pair before and after a georectification model has been applied, where as i represents the number of coordinate pairs used. Low and high RMSE values imply lower and higher accuracy, respectively.

3.2.2 Data preparation

A 1976 black and white aerial photograph subset of the study area was georectified to evaluate the hypothesis of this study. Prior to georectification, the aerial photograph was scanned using an HP Designjet 820 MFP scanner at a resolution of 600 dpi into uncompressed greyscale TIFF (Tagged Image File Format) file format. This resolution enabled small features such as small rock outcrops to be easily identified on the scanned image. The image subset used for this study had a dimension of 4.2 by 3.2 km; an image scale of 1:10000 cm; a landscape characterized by both uneven and even topography and with elevation varying from 1303 to 2000 m; and slopes ranging from 0.51 to 63% (see Figure 3.1 and Figure 3.2). The dimension of the image subset was considered to be large enough to render the image subset a local scale from which distortions of landscape features such as fence-lines resulting from different georectification models could be visually compared on a map. Figure 3.1 shows the extent of the target image (bottom right) with a superimposed 20 m interval contour line and a map insert covering the enlarged portion (left hand side of the map layout). Rock outcrops and a fence-line are evident in the map.

Using ArcGIS 9.2, the target image was georectified to a 2001 orthophoto (with a spatial resolution of 0.88m) obtained from the Chief Directorate for Surveys and Mapping, Department of Land Affairs.

3.2.3 Selection of GCPs and independent test points

A total of 70 control points, evenly distributed throughout the study area, were randomly selected in line with the observation of Shaker *et al*. (2005) and Lillesand *et al.* (2004) that a good distribution of GCPs yields better accuracy than dense but poorly distributed GCPs. The selected control points predominantly consisted of rock outcrops, road intersections, and houses identifiable on both the target and reference image (i.e. with correct latitude and longitude coordinates). Fifty of the above control points, evenly distributed throughout the study area, were randomly selected as GCPs used to fit the georectification models, whilst the remaining 20 were used as independent test points (Hughes *et al*., 2006). The reason for selecting 50 GCPs was that this number of GCPS was identifiable practically on the subset image and enabled an assessment of georectification accuracy that would allow the evaluation of the objectives of this study. More specifically, this number of GCPs was also considered large enough for testing the effects of altering the number of GCPs to this number. Twenty independent test points, evenly distributed throughout the subset image, was considered to be a large enough number for assessing accuracy as it was closest to 18 GCPs, the number that Aguilar *et al.* (2008) and Shaker *et al.* (2005) describe as being suitable to achieve modest accuracy. Figure 3.2 shows the spatial distribution of the 50 GCPs and 20 independent points used in this study.

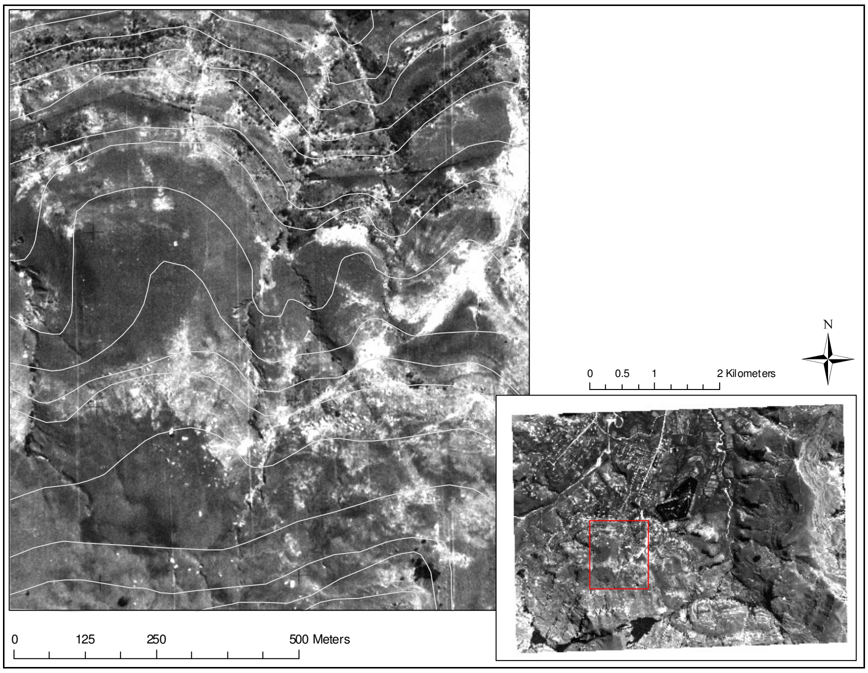

Figure 3.1 The map inset (bottom right) shows the subset map of the area of focus, while the main map shows visibility / interpretability of some of the land cover features used as GCPs (e.g. rock outcrops and the fence-line).

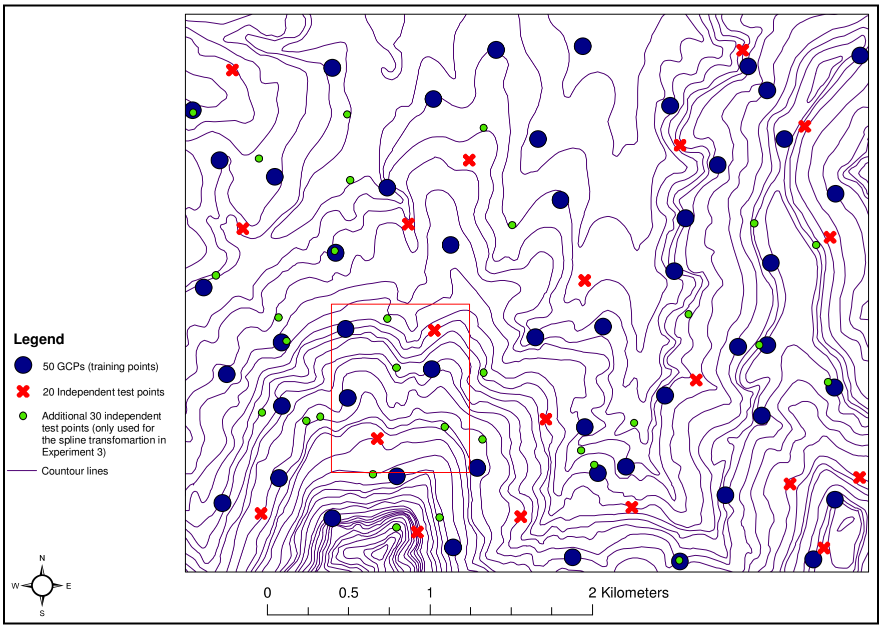

Figure 3.2 Spatial distribution of the 50 GCPs used. The red crosses represent the 20 independent test points used in Experiment I, while the green points represent an additional 30 independent test points making a total of 50 independent test points used in Experiment III.

3.2.4 Experimental setup

a) Experiment I: Number of GCPs on different georectification transformation models

Trials of 6, 8, 10, 15, 18, 20, 25, 30, 40, and 50 GCPs were undertaken using the four different transformation techniques, namely the first-, second-, and third-order polynomials and the spline transformation. The first three GCPs trials (i.e. 6, 8, and 10 GCPs) were selected approximately close to the minimum number of GCPs required for the georectification methods evaluated in this study to operate. Trials of 15, 18, and 20 GCPs were selected to evaluate accuracy performance slightly beyond the minimum number of GCPs required by the georectification methods used. The rest of the trials were selected to evaluate accuracy at a higher number of GCPs, since there is paucity of information in literature on how georectification accuracy performs at these high numbers of GCPs given the mountainous terrain of the study area. RMSE values based on 20 independent test points were generated using ArcGIS software package then analysed for comparison.

b) Experiment II: Different transformation models using a fixed number of GCPs

From results obtained in Experiment I, 18 GCPs were selected as a constant number of GCPs to test the transformative effect of the four transformation techniques on three types of digitized vector layers (namely, a point, polyline, and polygon which represented rock outcrops, a fence-line, and a patch of a bare soil surface respectively) generated before and after (i.e. using the reference and target image, respectively) the georectification process. These are displayed in Figure 3.5. This number of GCPs was selected because it produced an optimum accuracy at a low number of GCPs for all rectification methods and it was recommended by Hughes *et al.* (2006) for the first-, second- and third-order polynomials.

c) Experiment III: Number of GCPs on spline transformation

For this experiment, an additional 30 independent test points (Figure 3.2) were incorporated with the initial 20 test points, making a total of 50 test points. The number of independent test points was increased to 50 test points (i.e. n=50) to characterize a denser spatially distributed evaluation of positional error for this mountainous environment. Using these test points (i.e. n=50), a statistical variation test of the mean positional error attained by the spline transformation technique using the eight different GCPs trials (i.e. 10, 15, 18, 20, 25, 30, 40, and 50 GCPs) was performed. A box plot was used to summarize and compare positional errors produced by the above trials. These results were used to select trials having similar mean error values and a paired student *t-test* was performed to compare mean error values of trials / GCPs categories to show degree of variation. Statistical variations of the mean error values were determined between categories with GCPs that had similar mean values. This was conducted in the 50, 40, and 30 GCPs categories; and then the 10, 15, 18, 20, and 25 GCPs.

3.2.5 The relationship between (a) RMSE values obtained at the independent test points and (b) the slope and the distance to GCPs used to fit the model

Since slope was the main factor influencing georectification accuracy, the effect of slope on positional error obtained at the independent test points was statistically tested using a regression analysis. Additionally, it can be assumed that when independent test points are used to measure georectification accuracy, the distance between their location and that of the nearest GCPs utilized to fit the georectification model influences the georectification accuracy being quantified. Therefore, to test for statistical significance of these associations, the correlation between distance to the nearest GCPs used for fitting the model and positional error (RMSE) obtained at the individual test points was tested. These statistical tests were performed to evaluate whether these factors (i.e. slope and distance of independent test points from GCPs) had significant influences on georectification accuracy obtained when independent test points were used.

For this experiment, the statistical test was conducted on results based on georectification accuracy obtained when 50 GCPs and a spline transformation model to evaluate georectification performance were employed. The reason for selecting these criteria was that results from *Experiments I, II,* and *III* revealed that optimal georectification accuracy is obtained when a spline transformation model and the highest number of GCPs were used.

3.3 Results

Taking the number of GCPs and polynomial model used as significant factors that determine georectification accuracy, particularly for a mountainous landscape, results for the respective three experiments undertaken are presented in this section. A further subsection shows result obtained for statistical test of the relationship between a) RMSE values obtained at the independent test points and (b) the slope and the distance to GCPs used to fit the georectification model.

3.3.1 Experiment I: Number of GCPs on different georectification transformation models

The results indicate that accuracy is generally improved when the number of GCPs is increased and when utilizing the spline transformation method. Figure 3.3 shows the results obtained from the first experiment. With 3 GCPs, the first-order polynomial commences with a high RMSE value of 83.397m, sharply decreases 57.765m as GCPs are increased to 10, and then gradually fluctuates maintaining a lowest error value of 54.046m at 50 GCPs. Starting with 10 to 20 GCPs, the second-order polynomial maintains a similar pattern as the first-order polynomial but with slightly lower RMSE values. Its RMSE then slightly increases exceeding the first-order polynomial as GCPs are increased from 20 GCPs to 30 GCPs yielding an RMSE value of 55.761m and 58.46m respectively. The RMSE then sharply declines to an RMSE value of 37.97 m and 38.10m at 40 and 50 GCPs respectively. Starting with an RMSE value of 47.67 m at 10 GCPs, the third-order polynomial peaks with a value of 79.22m at 15 GCPs exceeding both the first- and second-order polynomial when this GCPs number is used, then sharply declines to a lower value of 46.109 m at 18 GCPs, 46.30.3 m at 25 GCPs, and 45.138 m at 30 GCPs. It then slightly declines to a value of 33.044 m and 31.66 m at 40 and 50 GCPs, respectively. Starting off with a maximum RMSE value of 44.40 m at 10 GCPs, the spline transformation model maintains slightly decreasing values of 43.46 m, 40.03 m, 39.86 m, 37.56 m, 26.33 m and 24.18m for 15, 18, 20, 25, 30, 40, and 50 GCPs respectively.

3.3.2 Experiment II: Different transformation models using a fixed number of GCPs

The distribution of the 18 control points used in this experiment are shown in Figure 3.4 which shows transformation distance around control points (represented by the distance link between the red and the green crosses) owing to the model used. Longer links between individual sets of GCPs represent higher RMSE values / residual error values, and vice versa for shorter links. Spatial distortions and positional discrepancies associated with the digitized vector types are shown in Figure 3.5. The black digitized vector layers (i.e. point, polyline, and the polygon) in this figure represent the digitized vectors that were generated from the 2001 reference image and that have minimal positional error. Layers depicted with different colours in Figure 3.5 represent new locations of the above vector layers that were generated after the georectification process using respective transformation method. These results show that spline transformation method has the least distortion on shapes and locations of features on the rectified image.

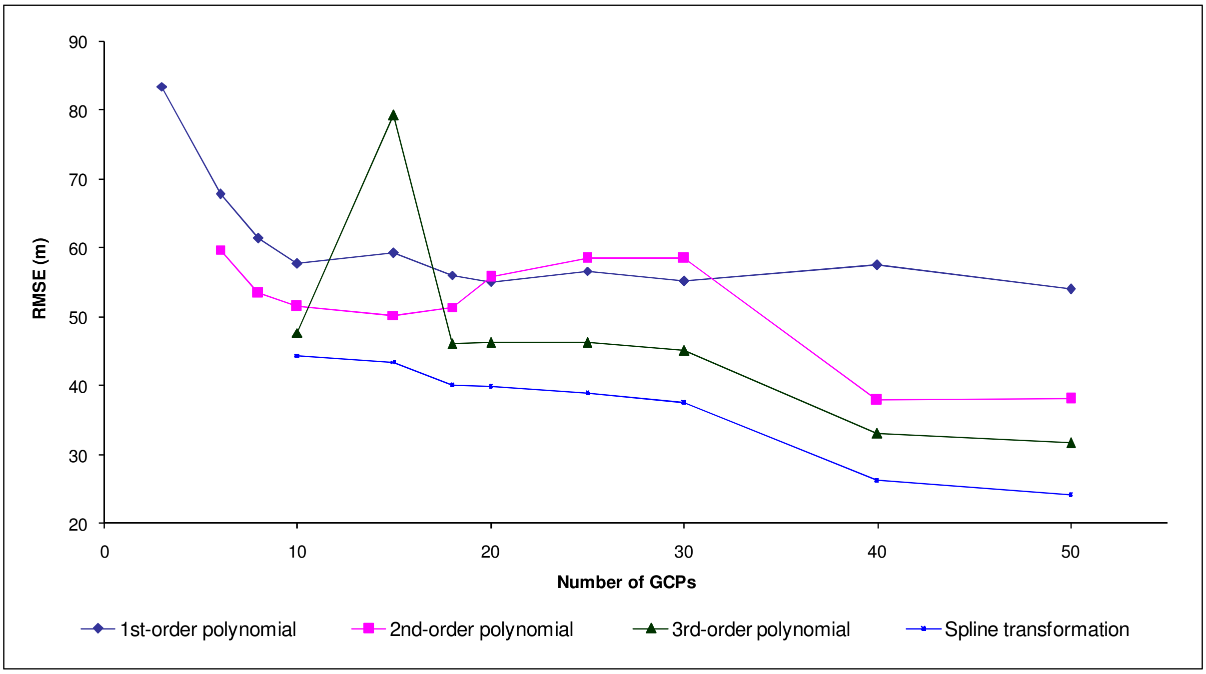

Figure 3.3 The graph showing georectification accuracy (RMSE) comparison between the various polynomial models when independent test points are used to quantify RMSE.

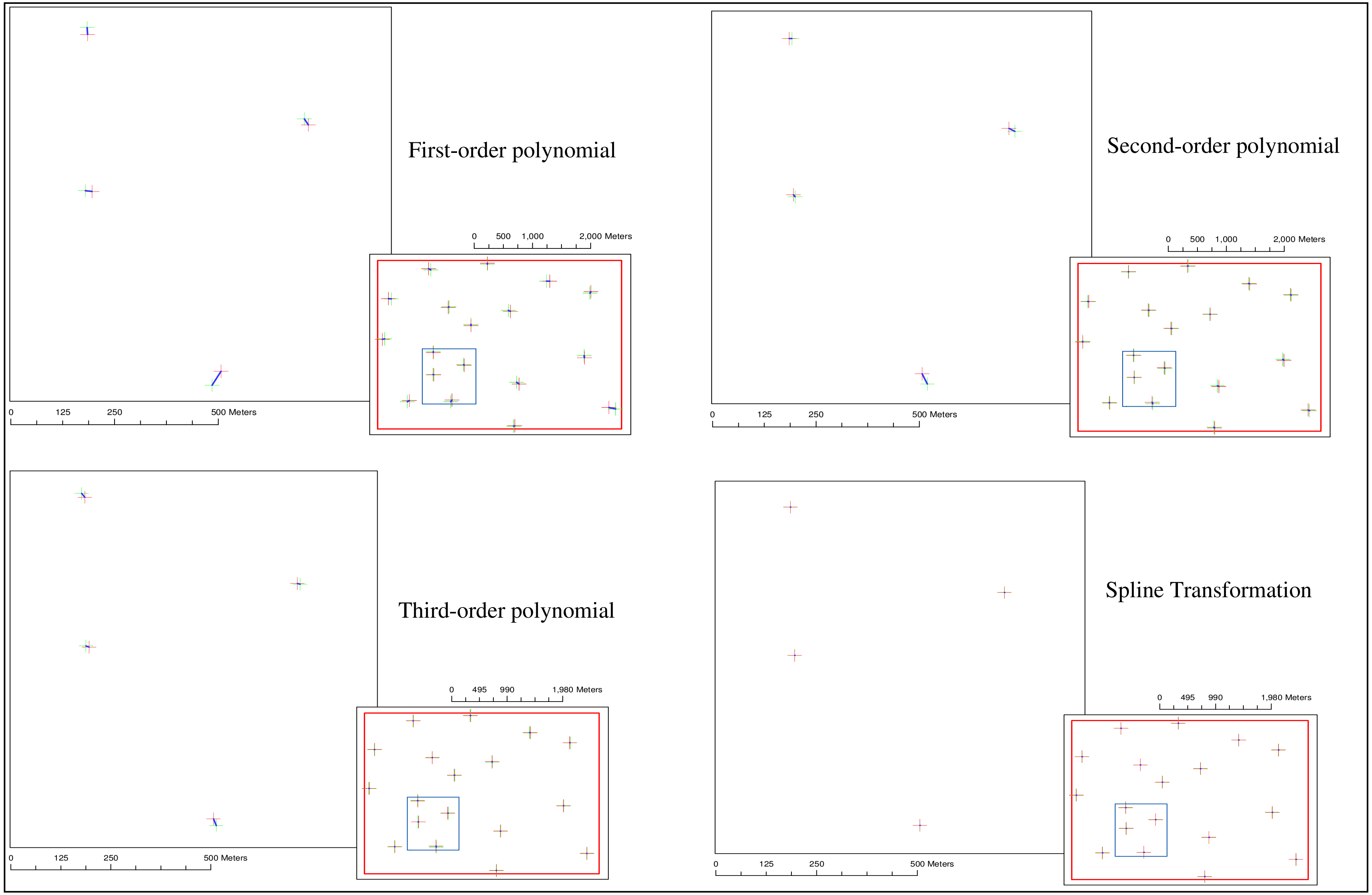

Figure 3.4 Distribution of the 18 control points and their transformation. Each pair of green and red crosses represents a similar feature identified as a GCP. The red crosses represent the actual location of the GCPs on the reference image, while the green crosses represent their new locations after a transformation model is applied. The blue link represents the associated displacement distance / positional error after transformation.

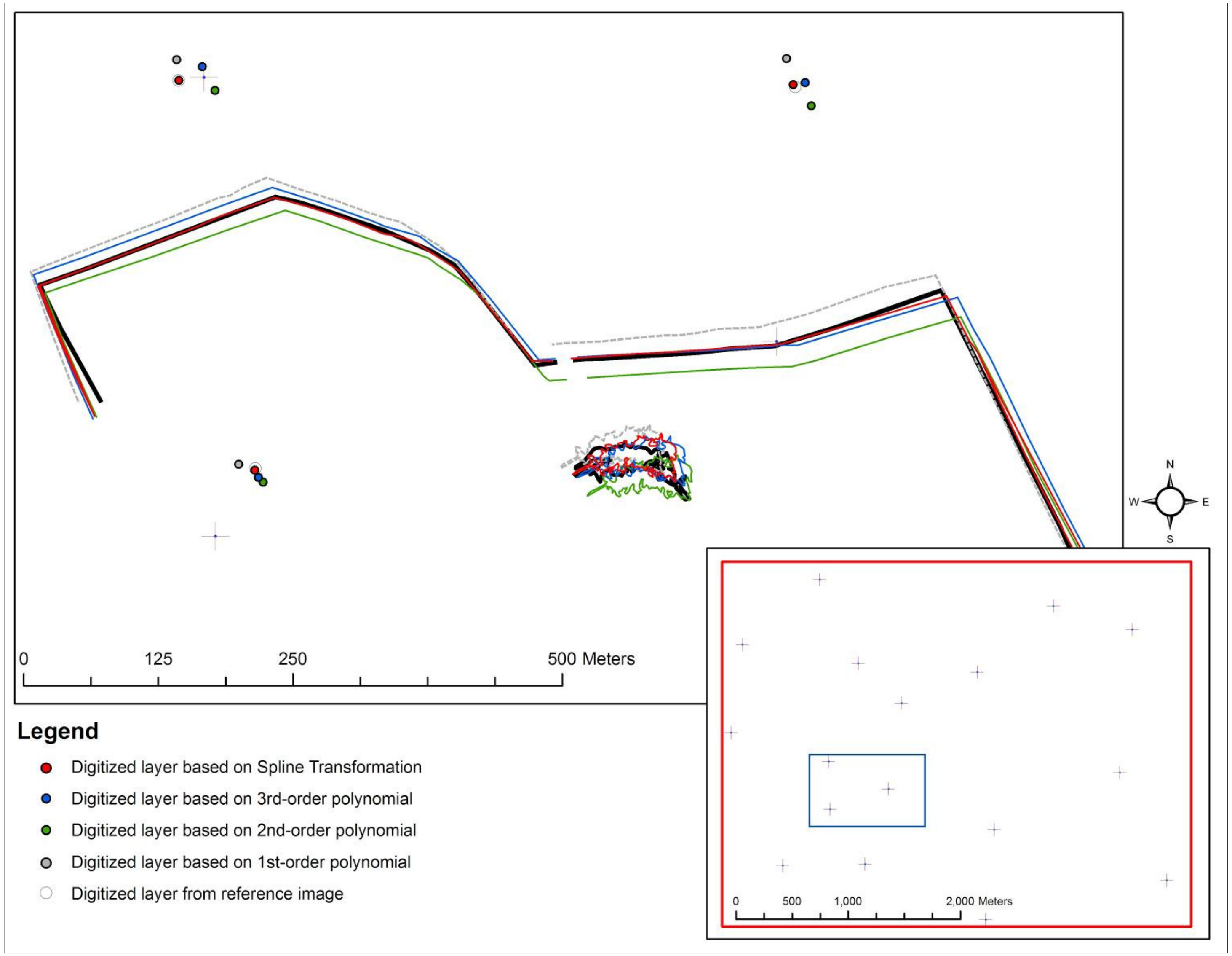

Figure 3.5 A map showing transformation of digitized vector layers. The original forms of these layers (i.e. before georectification) are depicted by the black vector layers (i.e. the black polyline, black polygon, and black points representing a fence-line, patchy bare soil surface and rock outcrops)

3.3.3 Experiment III: Number of GCPs on spline transformation

Effects of the number of GCPs on spline transformation accuracy and RMSE values based on independent test points are summarized in Figures 3.6 and 3.7 respectively. The 50 test points were normally distributed when 15, 18, and 50 GCPs were used. The 10 GCPs category yielded the lowest accuracy with a high error metric value. The 50 GCPs category yielded the best accuracy with the lowest median, lowest minimum and maximum, quartile error values, and the lowest quartile range. Trailing the 50 GCPs category, the 40 GCPs category had an RMSE value of 15.55 m, while the 30, 25 and 20 GCPs categories yielded RMSE values of 19.55758 m, 20.46308 m, and 20.4304 m respectively as shown in Figure 3.7. Georectification accuracy then slightly increased to an RMSE value of 22.32142 m with 18 GCPs but had a reasonably lower maximum error value which is ranked second after the 50 GCPs category. RMSE values rapidly increased to 29.42 m from 36.34 m, at 15 and 10 GCPs respectively.

Statistical variations of the mean error values among the 50, 40, and 30 GCPs categories indicated that a critical t value (p = 0.05) for 49 degrees of freedom was found to be 2.02. The calculated values *exceed* this value (see Table 1 in the Appendix). Thus there is less than a 5% probability of getting a value as high as this by chance alone. At this confidence level, it implies that the use of 50 GCPs yields higher georectification accuracy than that of the 30 and 40 GCPs categories. The 40 GCPs category showed a slightly higher accuracy than the 30 GCPs category.

Statistical variations of the mean error values among the 10, 15, 18, 20, and 25 GCPs categories indicated that a critical t value (p = 0.05) for 49 degrees of freedom was found to be 2.02. The calculated values between the 20 and 18; 20 and 25 did not *exceed* this value (see Table 1 in the Appendix). Thus there is more than a 5% probability of getting a value as high as this by chance alone. The calculated values between the 15 and 18; and between the 10 and 15 *exceeded* this value implying a less than a 5% probability of getting a value as high as this by chance alone. At these confidence levels, it implies that the 18, 20, and 25 GCPs categories yield similar but higher georectification accuracy compared to when 10 and 15 GCPs are used.

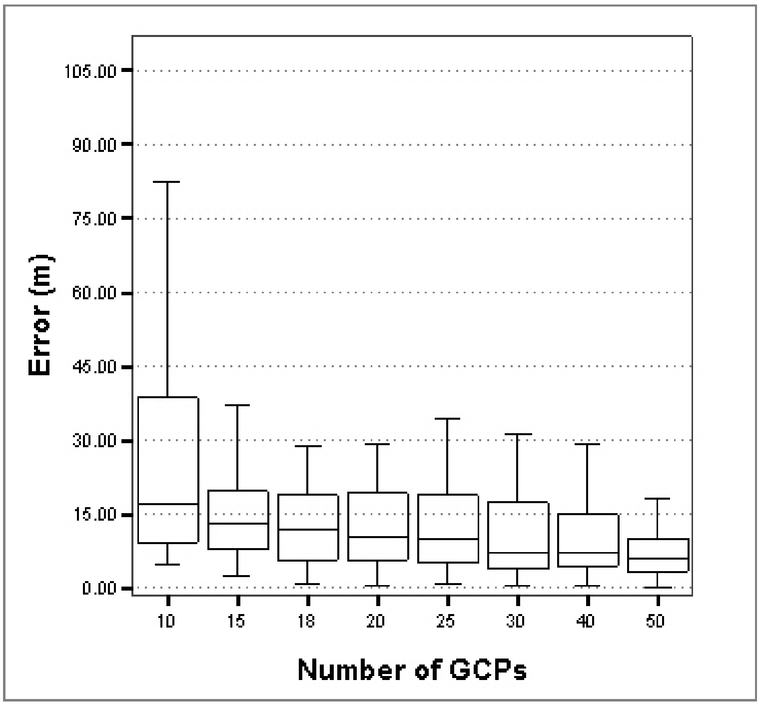

Figure 3.6 Boxplot showing the categories of the number of GCPs versus error matrices obtained for the 50 independent test points used to assess georectification accuracy.

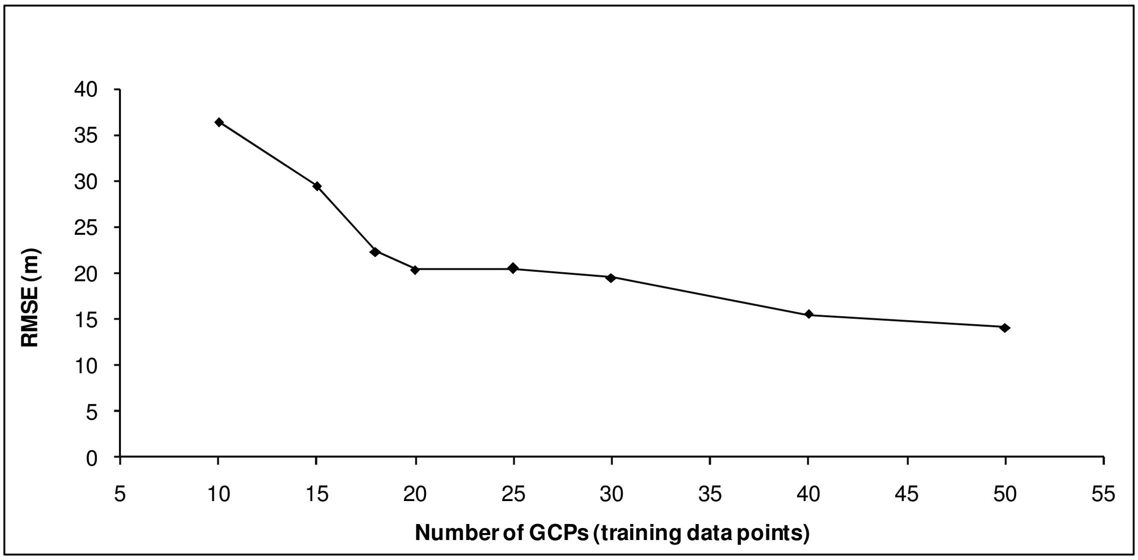

Figure 3.7 RMSE plot of 50 independent test points for the eight categories of GCP numbers on spline transformation.

3.2.1 The relationship between (a) RMSE value obtained at the independent test points and (b) the slope and distance from GCPs

A linear regression analysis to the test the relationship between positional errors obtained at the 20 independent points and the slope yielded a positive correlation coefficient with an r^2 value of 0.113 and a p-value of 0.147 (Figure 3.8). At this low r^2 value, it was evident that the slope had an insignificant effect on georectification accuracy when independent test points positioned on varying slope steepness were used.

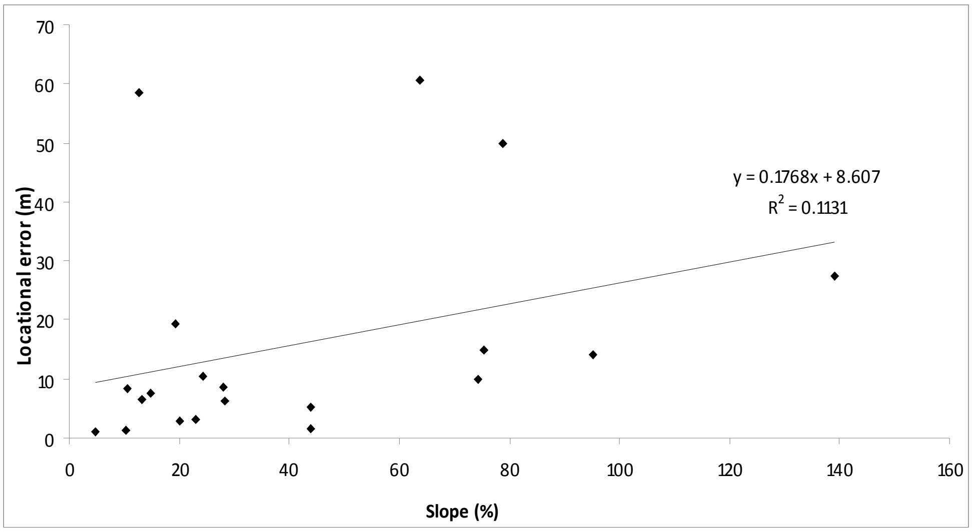

Figure 3.8 Relationship between slope and residual distance of the individual independent test points used to quantify locational / residual error.

Regarding the relationship between locational errors obtained at the 20 independent points and the distance from GCPs used to fit the georectification model, the regression analysis yielded a negative correlation coefficient with an r^2 value of 0.0258 and a p-value of 0.498 (Figure 3.9). At this low r^2 value, it was evident that the distance between GCPs used to fit the georectification model and the independent test points used to gauge locational error had an insignificant effect on georectification accuracy.

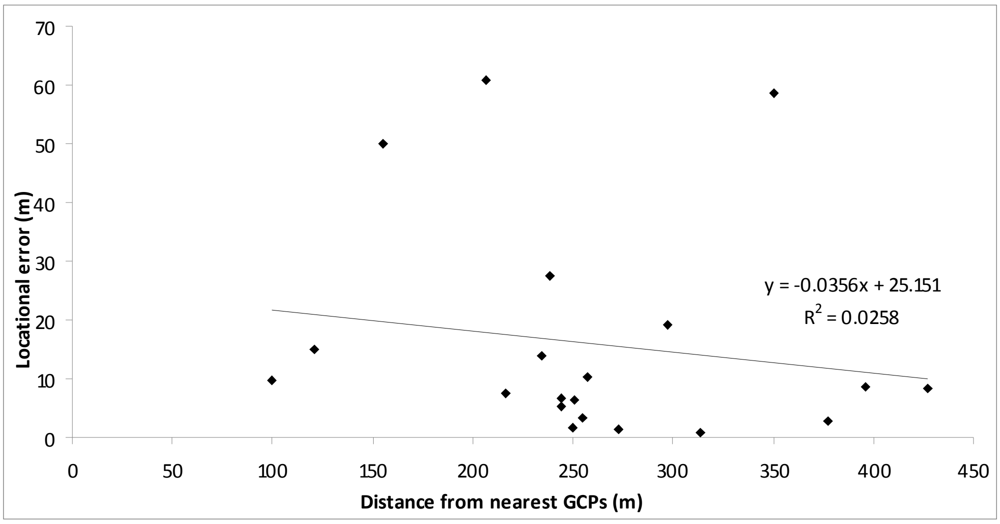

Figure 3.9 Relationship between the distances to GCPs used to fit the georectification model and residual distance of the individual independent test points used to quantify locational/ residual error.

3.4 Discussion and conclusion

Generally results show that georectification accuracy improves with higher order polynomials, agreeing with results of Rocchini and Di Rita (2005). Spline transformation, in particular, performed better than the first-, second- and third-order polynomials regardless of the number of GCPs used. Additionally, the accuracy of the spline transformation method improved with increased number of GCPs. As demonstrated in this study, the ability of the spline transformation method to wrap, shrink, and curve aerial photograph scenes as GCPs are added to the model enabled the model to improve positional accuracy when used to georectify datasets covering an uneven topography.

Georectification accuracy was more accurately evaluated using independent test points (Hughes *et al.,* 2006) as opposed to the standard RMSE values yielded by the model which does not represent the actual positional error after georectification. Statistically, the present study has shown that slope and locations of independent test points in relation to the fitted GCPs have insignificant effect on the overall positional accuracy, meaning that independent test points could be used to accurately quantify georectification accuracy (refer to Section 3.2.1, Figures 3.8 and 3.9). While using independent test points to quantify positional error, the third-order polynomial yielded satisfactory results when more than 18 GCPs were used, but it was out-performed by the first- and second-order polynomials when 15 GCPs were used. Hughes *et al.* (2006) reported similar findings, though terrain variation and slope steepness in their case was gentler than that of the present study. In the present study, RMSE values tended to slightly stabilize as GCPs exceeded 18 for the first-, second- and third-order polynomials.

The experimental results demonstrated that the effects of the number of GCPs and of the polynomial model used for georectification should not be overlooked because these determine the resultant positional accuracy, hence the efficacy, of georectified aerial photographs. While utilizing a large number of GCPs might be a time-consuming process, maximizing the number of evenly distributed GCPs in a study area is strongly encouraged, since all models generally yielded better accuracy with increased GCPs. The first-, second- and third-order polynomials produced satisfactory accuracy performance, when approximately 20 GCPs were used. This agrees with the findings of Shaker *et al.* (2005) that increasing the number of GCPs does not significantly improve georectification accuracy when most 2D transformation models (i.e. first-, second- and third-order polynomials) are applied. However, performance of the spline transformation method in the present study indicated that RMSE value is improved by an approximate margin of 22.22 m when the number of GCPs is increased from as low as 10 to 50 GCPs (i.e. 14.12 to 36.34 m). This is further confirmed by a statistical analysis using a student *t-test* on mean error values which showed that a higher number of GCPs produced lower mean error values, implying improved georectification accuracy.

Although satisfactory results were obtained, georectification accuracy is hindered by the lack of incorporating elevation effects using a DEM as a result of the unavailability of tools within the GIS software used in this study. Given this limitation, assessing georectification accuracy of various methods by incorporating DEMs to evaluate positional error for a mountainous landscape is a subject that can be explored, particularly when very steep valley walls and hill slopes dominate the landscape.

In this chapter, the relevance is highlighted of evaluating georectification performance of different georectification methods and other criteria (i.e. the number of GCPs) in order to aid an informed selection and implementation of georectification techniques for land degradation analyses. This is particularly important since even slight positional error can drastically affect the application and efficacy of the end products. More specifically, it is apparent that an increased number of GCPs improves the overall accuracy of the spline transformation method for a mountainous environment such as that of Okhombe. In addition, an even and dense distribution of GCPs is recommended, particularly when variation in elevation is high. It can be concluded that the hypothesis tested in this chapter (i.e. georectification accuracy increases with an increased georectification polynomial order based on the transformative characteristics of individual georectification methods used) was confirmed.

By assessing performance of various georectification techniques, the results of this chapter were used in selecting the best georectification technique and developing the methodology which were subsequently used for the change detection analysis presented in in Chapter Four.

Chapter Four

Spatio-temporal patterns of land degradation in the light of land cover conversions / changes in a communal landscape of KwaZulu-Natal province, South Africa

4.1 Introduction

In this chapter, literature material is reviewed, methodology is discussed and results are presented on change detection using aerial photographs. To begin, the relevance is highlighted of monitoring landscape change and land cover conversion particularly in the light of policy and land degradation as being one of the major environmental problems faced in communal areas. Previous work on land degradation and its nature in Okhombe are briefly outlined to contextualise the study. The roles of GIS and Remote Sensing in monitoring landscape changes and land degradation are outlined. Next, the processes of change detection and prediction analyses are discussed, before moving to their analyses undertaken in this chapter.

4.1.1 Policy relevance of monitoring landscape changes and land degradation in South Africa

Monitoring landscape change is increasingly becoming an important issue across various fields of development and sustainable resource management. The importance of landscape monitoring studies is relevant not only in knowledge generation within the scientific community, but also for state policy makers faced with the need to make informed decisions and find solutions on issues ranging from sustainable agricultural practices, land degradation, drought and biodiversity conservation yet being required to meet the needs of the general public (O'Meagher *et al.*, 1998). Policy interventions in South Africa on issues pertaining to land and environmental concerns have a considerably long history which provides valuable learning lessons and experiences on policy. Some of these policy interventions include the 1984 White Paper on Agricultural Policy (O'Meagher *et al.*, 1998) and the unpopular 1960s Betterment Scheme intended to combat land degradation. The interventions have had significant direct and indirect influences on different issues of the environments and societies in which they were implemented.

Currently, land degradation remains one of the most significant environmental issues threatening land productivity and poverty alleviation, despite efforts by government departments, national, and international organisations that promote the use of policy to monitor and control this phenomenon (DWAF, 2008).

In South Africa, numerous state strategic policies and plans have been targeted at local, provincial, and national levels to eradicate poverty whilst containing the issue of land degradation as part of a commitment to The United Nations Convention to Combat Desertification (UNCCD) objectives to attain sustainable land management. One of the essential tools of these strategic policies as DWAF (2008) outlines, is through education by ensuring desertification and land degradation awareness. Van Jaarsveld and Biggs (2000) note that this awareness can largely be promoted by monitoring how these problems have changed over the years. It is believed that land degradation and desertification can be minimized through such strategic policies and plans and through multi-disciplinary and inter-disciplinary approaches (Galvin *et al.*, 2001; DWAF, 2007) which are often lacking within existing structures (DWAF, 2008). According to the DWAF (2007), further constraints include the lack of knowledge on these issues particularly with regard to risks, management options, and costs involved; and lack of understanding about the causal factors and nature of these issues to devise appropriate local management strategies. This is clearly an area that requires appreciating the monitoring and quantification of the spatial extent of the problem at hand as has been demonstrated by numerous studies. An example of these studies includes that of Harrison and Shackleton (1999) who highlighted the significance of determining the rate of change in communal grazing lands using vegetation and soil variables to determine the resilience of grazing systems in these landscapes. Further studies include those conducted at a local scale as the nature of these problems differs from place to place.

4.1.2 Land degradation in Okhombe

Like other communal areas, land degradation in Okhombe is a significant problem affecting land productivity. This is the case despite various land use policies and strategies (namely the Betterment Scheme and the post-apartheid LandCare project) that have been partially implemented to minimize land degradation.

Studies conducted in Okhombe outlined and identified various types of land degradation. Sonneveld *et al.* (2005) studied the dynamics of land degradation at a sub-catchment scale that occurred from 1945 to 2000 by investigating changes in the number of erosional features identifiable on historical aerial photographs. They reported a decline in the numbers of erosional features (particularly in the active and weakly active gullies) between 1962 and 1975 followed by an increase up to 2000. The above pattern was evident in the combined undulated surface / bare soil surfaces, strongly active rills, and gullies mostly characterized by unvegetated hillslopes. The spatial pattern of land degradation at this scale showed a fluctuating behaviour with the majority of these features located within the rangeland. Using five landscape units based on the elevation range (i.e. the river valley ranging between 1250 and 1300 m; footslope between 1300 and 1330 m), midslope between 1330 and 1360 m; upperslope between 1360 and 1425 m; and the plateau ranging from 1425 to 1500 m), Sonneveld *et al.* (2005) reported sheet wash and bare soil surfaces to be mostly active on the hillslope landscape units (i.e. the upperslope and midslope landscape units).

Additional to the findings of Sonneveld *et al.* (2005), a veld assessment study conducted by Tau (2005) revealed poor conditions on both bottomlands and uplands. These conditions were attributed to grazing pressures characterized by the increasing presence of unpalatable grass species at the expense of their palatable counterparts. This supports the views of Meadows and Hoffman (2002) that soil degradation in communal areas is generally aggravated by grazing practices. Tau (2005) reported grass cover conditions in

Okhombe to be somewhat good enough to lessen considerable physical degradation. In addition, Tau (2005) reported healthier conditions to occur at the midslope followed by the bottom- and then upland slopes, despite findings by Sonneveld *et al.* (2005) that midslope had more severe erosion. From a geological perspective, Temme (2008) attributes this to the lack of available sediment material on the upperslope making downslopes the main source of sediments. However, the influence of land use and its change, particularly with grazing as a common practice, contributes to the loss of vegetation cover on such susceptible landscape units resulting in degradation and thus anthropogenic factors should not be overlooked. Other studies such as those of Keay-Bright and Boardman (2009) and Sonneveld *et al*. (2005) used historical information on land use management practices, population and livestock demographics, and rainfall data as causal factors to explain these trends. Studying and understanding land degradation in an environment with both physical and anthropological factors acting as causes of degradation can be conducted through a change detection assessment such as that used by Sonneveld *et al*. (2005).

4.1.3 GIS and Remote Sensing, land degradation, and landscape change detection

Through spatial data gathering and mapping, GIS, and Remote Sensing provide a broad resource management opportunity. Their ability to rapidly collect for remote areas spatial data that can be manipulated to meet desired output making them cost- effective tools for further analysis, is one of the important advantages these tools offer (Huang *et al.*, 2008; Lillesand *et al.*, 2004). Some areas for which these technologies can provide useful land use and rangeland assessment information (Lillesand *et al.*, 2004) include: understanding socio-economic effects of alternative land uses, improving and managing rangelands, designing and controlling grazing systems as well as providing information to policy makers regarding land use planning and management in areas of concern. In land degradation studies, satellite remotely sensed and aerial photography data have successfully been used to understand patterns and trends of land degradation (Palmer, *et al.*, 2004; Keay-Bright and Boardman, 2006); the effects of human-induced land degradation in the former homelands of northern South Africa (Wessels *et al.*, (2004); and the effects of grazing systems on vegetation cover (Archer, 2004). With regards to studies conducted in Okhombe, GIS and Remote Sensing can greatly enhance their output in a sense that these tools provide a platform for investigating issues spatially and integrating multidisciplinary knowledge for explanatory analysis. Galvin *et al*., (2001) and Boone *et al*. (2007) highlight that Remote Sensing analysis and results can contribute an explanatory dimension, often not present, to social science research that seeks to understand issues being studied. The same applies for GIS.

As numerous studies demonstrate, Remote Sensing is used mainly as a data collection tool by utilizing either satellite imagery or aerial photographs as data sources. GIS is often used for data analysis and manipulation although further remote sensing analyses are often undertaken, particularly in the case of satellite imagery, to extract more useful information (Lillesand *et al.*, 2004). Important procedures encompassing these analyses include data preparation comprising image restoration, georectification, and image enhancement; and image classification and digitization for creating desirable quantitative or categorical data (Campbell, 2002; Lillesand *et al.*, 2004).

The choice of using either satellite imagery or aerial photography generally depends on the desired output or purpose of the analysis as well as whether data can be used to derive these outputs (Lillesand *et al.*, 2004). Some of the key factors in this case include spatial and spectral resolutions which determine the mapping detail and temporal variability to be mapped such as the time period these data formats are able to cover.

Although satellite imagery is becoming increasingly useful due to its higher spectral resolution characteristic and advancement in methods of analysis (i.e. image data manipulation and information extraction as demonstrated by Archer, 2004; Chen and Rao, 2008; Wessels *et al.*, 2004; Budde *et al.*, 2004; Tanser and Palmer, 1999; Chikhaoui *et al.*, 2005), aerial photographs still offer undoubted advantages over satellite imagery as some studies have demonstrated. This is particularly the case in land degradation studies where understanding of this issue requires long-term monitoring that predates the launch and use of satellite imagery (e.g. Keay-Bright and Boardman, 2006; Kakembo, 2001; Hester *et al.,* 1996; Fensham *et al.,* 2007; Akbari *et al.,* 2003). These studies also reveal the importance of monitoring spatio-temporal patterns of land cover changes to provide information on how the dynamics between the two phenomena can be utilized for land use planning and management decision making.

4.1.4 Land degradation and land cover change detection

Land degradation can be quantified by evaluating land cover changes that have occured over a period of time. These include change from grassland vegetation, cultivated, and / or settlement areas to bare soil surfaces, rills, and / or gullies. Therefore, monitoring spatial changes and conversions in these land cover types provides a means of quantifying trends in land degradation. This is crucial for identifying the factors triggering apparent trends, the extent, and recovery rates because such changes have significant implications on land management and productivity (Hester *et al.,* 1996). As a result, understanding of land cover changes is a vital foundation for understanding interactions between human and natural phenomena such as those leading to land degradation (Lu *et al.,* 2004).

Change detection analysis usually comprises detecting change in the spatio-temporal patterns of land cover using datasets acquired at a minimum of two dates. Lambin (1997) points out four main analyses an ideal change detection analysis should have, namely:

- Spatial analysis identifying geographical locations of areas affected by or experiencing change as well as the magnitude of this change.
- Temporal analysis examining the rate of change and time initiated.
- Change process analysis identifying the nature of the change process regarding its spatial and temporal diffusion.
- Explanatory analysis seeking to identify the driving factors for change by investigating the relationship between detected change and occurrences of social, economic, and ecological factors known to influence such changes.

The above analyses require the use of historical data such as aerial photographs or satellite imagery with reasonable georectification accuracy to create land cover maps representing land cover conditions at specific times. Once established, appropriate change detection methods and models are then utilized.

Numerous works such as those of Lillesand *et al.* (2004) and Campbell (2002), outline different techniques of change detection in use; Lu *et al.* (2004) provide a comparative review of different methods currently in use. Some of these methods include: post-classification comparison, image differencing, image rationing, image regression, change vector analysis, artificial neural networks, and principal component analysis. Landscape change detection studies are based mainly on models, tools, and techniques that have been developed, tested, and employed mostly within the Remote Sensing field. The use of these tools for monitoring purposes ranges from agricultural purposes in crop and forest monitoring; urban change studies (Lillesand *et al.*, 2004); land cover and land use changes in land use planning and environmental monitoring studies (Feranec *et al.*, 2007, Shalaby and Tateishi, 2007); land degradation, drought, and desertification studies; alien plant invasions (Bradley and Mustard, 2006); to ecological and conservation monitoring (Munyati, 2000) amongst others. Of numerous other uses of change detection analyses, is their incorporation for predicting and modelling change conditions for unknown date, more especially for future land cover conditions whereby statistical and mathematical based models are utilized. A Markov Chains analysis is one of such models with the ability to model change probabilities. The Markov process has been used to model land cover changes in both urban (e.g. Huang *et al.*, 2008) and non-urban environments.

4.1.5 Lessons learnt from the review

While studies conducted on Okhombe have provided invaluable information on land degradation, changes in spatial extent of land degradation at a catchment scale have not been investigated. More specifically, no study has investigated the effects of land cover conversions on land degradation and / or predicted likely future conditions of land degradation. This is important since at a ward / catchment scale, Okhombe possesses a uniform manner of land use management, especially with regards to grazing systems and usage of other land cover types in relation to grazing practices.

A combination of the physical processes and land use management strategies to control livestock has had impacts on how the landscape has changed. For instance, although slope plays a significant role in development of land degradation features (Morgan, 1979), the influence of slope on the occurrence of spatial patterns of these features over the years in Okhombe have also not been investigated to the best of our knowledge. This is in contrast to Sonneveld *et al*. (2005) who utilized elevation ranges (i.e. landscape units) to identify dominance of these features within each landscape units. This method, however, does not describe the actual influence of slope steepness, a critical factor that determines erodability as Morgan (1979) notes. In addition to slope, fence-line contrasts of vegetation and land degradation condition have been identified by some researchers such as Palmer and Tanser (1999); and Sonneveld *et al.*, (2005) to influence patterns of land degradation. However, the effects of slope and fences on land degradation patterns have rarely been identified in communal areas such as Okhombe. More specifically, effects of access gates traversing these fence-lines (i.e. by leading livestock to the designated rangeland from kraals located within the settlements areas) on land degradation patterns in Okhombe have also not been identified. Thurow (2005) notes that access gates frequently used by livestock causes the loss of vegetation cover, increased soil crusting, and compaction which eventually results in concentrated runoff, increased erosion susceptibility, and then formation of land degradation features such as bare soil surfaces, rills, and gullies. Given that these conditions are spatial in nature and have been identified as affecting patterns of land degradation, GIS and Remote Rensing provide an opportunity of studying patterns of land degradation in Okhombe. GIS and remote sensing can greatly enhance such a study in that they provide a platform for investigating these phenomena spatially and for integrating multi-disciplinary knowledge for explanatory analysis.

4.2 Conclusion

The review of literature has highlighted the relevance of policy in the monitoring of landscape changes and land. Although land degradation in Okhombe has been studied and identified at different scales using different methods, a review of this literature shows that its spatial and temporal extent in relation to other land cover types at the ward /

catchment scale have not been assessed. Moreover, the effects of the landscape characteristics and land uses management structures such as the fence lines and access gates on spatial patterns of land degradation are not clearly understood.

GIS and Remote Sensing can be used to map land cover changes and / or conversions to understand the spatio-temporal extent of land degradation at the ward scale. To achieve this, change detection is a necessary procedure and thus ensuring superior mapping accuracy is of great value. As this study aims to detect changes in major land cover types to study spatial and temporal extent of land degradation, change detection analysis using remote sensing and GIS is also reviewed. The ability of GIS and Remote Sensing to predict unknown future land cover conditions is highlighted. Furthermore, slope and access to gates are highlighted as important site-specific factors that can influence trends in land degradation patterns.

4.3 Methods

4.3.1 Image datasets

Multi-temporal aerial photographs dating back to the 1940s were selected as the appropriate datasets. This is because the study intended to detect degradation trends dating as far back as the early 1900s, as opposed to satellite imagery that was available only from the 1970s. Five sets of aerial photographs obtained from the Department of Land Affairs' Chief Directorate for Surveys and Mapping were used, allowing for the detection of land cover changes that have occurred for over a period of 59 years, starting from 1945, 1962, 1976, 1992, and 2004. Table 4.1 shows properties of these aerial photographs.

Ancillary datasets used as reference data were collected to support pre-processing of the above data. These included three rectified topographic maps of 1979, 1986, and 2000; a 1984 orthophoto; orthorectified 2001 aerial photographs; a rectified 2008 SPOT 5 satellite image covering the entire study area; and GCPs (see description of GCPs in

Section 3.2.3) collected with a Global Positioning System (GPS) with positional error of +/-5m during a field visit in April 2008.

4.3.2 Data pre-processing

Pre-processing of the dataset consisted of two essential procedures, namely: georectification of the aerial photographs and an on-screen image digitization of land cover classes. Georectification was mandatory to minimize positional errors that would affect change detection accuracy. Digitization of land cover classes of concern was used to create various land cover maps required for analyses of landscape change and prediction. The following two procedures were curried out in ArcGIS 9.3.

Table 4.1 Aerial photographs used in the study

Date taken	Number of aerial photographs used	Scale	Job and Strip No.	Photo numbers
1945 (April and May)	11	1:6666	79;9	4158 & 4160
			79;10	4092, 4093 & 4095
			79;11	4073, 4075 & 4076
			79;12	4011, 4013 & 4014
1962 (July)	3	1:10000	477;27	1040 & 1041
			477;28	1080
1976 (June)	2	1:10000	756;17A	3040
			756;16	2660
1992 (June)	2	1:16666	965;11	2013
			965;10	133
2004 (July)	2	1:16666	1088;10E	0603
			1088;11E	0626

a) Georectification and digitization

The spline georectification technique and a minimum number of 40 evenly distributed GCPs within each photograph were used to georectify all the aerial photograph. The selection of these criteria (i.e. spline georectification technique and a minimum of 40 GCPs) was based on experiments outlined in Chapter Three. Again, the georectification procedures undertaken determined the accuracy of the final change detection results whose accuracy is dependent on the positional accuracy of individual pixels on the aerial photographs used (Boone *et al.*, 2007). A good positional accuracy of individual pixels that make up the entre aerial photographs implies that given two images covering the same geographic area, pixels of a feature in the image from a particular date correspond spatially to the location of pixels of the same feature in the image taken at a different date. Following georectification, major land cover types found in the study area were identified (see Table 4.2). The major land cover types were identifiable on all aerial photographs throughout the period covered by the research. These major land cover types were then manually digitized from the newly georectified aerial photographs using shape, pattern, tone, texture and association, after Lillesand *et al.* (2004), Campbell (2002), and Harvey and Hill (2001), to distinguish boundaries between the land cover types as described in Table 4.2. Identification of bare soil surfaces was efficiently facilitated by their clearly distinguishable bright colour against that of other land cover types. Topographic shadows, however, affected identification of gullies in some instances.

On completion of digitization, five vector maps, each having the land cover types, as listed below, for each respective year, were created. The vector layers were converted into TIFF raster formats while standardizing the scale and map dimensions by resampling pixel size to 5 m and preserving a standard *column: row* ratio of *1614: 1745 pixels* for the resulting five land cover maps. This was conducted because the change detection modeller utilized, required that all image datasets utilized, should possess standardized image properties to allow comparisons between individual images' pixels. The maps were imported into IDRISI raster format for further change detection and prediction analyses using the Land Change Modeler embedded in IDRISI 15.0 Andes version.

Table 4.2 Descriptions of land cover types used in the study as identified on ancillary data and during the field visits

	Descriptions	**Various land cover included in this class**
Settlements	Areas covering homesteads.	Bare soil surfaces around homesteads, cattle sheds, home-gardens, and fields inside homestead compounds. These were often noticed to have angular shapes on aerial photographs.
Cultivated fields	Large cultivated areas occupying mainly the lower altitudes and in close proximity to homesteads but distinctive from home-gardens.	Cultivated and uncultivated fields located on land parcels designated for cultivation.
Grassland/rangeland	Areas covered by grass vegetation where livestock normally graze.	Grass vegetation species and not mixed with shrub or woody vegetation.
Bare soil surfaces	Areas with exposed soil surfaces that appeared with lighter colours on black and white aerial photographs.	Eroded surfaces, and rills.
Woody vegetation	The other vegetation type aside from grassland.	Shrubs and indigenous forest vegetation, some with a mixture of grass species as ground cover vegetation.
Gullies	Excessively eroded areas.	Gullies and rills.

4.3.3 Land Change Modeler: a tool for change detection and prediction analyses

Change detection and predictions analyses were carried out using the Land Change Modeler for Ecological Sustainability (LCM), a horizontal application embedded in IDRISI 15 Andes version with tools for quantitative assessment of change analysis, change transitions, transition potential, and change prediction. This modeller is based on remote sensing transition sub-models such as crosstabulation classification tools; the enhanced Multi-Layer Perceptron (MLP) neutral network for change detection and change transition modelling; and a Markov Chain analysis for change prediction.

The cross-tabulation classification process compares the data from a pair of qualitative images taken at different dates and indicating different classes (e.g. land cover types) to analyse change. A cross-tabulation table created during the process shows the frequency with which classes have changed or remained the same for the two dates plotted on separate axes (IDRISI, 2006). Similarly, a new image representing these states is created indicating all unchanged and changed classes.

The LCM enhances representation of these change analysis and modelling results by detailing gains and losses, net changes, contributors to net change, spatial trends of change, and modelling change transitions which describe change properties. These are described as follows (IDRISI, 2006):

- Gains and losses incurred by particular land cover categories. The gains show areas in the later date that are covered by a certain land cover category but not covered in the earlier date. The opposite applies for the losses (i.e. areas covered in the later date but not covered in the earlier data).
- Net changes: this is calculated by taking the difference between all the areas covered by a land cover in the earlier date together with its gains and then subtracting the losses incurred. Net changes show the quantity of land cover changes that have taken place for each land cover category between two consecutive dates.
- Contributors to net change experienced by a particular land cover type and thus the extent of change transitions experienced by all land cover categories to an

individual category can be measured. This helps to graphically quantify categories contributing to any changes experienced by an individual category.

- Patterns of change are identified using a Spatial Trend Analysis tool which facilitates in interpreting general patterns of changes detected.
- The model also allows modelling and quantifying all transitions occurring in involved land cover types, which are later used to predict future landscape changes based on a Markov Chain or an external change prediction models.

4.3.4 Change detection analysis

Using the five sets of land cover maps produced, change was detected between the following periods: 1945 to 1962, 1962 to 1976, 1976 to 1992, and 1992 to 2004. The gains and losses, net changes, and contributors to net change experienced by the various land cover types were quantified and examined. Since the study aimed to map temporal distribution of land degradation, types of land cover that contributed to net change experienced by bare soil surfaces were mapped, graphically represented and examined to determine possible factors responsible for its detected changes.

To aid interpretation and discussion of the results, influences of slope and the locations of access gates leading into the areas designated for grazing were investigated as outlined in the following sub-section. Therefore, the results of this sub-section are presented within the discussion section of this chapter.

a) The effect of slope and distance from access gates on observed patterns of land degradation

To investigate landscape variables influencing the detected spatial patterns of land degradation, the slope and distance of bare soil surfaces from access gates (also referred to as gates leading livestock into the grazing areas from homesteads across the fence-line separating these two land use types) were taken into consideration for the respective time periods. For the first variable, it was hypothesized that an increase in bare soil surface area with an increase in slope steepness would imply a significant relationship between the two variables. Thus the null hypothesis (H_0) tested was that *change in slope steepness* *does not affect bare soil surface sizes*. However, as highlighted in Section 4.1.5, the placement of access gates within certain slope classes influences spatial patterns of bare soil surfaces. Therefore, for the second variable, the test was for the association of the distances between locations of size categories of bare soil surface patches with access gates. Figure 4.12 shows spatial locations of the main access gates within Okhombe for the four time periods. The total number of access gates located within each of the seven slope categories are tabulated in Table 2 in the Appendix.

Bare soil surfaces were considered to be the main indicators of land degradation. The correlation of areal coverage of various land cover types with slope and distance from access routes was used to determine how these factors influence patterns of land degradation in this landscape. Slope is measured in percent slope with higher percentages representing steeper slopes and is expressed thus (ESRI, 2006):

$$\text{Slope \%} = [(\text{Vertical distance x Horizontal distance}) \text{ x } 100] \quad (4.1)$$

A slope map of Okhombe was created from a 20 m resolution DEM using the surface analysis function in the Spatial Analysts tool in ArcGIS.

Landscape units employed by Sonneveld *et al.* (2005) and Tau (2005) are incorporated but slope, as a relatively more critical factor, is utilized since these landscape units only represent variation in elevation but do not define slope steepness (i.e. different slope steepness could be found within any of these landscape units as shown in Table 4.3). Therefore, these landscape units are used for reference purposes to describe the elevation ranges of the study area. Figure 4.1 illustrates the five different landscape units in relation to locations of the grazing camps and fence-lines separating major land uses in Okhombe. These are used to illustrate landscape unit terminologies used in this study.

Table 4.3 Characteristics of the five landscape units as identified by Sonneveld *et al.* (2005) with adjusted highest and lowest values to represent the entire elevation range at the catchment level

Landscape unit	**Elevation range above sea level (m)**	Means slope (%)	Slope range (%)
River Valley	1192 – 1300	3.97	0.02 – 30.2
Footslope	1300 – 1330	5.6	0.02 – 44.2
Midslope	1330 – 1360	13.67	0.1 – 49
Upperslope	1360 – 1425	12.55	0.1 – 45.6
Plateau	1425 – 2043	18.78	0.1 – 69

For the first statistical test, a one-way ANOVA was done to determine the association between slope steepness (expressed as slope categories calculated from slope percentages) and area size of bare soil surface patches found within the individual slope category. This was conducted for the five time periods covered by the research. Slope percentages were classified into seven classes as follows (HLURB, 2007):

Table 4.4 Description of slope classes used to test the statistical relationship between slope category and area covered by bare soil surface patches within individual slope classes

Slope class	**Slope range (%)**	**Description**
SC1	0 – 2 %	Level to nearly level
SC2	2 – 5 %	Very gently sloping
SC3	5 – 8 %	Very gently sloping to undulating
SC4	8 – 18 %	Moderate sloping to rolling
SC5	18 – 25 %	Strongly sloping to strongly rolling
SC6	25 – 40 %:	Steep
SC7	>40 %	Very steep.

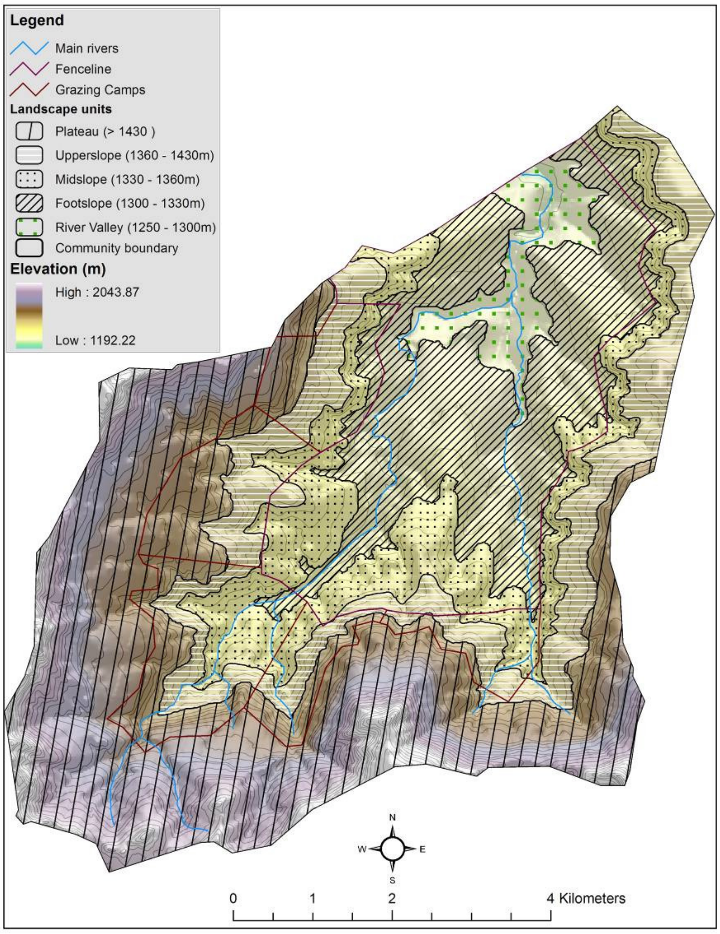

Figure 4.1 Landscape units super imposed on a 20 m contour layer and a DEM.

For correlation between patch size categories and their distance from access gates, a Spearman correlation analysis was used to establish their relationship. Identified bare soil surfaces in 1945, 1962, 1976, 1992, and 2004 were converted into raster formats and categorized into ten classes based on their sizes using a Natural breaks (Jenks) thematic classification method within ArcMap 9.3. On this scale of 10 classes, higher class values represent large bare soil patches while smaller class values represent smaller bare soil patches.

Larger patches are characterized by areas that have an intensified land degradation over a larger area (and possibly their formation occurring for longer time periods) as opposed to their smaller counterparts. Therefore, categorizing patch sizes enables one to determine how intensification of land degradation is related to distance to access gates. In addition, it was imperative to categorize the copious patches into categories in order to understand how locations of access gates influence land degradation patterns resulting from accessibility to grazing land by livestock.

It was for this reason that the Natural Breaks thematic classification method was used because it statistically classified bare soil patches based on their natural groupings inherent within the dataset by setting class breaks at relatively large intervals along the end tails of the histogram, with low numbers representing large patches and *vice versa* (ESRI, 2006). In essence, the method enables the numerous small bare soil patches with negligible area size differences to be grouped into categories based on the area size differences and thus a classification with reasonable class breaks is produced. To illustrate this, see Figure 4.2 which shows the Natural breaks (Jenks) classification method parameters used to classify rasterised bare soil surfaces dataset of the 2004 land cover map.

To calculate the distance from access gates, a distance raster layer was created using the distance function in Spatial Analyst Tool from GIS point layers of access gates for the five time periods. The distance raster layers for the respective time periods were then used to determine the mean distance from different patch sizes of bare soil surfaces to the nearest access gates.

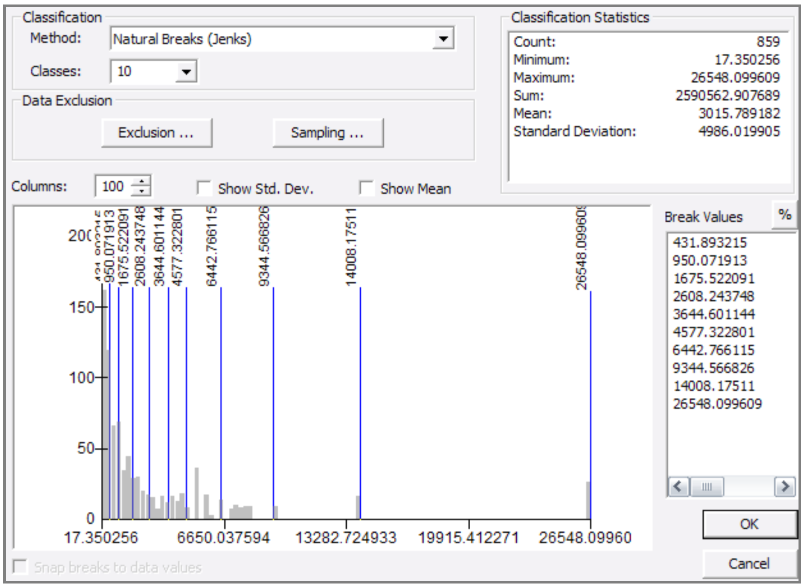

Figure 4.2 An example of the Natural Breaks (Jenks) classification method on the 2004 bare soil patches. The historgram (shaded in grey) shows distribution of patch sizes. The blue lines represent break values at which the classes are defined. The vertical axis represnts the number of patches, while the horizontal axis represents size (m^2) of these patches.

4.3.5 Change prediction analysis

A Markov Chain analysis embedded in IDRISI Andes Edition, was used to predict land cover conditions for the year 2016 (i.e. a 12 year interval from the previous known state) based on change transitions of past states (i.e. from 1992 to 2004, with an interval of 12 years).

A Markov Chain analysis is a stochastic process that describes certain types of conditions that shift in sequential steps through sets of states (Winkler, 2003). Future or unknown states, say at time *t3,* are modelled in a Markov chain analysis through modelling change transitions of previous and present known states at time *t1* and *t2 (Clark's Lab)*,hence, using land cover maps in a change modelling process, a Markov Chain model highlights areas of potential change based on detected change transitions. The model generates a transition probability matrix describing transition probability (i.e. the likelihood that a pixel of a given class will remain the same or change to any other class) of each land cover type into every other class (IDRISI, 2006); transition area matrix showing the actual area expected to change; and a set of conditional probability images expressing the likelihood that each pixel of every land cover category will be allocated to a certain category in the specified time period (IDRISI, 2006). Although a Markov Chain analysis is a good tool for predicting change, landscape patterns resulting from complex interactions of biophysical, socio-economic, and political factors make its prediction uncertain in landscapes where such levels of interaction exist.

For this study, to evaluate the accuracy of the modelled results, the probabilities of land cover to change by the year 2004 were modelled based on the detected change transitions generated for the period 1976 to 1992. These results were compared to the known 2004 land cover conditions.

4.4 Results

Maps of five lands cover types for the five different time periods (i.e. for 1945, 1962, 1976, 1992, and 2004) were produced, each showing the six major land cover types (Figure 4.4). Following a change detection analysis outlined in Section 4.3.4, quantitative results are presented below, with particular focus on land cover changes portraying land degradation. Furthermore, statistical test results of the correlation between a) detected patch sizes of bare soil surfaces and b) distance to access gates and slope steepness for the respective time periods are presented.

From a visual interpretation of changes shown in Figure 4.4, it is evident that the Okhombe landscape has experienced both major and minor changes. Settlement areas in particular, have dramatically increased in size. Areas covered with cultivated fields, on the other hand, which were scattered in 1945, became more clustered and increased in size between 1962, 1976 to 1992 then slightly declined in 2004. An enclosing fence-line restricted the extent of cultivated fields as well as enclosing expanding settlements within the fenced areas. Woody vegetation showed minor changes overall, but since 1976 a few patches have dramatically encroached on the settlement areas, particularly in the south-eastern corner of the enclosing fence-line. Overall, bare soil surfaces did not reveal remarkable increase or decline in over the years (see also Table 4.5 and Figure 4.3); although the later dates (i.e. from 1992 to 2004) show revegetation of previous bare soil surfaces as demonstrated by the decline in their patch sizes. Bare soil surfaces have, however, significantly increased or declined in specific parts of the study area, probably due to variations in the type and magnitude of the causal factors that were intensified in these regions at the time. It is also worth noting that bare soil surfaces exhibit elongated patterns and shapes which are mainly attributed to grazing and foot paths. Gullies were established mainly on areas previously covered by bare soil surface. Their areal coverage generally increased over the years except for the 1962 to 1976 period, while the 2004 land cover map showed their highest area coverage (Table 4.5).

Table 4.5 Calculated area (in Hectares) covered by the six land cover types of Okhombe for 1945, 1962, 1976, 1992, and 2004

	1945	1962	1976	1992	2004
Bare soil surface	178.706	154.188	123.689	150.528	90.360
Gullies	2.942	3.048	1.475	4.761	6.075
Settlements	24.652	111.990	228.109	329.414	408.052
Cultivated areas	616.318	514.539	591.980	607.571	466.531
Grassland	3625.961	3682.212	3497.017	3318.516	3436.783
Woody vegetation	137.688	135.557	165.047	208.927	190.610

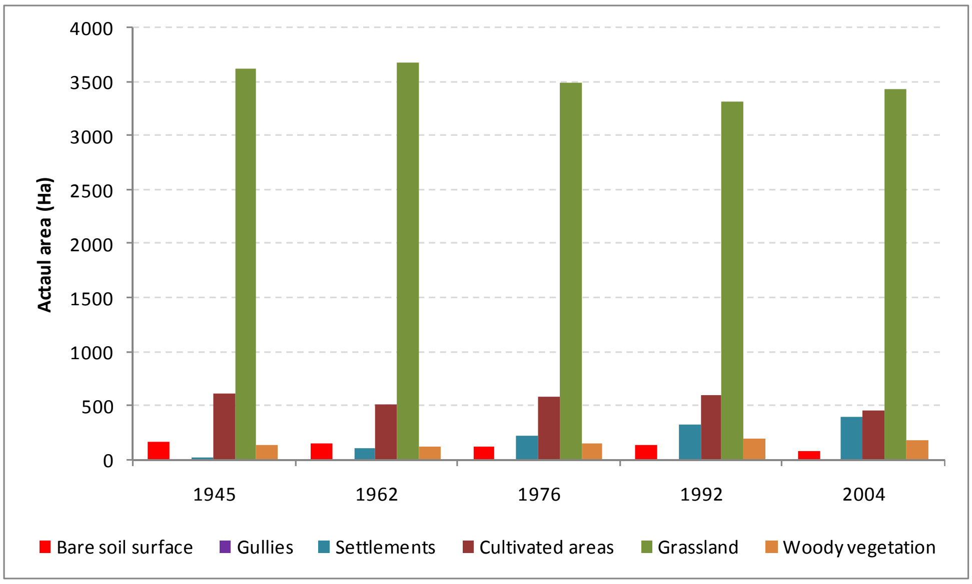

Figure 4.3 Graphical comparison of area values shown in Table 4.5.

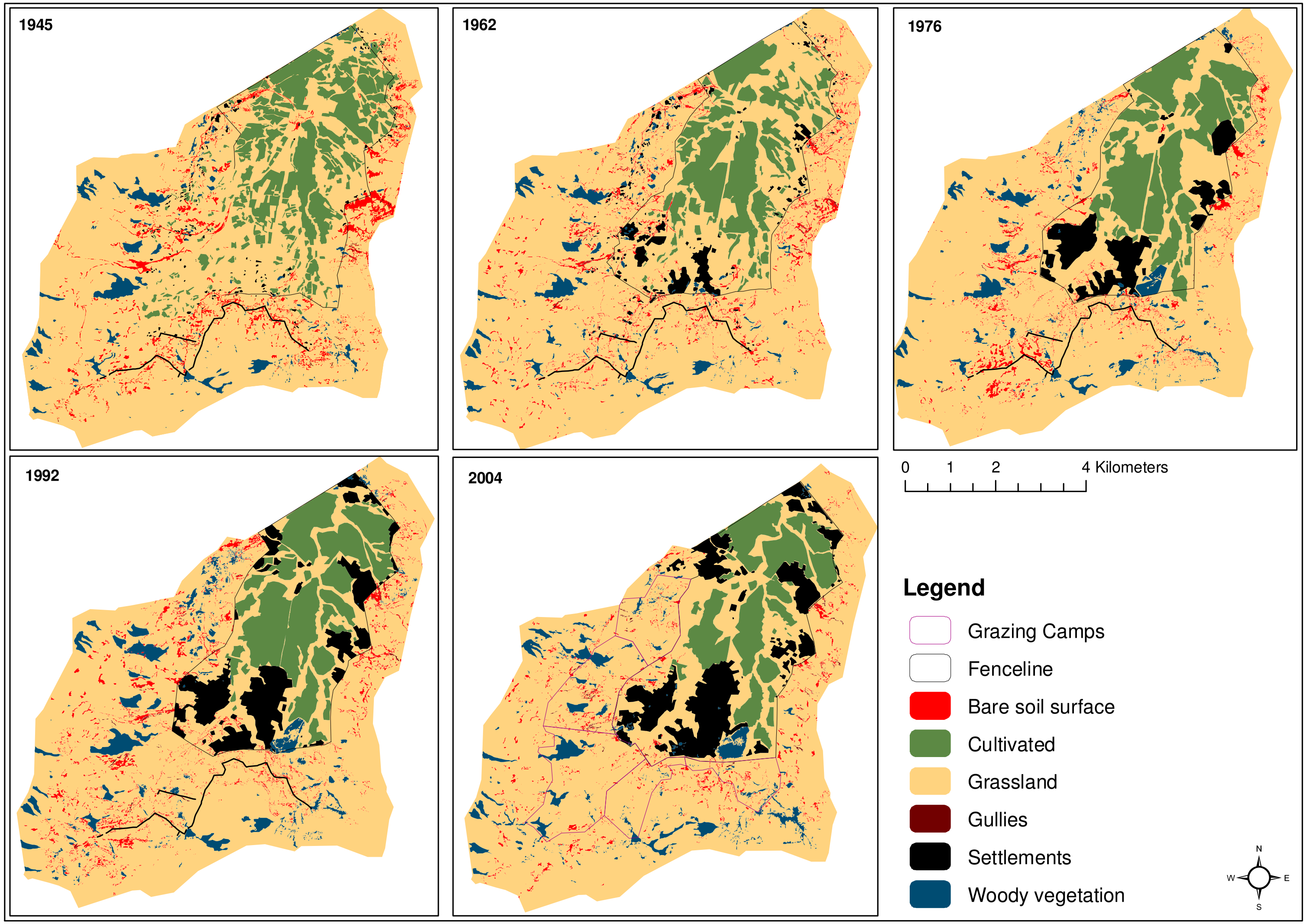

Figure 4.4 Digitized land cover maps of 1945, 1962, 1976, 1992, and 2004.

4.4.1 Change analysis using Land Change Modeler (LCM)

In Figure 4.6, four change maps are shown for the periods of 1945 to 1962, 1962 to 1976, 1976 to 1992, and 1992 to 2004. They were produced using sub-models embedded in LCM. The most detectable changes in grassland, bare soil surfaces, and woody vegetation are observed along the outskirts of the study area (mainly outside the fence-lines or on the midslope, upperslope, and plateau areas designated for grazing); changes in grassland, cultivation, settlements, woody vegetation, and to a lesser extent, bare soil surfaces, are noticed along the valley (i.e. footslope and river valley).

a) *Land cover transformation and conversions (i.e. gains and losses) and net changes experienced by the various land cover categories)*

Land cover changes that occurred from 1945 to 1962, 1962 to 1976, 1976 to 1992, and 1992 to 2004 were comprehensively quantified using the Land Change Modeler. Transformations and conversions experienced by the various land cover categories are quantified in the form of gains and losses, and net changes shown in Figure 4.5 and Figure 4.7, respectively.

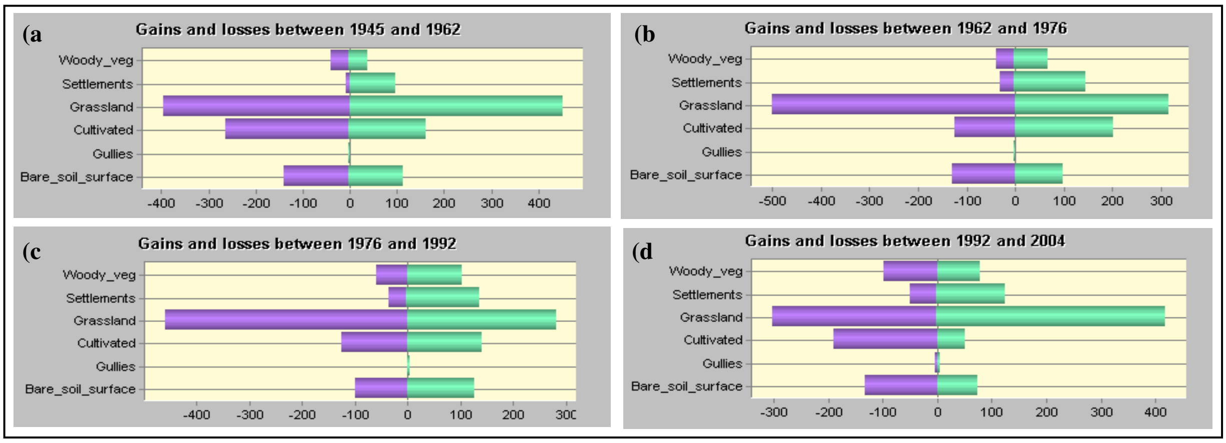

Figure 4.5 Gains and losses experienced by the various categories of land cover (gains and losses are represented by the positive and negative values, respectively).

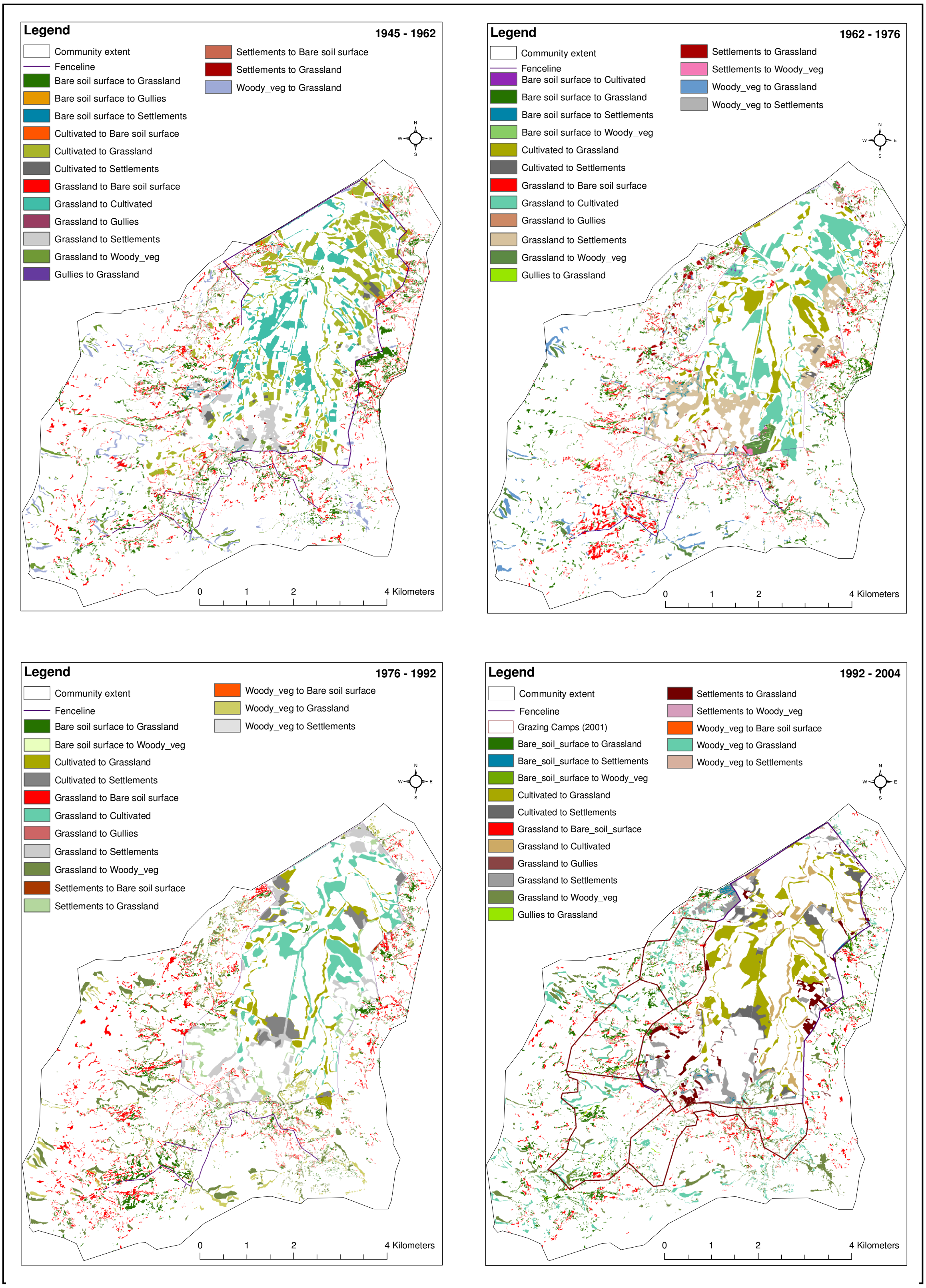

Figure 4.6 Resultant change detection maps using LCM.

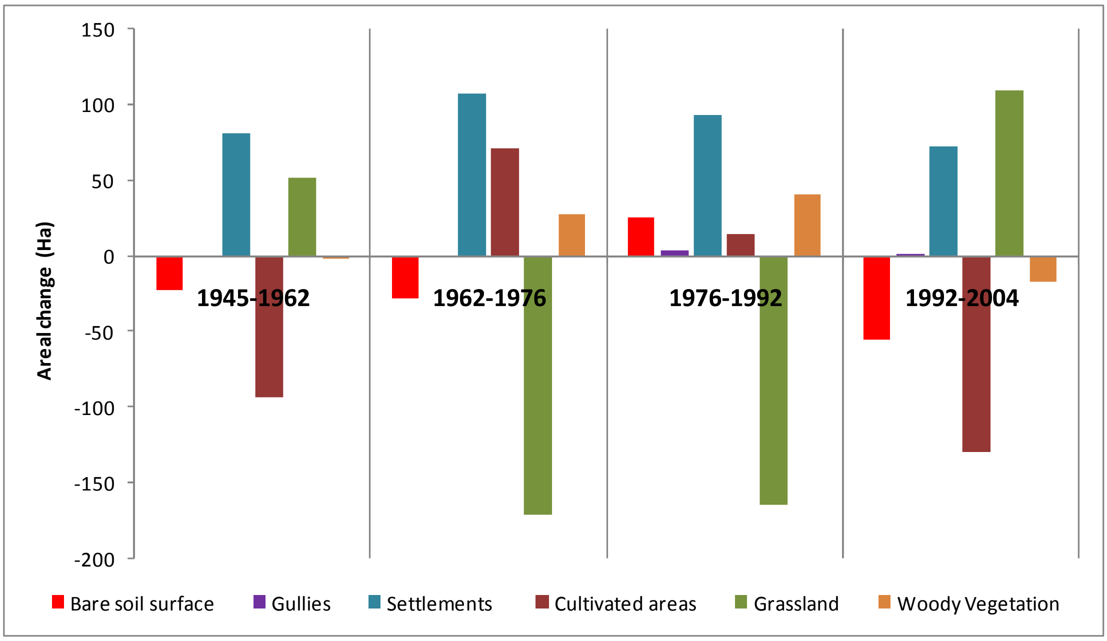

Figure 4.7 Graphical representation of net changes that occurred over the four time periods. Negative values represent the amount of areas loss experienced by the respective land cover type**.**

All land cover categories, with the exception of gullies, experienced noticeable gains and losses (Figure 4.5). All land cover categories experienced loss with the settlements category experiencing minor loss from 1945 to 1962. This implies that the majority of the areas previously covered by settlements did not change or transform to other categories but rather expanded in size. It is also noted that over the four periods during which land cover change is detected, all categories were dynamic and at times experienced more gain than loss and *vice versa*. For instance, cultivated areas experienced more loss than gain from 1992 to 2004 as compared to the other time periods. To derive overall changes that have occurred from the gains and losses values, the model computed net changes.

Figure 4.7 shows the net changes that occurred. Settlement is the sole category showing an increase over the time period, but its rates of increase slightly decreased by 36 Ha from the 1962-1976 to the 1992-2004 time period. Bare soil surfaces declined from 1945 to 1962 and 1962 to 1976, and experienced their only increase, of approximately 26 Ha, between 1976 and 1992, and then sharply declined from 1992 to 2004. The majority of bare soil surfaces were located within the SC4 slope category (a moderately steep slope) which also has the highest number of access gates (refer to Table 2 in the Appendix, Figure 4.12, and Table 4.4).

Closely related to the detected increase in bare soil surfaces between 1976 and 1992, is a net increase of 2.7 Ha detected for the gullies, the largest after 1.3 Ha and 0.1 Ha for the 1945 – 1962 and 1992 – 2004 time periods, respectively. The only decline in gullies, of approximately 1.6 Ha, was experienced from 1962 to 1976. Although net changes experienced by gullies, compared to other land cover categories, were relatively small, their relevance is no less important, particularly for the purpose of this study, as a considerable area (up to 6 Ha) was detected for these erosional features in the years 2004 (see also Table 4.5).

The majority of the observed net increase experienced by all land cover types is due to conversion from grassland. It is noticeable that the 1945-1962 period experienced an increase in settlement areas, a slight increase in grassland, and a decrease in bare soil surfaces, cultivated fields, and woody vegetation. The 1962-1976 period experienced a sharp decline in grassland which probably contributed to a) the evidenced increase in cultivated fields, settlement areas, and woody vegetation and b) a slight decline in bare soil surface. Conversely, the 1976-1992 period experienced a decline only in grassland areas while the remaining categories, bare soil surfaces, and gullies in particularly, increased as outlined above. Lastly, the 1992-2004 period experienced a different situation, with increasing grassland and settlements while bare soil surfaces, cultivated fields, and wood vegetation areas declined. Figure 4.7 reveals that grassland may have acted as a major land contributor to the rest of categories. For the scope of this study, land cover change contributions made to bare soil surfaces, gullies, and to a lesser extent, woody vegetation are examined and represented in Figures 5.6, 5.7, and 5.8 as these three land cover types characterise land degradation associated with grazing pressures (DEAT, 2008).

b) *Contribution by various land cover categories to net change experienced by bare soil surface, gullies, and woody vegetation categories*

Using LCM, an assessment was made to analyse which of these categories acted as the major contributor to net changes (either increase or decline) experienced by bare soil surfaces, gullies, and woody vegetation for the four time periods in order to explain possible causes of observed land degradation patterns. Figures 4.8, 4.9, and 4.10 show these contributions as well as how these land cover types changed as shown in the previous section.

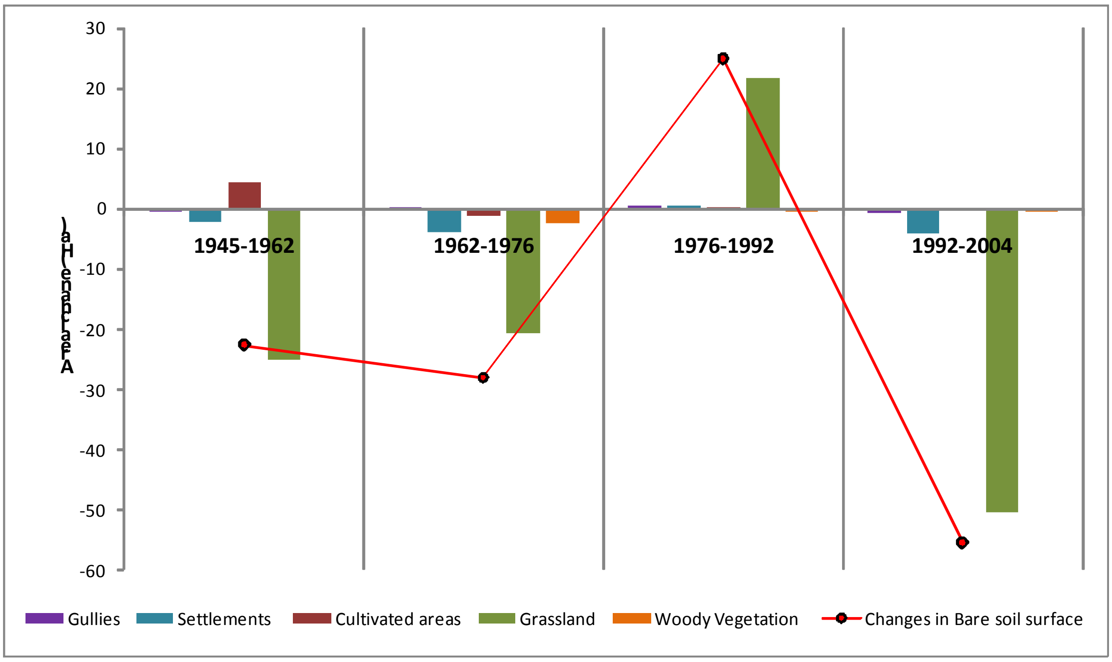

Figure 4.8 Contributors to net change experienced by the bare soil surface category. Negative values represent the area (Ha) of land cover type(s) that contributed to the observed decline in bare soil surface; while the positive values represent the opposite, i.e. the area (Ha) of land cover type(s) that contributed to the observed increase in bare soil surface. The line graph shows net changes experienced by bare soil surfaces during the respective time period with all negative values representing the only time a decline was experienced and *vice versa* for the positive values.

The graph in Figure 4.8 shows land cover categories that made the highest contribution to changes experienced by bare soil surface for the specified change periods. Grassland vegetation is the most significant net contributor to change experienced by bare soil surfaces. From 1945 to 1962, approximately 4 Ha of cultivated fields changed to bare soil surfaces. For this period, the majority of the areal decline experienced by bare soil surfaces was from areas which were bare in 1945 and re-vegetated by grassland while a minority of these bare areas were lost to settlements and gullies that had increased by 1962. From 1962 to 1976, further bare soil surfaces were invaded by all the other categories, resulting in an areal decline of bare soil surfaces as shown in Figures 4.7 and 4.8. This decline is, however, not evidenced at all localized scales within Okhombe as was observed in the south-western part, where bare soil surfaces significantly increased (see Figure 4.6). This could be attributed to the varying grazing pressures at these localized scales and/ or a combination of grazing and other factors such as slope and rainfall. of the four periods, the 1976 - 1992 period experienced an increase in bare soil surfaces, of which the majority were previously (i.e. in 1976) covered by grassland and later (i.e. in 1992) by bare soil surfaces. For the 1976 - 1992 period, most of these increases were in the western part of the study area (see Figure 4.6), an area covering the largest grazing land. For the other time periods, a decline in bare soil surfaces are accounted for by improving grassland within the most recent period (i.e. between 1992 and 2004) showing the most grassland regeneration (approximately 50 Ha) from areas that were previously bare soil surfaces.

The main contributors to changes experienced by gullies were grassland and bare soil surfaces as shown in Figure 4.9. Clearly, the reason for the observed conversion from gullies to grassland vegetation can be attributed to the fact that these grassland areas could have been transformed into bare soil surfaces during the intermediate time periods not covered by this analysis and then into gullies at the time period covered by this study. Results showing classes contributing to net changes experienced by bare soil surfaces (Figure 4.8) also support this, in the sense that grassland vegetation was the largest contributor of gains experienced by bare soil surfaces. This implies that bare soil surfaces played a significant role in the establishment of gullies. The smallest increase in gullies, namely that experienced between 1945 and 1962, resulted primarily from bare soil surfaces. This was followed by the recovering grassland from 1962 to 1976. The 1976 - 1992 period saw a further increase in gullies as a result of diminishing grassland vegetation (Figure 4.7), although many of these areas were previously bare soil surfaces. Unlike during other time periods where cultivated areas accounted for a significant loss in grassland vegetation, from 1976 – 1992 the increase in bare soil surfaces and gullies accounted for much of the grassland loss experienced. From 1992 to 2004, gullies increased by a further 1.3 Ha, but at a lower rate as compared to the 1976 – 1992 period (Figure 4.9).

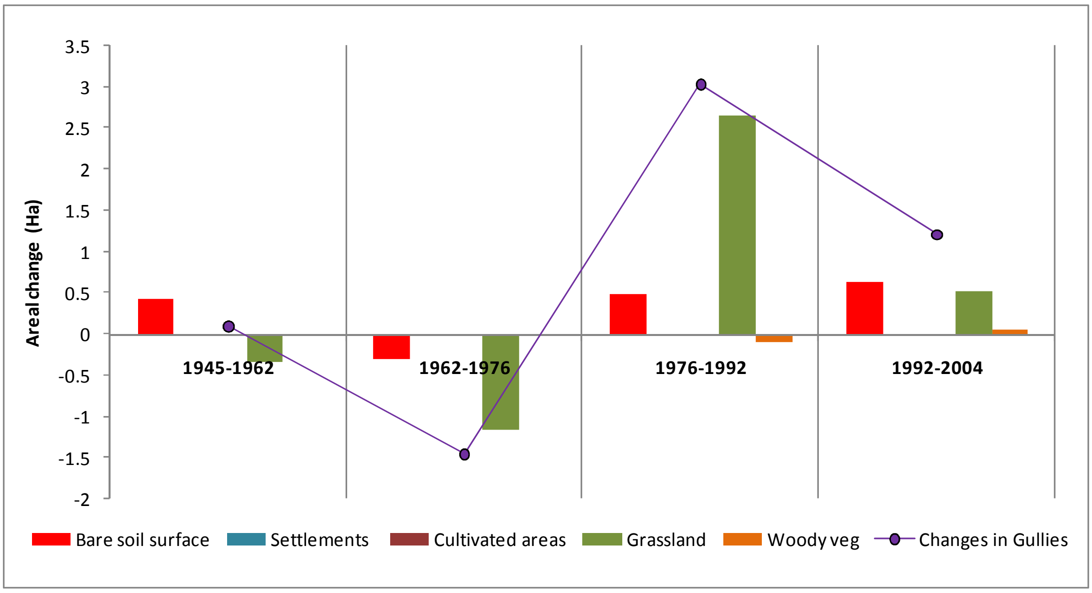

Figure 4.9 Contributors to net change experienced by the gullies. Negative values represent the area (Ha) of land cover type(s) that contributed to the observed decline in gullies, while the positive values represent the opposite, i.e. the area (Ha) of land cover type(s) that contributed to the observed increase in gullies. The line graph shows net changes experienced by gullies during the respective time period with all negative values representing the only time a decline was experienced and *vice versa* for the positive values.

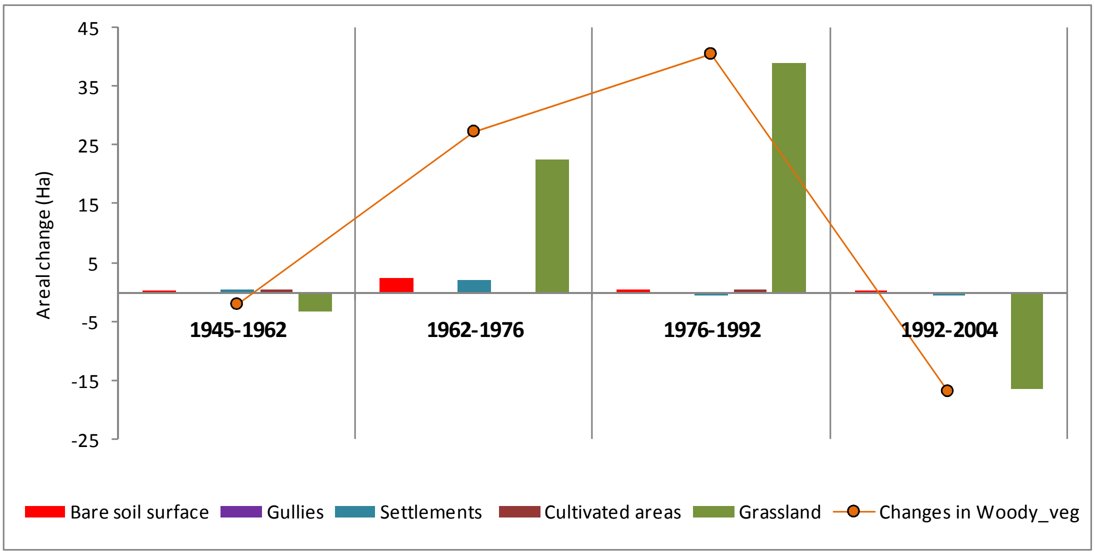

Figure 4.10 Contributors to net change experienced by woody vegetation. Negative values represent the area (Ha) of land cover type(s) that contributed to the observed decline in woody vegetation, while the positive values represent the opposite, i.e. the area (Ha) of land cover type(s) that contributed to the observed increase in woody vegetation. The line graph shows net changes experienced by woody vegetation during the respective time period with all negative values representing the only time a decline was experienced and *vice versa* for the positive values.

Loss in grassland vegetation, once again, resulted in an increase in woody vegetation that occurred from 1962 to 1992 as shown in Figure 4.10. The largest decline (approximately 15 Ha) occurred from 1992 to 2004 while the smallest decline (of about 3 Ha) occurred from 1945 to 1962. The 1962 – 1976 period experienced an interesting situation in that, although small in comparison to grassland vegetation loss, about 3 Ha of bare soil surfaces contributed the increase in woody vegetation.

c) Changes in grassland vegetation within the rangeland

Because all changes within the rangeland were linked to land degradation, changes in grassland vegetation cover were assessed by looking at the gains and losses experienced by the grassland cover type. Loss in grassland vegetation occurred only from 1962 to 1976 and 1976 to 1992. Settlements and cultivated fields occupying areas enclosed by the fence-lines accounted for the majority of the loss of grassland within this area; while bare soil, gullies, and woody vegetation were responsible for the loss of grassland vegetation cover within the rangeland. This indicates deteriorating rangeland conditions in cases where bare soil, gullies, and woody vegetation within the rangeland. The 1976 – 1992 period is characterized by this condition as shown in Figure 4.7 and the map in Figure 4.6 showing spatial distribution of grassland loss transformation.

There was no significant direct loss of grassland vegetation to gullies, but there was an indirect loss to bare soil surfaces and then to gullies. This implied an intensification of erosional features at the deteriorated locations. Transformation of grassland to woody vegetation occurred throughout the rangeland irrespective of the elevation and / or slope; however, some of these transformations occurred on land previously covered by bare soil surfaces and on north facing slopes mainly along the south-eastern part of Okhombe (Figure 4.6). This loss of grassland vegetation to woody vegetation may be presumably bush encroachment.

4.4.2 Change prediction using a Markov Chain analysis

For the Markov Chain analysis performed using the 1972 and 1992 land cover maps to predict the 2004 land cover conditions, the probability of change is shown in Table 4.6. This represents an evaluation of performance of the model. Probability of the six major land cover types to changing by the year 2016, using the 1992 to 2004 transitions are shown in Table 4.7.

Table 4.6 Markov prediction of 2004 land cover conditions based on the 1976 to 1992 transitions

Given:	*Probability of changing to:*					
	Bare soil surfaces	**Gullies**	**Cultivated fields**	**Grassland**	**Settlements**	**Woody vegetation**
Bare soil surfaces	0.1564	0.0062	0.0003	0.8148	0.0066	0.0149
Gullies	0.1439	0.0920	0.0000	0.6726	0.0149	0.0766
Cultivated fields	0.0007	0.0000	0.6695	0.1885	0.1395	0.0017
Grassland	0.0687	0.0022	0.0801	0.7378	0.0466	0.0562
Settlements	0.0114	0.0001	0.0016	0.2676	0.7145	0.0048
Woody vegetation	0.0099	0.0000	0.0000	0.4356	0.0086	0.5458

According to the Markov Chain model predicting the 2004 land cover conditions based on the 1976 to 1992 transitions (Table 4.6), the probabilities are generally high of bare soil surfaces and gullies changing to grassland, at 81 % and 67 %, respectively, while woody vegetation has a probability of 43 %. On the other hand, the probabilities of grassland changing to bare soil surfaces, gullies, and woody vegetation is 7 %, 0.2 %, and 6 %, respectively. In contrast to this, there is a 71 % probability of grassland remaining the same, a 4 % probability of changing to settlements, and an 18 % probability of changing to cultivated fields. Chances of bare soil surfaces of remaining the same are 15.6%, gullies changing to bare soil surfaces being 14%, while those of bare soil surfaces changing to gullies are as low as 0.6%.

On comparing the above results to the mapped actual 2004 conditions shown in Figure 4.4 and Table 4.5, it is found that prediction results for gullies and woody vegetation are overestimated while these for bare soil surfaces can be accepted to a certain degree. For the majority of the other land cover changes, change probability percentages are in contrast to the actual changes shown in Figure 4.7. For instance, grassland remaining unchanged and cultivation increasing is in fact not so.

Table 4.7 Markov prediction of 2016 land cover conditions based on the 1992 to 2004 transitions

Given:	*Probability of changing to:*					
	Bare soil surfaces	**Gullies**	**Cultivated fields**	**Grassland**	**Settlements**	**Woody vegetation**
Bare soil surfaces	0.0963	0.0062	0.0000	<u>0.8525</u>	0.0333	0.0098
Gullies	0.0477	0.0561	0.0000	<u>0.8830</u>	0.0132	0.0000
Cultivated fields	0.0003	0.0000	<u>0.5821</u>	<u>0.3288</u>	0.0874	0.0002
Grassland	0.0536	0.0036	0.0374	<u>0.7722</u>	0.0594	0.0563
Settlements	0.0023	0.0003	0.0033	0.2515	<u>0.7233</u>	0.0158
Woody vegetation	0.0060	0.0003	0.0000	<u>0.5209</u>	0.0195	<u>0.4522</u>

While predicting for the 2016 land cover conditions based on the 1992 to 2004 transitions, the Markov chain model predicts a relatively high probability of bare soil surfaces and gullies changing to grassland, at 85% and 88 %, respectively, and a probability of woody vegetation changing to grassland, at 52 %. The probability of grassland remaining grassland increased and is 77 %, changing to settlement was 5 %, and changing to cultivated fields is 3 %, a very low probability. The probabilities of grassland changing to bare soils surfaces, gullies, and woody vegetation are 5 %, 0.3 %, and 5 %, respectively.

4.5 Discussion

Changing patterns of land degradation in South African communal areas over the past sixty years are perceived to have been on the rise. However, their spatial patterns have scarcely been investigated, particularly with regard to unique topographical characteristics of these areas and land cover conversions resulting from various land use management practices and interventions implemented over the years. The results of this chapter are discussed in three main sections, namely: (i) land cover changes and conversions describing trends in land degradation patterns, (ii) explaination of observed patterns of land degradation in relation to slope and the roles played by access gates (major landscape structures that were result of land use management interventions and land use changes), and (iii) prediction future land cover conditions to forecast spatial extent of possible land degradation based on known past and current states.

4.5.1 Land cover conversions and changes describing trends in land degradation patterns

The results of this study have shown that areal coverage of land degradation from 1945 to 2004 in Okhombe has not significantly increased or declined has but fluctuated over the period.

a) Land cover transformations and conversions and net changes experienced by the various land cover categories

Areal coverage by gullies has significantly increased from 1992 to 2004, having mainly resulted from bare soil surfaces that had persisted for relatively long periods. The results show that the period of 1976 to 1992 is the only period that experienced an increase in total bare soil surfaces, a period that also received low rainfall between 1981 and 1983 (Figure 2.1). This is the only period that an increase in bare soil surfaces and gullies resulted in a significant decline in land covered by grassland vegetation. Furthermore, these conditions occurred after a period, 1962 to 1976, characterized by recovering degraded areas and increasing cultivated fields. At a catchment scale, these findings confirm those of Sonneveld *et al.* (2005) that were conducted at a sub-catchment scale. However, the present study shows that there is insignificant variation in the degree of changes in land degradation patterns from place to place across this landscape, a case that certainly contrasts with the findings obtained at a sub-catchment scale by Sonneveld *et al.* (2005).

Generally, the results show that the most severe patterns of land degradation developed along changing patterns of settlements following the implementation of the Betterment Scheme in the 1960s that resulted in the relocation of settlements into a nucleated form along the valley. Settlement is the only category that significantly increased over the time period.

b) Contribution from various land cover categories to net change experienced by bare soil surfaces

Grassland vegetation is identified as being the most significant net contributor to change experienced by bare soil surfaces. This could be attributed to varying grazing pressures, a single of land use this area (i.e. grassland) was designated and is commonly used for as highlighted by Meadows and Hoffman (2002).

The fluctuating size of bare soil surfaces at different time periods and different localized sites of Okhombe has been characterized by a) periods of re-vegetation by grass of previously degraded areas and b) as the loss of grassland vegetation and cultivated areas to bare soil surfaces. The recent period (1992 to 2004) had the highest improvement in grassland vegetation, as more areas previously covered by bare soil surfaces were re-vegetated by grass. Certainly, this does not imply that veld condition improved, especially for a landscape which is highly dependent on grassland quality for grazing practices. Increasing amount of unpalatable grass species noted by Tau (2005) could have accounted for the majority of this grass regeneration.

Other distinct changes evident include the recent decline in cultivated areas and encroaching of woody vegetation on land previously covered by bare soil surface from 1962 to 1976. The decline in cultivated areas has been attributed to the apparent increase in soil erosion as noted by the community in Okhombe (Everson *et al.*, 2007). In comparison of this view to the observed case in the current study, we find out that neither bare soil surfaces nor gullies have significantly increased as a result of declining cultivated areas during the recent period (see Figures 4.8 and 4.9). Deviation between these two findings is likely a result of the variation of how the issues being investigated, namely soil erosion or land degradation, are defined and measured in the two cases.

In addition to the above perceptions regarding the causes of land degradation, community attributes expansion of land degradation through gullies to uncontrolled livestock movement, the use of sledges and inappropriate tillage practices (Everson *et al.*, 2007). In the current study, uncontrolled cattle movement can be linked to the overutilization of access gates, particularly these situated on steep slopes, which were found to influence the detected patterns of land degradation.

c) *Changes in grassland vegetation within the rangeland*

Crucial land cover conversions from grassland vegetation to bare soil surfaces and *vice versa* that occurred within the rangeland are highlighted in the previous sections. The results also show that the loss of grassland vegetation to bare soil surfaces occurred mainly throughout the rangeland along both the Midslope and Plateau. This pattern is clearly distinct from that of other time periods apart from the 1945 – 1962 period (in terms of its magnitude and density but with similar distribution), where these patterns in other time periods generally occurred in localized areas. For instance, between 1962 and 1976 bare soil surfaces occurred mainly along the periphery of the fence-line on the Midslope (Figure 4.6) but not on the Plateau.

Furthermore, the results also show that grassland vegetation greatly contributed to encroachment by woody vegetation. Perhaps being one of the most flourishing periods, 1962 to 1976 experienced a significant increase in woody vegetation, a condition that could have been accelerated by overgrazing as woody vegetation grew on areas that were previously bare soil surfaces. A further increase in woody vegetation is also observed during the next driest period, that of 1976 to 1992.

Both catchment scale and localized changes in bare soil surfaces in different parts of Okhombe can be attributed to a range of factors that include rainfall variability (Dube and Pickup, 2001; DEAT, 2008), varying grazing intensity, carrying capacity, choice of grazing area, soil properties, and slope amongst others. Low rainfall, for instance, caused unfavourable dry conditions during the early 1980s which caused dramatic changes in all land cover types. Influence of slope and access gates imposed by fence-lines along the mountainous terrain of Okhombe are discussed in the following section.

4.5.2 Explaining observed patterns of land degradation in relation to the influence of slope and the role played by access gates

Like rainfall, slope steepness was expected to have a significant influence on the patterns of land degradation while moderate significance was expected for distance of bare soil surfaces from access gates. However, the results revealed a slightly different case.

Results of a one-way ANOVA showed no significant differences in mean patch size of bare soil surfaces among the seven slope classes. This implies that change in slope steepness does not significantly affect the sizes of bare soil surfaces. These findings are supported by these of Harris *et al*. (2002) who reported cattle grazing activity to occur mostly on slopes less than 10% which includes SC1, SC2, SC3 and some of SC4 in the present study (refer to Table 4.4 and Figure 4.12). However, the exclusion of certain land, by the use of fences from grazing could have resulted in observed patterns of land degradation associated with grazing pressure. In addition, the observed patterns of land degradation are further aggravated by the presence of access gates on fence-lines separating the rangeland located at higher elevation and the settlements within the valley. Since most livestock is driven through these access gates, at least twice on a day, the soil along the cattle tracks is subject to continuous soil compaction and increased land degradation. Thurow (2005) notes that the impacts resulting from continuous utilization of paths to have considerable degradation on the land. Thus it is worth noting the possible effects of distance to access gates have on patterns of land degradation in Okhombe.

As shown in Figure 4.11, the relationships between patch size categories of bare soil surfaces and the mean distance to access gates, to test for the statistical significance that this distance has on changing patterns of land degradation, are plotted for the specific periods.

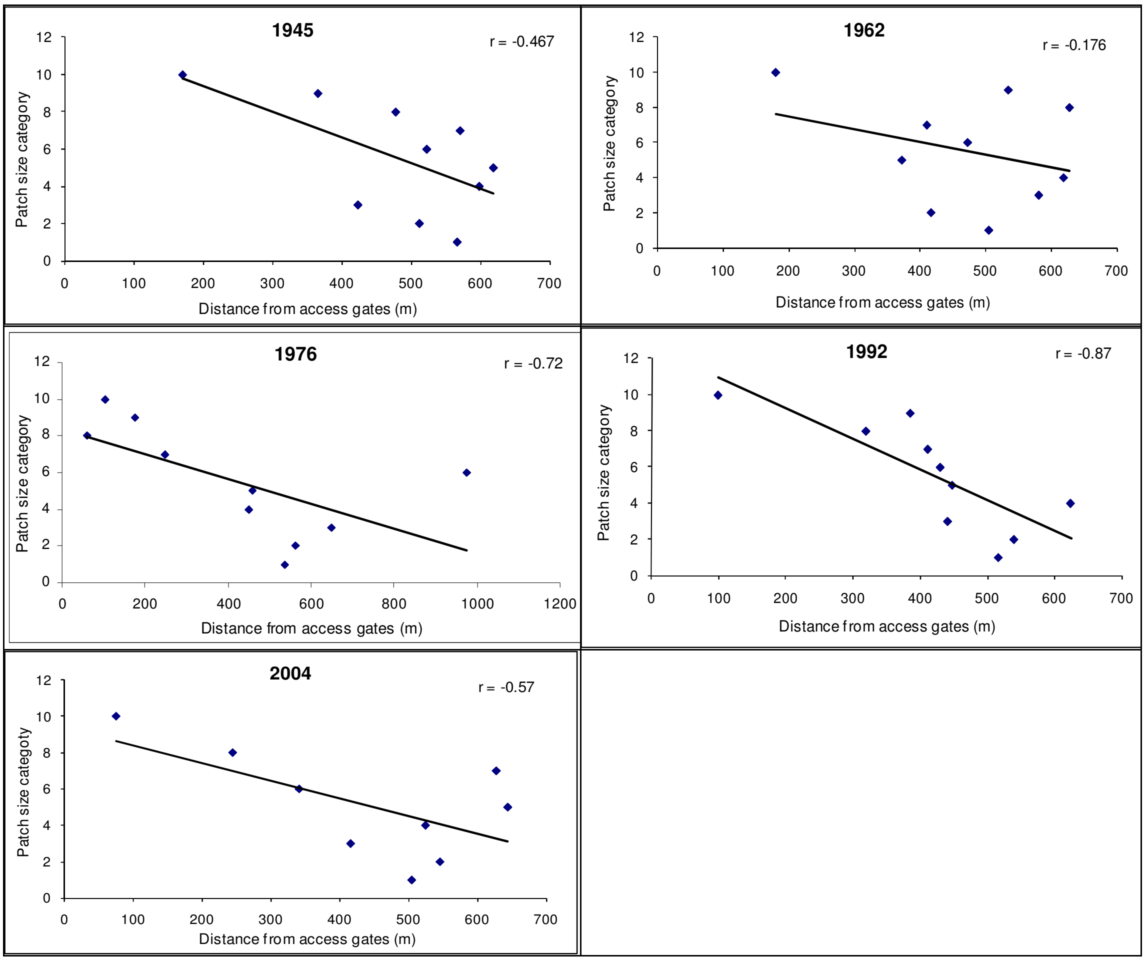

Figure 4.11 Size categories of bare soil surfaces vs. distance to access gates in multi-temporal land cover maps used for the change detection analysis.

The results of a Spearman correlation analysis for the above-mentioned test yielded a fluctuating negative r value of -0.467, -0.176 -0.72, - 0.87, and -0.57 for the 1945, 1962, 1976, 1992, and 2004 time periods, respectively (significant: $p< 0.05$). All the time periods, with the exception of 1962, had reasonably high negative correlations. This analysis showed that the relationship between area covered by bare soil surfaces and the distance to access gates is statistically significant, at least for 1945, 1976, and 2004 and more especially for 1992, followed by 1976. Overall, these results showed that large patches of bare soil surfaces are located close to access gates. The trends over the years can be attributed to the shifted locations of access gates along the eastern parts of Okhombe between 1945 and 2004 which (in Figure 4. 12) shows an extended cattle path linking the earlier, namely 1945, and later access gates. Such patterns, however, are also products of numerous factors acting upon the landscape simultaneously such as the dry period that occurred between 1980 and 1984 (Figure 2.1).

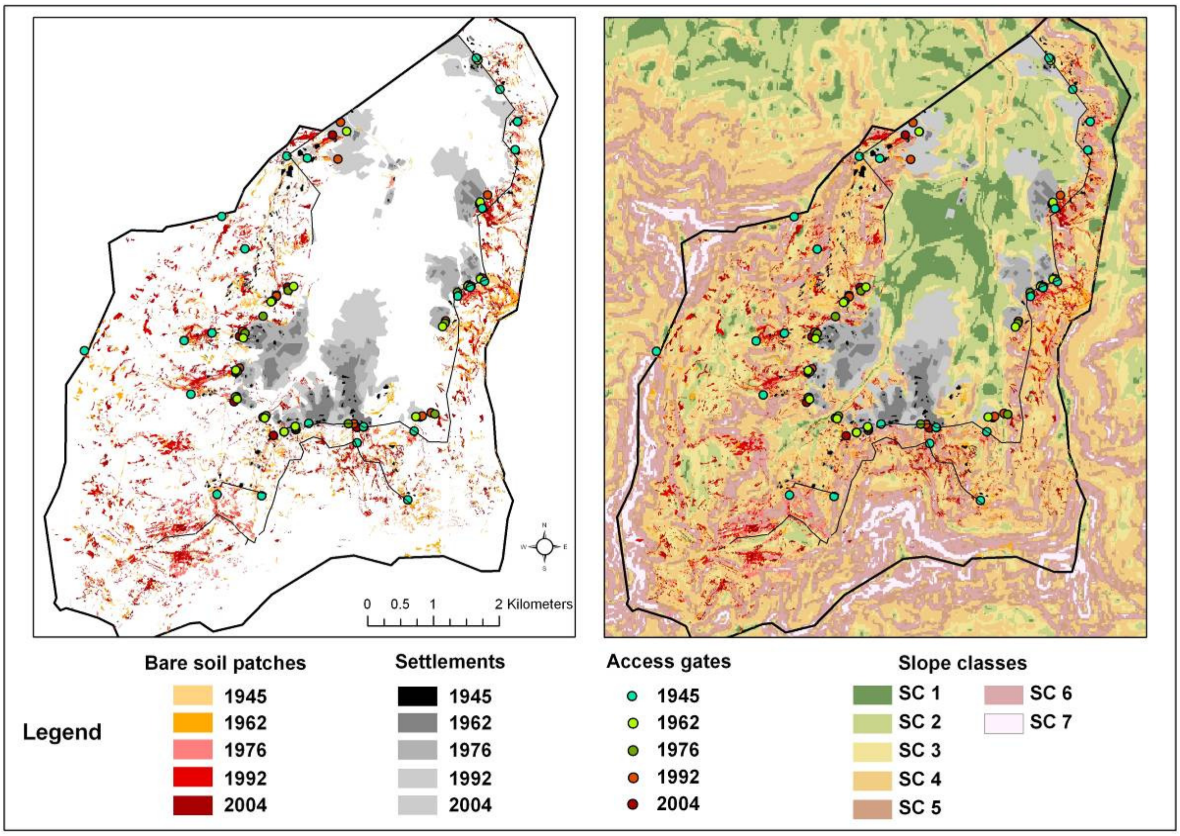

Figure 4.12 Locations of access gates over the years in relation to detected patterns of bare soil surfaces, settlements, and slope classes.

4.5.3 Predicting future land cover conditions to forecast possible land degradation patterns based on known past and current states.

Results of a Markov Chain analysis have shown that the model underestimates the likelihood of any land cover type changing at a future date. This is demonstrated on comparison of the actual spatial extent of 2004 and the predicted conditions for the same year using change transitions of 1976 and 1992. The prediction accuracy is hindered mainly by the assumption of the model that forecasting future states of a land cover type depends on its preceding extent and land cover types. Like the rest of the other classes, the changes in the spatial extent of bare soil surfaces over the years have been highly dynamic as a result of numerous complex external factors that a Markov Chain analysis does not incorporate. Some of these factors may include the criteria used by the locals in the selection of grazing areas and how this changes with time, grazing preference by cattle, and declining grazing activity as a result of socio-economic factors and veld conditions amongst others.

With the above case, prediction of land cover to change for a future unknown state (in the present case for 2016) using a Markov chain model is problematic. Overall, the model predicts declining land degradation (using bare soils surfaces and gullies). For bare soil surfaces and gullies the model yields high probability of these changing to grassland, a condition that would be presumably characterized by low grazing pressure and at least favourable rainfall. However, it is important to note that there is a relatively high probability for woody vegetation to encroach on grassland, a scenario that should not be overlooked because studies in other parts of South Africa have shown increasing woody vegetation to be threatening grazing and water resources (DEAT, 2008). Therefore, though predicting future land cover conditions using a Markov Chain model are problematic as demonstrated by the results, the model generates a scenario worth noting for possible future conditions.

4.6 Conclusion

The main aim of this study was to investigate the spatio-temporal patterns of land degradation in the light of land cover conversions and changes in Okhombe. The following conclusions can be drawn from this study:

- The spatio-temporal patterns of land degradation in Okhombe have not experienced considerable changes as demonstrated by land cover conversions which portray land degradation trends. The result rather demonstrated that the extent of land degradation have fluctuated in different localized areas of Okhombe in response to localized underlying physical factors, landscape characteristics, and socio-economic activities for example.

- Numerous factors have influenced the observed patterns. These include site-specific factors (soil properties, rainfall, vegetation cover, grazing intensity and slope,); however, land cover changes responding to anthropogenic factors were significant in shaping these patterns. Relocation of settlement areas and land use management (i.e. which land is to be used for certain activities) are some of these factors.
- Land degradation patterns are intensified by access gates located on moderately steep slopes, although a combination of various other factors also contributed to these patterns. Among those could be the effects of clearing of woody vegetation for a variety of purposes such as fuel, building construction, etc.

Chapter Five

Conclusion

5.1 Introduction

In this chapter, the aim and objectives of the study presented in Chapter One are reviewed to evaluate how these were achieved. In addition, limitations of some aspect of the study are outlined and recommendations arising from the findings are made for future research.

5.2 Reviewing of the aim and objectives

5.2.1 The aim

This research aimed to use GIS and Remote Sensing techniques in order to assess spatial and temporal extent of land degradation in Okhombe, a communal area in the mountainous region of KwaZulu-Natal province, South Africa.

The study has highlighted the significance of investigating historical changes in land degradation patterns to better understand the emergent nature of such landscape issue and identify possible causal factors behind the detected changes. The study provides invaluable information that has implications for the management of rangeland and the identification of areas that need further research as is pointed out later on in this chapter. This study also highlights that GIS and Remote Sensing can play significant roles in the study of any complex landscape issues that are spatial in nature, whether they are directly and / or indirectly linked to other landscape issues. To achieve the aim and arrive at the above-mentioned conclusions regarding the study, methodological aspects were addressed using the following main objectives. In the following sections, these are examined again to assess how close they were achieved.

5.2.2 Objectives

- To evaluate the accuracy of different georectification techniques in a mountainous environment.

Given the mountainous terrain of Okhombe, attaining superior georectification accuracy that would allow accurate overlaying of the different historical aerial photographs used to study landscape change was of great importance. Four different georectification methods were evaluated while the numbers of GCPs used by the models were altered to assess their effects on accuracy performance. An image subset, covering part of the study area with steep slopes and a hilly terrain, was effectively used to test these criteria (i.e. type of georectification method and the number of GCPs). Higher accuracy was achieved when the spline transformation model was used and the number of GCPs was increased to at least 50 GCPs, particularly for hilly regions because the model is able to curve, wrap, shrink, and stretch the dataset in order to account for this terrain variation. The spline transformation method was thus selected as being the most accurate georectification method to use for the rest of the historical aerial photographs used in this research.

- To map land cover change and indicators of land degradation from 1945, 1962, 1976, 1992, to 2004.

Six major land cover types that potentially portray land degradation trends were mapped for the above time periods. Five time periods between 1945 and 2004 were selected to allow for a comprehensive assessment of land degradation changes and for detection of how the landscape has changed in response to different factors encountered over the years. More specifically, the nature of land degradation patterns in Okhombe was studied by identifying spatial patterns of land cover changes and conversions that portray this phenomenon (e.g. conversions from grassland vegetation, settlements, and cultivated areas to bare soil surfaces). Furthermore, an explanatory analysis of detected extent of land degradation was conducted mainly focusing on the effects of slope and access gates within the landscape to aid the understanding of emerging patterns. The results showed that the more significant landscape dynamics were related to the expansion of settlements. Thus it can be concluded that considerable change in the patterns of land degradation were linked to changes and locations of settlement areas. However, due to the physical shapes of most land degradation features (i.e. bare soil surfaces and gullies) it was concluded that the majority of these patterns resulted from grazing practices. It was concluded that these patterns were intensified by the locations of access gates on moderately steep slopes and by numerous other factors such as rainfall and socio-economic factors.

- To predict future land cover conditions and patterns of land degradation based on transition states of the detected changes in land cover.

Having detected changes that occurred over the past sixty years using five different time periods, the prediction was attempted of how future land cover conditions would be. Since GIS and Remote Sensing provided means of predicting unknown conditions based on known states, a Markov Chain model was used to predict land cover conditions in 2016. Accuracy of the model was evaluated using the 1976 – 1992 change transitions to predict to the known conditions of 2004. Although the results were unsatisfactory, the model proved to be a useful scenario building tool, because it highlighted that the extent of woody vegetation are likely to increase by the year 2016. This is a case worth noting as this land cover type has gradually increased in some parts of Okhombe, colonizing mainly areas that were previously grassland, a useful resource for grazing practices in the area.

5.3 Limitations and recommendations of this study

In this section, certain limitations of the study are outlined, and recommendations are made where necessary.

- One of the limitations of the study was that positional error resulting from regions of the study area with steeper slopes affected georectification accuracy of aerial photography. Although spline transformation proved to be a reasonable technique, using more sophisticated methods and inputs such as incorporating Digital Elevation Models (DEMs) as some studies have suggested could have minimized this effect. However, due to high computational cost often associated with some of the methodologies and equipment, the spline transformation method widely available in most desktop GIS and Remote Sensing software was considered to be appropriate for the scope of this study. Given this limitation, assessing georectification accuracy of various methods by incorporating DEMs to evaluate positional error for mountainous landscapes is a subject that needs to be further explored, particularly when very steep valley walls and hillslopes dominate the landscape.

- Identification of gullies on aerial photographs covering a mountainous environment in this study was hindered by shadowing effects and image grayscale where these features were often confused with bare soil surfaces. This is often more problematic when older aerial photographs are used for the analysis and there are no recorded locations (i.e. geographical coordinates) of these features. To overcome this drawback, appropriate image enhancement techniques and methods able to enhance detection and to discriminate difference between these features need to be studied.

- Predicting future land cover condition is a probability based procedure that used past land cover change transitions. Often, changes that have occurred are independent of each other due to their independent complex causal factors, yet the Markov Chain model assumes that these changes are dependant. Moreover, effects of factors triggering some of these changes are not incorporated due to their complexity and the particular scope of this study.

- Although site-specific factors such as slope, development of road networks, and proximity to some resources can be incorporated into change prediction models like the Markov Chain model to improve their accuracy, socio-economic related issues that play a vital role in shaping the landscape cannot often be integrated into these models. These issues include: perception of the community towards different grazing resources and grazing practices; factors influencing decisions of how land is used and how these decisions are made; external socio-economic and political factors such as migration, dependency on social grants and its effect on how land resources is used; the effects of policies on such landscapes; and the question of whether factors such as high levels of poverty are indeed some of the underlying causes of land degradation. These are among many other areas that need further inter-disciplinary research. To fully understand any landscape changes (e.g. land degradation trends) occurring within an environment like Okhombe, requires appreciation of such complex issues that have shaped the landscape as it is currently known.

5.4 Concluding remarks

It is concluded that at a catchment scale, the spatial and temporal patterns of land degradation in Okhombe have not significantly changed. Despite this, the study has demonstrated the role played by of land cover changes and conversions in influencing patterns of land degradation. Furthermore, the study has also shown how landscape characteristics and effects of land use management (especially slope and access gates) influence prevalent patterns of land degradation, often described as being severe in communal areas. Therefore, locations of access gates leading into the rangeland have implications on the development of features of land degradation and thus the placement of gates in the future needs to be done bearing in mind the erosion susceptibility of the land unit on which gates are to be built.

The study contributes to other studies currently being undertaken to better understand changes in the communal grazing area of Okhombe in order to address challenges faced in cattle grazing management in communal areas.

References

Acocks, J.P.H., (1988), 'Veld types of South Africa'. *Memoir of the Botanical Survey of South Africa*, 57, pp. 146.

Aguilar, M.A., Agüera, F., Aguilar, F. J. and Carvajal, F., (2008), 'Geometric accuracy assessment of the orthorectification process from very high resolution satellite imagery for Common Agricultural Policy purposes', *International Journal of Remote Sensing*, 29:24, 7181 – 7197.

Akbari, H., Rose, L.S., and Taha, H., (2003), 'Analyzing the land cover of an urban environment using high-resolution orthophotos', *Landscape and Urban Planning*, 63, pp. 1 – 14.

Angassa, A., (2002), 'The effect of clearing bushes and shrubs on range condition in Borana, Ethiopia', *Tropical Grasslands*, 36, pp. 69 – 76.

Archer, E.R.M., (2004), Beyond the "climate versus grazing" impasse: using remote sensing to investigate the effects of grazing system choice on vegetation cover in the eastern Karoo, *Journal of Arid Environments*, 5, pp. 381 – 408.

Boone, R.B., Lackett, J.M., Galvin, K.A., Ojima, D.S., and Tucker III, C.J., (2007), 'Links and broken chains: evidence of human-caused changes in land cover in remotely sensed images', *Environmental Science and Policy*, 10, pp. 135 – 149.

Bradley B.A., and Mustard, J.F., (2006), 'Characterizing the landscape dynamics of an invasive plant and risk of invasion using Remote Sensing', *Ecological Applications*, 3, pp. 1132 – 1147.

Boone, R.B., Lackett, J.M., Galvin, K.A., Ojima, D., S., and Tucker III, C.J., (2007), 'Links and broken chains: evidence of human-caused changes in land cover in remotely sensed images', *Environmental Science and Policy*, 10, pp.135 – 149.

Budde, M.E., Tappan, G., Rowlanda, J., Lewisb, J. and Tieszen, L.L., (2004), 'Assessing land cover performance in Senegal, West Africa using 1-km integrated NDVI and local variance analysis', *Journal of Arid Environments*, 59, pp. 481 – 498.

Camp, K.G.T., (1999), The Bioresource Groups of KwaZulu-Natal., Cedara reports N/A/99/12-17.

Campbell, J.B., (2002), Introduction to Remote Sensing, Taylor and Francis, New York.

Chen, S. and Rao, P., (2008), 'Land degradation monitoring using multi-temporal Landsat TM/ETM data in a transition zone between grassland and cropland of northeast China', *International Journal of Remote Sensing*, 29:7, pp. 2055 – 2073.

Chikhaoui, M., Bonn, F.,Bokoye, A.I., and Merzouk, A., (2005), 'A spectral index for land degradation mapping using ASTER data: Application to a semi-arid Mediterranean catchment', *International Journal of Applied Earth Observation and Geoinformation,* 7, pp. 140–153.

Cots-Folch, R., Aitkenhead, M.J. and Martínez-Casasnovas, J, A. (2007) 'Mapping land cover from detailed aerial photography data using textural and neural network analysis', *International Journal of Remote Sensing*, 28:7, 1625 – 1642.

Coxhead I. and Oygard, R., (2007, unpublished), Land Degradation, Draft submitted for Copenhagen Consensus 2008.

de Castro, E.C., (2005), Aerial photo land cover classification of cerrado physiognomies: detailed or accurate maps, The Proceedings of the XII Brazilian Remote Sensing Symposium, Goiania, Brazil, 16-21 April 2005, INPE, pp. 1175-1181.

de Villiers, M.C., Pretorius, D.J., Barnard, R.O., van Zyl, A.J., and le Clus, C.F., (2002), Land Degradation Assessment in Dryland Areas: South Africa, ARC-Institute for Soil, Climate and Water, Pretoria.

DEAT, (2008), Agriculture-induced land degradation: a consideration Of key emerging issues that may impact the state of the Environment, Emerging Issues Paper: Land degradation, Department of Environmental Affairs and Tourism (DEAT), Pretoria.

Doytsher, Y., (2000), 'A rubber sheeting algorithm for non-rectangular maps', *Computers and Geosciences*, 26, pp. 1001 – 1010.

Dube, O.P., and Pickup, G., (2001), Effects of rainfall variability and communal and semi-commercial grazing on land cover in southern African rangelands, *Climate Research*, 17, pp. 195 – 208.

ESRI, (2007), *ArcGIS Desktop Help*, Environmental Systems Research Institute, Inc.

Everson, T.M., Everson, C.S. and Zuma, K.D., (2007), Community based research on the influence of rehabilitation techniques on the management of degraded catchments, Water Research Commission Report No. 1316/1/07, Pretoria.

Feranec, J., Hazeu, G., Christensen, S., and Jaffrain, G., (2007), 'Corine land cover change detection in Europe (case studies of the Netherlands and Slovakia)', *Land Use Policy*, 24, pp. 234 – 247.

Fensham, R.J., Bray, S.G. and Fairfax, R.J., (2007), 'Evaluation of aerial photography for predicting trends in structural attributes of Australian woodland including comparison with ground-based monitoring data', *Journal of Environmental Management*, 83, pp. 392 – 401.

Friedel, M.H., (1997), 'Discontinuous change in arid woodland and grassland vegetation along gradients of cattle grazing in central, Australia', Jou*rnal of Arid Environments*, 37, pp. 145 – 164.

Galvin, K.A., Boone, R.B., Smith, N.M., Lynn, S.J., (2001), 'Impacts of climate variability on East African pastoralists: linking social science and remote sensing', *Climate Research*, 19, pp. 161 – 172.

Garland, G., Hoffman, M.T. and Todd, S. (1999). Soil egradation. In: Hoffman. M.T., Todd, S., Ntshona, Z and Turner, S. (eds) Land Degradation in South Africa. Department of Environmental Affairs and Tourism, Pretoria.

Harrison, Y.A. and Shackleton, C.M., (1999), 'Resilience of South African communal grazing lands after the removal of high grazing pressure', *Land Degradation and Development*, 10, 225 – 239.

Harvey, K.R. and Hill, G.J.E., (2001), 'Vegetation mapping of a tropical freshwater swamp in the Northern Territory, Australia: a comparison of aerial photography, Landsat TM and SPOT satellite imagery', *International Journal of Remote Sensing*, 22:15,2911 – 2625.

Herwitz, S.R., Sandler, B. and Slye, R.E., (2000), 'Twenty-one years of crown area change in the Jasper Ridge Biological Preserve based on georeferenced multi-temporal aerial photographs', *International Journal of Remote Sensing*, 21(1), pp. 45 – 60.

Hester, A.J., Miller, D.R. and Towers, W., (1996), 'Landscape-scale vegetation change in the Cairngorms, Scotland, 1946 – 1988: Implications for land management', *Biological Conservation*, 77, pp. 41 – 51.

Hoffman, M.T, Todd S, Ntshona, Z. and Turner, S, (1999), *Land degradation in South Africa*, Department of Environment Affairs and Tourism, Pretoria.

Hoffman, M.T., and Todd, S., (2000), 'A national review of land degradation in South Africa: in influence of biophysical and socio-economic factors', *Journal of South African Studies*, 26, 4, pp. 742 – 758.

HLURB, (2007), Environmental Management: Slope, GIS Cookbook for LGUs, version 1.0, Housing and Land Use Regulatory Board (HLURB), Quezon City, Philippines, URL:http://www.cookbook.hlurb.gov.ph/0-02-table-contents, (Accessed: 17 March 2009).

Huang, W., Liu, H., Luan, Q., Jiang, Q., Liu, J. and Liu H. (2008), Detection and prediction of land use change in Beijing based on Remote Sensing and GIS, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Vol. XXXVII. Part B6b. Beijing 2008.*

Hudak, A.T., and Wessman, C.A. (1998), 'Textural analysis of historical aerial photography to characterize woody plant encroachment in South African savanna'. *Remote Sensing of Environment*, 66, pp. 317 – 330.

Hughes M.L., McDowell, P.F. and Marcus, W. A., (2006), 'Accuracy assessment of georectified aerial photographs: Implications for measuring lateral channel movement in a GIS', *Geomorphology*, 74, pp. 1 – 16.

Hurskainen, P. and Pellikka, P. (2004), Change detection of informal settlement using multi-temporal aerial photographs: the case of Voi, SE-Kenya, Proceedings of the 5th AARSE conference (African Association of Remote Sensing of the Environment), 2004.

IDRISI, (2006), IDRISI Andes Help, Clark labs, Clark University, MA., USA.

Institute for Commercial Forestry Research (ICFR) and School of Bioresources Engineering and Environmental Hydrology (BEEH), (2004), The Daily Rainfall Data Extraction Utility.

James Keay-Bright, John Boardman, (2009), 'Evidence from field-based studies of rates of soil erosion on degraded land in the central Karoo', *South Africa Geomorphology*, 103, pp. 455 – 465.

Jovanovic, V.M., Lewicki, S. A., Smyth, M.M., Zong, J. and Korechoff, R.P., (November, 1999), *Level 1 Georectification and Registration Algorithm Theoretical Basis,* Multi-angle Imaging Spectro-Radiometer, Jet Propulsion Laboratory, California Institute of Technology.

Kakembo, V., (2001), 'Trends in vegetation degradation in relation to land tenure, rainfall, and population changes in Peddie District, Eastern Cape, South Africa', *Environmental Management*, 28: 1, pp. 39 – 46.

Katz, M.M., chair. 1994. Interim report of the Commission of Inquiry into Certain Aspects of the Tax Structure of South Africa. Pretoria: Government Printer, 294 pp. 25.

Kaufmann, R.K. and Seto, K.C., (2001), 'Change detection, accuracy, and bias in a sequential analysis of Landsat imagery in the Pearl River Delta, China: econometric techniques, Agriculture', *Ecosystems and Environment*, 85, pp. 95 –105.

Keay-Bright, J., and Boardman, J., (2006), 'Changes in the distribution of degraded land over time in the central Karoo, South Africa', *Catena*, 67, pp. 1 – 14.

Lambin, E.F., (1997), 'Modelling and monitoring land-cover change processes in tropical regions', *Progress in Physical Geography*, 21, pp. 375–393.

Leica Geosystems (2003), *ERDAS Imagine TourGuide,* Atlanta, Georgia, GIS and Mapping.

Laliberte, A.S., Rango, A., Havstad, K.M., Paris, J.F., Beck, R.F., McNeely, R. and Gonzalez, A.L., (2004), 'Object-oriented image analysis for mapping shrub encroachment from 1937 to 2003 in southern New Mexico', *Remote Sensing of Environment*, 93, pp. 198 – 210.

Lillesand T.M., Kiefer, R.W., and Chipman J.W. (2004). Remote Sensing and Image Interpretation. John Wiley and Sons, Inc. New York.

Lu, D., Mausel, P., Brondizio, E. and Moran, E., (2004), Change detection techniques, *International Journal of Remote Sensing*, 25, 12, pp. 2365–2407.

Meadows M.E., and Hoffman, M.T., (2002), The nature, extent and causes of land degradation in South Africa: legacy of the past, lessons for the future? *Area*, 34:4, pp. 428–437.

Meadows, M.E., and Hoffman, M.T., (2003), ‘Land degradation and climate change in South Africa’, *The Geographical Journal,* 169:2, pp. 168–177.

Meadows, M.E., and Hoffman, M.T., (2002), ‘The nature, extent and causes of land degradation in South Africa: legacy of the past, lessons for the future?’ *Area*, 34, 4, pp. 428–437.

Morgan, R.P.C., (1979), Soil Erosion, Longman Group Limited, New York.

Munyati, C., (2000), ‘Wetland change detection on the Kafue Flats, Zambia, by classification of a multitemporal remote sensing image dataset’, *International Journal of Remote Sensing*, 21:9, pp. 1787–1806.

Okeke, F. and Karnieli, A., (2006), 'Methods for fuzzy classification and accuracy assessment of historical aerial photographs for vegetation change analyses. Part II: Practical application', *International Journal of Remote Sensing*, 27:9, pp. 1825 — 1838.

O'Meagher, B., du Pisani L.G. and White, D.H., (1998), ‘Evolution of drought policy and related science in Australia and South Africa’, *Agricultural Systems,* 57:3, pp. 231-258.

Palmer, A.R., and Tanser, F.C., (1999), Spatial diversity indices and landscape transformation in South Africa – can these be used to monitor degradation? The proceedings of the VIth International Rangeland Congress, Townsville, Queensland, Australia, July 19 - 23, 1999.

Palmer, A.V. and van Rooyen, A.F., (1998), ‘Detecting vegetation change in the southern Kalahari using Landsat TM data’, *Journal of Arid Environment*, 39, pp. 143 – 154.

Palmer, A.R, Kakembo, V., Lloyd, W., and Ainslie, A., (2004), Degradation patterns and trends in the Succulent Thicket, Proceedings of the Thicket Forum held at Zuurberg Inn, Addo Elephant National Park, May 2004.

Palmer, A.R., Killer, F.J., Avis, A.M., and Tongway, D., (2001), ‘Defining function in rangelands of the Peddie district, Eastern Cape, using Landscape Function Analysis’, *African Journal of Range and Forage Science,*18, pp. 53–58.

Rocchinia, D. and Di Rita, A. (2005), ‘Relief effects on aerial photos geometric correction’, *Applied Geography*, 25, pp. 159 – 168.

Seppe C., (2004), Photo mapping of Great Britain: A growing opportunity? *The Cartographic Journal,* 41(2), pp. 95–100.

Shaker, A., Shi, W. and Barakat, H.(2005), ‘Assessment of the rectification accuracy of IKONOS imagery based on two-dimensional models’, *International Journal of Remote Sensing*, 26:4, pp. 719 – 731.

Shalaby, A. and Tateishi, R. (2007), ‘Remote sensing and GIS for mapping and monitoring land cover and land-use changes in the Northwestern coastal zone of Egypt’, *Applied Geography*, 27, pp. 28–41.

Slama, C.C., Theurer, C., Henriksen, and S.W. (Eds.), (1980), Manual of Photogrammetry, 4th edition. American Society of Photogrammetry, Falls Church, VA.

Sonneveld, M.P.W., Everson, T.M. and Veldkamp, A., (2005), 'Multi-scale analysis of soil erosion dynamics in KwaZulu-Natal, South Africa'. *Land Degradation and Development*, 16, pp. 287 – 301.

DWAF, (2008), South Africa's review report for the sixteenth session of the United Nations Commission on Sustainable Development (csd-16), Department of Water Affairs and Forestry, Pretoria.

Tanser, F. C., and Palmer, A. R., (1999), 'The application of a remotely-sensed diversity index to monitor degradation patterns in a semi-arid, heterogeneous, South African landscape', *Journal of Arid Environments*, 43, pp. 477–484.

Tau, M., (2005) *Grazing management in the communal rangelands of the Upper Thukela, KwaZulu-Natal*. Masters thesis, University of KwaZulu-Natal.

Temme, A.J.A.M., (2008), *Understanding landscape dynamics over thousands of years: combining field and model work. With a case study in the Drakensberg Foothills, KwaZulu-Natal, South Africa*, PhD thesis, Wageningen University, The Netherlands.

Thurow, T.L., (2005), Grazing practices, soil conservation. In Wilson G. Pond and Alan W. Bell, 2005 (eds), Encyclopedia of Animal Science, Marcel Dekker, Inc. pp. 499 – 501.

Valentin, C., Poesen, J., and Yong Li, (2005), 'Gully erosion: Impacts, factors and control', *Catena*, 63, pp. 132–153.

van Jaarsveld, A.S., and Biggs, H.C., (2000), 'Broad participation enhances initial steps towards a South African ecosystem observatory system (LTER)', *South African Journal of Science*, 96, pp. 63 - 66.

Versveld D.B., le Maitre D.C., and Chapman, R.A., (1998), Alien invading plants and water resources in South Africa: a preliminary assessment, Water Research Commission, Pretoria.

Wessels, K.J., Prince, S.D., Malherbe, J., Small, J., Frost, P.E., and VanZyl, D., (2007), 'Can human-induced land degradation be distinguished from the effects of rainfall variability? A case study in South Africa', *Journal of Arid Environments*, 68, pp. 271 – 297.

Wessels, K.J., Prince, S.D., Frost, P.E., and van Zyl, D., (2004), 'Assessing the effects of human-induced land degradation in the former homelands of northern South Africa with a 1 km AVHRR NDVI time-series', *Remote Sensing of Environment*, 91, pp. 47–67.

Winkler, G., (2003), Image analysis, random fields and Markov chain Monte Carlo methods: a mathematical introduction, Springer Verlag, Berlin, Heidelberg, New York.

Xie, H., Hicks, N., Keller, G. R., Huang, H. and Kreinovich, V., (2003), 'An IDL/ENVI implementation of the FFT-based algorithm for automatic image registration', *Computers and Geosciences*, 29, pp. 1045 – 1055.

Yanalak, M., Ipbuker, C., Coskun, M. Z. and Bildirici, I. O., (2005), 'New Local Transformation Method: Non-Sibsonian Transformation', *Journal of Surveying Engineering,* 131:1 (1), pp. 1-8.

Zhan, X., Sohlberg, R.A., Townshend, J.R.G., DiMiceli, C., Carroll, M.L., Eastman, J.C., Hansen, M.C. and DeFries, R.S., (2002), 'Detection of land cover changes using MODIS 250 m data', *Remote Sensing of Environment*, 83, pp. 336 – 350.

Appendices

Table 1 Paired sample statistics showing the calculated *t* value for the selected pairs of GCPs categories used by the spline transformation method

Paired Samples Statistics

	Pairs of GCPs Categories	Mean	n	Std. Deviation	Std. Error Mean	*t* value	Degree of freedom
Pair 1	**10**	27.1224	50	24.436249	3.4558075	4.24	49
	20	14.644426	50	14.390404	2.0351104		
Pair 2	**10**	27.1224	50	24.436249	3.4558075	6.63	49
	50	9.1432314	50	10.868672	1.5370623		
Pair 3	**20**	14.644426	50	14.390404	2.0351104	5.165	49
	50	9.1432314	50	10.868672	1.5370623		
Pair 4	**30**	13.077532	50	14.689899	2.0774654	3.862	49
	50	9.1432314	50	10.868672	1.5370623		
Pair 5	**40**	10.93177	50	11.167313	1.5792966	3.689	49
	50	9.1432314	50	10.868672	1.5370623		
Pair 6	**18**	15.888738	50	15.836979	2.2396871	1.939	49
	20	14.644426	50	14.390404	2.0351104		
Pair 7	**20**	14.644426	50	14.390404	2.0351104	0.663	49
	25	14.243118	50	14.841717	2.0989358		
Pair 8	**15**	20.177108	50	21.625751	3.0583431	2.474	49
	18	15.888738	50	15.836979	2.2396871		
Pair 9	**10**	27.1224	50	24.436249	3.4558075	2.68	49
	15	20.177108	50	21.625751	3.0583431		
Pair 10	**10**	27.1224	50	24.436249	3.4558075	4.24	49
	20	14.644426	50	14.390404	2.0351104		
Pair 11	**20**	14.644426	50	14.390404	2.0351104	2.301	49
	30	13.077532	50	14.689899	2.0774654		

Table 2 The number of access gates within each slope class. Their total number and percentage for each slope class are also provided

	Period	Total number of Access gates	SC1	SC2	SC3	SC4	SC5	SC6	SC7
	1945	**23**	0	2	2	11	6	2	0
	1962	**16**	0	3	4	8	1	0	0
	1976	**16**	1	2	3	9	1	0	0
	1992	**19**	0	5	5	7	2	0	0
	2004	**12**	0	1	1	10	0	0	0
Total Access gates		**86**	**1**	**13**	**15**	**45**	**10**	**2**	**0**
% access gates per SC			1.2	15.1	17.4	52.3	11.6	2.3	0.0