LAND DEGRADATION IN LESOTHO: A SYNOPTIC PERSPECTIVE

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Thesis presented in partial fulfilment of the requirements for the degree of Master of Natural Science at the University of Stellenbosch

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April 2005

DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Signature:

Date:

ABSTRACT

Land degradation in Lesotho is undermining the finite resource on which people depend for survival. Use of satellite imagery has been recommended for monitoring land degradation because remotely sensed data enable monitoring of large areas at more frequent intervals than intensive ground based research. Various techniques have been developed for land cover change detection. In the present study, vegetation changes were identified by image differencing, which involved finding the difference between the earlier date NDVI image and the later date image. NDVI images are among products that are generated from the NOAA AVHRR sensor to provide information about the quantity of biomass on the earth's surface. The resulting NDVI change data showed land areas that had experienced vegetation loss, which were identified as *potentially* degraded. The change data were combined with other data sets to determine how potentially degraded areas were influenced by different environmental variables and population pressure. These data sets included land cover, ecological zones, elevation, soil and human and livestock populations. By integrating NDVI data with ancillary data, land degradation was attributed to both demographic pressure and biophysical factors. Widespread degradation was detected on the arable parts of the Lowlands where cultivation was intensive and human settlements were extensive. Signs of grassland depletion and forest decline were also evident and were attributed to population expansion, overgrazing and indiscriminate cutting of trees and shrubs for firewood. Extensive biomass decline was also associated more with soils in the lowlands derived from sedimentary rocks than soils of basalt origin that occur mostly in the highlands. Significant degradation was evident on gentle slopes where land uses such as cultivation and expansion of settlements were identified as the main causes of the degradation. There was evidence of greater vegetation depletion on north and east-facing slopes than on other slopes. The depletion was attributed to the fragility of ecosystems resulting from intense solar radiation. The study demonstrated that NOAA AVHRR NDVI images could be used effectively for detecting land cover changes in Lesotho. However, future research could focus on obtaining and using high resolution data for detailed analysis of factors driving land degradation.

Key words: land degradation, vegetation loss, soil, altitude, slope, aspect, population density, satellite imagery, NOAA AVHRR NDVI, change detection.

OPSOMMING

Die agteruitgang van die bodem in Lesotho is besig om diè skaars hulpbron waarop die mense vir oorlewing steun, in gevaar te stel. Die gebruik van satellietbeelde word aanbeveel vir die monitor van bodemagteruitgang omdat hierdie tipe beelde die moniteer van groot gebiede oor korter tydsintervalle moontlik maak en dus meer kostedoeltreffend is as navorsing wat op veldwerk berus. Verskeie tegnieke word aanbeveel vir die opsporing van verandering in grondbedekking. Tydens hierdie studie is veranderinge in plantegroeibedekking geïdentifiseer deur beeldverskille wat beteken dat die verskil tussen ‘n vroeëre beeld en ‘n latere beeld gevind moes word. NDVI beelde is van die produkte wat deur die NOAA AVHRR sensor genereer word om inligting te verskaf i.v.m. die biomassa op die aardoppervlak. Hierdie data het aangedui watter gebiede ’n verlies aan plantegroeibedekking ondergaan het en dus as potensiëel gedegradeer beskou kan word. Dié data i.v.m. plantegroeiverandering is gekombineer met ander datastelle om vas te stel hoe die potensiëel gedegradeerde gebiede deur verskillend omgewingsveranderlikes en bevolkingsdruk beïnvloed is. Hierdie datastelle sluit in bodembedekking, ekologiese sones, hoogte bo seespieël, gronde en menslike- en dierlike bevolkings. Deur die NDVI data met die bykomende data te ïntegreer, is bevind dat bodemagteruitgang toegeskryf kan word aan demografiese druk asook biofisiese faktore. Daar is wydverspreide bodemagteruitgang in die bewerkbare gedeeltes van die Laaglande waar verbouing intensief beoefen word en waar baie mense woon. Daar is ook tekens dat die grasveld en woude agteruitgaan weens bevolkingsgroei, oorbeweiding en die onoordeelkundige afkap van bome en struike vir vuurmaakhout. Aansienlike afnames in biomassa word ook meer dikwels met gronde in die Laaglande afkomstig van afsettingsgesteentes geassosieër as met gronde afkomstig van basaltgesteentes. Betekenisvolle agteruitgang kan duidelik gesien word op geleidelike hellings waar verbouing en stedelike nedersettings geïdentifiseer is. Daar is ook tekens dat die agteruitgang van die plantbedekking meer ernstig is op hellings met ’n noord- of suidaansig as op ander hellings. Hierdie agteruitgang word toegeskryf aan die broosheid van ekosisteme as gevolg van groter uitdroging weens meer intense sonsbestraling. Die studie demonstreer data NOAA AVHRR beelde effektief gebruik kan word om veranderings in grondbedekking op ’n regionale skaal te spoor. Toekomstige narvosing kan egter

fokus op die verkryging en gebruik van hoë-resolusie data vir ‘n meer gedetailleerde ontleding van die faktore wat vir die agteruitgang van die bodem verantwoordelik is.

Sleutelwoorde: bodemagteruitgang, plantegroei, grond, hoogte, helling, aansig, bevolkingsdigtheid, satellietbeelde, NOAA AVHRR NDVI, veranderingsopsporing.

ACKNOWLEDGEMENTS

I wish to thank Professor HL Zietsman for his insight throughout the thesis. I would also like to acknowledge Mr D van Zyl of the Agricultural Research Council, Institute for Soil, Climate and Water (ARC – ISCW), for providing the satellite data essential for this thesis. I am grateful for the assistance of Mr L Bulane from Lesotho Meteorological Services (LESMET), for making Lesotho rainfall data available to me. My thanks also to Carlos: I barely had time for you but you never gave up on me. I thank my friends for their endless love and support despite the distance that separates us. To my family: our prayers have been heard, I am finally getting my degree.

ACRONYMS

ARC-ISCW	Agricultural Research Council – Institute of Soil, Climate and Water
AVHRR	Advanced Very High Resolution Radiometer
CSIR	Council for Scientific and Industrial Research
ETM	Enhanced Thematic Mapper
ISCGM	International Steering Committee for Global Mapping
LESMET	Lesotho Meteorological Services
LAI	Leaf Area Index
MDTP	Maluti Drakensberg Transfrontier Project
MSS	Multispectral Scanner
NDVI	Normalised Difference Vegetation Index
NES	National Environment Secretariat
NIR	Near Infrared Radiation
NOAA	National Oceanic and Atmospheric Administration
NPP	Net Primary Productivity
SAHIMS	Southern Africa Humanitarian Information Management Service
SPOT	Systeme Pour l'Observation de la Terre
UN	United Nations
UNCOD	United Nations Conference on Desertification
UNEP	United Nations Environmental Programme
WMO	World Meteorological Organisation

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CHAPTER 1: LAND DEGRADATION

Introduction of the thesis commences with a definition of land degradation and its causes. Problems of land degradation at global, regional and national scales are also indicated, with special attention on drought, desertification and soil degradation processes. Then the land degradation situation in Lesotho is highlighted to show the need for a countrywide approach to studying the phenomenon. The latter sections are dedicated to methods used for monitoring the land surface and the success with which satellite imagery has been used in this regard. A methodology adopted for monitoring land degradation in Lesotho is described and reported on.

1.1 THE PROBLEM OF LAND DEGRADATION

Much of the earth is degraded, is being degraded or is at risk of degradation (Barrow 1991), therefore it is not surprising that environmental degradation has become an increasingly critical issue worldwide. Briefly, environmental degradation is caused by pollution, overexploitation of natural resources, deforestation, global warming, unsustainable agricultural practices, habitat destruction and loss of biodiversity. It follows then that degradation manifests itself in the decline of the quality of air, land and water. Dumanski & Pieri (2000:93) define land as 'The combined resources of terrain, water, soil and abiotic resources'. The definition was modified to exclude water resources and hence made more suitable to adopt in the present study because the study is not concerned with degradation of water. The focus of the study is specifically on land degradation, a phenomenon that has received considerable attention because of the threat it poses to environmental quality and human health.

Land degradation adversely affects the potential productivity of land. It is driven by the interaction of various climatic characteristics and ecologically unsustainable human activities (Sommer, Hill & Megier 1998). Various studies have identified causes of land degradation as: droughts, desertification, soil salinity and water logging, (Behera et al. 1988), overgrazing, deforestation, unsustainable agricultural practices (Ayoub 1997), conversion of rangeland to cropland, and uncontrolled expansion of urban and rural settlements at the cost of arable land (Khresat, Rawajfih & Mohammad 1998). In short, key aspects of land degradation are anthropogenic activities, drought, desertification and soil degradation. Each of these key aspects will be discussed in subsequent sections.

1.1.1 Drought

Drought is a climatic event that frequently occurs in arid, semi-arid and dry sub-humid lands. The World Meteorological Organization (WMO) (1975) defines drought as ‘a deficit of rainfall in respect to the long term mean, affecting a large area for one or several seasons or years that drastically reduces primary production in natural ecosystems and rainfed agriculture’. Rainfall deficit is the most important climatic variable indicating the presence and severity of drought. Rainfall shortages cause a decrease in water supply to levels that are insufficient to fulfill requirements for domestic, agricultural, industrial and ecological water demands.

Impacts of drought are evident in the state of soil and vegetation and are most severe in landscapes that have been destabilized by anthropogenic pressure. The Sudano Sahelian zone located between latitudes 10^o N and 20^o N and extending from Cape Verde in the west to Somalia in the east, is a good example of a region severely affected by drought. The area has received much international attention and is said to be undergoing severe desertification, which, among other factors, is attributed to prolonged drought (Obia 1997). The following overview of desertification is important in attempting to understand implications of drought.

1.1.2 Desertification

Desertification implies the spread of desert-like conditions and in a decline in the biological productivity of land. At the United Nations Conference on Desertification (UNCOD) (1977:265), desertification was defined as ‘a reduction of the land production potential in arid, semi arid and dry sub-humid zones, that may ultimately lead to desert-like conditions’. The modified version of the definition accepted at the Earth summit in Rio de Janeiro (United Nations 1992:244), describes desertification as ‘land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors including climate variation and human activities’. The definition shows that desertification is not only attributed to climatic factors but also to inappropriate land use. In addition, other non-climatic variables that contribute to desertification include soil structure and texture, topography and vegetation types that are characteristic of an area. Desertification can be regarded as a form of land degradation aggravated by drought, physical factors and land use pressure. In addition to desertification, it is important to discuss soil degradation in the study of land degradation.

1.1.3 Soil degradation

Soil is considered degraded if anthropogenic [sic] or natural processes occurring in soil have lowered the potential quantity and quality of biomass production (Snakin, Krechetov, Kuzovnikova, Alyabina, Gurov & Stepichev 1996), which may ultimately cause land to become unproductive. The authors divide soil degradation processes into physical, chemical and biological degradation. Physical degradation includes compaction, erosion, surface sealing, and other phenomena that affect plant roots and water movement. Chemical degradation refers to salinization, acidification, loss of organic matter, loss of nutrients, pesticide accumulation and accumulation of toxic elements. Biological degradation entails the loss of biodiversity and optimum proportion of different species of soil microorganisms, and soil contamination by pathogenic microorganisms. Soil degradation can also manifest itself as soil erosion in the form of water and wind erosion (Bojo 1996). Soil erosion is a normal process that entails weathering of the landscape and is largely controlled by climate, topography, soils and vegetation cover (Wickens 1997). Accelerated erosion, however, occurs when human and livestock pressures exacerbate the normal processes of erosion.

The preceding subsections show that drought, desertification and soil degradation are intricately linked to land degradation. On the basis of the relationship and for the purposes of the present study, in subsequent discussions, land degradation should be regarded as a phenomenon that can be equated with desertification, is brought about by drought and human activities, and manifests in soil degradation. Moreover, land degradation implies disturbance of vegetation leading to decrease in vegetation cover and species diversity. As a result vegetation serves as the main indicator of land deterioration in the present study. Because of the negative implications of land degradation, concern has been mounting over the years as evidenced by extensive studies that have been conducted on the subject (Ayoub 1997; Barrow 1991; Bojo 1996). In the following section reference is made to some of the findings derived from studies of global land degradation.

1.1.4 Land degradation at global scales

Land degradation has been investigated extensively on different scales. Barrow (1991) studied global trends in land degradation; Bojo (1996), Abahussain, Abdu, Al-Zaburi, El-Deen & Abdul-Raheem (2002) and Fu (2003) investigated land degradation on a regional scale; whereas more localised studies were conducted by Meadows (2003) and Feoli, Vuerich & Zerihun (2002). The UNEP world atlas of desertification (UNEP 1992) showed that 70% of agricultural land in the world's dry lands is affected by various forms of land degradation. Every year about six million hectares of previously productive land in arid, semi-arid and dry sub-humid areas are said to lose their capacity to produce food. Moreover, UNEP emphasizes that Asia suffers the worst desertification. According to Fu (2002), 80% of the East Asia zone has been affected by widespread land degradation.

UNEP also asserts that North America and Africa are by far the worst off with 76% and 73% respectively of their dry lands degraded. Barrow (1991) adds that as much as 26% of Africa's total land area has suffered, or is undergoing moderate or severe desertification. The assessment of Abahussain et al. (2002) of the state of desertification in the Arab region revealed that most of the land resources are either desertified or vulnerable to desertification, thus affecting food security and development in the region. Ablegawad (in Abahussain et al. 2002) estimated the total areas desertified and vulnerable to desertification in the region of about 86,7% of the total land area. In Ethiopia, Feoli, Vuerich & Zerihun (2002) found that pressure exerted on the environment by the growing human and livestock populations has exacerbated the rapid depletion of the natural resource base. Other studies show that most of southern Africa from the Western Cape to Southern Angola and central Mozambique is considered dry land susceptible to land degradation (Meadows 2003; Boardman, Parsons, Holland, Holmes & Washington 2003; Barrow 1991). Lesotho is one of the countries in southern Africa that is experiencing serious land degradation as will be illustrated in the section below.

1.1.5 Land degradation in Lesotho

Concern for land degradation in Lesotho dates back to the late 1800s when early missionaries reported the development of gullies caused by soil erosion (Couzens 2003). Today, the state of the land is described as critical and the country is known for its prominent soil erosion. Soil erosion is a major threat to the dependency of the Basotho on the land resources. Approximately 85% of the population derive their livelihood from agriculture (Makhale, Pers com 2005) and livestock rely heavily on rangelands for fodder. Soil erosion is further aggravated by the vulnerability of the country to drought and the setting in of desertification conditions.

Soil erosion on arable land is caused by unsustainable cropping practices and extension of cultivation to steep slopes (Reizeboz & Chakela 1985). The authors reported that increase of livestock herds has also resulted in overgrazing and degradation of rangelands. Furthermore, the conversion of woodlands and shrublands into croplands and built-up areas has caused a substantial loss of vegetation cover thus contributing to soil erosion. An estimated 0,25% of arable land is lost each year to soil erosion (Moyo & O'Keefe 1993) and it is widely acknowledged that productive arable land has declined from 13% in the 1960s to 9% of the total land area due to soil erosion.

Various researchers have studied specific aspects of land degradation in Lesotho. Chakela (1981) investigated soil erosion and reservoir sedimentation in two catchments namely, Roma valley and Maliele, using quantitative ground based survey methods. Other multidisciplinary research programmes such as the Maluti and Drakensberg Catchment Conservation Programme and the Lesotho Highlands Water Project Baseline Biological Surveys have reported on various aspects of environmental degradation. Degradation appears to be continuing unabated despite efforts to combat it (NES 1999). Part of the reason could be a poor understanding of the nature of degradation. An accurate assessment of the patterns and processes of land degradation is essential to avoid ineffective and impractical control strategies, and this could be achieved by the use of satellite imagery

1.2 LAND DEGRADATION FROM A SATELLITE PERSPECTIVE

The statistics cited in Section 1.1.4 on land deterioration in Africa are alarming. A number of such findings have been subject to much debate and as Bojo (1996) noted, subjective notions of the significance of land degradation in Africa vary from light-hearted dismissal to exaggerated alarmism. Stocking's (1995) opinion is that some figures are badly founded on extrapolation of measurements taken at one scale for estimates based on an entirely different scale. It follows then that some of the methods used to study land degradation were not appropriate if they yielded unreliable results. In contrast, methods using GIS and remote sensing have been found to be more reliable for mapping, monitoring and modelling terrestrial resources than most ground based studies. Subsequent sections show how satellite imagery has been used as a practical alternative to other methods for monitoring land resources and hence land degradation.

1.2.1 Use of satellite imagery for monitoring land resources

Wilkie & Finn (1996) define remote sensing as 'a process that measures a phenomenon without coming into contact with it… It is a physical or computer based representation of the radiation reflected from or emitted by terrain features or phenomena'. Remotely sensed data offer the means to extend the knowledge gained from intensive *in situ* ecological research to larger geographic areas, at more frequent intervals, and over a longer time span (Barrow 1991).

There has been widespread application of remote sensing to monitor the land surface. For instance, Edwards, Wellens & Al-Eisawi (1999) found satellite data a practical option for mapping and monitoring grazing resources in the Badia region, an area of about 11,201km^2. Traditional ground based survey and mapping techniques were considered inappropriate for mapping such a large area. Similarly, Hudak & Wessman (2000) assessed deforestation in Malawi with the aid of satellite data and found the spatial extent of the Landsat images viable for studying vegetation structure. Although remote sensing derived data have been proven useful in monitoring land degradation, in some poor countries the technology has not been fully exploited. This shortcoming possibly results from the high costs of purchasing remotely sensed images, the accompanying hardware and software, as well as the costs of training personnel to process the data. Lesotho experiences similar problems, but the technology is also under-exploited because of insufficient understanding of its potential. Lastly, land degradation research in Lesotho tends to constitute isolated ground based studies (Section 1.1.5) and risks being duplicated.

1.2.2 Recent use of satellite imagery in Lesotho

The government of Lesotho has begun to acknowledge the benefits of remote sensing although the awareness is in its early stages. A notable government initiative is the recent campaign by the Land Use Planning division to prevent illegal encroachment on agricultural land. At the time of writing, Spot satellite imagery was being evaluated for four identified pilot areas in the country namely, Thaba-Tseka, Butha-Buthe, Ha Makhalanyane and Mohale's Hoek. The present study will focus on land degradation from a broader point of view by combining satellite derived data with other GIS data sets such as vegetation, land cover, soil, elevation and land use. The reason for this is that the complex factors governing terrestrial degradation cannot be understood fully from isolated studies alone. What is required is a synoptic perspective in which the rate and extent of land degradation can be understood within the national context. To add another dimension, Khawlie, Awad, Shaban, Bou Kheir & Abdallah (2002) found remote sensing techniques to be optimum tools in studying mountain regions because the rugged nature of mountains makes data gathering a daunting task. Since Lesotho is characteristically mountainous, the problem of difficult terrain can be overcome by use of remotely sensed data.

Information required to monitor land deterioration can be obtained from studying vegetation behaviour (Belward 1991). The development of vegetation cover is one of the primary indicators for land degradation (Hostert, Röder & Hill 2003) mainly because vegetation is dynamic in responding and adapting to prevailing environmental conditions. Vegetation will serve as a good indicator of land deterioration because the decline in Lesotho's vegetation cover has been associated with accelerated soil degradation and reduced arable land as evidenced by widespread gullies throughout the country. Remote sensing change detection in Lesotho can provide deeper insight into the causes and consequences of land degradation and the information can serve as a strong scientific basis for land management strategies. Having established the background for studying land degradation in Lesotho, the aim and objectives of the study will be presented in the next section.

1.3 AIM AND OBJECTIVES

This study addresses how spatially explicit information about land degradation processes can be derived from satellite data. The study capitalizes on the 1km^2 low spatial resolution of AVHRR imagery. The AVHRR sensor captures images of large geographical areas and therefore enables monitoring of land resources at global, regional and national scales. In view of this, AVHRR imagery was found to be suitable for nationwide monitoring of land degradation in Lesotho and by analogy, to obtain a synoptic perspective of degradation in the country.

A synoptic view of land degradation was achieved by specifying the following objectives:

- To determine vegetation change between 1989 and 1999 in Lesotho using satellite derived NDVI images
- To demarcate degraded areas
- To quantify the extent of the degradation
- To determine causes and factors underlying land degradation.

The preceding sections showed the need for a countrywide study of land deterioration in Lesotho and how the present study sought to monitor the degradation. In subsequent sections, attention will be focused on the methodology used for achieving the objectives.

1.4 RESEARCH FRAMEWORK

The present section presents the framework of the study and subsequently the methodology used for analysing land degradation between 1989 and 1999 in Lesotho. The research framework is outlined by defining the report structure and then describing the contents of the thesis. The study is summarised in Figure 1.1 of the research design.

The research report comprises seven chapters. The first chapter introduced the theme of the research by defining land degradation and associated problems. Common causes of land degradation were discussed as the basis for determining causes of degradation in Lesotho. Thereafter problems concerning the deterioration of land resources in Lesotho were emphasised. Then the need for monitoring land degradation in the country using satellite data was indicated and lastly the objectives were stated.

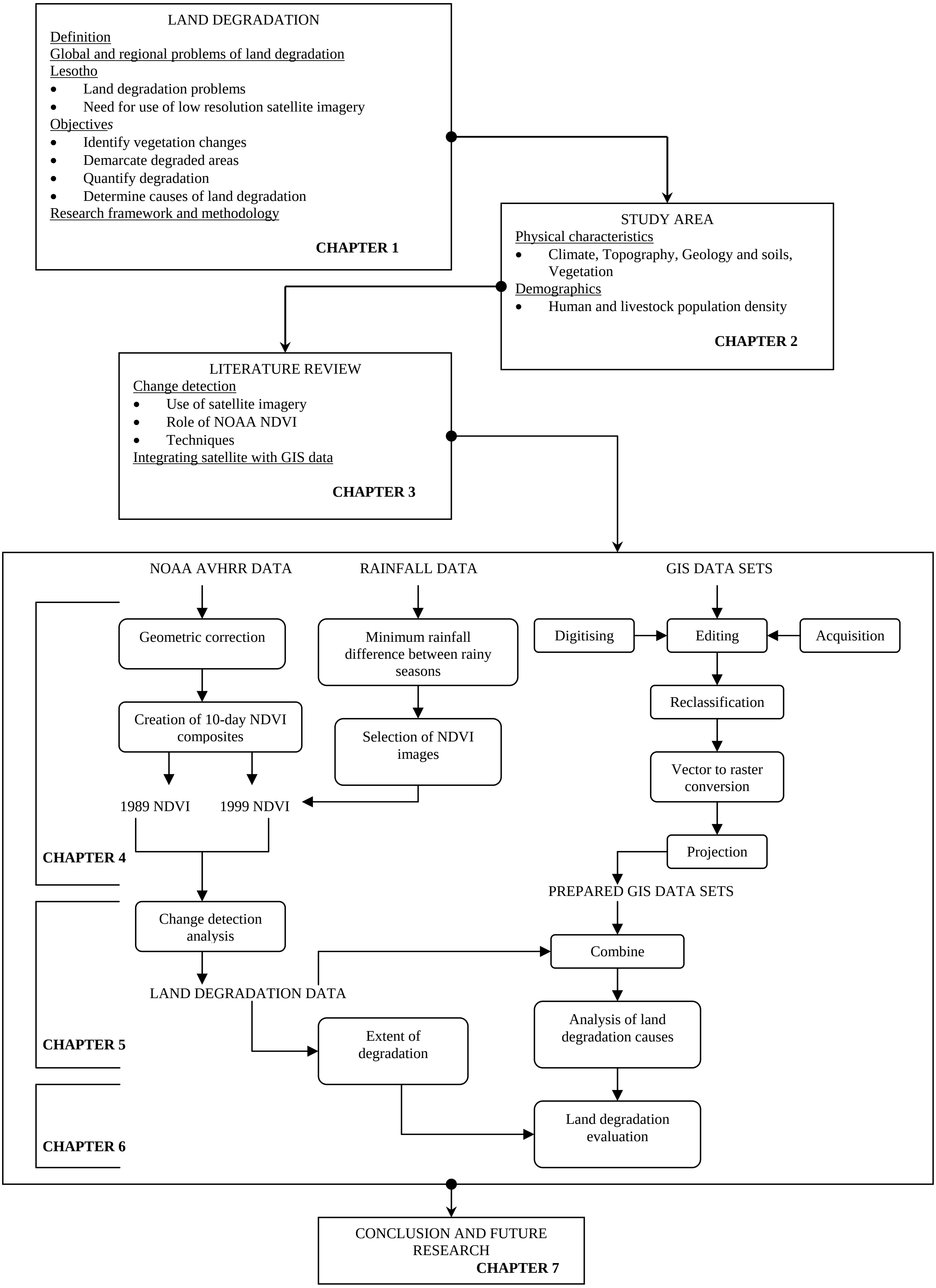

Figure 1.1 Research design

The second chapter describes the study area in terms of climate, topography, soils and vegetation as well as human and livestock population densities. The characteristics were considered important in the present study because they influence land degradation.

The theoretical background of the study is presented in Chapter 3. The chapter mainly reviews methods applied in previous studies involving use of satellite imagery to monitor land cover changes. Emphasis was given to the pivotal role of vegetation indices, especially AVHRR NDVI in change detection research.

The fourth chapter is about procedures used to prepare available datasets for analysis of land degradation. The methodology used to achieve the study objectives is presented in Chapter 5 of the report. In brief, analyses methods involved determining vegetation loss from 1989 to 1999 and then identifying degraded areas, based on NDVI decline. The resulting data were then combined with other data sets, using grid overlay operations to find causes of land degradation. Results of the analyses are presented and discussed in the sixth chapter, where the extent of degradation and influential factors are evaluated. The conclusion and recommendations follow in Chapter 7.

1.5 SUMMARY

Land degradation is undermining the finite resource on which people depend for survival. Recent developments have shown that satellite imagery is a much better alternative for gathering data than conventional intensive fieldwork, especially when studying areas of considerable spatial extent and areas that are not easily accessible. Based on findings from previous studies, the current research attempts to provide a suitable methodological framework for deriving useful information on landscape change and associated causal factors. Researchers have demonstrated that remotely sensed data can provide a satisfactory perception of the true nature and extent of land degradation. Discussions thus far have justified the need for undertaking the present study. In the next chapter the study area will be described prior to reviewing methodologies used for analysing land degradation.

CHAPTER 2: STUDY AREA

This chapter describes physical and demographic characteristics of the study area, Lesotho. The purpose of providing such background was to draw attention to aspects of the country that were relevant to the present study. Lesotho is a mountainous country of about 30,355 km^2 enclaved within the Republic of South Africa (Figure 2.1). The country lies between 28^o and 31^o south latitude, and between 27^o and 30^o east longitude (NES 2000), and is divided into 10 administrative districts. In subsequent sections details of the country's physical and demographic variables will be provided.

Figure 2.1 Location of Lesotho

2.1 CLIMATE

An overview of Lesotho's climate is relevant to this study because climatic changes, especially drought conditions, have been associated with land degradation. Climate in Lesotho is said to be temperate. The average annual rainfall over the entire country ranges from about 500mm to 1300mm. The highest rainfall values are recorded in the northern part of the highlands, while in the Lowlands, mean annual rainfall ranges between 650mm and 850mm with a general increase from west to east. Reizebos & Chakela (1985) indicate that, apart from the spatial variation in rainfall, there are two types of temporal variation namely, a large variation from year to year and seasonal variation. Moreover, over 85% of the rainfall is concentrated in the summer months from October to April, the peak of the rainy season being from December to February.

Temperatures in the Lowlands range from a mean maximum of 28^{o}C or higher in February, which is the warmest month, to a minimum of 2^{o}C (Moyo & O'Keefe 1993) in the coldest winter period from June to July. The range in the highlands is much greater with temperatures falling below 0^{o}C in winter. In winter, from May to September, snow is common in the highlands at elevations above 3000m above sea level (a.s.l.), and occasionally also falls in the Lowlands. Frost occurs frequently in the mountains but in the Lowlands it is typically experienced about 80 days per year. Reizebos and Chakela (1985) show that although the temperature regime may form a serious constraint for annual crops, it is especially the occurrence of frost early in spring or in fall that forms an important climatic factor determining agricultural potentials. In addition, the authors point out that high temperatures can be hazardous to some crops especially in combination with the occurrence of limited amounts of available soil moisture. For most of the year, the Lesotho climate is characterized by clear skies with a mean 8,8 hours of daily sunshine (NES 2000) with great intensity because of the high altitude and the low levels of atmospheric pollution.

The foregoing discussions show that major climatic variables in Lesotho that reduce land and agricultural potential are low temperatures, snow and frost especially in the highlands, high temperatures during summer and lack of soil moisture resulting from rainfall shortages. Recent droughts resulting from insufficient rainfall have also contributed to land deterioration in the country. These necessitated an assessment of the possible role of the climatic variables on land degradation during the study period.

2.2 TOPOGRAPHY

Lesotho's mountainous terrain influences land degradation because soil erosion in the country is often attributed to torrential rain and runoff on mountain slopes. It was therefore important to provide an overview of the nature of the country's terrain. The country's minimum and maximum altitudes range from approximately 1388m to 3482m a.s.l.. The country is divided into four ecological regions: Lowlands, Foothills, Mountains and the Senqu (Orange) river valley as shown in Figure 2.2.

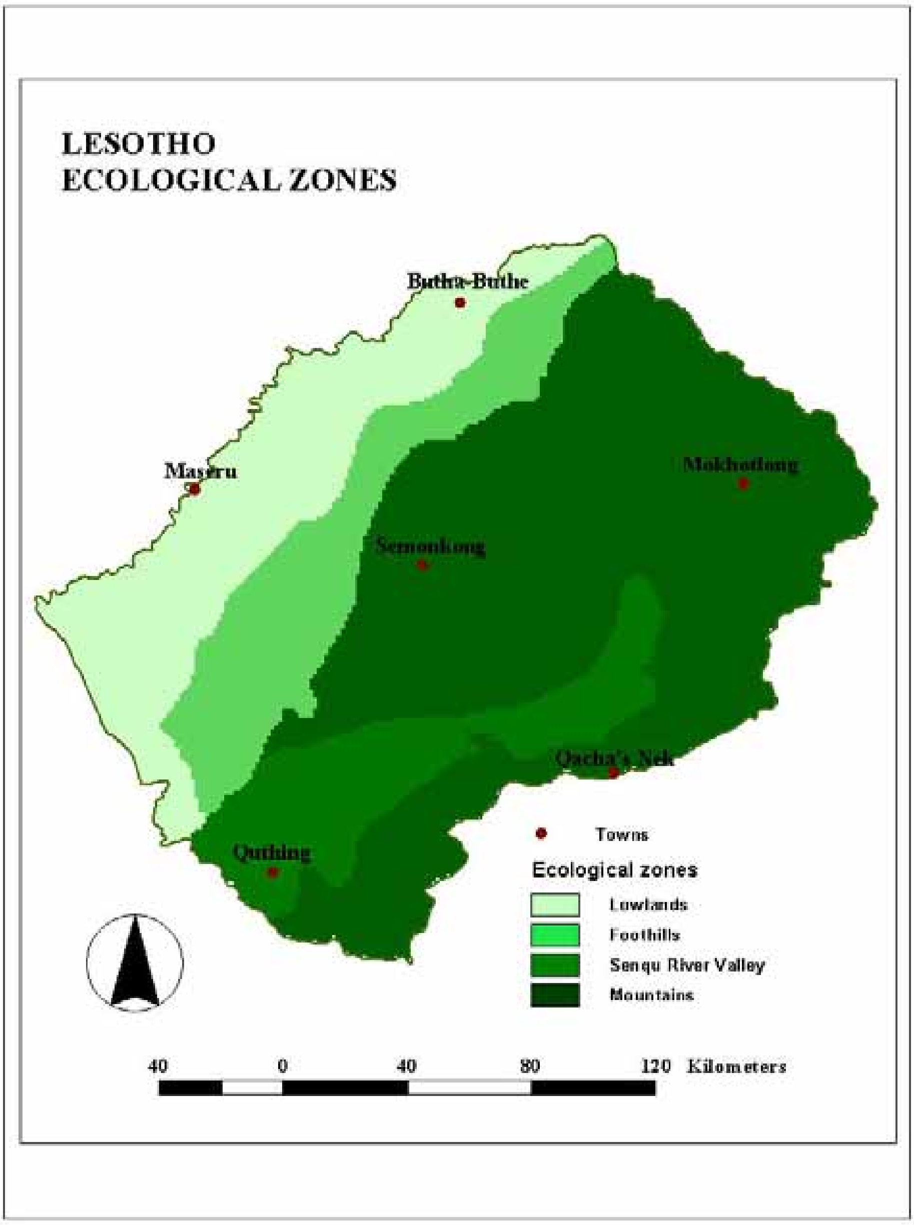

Figure 2.2 Ecological zones of Lesotho
Source: SAHIMS 1999

The Lowlands region is defined as the area of western Lesotho, which lies at an altitude of between 1400m and 1800m a.s.l. and comprises 20% of the total land surface. The eastern boundary of the Lowlands is the western edge of the Foothills zone, situated at an altitude between 1800m and 2200m a.s.l. and extends mainly across flat plateau to steep slopes that rise to the zone's eastern boundary. Foothills comprise 14% of Lesotho's total land surface. The Senqu River Valley constitutes about 12% of the total land surface and stretches into the southeastern mountain region of the country. The mountain zone, also known as the Maluti, occupies the remaining 54% of the land area. The Maluti occupy the region distinguished by altitudes ranging from 2200m to 3484m a.s.l.. The significance of studying land degradation within ecological zones and assessing the role of slope on land degradation was based on the topographical features discussed above.

2.3 GEOLOGY AND SOILS

The description of Lesotho's soil types and geological structure provides the basis for relating soil properties and parent material to land degradation. As a result, this section highlights characteristics of Lesotho soils that aided in further analysis of land degradation. Geological formations of Lesotho are shown in Figure 2.3 while Figure 2.4 shows the country's soils modified from Carrol and Bawden (1966). Below is an account of the country's geology according to Reizebos & Chakela (1985).

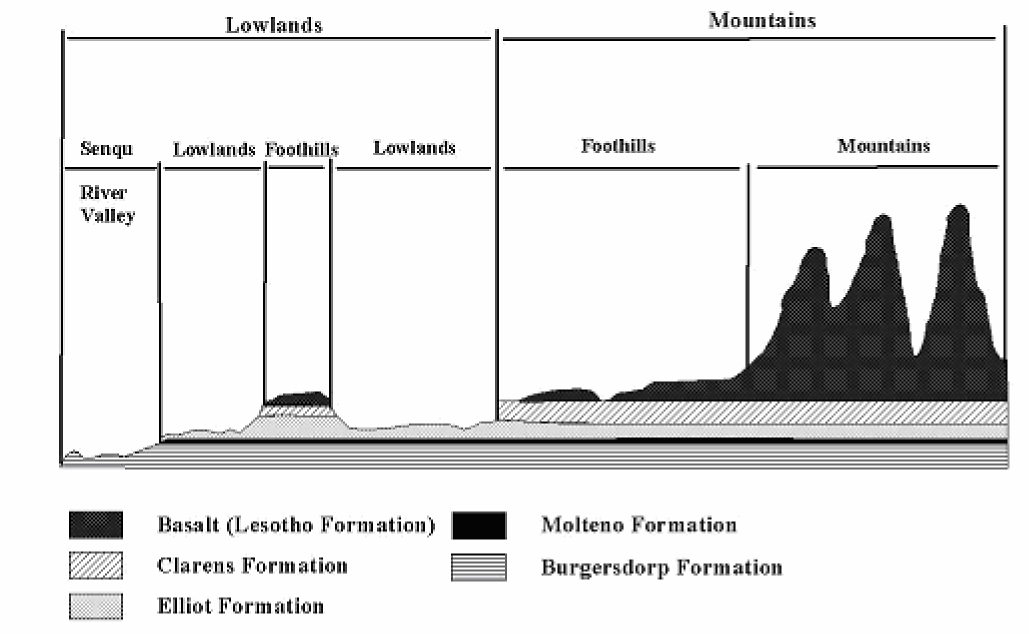

Figure 2.3 Geological formations of Lesotho

Source: Modified from Chakela & Reizebos 1984

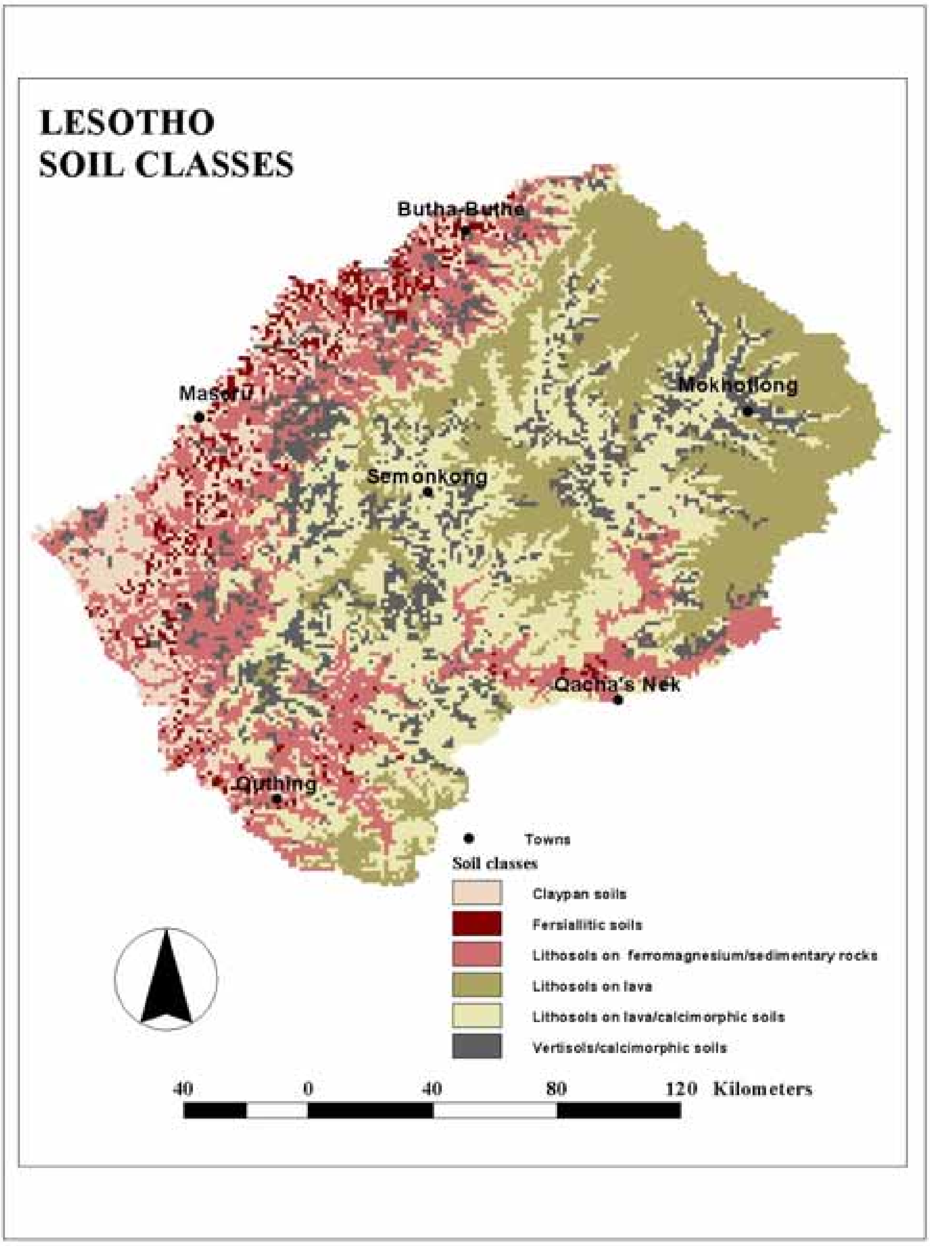

Figure 2.4 Simplified soil classes of Lesotho

Source: Modified from Carrol & Bawden 1966

Outcropping rocks in Lesotho may be divided into sedimentary strata and basaltic lavas. The sedimentary rocks are found in the western and southern part of the country. The oldest formation is the Burgersdorp Formation consisting of shales, mudstones and some buff sandstone. On top of this formation is the Molteno Formation with coarse white arkosic grits and gritty sandstones, mainly pebbly with occasional thin shaly sandstones and bluish mudstones. On the Molteno sediments is the Elliot Formation, characterized by mudstone shales and medium to fine grained sandstones. The Elliot Formation underlies the whole of Lesotho and outcrops over most of its Lowlands. The Clarens Formation is a massive, very fine grained sandstone, resting on the Elliot Formation. The Lesotho Formation consists of massive basaltic lava flows and reaches a thickness of up to 1500m. The lavas form the mountain area and outcrops occur over 73% of the surface of Lesotho.

The soils of Lesotho have been studied and grouped into different levels of detail by various authors. According to the classification of Carrol & Bawden (1966), lithosols are the dominant soil type in Lesotho (Figure 2.4). Generally, Lesotho soils are either of sedimentary or basaltic origin. Soils of sedimentary origin are more common in the Lowlands whilst those derived from basalt and dolerite origins are more common in the mountains. Mixtures and variations occur throughout the country. In addition, most soils in the flatter and gently sloping areas tend to be moderately deep to deep and well drained while mountain soils tend to be more shallow and stony. Furthermore, the principal arable soils of the Lowlands and Foothills are yellowish red to yellowish brown loams with sandy loam topsoil. The soils are moderately fertile and slightly acid and are prone to wind and water erosion.

2.4 VEGETATION

Vegetation is the primary indicator of land degradation in the current study and hence it was important to provide an overview of vegetation types found in Lesotho. Low & Rebelo (1996) described three main vegetation zones found in Lesotho: the Highveld, Alti-mountain and Afro-mountain grassland zones (Figure 2.5). The general characteristics of each biome were described by Low & Rebelo (1996) as follows. The Highveld grassland zone corresponds approximately to the Lowlands and the lowest part of the Senqu River Valley. Plant distribution in the zone is influenced by terrain form and associated with soil depth, soil moisture, rockiness of soil surface and grazing intensity. To a lesser degree, the distribution is influenced by soil types. The Highveld grassland area is mainly used for cultivation of wheat and maize with dairy farming also being important.

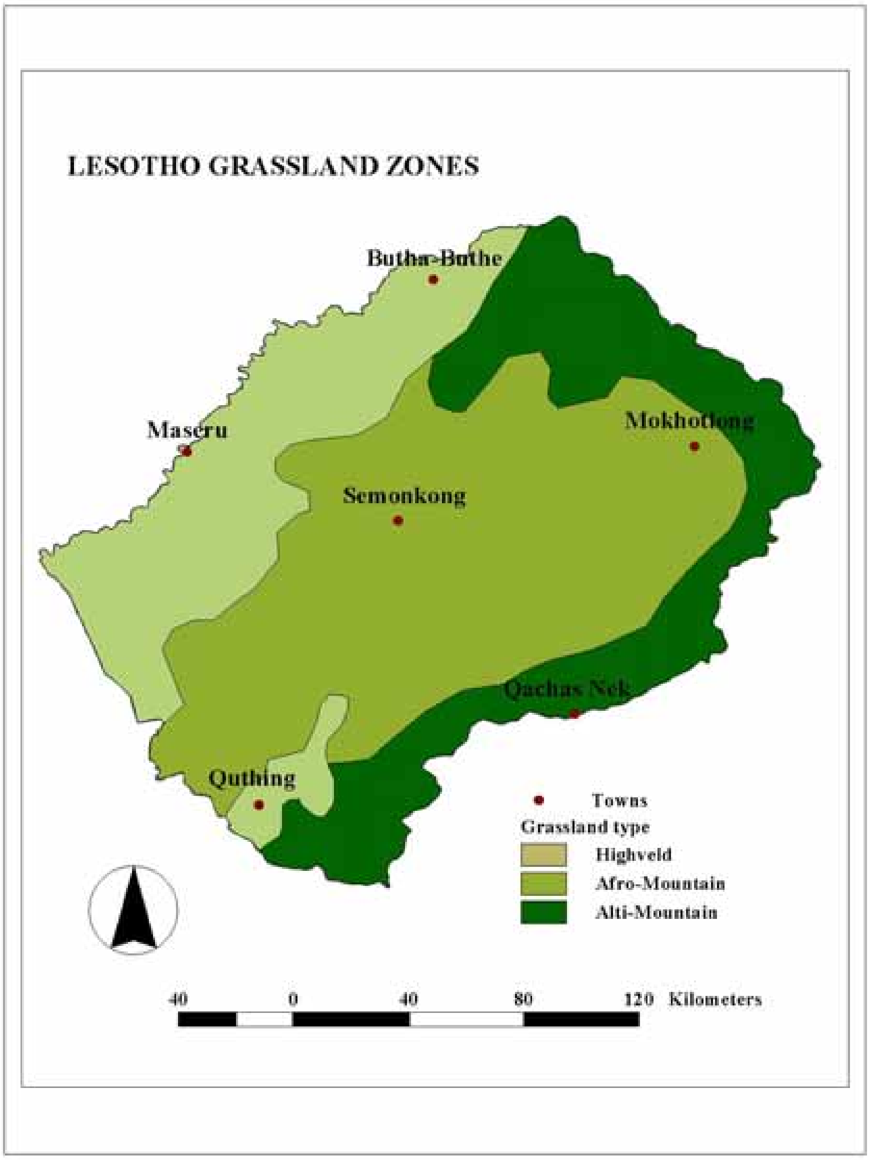

Figure 2.5 Main grassland vegetation zones of Lesotho
Source: Modified from Low & Rebelo 1996

The Afro-mountain grassland type occurs in Lesotho at altitudes between 1700m and 2500m a.s.l. and higher. It consists of the remainder of the Maluti, the upper Senqu River Valley and the Foothills. A large number of plant communities occur within the biome because the rugged topography creates a variety of habitats with some forest encroachment appearing locally. The Afro-mountain grassland vegetation type is mainly used for grazing.

The Alti-mountain grassland occurs on the steep, treeless, alpine upper mountain region of Lesotho over 2500m a.s.l.. The area of this grassland type is determined by extremely high altitudes with associated low temperatures and snow during winter. The zone is also experiencing Karoo encroachment because of excessive grazing pressure coupled with relatively low rainfall. The area is mainly used for grazing by livestock and is an important water catchment area. Within the three zones can be found small areas of woodland, forest and wetlands. The grassland biomes have been considerably modified by current land uses comprising livestock grazing, with large parts taken over for cultivation. The vegetation types found within each grassland zone are given in Table 2.1.

Table 2.1 Lesotho vegetation zones

MAIN VEGETATION ZONES WITH SUBCOMPONENTS	AREA (Km^2)	% OF TOTAL
HIGHVELD GRASSLAND		
Grassland & rocky outcrops	1 230	4,1
Gully eroded areas	600	2,0
Indigenous forest	20	0,07
Exotic wooded areas	20	0,07
Plantation forest	90	0,30
Shrubland & thickets	200	0,61
Cultivated land	3 700	12,2
Wetlands	10	0,03
Open water	10	0,03
Settlements & Roads	1 200	4,0
AFRO MOUNTAIN GRASSLAND		
Grassland & rocky outcrops	7 020	23,2
Indigenous forest	20	0,07
Exotic wooded areas	-	-
Plantation forest	10	0,03
Shrubland & thickets	4 800	15,8
Cultivated land	3 800	12,6
Wetlands	10	0,03
Open water	10	0,13
Settlements & Roads	400	1,3
ALTI MOUNTAIN GRASSLAND		
Grassland & rocky outcrops	6 680	22,0
Shrubland	400	1,3
Wetlands	40	0,13
TOTAL	**30 300**	**100,0**

Source: NES 2000: 13

The major crops grown in Lesotho are maize, wheat, sorghum, beans and peas. Most crops are grown during summer. Wheat and peas are grown in summer and winter. Winter wheat and peas are grown in the Lowlands while summer wheat and peas are grown in the mountains. Crop production is characterized by a high proportion of subsistence farming, with over 70% being consumed and not marketed. Lesotho is experiencing a decline in agricultural crop production (Makhale Pers com 2005). The decline is attributed to drought, low crop yields, low fertilizer application rates, low and erratic rainfall, hail, frost, soil erosion and mismanagement of agricultural land.

2.5 HUMAN POPULATION AND LIVESTOCK DENSITIES

According to the 1996 population census, the total population was estimated at approximately 2 million people (Bureau of Statistics 1996). About 30% of the total population lives in the highlands, 20% in the Foothills and the rest in the Lowlands (Moyo & O'Keefe 1993). According to the authors, Maseru, with a population of 477 599 (Table 2.2), has the largest concentration of population and the highest annual growth rate of about 7%. Table 2.2 also shows population densities per km^2 of both the total land surface and arable land. According to the 1996 census, average population density was approximately 816 persons per $km^2$of arable land area. Figure 2.6 shows human population densities per km^2 of total land by district.

Table 2.2 Human population densities by district

DISTRICT	TOTAL POPULATION	TOTAL AREA (km^2)	POPULATION DENSITY (PEOPLE PER km^2	ARABLE AREA (Km^2)	POPULATION DENSITY PER ARABLE km^2
Butha-Buthe	126907	1767	72	105	1209
Leribe	362339	2828	128	424	855
Berea	300557	2222	135	326	922
Maseru	477599	4279	112	463	1032
Mafeteng	238946	2119	113	531	450
Mohale's Hoek	206842	3530	59	396	522
Quthing	140641	2916	48	155	907
Qacha's nek	80323	2349	34	85	945
Mokhotlong	89705	4075	22	161	557
Thaba Tseka	133680	4270	31	176	760
Lesotho	**2157539**	**30355**	**75**	**2822**	**816**

Source: Modified from Bureau of Statistics Lesotho, 1996

The livestock sector consists of cattle, sheep, goats, horses, donkeys, pigs and poultry. The first three dominate the sector. Livestock densities per km^2 of total area by district, expressed as Large Stock Units (LSU) are shown in Figure 2.7, which was created with the aid of numbers shown in Table 2.3. Livestock are kept for both

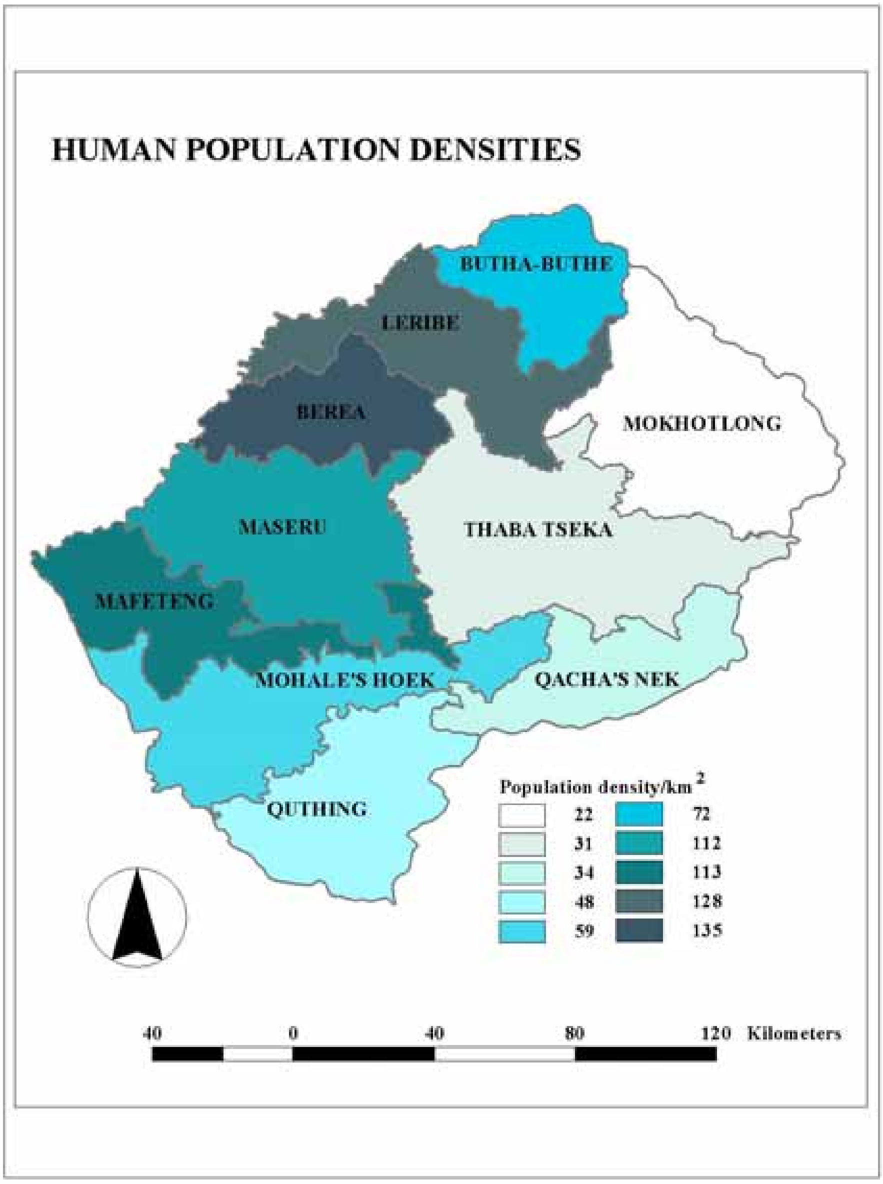

Figure 2.6 Lesotho human population densities by district

economic and social reasons. Cattle are raised mostly for socio-cultural ceremonies such as bride wealth. Sheep are of the Merino type and are raised for the sale of their wool, for slaughter and ceremonial purposes. Goats are of the Angora type and are raised for the sale of mohair and ceremonial purposes too. Horses and donkeys are used for transporting goods while horses are used for human transportation.

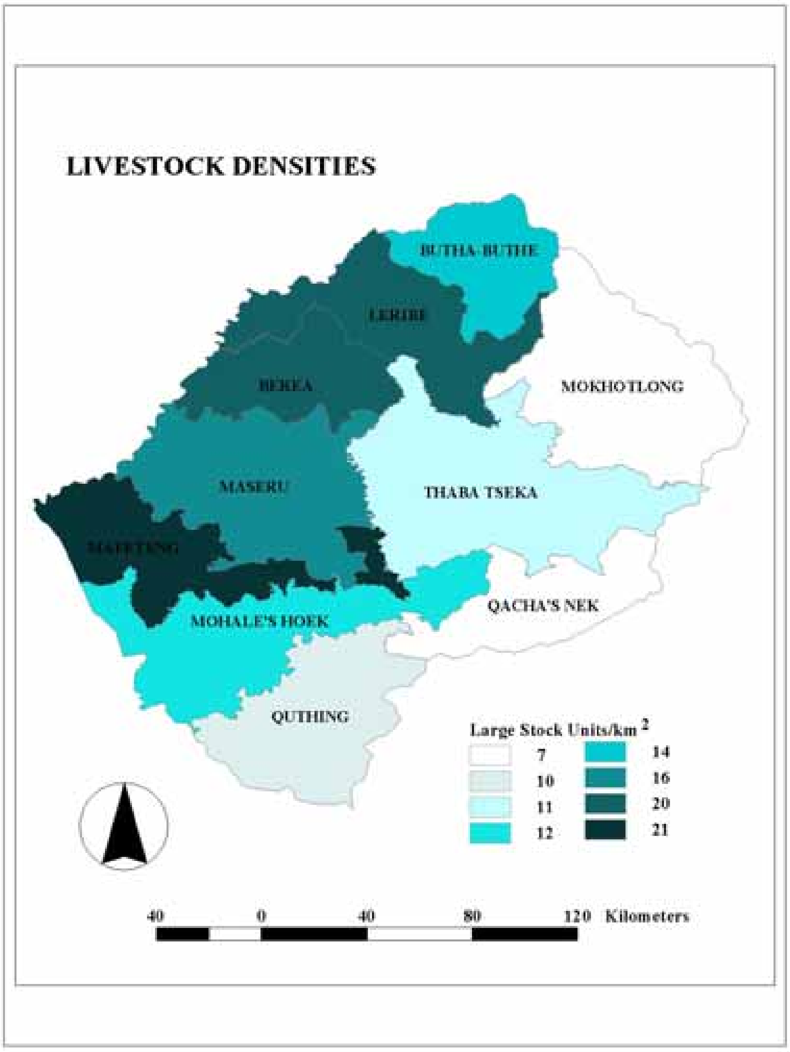

Figure 2.7 Lesotho livestock densities by district

Table 2.3 Stock numbers per district

DISTRICT	CATTLE	SHEEP	GOATS	AVERAGE LSU	LSU/km^2
Butha-Buthe	47134	56907	76200	26682	14
Leribe	117400	106600	81200	57824	20
Berea	96300	63800	58000	45704	20
Maseru	127600	191000	136000	69629	16
Mafeteng	83100	147700	62700	44873	21
Mohale's Hoek	67500	104000	176800	43622	12
Quthing	49500	99500	100100	31280	10
Qacha's nek	29400	56300	44400	17485	7
Mokhotlong	48800	147800	69200	31455	7
Thaba Tseka	88400	135500	133000	50853	11
TOTAL	**755134**	**1109107**	**937600**		

Source: Modified from Bureau of Statistics Lesotho, 2000

2.6 SUMMARY

Variables relevant to the study of land degradation in Lesotho have been identified. They are biophysical, climatic and demographic elements of the environment. The variables have been selected to aid in determining patterns and causes of land degradation in Lesotho. Vegetation plays a central role in the study because it serves as the indicator of land degradation. The following chapter provides the theoretical background of the study and will highlight the role of vegetation in change detection research.

CHAPTER 3: REVIEW OF LITERATURE

This chapter reviews previous studies that were undertaken for change detection analysis. The main themes of the chapter include satellite remote sensing, vegetation and vegetation indices as well as techniques used for change analysis. An overview of satellite remote sensing is important in understanding processes of creating satellite imagery. A discussion of the role of vegetation in change detection is relevant because land degradation analysis in the present study was based on the use of vegetation indices derived from satellite imagery. The last sections of the chapter establish a suitable methodology for use in the present study by evaluating techniques applied in other similar studies.

3.1 INTRODUCTION

In the last three decades, remote sensing technologies have evolved dramatically to include a suite of earth orbiting satellite systems designed for the observation of the earth's resources. Early satellites such as the coarse spatial resolution NOAA AVHRR, started operating in 1960 and were designed for meteorological observation purposes. Civilian remote sensing of the earth's surface from space began in 1972 with the launch of the medium resolution Landsat Multispectral Scanner System (MSS), followed by the Thematic Mapper (TM) and later the Enhanced Thematic Mapper (ETM+) systems. The last two decades have seen a proliferation of satellites subsequent to the launch of the SPOT and IRS series of satellites. Recently, high spatial resolution sensors, such as IKONOS 2, QUICKBIRD 2 and ORBVIEW 3, have been developed. The section below presents concepts of remote sensing and processes by which satellite sensors acquire images of the earth's surface.

3.1.1 Concepts of satellite remote sensing

Remote sensing obtains information about an object, area or phenomenon by measuring electromagnetic radiation (EMR). EMR emitted by the sun covers a broad range of wavelengths that includes high frequency short wavelength gamma rays, X-rays, ultraviolet, visible light, infrared (IR) and microwaves, and low frequency, long wavelength radio waves (Wilkie & Finn 1996). The technology is based on the fact that objects on earth reflect or emit radiation, which can then be recorded by remote sensor instruments. Remote sensing instruments can be grouped generally into active or passive systems. Passive remote sensing utilizes instruments designed to sense energy reflected or emitted by the earth. Active sensors operate independently of solar or terrestrial radiation (Campbell 2002) and record reflection of their own transmitted energy. The present study focused on principles of passive remote sensing because in the study, land degradation was monitored using satellite imagery generated by passive sensors. The sensors record energy in different bands of the electromagnetic spectrum, a property which is determined by the design of the instruments. For example, the Landsat TM is sensitive in seven spectral bands, which are found in the blue, green, red and far infrared channels of the spectrum. SPOT 4 images in four spectral bands that include green, red, near infrared and mid-infrared channels. A more comprehensive description of spectral properties of available sensors can be found in Campbell (2002). The author indicates that combinations of spectral bands for a specific purpose vary according to each study, season, geographic region and other factors so that a single selection of bands is unlikely to be equally effective in all circumstances. The AVHRR sensor detects radiation in 5 bands found in the visible, near and mid-infrared, and thermal infrared portions of the spectrum. The temporal resolution of the sensor is very high and the sensor orbits the earth 14 times a day at an altitude of 833km. In addition, the sensor has a spatial resolution of approximately 1.1km at nadir and generates 10 bit images. AVHRR data provide opportunities for studying and monitoring vegetation conditions in ecosystems including forests and grasslands (Kidwell 1995).

Advances in remote sensing have made the technology a valuable source of land cover and land use information, enabling a large selection of remotely sensed images based on spatial, spectral, temporal and radiometric resolution. Spatial resolution refers to the fineness of detail of a land area visible in an image and is usually depicted as a square grid cell or pixel. Spectral resolution relates to properties of a feature, expressed as the range of brightness values in a number of spectral bands that distinguish the feature from other features (Wilkie & Finn 1996). Temporal resolution refers to the frequency with which a remote sensing system can map and revisit areas. Lastly, radiometric resolution can be described as the ability of an imaging system to record many levels of brightness (Campbell 2002). Remotely sensed data are recorded in digital form and therefore a wide range of processing techniques are available to monitor land surface changes. The following section defines key aspects of the land surface, land cover and land use, and gives insight into the use of satellite imagery to monitor land surface change.

3.1.2 Land surface change and remote sensing

The earth's land surface can be described in terms of land cover and land use. Both land use and land cover changes affect ecosystem condition and function (Lunetta, Johnson, Lyon & Crotwell 2003) and hence necessitate landscape change research. Mulders (2001) asserts that land use provides more information on landscape status and therefore can be more informative than land cover. In support of the idea, Mendoza & Etter (2002) add that at different temporal scales, human land use activities are basic factors shaping landscape change. There are three broad types of land uses: agrarian uses (including forestry and agriculture), industrial-urban uses (settlements, industries), and conservation. Change processes involving these categories often lead to land degradation (Sommer, Hill & Megier 1998) and so it is important to investigate how land uses affect land degradation. It is important to note that land cover and not land use can be derived using remote sensing. As a result, studying land cover changes can facilitate land degradation analysis and aid in obtaining information about land uses associated with the phenomenon.

Multi-temporal analysis of satellite imagery has become effective for landscape change detection because of the high correlation between spectral variation in the imagery and land surface change. Digital change detection also allows identification of major processes of change (Mertens & Lambin 1999) and thus enables monitoring of land degradation. Vegetation is one of the most widely used land cover features that aid change detection. The next section will give a brief overview of the most important remote sensing methods used for measuring land cover change.

3.2 ROLE OF VEGETATION

Vegetation is the most commonly used indicator of land degradation in remote sensing based studies. To this end, vegetation indices are constructed to make it possible to study vegetation properties. These properties are discussed in Section 3.2.1 below. Studies of vegetation are founded on the characteristic low reflectance patterns of green vegetation in the visible portion of the spectrum (particularly red) and a strong reflectance in the near-infrared channel (NIR). Absorption of red light is important for plants to photosynthesize. The NIR light cannot be used by green plants for photosynthesis and has undesirable heating effects and hence low absorption is of advantage (Fogg 1968). Chlorophyll absorbs EMR at 0,62 to 0,7μm, giving the low reflection in the red band and reflects in the near infrared 0,74 to 431,1μm giving the high NIR reflectance (Dalezios, Domenikiotis, Loukas, Tzortiios & Kalaitzidis 2000). This forms the basis for vegetation indices.

3.2.1 Vegetation and NDVI

Vegetation detection by remote sensing mostly entails investigation of plant biomass (or phytomass), phenology, physiognomy, floristic composition, Net Primary Productivity (NPP) and leaf area to compute the Leaf Area Index (LAI). Biomass and phytomass refer to the total mass of vegetative tissue. Phenology is the study of temporal aspects of recurrent natural phenomena and their relation to weather and climate (Lincoln, Boxshall & Clark 1983) and often refers to seasonal vegetation changes (Campbell 2002). Physiognomy describes characteristic features, structure or appearance of vegetation. Plant species of a given area make up the area's floristic composition. NPP is the amount of carbon fixed by plants (Milesi, Elvidge, Nemani & Running 2003). LAI is the area of leaf surface per unit area of soil surface (Campbell 2002). The following section draws attention to different vegetation indices and their application in studying the plant properties in relation to land degradation. The indices are constructed using satellite data acquired by different sensors.

The most widely used index is the Normalized Difference Vegetation Index (NDVI). High values of NDVI are characteristic of areas with substantial proportions of healthy vegetation. The index is computed by dividing the difference of the NIR and visible (red) bands by their sum as given by the equation:

$$NDVI = (NIR - red)/(NIR + red)$$

Researchers have reported various findings using NDVI in a range of applications. For instance, Johnson, Roczen, Youkhana, Nemani & Bosch (2003) were able to map vineyard leaf area by computing LAI using NDVI derived from IKONOS imagery. The researchers found a significant relationship between ground and image based leaf area. The low resolution NOAA AVHRR NDVI also produced satisfactory results in the approximation of cotton yield and biomass (Dalezios et al. 2000). Holm, Cridland

& Roderick (2002) also attained a good correlation of ground based and remotely sensed estimates of phytomass in the arid shrublands of western Australia. The study proved NOAA NDVI to be a reasonable estimate of total phytomass and hence was considered an effective indicator of degradation in the area. A similar study by Archer (2004) showed that NOAA AVHRR derived NDVI can effectively detect biomass in the eastern Karoo of South Africa. Furthermore, a near to real-time monitoring of both herbaceous and woody plant biomass by Sannier, Taylor & Du Plessis (2002), using AVHRR NDVI, enabled the researchers to produce biomass maps for fire risk assessment. The reliability of Landsat MSS NDVI in estimating woody plant cover was demonstrated by Hudak & Wessman (2000) in the savanna woodland of Malawi since correlation between NDVI values and field measurements of percentage woody cover was significant. By contrast, Edwards, Wellens & Al-Eisawi (1999) found a poor correlation between field estimates of percentage vegetation cover with ATSR-2 and AVHRR NDVI data in the arid Badia region. Use of NDVI in the region was constrained by problems of low vegetation cover, highly reflective soils, shadow and non-photosynthetically active vegetation. The implication is that NDVI can be effective in monitoring vegetation across various climatic zones, but it performs better in areas with middle and higher vegetation densities. It is important to note that NDVI is a poor indicator and saturates at high biomass. With the foregoing examples of the use of NDVI to monitor the land surface, attention will be shifted to NDVI derived from the AVHRR sensor to show the relevance of applying the index in the present study.

3.2.2 AVHRR NDVI

The studies cited show applications of NDVI derived from varying resolution satellite sensors, including high resolution IKONOS, medium resolution Landsat TM and low resolution instruments such as NOAA AVHRR. The current study is concerned with extracting information about biomass and vegetation cover from NDVI produced from the NOAA AVHRR sensor. AVHRR derived NDVI has a low spatial resolution of $1km^2$ which enables coverage of large geographic areas. AVHRR NDVI data are a viable option for assessing land degradation over the whole area of Lesotho. The demonstrated reliability of NOAA NDVI in estimating biomass and vegetation cover render the NDVI data suitable for identifying changes in the grassland biomes of Lesotho. Although the index is likely to be ineffective in areas with sparse vegetation, it can be applied in Lesotho because of the country's characteristic temperate climate, which results in a sufficiently dense vegetation cover to be captured by satellite imagery. In essence, analysis of AVHRR NDVI images will be central to the present study of land degradation. It would also be helpful to correlate the NDVI data with ground based estimates of vegetation for validation purposes, but fieldwork will not be undertaken because of resource and time constraints. Where possible, the study will rely on personal communication with observers familiar with the study area to confirm findings of the present study. Having established a background for using coarse resolution NDVI data, it is necessary to review remote sensing analysis techniques that are applied to monitor landscape changes. Such evaluation attempts to put into perspective techniques best suited to analyse AVHRR NDVI images.

3.3 CHANGE ANALYSIS

The basic requirement for remote sensing change detection is the availability of imagery from at least two comparable dates which enable the same area of land to be observed. The images must register and have comparable levels of resolution to minimize errors that may be misinterpreted as change. Since multi-temporal techniques are built on single date processing techniques (Prenzel 2003), change analysis images are subjected to similar preprocessing operations that prepare the data for subsequent analysis. Most preprocessing operations can be categorized into radiometric calibration and geometric correction (Campbell 2002).

3.3.1 Image preprocessing

Geometric correction is a process of minimizing geometric distortions in an image caused by systematic and unsystematic sensor errors. Geometric errors such as mirror-scan velocity variance and panoramic distortion can be corrected using sensor characteristics and ephemeris data. An alternative technique uses common Ground Control Points (GCPs) to match image coordinates with map coordinates. GCPs are used to develop a mathematical transformation for rectifying an image. The transformations can be either linear or non-linear depending on the number of GCPs. A measure of the accuracy of transformation from one coordinate system to another is the Root Mean Square (RMS) error. In image rectification, resampling calculates pixel values for the rectified image. Resampling can be carried out by the nearest neighbour, bilinear interpolation or cubic convolution methods. The process of resampling can change the actual measured pixel values thus affecting the quantitative value of an image.

Radiometric preprocessing is performed to change the brightness values of an image from values measured by a satellite in order to minimize atmospheric, view and sun angle effects. The entire process of radiometric correction involves conversion of digital values recorded by a sensor to radiance, conversion of radiance to reflectance followed by atmospheric correction to remove effects due to absorption and scattering. Approaches to remote sensing change detection are either qualitative or quantitative. The former are used where the degree of change is to be assessed while the latter apply where change is to be measured. To this end, radiometric correction is carried out to normalize images to each other so that the images can be compared but not used for quantitative measurements. The following studies illustrate the types of preprocessing operations that can be performed on satellite derived data and the extent to which the operations vary in different studies.

Prior to monitoring desertification, Collado, Chuvieco & Camarasa (2002) co-registered two Landsat images of 30m spatial resolution, using 13 common control points. The calculated RMS error was within 0,27 pixels. The images were resampled to a common resolution of 50m since they were acquired from the MSS and TM sensors. In another change detection study, Vasconcelos, Mussa Biai, Araujo & Diniz (2002) geometrically corrected Landsat TM images by the image-to-map method, with a linear polynomial transformation and nearest neighbour sampling. Rees, Williams & Vitebsky (2003) and Hudak & Wessman (2000) performed both image-to-map and image-to-image registration in a time-series analysis of land cover changes. In the latter study, image-to-map registration followed by image-to-image registration was performed using 15 and 16 GCPs, which produced RMS errors of less that 0,5 pixel. Collado, Chuvieco & Camasara (2002) and Hudak & Wessman (2000) carried out similar methods of radiometric correction. The former transformed image digital values to reflectance and corrected atmospheric errors using a method based on adaptation of the dark object method. The latter corrected for atmospheric path radiance by subtracting band minimum values from within the darkest topographic shadow and then calibrated images to correct for different sun elevation angles and sensor gain or offset. In another study, Imbernon (1999) completed image preparation by using various filters to improve images for further analysis.

In summary, image preprocessing serves to minimize error for subsequent analysis. As a preliminary step, it is advisable to obtain images produced by the same sensor acquired on anniversary dates; with scenes captured under clear atmospheric conditions. The studies also show that accuracy of registration is not so much affected by registering of an image to another or to a map, but to a large extent by the number of GCPs as well as the transformation algorithm used. The more complex cubic convolution method requires a higher number of GCPs. The choice of resampling algorithm depends on its advantages over other algorithms. According to Campbell (2002) cubic convolution is the most widely used method although Kovalick (in Campbell 2002) found the nearest neighbour method to be computationally the most efficient of the methods. In addition, it is common practice to evenly distribute GCPs throughout an image to obtain good registration results. To this effect, in the current study, maps will be registered and rectified using algorithms that alter data the least. The significance of the discussion on resampling maps to the same resolution (Collado, Chuvieco & Camarasa 2002) is that multiple data sets derived from different sources will be brought to the same resolution for effective analysis. Radiometric calibration will not be carried out and the study will rely on corrections performed by the data supplier. Moreover, the generation of NDVI images compensates for the radiometric differences.

3.3.2 Techniques of change detection

Many techniques have been implemented to detect and record differences depicted in satellite images that may be attributable to landscape change. The methods comprise linear procedures that apply image algebra, classification routines for post-classification comparison, data transformation into vegetation indices and PCA, Change Vector Analysis (CVA) and subjective visual interpretation. Each of the methods are discussed in subsequent sections.

3.3.2.1 Post-classification comparison

Post-classification comparison starts with independent classification of multi-date images, followed by comparison of classified images. Two basic methods are supervised and unsupervised classification. The former uses information derived from a few areas of known identity to classify the remainder of an image. Various algorithms are implemented for supervised classification. Unsupervised classification searches for natural groupings of pixels based on their brightness in several spectral channels. The analyst then attempts to assign these natural classes to the user defined information categories (Campbell 2002).

Ringrose, Vanderpost & Matherson (1996) used a classification change analysis technique by classifying a single date Landsat TM image and later associating image data with field data. Although the researchers were able to identify areas depleted of vegetation, most land degradation studies favor multi-date images. Multi-temporal analysis is a more informative way of recording evolution of vegetation patterns over a specific time period than any other way using single date images. In the light of multi-temporal analysis, Vasconcelos et al (2002) identified important vegetation changes in Guinea Bissau from 1956 to 1998 by comparing Landsat TM images (classified with the maximum likelihood algorithm of supervised classification) with agro-ecological maps. The maps of the earlier period were used presumably because Landsat images of the time are not available. A potential source of error, however, lay in interpreting classified land cover maps that were generated using different cartographic methods and had inconsistent levels of detail. If study periods fall within the remote sensing era, Almeida-Filho & Shimabukuro (2002) argue that errors can be partially minimized by using multi-date images acquired by the same sensor.

Besides the time factor, the need for cloud free images can be a limiting factor in acquiring same sensor images as was the case in a study by Rees, Williams & Vitebsky (2003). The researchers required cloud free images that coincided with the peak of the growing season and had to choose Landsat TM and Landsat ETM+ images. Tømmervik, Hødga & Solheim (2003) show that other additional requirements pertaining to a specific study determine the choice of images. Following a selection of Landsat TM and Landsat MSS images, the authors found results of a hybrid classification that combined supervised and unsupervised classification satisfactory for monitoring vegetation cover changes. It is important to mention that, in some of the studies, PCA was applied to enhance information unique to individual spectral bands (Ringrose & Vanderpost 1996; Almeida-Filho & Shimabukuro 2002; Rees, Williams & Vitebsky 2003).

The preceding discussion highlights the selection of appropriate images as an important prerequisite in change oriented studies. The benefits of classification based methods are evident in the success with which areas of change were identified and mapped. The shortcomings of post-classification procedures are reviewed below mainly because they limit use of the methods for studying land degradation in Lesotho. Almeida-Filho & Shimabukuro (2002) recognised the difficulty of achieving similar classification accuracy for sets of multi-date images, despite image enhancement. In such cases, artifacts of classification are likely to be misinterpreted for land cover changes during comparison of classified images. Moreover, performing adequate accuracy assessment on historical data sets may be a daunting task in post-classification analysis (Yuan & Elvidge 1998) as demonstrated by Vasconcelos et al (2002). Effectively, reliable ground truth data is needed to validate results of image classification. The fieldwork necessary for the validation is sometimes time-consuming and according to Khawlie et al. (2002) is not always feasible especially in areas of difficult terrain. In view of the hindrances, it was necessary to review alternative techniques to apply in Lesotho. The ideal techniques need to take into account the limited availability of resources and the inaccessible mountainous landscape of the country.

3.3.2.2 Image differencing

In a pilot study by Yuan & Elvidge (1998), automated image differencing and NDVI differencing outperformed most other change detection techniques. The idea is supported by Hudak & Wessman (2000) who calculated NDVI from a time series of Landsat MSS images. The authors found NDVI differencing adequate for detecting woody canopy cover change even though the procedure was not automated. Bucini & Lambin (2002) also generated a change map by image differencing. They determined impacts of fire on land cover change by overlaying the change map with burnt area and vegetation maps. In an improved procedure, Collado, Chuvieco & Camarasa (2002) derived proportions of different land covers that compose mixed pixels by applying Spectral Mixture Analysis (SMA), prior to image differencing. The technique emphasized signs of degradation in a semi-arid territory of Argentina because the mixture of vegetation and soil detection is common in arid areas. Simple differences between unmixed images of sand and water provided relevant information on degraded areas in the study area.

Unlike post-classification comparison, image differencing methods do not require intensive computational and labelling requirements. Methods adopted in the study of Lesotho will be based on NDVI image differencing primarily because the index has been proven effective in detecting vegetation change. Another reason for this choice is based on the idea of Yuan & Elvidge (1998), who showed that NDVI image differencing outperforms other methods. Since Bucini & Lambin (2002) successfully combined a change map (derived from image differencing) with other data sets, the example of overlaying maps is considered relevant to relate land degradation to other variables pertaining to Lesotho. SMA is most suitable for applying in areas where problems of mixed pixels are likely to be experienced. However, the present study will focus on using conventional image differencing because there has not been previous research to show that mixed pixels in Lesotho are problematic. Existing techniques involving SMA will be left for future studies when remote sensing technology is fully adopted in the country.

3.3.2.3 Other methods

Kressler & Steinnocher (1999) used a variation of the SMA technique from that followed by Collado, Chivieco & Camarasa (2002), but the procedure was equally successful in highlighting modified land cover types. In the study, fraction images, calculated for end members after unmixing two NOAA-AVHRR images, were visually compared. Muller & Zeller (2002) and Mendoza & Etter (2002) also visually interpreted a time series of images with the aid of base maps for reference. The latter determined the rate of change through regression models. In a different study, Archer (2004) created NDVI profiles of land management units and through statistical regression analyses, established causes of land cover change. The studies indicate that statistical models in change research play a significant role, particularly when attempting to correlate observed changes with other environmental variables. On a different note, Palmer & Van Rooyen (1998) employed a method involving change vector analysis (CVA). CVA uses any number of spectral bands from multi-date satellite data to produce change images that yield information about both magnitude and direction of differences in pixel values. The researchers showed that, when integrated with ground reference information, CVA can help to identify sites experiencing changes that could be ascribed to desertification.

The studies point to use of satellite change data, with other data sets, to make land degradation analysis meaningful. The additional data sets representing different environmental variables, can form part of any investigation, in conjunction with the preliminary remote sensing methods used to derive change data. The ancillary data sets are normally acquired by methods other than remote sensing and the most prominent are based on GIS. Associations between remotely sensed and ancillary data are therefore commonly established within a GIS framework as shown below.

3.3.3 Integrating GIS with remote sensing

As previously stated, change detection usually culminates in associations being established between remotely sensed changes and other environmental variables, specifically biophysical and socio-economic. The objective is chiefly to determine factors that bring about the changes and to isolate those responsible for land degradation. A varied range of previous works shows that such relationships are typically established by bringing data from different sources together into a common database in a GIS and then performing spatial analyses. The type of spatial analyses and statistical models that can be applied vary according to study objectives and the context within which research is carried out.

Below is an account of the types of analysis carried out by integrating GIS and remote sensing techniques and data. Archer (2004) performed multivariate and spatial analyses to correlate NDVI (from which the influence of rainfall had been removed) with stocking strategies. Following fieldwork, farm boundaries in the study were digitized and superimposed on the NDVI data. Results of regressions showed that veld cover change is a response to land use associated with stocking practices. Ringrose & Vanderpost (1996) digitized topographic and infrastructure maps for input into GIS. Spatial analysis included creation of buffers around villages and boreholes, to find the extent to which human and livestock activity may be implicated in savanna vegetation changes. After overlaying the map showing buffers on a satellite derived vegetation map, human and livestock activities were found to be responsible for savanna vegetation depletion. With an emphasis on analyzing interactions between fires and land cover, Bucini & Lambin (2002) superimposed a land cover change map on a burnt area map. Results suggested that multivariate regression models improved analysis of spatial associations between landscape attributes and burning events.

More parameters were incorporated by Feoli, Vuerich & Zerihun (2002) by integrating socio-economic data of livestock and human populations with geophysical data obtained from maps of land cover, NDVI, precipitation, geomorphology and soil erosion. Through multivariate and correlation analysis, vegetation biomass was found to decrease with increasing human pressure. From a different point of view, Muller & Zeller (2002) combined policy and technology variables, in addition to land cover change, biophysical and socio-economic data. All data were spatially referenced using GIS after which the Multinomial logit model was applied to explore relationships between rural development policies and land cover change. Briefly, the model estimated the probabilities of a pixel having one of several land cover classes during either of the two study periods and hence facilitated detection of conversions between land cover types.

3.4 SUMMARY

The foregoing discussions clearly show the strong capabilities of remote sensing that include multi-temporal and broad spatial coverage of land surface features and the availability of diverse processing techniques to identify changes between different time periods. The discussions also indicate how remote sensing and other data sets are combined into a common database for GIS spatial analysis. Integrating the data sets provides a better understanding of the driving forces and consequences of land cover changes.

It is also important to note that sufficient time should be allowed for change to be detectable. In the current study, a decade was regarded adequate for land cover changes, symptomatic of land degradation, to be observable in Lesotho. Once a land cover change map is produced, using one of the existing methods of digital analysis, GIS plays an important role in data capture including digitizing (Ringrose & Vanderpost 1996; Archer 2004), geo-referencing (Hudak & Wessman 2000; Sannier, Taylor & Du Plessis 2002) and various spatial analyses such as map overlaying

(Bucini & Lambin 2002; Ringrose & Vanderpost 1996), buffer creation (Hudak & Wessman 2000) and many others. In the study of Lesotho, different data layers will be merged with satellite change data by overlay analysis to determine vegetation changes associated with land degradation. The importance of statistical analyses has also been demonstrated and is considered worthwhile to determine relationships between both biophysical elements and human pressure on land cover changes. Some studies further incorporate qualitative data (Archer 2004 and Muller & Zeller 2002) but such will fall outside the scope of this study.

3.5 CONCLUSION

The literature shows that remote sensing technology has a wide range of applications. There are numerous techniques that have been developed and used for global, regional and national scale monitoring of landscape changes. Vegetation is one of the most commonly used indicators of change and, accordingly, use of remote sensing vegetation indices facilitates change detection research. Archer (2004) indicates that NDVI involving the AVHRR sensors abound the NOAA satellites is the most commonly used of the indices to date. The sensor is advantageous over other sensors because of its high temporal resolution and coverage of large areas. It is against this background that the potential of remote sensing will be explored to detect and map land cover changes in Lesotho.

Kakonge (2002) indicates that in Lesotho land degradation has become more pronounced over recent years because of overgrazing of rangelands, soil erosion and loss of organic content and nutrients from the soil caused by poor agricultural practices. With the approaches and increasing opportunities available today to exploit the technology, it is reasonable to conclude that remote sensing tools can provide relevant information regarding land degradation in Lesotho.

CHAPTER 4: DATA PREPARATION

This chapter reports on procedures used to prepare satellite imagery and other data sets for use in analysing land degradation. Data preparation began with acquisition of Lesotho rainfall data and manipulating the data to aid in selecting appropriate satellite images for detecting vegetation changes. The chapter also presents methods used by the supplier for preprocessing the images to generate NDVI images. Procedures carried out to prepare the NDVI images to make them suitable for further analyses are also described. Sources of other data sets comprising land cover, ecological zones, elevation and soil data are indicated. The final sections highlight modifications performed on the ancillary data sets prior to analysis of land degradation.

4.1 RAINFALL DATA PREPARATION AND SELECTION OF IMAGES

Rainfall data were obtained from the Lesotho Meteorological Services and comprised monthly records from 1985 to 2002. Out of about 100 weather stations across Lesotho, data were used from only 18 stations (Figure 4.1), those with the fewest missing records.

The data were then manipulated to find two seasons with similar rainfall patterns from which two satellite images could be selected. This is because change detection requires at least two sets of imagery from two separate dates, one for an earlier date and the other for a later date. Rainfall data preparation was based on the notion that the previous two months of rainfall would have the greatest effect on vegetation due to the lag in vegetation cover response. Calculations were therefore based on the peak of the rainy season in Lesotho, which is from November to January.

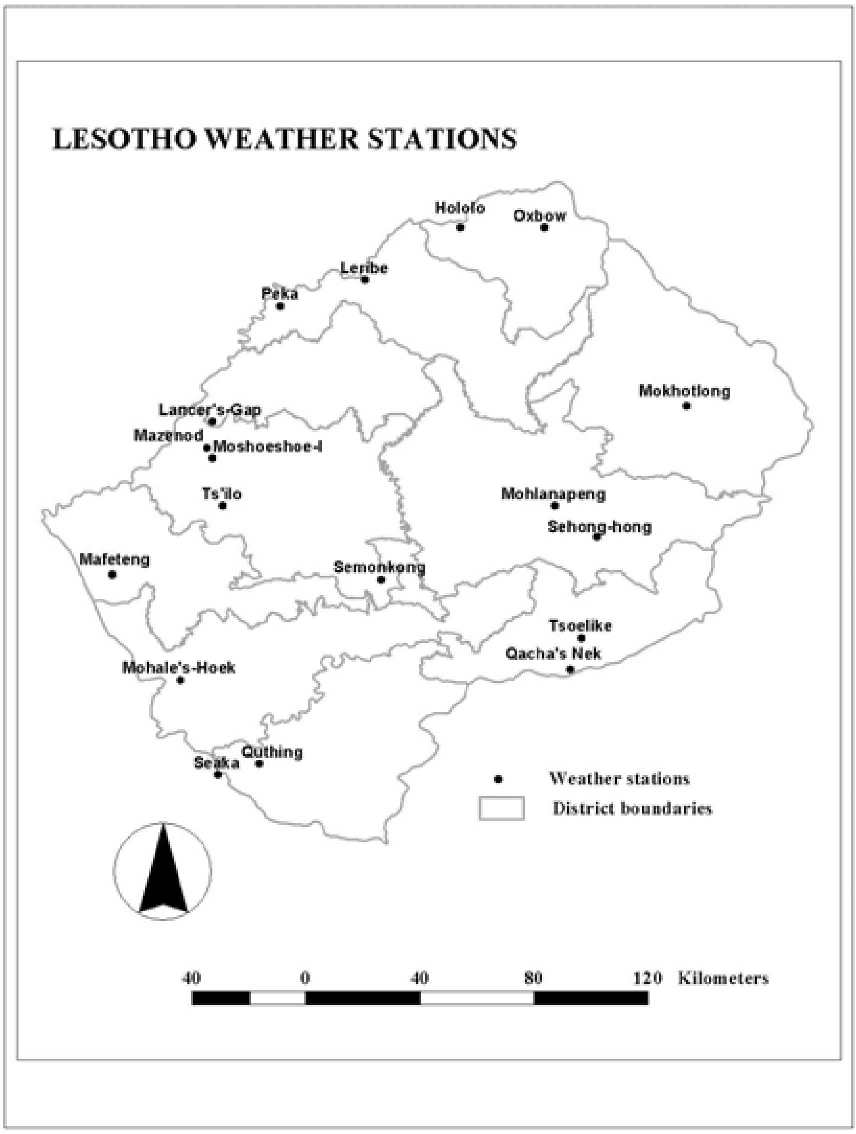

Figure 4.1 Selected weather stations in Lesotho with relatively complete rainfall data

The data were divided into two sets; one from which the earlier date image would be selected and the other for the later date image. Each set comprised seven rainy periods i.e. from 1985 to 1991 and from 1995 to 2001. Each rainy period constituted the monthly rainfall for November, December and January. The first criterion for the choice of the earlier and later dates was that they be separated by a minimum of 10 years to allow sufficient time for change to be detectable. Secondly, the two dates had to have the lowest rainfall difference so that vegetation response was comparable at both dates. Calculation of rainfall differences was possible between rainy periods that were 10 to 16 years apart. In consultation with Kidd 2003 (Pers com), the following formula was used to calculate rainfall differences between pairs of rainy seasons:

$$\text{rainfall difference} = \sum_{i=1}^{3}\sum_{j=1}^{k}\left(rain_{t-i,k} - rain_{t-i+\Delta t,k}\right)^2$$

Where:

i : 1 to 3 (3 months rainy period)
k : Number of stations
t : Date of first period
Δt : Difference between 2 time periods

The formula first calculated the squared difference of rainfall between the first and second dates for each of the stations over a 3-month period. These differences were then summed to provide an overall measure of the difference in rainfall between the two seasons. The differences obtained are shown in Table 4.1.

Table 4.1 Rainfall differences (mm) between rainy periods (1985 to 2001)

Rainfall periods	**Rainfall differences between rainy periods (mm)**						
	10 years	**11 years**	**12 years**	**13 years**	**14 years**	**15 years**	**16 years**
1985 to 2001	1985-1995	1985-1996	1985-1997	1985-1998	1988-1999	1985-2000	1995-2001
	3 724	6 484	5209	5 032	5 591	7 659	8 383
1986 to 2001	1986-1996	1986-1997	1986-1998	1986-1999	1986-2000	1986-2001	
	5 512	7600	4 588	14 990	13 150	13 003	
1987 to 2001	1987-1987	1987-1998	1987-1999	1987-2000	1987-2001		
	5102	5 533	7 270	13 752	10 722		
1988 to 2001	1988-1998	1988-1999	1988-2000	1988-2001			
	3 348	5 763	10 553	9 526			
1989 to 2001	1989-1999	1989-2000	1989-2001				
	9 927	12 029	7 527				
1990 to 2001	1990-2000	1990-2001					
	17 986	10 578					
1991 to 2001	1991-2001						
	12 894						

From the results, the lowest difference was found between the rainy period beginning in November 1988 (November 1988, December 1988, January 1989) and the period beginning in November 1998 (i.e. November 1998, December 1998, January 1999). Based on the outcome, two images captured in January of 1989 and 1999 by the

NOAA AVHRR satellite sensor were selected for studying land degradation in Lesotho.

4.2 SATELLITE DATA – NOAA AVHRR NDVI

The low spatial resolution and the high temporal resolution of the NOAA AVHRR sensor provide images that show the whole area of Lesotho. The satellite images were obtained from the Agricultural Research Council, Institute for Soil, Climate and Water (ARC - ISCW) in Pretoria. The data comprised monthly NDVI images in Erdas LAN format dating from 1985 to 2003. Only the 1989 and 1999 images selected from this data series as described in the previous section were used in the present study.

The images were processed at source and the following is an outline of the applied procedure according to Van Zyl 2004 (Pers com). The processing of the satellite data was automated. The images were geometrically corrected with the use of orbital parameters, and with 300 ground control image subsets. No atmospheric correction was applied to the images because of a lack of atmospheric water vapour and aerosol optical depth data. A cloud mask was generated to eliminate clouds in the images. NDVI images were then calculated from channel one and channel two and transformed to eight-bit values. The maximum value of daily NDVI was selected over a 10-day period (dekad) for every pixel to create maximum NDVI composites.

For each month three maximum NDVI composites were created. The first was a composite of the second and third dekad of a previous month plus one dekad of the current month. The second was a composite of the third dekad of the previous month, plus the first and second dekads of current month. The last composite comprised all three dekad images of the current month. For the present study, a composite of the three dekads of January 1989 and January 1999 were selected, mainly because the composites reflected more closely the vegetation conditions in January. Calculated NDVI values in each composite ranged from zero to 0,6375, based on the assumption that values less than zero were bare ground and values greater than 0,6375 were not possible (Van Zyl, Pers com 2004). The values were multiplied by a factor of 400 to get gray scale values from 0 to 255 (8 bit). Both composites were converted to the grids shown in Figures 4.2 and 4.3 in the Arc/Info grid module. The values were categorized into equal sized ranges from zero to 255 to portray NDVI distribution across Lesotho.

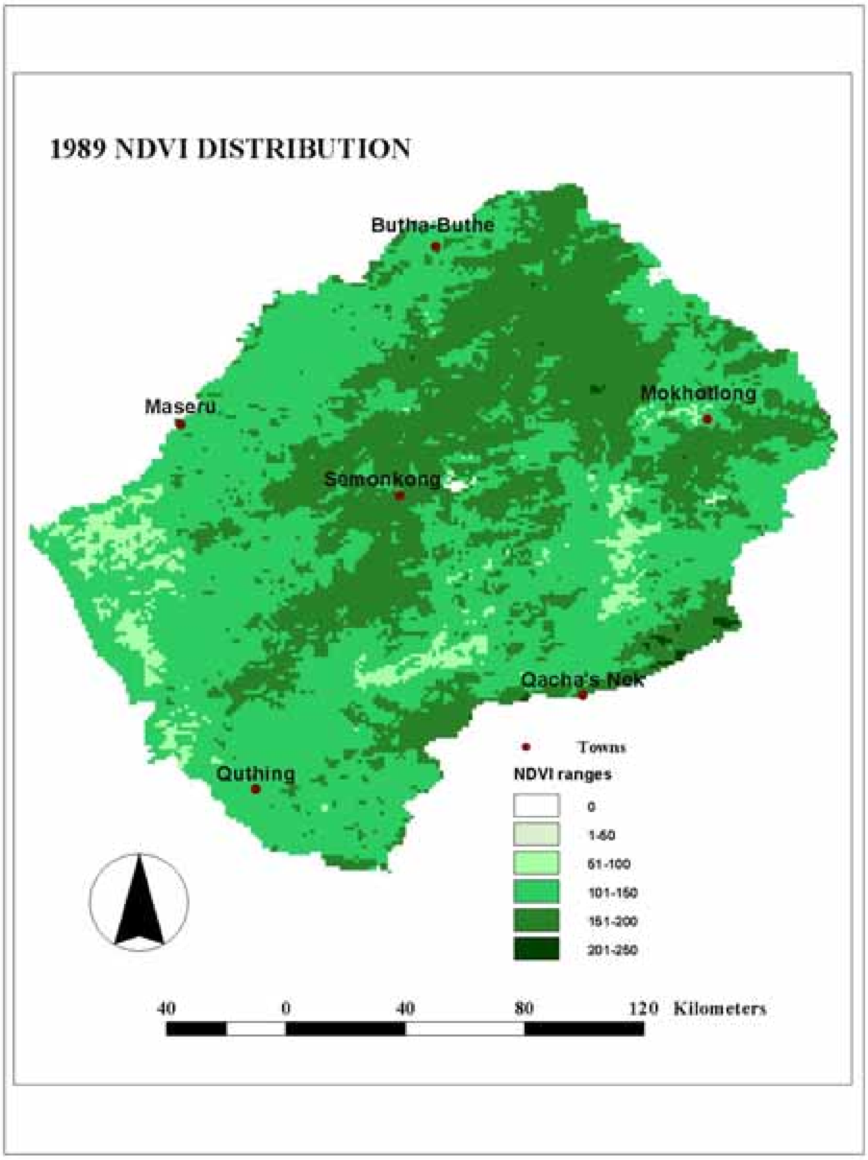

Figure 4.2 Distribution of mean January NDVI in 1989 in Lesotho

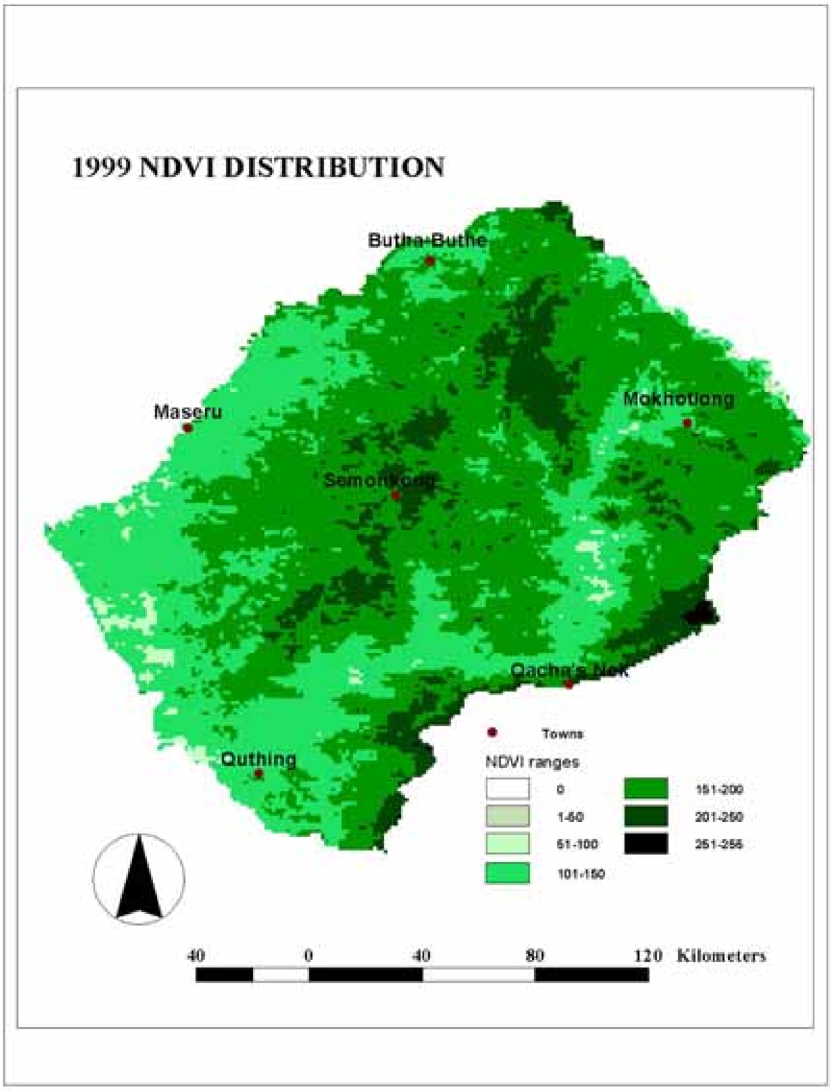

Figure 4.3 Distribution of mean January NDVI in1999 in Lesotho

It is necessary to compare distribution of NDVI between the two figures to determine changes due to vegetation loss, and hence land degradation. NDVI ranges in the two figures are compared in Table 4.2. The mean NDVI values in 1989 were concentrated mostly in the lower ranges, whereas in 1999 most values were found in the higher ranges. In 1989, most of the values in Lesotho fell in the range of 101 to 150. The area with NDVI between 51 and 100 was comparatively larger in 1989 than in 1999. In 1999, a large part of the country was covered with vegetation for which NDVI values ranged between 151 and 200. Furthermore, there was a greater area with values in the

201 to 250 and higher category in 1999 than in 1989. In general vegetation thrived better in 1999 than in 1989.

Table 4.2 Comparison of NDVI in 1989 and 1999

NDVI ranges	PIXEL COUNT (1989)	% OF TOTAL AREA IN 1989	PIXEL COUNT (1989)	% OF TOTAL AREA IN 1999
0	30	0,1	5	0,02
1 – 50	3	0,01	13	0,1
51 – 100	998	4	408	2
101 – 150	13309	58	7778	34
151 – 200	8565	37	12117	53
201 – 250	59	0,3	2596	11
251 - 255	-	-	47	0,2
TOTAL	**22964**	**100**	**22964**	**100**

The difference can be accounted for by the higher amount of rainfall in the two months preceding capturing of the 1999 image. Average rainfall figures in both the 1989 and 1999 rainy seasons are shown in Figure 4.4. By implication, there was healthier vegetation as a result of the higher rainfall in 1999 than in 1989 and hence higher calculated NDVI values. An attempt was made to eliminate the rainfall differences by correlating NDVI with rainfall in each image, using the logic of a linear equation. However, it was not possible to remove the differences because of poor correlations between NDVI and rainfall in both 1989 and 1999.

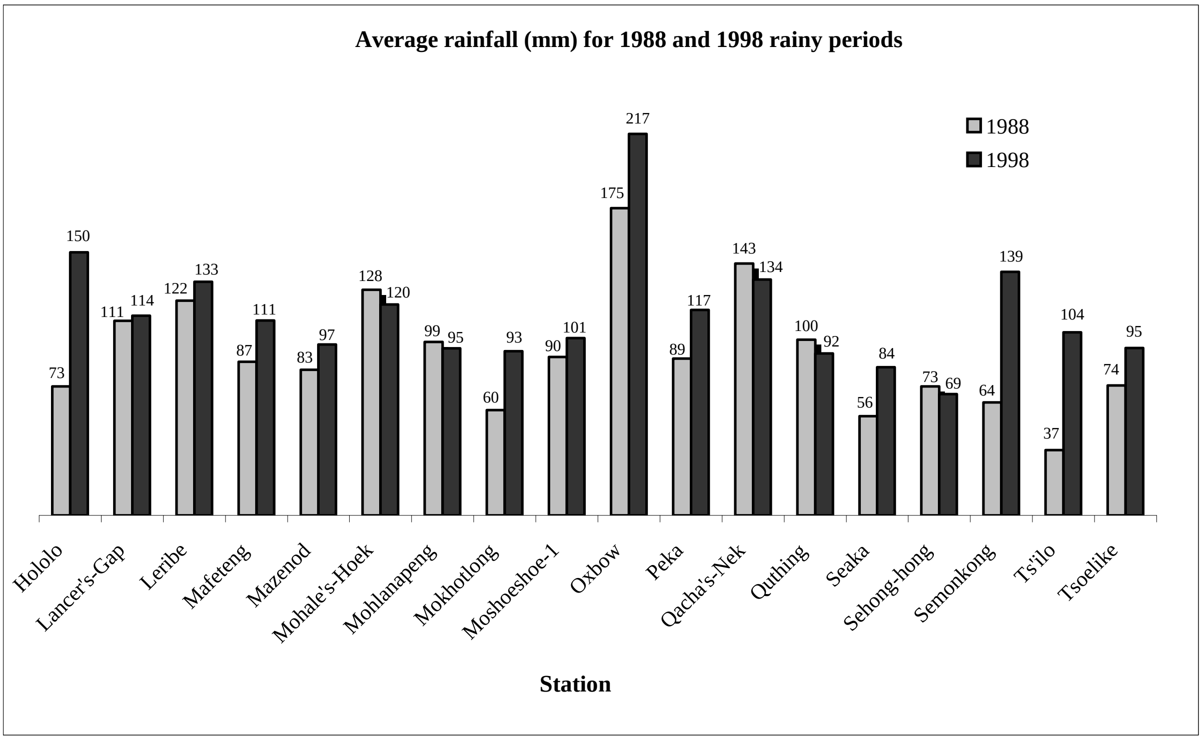

Figure 4.4 Average rainfall for rainy periods of 1988 and 1998 in Lesotho

Despite the rainfall differences, the two NDVI images were selected for use because they were acquired on two dates that had the most comparable rainy seasons out of all others in Lesotho (section 4.1).

Following selection of the images, other data sets were obtained and were subjected to operations to make them suitable for use with the images. The section below is a description of the sources and operations performed on the data sets.

4.3 OTHER DATA SETS

Ancillary data sets were selected for use in the present study to aid in determining causes and factors underlying land degradation. In addition the data assisted in identifying land surface features which are most vulnerable to land degradation. The data sets were obtained from a number of sources and had various resolutions. Data sets also came from tabular records in reports and from a hard copy map. Preprocessing was carried out in Arc/Info and all maps were projected to the Albers equal area projection, using projection parameters shown below.

Projection:	Albers
Units:	Meters
Spheroid:	WGS 84
1st Standard parallel:	-30
2nd Standard parallel:	-28
Central meridian:	28
Reference latitude:	0
False easting:	0
False northing:	0

The following provides the sources and operations performed on the data sets in preparation for further analysis.

4.3.1 Land cover

Acquisition of the land cover data was necessary because the data contained vegetation types of Lesotho and vegetation served as the main indicator of land degradation in the present study.

Lesotho land cover data were obtained from a CD of the national land cover database produced for South Africa, Lesotho and Swaziland by ARC in association with the Council for Scientific and Industrial Research (CSIR) (Thomson 2001). The database had been produced at a scale of 1:250 000 from 1994 to 1995 Landsat TM satellite imagery and was available in digital vector format. The database conformed to the land cover classification standards proposed for the AFRICOVER project of the Food and Agricultural Organization (FAO). Additionally, a standard seasonal time frame was adopted to optimize final land cover data on vegetation and crop cover for each geographical region, and to minimize temporal drought effects and land cover variability between adjacent images received in different years. The land cover classification had been formally verified by site visits whereby a series of grid point locations was evaluated.

The Lesotho database originally had minimum mapping units of 25ha and contained 21 land cover classes. The number of classes was reduced to facilitate analysis by grouping together classes of cultivated, urban or built-up, degraded land and shrubs as shown in Table 4.3 and Figure 4.5. The map was converted to a grid in ArcView and the cell size resampled to 1km to match the resolution of the NDVI images.

Table 4.3 Reclassified SA land cover types for Lesotho (1995)

CLASS	ORIGINAL CATEGORY	CLASS	NEW CATEGORY
11	Barren rock	1	Barren rock
22 21 23	Cultivated: temporary- commercial dry land Cultivated: temporary – commercial irrigated Cultivated: temporary – semi-commercial/ subsistence dry land	2	Cultivated: temporary
13 14 15	Degraded: forest and woodland Degraded: thicket and bush land etc Degraded : unimproved grassland	3	Degraded: thicket, bush land, unimproved grassland etc
12	Dongas and sheet erosion scars	4	Dongas and gullies
2 8	Forest Forest plantations	5	Forest and Forest plantations
5 7 4 3 6	Herb land Improved grassland Shrub land and low fynbos Thicket and bush land etc. Unimproved grassland	6	Grassland, shrub land and thickets
31	Mines and quarries	7	Mines and quarries
29 30 24	Urban/built-up land : commercial Urban/built-up land : industrial/transport Urban/built-up land : residential	8	Urban/built-up
9	Water bodies	9	Water bodies
10	Wetlands	10	Wetlands

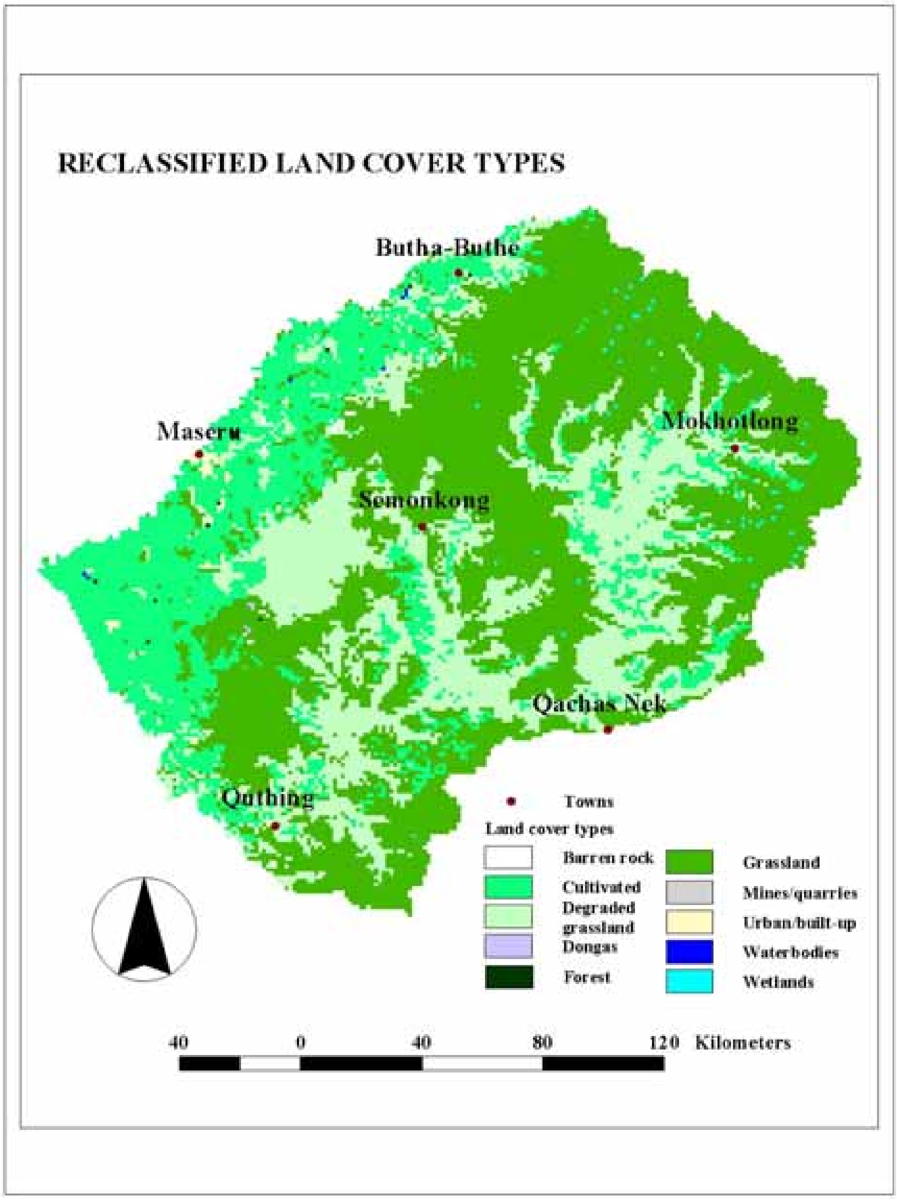

Figure 4.5 Reclassified SA land cover for Lesotho (1995)

4.3.2 Ecological zones

The ecological zones data was selected to aid in determining patterns of land degradation within the zones. The data used were vector ESRI shapefiles produced in 1999 and obtained from the Southern African Humanitarian Information Management Service (SAHIMS). The ecological zones layer, shown in Figure 2.2, was created by Vulnerability Analysis and Mapping (VAM), a unit of the World Food Programme (WFP) that supports and promotes the use of mapping, spatial analysis and GIS technology. In producing the data, VAM adopted UN cartographic standards and the reliability of the data was good. The data shows locations and boundaries of the zones in Lesotho.

4.3.3 Altitude

Altitude data were acquired for relating land degradation to different altitudes of Lesotho. The data were also used to generate slope and aspect images. Figure 4.6 shows the range of altitudes in Lesotho.

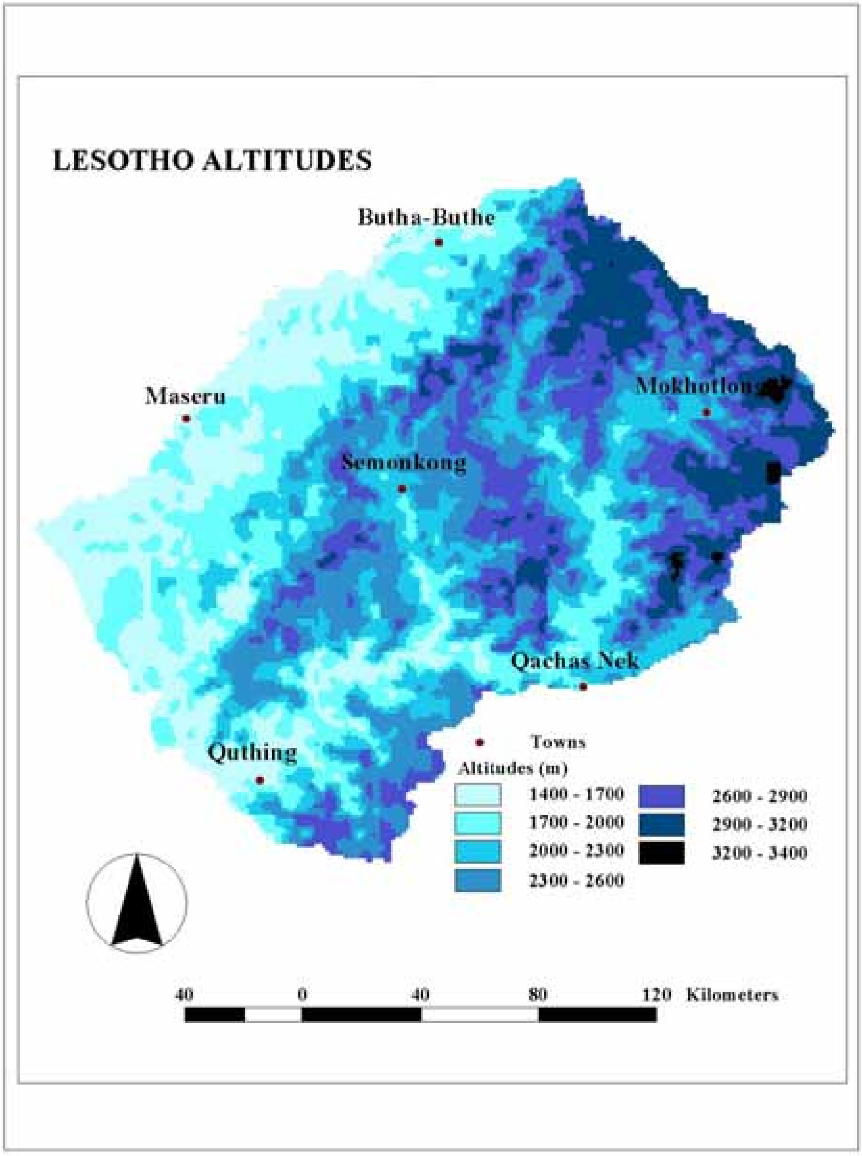

Figure 4.6 Lesotho elevation

Source: SAHIMS 2003

The International Steering Committee for Global Mapping (ISCGM) has generated a group of global data sets, which are of known and verified quality with consistent standardized specifications. The specifications are in most part consistent with the ISO TC211 recommendations for geographic data sets. The data sets were derived from 1km AVHRR data for 1992 to 1993. The elevation layer of Lesotho was acquired from the ISCGM website and was available in raster (BIL) image format. Finer resolution datasets on elevation could not be found. The layer was produced from the global 30 arc second elevation data set (GTOPO30).

The global map data were originally arranged in tiles for ease of managing the large amounts of the data. The Lesotho elevation layer was organized in two separate tiles, which were mosaiced in Erdas Imagine software. Since the original tiles included parts of South Africa, preprocessing was completed by sub-setting the Lesotho area. From the elevation data, percentage slope was calculated and classified into four classes as shown in Figure 4.7. In addition, direction of slope (aspect), was also derived from the elevation data and classified as indicated in Figure 4.8. The pixel resolution of the grids matched the resolution of the NDVI images derived from NOAA AVHRR data.

4.3.4 Soil

Soil data were important in determining the types of soils most vulnerable to degradation. The data were generated from a 1:250 000 scale hard copy soil map of Lesotho produced by Carrol & Bawden (1966). The map was scanned and geo-referenced in Arc/Info using eight control points. The rectified map was digitized, edited and reclassified in ArcView. There were 26 original soil units, which were either simple or binary associations (Table 4.4). The predominant constituent of each association was placed first. The original units were generalized into the 6 classes shown in Figure 2.4, following a discussion with Schloms (2004, Pers com).

The resulting classes were then assigned degrees of erodibility. Soil erodibility is a measure of the soil’s susceptibility to detachment and transport by erosion agents (Lal & Elliot 1994) and is determined by physical and chemical properties of soil. There have been many efforts to measure erodibility (Bryan in Toy, Foster & Renard 2002) but quantifying erodibility of Lesotho soils was outside the scope of the present study.

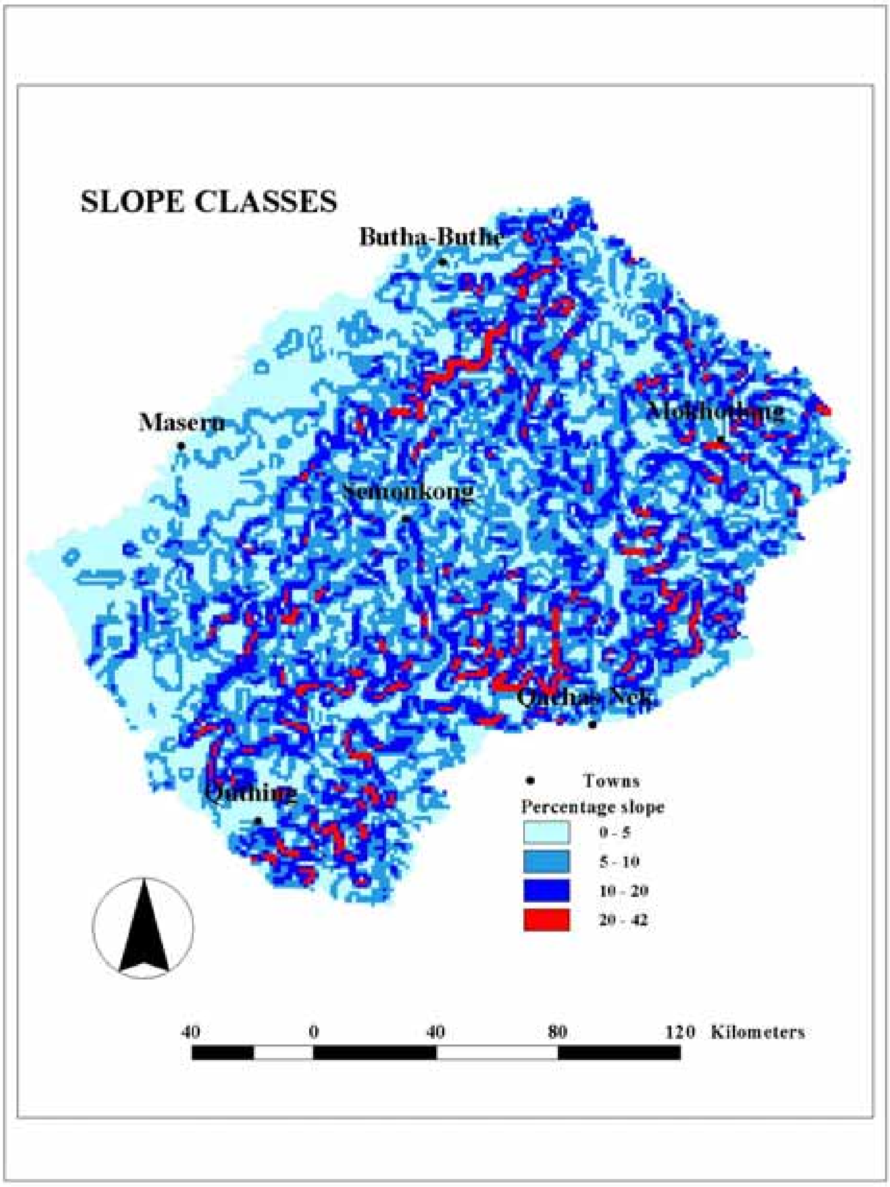

Figure 4.7 Slopes of Lesotho expressed as percentages derived from elevation

Therefore erodibility was expressed broadly as low, medium or high depending on the soil type. In addition, the depth of each soil type was indicated and expressed as very shallow, shallow, moderately deep, deep and very deep. As a final step, the soil map was converted to a grid map with a cell resolution of 1km.

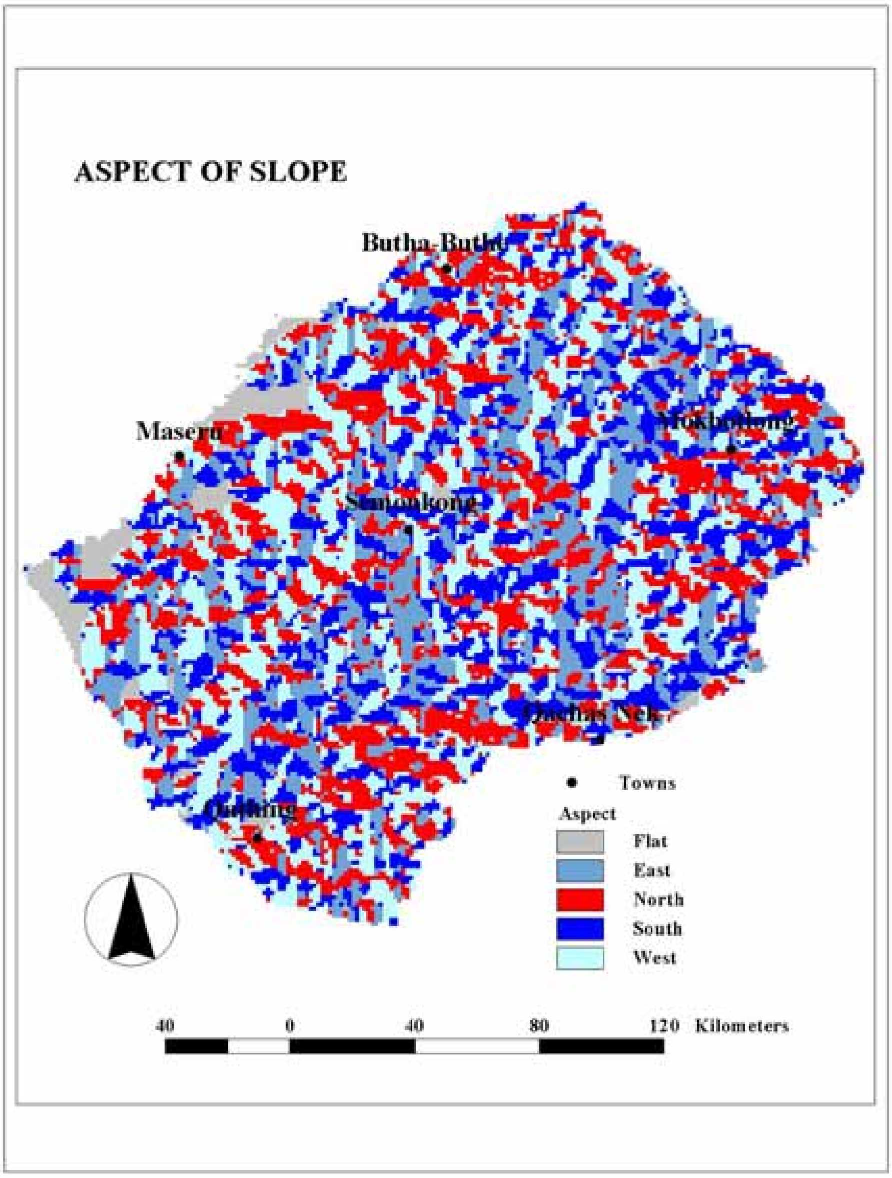

Figure 4.8 Aspect of Lesotho derived from elevation

4.3.5 Human and livestock populations

The populations data were acquired for deriving population densities in the districts of Lesotho and determining the link between the densities and land deterioration. Both sets of data were obtained from Lesotho Bureau of Statistics census reports and modified to the form presented in Section 2.5, Tables 2.2 and 2.3. As indicated, from the 1996 population census data, population density per district was calculated.

Table 4.4 Reclassified soil types of Lesotho

ORIGINAL CLASS	ORIGINAL CATEGORY	CONVERTED CLASS	NEW CATEGORY
1 2	Lithosols on lava Lithosols on lava/basalt rock debris	1	Lithosols on lava
3	Lithosols on lava/Calcimorphic soils	2	Lithosols on lava/Calcimorphic soils
4 5 6 7 8 9 26	Lithosols on rocks rich in ferromagnesium minerals Lithosols on rocks rich in ferromagnesium minerals/ Eutrophic brown soils Lithosols on sedimentary rocks/ sedimentary rock debris Lithosols on sedimentary rocks/ Fersiallitic soils Lithosols on sedimentary rocks/Ferralitic soils Juvenile soils on recent riverine alluvium Ferralitic soils/Lithosols	3	Lithosols on ferromagnesium and sedimentary rocks, Ferralitic soils
10 11 12 13 14 21	Calcimorphic soils/Lithosols on lava Calcimorphic soils/Vertisols Vertisols of Lithomorphic origin Vertisols of Lithomorphic origin/ Calcimorphic soils Vertisols of topographic depressions Eutrophic brown soils/Vertisols	4	Vertisols and Calcimorphic soils
15 16 17 18 19 20	Claypan soils (Maseru set) Claypan soils/Vertisols Claypan soils (Maseru set/Sephula set) Claypan soils (Fersiallitic soils) Claypan soils (Sephula set) Claypan soils (Sephula set/Maseru set)	5	Claypan soils
22 23 24 25	Fersiallitic soils Fersiallitic soils/Lithosols Fersiallitic soils/Claypan soils Fersiallitic-Lithosol intergrades	6	Fersiallitic soils

Table 4.5 Depth and erodibility of Lesotho soils

Soil Class	Depth	Erodibility
1	Shallow	Low
2	Shallow	Medium
3	Shallow	Low
4	Shallow/Moderately deep	High
5	Shallow	High
6	Deep	Low

The numbers of domestic livestock were converted to large stock units (LSU), using recommended conversion factors supplied by Herselman (2004, Pers com) of the Grootfontein Agricultural Development Institute. The conversion factors for cattle, sheep and goats were 1,21 , 0,15 and 0,14 respectively. The LSU equivalent for cattle was selected based on the assumption that one cow in Lesotho was a medium beef breed with an approximate mass of 525kg. Lesotho sheep are reared for wool and the LSU equivalent was selected with the assumption that a wool producing sheep weighed approximately 50kg. The LSU conversion value for Angora goats was used on the basis that one such goat had an approximate mass of 42kg. After obtaining LSU for different animals, the average LSU for each district were calculated and thereafter, LSU/km^2 were derived. Human population and livestock densities are shown in Figures 2.6 and 2.7.

4.4 SUMMARY

The foregoing modifications to ancillary data were necessary before any analysis could be performed. Rainfall data aided in selecting the two NDVI images that would be used for change analysis. All the other data sets were obtained from different sources which are indicated in Table 4.6 and were made comparable to one another by gridding and resampling.

Table 4.6 Ancillary data sets of Lesotho and creation dates

Data sets	**Source**	**Year created**
Land cover	ARC-LNR/CSIR	From 1994 to 1995
Ecological zones	SAHIMS	1999
Soil	Hard copy map	1962
Elevation	ISCGM	2001
Population	Lesotho census	1996

The data were integrated from various sources for analysis because no single source of data had all the variables. The different creation dates of most variables were not crucial, especially those concerning the ecological zones, soil and elevation layers. These are most unlikely to undergo significant changes over short time scales. However, there was concern about land cover because it can be modified easily by human activities. The land cover data were, however believed to be close representations of overall land cover conditions of Lesotho between 1989 and 1999, which rendered the data suitable for further use. Human population numbers are also likely to have been higher in 1999 than in 1989, but as with land cover, using population density distribution instead of actual figures provided a good indication of how population distribution relates to spatial land degradation patterns.

In summary, data pre-processing was carried out using Arc/Info and ArcView software, and entailed:

- digitizing
- editing
- reclassifying maps
- converting the maps to grids, resampling the cell size of higher resolution grids to 1km
- projecting the grids to a common Albers equal area projection.

In the next chapter, the data sets were subjected to analysis in order to address the objectives of studying land degradation in Lesotho.

CHAPTER 5: ANALYSIS OF LAND DEGRADATION

This chapter presents the analysis of land degradation in Lesotho. The analyses were carried out in ArcView and in the Arc/Info Grid module and mainly involved identifying and demarcating degraded areas, as well as assessing the extent and severity of land degradation. In addition, population density and biophysical data sets were combined with data depicting degraded areas to determine possible causes of land degradation. Details of operations performed on the data sets are provided in the sections below.

5.1 IDENTIFYING AND QUANTIFYING LAND DEGRADATION

In the present section, a distinction is made between types of vegetation changes that occurred in Lesotho between 1989 and 1999. This was done to identify changes associated with land degradation and thereafter, to isolate potentially degraded areas. The extent of degradation was determined and expressed as area per km^2 of total land area. Then severity of degradation in each of the 10 districts of the country was established using predetermined severity criteria.

5.1.1 Identifying vegetation changes from 1989 to 1999

Vegetation changes were identified by subtracting the 1989 NDVI data from the 1999 NDVI data. Figure 5.1 shows not only areas that changed but also those that did not undergo modifications between the two years. From the changes, areas that experienced vegetation loss and areas in which vegetation became abundant could be distinguished.

Gray scale NDVI change values in Figure 5.1 ranged from -161 to 227. This range can be interpreted as NDVI values in the range from –0,425 to 0,5675. All pixels with negative values represented areas in which NDVI decreased. Pixels with zero values represented areas that did not experience any changes, while the last category, with values from 1 to 227, corresponded to an increase in NDVI. Following identification of vegetation changes, the changes were quantified.

Criteria for establishing the magnitude of change were based on grid cell counts. The number of pixels in each change category was converted to a percentage of the total number of pixels. Based on the known total area of Lesotho, the percentages were then used to calculate the area in km^2 that experienced the changes as indicated in Table 5.1.

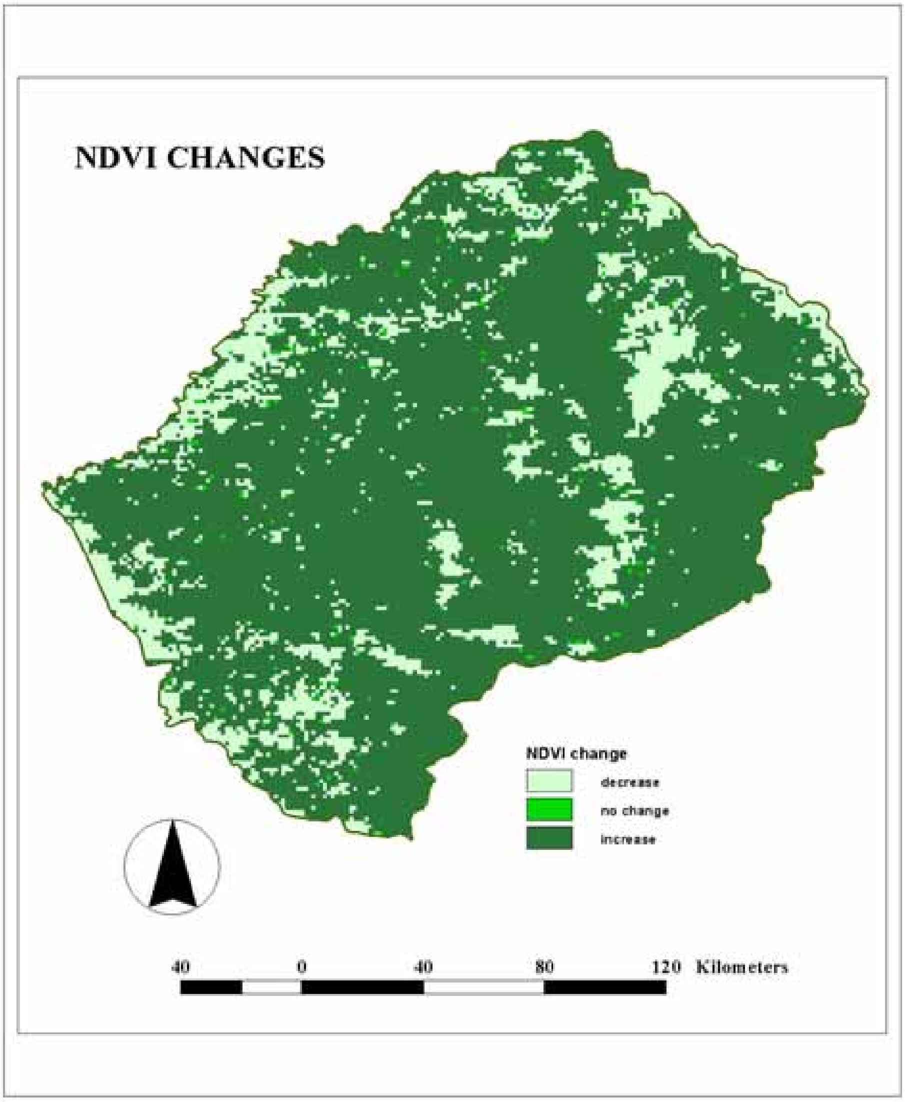

Figure 5.1 NDVI changes in Lesotho from 1989 to 1999

Table 5.1 Extent of areas that experienced changes in Lesotho (1989-1999)

Nature of change	**Pixel count**	**Percentage of total**	**Area (km^2)**
Decrease	4091	18	5464
No change	242	1	304
Increase	18631	81	24588
Total	**22964**	**100**	**30355**

After the changes were identified and quantified, areas that appeared to have undergone degradation between 1989 and 1999 were isolated. The following section provides an account of how such locations were demarcated for analysis of land degradation.

5.1.2 Demarcating potentially degraded areas

NDVI is a reflection of the relative amount of vegetation present in an image. In retrospect, bare soil and vegetation respond differently to radiation and hence have different NDVI values. Cracknell (1997) compared reflectance patterns of herbaceous vegetation and soil as follows. The spectral reflectivity of a vegetated surface is generally high in the NIR wavelength, therefore, for such a surface, the signal value generated in band 2 of AVHRR will be high. At a stage of vigorous growth of vegetation, the reflectivity in the NIR will be higher than at any other stage in the growth cycle of plants. Dead or dormant vegetation has a higher reflectance in the visible spectrum than healthy living vegetation, and lower reflectance in the NIR channel. Bare soil has a higher reflectance than green vegetation and a lower reflectance than dead vegetation in the visible channel. In the NIR, bare soil typically has a lower reflectance than green and dead vegetation.

It was against this background that some parts of Lesotho were recognized as potentially degraded. Since NDVI is a measure of living green vegetation, NDVI changes observed in Lesotho from 1989 to 1999 indicated that there were places in the country with healthy vegetation while in others vegetation vigour declined. The latter are of interest to this study because through a series of processes, vegetation loss leads to land degradation. It follows then that places that experienced a decline in NDVI are potentially degraded. Areas with negative NDVI values were therefore demarcated as potentially degraded. Degradation was probably more extensive than documented here, because 1999 NDVI values were on average higher than 1989 values due to the higher rainfall recorded in the rainy period preceding January 1999. Demarcating the areas aided in estimating the extent and severity of land degradation. The procedures followed are described in the section below.

5.1.3 Determining the extent and severity of land degradation

The extent of land affected by degradation was determined using the total area of each district and degraded place. The calculations enabled an expression of degradation as a percent of total district area and results obtained are shown in Table 5.2. Then, severity of degradation was established by statistically dividing percent degradation into quartiles for defining four levels of severity: low, moderate, high and very high. The ranges were rounded to the nearest integer. Districts with less than 13% of their land degraded were considered to have low severity, while 14% to 17% deterioration was taken to represent moderate severity. High and very high severity was assigned to districts where 18% to 23% and over 24% respectively of the land surface suffered degradation. Figure 5.2 shows severity of the deterioration in the districts.

Table 5.2 Extent and severity of degradation by district in Lesotho (1989–1999)

District	Total area km^2	Total pixel count	Pixels degraded	Degradation as % of total pixels	Area degraded km^2	Severity
Berea	2222	1488	398	27	594	Very high
Butha-Buthe	1767	1364	300	22	389	High
Leribe	2828	2119	273	13	364	Low
Mafeteng	2119	1972	287	15	308	Moderate
Maseru	4279	2846	350	12	526	Low
Mohale's Hoek	3530	2568	598	23	822	High
Mokhotlong	4075	3131	825	26	1074	Very High
Qacha's nek	2349	1649	178	11	254	Low
Quthing	2916	2234	376	18	517	High
Thaba-Tseka	4270	3644	479	13	561	Low
Total	30355	23015	4084	18	5409	High

After assessing the magnitude and severity of degradation, further analyses were carried out using other GIS data sets to determine causes of land degradation.

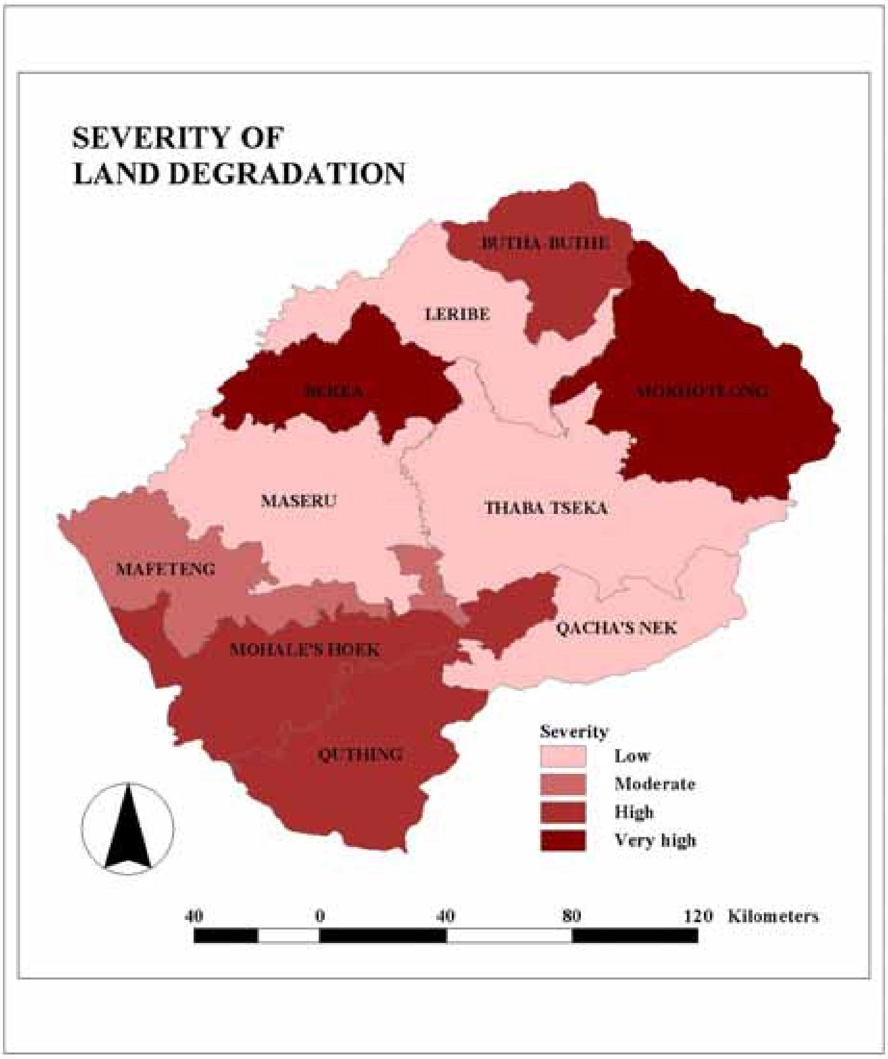

Figure 5.2 Severity of land degradation by district in Lesotho (1989–1999)

5.2 DETERMINING CAUSES AND FACTORS UNDERLYING LAND DEGRADATION

In this section ancillary data sets were combined with the NDVI change data using the COMBINE function of the Arc/Info GIS. Grid cell values and grid cell counts were used to distinguish between landscape variables and to quantify land degradation respectively. The variables were cross-tabulated with NDVI change to establish relationships between biophysical factors, as well as population density and land degradation. The procedure is summarized in Figure 5.3.

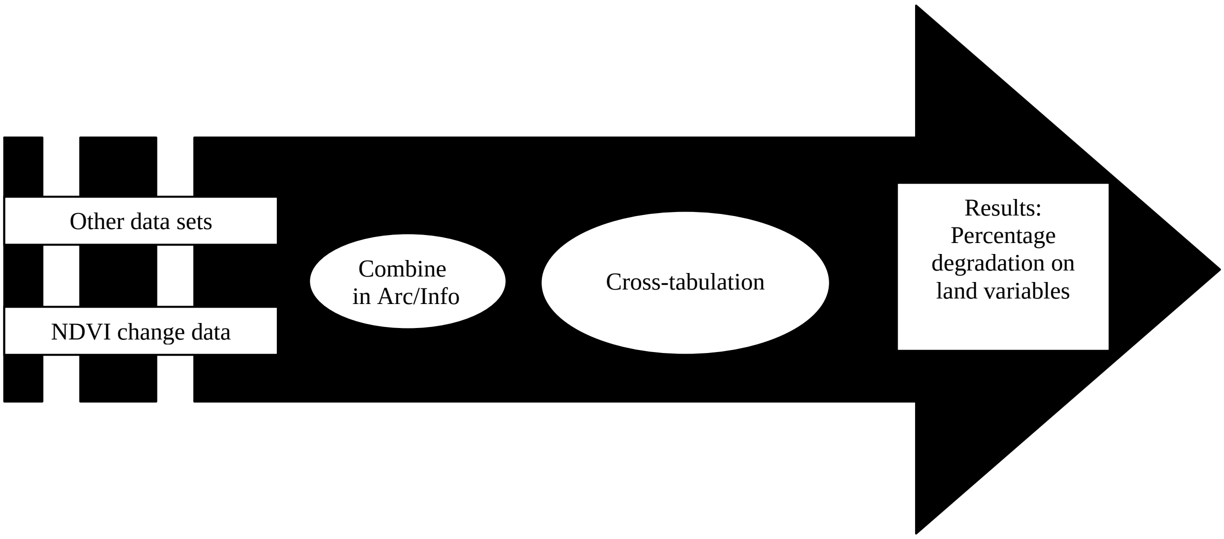

Figure 5.3 Method used for analysing causes of land degradation in Lesotho

The following sections only highlight procedures used for establishing relations between land degradation and ancillary data to determine causes of the degradation. A comprehensive discussion and interpretation of the results will be provided in Chapter 6.

5.2.1 Land cover

This section presents analysis of the relation between land cover types and land degradation. According to the land cover classification adopted in the study, grassland, shrubs and thickets cover the major part of the land area, while the remaining classes occupy only about 1% of the land area. Degradation that affected different land cover types was determined by combining the land cover data with the vegetation change data.

Special attention was paid to land cover classes that coincided with degraded areas because such areas represent land cover types that were likely to have been affected by degradation. The percentage of degraded areas to the total area of each land cover type was computed to quantify the degradation. Deriving the proportion of degraded land to total land cover area enabled an identification of land cover types that suffered the greatest degradation. Since only single date land cover data were available for analysis, the relationship was determined to provide an indication of land cover classes that suffered degradation and not to assess conversion between land cover.

types. After determining possible degradation on land cover, the study proceeded to establish possible links between soil types and degradation.

5.2.2 Soil types, depth and erodibility

Soil deterioration was associated with land degradation primarily because soil is a component of land on which impacts of degradation become manifested. Soils when related to vegetation depletion provide information about vulnerability of different soil types to degradation.

Most soils in Lesotho are of sedimentary or basaltic origin (Reizebos & Chakela 1984) but mixtures and variations occur throughout the whole country. The majority of soils are lithosols and are found in approximately 52% of the land area, particularly in the mountains. Using the general background of soil origin, the soils are mainly derived from basalt lavas and are characteristically shallow. Vertisols, fertiallitic and claypan soils constitute the remaining 48% and occur mostly in the Lowlands (Figure 2.4). Based on the idea of Reizebos & Chakela (1985), fertiallitic and claypan soils originate mostly from sedimentary rocks since they are found in the Lowlands. According to the classification of soils adopted in the present study, vertisols have a lithomorphic origin and hence are assumed to originate mainly from basalt lavas. The most important property of vertisols is the dominance of clay. Claypan soils are distinguished by a compact layer in the profile, having a higher content of clay than the overlying material, from which it is separated by a defined boundary.

Susceptibility of soil to erosion is determined by soil erodibility, because some soils erode easily and some do not. Erodibility is a function of various soil properties such as permeability, texture, structure and ease of dispersion (Andre & Anderson 1961), and soil profile characteristics such as soil depth (Veihe 2001). The vertisols in Lesotho were assigned low erodibilty in the present study as suggested by Schloms (2004 Pers com). In addition, fertiallitic soils and lithosols were assigned low erodibility, while claypan soils were regarded as highly erodible. Since most soils in the flat and gently sloping areas tend to be moderately deep to deep, soils in the Lowlands were taken to be deep. In contrast, soils on mountain slopes tend to be shallow and as a result, the mountain lithosols were considered to be shallow. The relation between soil and land degradation in Lesotho was determined by combining the NDVI change data with soil data.

After relating degradation to soil classes, soil depth and erodibility were considered to find out whether these properties can be associated with land degradation. Figure 5.4 shows depths of different soil types and in Figure 5.5 erodibility of soils is presented.

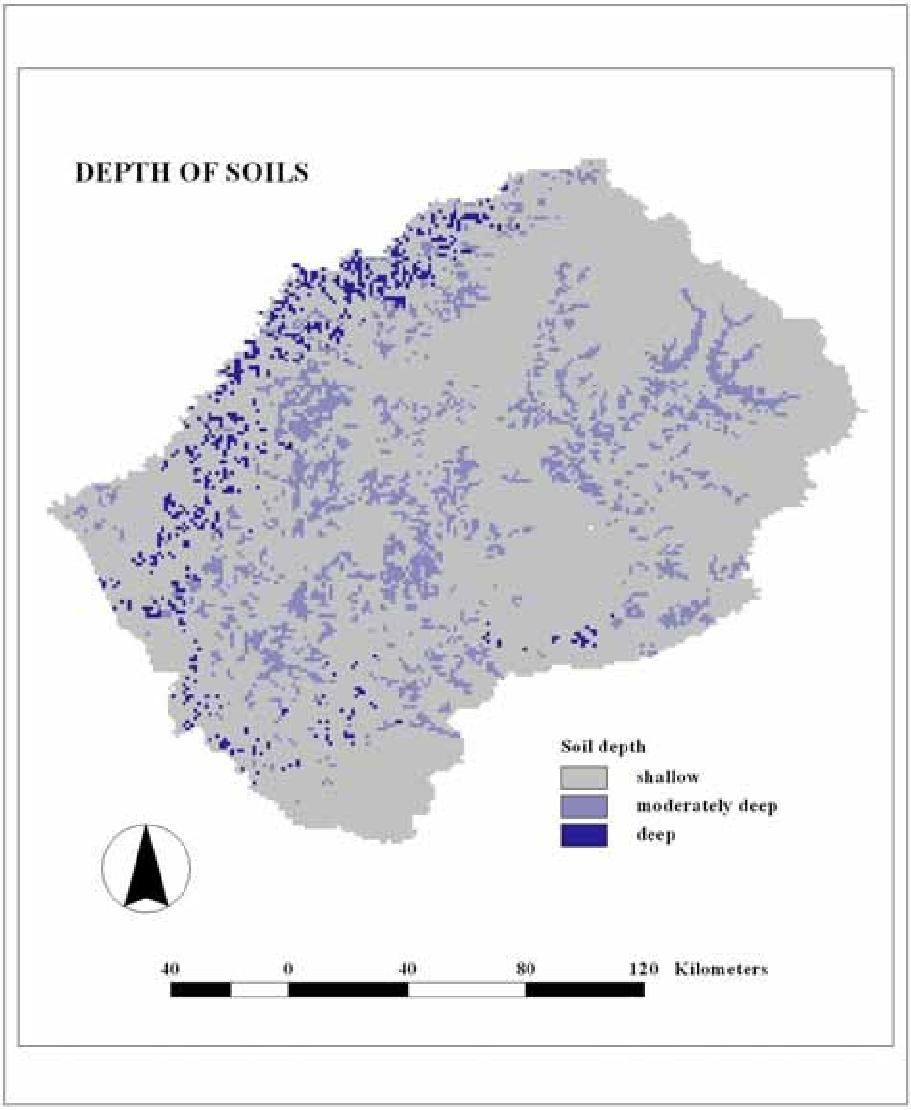

Figure 5.4 Depth of soils in Lesotho

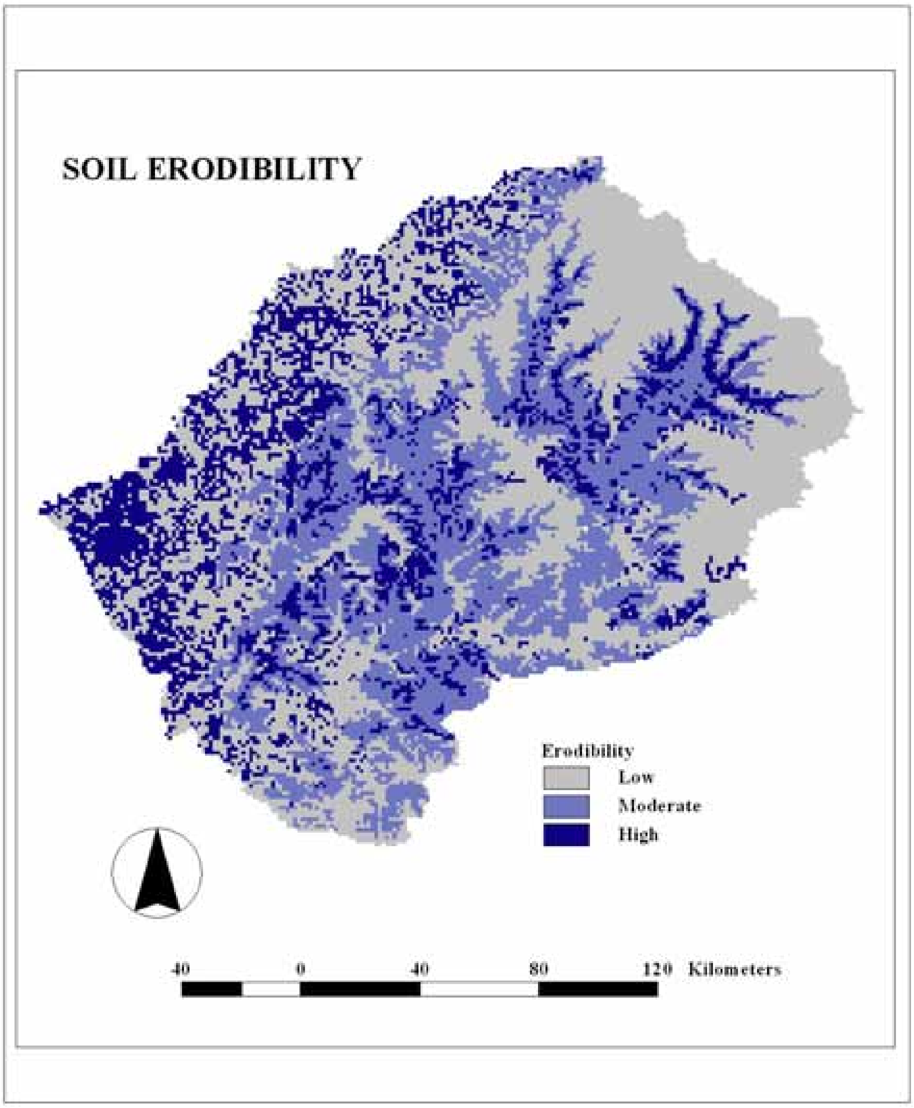

Figure 5.5 Erodibility of soils in Lesotho

The following section describes how degradation in ecological zones was determined.

5.2.3 Ecological zones

The widely accepted system for classifying the ecological zones of Lesotho divides the country into four zones: Lowlands, Foothills, Senqu River Valley and Highlands. The zones have distinguishing characteristics that include geology, elevation, vegetation and land cover. It was necessary to find the relation between patterns of vegetation loss and land degradation within each zone by the overlay of the ecological zones data with the change map.

After analysis of land degradation in ecological zones, the extent of degradation was related to altitude, slope and aspect. The procedures followed are described in the sections that follow

5.2.4 Altitude, slope and aspect

Mountain ecosystems are fragile because of their steep terrain, among other things. Torrential rain with the resultant high run-off on the steep slopes aggravates soil erosion and ultimately causes land cover to deteriorate (Khawlie et al. 2003). As Lesotho is mountainous, with elevations exceeding 3400m a.s.l., it was important to determine the nature of degradation at different elevations. The analysis was carried out by classifying elevation into seven even 300m ranges, beginning at 1400m and ending above 3400m. The assumption was that a 300m elevation interval is sufficient for differences pertaining to land degradation to be noticeable.

In addition to elevation, slopes which were affected by degradation were identified because mountain surfaces inherently have steep slopes. Steepness of slope is significant in the study of land degradation mainly because of the impacts of soil erosion caused by water on the slopes. The link between slope and vegetation loss was determined by deriving the percentage steepness of slopes, and dividing the percentages into the following four ranges: the 0 to 5% slope category representing relatively flat areas, 5% to 10% for moderately steep slopes, and 10% to 20% for steep slopes. Slopes greater than 20% are considered to be very steep.

It was also important to consider how the direction of slopes relative to the sun influences land degradation. According to Evans (in DeMers 1996) aspect is the compass direction associated with each slope. Knowing aspect helps to determine both the availability of sunlight to green plants, and slopes that are oriented towards prevailing winds. In Lesotho, north facing slopes receive more sunlight over a year, and tend to have warmer soils on which plants thrive than south-facing slopes. South-facing slopes are therefore inherently cooler and more damp than their north-facing counterparts. West-facing slopes receive afternoon sun while east-facing slopes receive morning sunlight. Land degradation on slopes facing in the four cardinal directions namely, north, east, south and west, was analyzed and results obtained are shown in Table 5.4.

After associating land deterioration with altitude, slope and aspect, attention was focused on establishing how human and livestock population densities influence land degradation. The following sections explain how the relationships were analysed.

5.2.5 Human population and livestock densities

Human land activities contribute significantly to land cover changes, which in turn often lead to land degradation. Such land cover modification by humans are largely consequences of population growth. It follows then that population density can provide useful information about land degradation. Amissah-Arthur & Miller (2002) noted that there is mounting evidence of negative environmental effects of high human densities resulting from population growth.

In view of the significance of population to environmental deterioration, it was considered worthwhile to study relations between Lesotho's human population and land degradation. To achieve this, population densities per km^2 were derived for each district of Lesotho using the 1996 census figures. Population density provides an indication of the amount of demographic pressure exerted on an area of land. The densities data were combined with land degradation data.

Besides human population densities, stock farming is an important aspect of land use that can have negative impacts on rangelands, if livestock grazing is not properly controlled. The study undertook to investigate the role of the livestock in the degradation that occurred from 1989 to 1999. The number of cattle, sheep and goats in each district was converted to Large Stock Units (LSU) (Section 4.3.5). Data representing LSU/km^2 were combined with the degradation data.

5.3 SUMMARY

The analyses involved use of various data sets to determine factors underlying land degradation from 1989 to 1999. Both biophysical and demographic variables formed the core of analyses because the variables can be related to land degradation. It was important to determine how extensive degraded areas were and to assess severity of degradation. The results obtained in the present chapter are discussed in detail in Chapter 6.

CHAPTER 6: THE LAND DEGRADATION SCENARIO IN LESOTHO

In this chapter an interpretation is offered of the results obtained from analysing data on land degradation from 1989 to 1999. The first section focuses on the nature of vegetation changes and proceeds to a discussion of the extent to which the country was affected by the phenomenon and how severe degradation was during the decade. In the second section, relationships between land degradation and other environmental variables are discussed to determine causes of the deterioration.

6.1 VEGETATION CHANGES AND LAND DEGRADATION FROM 1989 TO 1999

The current section emphasizes vegetation changes that occurred in Lesotho between 1989 and 1999. The identified changes enabled potentially degraded areas to be isolated. The approximate extent of degraded areas is discussed and the severity of degradation in each district is indicated.

6.1.1 The nature of vegetation changes

The following is an evaluation of vegetation changes that occurred between 1989 and 1999. According to Table 5.1, the greatest change affected approximately 81% of the total land area on which NDVI increased, and about 18% of the land area experienced a decline in NDVI. Since vegetation was more vigorous in 1999 than in 1989 because of higher rainfall recorded in the former year, the estimates presented here do not necessarily reflect the extent of degradation between the two years. However, these estimates were used together with information gathered from personal communication with local experts to draw conclusions regarding potential land degradation that occurred during the study period.

6.1.2 Overview of land degradation in Lesotho

Visual interpretation of vegetation loss indicates that the greatest decline took place in parts of Lesotho highlighted in Figure 6.1. The degradation affected an estimated 18% of the total land surface. This means that the rate of vegetation loss is about 1.8% per annum. The estimate however, stands to be corrected and is only intended to provide a general idea of the rate of degradation.

If the estimate is a true reflection of reality, then the finding supports the claim that land degradation is threatening the dependency of Basotho on land. Previous findings by Moyo and O'Keefe (1993) estimated that 0.25 % of soil is lost from arable land annually. This finding and the present estimate of vegetation loss show that both vegetation and soil loss are important processes of land degradation in Lesotho.

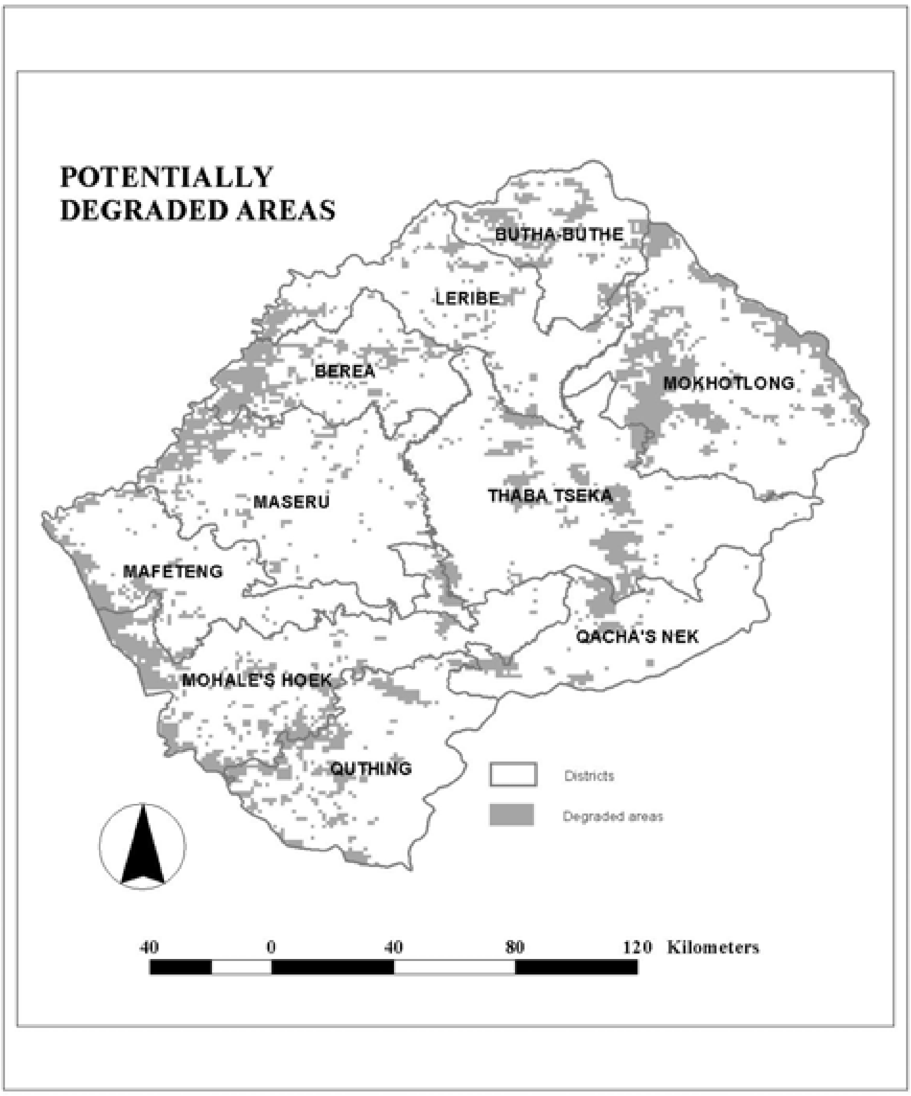

Figure 6.1 Potentially degraded areas of Lesotho from 1989 to 1999

Having established a broad view of land degradation in Lesotho, the scope of discussion was narrowed to land deterioration at the level of districts and is discussed in the section below.

6.1.3 Extent and severity of land degradation

The extent of degradation was determined by calculating the percentage of degraded land to the total area of each district. Estimates of the degree to which each district experienced degradation are shown in Figure 6.2.

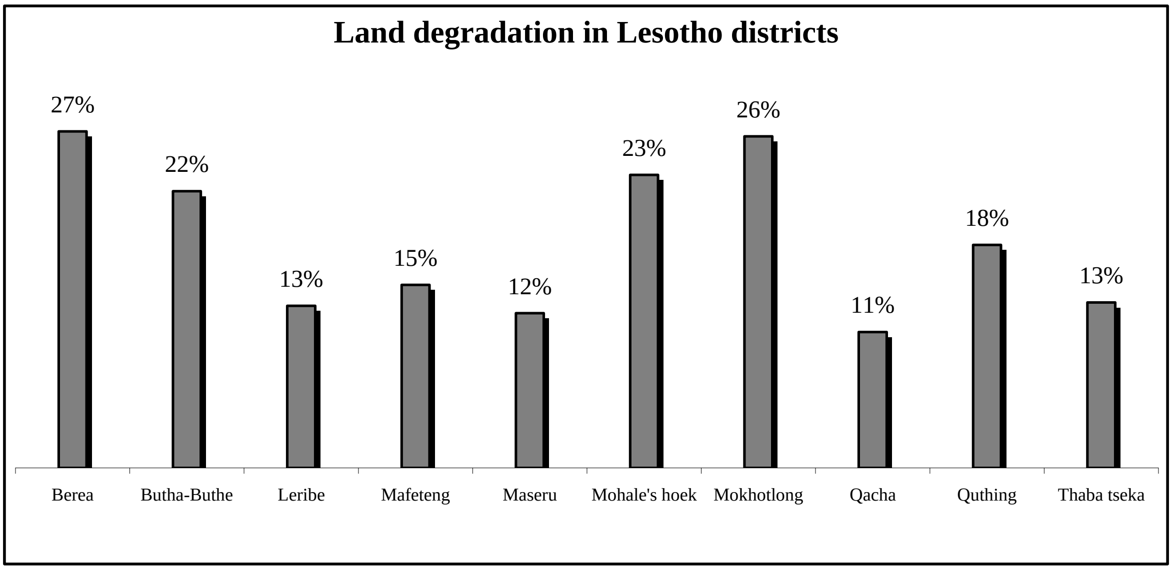

Figure 6.2 Extent of land degradation in the districts of Lesotho

Qacha's Nek experienced the lowest degradation of 11% and Berea the highest degradation (27%). Mokhotlong also experienced significant vegetation loss (26%) of the land area. Severity of degradation for each district was presented in Figure 5.3. Based on the results, degradation severity was minimal in Maseru, Qacha, Thaba-Tseka and Leribe. Mafeteng underwent moderate degradation, while Butha-Buthe, Quthing and Mohale's Hoek were severely degraded. Land degradation was very severe in Berea and Mokhotlong. A study by Costa and Baehr (s.d.) assisted in attempting to validate the results presented in Figure 6.2. According to the authors, soil erosion hazard was rated as very high in Mokhotlong and high in Mohale's hoek and Berea, which suggests the possibility of degradation being extensive in the three districts as presented here. Furthermore Mokebe (2005, Pers com), confirmed the likelihood of land becoming degraded in the lowlands of Lesotho, especially along the western boundary of the country because of fragile soils that are susceptible to erosion. According to the conservation officer, land has increasingly deteriorated throughout the whole country as confirmed by direct field observations made over the years. Mabote (2005, Pers com) explained that degradation in Mokhotlong, which falls within the Maloti Drakensberg Transfrontier Project (MDTP) area, land degradation was considerable, in a similar manner to that depicted in Figure 6.1.

The preceding discussions have put the Lesotho land degradation situation in perspective. Subsequent sections therefore cover causes and factors underlying the degradation.

6.2 CAUSES AND FACTORS UNDERLYING LAND DEGRADATION

The current section interprets results obtained after assessing possible factors responsible for land degradation in Lesotho from 1989 to 1999. Specific environmental elements that were studied to determine the causes of deterioration include: land cover and soil types, altitude, slope and direction of slope, and human and livestock population densities.

6.2.1 Land cover types

Associating land cover types with degraded areas aided the identification of land cover types that were likely to have experienced high degradation. According to Figure 6.3, all land cover types, except water, experienced loss of vegetation.

In relation to water, 15% of the total wetlands area suffered vegetation loss. The degradation was undoubtedly loss of wetland type vegetation, which is currently a serious problem in Lesotho. The majority of these wetlands are located in the Mokhotlong district as shown in Figure 4.5, where severity of degradation was found to be highest.

The low spatial resolution of NOAA AVHRR might explain the high loss of vegetation associated with rock surfaces. Because of the low resolution of the sensor, vegetation that occurred within an area of rock surfaces covered by one square pixel

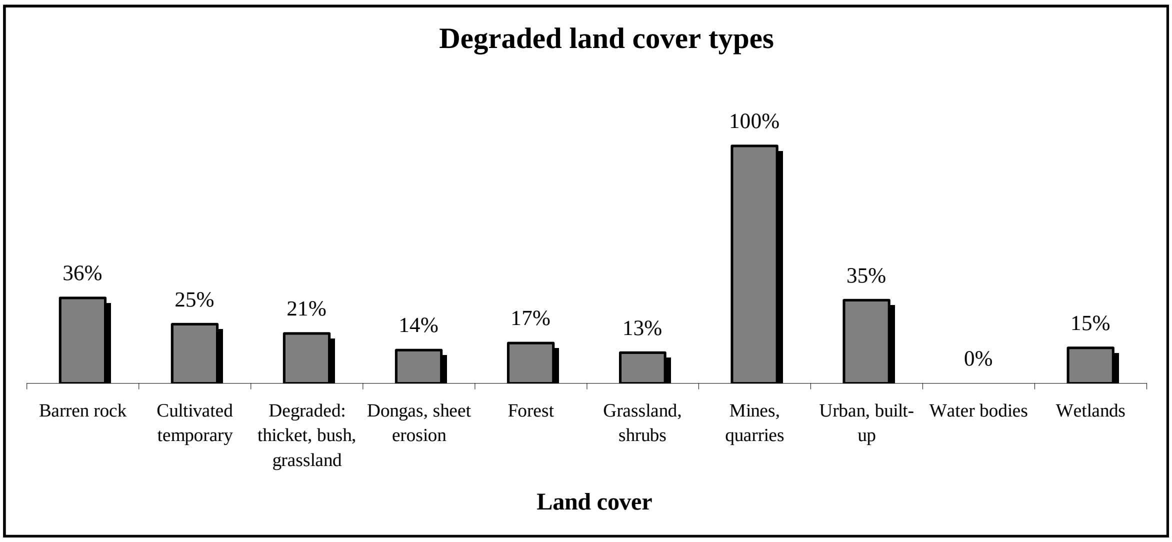

Figure 6.3 Land degradation associated with different land cover types of Lesotho

might have caused higher values of NDVI to be recorded in the 1989 and 1999 NDVI images.The areas classified as barren rock were derived from the higher resolution Landsat TM images and were therefore less generalized than NOAA AVHRR image data.

The mines and quarries class covers only about 0,004% of the total country area and experienced a unique 100% loss of vegetation. The location of the mine corresponds to the Lets'eng-la-terai diamond mine in Mokhotlong situated at $28^0 55^/ 0^{//}$ S and $28^0 49^/ 0^{//}$ E. The mine ceased operating in 1992 and mining activities that were carried out when the mine was still operating commercially from 1989 to 1992 are believed to be the reason for the deterioration. Individual diamond diggings can also account for continued degradation after the mine was closed.

Vegetation loss in built-up areas was also high. The vegetation degradation was attributed to expansion of settlements based on findings by Reizebos & Chakela (1985) that conversion of vegetated areas into built-up areas resulted in substantial loss of vegetation cover.

Crop farming on Lesotho's arable land is extensive and cultivated areas seem to have experienced a decline in vegetation from 1989 to 1999. Cultivation is carried out mostly along the western border of the country, comprising wheat, maize and sorghum. Decline in vegetation on cultivated fields is not necessarily an indication of degradation but the possibility cannot be disregarded especially when droughts have been reported in Lesotho. The Bureau of Statistics (1992) reported that during the 1991 and 1992 cropping season crop failure was high due to severe drought in Lesotho. The drought and other drought spells over the last decade could have induced the degradation crop fields implied in the present findings. As a result, potential degradation on arable land can be attributed mainly to climate change resulting in droughts, unsustainable farming practices and soil erosion.

Land with forest and forest plantations constitutes less than 1% of the total land area but draws attention to a serious problem facing Lesotho: forested areas experienced 17% vegetation decline. This loss is evidence of the cutting down of trees for firewood. Over-harvesting of trees is known to aggravate soil erosion and land degradation in the country.

In areas classified as gullies land degradation was detected. Soil erosion is critical in Lesotho and there is extensive gully formation across the country. The present results confirm that gully erosion occurred between 1989 and 1999, and the process was inevitably accompanied by loss of vegetation in surrounding areas.

The remaining land cover types of the grassland biome also underwent extensive degradation. Interestingly, the greatest vegetation loss occurred on degraded grassland zones. This confirms the land cover class categorized as degraded.

The above findings shed light on land cover classes that were possibly affected by land degradation between 1989 and 1999. However, at this stage, causes of the degradation can only be assumed. One assumption is that anthropogenic influences are the causes of the deterioration because human activities are intense in urban areas and on agricultural land. Humans can also be implicated in the depletion of the grassland vegetation because of the practice of collecting firewood from wooded areas, and the grazing of domestic animals. In addition, climate change resulting in droughts can be implicated in land degradation observable from 1989 to 1999. Having determined potentially degraded land cover types, attention will now focus on the related issue of soil types that were possibly affected by degradation.

6.2.2 Soil classes

In order to associate land degradation with soil types, the role of parent material was taken into account, mainly because the link between soil characteristics and geology has been recognized (Weaver 1991). The relation between land degradation and soil depth, as well as erodibility, was also determined. Potential vegetation degradation associated with different soil classes is presented in Figure 6.4.

Maximum vegetation degradation is associated with claypan soils. These soils are found mostly in the western parts of Lesotho (Figure 2.4) and on 9% of the total land area. If erodibility and depth play significant roles in soil degradation, then degradation associated with claypan soils can be accounted for by the high erodibility and shallow depth of these soils. Fertiallitic soils underwent less degradation than claypan soils. The former soils constitute only 3% of the land area and, like claypan soils, occur mostly in the western parts of Lesotho. Since fertiallitic soils are deep and show signs of extensive degradation, soil depth is not the most important factor in vegetation degradation. Degradation was also extensive on lithosols associated with sedimentary rocks. These Lithosols are found mainly in the western and eastern parts of the country.

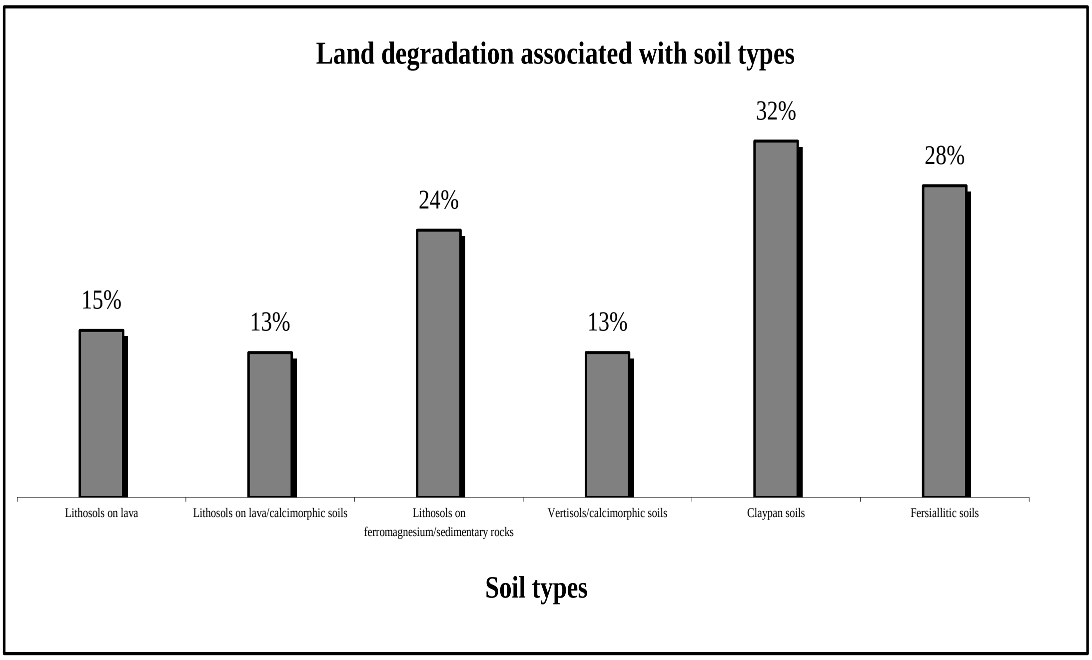

Figure 6.4 Land degradation associated with different soil classes of Lesotho

Although lithosols are shallow, they are not easily erodible, which is an indication that soil degradation depends on factors other than soil depth and erodibility. Deterioration of lithosols and vertisols associated with calcimorphic soils was low. Perhaps the limestone common to both soil types was the reason for the low degradation but this can only be verified by further research. The vertisols occupy 13% of the land area while the lithosols are found in a larger percentage (32%) of the land area. The vertisols are deep compared to the shallow lithosols, but both soil types experienced the same degree of degradation. This finding confirms the earlier statement that factors other than soil depth were more influential to the soil degradation.

Further association of soil classes and land cover types with land degradation was carried out within the broader context of ecological zones. The following is an account of land degradation within the ecological zones.

6.2.3 Ecological zones

Lesotho’s ecological zones have characteristic geology, soil properties, vegetation and altitude. The relationships between the individual biophysical elements and land degradation have been discussed previously. The role of altitude in influencing land degradation will be presented in subsequent sections. The ecological zones perspective also makes reference to human and livestock influences. Other links between population density and land degradation are presented in later sections. As a point of departure, proportions of different soil and land cover types within each zone are shown in Table 6.1.

As shown in Figure 6.5 the greatest extent of degradation occurred in the Lowlands and in the Senqu River Valley, and affected 28% of the total land area. Lowlands comprise approximately 20% of the total land area and are dominated by claypan soils and lithosols. Vertisols and fertiallitic soils are also found in a fairly large area. The zone is extensively cultivated as about 73% of the total area is used mainly for wheat and maize. Dairy farming is also important in the zone. NES (1999) reported that the area is densely populated with people and animals and that land degradation in the Lowlands was the result of poor agricultural practices.

Table 6.1 Soil classes and land cover types found in Lesotho's ecological zones

VARIABLE	ZONES							
	Lowlands		Foothills		Mountains		Senqu river valley	
SOIL TYPES	Count	%	Count	%	Count	%	Count	%
Lithosols on lava	6	0	369	11	5291	43,1	33	1,2
Vertisols and calcimorphic soils	470	10	558	17	1663	13,5	232	8,4
Lithosols on lava and on calcimorphic soils	132	3	1305	40	4639	37,8	1166	42
Claypan soils	1714	38	82	3	11	0,1	167	6
Lithosols on ferromagnesium and on sedimentary rocks	1625	36	928	29	169	5,4	1102	39,7
Ferstiallitc soils	593	13	14	0	14	0,1	75	2,7
TOTAL	4540	100	3256	100	12287	100	2775	100
LAND COVER TYPES								
Barren rock	29	1	6	0	3	0	9	0
Cultivated temporary	3317	73	430	13	994	8	401	14
Degraded: Thicket, bush and grassland	601	13	938	29	3208	26	1433	52
Dongas, Sheet erosion scars	-	-	7	0	-	-	-	-
Forest and forest plantations	11	0	1	0	-	-	-	-
Grassland and shrubs	490	11	1876	58	7995	65	936	34
Mines and quarries	-	-	-	-	1	0	-	-
Urban and built-up	75	2	1	0	8	0	1	0
Water bodies	7	0	-	-	-	-	-	-
Wetlands	1	0	1	0	45	0	-	-
TOTAL	4531	100	3260	100	12254	100	2780	100

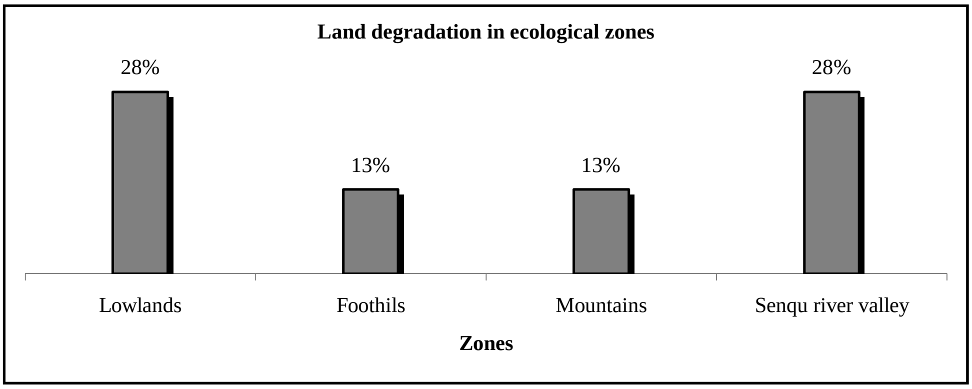

Figure 6.5 Land degradation in Lesotho's ecological zones

According to figures shown in Table 6.1, approximately half of the Lowlands grassland vegetation is degraded. In view of these facts, degradation of Lowlands from 1989 to 1999 was attributed to unsustainable agricultural practices, overgrazing and expansion of human settlements. The degradation could also be the result of high vulnerability of the zone to erosion because of the high susceptibility to erosion of its claypan soils.

The Senqu River Valley constitutes only about 12% of the land surface but also experienced substantial vegetation loss. The valley is dominated by lithosols and calcimorphic soils. Approximately 14% of the Senqu valley is used for crop cultivation and hence the high decline of vegetation between 1989 and 1999, as in the Lowlands, can be attributed to poor agricultural practices. Vegetation depletion can also be the result of grazing since Low & Rebelo (1996) found that the zone is used mainly for livestock grazing. Although built-up areas constituted only 0,04% of the total area, the authors indicated that pressure of increased human settlement on vegetated land was aggravating vegetation loss. This demonstrates that the Senqu River Valley grassland biome was increasingly taken over by settlements between 1989 and 1999 and this consequently lowered vegetation cover.

The Foothills and Mountain zones comprise 14% and 54% of Lesotho's land area, respectively. In both zones, land degradation affected 13% of the total area from 1989 to 1999. Lithosols and calcimorphic soils are the major soil types in the Mountain zone. As shown in Table 6.1, the mountain zone is the least cultivated in Lesotho. This means that pressure from agriculture in the Mountain zone was low and hence cultivation had a limited influence on loss of vegetation between 1989 and 1999. Grazing by domestic livestock is important in the Mountain zone and therefore it can be assumed that land degradation in the zone was the result of overgrazing. Since land degradation is a consequence of interactions between various factors, other physical factors such as steep terrain, severe climatic conditions and fragile soils are believed to have played a role in the deterioration that was detected. The main soil types found in the Foothills zone are lithosols, and the percentage of vertisols is relatively high. The areas of cultivated land is approximately equal to that of cultivated land in the Senqu River Valley. This shows that, in the Foothills, cultivation is more important than in the Mountain zone because of more favourable terrain and climatic conditions.

Terrain was implicated in the foregoing discussions as a significant cause of land degradation in Lesotho. Mountains, high altitudes and steep slopes are important terrain features of the country hence an account of how these features influenced land degradation from 1989 to 1999 is set out below.

6.2.4 Altitude

A simplified map of altitude variations in each ecological zone is shown in Figure 6.7.

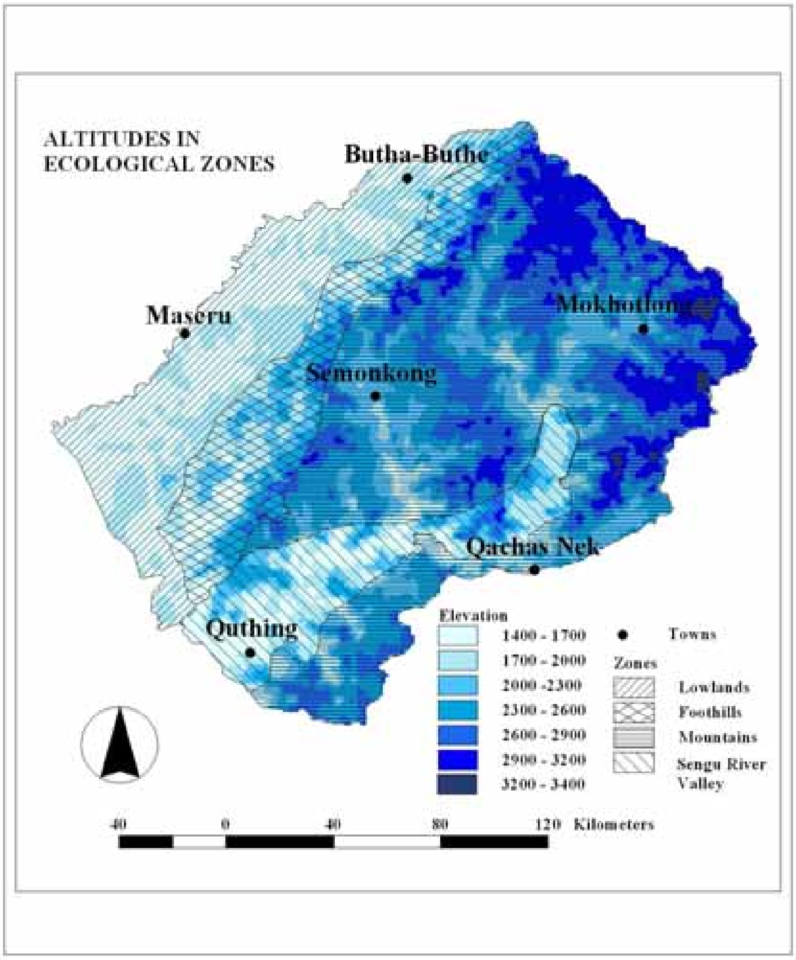

Figure 6.6 Elevations in different ecological zones of Lesotho

Figure 6.7 shows the extent of degradation at different altitudes. Maximum land degradation occurred at the lowest altitudes, from 1400m to 1700m, which is the range typical of the Lowlands and Senqu River Valley. In the next range, between 1700m and 2000m, the extent of degraded land in relation to total land area was slightly lower but equally significant. This is a sign that degradation had great impacts in the low-lying areas of Lesotho.

It is important to note that low altitude areas are used primarily for cultivation, which accounts for 57% of the total land surface. This is further evidence that agriculture contributed significantly to land degradation.

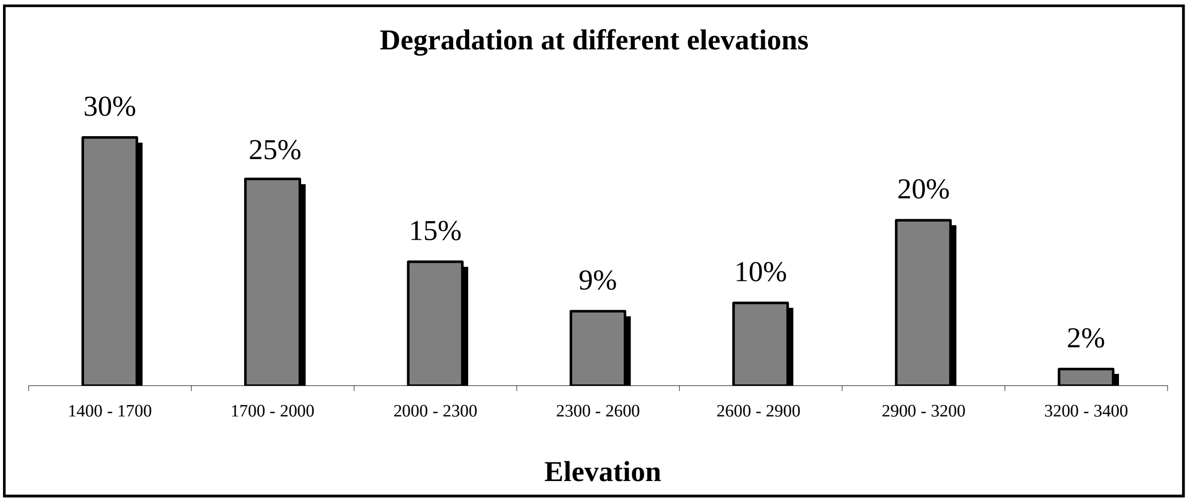

Figure 6.7 Land degradation at different terrain altitudes of Lesotho

From Table 6.1 it is evident that the density of built-up areas is higher at lower altitudes than in the highlands. Therefore, land degradation in zones below 2000m was likely to have been influenced by expansion of settlements.

Vegetation degradation decreased steadily with increasing altitude to the height of 2900m. These altitudes correspond to the Senqu River Valley, highest part of the Foothills and lower part of the Mountain zone. However, there was abrupt vegetation decline between 2900m and 3200m, and the least degradation occurred at the highest elevations, between 3200m to 3400m, in a zone that makes up only 0,4% of the total land surface.

The low degradation from 2000m to 2900m, and between 3200m and 3400m, can be attributed more to natural processes of degradation than to anthropogenic influences. This is because harsh climatic conditions coupled with difficult terrain make the zone unfavourable for human settlement. According to NES (2000), at altitudes higher than 2500m, snow and frost can occur throughout the year and during winter, temperatures can fall to -20^{0}C at night while daily average temperatures may be below freezing point. Moreover the area is above the level at which field crops can be cultivated, and there are only a few special purpose human settlements such as resorts and other tourist attractions. In summer however, the whole area of the highlands is grazed and therefore the low NDVI recorded suggests that in the highlands overgrazing is considerable. The amount of degradation also indicates that grazing might be more intensive in this zone than elsewhere in the highlands.

Even though lithosols are not vulnerable to erosion, at high altitudes the soils are prone to erosion because of steep slopes and torrential rain. The shallowness of the lithosols might have contributed more to land degradation in this zone than at lower elevations. In addition, slope becomes important as altitude increases. The following section analyses the relationship between steepness of slope and land degradation.

6.2.4.1 Steepness of slope

As depicted in Figure 6.8, degradation was highest on the gentle slopes and gradually declined so that steepest slopes experienced the lowest vegetation loss.

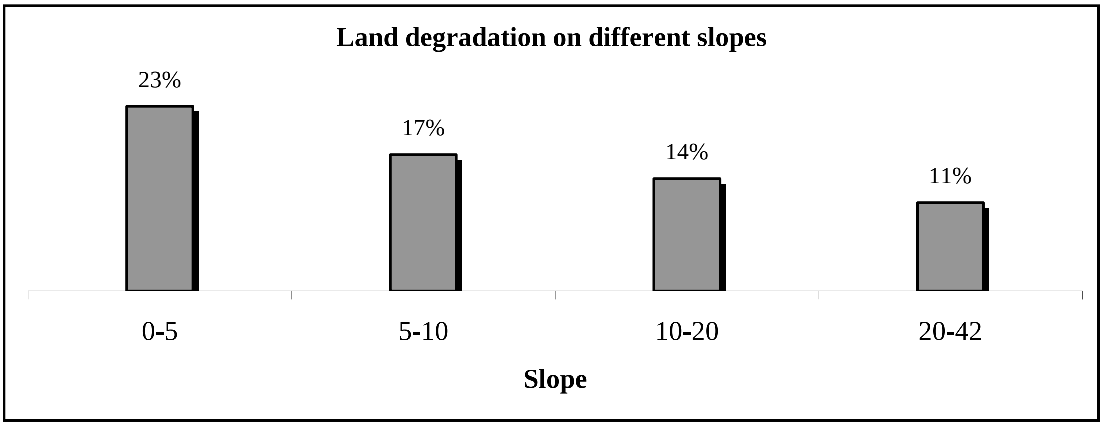

Figure 6.8 Land degradation on different slopes

The parts of the country with slopes less than 5% experienced extensive vegetation loss. These slopes are more prevalent in the Lowlands and are found on an estimated 74% of the zone's terrain (Table 6.2). The slopes constitute about 34% of the Foothills and 35% of Senqu River Valley as well as the Mountain zone. Vegetation loss on parts of the country with gentle slopes can be attributed more to human activities than steepness of terrain. This is mainly because gentle slopes are suitable for cultivation and arable areas have the largest concentration of people, with average population density of 816 persons per km^2.

Table 6.2 Slopes found in different ecological zones of Lesotho

PERCENT SLOPE	**ECOLOGICAL ZONES**							
	Lowlands		Foothills		Mountains		Senqu River Valley	
	Count	%	Count	%	Count	%	Count	%
0-5	3361	74,3	1118	34	4316	35	963	34,7
5-10	923	20,4	1043	32	4243	35	773	27,9
10-20	232	5,1	931	29	3208	26	825	29,8
20-42	9	0,2	167	5	479	4	211	7,6
TOTAL	4525	100	3259	100	12246	100	2772	100

In summary, land degradation decreased with increasing slope steepness. It follows then that slope gradient relates to degradation but the impacts were exacerbated by pressure from human activities, which happened to be high on level parts of the country. The following section adds another point of view to the topography-land degradation relationship by investigating vegetation depletion in relation to direction of slope towards the sun.

6.2.4.2 Aspect

Research involving aspect places emphasis on studying north and south-facing slopes, as was done by Andre & Anderson (1961), Churchill (1981) and Weaver (1991). Slopes in Lesotho were grouped into four directions for more insight into how land degradation was related to aspect. The following is an account of land degradation on slopes facing north, east, south and west. Table 6.3 shows slope directions in different ecological zones.

Table 6.3 Slope directions in different ecological zones

ASPECT	ECOLOGICAL ZONES							
	Lowlands		Foothills		Mountains		Senqu River valley	
	Count	%	Count	%	Count	%	Count	%
Flat	722	16	38	1	132	1	53	1,91
North	1138	25	884	27	2757	22	630	22,61
East	723	16	486	15	2822	23	599	21,61
South	767	17	583	18	3155	26	747	26,95
West	1206	26	1268	39	3480	28	743	26,80
TOTAL	4556	100	3259	100	12346	100	2772	100

As Table 6.3 shows, 39% of slopes face west in the Foothills and a notable 27% of slopes are north-facing. The Mountains and the Senqu River Valley are dominated by west and south-oriented slopes. There are similar proportions of cultivated areas, with minor differences in all slope directions.

Figure 6.9 relates degradation between 1989 and 1999 to aspect. The range of degraded vegetation in relation to aspect is narrow, from 15% to 18%.

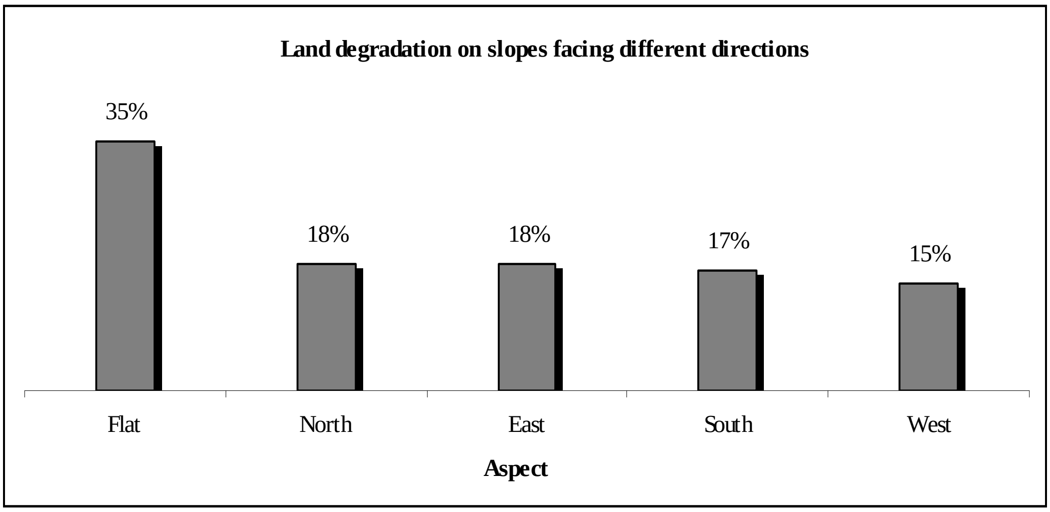

Figure 6.9 Land degradation in Lesotho in relation to slope direction

Land degradation on flat areas was greatest while the degree of degradation on other slopes was similar. Soil erosion of slopes oriented both north and south is well documented and, as a result, more emphasis was given to characteristics of these slopes to explain the observed NDVI decline. Weaver (1991) found north-facing slopes more heavily eroded than south-facing slopes in the Ciskei. The results are similar in the present study. In Lesotho, north-facing slopes receive more solar radiation than south-facing slopes and tend to be drier. The latter have higher antecedent moisture than the former and are more conducive for plants to thrive, which might explain the higher vegetation depletion on the north-facing slopes. Since a significant area of north-oriented slopes is cultivated, the strain of agriculture and overgrazing probably played significant roles in the degradation. There was a higher percentage of settlements on east-facing slopes than on the north-facing slopes, and hence vegetation decline can be attributed more to human interference than to climatic conditions. West-facing slopes are sunny because they receive afternoon sunlight but like east slopes, receive lower solar radiation than north-facing slopes.

In the preceding section, human activities and overgrazing were implicated as possible causes of land degradation. A detailed assessment of the link between population densities to land degradation is provided below to confirm the assumptions.

6.2.5 Human population and livestock densities

The Lesotho population growth rate during the decade of 1989 to 1999 was estimated at 2.6% per annum (NES 2000). High human population in Lesotho is associated with high stocking rates, which exert pressure on land resources. In view of this, the relationship between population densities and land degradation in Lesotho during the study period is described below.

The highest human population densities are found in Berea, Leribe, Mafeteng and Maseru (Figure 2.6). Mokhotlong has the lowest population density while Qacha, Thaba-Tseka and Quthing have lower densities than Mokhotlong. In the remaining districts of Mohale’s Hoek and Butha-Buthe, population densities are moderately high. From Figure 6.2, Mokhotlong experienced high degradation even though it has the lowest population density. Berea, Butha-Buthe and Mohale’s Hoek were also significantly affected by land degradation. Out of the three districts, Berea has the highest population density of 135 persons/km^2 against an average of 75 persons/km^2. In Quthing, where population density is relatively low, degraded land as a percent of total area was moderately high while degraded land was quite low in the highly populated Mafeteng district. Leribe and Maseru have population densities greater than average but only 13% and 12% of their total land areas suffered degradation, which is comparable to the area of degraded land in the low population density of the Thaba-Tseka district. Qacha’s nek is not densely populated and experienced the lowest vegetation depletion. The results can be explained by assuming that there was expansion of population into lower density areas.

The findings suggest the possibility of a direct relationship between land degradation and population density as, for instance, in Berea, Butha-Buthe, Qacha’s nek and Thaba-Tseka. In the remaining six districts, there is no clear-cut relation of population density to land degradation. Before drawing conclusions about findings thus far, attention will be focused on the relationship of animal density to land degradation. Figure 6.10 shows land degradation versus livestock numbers in Lesotho districts.

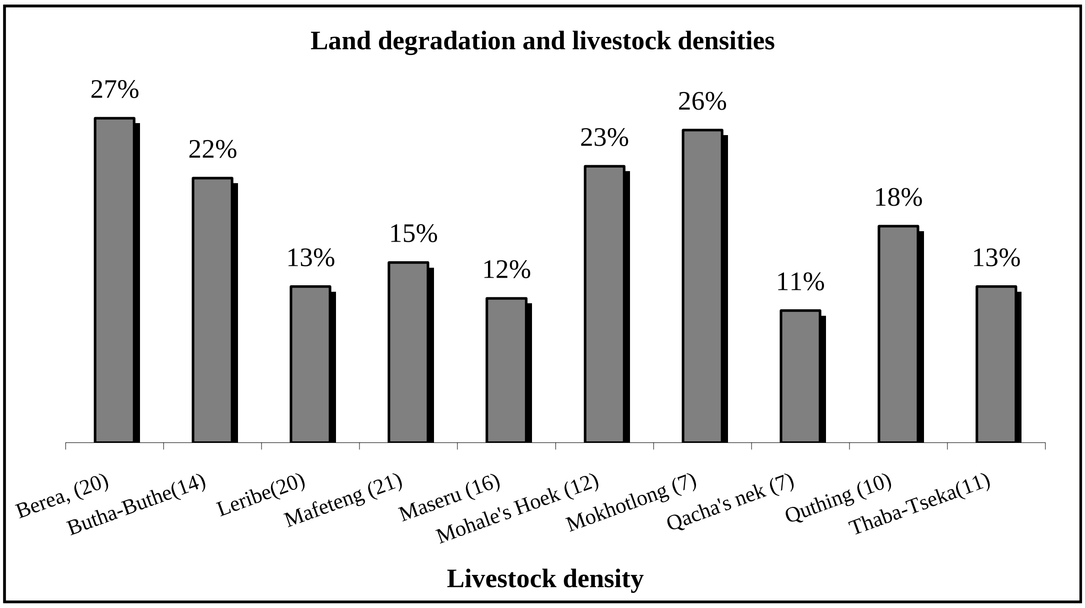

Figure 6.10 Land degradation and livestock densities in Lesotho

Berea, Mafeteng and Leribe have the highest stocking rates, followed by Maseru and Butha-Buthe. Mohale’s Hoek, Quthing and Thaba-Tseka have fairly high livestock densities while the lowest density is found in Mokhotlong and Qacha’s nek. High stocking rates in Berea are accompanied by considerable vegetation loss, whilst low stocking rates had little impact on land degradation as is the case in the Qacha’s nek district.

Leribe, Mafeteng and Maseru have higher stocking densities than Butha-Buthe and Quthing but had a smaller area of land affected by degradation. Moreover, Mohale’s Hoek and Thaba-Tseka have similar stocking densities but the former experienced more degradation than the latter. In Mokhotlong where stocking density is very low, the highest percentage of total land area suffered degradation. So far, there is little indication that heavily degraded areas occur in highly populated areas, which necessitates an investigation of the relationship from a different point of view. Human and livestock population densities on arable land were therefore considered to account for the fact that the less mountainous areas of the country are the most densely populated. Table 6.4 shows population densities per km^2 of cultivable land and degraded land in all districts. The relationships are shown in Figures 6.11 and 6.12.

Table 6.4 Human and livestock densities per km^2 of Lesotho's arable land

District	Percent degraded	Arable area km^2	Percent of total area	Population density per km^2 of arable land	LSU per km^2 of arable land
Berea	27	326	15	922	140
Butha-Buthe	22	105	6	1209	254
Leribe	13	424	15	855	136
Mafeteng	15	531	25	450	85
Maseru	12	463	11	1032	150
Mohale's Hoek	23	396	11	522	110
Mokhotlong	26	161	4	557	195
Qacha	11	85	4	945	206
Quthing	18	155	5	907	202
Thaba-Tseka	13	176	4	760	289
AVERAGE				**816**	**177**

Table 6.4 brings to attention that humans and livestock are concentrated in small areas of land relative to the total land area. The districts which appear in the upper half of the table, except Butha-Buthe, are typically Lowlands districts while the remaining districts in the list are mountainous.

From Figures 6.11 and 6.12, there are no clear relationships between population densities and land deterioration. However, the following statements can be made based on Table 6.4 but need to be investigated further in the future. Land in the highland districts suffered considerable deterioration and, in these districts, livestock density is higher than the average 177 LSU/km^2. This is an indication that high animal stocking rate is more accountable for degradation than human population density. This is especially true as NES (2000) showed that livestock are driven from other ecological zones to the Mountain zone for summer grazing, and hence bring about significant degradation of highland rangelands.

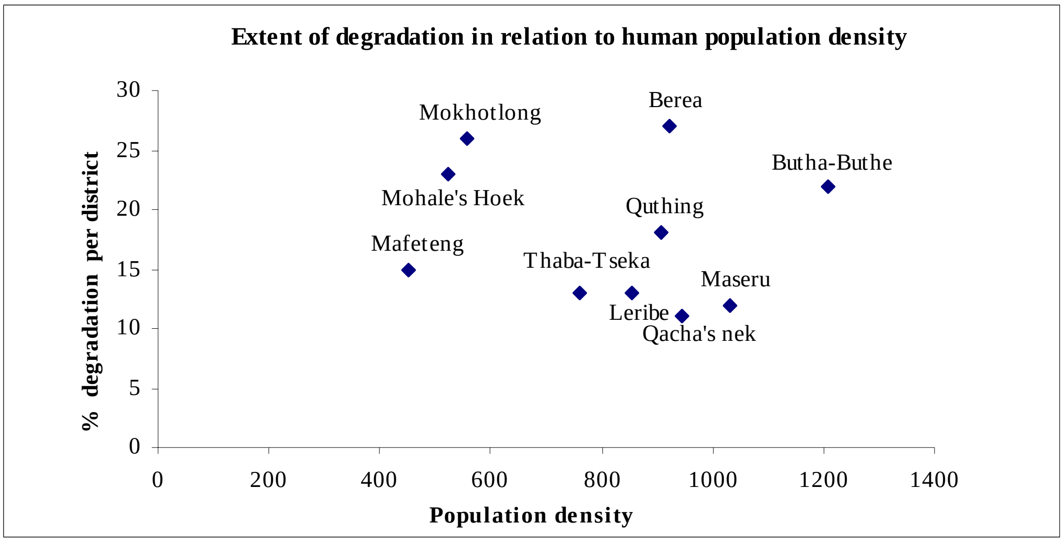

Figure 6.11 Human population densities and land degradation in Lesotho

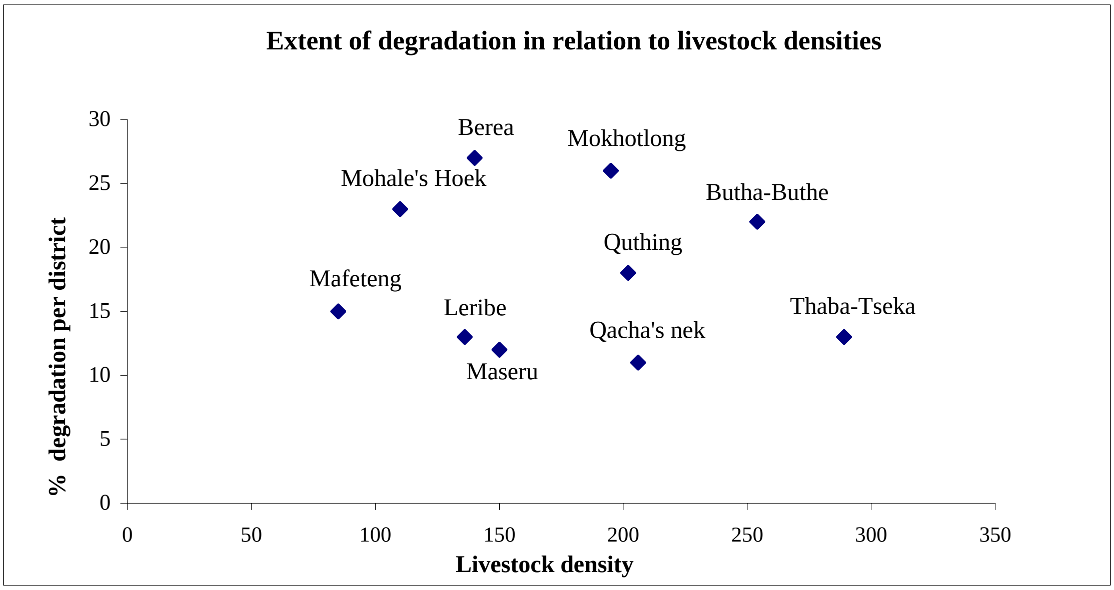

Figure 6.12 Livestock densities and land degradation in Lesotho

In Butha-Buthe, high human population density might be equally influential as well. In Maseru, human population density is significantly high on arable land, while stocking rate is low. This implies that pressure exerted by people had more negative impacts on land than livestock. In Mafeteng, the low degradation can be attributed to low human and livestock densities. In the rest of the districts, it is possible that factors other than population density were more important causes of land degradation.

6.3 SUMMARY

Lesotho experienced significant land cover changes from 1989 to 1999. Some of the changes were associated with land degradation because of apparent loss of vegetation over the time period. Impacts of land degradation varied across the country so that severity of degradation ranged from low to high in different districts. By studying environmental variables, land degradation was attributed to both demographic pressure and biophysical factors. Cultivation and overgrazing on marginal lands seemed to have played a pivotal role in vegetation loss. Widespread degradation was detected on the arable parts of the Lowlands where both cultivation and human settlements were extensive. Signs of grassland depletion and forest decline were also evident and were attributed to population expansion, overgrazing and indiscriminate cutting of trees and shrubs for firewood.

CHAPTER 7: CONCLUSION AND FUTURE RESEARCH

7.1 SUMMARY

The study demonstrated that NOAA AVHRR NDVI images can be used effectively for detecting land cover changes in Lesotho. The sensor acquires images at low spatial resolution for coverage of large geographic regions of the earth. NDVI images are among products that are generated from the AVHRR data to provide information about the quantity of biomass on the earth's surface. Two such NDVI images were obtained to facilitate analysis of land degradation from 1989 to 1999 in Lesotho. Differences between the NDVI images made a nationwide monitoring of vegetation change possible and formed the basis for undertaking a synoptic assessment of land degradation.

Various remote sensing methods have been developed for land cover change detection and, in the present study, vegetation changes were identified by image differencing, which involved finding the difference between the earlier date NDVI image and the later date image. The resulting NDVI change map showed land areas that had experienced vegetation loss, which were identified as potentially degraded. The change data was combined with other data sets to determine how potentially degraded areas were influenced by different environmental variables and population pressure. These relationships hinted at some causes of land degradation in Lesotho. Analysis procedures also showed that remotely sensed data can be successfully integrated with other data sets, using GIS techniques, to derive useful information about land degradation. The following section presents the conclusion reached from results of land degradation analyses.

7.2 CONCLUSION

Previous studies have reported on the magnitude and significance of land degradation in Sub-Saharan Africa. Some of the findings were considered to be subjective exaggerations concerning the extent and progress of land degradation. Use of remote sensing methods has been recommended for monitoring land degradation because remotely sensed data enable monitoring of large areas at more frequent intervals than intensive ground based research. As a result, the present research addressed the perceptions that the Southern African region continues to undergo severe land degradation, and that the phenomenon can be successfully monitored using remote sensing change detection. According to previous findings, drought and desertification combined with overexploitation of land resources, were causing the quality of land resources to diminish. In this regard, the present study made use of satellite data in addressing three themes: identifying degraded areas, establishing the extent of degradation, and determining causes of land deterioration.

Regarding remote sensing change detection, the results showed that there were considerable vegetation changes in Lesotho during the study decade, as depicted by NDVI changes. It follows then that NDVI differencing was appropriate for determining vegetation depletion in the country. Since decline in NDVI values reflected vegetation depletion, the depletion was taken to be an indication of potential land degradation because vegetation loss usually implies ecosystem disturbance. However, the areas were recognized as *potentially* degraded to account for land use activities that involved removal of vegetation without necessarily causing degradation. The magnitude of land degradation was quantified using grid cell based calculations and potentially degraded areas were found to constitute a significant proportion of the total land area, in spite of the fact that overall NDVI values increased between 1989 and 1999 due to a higher seasonal rainfall in 1999. The extent of degradation was found to vary between districts and between ecological zones. Severity of degradation, as reflected by the area of degraded land to the total land area of each district, ranged from low to high. This result reflected the degree to which impacts of biophysical variables and human activities on land varied from one district to another.

Vegetation depletion appeared to be predominantly the result of anthropogenic pressure, especially livestock pressure. A link was also found between vegetation decline and topography, altitude and geology. The location of degraded areas corresponded to significant areas of grassland. Potential grassland degradation was attributed mainly to overgrazing and to the practice of wood collection for fuel. In the light of livestock grazing, high degradation occurred in districts with higher stocking rates per km^2 of arable land than human population density. This is an indication that overgrazing is a consequence of overstocking, and it resulted in considerable rangeland vegetation loss. This is not to say that humans did not contribute to the deterioration, but that there was a more direct relation between livestock population density than human population density to vegetation decline in each district. The role of humans was inferred from the extensive loss of vegetation that occurred in the Lowlands zone where the landscape is flatter and has a greater extent of settlements, cultivated areas and other economic activities than in any other zone. The Lowlands are densely populated and more so because people tend to migrate to peri-urban areas for better access to social facilities and services. Besides high stocking rates, land degradation in the Lowlands was attributed to population density accompanied by intensive land use activities. Cultivation was also important in this regard because locations of degraded areas mostly coincided with cultivated areas. Deterioration of agricultural land is an indication of a decline in agricultural productivity. Reasons for the decline have been cited in previous studies as drought, improper farming practices and encroachment of buildings onto agriculturally productive land. The degradation was also a sign of increased intensity of cultivation and cultivation on marginal lands to accommodate demands brought about by population expansion. In the highlands, degraded areas that were identified were more likely to be the result of livestock overgrazing and harsh climatic conditions that create conditions unfavourable for the recovery of vegetation from prolonged livestock pressure.

Concerning soils and geology, extensive biomass decline was associated more with soils in the Lowlands derived from sedimentary rocks than soils of basalt origin that occur mostly in the highlands. Apart from parent material, soil erodibility provided a better indication of susceptibility to erosion than soil depth. Hence the mountain zone lithosols with low erodibility experienced lower degradation than the easily erodible claypan soils found predominantly in the lower altitudes. Significant degradation was also detectable on gentle slopes where land uses such as cultivation and expansion of settlements were identified as the main causes of the degradation. There was also evidence of greater vegetation depletion on north and east-facing slopes than on other slopes. The depletion was considered to be the result of the fragility of ecosystems resulting from lack of soil moisture caused by intense solar radiation. This, combined with land use exacerbated land degradation.

Drought is believed to have played a significant role in the land degradation that occurred from 1989 to 1999. Impacts of drought were not investigated but were only assumed because other studies indicated that Lesotho has suffered from recurrent droughts over the recent past. Moreover, desertification conditions are believed to be setting in, in the country. A synoptic assessment of the impacts of drought and desertification has been left for subsequent studies. The following sections highlight limitations encountered in the study, such as those that hindered the assessment of the role of drought in land degradation. Following the limitations, recommendations on further research to improve the present study are highlighted.

7.3 LIMITATIONS

Limited rainfall data were available from all weather stations in Lesotho. As a result calculations involving monthly rainfall data, performed prior to obtaining NDVI images, were based on limited rainfall records. However, available data facilitated detection of land cover changes from which reasonable conclusions regarding land degradation were drawn. Still on the issue of data availability, only single date land cover data were obtainable for relating vegetation to land cover types. This is because there are few digital GIS data sets that have been generated for Lesotho as GIS technology is not yet fully established in the country. Even though useful information was derived, specific conversion between land cover types could have shed more light on the nature of land degradation. In addition, the scale and historical focus of the study, coupled with time and budget constraints made it impossible to conduct field visits for verifying location of potentially degraded areas. Recommendations are made for future research to address the above shortcomings.

7.4 FURTHER RESEARCH

Low spatial resolution satellite data were useful for identifying nationwide land degradation. Future research could focus on obtaining and using high resolution data for a detailed analysis of factors underlying land degradation. Another study could focus on the relation of land degradation to a specific element of the environment, for instance, the impacts of human and livestock pressure on land resources. In this regard, elaborate statistical correlations can be applied to quantify the relationships. On a different note, the impacts of climatic conditions, including drought, could also be investigated in separate research to establish how climate is accountable for land degradation. Finally, methods of change detection other than image differencing could be used to further develop remote sensing research in Lesotho.

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